Beneficial Use of Produced Water in Texas

Texas Produced Water Consortium Report to the Texas Legislature 2024

Texas Produced
Water Consortium

Acknowledgment

The Texas Produced Water Consortium (Consortium) was created by the Texas Legislature through the passage of Senate Bill 601 during the 87th Regular Session in 2021 to bring together information resources to study the economics of and technology related to, and the environmental and public health considerations for, beneficial uses of fluid oil and gas waste.

Although it is housed at Texas Tech University, the Consortium is comprised of the involvement and contributions of a wide and diverse spectrum of members representing all facets of the produced water space. Without their support, feedback, and expertise the Consortium itself would not exist. TxPWC would also like to thank the leadership of the State of Texas for their continued dedication to future resource planning of our state.

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1 Executive Summary

1.1 Legislative Updates Since the 2022 Report

Since its inception in 2021, the Texas Produced Water Consortium has joined a growing chorus of stakeholders with a vested interest in finding new solutions for produced water management across our state and nation. As outlined in our 2022 Report to the Texas Legislature, Texas is a state plagued by current and rapidly increasing water shortage concerns[1]. Meanwhile, the oil & gas industry generates excess quantities of produced water as a byproduct that has to be managed by their operations. The Texas Legislature has a storied history of water-forward thinking, and thus the Consortium was created to bring together information resources to determine the environmental and economical viability of treating produced water for beneficial use outside of the oil & gas industry. During the 88th Regular Session in 2023, the Legislature passed Senate Bill (SB) 1047 and appropriated an additional $5 million to the Consortium to continue its work towards finding solutions, namely focused on the establishment of pilot projects designed to provide information on achievable water qualities and treatment technology capabilities in a rapidly evolving landscape of water management options.

That same year, the Texas Legislature also passed one of the most significant water-related pieces of legislation in its near 200-year existence with SB 28 and the associated Senate Joint Resolution (SJR) 75. These paved the way for voters statewide to approve the development of a new $1 billion water fund, administered by the Texas Water Development Board, under Proposition 6. Under the provisions of SB 28, this new fund is to be utilized across a wide variety of projects, including a significant approach to addressing aging infrastructure and mitigating water loss. Additionally, a minimum of 25% of the fund must go towards projects promoting the development of new water sources, specifically to include marine and brackish desalination, and produced water treatment. Prop 6 received one of the highest passage rates on the November 2023 ballot with 78% approval, or almost 2 million ‘yes’ votes[2]. By comparison, voters approved the 2013 creation of the $2 billion State Water Implementation Fund for Texas with 73% approval[3], potentially indicating both a widespread and growing acceptance for water infrastructure related funding. While there is still significantly more work to be done to address future water needs for all Texans, this is an achievement that warrants immense exaltation for the policymakers, regulators, and voters of this state.

1.2 Pilot Projects

Being able to demonstrate water treatment capabilities is paramount to the purpose of the Consortium. Taking the theoretical into the practical through pilot projects is a crucial step in advancing the potential for utilizing all new water sources in an economical manner. What we achieve through the process of produced water treatment translates into the furtherance of

[1] https://www.depts.ttu.edu/research/tx-water-consortium/downloads/22-TXPWC-Report-Texas-Legislature.pdf
[2] https://ballotpedia.org/Texas_Proposition_6,_Creation_of_the_Water_Fund_Amendment_(2023)
[3] https://ballotpedia.org/Texas_State_Water_Fund_Amendment,_Proposition_6_(2013)

knowledge and promising potential for other water sources, especially those with lower salinity such as seawater and brackish water.

Over the past year, the Consortium has worked with multiple companies operating pilot projects across the Delaware and Midland Basins to obtain samples for constituent analysis and associated whole effluent toxicity testing. Samples were submitted to a third party NELAP certified laboratory, Eurofins Scientific. While the Consortium members are currently reviewing that data for a future white paper, initial results reported by Eurofins and the participating projects show very promising results. Across the five (5) current projects, incoming raw water salinity ranged from 55,000 mg/L total dissolved solids (TDS) up to 190,000 mg/L. The resulting treated water salinities ranged from as low as 36 mg/L to 900 mg/L TDS with an average of 376 mg/L TDS.

TDS is just one of a panoply of constituents that must be considered as we continue discussing produced water's viability as a new water source for uses beyond the oil & gas industry, but these results are positive indications thus far. The Consortium is working to produce a thorough examination of constituent analysis and member discussion later this year.

1.3 Standards

Through state and federal delegation over the past decade, both the Railroad Commission of Texas (RRC) and the Texas Commission on Environmental Quality (TCEQ) have certain jurisdictions regarding the permitting of produced water for various uses and discharges. In brief, TCEQ is responsible for permitting all direct surface water discharges to "water in the State," while RRC is currently responsible for permitting all other potential beneficial uses[4]. Both agencies have already begun implementing measures addressing the potential for permitting produced water for beneficial reuse outlined later in this report.

In January 2024, the RRC promulgated a pilot study framework for produced water recycling through land application[5]. This initial approach to piloting and permitting includes many quality variables for consideration, including an approach to limiting the concentration of constituents such as ammonia which is a source of nitrogen that could prove beneficial in certain crop applications. There are other exclusions at present, however, that warrant further consideration such as benzene, toluene, ethylbenzene and xylene, otherwise known as BTEX. Likewise, TCEQ has a long history of delegated authority by the EPA to regulate various water permits; most applicably given control to administer the National Pollutant Discharge Elimination System (NPDES) for discharges from produced water in 2021[6]. These programs are backed by decades of research leading to foundational knowledge and resulting permit standards for potable and non-potable water uses.

These existing standards are the obvious choice as a starting reference for treated produced water permitting. Additionally, the purpose of this Consortium is to work with all state regulatory agencies in the continuous review of data and analysis of produced water treatment capabilities and achievable qualities while providing recommendations to their permitting

[4] Texas Water Code §26.131
[5] https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/environmental-permit-types/pilot-projects/
[6] https://www.epa.gov/newsreleases/epa-approves-clean-water-program-texas-commission-environmental-quality

processes for any revisions or additions that Consortium members feel necessary. Forthcoming publications on data review will provide crucial guidance and insights for these agencies in the continuation of their regulatory oversight.

1.4 Economics

Economic viability continues to be the most significant hurdle to beneficial use of treated produced water. From the Consortium's 2022 report, the cost of disposal via injection (estimated at between $0.60-0.70/bbl) drastically outweighs the current capital and operating costs required to treat produced water to beneficial reuse qualities, even offset by the potential value of that treated water to external users such as irrigated agriculture and municipalities, among others[7]. Progress in technological efficiencies, declining available water resources, and other market forces will continue to narrow that delta over time.

In order to better understand future potential values, the Consortium contracted with WestWater Research to dive deeper into the projected value of freshwater resources across the Permian Basin to more realistically inform the potential value of treated produced water as a new source or an offset to freshwater. The two most identifiable users in the region, being irrigated agriculture and municipalities, were utilized to develop projections of "willingness to pay" for freshwater resources aligned with Texas Water Development Board (TWDB) State Water Plan estimates to the year 2050. The outlook for irrigated agriculture remains largely unchanged from our 2022 report, with a marginal increase in willingness to pay of $0.0020-0.0045/bbl by 2050 under current market conditions. Municipal value, however, shows a stark contrast between current and projected water values depending on future shortages and availability of resources, potentially rising as high as $0.69-0.85/bbl in that same period under extreme circumstances as illustrated in Table 1. These estimates underscore several critical realizations; first, our current prices for freshwater are likely well undervalued. Second, without an absolute guarantee of future resource adequacy through development and improved access to new and existing water sources, scarcity conditions could lead to a momentous rise in cost for future populations.

Table 1: WestWater Research estimated willingness to pay for municipal shortage avoidance.

Estimated WTP under Multiple Shortage Scenarios (2030-2050), ($/AF			
Shortage Level	Year		
	2030	2040	2050
5%	$2,790	$2,931	$2,999
10%	**$3,341***	$3,509	$3,591
15%	$4,043	$4,246	**$4,344****
20%	$4,948	$5,196	$5,317
25%	$6,135	$6,443	$6,593

*Average projected shortage across the Permian Basin in 2030 is 9.4%.
**Average projected shortage across the Permian Basin in 2050 is 13.7%.

In considering other pathways to economic viability for a system of treating produced water, carbon capture/sequestration could be a considerable alternative especially when appropriately paired with land application with a target towards crop propagation and/or ecosystem restoration. This is a bourgeoning area, however, with the ongoing development of carbon markets and federal regulations, and industry participation in establishing varying infrastructure as a result. Further information is needed both on the stability of future markets as

[7] https://www.depts.ttu.edu/research/tx-water-consortium/downloads/22-TXPWC-Report-Texas-Legislature.pdf

well as our continued efforts to assess environmental impacts to land, wildlife and livestock that are an essential component of prairie ecosystems.

The Consortium also takes this opportunity to highlight the work of our partners at the Department of Energy with their **P**roduced Water **A**pplication for Beneficial **R**euse, **E**nvironmental Impact and **T**reatment **O**ptimization (PARETO) software, an undertaking 3-years in the making. The initiative is committed to developing open-source decision-support software for the broader produced water (PW) community. The PARETO suite of tools facilitates cost-effective, resource-efficient, and environmentally sustainable PW management decisions using mathematical optimization tools. The tools have been designed with input and feedback from O&G (oil and gas) industry stakeholders since the project's inception and support all major stages of well operation, PW treatment, disposal, and beneficial reuse. More information on the PARETO project can be found in the addendum section.

1.5 Technologies & Volumes

Following up on the multitude of treatment technology options explored in our 2022 report, the Consortium ventured to further narrow in on the current potential leading systems for treating varying qualities of water across the Permian Basin. While there are many treatment systems, both established and novel, that more than warrant continued consideration, the review of this report focuses specifically on the potential for reverse osmosis/ultra high pressure reverse osmosis (RO/UHP-RO) and mechanical vapor compression/recompression (MVR) as the most efficient current commercial technologies.

In instances where salinity approaches an average of 70,000-80,000 mg/L TDS, as can be the case in certain areas of the Delaware Basin, a RO/UHP-RO treatment system (membrane based technology) could be the most cost-effective treatment approach as opposed to MVR. This represents an uptick in membrane capabilities that have historically been limited by their lower level tolerances for salinity compared to thermal processes. More work through laboratory and field trials should be conducted for increased understanding.

Alternatively, thermal desalination through systems like MVR continues to be the most robust approach to dealing with higher salinity ranges like the averages we see in the Midland Basin and parts of the Delaware as well, 120,000-130,000 mg/L TDS to be specific. At this elevated salinity, and taking into consideration common issues such as scaling of calcium carbonate and ammonia carryover, MVR may provide a cost-benefit in energy savings as well as post-treatment reduction.

Outlined in an addendum at the end of this report is an updated analysis of current and projected produced water volumes in the Permian Basin. Currently, the daily water production from unconventional (horizontal wells) in the Permian basin is 12 MMBbls (1,547 Acre-Feet) split roughly 50/50 between the Midland and Delaware Basins. The production forecast shows a maximum daily rate of 15 MMBbls (1,935 Acre-Feet) in 2042 in our projected base case. A review of an additional 7,000 samples also shows the potential for major portions of the Delaware to experience lower salinity than the Midland, potentially leading to higher recovery rates and more affordable treatment approaches.

1.6 Upcoming Research Projects

The Consortium continues to pursue all options for achieving environmentally safe and economically viable options for treating and reusing produced water; to that end, and in addition to the continued research outlined already, there are a few other projects specifically slated for development in the coming year(s).

Beyond the traditional crops grown in the oil & gas producing regions of Texas, alternative crops could provide opportunities through both increased economic value and better utilization of varying quality waters, particularly those higher in salinity. One such targeted crop that the Consortium will be partnering in the research of is guayule, namely as a source of latex rubber. Guayule offers several advantages over traditionally produced crops, including reduced water use and management inputs, as well as the creation of a stable ecosystem for pollinators between harvests. The natural rubber latex derived from production of guayule could also become a key supplemental cash crop in areas struggling with water availability or quality, contributing to a sustainable production system based on ecosystem and resource conservation. Produced water studies on guayule latex will take place in the greenhouse and garden complex of Texas Tech University. Latex yields, properties, plant physiology, water use efficiency, nutritional status, and overall plant biomass will be identified over a period of one year.

Another crucial area of interest shared by industry participants and external markets is the potential for critical mineral recovery from produced water. The concentration of these mineral resources could lead to manufacturing of high-value products to enhance economic growth and job creation. Partnering with the University of Texas at Austin and pursuing grant funding from the U.S. Department of Energy's Fossil Energy and Carbon Management office, this project will characterize and assess critical mineral resource potential in oil and gas industry waste, produced water and subsurface brines, coal (primarily lignite), coal ash and other coal mine related waste, and other non-fuel mine and processing waste material (e.g., red mud from bauxite processing), sedimentary rocks, drill cuttings and other subsurface rock material with critical mineral potential across the Permian Basin and the Gulf Coast.

2 Update on Pilot Projects

On January 12, 2024 the Consortium released a request for proposals (RFP) for analytical support for treatment of produced water as part of its pilot project program directed by the Texas Legislature through SB 601 (87R) and SB 1047 (88R). The main purpose of these pilot projects is to support assessment of treatment capabilities and associated costs of technologies for potential social beneficial use of treated produced water. The program is designed to provide coverage of expenses related to the analysis of treated produced water samples from existing treatment operations through a third-party, National Environmental Laboratory Accreditation Program (NELAP) certified laboratory[8]. The Consortium, following a rigorous state-mandated procurement process through Texas Tech University, selected Eurofins Scientific as the laboratory for this analysis.

As of the release of this report, the Consortium has five (5) pilot project participants and continues to review responses on a rolling basis for future consideration. These current projects are spread across multiple basins in the Permian and represent a wide range of treatment capabilities, including varying levels of scalability, providing an excellent foundation of knowledge regarding the current state of produced water treatment. Consortium members are currently reviewing recently-issued final reports from Eurofins regarding sample analyses in anticipation of an extensive analytical report to include critical member discussion and input, projected for release by the end of 2024.

Project information is as follows:

1. Pilot A: Delaware basin collection. Pilot operation ran from March-June 2024 at a site near Orla, TX, at a scale of >100 barrels per day (BPD). The system comprised of a pre-treatment, thermal based desalination, and post-treatment train process. Inlet raw water quality ranged in salinity from 111,000 to 140,000 mg/L in Total Dissolved Solids (TDS). Preliminary analysis indicates the resulting finished water achieved an average quality of 311 mg/L TDS.
2. Pilot B: Midland basin collection. Pilot operation ran from January-August 2024 at a site near Midland, TX, at a scale of approximately 350 BPD. The system comprised of a pre-treatment process and thermo-mechanical desalination unit. Inlet raw water quality ranged in salinity from 125,000 to 190,000 mg/L in Total Dissolved Solids (TDS). Preliminary analysis indicates the resulting finished water achieved an average quality of 36 mg/L TDS.
3. Pilot C: Delaware basin collection. Pilot operation is running from mid-July through October2024 at a site near Orla, TX at a scale of approximately 500 BPD. The system is comprised of a pre-treatment, advanced membrane desalination, and post-treatment train process. Inlet raw water quality averaged approximately 120,000 mg/L in Total Dissolved Solids (TDS). Preliminary analysis indicates the resulting finished water achieved an average quality of 900 mg/L TDS.
4. Pilot D: Midland & Delaware basin collection. Pilot operation began in December 2023 at a site near Midland, TX, at a scale of >100 BPD. The system is comprised of a pre-treatment, advanced thermal desalination, polishing and disinfection train process. Inlet

[8] https://nelac-institute.org/content/NELAP/index.php

raw water quality averaged approximately 120,000 mg/L in Total Dissolved Solids (TDS). Preliminary analysis indicates the resulting finished water achieved an average quality of 456 mg/L TDS.

5. Pilot E: Midland basin collection. Pilot operation began in Fall 2023 at a site near Colorado City, TX at a scale of approximately 132 BPD. The system is comprised of multiple reverse osmosis processes. Inlet raw water quality averaged approximately 55,000 mg/L in Total Dissolved Solids (TDS). Preliminary analysis indicates the resulting finished water achieved an average quality of 179 mg/L TDS.

3 Review of standards and guidelines for use of treated produced water in irrigation (land application) and discharge to surface water

Treated produced water may be used beneficially in various applications (*e.g.*, cooling towers, land application, irrigation, discharge to surface water, *etc.*), subject to governing standards to protect humans and the environment[9]. In some applications, guidelines may also be relevant. This section provides a brief summary of standards and guidelines related to land application (irrigation) and discharge to surface water.
Depending on the application, use of treated produced water in the State of Texas may be governed by standards and permitting processes by:

(a) federal and state rules,
(b) a state agency with primacy to operate on behalf of a federal agency, or
(c) only state rules

Since the early 1900s, relevant state and federal regulations have been developed, and in summary:

- land application (irrigation)
    - treated produced water applied to land (irrigation) is regulated by the Railroad Commission (RRC) of Texas
    - land application of all other industrial wastewater is regulated by the Texas Commission on Environmental Quality (TCEQ) through the Texas Land Application Permits (TLAP) program
- discharge to surface water
    - state authority to discharge to "water in the state" is regulated by the TCEQ under Texas Water Code Chapter 26
    - federal authority to discharge to "waters of the United States" is regulated under the federal Clean Water Act; the U.S. Environmental Protection Agency (EPA) delegated authority to the TCEQ to regulate these discharges through the Texas Pollutant Discharge Elimination System (TPDES) program

3.1 Federal Standards: Clean Water Act

The Federal Water Pollution Control Act (FWPCA), originally enacted in 1948 and later substantially expanded in 1972 as the Clean Water Act (CWA), and applies to navigable waters of the United States. The CWA is codified in 33 U.S.C. § 1251[10] *et seq*, while the CWA is

[9] Amy Hardberger. (2024) The Challenges and Opportunities of Beneficially Reusing Produced Water, 34 *Duke Environmental Law & Policy Forum* 1-48
Available at: https://scholarship.law.duke.edu/delpf/vol34/iss1/1, accessed 2024-SEP-01
[10] United States Code, Title 33 Navigation and Navigable Waters, §1251, available at https://www.govinfo.gov/link/uscode/33/1251, accessed 2024-AUG-27

implemented by the Environmental Protection Agency (EPA) in Title 40 of the Code of Federal Regulations (CFR).[11]

3.1.1 40 CFR Chapter I, Subchapter D Water Programs

"Water Programs" are covered in 40 CFR Chapter I Subchapter D[12], and select Parts relevant to management of discharge of waters from industrial sources are highlighted here.

- Parts 110[13] and 112[14] prohibit the discharge of oil to the environment and prescribe general prevention of oil pollution, including petroleum oils.
- Part 116[15] designates hazardous substances (listed in Table 116.4[16], which includes benzene, toluene, ethylbenzene, and xylenes (BTEX) and ammonia).
- Parts 120 and 122 define "waters of the United States".
- Parts 122 through 125 outline the National Pollutant Discharge Elimination System (NPDES) program.
    - From 40 CFR Chapter I Subchapter D Part §122.1(b)(1)[17]:
      The NPDES program requires permits for the discharge of "pollutants" from any "point source" into "waters of the United States." The terms "pollutant", "point source" and "waters of the United States" are defined at § 122.2.
    - From 40 CFR Chapter I, Subchapter D, Part 122, Subpart A, §122.2 Definitions[18], several key definitions are highlighted here:

[11] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, available at https://www.ecfr.gov/current/title-40/chapter-I, accessed 2024-AUG-27

[12] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D, accessed 2024-SEP-02

[13] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 110 Discharge of Oil, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-110, accessed 2024-SEP-02

[14] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 112 Oil Pollution Prevention, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-112, accessed 2024-SEP-02

[15] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 116 Designation of Hazardous Substances, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-116, accessed 2024-SEP-02

[16] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 116 Designation of Hazardous Substances, Subsection 116.4 Designation of Hazardous Substances, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-116/section-116.4, accessed 2024-SEP-02

[17] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 122 EPA Administered Programs: The National Pollutant Discharge Elimination System, Subsection 122.1 Purpose and scope, available at https://www.ecfr.gov/current/title-40/part-122#p-122.1(b)(1), accessed 2024-SEP-02

[18] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 122 EPA Administered Programs: The National Pollutant Discharge Elimination System, Subsection 122.2 Definitions, available at https://www.ecfr.gov/current/title-40/section-122.2, accessed 2024-SEP-02

        - *Discharge when used without qualification means the "discharge of a pollutant."*
        - *Effluent limitation means any restriction imposed by the Director on quantities, discharge rates, and concentrations of "pollutants" which are "discharged" from "point sources" into "waters of the United States," the waters of the "contiguous zone," or the ocean.*
        - *Hazardous substance means any substance designated under 40 CFR part 116 pursuant to section 311 of CWA.*
        - *Pollutant means dredged spoil, solid waste, incinerator residue, filter backwash, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials (except those regulated under the Atomic Energy Act of 1954, as amended (42 U.S.C. 2011 et seq.)), heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste discharged into water. It does not mean:*
          (a) Sewage from vessels; or
          (b) Water, gas, or other material which is injected into a well to facilitate production of oil or gas, or water derived in association with oil and gas production and disposed of in a well, if the well used either to facilitate production or for disposal purposes is approved by authority of the State in which the well is located, and if the State determines that the injection or disposal will not result in the degradation of ground or surface water resources.
        - *Toxic pollutant means any pollutant listed as toxic under section 307(a)(1) or, in the case of "sludge use or disposal practices," any pollutant identified in regulations implementing section 405(d) of the CWA.*
        - *Variance means any mechanism or provision under section 301 or 316 of CWA or under 40 CFR part 125, or in the applicable "effluent limitations guidelines" which allows modification to or waiver of the generally applicable effluent limitation requirements or time deadlines of CWA. This includes provisions which allow the establishment of alternative limitations based on fundamentally different factors or on sections 301(c), 301(g), 301(h), 301(i), or 316(a) of CWA.*
        - *Whole effluent toxicity means the aggregate toxic effect of an effluent measured directly by a toxicity test.*
    - state program requirements (Part 123)
- water quality planning and management (Part 130)

- water quality standards (WQS) (Part 131), including federally promulgated WQS by state (Subpart D), but Texas is not included here.
- hazardous waste injection restrictions (Part148)

3.1.2 40 CFR Chapter I, Subchapter N Effluent Guidelines and Standards

Effluent Guidelines and Standards for various types and categories related to oil and gas are covered by 40 CFR Chapter I Subchapter N:

- general provisions (Part 401)
- petroleum refining (Part 419)
- oil and gas extraction (Part 435)
- centralized waste treatment category (Part 437)

The effluent guidelines and standards in 40 CFR Part 435 prohibit point source discharges of produced water east of the 98th meridian, but they do allow discharges west of the 98th meridian if they are of adequate quality and are put to beneficial use for agriculture or wildlife purposes. Presently, the EPA is engaged in research[19] and stakeholder engagement[20] aimed at looking at additional guidance or standards for the discharge of treated produced water west of the 98th Meridian for beneficial reuse. The EPA is also involved with a broader group of water reuse stakeholders through the National Water Reuse Action Plan (WRAP)[21], and Action 2.3 Study of Oil and Gas Extraction Wastewater Management[22] was completed in 2021. These efforts could lead to the development of additional standards or guidance.

3.2 Texas Standards

In the State of Texas, relevant regulations are found in the Water Code of the Texas Constitution and Statutes[23] and in the Texas Administrative Code: Title 16 Economic Regulation Part 1 Railroad Commission of Texas[24], Title 30 Environmental Quality[25], and Title 31 Natural

[19] Environmental Protection Agency, Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes, EPA Report 821-R-18-004, available at https://www.epa.gov/eg/centralized-waste-treatment-effluent-guidelines, accessed 2025-SEP-25

[20] Environmental Protection Agency, Final Report: Oil and Gas Extraction Wastewater Management, Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act, EPA Report 821-S19-001, available at https://www.epa.gov/eg/final-report-oil-and-gas-extraction-wastewater-management, accessed 2024-SEP-25

[21] Environmental Protection Agency, National Water Reuse Action Plan: Online Platform. Available at https://www.epa.gov/waterreuse/national-water-reuse-action-plan-online-platform, accessed 2024-SEP-25

[22] Environmental Protection Agency, National Water Reuse Action Plan, Action 2.3 Study of Oil and Gas Extraction Wastewater Management, available at https://www.epa.gov/waterreuse/national-water-reuse-action-plan-online-platform?action=2.3, accessed 2024-SEP-25

[23] Texas Constitution and Statutes, Water Code, available at https://statutes.capitol.texas.gov/, accessed 2024-SEP-24

[24] Texas Administrative Code, Title 16 Economic Regulation, Part 1 Railroad Commission of Texas, available at https://texreg.sos.state.tx.us/public/readtac$ext.ViewTAC?tac_view=3&ti=16&pt=1, accessed 2024-SEP-24

[25] Texas Administrative Code, Title 30 Environmental Quality, available at https://texreg.sos.state.tx.us/public/readtac$ext.ViewTAC?tac_view=2&ti=30, accessed 2024-SEP-24

Resources and Conservation.[26]. Historically, the Texas Railroad Commission (RRC) permitted produced water discharges, and the Texas Commission on Environmental Quality (TCEQ) permitted all other industrial wastewater discharges. Following passage of House Bill 2771, (86th Texas Legislature, 2019) and TCEQ obtaining delegation of federal permitting authority from EPA for produced water discharges, the state authority for permitting produced water discharges to surface water bodies transferred from the RRC to the TCEQ. TCEQ obtained federal permitting authority from EPA in January 2021 and now has both state and federal permitting authority for all industrial wastewater discharges to surface waters in the state, including produced water.

3.2.1 Railroad Commission (RRC) of Texas

Historically, most of the water produced with oil and gas in Texas has been disposed of by deep well injection (DWI) through salt water disposal (SWD) wells permitted by Texas Railroad Commission (RRC). Recently, the upstream industry has made great strides in recycling produced water in their operations, which has significantly decreased the industry's need for freshwater sources. In 2021, Texas House Bill 3516 of the 87th Texas Legislature directed the RRC to encourage the commercial recycling of liquid oil and gas wastes, including produced water.

From the RRC website[27]:

> *The RRC's general recycling authority can be found in Natural Resources Code §122 (relating to Treatment and Recycling for Beneficial Use of Fluid Oil and Gas Waste), which states the RRC shall adopt rules that encourage fluid oil and gas waste recycling for beneficial purposes. The RRC has promulgated rules in 16 Texas Administrative Code (TAC) §3.8 (relating to Water Protection) that provide for three categories of recycling: prohibited, authorized, and permitted (16 TAC §3.8(d)(7)(A), (B), and (C), respectively). In addition, 16 TAC Chapter 4 contains rules for commercial recycling of oil and gas waste. The permitted recycling provisions in 16 TAC §3.8(d)(7)(C) provide the framework that RRC staff will employ to authorize pilot studies for the recycling of produced water:*
> *(C) Permitted recycling.*
> *(i) Treated fluid may be reused in any manner, other than the manner authorized by subparagraph (B) of this paragraph1, pursuant to a permit issued by the director on a case-by-case basis, taking into account the source of the fluids, the anticipated constituents of concern, the volume of fluids, the location, and the proposed reuse of the treated fluids. Fluid that meets the requirements of a permit issued under this clause is a recyclable product.*

[26] Texas Administrative Code, Title 31 Natural Resources and Conservation, available at https://texreg.sos.state.tx.us/public/readtac$ext.ViewTAC?tac_view=2&ti=31, accessed 2024-SEP-24

[27] Texas Railroad Commission, Oil and Gas, Applications and Permits, Environmental Permit Types, Pilot Projects, available at https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/environmental-permit-types/pilot-projects/, Accessed 2024-SEP-01

3.2.1.1 RRC Pilot study for land application of treated produced water

The RRC developed a framework for the beneficial use of treated produced water, beginning with a pilot study program[28], and in January of 2024, RRC released the Produced Water Beneficial Reuse Framework for Pilot Study Authorization ("Pilot Study Framework")[29]. Limits of water quality parameters are listed in Appendix C (p. 25-26) of the Pilot Study Framework, and Table 2 compares these limits with other standards and guidelines for irrigation, wildlife, and livestock because in large area applications, it is infeasible to perfectly prevent wildlife and range livestock from accessing the irrigated acreage.

Noticeably present in the RRC Pilot Study Framework is a limit on the concentration of ammonia (30 mg/L as nitrogen). Literature[30] [31] [32] [33] [34] [35] indicate that terrestrial organisms are less sensitive to ammonia than aquatic organisms, so it appears appropriate to have different standards for land application (soil toxicity) versus surface water discharge (aquatic toxicity). While nitrogen sources (*e.g.*, ammonia, urea, and nitrate) can be applied to crops as a fertilizer to increase crop yields, excess nitrogen can be detrimental. For example, applying 4 acre-feet of water per acre (*i.e.*, 48 inches of irrigation depth) in a growing season at the limit of 30 mg/L as nitrogen is equivalent to applying 326 pounds of ammonia-nitrogen per acre; some crop-soil combinations would be able to assimilate this mass loading of nitrogen, while others would not. Furthermore, aerobic bacteria can oxidize ammonia/ammonium to nitrate; the Food and Agriculture Organization (FAO) of the United Nations indicates that there is no restriction for the use of irrigation water with less than 5 mg/L of nitrate as nitrogen[36]. Thus, it may be advantageous to some operators to treat produced water to a nitrogen (nitrate or ammonia) concentration less than the RRC Pilot Study Framework limit of 30 mg/L.

[28] Texas Railroad Commission, Oil and Gas, Applications and Permits, Environmental Permit Types, Pilot Projects, available at https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/environmental-permit-types/pilot-projects/, accessed 2024-SEP-02

[29] Texas Railroad Commission, Oil and Gas Division, Technical Permitting Section, Environmental Permits and Support Unit, Produced Water Beneficial Reuse Framework for Pilot Study Authorization, available at https://www.rrc.texas.gov/media/nznn2wsj/240108-produced-water-framework-final.pdf, accessed 2024-SEP-01

[30] Niemeyer JC, Medici LO, Correa B, Godoy D, Ribeiro G, Ferreira Lima S de O, de Santo FB, Carvalho DF de. 2020. Treated produced water in irrigation: Effects on soil fauna and aquatic organisms. *Chemosphere*. 240:124791. Available at https://doi.org/10.1016/j.chemosphere.2019.124791, accessed 2024-SEP-25.

[31] Andrade BG, Andrade VT, Costa BRS, Campos JC, Dezotti M. 2011. Distillation of oil field produced water for reuse on irrigation water: evaluation of pollutants removal and ecotoxicity. *J Water Reuse Desalination*. 1(4):224–236. Available at https://doi.org/10.2166/wrd.2011.044, accessed 2024-SEP-25

[32] Ferreira RNC, Weber OB, Crisóstomo LA. 2015. Produced water irrigation changes the soil mesofauna community in a semiarid agroecosystem. *Environ Monit Assess*. 187(8):520. Available at https://doi.org/10.1007/s10661-015-4744-7, accessed 2024-SEP-25

[33] Rossetto CAV, Medici LO, Morais CSB de, Martins R da CF, Carvalho DF de. 2021. Seed germination and performance of sunflower seedlings submitted to produced water. *Ciênc E Agrotecnologia*. 45. Available at https://doi.org/10.1590/1413-7054202145010521, accessed 2024-SEP-25

[34] Sousa AF, Crisostomo LA, Weber OB, Escobar MEO, OLIVEIRA TSD. 2016. Nutrient content in sunflowers irrigated with oil exploration water. *Rev Caatinga*. 29(01):94–100. Available at https://doi.org/10.1590/1983-21252016v29n111rc, accessed 2024-SEP-25

[35] Huff L, Delos C, Gallagher K, Beaman J. 2013. Aquatic life ambient water quality criteria for ammonia-freshwater. Wash DC US Environ Prot Agency. Available at https://www.epa.gov/sites/default/files/2015-08/documents/aquatic-life-ambient-water-quality-criteria-for-ammonia-freshwater-2013.pdf, accessed 2024-SEP-25

[36] Food and Agriculture Organization (FAO) of the United Nations. (1985) Water quality for agriculture, §1.4 Water Quality Guidelines, Table 1 Guidelines for Interpretations of Water Quality for Irrigation, https://www.fao.org/4/t0234e/T0234E01.htm#ch1.4, accessed 2024-SEP-03

Noticeably absent from the list of water quality parameters are benzene, toluene, ethylbenzene, xylenes (BTEX) compounds, which are listed as hazardous substances in 40 CFR Chapter I, Subchapter D, Part 116, §116.4[37] and found in produced water. RRC could consider implementing limits for these compounds in the Pilot Study Framework. Risk characterization should consider the biodegradability and partitioning of these constituents during evaluation of potential screening values.[38] [39] [40] [41]

While the Pilot Study Framework does prohibit runoff and impact to groundwater, it does not specify hydraulic loading limits (*i.e.*, maximum daily volumetric flux) for land application.

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[37] Code of Federal Regulations, Title 40 Protection of the Environment, Chapter I Environmental Protection Agency, Subchapter D Water Programs, Part 116 Designation of Hazardous Substances, Subsection 116.4 Designation of Hazardous Substances, available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-116/section-116.4, accessed 2024-SEP-02

[38] M. Pattanyek and S. J. McMillen (2008) Risk Assessment for Livestock in the Oriente Region of Ecuador. SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Nice, France. Available at https://doi.org/10.2118/111955-MS, accessed 2024-SEP-25

[39] American Petroleum Institute (2004) Risk-Based Screening Levels for the Protection of Livestock Exposed to Petroleum Hydrocarbons. Available at https://www.api.org/environment-health-and-safety/environmental-performance/~/~/media/files/ehs/environmental_performance/final_as_published_4733.ashx, accessed 2024-SEP-25

[40] Craig W. Davis, David M. Brown, Chesney Swansborough, Christopher B. Hughes, Louise Camenzuli, Leslie J. Saunders, Delina Y. Lyon (2024) Predicting Hydrocarbon Primary Biodegradation in Soil and Sediment Systems Using System Parameterization and Machine Learning. *Environmental Toxicology and Chemistry*. Vol. 43, Iss. 6 Available at https://doi.org/10.1002/etc.5857, accessed 2024-SEP-25

[41] Craig Warren Davis, Louise Camenzuli, Aaron D. Redman (2022) Predicting Primary Biodegradation of Petroleum Hydrocarbons in Aquatic Systems: Integrating System and Molecular Structure Parameters using a Novel Machine-Learning Framework. *Environmental Toxicology and Chemistry*. Vol. 41, Iss. 6, available at https://doi.org/10.1002/etc.5328, accessed 2024-SEP-25

Table 2: Comparison of Texas RRC Pilot Study Framework water quality limits with other standards and guidelines for irrigation, wildlife, and livestock.

Source			**TX RRC**	**NM**	**FAO**	**GWPC**	**GWPC**	**Karim et al**	**Karim et al**	**Karim et al**	**Karim et al**	**MT**	**MT**	**NM**	**GWPC**	**NRC**
Use Category			Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Wildlife & Livestock	Wildlife & Livestock	Livestock	Livestock	Livestock
Constituent	**CAS**	**Units**				Long-term	Short-term	Corn	Sorghum	Cotton	Wheat	MPDES 2015-2019	MPDES 2020			Cattle
Alkalinity, tot	-	mg/L as CaCO3	100													
Aluminum	7429-90-5	mg/L	5	5	5	5	20								5	0.5
Arsenic	7440-38-2	mg/L	0.1	0.1	0.1	0.1	2					0.5	0.5	0.2	0.2	0.05
Beryllium	7440-41-7	mg/L	0.1		0.1	0.1	0.5									
Boron	7440-42-8	mg/L	0.75	0.75		0.75	2	2	3	3	3	5		5	5	5
Cadmium	7440-43-9	mg/L	0.01	0.01	0.01	0.01	0.05						0.08	0.05	0.05	0.005
Chloride	16887-00-6	mg/L	100					533	710	710						
Chromium	7440-47-3	mg/L	0.1	0.1	0.1	0.1	1						1	1	1	0.1
Cobalt	7440-48-4	mg/L	0.05	0.05	0.05	0.05	5						1	1	1	1
Copper	7440-50-8	mg/L	0.2	0.2	0.2	0.2	5					0.5	0.5	0.5	10.5	1
Cyanide, tot	57-12-5	mg/L														
Electrical Conductivity	-	µS/cm	1500					1100	1700	5100	4000	11000				
Fluoride	16984-48-8	mg/L	1		1	1	15					3	2		2	2
Gross Alpha/Beta	-	pCi/L	15													
Hardness, tot	-	mg/L	150													
Iron	7439-89-6	mg/L	5		5	5	20									
Lead	7439-92-1	mg/L	5	5	5	5	10					0.1	0.1	0.1	0.1	0.015
Lithium	7439-93-2	mg/L	2.5		2.5	2.5	2.5									
Manganese	7439-96-5	mg/L	0.2		0.2	0.2	10									0.05
Mercury	7439-97-6	mg/L												0.01	0.01	0.01
Molybdenum	7439-98-7	mg/L	0.01	1	0.01	0.01	0.05									
Nickel	7440-02-0	mg/L	0.2		0.2	0.2	2									0.25
Nitrite+Nitrate	14797-65-0 14797-55-8	mg/L as N												132	110	
Nitrogen, ammonia	7664-41-7	mg/L as N	30													
Nitrogen, nitrate	14797-55-8	mg/L as N	45									100	100			
Nitrogen, nitrite	14797-65-0	mg/L as N	10									10	10		10	
pH	-		6.5-8.4									6.0-9.0	6.0-9.0			
Phosphorus	7723-14-0	mg/L	5													
Radium 226	13982-63-3	pCi/L	30													
Radium 228	15262-20-1	pCi/L	30													
Selenium	7782-49-2	mg/L	0.02		0.02	0.02	0.02					0.05	0.05	0.05	0.05	0.05
Sodium	7440-23-5	mg/L	100					533	710	710		2250				
Sodium Absorption Ratio	-	mg/L	4					10	10	10	13					
Strontium	7440-24-6	mg/L		8 pCi/L												
Sulfate	14808-79-8	mg/L										2500	2500			
Total Dissolved Solids	-	mg/L	1000					704	1088	3264	2200	5000	5000		10000	
Total Metals		mg/L	10													
Total Oil and Grease	-	mg/L	35									10	10			
Total Organic Carbon	-	mg/L	10													
Total Petroleum Hydrocarbons	-	mg/L	10													
Turbidity	-	NTU	30													
Vanadium	7440-62-2	mg/L	0.1		0.1	0.1	1								0.1	0.1
Zinc	7440-66-6	mg/L	2		2	2	10					25	25		24	5

3.2.2 Texas Commission on Environmental Quality (TCEQ)

In 1998, the U.S. EPA delegated authority to TCEQ to manage the NPDES program for the State which was named the Texas Pollutant Discharge Elimination System (TPDES, typically pronounced "tip-dees"). Through the TPDES and Texas Land Application Permits (TLAPs, typically pronounced "tee-laps")[42] programs, TCEQ permits several types of treated wastewaters and stormwater[43], including discharges of treated industrial wastewater into or adjacent to "water in the state." . Under Texas Water Code Section 26.001[44], defines "water in the state":

> *"Water" or "water in the state" means groundwater, percolating or otherwise, lakes, bays, ponds, impounding reservoirs, springs, rivers, streams, creeks, estuaries, marshes, inlets, canals, the Gulf of Mexico inside the territorial limits of the state, and all other bodies of surface water, natural or artificial, inland or coastal, fresh or salt, navigable or nonnavigable, and including the beds and banks of all watercourses and bodies of surface water, that are wholly or partially inside or bordering the state or inside the jurisdiction of the state.*

An entity that desires permitting of an industrial wastewater must apply to TCEQ for a permit (TCEQ Form 10055 Industrial Wastewater Permit Application[45]), which can either be a TLAP or TPDES permit. At the time of this writing, the TCEQ has several programs that authorize the discharge of oil and gas wastewater[46]. Several key programs are summarized below.

3.2.2.1 TPDES permitting of treated produced water discharges to "water in the State"

In 2019, Texas House Bill 2771 (86^{th} Legislature) directed TCEQ to seek delegation from EPA for discharges of treated produced water into "water in the State". EPA approved TCEQ's delegation request effective January 15, 2021, and upon delegation, the state program for issuing discharge permits for treated produced water transferred from RRC to TCEQ (through the TPDES).

An applicant seeking a permit to discharge wastewaters into water in the State generated during oil and gas exploration and production activities located west of the 98^{th} Meridian must apply for an individual permit. The application consists of an Administrative Application form

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[42] Texas Commission on Environmental Quality, Industrial Wastewater Discharges: The Permit Process, available at https://www.tceq.texas.gov/permitting/wastewater/industrial/TPDES_industrial_wastewater_steps.html, accessed 2024-SEP-02

[43] Texas Commission on Environmental Quality, Wastewater and Stormwater, Types of wastewater and stormwater permits and registrations, and how to apply for them. Permitting requirements. Participating in the permitting process., available at https://www.tceq.texas.gov/permitting/wastewater, accessed 2024-SEP-02

[44] Texas Constitution and Statutes, Water Code, Chapter 26 Water Quality Control, available at https://statutes.capitol.texas.gov/Docs/WA/htm/WA.26.htm, accessed 2024-SEP-02

[45] Texas Commission on Environmental Quality, Industrial Wastewater Permit Application Technical Report 1.0, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/forms-tools/10055.docx, accessed 2024-SEP-02

[46] Texas Commission on Environmental Quality, Oil and Gas Wastewater Permits, Wastewater permitting authority for oil and gas discharges and information about the stakeholder group and House Bill 2771., available at https://www.tceq.texas.gov/permitting/wastewater/oilandgas and Oil and Gas Wastewater Permits, Permits for oil and gas facilities, requirements for each type, and links and information on how to apply, available at https://www.tceq.texas.gov/assistance/industry/oil-and-gas/oil-and-gas-wastewater-permits, accessed 2024-SEP-02

(TCEQ Form 20893[47]) and the Industrial Wastewater Technical Application Form (TCEQ Form 10055). Individual permit applicants will be required to submit additional information, such as treatment processes and analyses for an enhanced list of pollutants, as part of the application process. Additionally, draft permits will include acute and chronic Whole Effluent Toxicity (WET) testing. Applicants may need additional authorizations from the TCEQ Waste Permits Division[48] or the TCEQ Air Permits Division.

3.2.2.2 General Permit TXG310000 for onshore stripper wells east of 98th meridian and coastal and territorial seas facilities

TCEQ has issued an Oil and Gas Extraction TPDES General Permit No. TXG310000, with an effective date of January 10, 2024[49]. This general permit is applicable for an onshore stripper well facility located east of the 98th meridian, a coastal facility, or a territorial seas facility that intends to discharge wastes associated with oil and gas extraction activities into water in the state. Details regarding applicability and limits are provided in the General Permit TXG310000[50] and corresponding Fact Sheet.[51]

3.2.2.3 General Permit WQG280000 for discharges located on the outer continental shelf

TCEQ has issued a Oil and Gas Outer Continental Shelf (OCS) General Permit No. WQG280000, with an effective date of January 10, 2024.[52] This general permit is applicable to facilities that discharge waste associated with oil and gas extraction activities into the Gulf of Mexico located greater than 3.0 statute miles and less than 10.357 statute miles from the Texas coastline.Details regarding applicability and limits are provided in the General Permit WQG280000[53] and corresponding Fact Sheet[54].

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[47] Texas Commission on Environmental Quality, Industrial Wastewater Application Checklist For Oil And Gas Extraction Permits Issued Under Texas Water Code Chapter 26, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/forms-tools/20893.docx, accessed 2024-SEP-02

[48] Texas Commission on Environmental Quality, Waste Management: Requirements and Permits Requirements to transport and dispose of municipal solid, industrial and hazardous, and other wastes. Pending and current permits. Registration status., available at https://www.tceq.texas.gov/permitting/waste_permits, accessed 2024-SEP-02

[49] Texas Commission on Environmental Quality, Wastewater Discharges from Oil and Gas Extraction Facilities: Obtaining Coverage under General Permit TXG310000, available at https://www.tceq.texas.gov/permitting/wastewater/txg31-steps, accessed 2024-SEP-03

[50] Texas Commission on Environmental Quality, TPDES General Permit to Discharge Wastewater Associated with Oil and Gas Extraction Activities, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/oil-gas-extraction/txg31_general-permit_issued.pdf, accessed 2024-SEP-03

[51] Texas Commission on Environmental Quality, Fact Sheet And Executive Director's Final Decision, For proposed Texas Pollutant Discharge Elimination System (TPDES) General Permit No. TXG310000 to discharge wastewater associated with oil and gas extraction activities into water in the state., available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/oil-gas-extraction/txg310000-fact-sheet_issued.docx, accessed 2024-SEP-03

[52] Texas Commission on Environmental Quality, Wastewater Discharges from Oil and Gas Outer Continental Shelf Facilities: Obtaining Coverage under General Permit WQG280000, available at https://www.tceq.texas.gov/permitting/wastewater/wqg28-steps/view, accessed 2024-SEP-03

[53] Texas Commission on Environmental Quality, Oil and Gas Outer Continental Shelf General Permit No. WQG280000, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/oil-gas-outer-continental-shelf/wqg280000-draft-permit_issued.pdf/view, accessed 2024-SEP-03

[54] Texas Commission on Environmental Quality, Fact Sheet And Executive Director's Final Decision, General Permit No. WQG280000 to discharge wastes associated with oil and gas extraction activities into the Gulf of Mexico (between 3.0 and 10.357 statute miles from the Texas coastline)., available at

3.2.2.4 Other petroleum-related permits

TCEQ renewed TPDES General Permit No. TXG34000, with an effective date of October 24, 2022[55]. TPDES GP No. TXG34000 regulates discharges of facility wastewater, contact stormwater, and stormwater associated with industrial activities into or adjacent to water in the state from petroleum bulk stations and terminals. Details regarding applicability and limits are provided in the General Permit.[56]

The Hydrostatic Test Water General Permit TXG670000, effective October 21, 2020, authorizes the discharge of water resulting from a hydrostatic test of a vessel into or adjacent to water in the state[57]. Details regarding applicability and limits are provided in the General Permit[58].

TCEQ renewed the TPDES Petroleum Contaminated Water General Permit, TXG830000, which has been issued with an effective date of September 12, 2023[59]. This permit covers certain discharges of petroleum-contaminated water in Texas. Details regarding applicability and limits are provided in the General Permit[60] and corresponding Fact Sheet.[61]

3.2.2.5 Land application (TLAP) for domestic and non-oil-and-gas industrial wastewater

TLAPs authorize disposal of treated domestic and non-oil-and-gas wastewater at a property, not discharging into water in the State. TCEQ issues several TLAPs: (1) evaporation (30 TAC 309), (2) surface irrigation (30 TAC 309), (3) subsurface irrigation (30 TAC 309), and (4) subsurface area drip dispersal system (SADDS) (30 TAC 222). TCEQ Form 10054[62] is

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https://www.tceq.texas.gov/downloads/permitting/wastewater/general/oil-gas-outer-continental-shelf/wqg280000-fact-sheet_issued.docx/view, accessed 2024-SEP-03

[55] Texas Commission on Environmental Quality, Water Discharges from Petroleum Bulk Stations and Terminals: *Am I Regulated?*, available at https://www.tceq.texas.gov/permitting/wastewater/general/TXG34_AIR.html, accessed 2024-SEP-03

[56] Texas Commission on Environmental Quality, General Permit To Discharge Wastes under provisions of Section 402 of the Clean Water Act: National Pollutant Discharge Elimination System and Chapter 26 of the Texas Water Code: Water Quality Control, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/petroleum-stations-terminals/txg340000-issued-2022.pdf, accessed 2024-SEP-03

[57] Texas Commission on Environmental Quality, Hydrostatic Test Water Discharges: Obtaining Coverage Under General Permit No. TXG670000, available at https://www.tceq.texas.gov/permitting/wastewater/general/TXG67_steps.html, accessed 2024-SEP-03

[58] Texas Commission on Environmental Quality, TPDES General Permit Number TXG670000 Relating To Discharges Of Hydrostatic Test Water, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/hydrostatic-test-water/txg67-issued-permit-11-3-2020.docx, accessed 2024-SEP-02

[59] Texas Commission on Environmental Quality, General Permit Requirements for the Discharge of Petroleum Contaminated Water, available at https://www.tceq.texas.gov/permitting/wastewater/general/TXG83_steps.html, accessed 2024-SEP-03

[60] Texas Commission on Environmental Quality, General Permit To Discharge Wastes, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/txg830000-2023.pdf, accessed 2024-SEP-03

[61] Texas Commission on Environmental Quality, Fact Sheet And Executive Director's Final Decision Texas Pollutant Discharge Elimination System General Permit TXG830000, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/general/22032-fact-sheet-final.docx, accessed 2024-SEP-03

[62] Texas Commission on Environmental Quality, Domestic Wastewater Permit Application Technical Report 1.0, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/forms-tools/10054.docx, accessed 2024-SEP-03

required. The application process involves a review of several aspects of the site: geologic (surface water, groundwater, wells, topography, etc.), hydraulic (water application rate, average rainfall, evapotranspiration), and agronomic (water application rate, average rainfall, evapotranspiration, nutrient application rate, cropping plan, dry matter production, *etc.*). Additionally, per 30 TAC 222 all SADDS will have a maximum application rate of 0.1 gal/ft²/day (4.88 acre-feet/acre per year), and per TCEQ policy, all subsurface irrigation systems under 30 TAC 309 will have a maximum application rate of 0.1 gal/ft²/day (4.88 acre-feet/acre per year). An irrigation spreadsheet has been developed by the TCEQ.

3.2.2.6 Use of domestic and non-oil-and-gas industrial reclaimed water

TCEQ has an existing program (State authority TWC Ch 26) for reusing domestic and non-oil-and-gas industrial reclaimed water[63].The program has established fit-for-purpose standards that must be met before it can be reused (30 TAC 210[64]). Requirements for use of industrial reclaimed water are covered in 30 TAC 210 Subchapter E.[65]

3.3 Other State Standards

3.3.1 Montana

The Montana Department of Environmental Quality (MDEQ)[66] is responsible for regulating water quality standards in the state, particularly in relation to oil and gas operations. The MDEQ establishes rules to protect water resources by setting criteria for pollutant levels and maintaining standards for various water uses, including livestock and wildlife drinking water. The Montana Bureau of Mines and Geology[67] supports these efforts by providing research and data on groundwater and surface water quality, which informs regulatory decisions and water management policies. The Fact Sheet[68] for MDEQ's Montana Pollutant Discharge Elimination System (MPDES) Produced Water General Permit (PWGP) explains that the permit (MTG310000) allows for discharge to ephemeral receiving waters (ARM 17.30.602) or discharge for wildlife propagation (40 CFR 435.51). The permit allows for either Technology Based Effluent Limits (Fact Sheet §IV, p. 6) or Water Quality Based Effluent Limits (Fact Sheet §V, p. 7). Per Fact Sheet §V, subsection C Beneficial Use: Wildlife or Livestock Watering, "irrigation with produced water to agricultural fields or rangeland is not considered a beneficial

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63 Texas Commission on Environmental Quality, Requirements for Reclaimed Water, Definition for and uses of municipal (also called domestic) and industrial reclaimed water., available at https://www.tceq.texas.gov/assistance/water/reclaimed_water.html, accessed 2024-SEP-02

64 Texas Administrative Code, Title 30 Environmental Quality, Part 1 Texas Commission on Environmental Quality, Chapter 210 Use of Reclaimed Water, available at https://texreg.sos.state.tx.us/public/readtac%24ext.ViewTAC?tac_view=4&ti=30&pt=1&ch=210, accessed 2024-SEP-03

65 Texas Administrative Code, Title 30 Environmental Quality, Part 1 Texas Commission on Environmental Quality, Chapter 210 Use of Reclaimed Water, Subchapter E Special Requirements For Use Of Industrial Reclaimed Water, available at https://texreg.sos.state.tx.us/public/readtac$ext.ViewTAC?tac_view=5&ti=30&pt=1&ch=210&sch=E&rl=Y, accessed 2024-SEP-02

66 Montana Department of Environmental Quality, available at https://deq.mt.gov/, accessed 2024-SEP-25

67 Montana Bureau of Mines & Geology, available at https://www.mbmg.mtech.edu/#gsc.tab=0, accessed 2024-SEP-25

68 Montana Department of Environmental Quality, Water Quality Division, Montana Pollutant Discharge Elimination System (MPDES) Fact Sheet for Produced Water General Permit, Available at https://deq.mt.gov/files/water/Forms/2020_FS_MTG310000.pdf, accessed 2024-SEP-25

use of produced water." Water quality criteria for Wildlife and Livestock Drinking Water for 2015-2019 are listed in Table 3 (p. 6) of the Fact Sheet, and 2020 water quality criteria for Wildlife and Livestock Drinking Water are listed in Table 6 (p. 11) of the Fact Sheet. These Montana water quality criteria for the previous and current MPDES permit for produced water are listed in Table 2.

3.3.2 New Mexico

New Mexico has two governing parties that regulate the use of produced water. The New Mexico Oil Conservation Division (OCD)[69] within the New Mexico Energy, Minerals and Natural Resources Department is the primary regulator for these standards. The NMOCD regulates following the Oil and Gas Act and has the authority over the reuse of produced water for oil and gas uses. The New Mexico Water Quality Control Commission[70] within the New Mexico Environment Department regulates all other uses of produced water. Environmental protection is addressed in Title 20[71] of the New Mexico Administrative Code (NMAC), including New Mexico regulatory constituent limits for drinking water, irrigation, livestock water, wildlife, and aquatic life (acute and chronic). New Mexico water quality limits for irrigation and livestock are listed in Table 2.

3.3.3 Colorado

The Colorado Water Quality Control Commission (CWQCC)[72] is a division of the Colorado Department of Public Health and Environment (CDPHE)[73] and is the regulatory body tasked with safeguarding the state's water resources. Operating within the framework established by the Colorado Water Quality Control Act, the CWQCC develops and implements policies, standards, and regulations to ensure that water quality meets established benchmarks. The Commission's responsibilities encompass setting water quality classifications, developing standards for pollutants and contaminants, and overseeing the implementation of measures to achieve and maintain these standards. Through its oversight and regulatory authority, the CWQCC plays a pivotal role in protecting Colorado's valuable water resources for both human and environmental health. The Colorado Oil and Gas Conservation Commission (COGCC) is responsible for regulating the development and production of oil and gas resources in Colorado, including the treatment and disposal of oil and gas production waste. In 2023, the Colorado State Legislature created the Colorado Produced Water Consortium (CPWC), housed in the Colorado Department of Natural Resources. The CPWC is currently working in cooperation with the Texas and New Mexico Consortiums exploring state standards for produced water reuse.

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[69] New Mexico Energy, Minerals and Natural Resources Department, Oil Conservation Division, available at https://www.emnrd.nm.gov/ocd/, accessed 2024-SEP-25

[70] New Mexico Environment Department, Water Quality Control Commission, Available at https://www.env.nm.gov/opf/water-quality-control-commission/, accessed 2024-SEP-25

[71] New Mexico Administrative Code, Title 20 Environmental Protection, available at https://www.srca.nm.gov/nmac-home/nmac-titles/title-20-environmental-protection/, accessed 2024-SEP-25

[72] Colorado Department of Public Health and Environment, Colorado Water Quality Control Commission, available at https://cdphe.colorado.gov/wqcc, accessed 2024-SEP-25

[73] Colorado Department of Public Health and Environment, available at https://cdphe.colorado.gov/, accessed 2024-SEP-25

3.4 Guidelines

In addition to federal and state standards, there also exist guidelines for certain applications.

3.4.1 Food and Agriculture Organization (FAO) of the United Nations

The Food and Agriculture Organization (FAO) of the United Nations (UN) published a landmark guidance document on Water Quality for Agriculture (Ayers & Westcot, 1994)[74], and Table 21 of §5.5.2 Toxicities[75] lists recommended maximum concentrations of trace elements in irrigation water. These FAO water quality concentration limits are listed in are listed in Table 2. Referencing this FAO work, researchers Karim et al (2020)[76] summarized select water quality limits for four crops in supplementary material[77].

3.4.2 Groundwater Protection Council (GWPC)

The GPWC 2015 report on Produced Water Reuse in Oklahoma 2015: Regulatory Considerations and References[78] includes recommended constituent concentration limits for general surface water discharge, livestock drinking water, and irrigation water. The purpose of this document is to report the findings of information to better understand produced water discharge, disposal, and re-use issues in the state of Oklahoma. Recommended water quality concentration limits for livestock drinking water are listed in Table 2-2 (p. 29 of the GWPC 2015 report) from Guerra, Dahm, and Dundorf (2011)[79], and recommended water quality concentration limits for long-term and short-term use for irrigation are listed in Table 2-5 (p. 31). These concentration limits summarized in the GWPC 2015 report are listed in Table 2.

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[74] R.S. Ayers and D.W. Westcot (1994) Water Quality for Agriculture. Food and Agriculture Organization of the United Nations, Rome, ISBN 92-5-102263-1, available at https://www.fao.org/4/t0234e/T0234E00.htm#TOC, accessed 2024-SEP-25

[75] R.S. Ayers and D.W. Westcot (1994) Water Quality for Agriculture, Section 5 Miscellaneous Problems, Subsection 5.5.2 Toxicities, Table 21 Recommended Maximum Concentrations of Trace Elements in Irrigation Water. Food and Agriculture Organization of the United Nations, Rome, ISBN 92-5-102263-1, available at https://www.fao.org/4/t0234e/T0234E06.htm#ch5.5.2, accessed 2024-SEP-25

[76] Karim, Gonzalez Cruz, Hernandez, and Uddameri (2020) A GIS-Based Fit for the Purpose Assessment of Brackish Groundwater Formations as an Alternative to Freshwater Aquifers. *Water* 12(8), 2299; available at https://doi.org/10.3390/w12082299, accessed 2024-SEP-25

[77] Karim, Gonzalez Cruz, Hernandez, and Uddameri (2020) Supplementary Material, available at https://www.mdpi.com/2073-4441/12/8/2299/s1?version=1597575659, accessed 2024-SEP-25

[78] Groundwater Protection Council (2015) Produced Water Reuse in Oklahoma: Regulatory Considerations and References, available at https://www.gwpc.org/wp-content/uploads/2022/12/Oklahoma_Produced_Water_Project_Summary_Report.pdf, accessed 2024-SEP-25

[79] Guerra, K., Dahm, K., and Dundorf, S. (2011) Science and Technology Program Report No. 157, Oil and Gas Produced Water Management and Beneficial Use in the Western United States, U.S. Department of the Interior, Bureau of Reclamation, available at https://www.usbr.gov/research/dwpr/reportpdfs/report157.pdf, accessed 2024-SEP-25

3.4.3 National Research Council (NRC)

Water quality limits of potentially toxic nutrients for cattle drinking water are listed in Table 8-4 (p. 182) in the National Research Council's publication on Nutrient Requirements of Dairy Cattle [80], and these values are included in Table 2.

3.5 Ongoing and Future Research

Ongoing and future research by the Texas Produced Water Consortium explores identification of compounds typically present in produced water and treated produced water. This research may have future implications for particular treatment processes required to meet existing water quality standards or guidelines, or it may have implications for the development of additional water quality standards, guidelines, or analytical methods.

Pages 19-33 of the 82-page TCEQ TPDES Form 10055[81] lists tables of water quality analytes that most TPDES permits follow; before each table, a brief paragraph indicates if this table applies or not. Some tables such as Table 1 and Table 2 are "required for all external outfalls for all TPDES permit applications," but others are much more specific. Some analytical methods have issues with raw produced water but are applicable for post-treatment water. Also, there are constituents in produced water that do not presently have EPA/TCEQ-approved analytical methods; this is a subject of ongoing research for the Texas Produced Water Consortium and consortia of other States. [82] [83]

Quantitative structure–activity relationship models (QSAR models) can be developed to estimate the effects of exposure of an organism based on the concentrations of dissolved constituents in treated produced water. With respect to screening water quality data from the ongoing produced water pilots, there are a number of QSAR-based approaches that could be used to estimate predicted no-effect concentration (PNEC) for ecological organisms (plants,

[80] National Research Council. 2001. *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001*. Washington, DC: The National Academies Press. Chapter 8 Water, Section Water Quality, Table 8-4, available at https://doi.org/10.17226/9825, accessed 2024-SEP-25

[81] Texas Commission on Environmental Quality, Industrial Wastewater Permit Application Technical Report 1.0, available at https://www.tceq.texas.gov/downloads/permitting/wastewater/forms-tools/10055.docx, accessed 2024-SEP-02

[82] Andrade BG, Andrade VT, Costa BRS, Campos JC, Dezotti M. 2011. Distillation of oil field produced water for reuse on irrigation water: evaluation of pollutants removal and ecotoxicity. *J Water Reuse Desalination*. 1(4):224–236. Available at https://doi.org/10.2166/wrd.2011.044, accessed 2024-SEP-25

[83] Tarazona Y, Wang HB, Hightower M, Xu P, Zhang Y. 2024. Benchmarking produced water treatment strategies for non-toxic effluents: integrating thermal distillation with granular activated carbon and zeolite post-treatment. *J Hazard Mater.*:135549. Available at https://doi.org/10.1016/j.jhazmat.2024.135549, accessed 2024-SEP-25

invertebrates, fish, etc) for organic constituents.[84] [85] [86] This approach could be used to screen the chemical data from the pilots to focus attention on constituents that are frequently detectable and near the estimated PNEC.

For surface water discharge, there are a number of organisms that are relatively easy to culture (*e.g.*, fathead minnow *Pimephales promelas*, water fleas *Daphnia pulex* and *Ceriodaphnia dubia*), and can provide acute and chronic endpoints in relative short time frames (*e.g.*, less than 7 days). Ongoing research investigates and compares other aquatic toxicity and WET test methods for aquatic organisms (*e.g.*, Zebrafish embryo toxicity (ZFET) screen[87]).. Some of these test species and methods are included in ongoing pilot studies, and results are forthcoming.

Terrestrial tests are generally longer (*e.g.*, 14 to 50 days) depending on the endpoints, and maintaining constant exposure to the test chemicals in those long term tests can be challenging. The RRC could consider possible testing of soil-relevant organisms which may require some method development to meet regulatory needs (*e.g.*, earthworm *Eisenia fetida*[88] [89], soil nematode *Caenorhabditis elegans*[90] [91], and phytotoxicity with alfalfa *medicago sativa*[92] and Northern wheatgrass *Elymus lanceolatus*). NemaLife testing with *C. elegans* (soil nematode) is tested in short term aquatic assays that could be useful for acute and chronic endpoints; research results indicate that these tests could be appropriate to evaluate effects from metals, ammonia, and salt,

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[84] McGrath JA, Fanelli CJ, Di Toro DM, Parkerton TF, Redman AD, Paumen ML, Comber M, Eadsforth CV, den Haan K. 2018. Re-evaluation of target lipid model–derived HC5 predictions for hydrocarbons. *Environ Toxicol Chem.* 37(6):1579–1593. Available at https://doi.org/10.1002/etc.4100, accessed 2024-SEP-25

[85] Boone KS, Di Toro DM, Davis CW, Parkerton TF, Redman A. 2024. In Silico Acute Aquatic Hazard Assessment and Prioritization Using a Grouped Target Site Model: A Case Study of Organic Substances Reported in Permian Basin Hydraulic Fracturing Operations. *Environ Toxicol Chem.* 43(5):1161–1172. Available at https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5826, accessed 2024-SEP-25

[86] Aaron D. Redman, Thomas F. Parkerton, Miriam Leon Paumen, Joy A. McGrath, Klaas den Haan, Dominic M. Di Toro (2014) Extension and validation of the target lipid model for deriving predicted no-effect concentrations for soils and sediments. *Environ Toxicol Chem.* Vol 33, Iss. 12. Available at https://doi.org/10.1002/etc.2737, accessed 2024-SEP-25

[87] J. Crago and R. Klaper (2018) Place-based screening of mixtures of dominant emerging contaminants measured in Lake Michigan using zebrafish embryo gene expression assay, *Chemosphere,* V. 193, available at https://doi.org/10.1016/j.chemosphere.2017.11.043, accessed 2024-SEP-03

[88] I.A. Bamgbose and T.A. Anderson (2020) Ecotoxicity of three plant-based biodiesels and diesel using, *Eisenia fetida, Environmental Pollution*, V. 260, available at https://doi.org/10.1016/j.envpol.2020.113965, accessed 2024-SEP-03

[89] L.A. Westbrook et. al. (2020) Terrestrial Toxicity of Synthetic Gas-to-Liquid versus Crude Oil–Derived Drilling Fluids in Soil, *Environmental Toxicology and Chemistry,* V. 39, available at https://doi.org/10.1002/etc.4658, accessed 2024-SEP-03

[90] Rahman M, Edwards H, Birze N, Gabrilska R, Rumbaugh KP, Blawzdziewicz J, Szewczyk NJ, Driscoll M, Vanapalli SA. 2020. NemaLife chip: a micropillar-based microfluidic culture device optimized for aging studies in crawling *C. elegans*. *Sci Rep*. 10(1):16190. Available at https://doi.org/10.1038/s41598-020-73002-6, accessed 2024-SEP-25

[91] Dubey J, Mondal S, Koushika SP. 2022. A Simple Microfluidic Chip for Long-Term Growth and Imaging of *Caenorhabditis elegans*. JoVE J Vis Exp.(182):e63136.

[92] I.A. Bamgbose and T.A. Anderson (2015) Phytotoxicity of three plant-based biodiesels, unmodified castor oil, and Diesel fuel to alfalfa (*Medicago sativa L.*), lettuce (*Lactuca sativa L.*), radish (*Raphanus sativus*), and wheatgrass (*Triticum aestivum*), *Ecotoxicology and Environmental Safety,* V. 122, available at, https://doi.org/10.1016/j.ecoenv.2015.08.003, accessed 2024-SEP-03

but they may need method development to avoid loss of certain organic materials (*e.g.*, BTEX) to the silicone rubber substrate.

4 Economic Insights

The purpose of the Texas Produced Water Consortium is to identify viable beneficial use alternatives for treated produced water as a potential new water source to address availability and demand shortfalls outlined in the Texas Water Plan. Consortium stakeholders initially identified numerous beneficial use options, including: industrial use, construction, power generation, mineral extraction products, irrigation, livestock watering (milking, non-milking animals), reclaimed water (blended with other treated water), and groundwater restoration/storage.

4.1 WestWater Research Analysis: Projected Demand and Economic Analysis of Freshwater Resources

The direct transfer of treated produced water to an end user is the most appealing alternative to immediate reuse or underground injection because they, too, represent a clear productive use to society. The appeal lies in the potential for the oil and gas industry to receive direct compensation to cover most, if not all, of the cost associated with enhanced treatment to meet the needs of users outside the industry. To identify the price potential end users would be willing to pay requires that an accurate estimate of demand for the resource be obtained. To this end, WestWater Research, LLC was contracted to provide analysis of market trends for freshwater in the Permian Basin region of Texas.[1]

The two largest current potential users of treated produced water in the Permian Basin are irrigated agriculture and municipalities. While there is an economic development potential for other sectors to grow in the region as a result of access to new/increased water resources, our current approach to projecting the demand for treated produced water is evaluated by determining the total demand for fresh water by irrigated agriculture and municipalities, less availability of current freshwater assets. In other words, the amount of treated produced water that an end user is willing to buy at a particular price is the difference between the total amount of freshwater that they would buy at that price and the amount available. Analyses were conducted for both current and future conditions, with estimates to the year 2050 to align with the State Water Plan published by the Texas Water Development Board.

4.1.1 Irrigated Agriculture

Within the Permian Basin region, irrigated agriculture accounts for approximately 75% of total water use. This is largely due to the spatial distribution of freshwater resources, the relatively low cost of its extraction compared to value generation, and potential alternative users not willing to pay the price necessary to redirect the water from its current use. Models employed by WestWater predict shortages in the Permian Basin agricultural sector of over 200,000 acre-feet per year (AFY) by the year 2030, and shortages nearing 300,000 AFY by the year 2050. The projected total quantity of water demanded for irrigated agriculture declines by 100,000 AFY between now and 2050, as marginal irrigated acreage is converted to dryland production; however, the long-term shortage could stay closer to 200,000 AFY with technologies that support use of deeper and/or less suitable groundwater resources.

Pumping costs represent the price that producers in this sector currently pay, as they represent the least cost mechanism to acquire freshwater resources for irrigation. Declines in groundwater volumes increase the costs of irrigation. Simultaneously, reduced pumping capacity increases the value to producers derived from the last unit of groundwater they can pump each year. This combination – so long as there is water physically accessible, there isn't a buyer of the water, or water isn't available to purchase at a price less than the pumping cost – will keep irrigated agriculture in the region on the projected path. WestWater estimates current pumping costs to be $13-$32/acre-foot (AF), or $0.0017-$0.0041/barrel (bbl). Those costs are projected to increase by year 2050 to $15-$35/AF, or $0.0020-$0.0045/bbl. The most reasonable conclusion, therefore, is that irrigated agriculture, en masse, is unlikely to be a net purchaser of treated produced water under current estimates and without any other anticipated market interference (such as government subsidization). This doesn't mean that there are no opportunities for transactions in this sector, just that the opportunities would likely be limited to serving as an alternative disposal mechanism that may offset some cost of treatment.

4.1.2 Municipalities

The demand for water by municipalities is more difficult to estimate than that of irrigated agriculture, as observations of end user consumption relative to price includes an expectation of water quality and delivery. The estimation is further complicated by a societal assumption that there exists an inherent right to inexpensive and high-quality water. This assumption has implications for how municipalities manage the water utility, resulting in observations of consumption from prices that are sufficiently low that demand is estimated to be highly price inelastic (changes in price result in very little change in quantity purchased). As such, use of current consumption fails to provide a meaningful estimate of municipal demand. WestWater worked around this challenge by estimating a lower bound of community willingness to pay using the EPA affordability threshold and an upper bound based on a municipality's desire to avoid shortage situations. Both estimates should result in prices exceeding current conditions.

The EPA affordability threshold assumes that the maximum willingness to pay in a community is 2.5% of median household income. The resulting maximum retail willingness to pay is multiplied by 73.5% to arrive at the maximum wholesale willingness to pay for the municipality. The remaining 26.5% of retail willingness to pay represents the average share of retail price attributable to distribution and related water system costs. Values were estimated out to the year 2050 based on current projections of population and income growth, by county, in the Permian Basin region. The maximum willingness to pay ranges between $0.19 and $0.43 per barrel currently ($1,912 and $3,325 per AF), and $0.25 and $0.45 per barrel in year 2050.

Another factor to consider in estimating demand for water at the municipal level is the effort to avoid facing water shortages, which are unfavorable politically and often lead to insufficient revenue generation to support needed expenditures on the water distribution system. WestWater's analysis included scenarios ranging between 5% and 25% shortages from projected demand over the next 25 years. Over the Permian Basin, WestWater projects average shortages in 2030 of 9.4% and average shortages of 13.7% in year 2050. At these shortage levels, the maximum willingness to pay is estimated at $0.43/bbl ($3,341/AF) in 2030 and $0.56/bbl ($4,344/AF) in 2050. If projected resources aren't available, or growth in population outpaces current projections, shortages of 20% or 25% in 2050 would result in maximum willingness to pay of $0.69/bbl and $0.85/bbl, respectively.

In summary, while the municipality is a more likely candidate as an end user of treated produced water, it may be some time before the need results in a level of compensation to justify the transactions. However, as communities plan to meet their water needs in the future, there is likely an opportunity for treated produced water to be included as part of the current portfolio of water sources to replace current use of an alternative source worth protecting for the future. Increasing the total cost of the water portfolio now has the potential to yield lower portfolio costs in the future by maintaining sufficient supplies of less expensive water sources.

The full report from WestWater Research, LLC can be found on the Texas Produced Water Consortium's website.

4.2 Targeted Research for Economic Viability of Treated Produced Water

4.2.1 Carbon Capture

Water intensive industries beyond the oil & gas sector are not currently prevalent in the Delaware and Midland basins, and the business models for those that do exist are viable under the current supply and demand for water in that region; i.e. their anticipated use would not significantly change if presented with access to the volumes of treated produced water we have for consideration. The Stratos Direct Air Capture (DAC) plant, currently under construction, will offer insights into DAC plant water needs as it comes online and is operationally tuned. Carbon capture is an important consideration of many producers as indicated by the investment in Stratos DAC reported to cost $1-1.5 Billion[93]. Carbon capture options are viable alternatives to offset PW treatment and distribution costs when they are considered as stacked or co-benefits to improve cost accounting for treatment of PW. While carbon capture plants are one alternative, they are expensive and require intense resource use in construction, require high energy inputs, and provide a number of other unknown variables that we will continue to evaluate for their impact to the economic viability of this option.

The highest oil and produced water production areas in the Permian Basin today were previously the southern end of the bison grazing range and covered by a healthy short-grass prairie ecosystem. Post-bison removal, intensive cattle grazing operations changed plant-soil coverage ratios, plant community composition, and spread invasive water tapping species like mesquite into the region. Literature indicates degraded prairie conditions, like those in the Delaware and Midland Basins of Texas, are likely to capture 0.3 tons of carbon per acre annually. This is equal to best practices of irrigated cotton production with a cover crop at 0.3 tons per acre/year. Restored healthy prairie ecosystems are shown to sequester up to 8 tons of carbon per acre per year (a 26.7x or 2667% increase).

Treated produced water can be used to solve a critical challenge in arid and semi-arid ecosystem restoration as water would be available for plant establishment and at critical points of plant growth and could be used nearly all year round across the entire region as some native species are better suited for fall planting than spring and summer. The potential impact of ecosystem restoration for agricultural production and grazing could be one of the largest restoration projects globally, and be equal to or greater than China's Loess Plateau 20-year

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[93] https://www.good.is/a-1-3-billion-direct-air-capture-plant-in-texas-will-remove-500-000-tons-of-co-2-every-year

restoration of 8.6 million yielding a 10x increase in that region's agricultural economy. Over the next 20 years, restoration of seventy (70%) percent of the Permian Basin's 12 million acres would equal 8.6 million acres and would increase carbon sequestration in the Permian Basin from 2.6 million to 68.8 tons annually. This is equivalent to 1.25 Stratos scale DAC plants according to Oxy's 55 million tons per year projections reported in May 2024[94].

In one carbon market scenario at $2.00 per ton per acre would total $17.2 million annually. The complexities of landowner lease agreements with O&G producers related to fresh (mainly aquifer) water use have complicated recycling of plentiful produced water for use in fracturing jobs due to potential lost income from landowner water sales to O&G producers. TPW use for land application to restore ecosystems and improve carbon credit revenue will provide another challenge in agreements but can offer a win-win scenario for landowners and producers should they choose to work together and share risks and costs for potential carbon earnings which can offset treatment costs of PW. The water impacts would be positively compounded by first nearly eliminating extraction of freshwater for fracturing jobs by using 100% recycled PW. This would also cut down on total water going to disposal wells lowering seismic risks and reduce total PW volume to be treated.

Carbon sequestration is only one of the stacked and co-benefits of a short-grass prairie ecosystem restoration approach. Research indicates healthy prairie ecosystems increase water infiltration and soil moisture for plant production, while reducing creek/stream/river flashiness and flooding during intense precipitation events. Increased infiltration can restore historic water base flows into streams, playas, seeps, aquifers, etc. and sustain water availability over longer periods of time essential to terrestrial and aquatic species or provide recharge to aquifers. Base flow is how water is seen in creeks and rivers between precipitation events[95].

Importantly, TPW use for large scale prairie restoration would not require any major changes in water movement infrastructure systems in place nor pumping distances (~3-mile radius) limiting CAPEX and holding current water network OPEX near constant assuming treatment occurs near active production areas. The only change would be the integration of perforated and/or gated pipes into existing distribution networks to allow the controlled and timed release of TPW into desired ecosystem restoration areas.

Additionally, native plant seeds could be harvested for additional restoration projects and become a valuable resource in the US's documented native seed supply shortfall (NAS, 2023). Commercial prices for native seeds range from $11 to $300 per pound of seed. Prairie restoration takes a minimum of 3 years for plant establishment, and will require some management of invasive species to prevent further invasive seed production. This is often done by shredding early growth weeds prior to seed distribution.

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[94] https://www.npr.org/2023/12/27/1210928126/oil-climate-change-carbon-capture-removal-direct-air-capture-occidental

[95] C.M. Stephens, U. Lall, F.M. Johnson, L.A. Marshall, "Landscape changes and their hydrologic effects: Interactions and feedbacks across scales", Earth-Science Reviews, Volume 212, 2021, 103466, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2020.103466.

As irrigated crop water becomes more scarce north of major oil production areas, feedlots and dairies will need additional feed sources and healthy prairie grazing options could offset some feed needs for beef cattle especially if restoration include some additional legumes (West, 2020?). Some restored prairie systems could potentially be cut for hay under more intensive TPW applications.

Large scale ecosystem restoration provides many stacked and co-benefits for use of TPW, however there are also challenges. Timing and volume of TPW for land application will need to be planned for each application area as conditions are highly variable across the region. Large scale centralized PW treatment plants would require pumping of PW over greater distances and could limit large scale land application options due to costs to move TPW post-treatment to restoration areas as is the case with irrigated agricultural options.

Under ideal TPW application scenarios for large scale ecosystem restoration, TPW application would be best used for plant establishment and move over time following fracturing jobs. Once initial ecosystem plant communities are established, then natural precipitation patterns should take over allowing TPW application to move to new restoration locations. Grazing is a natural and essential component of high functioning prairie ecosystems. Therefore, restoration areas will need to be grazed to effectively manage biomass growth, disturb soil surfaces with animal movement patterns, and provide animal waste essential to physical, chemical, and biologic aspects of healthy soils which are directly connected to healthy plants.

5 Desalination Technologies for Midland and Delaware Basin Produced Water

Diversion of produced water from deep well disposal to beneficial uses through desalination is increasingly of interest. This report examines the most promising technologies for desalination of Permian Basin produced water and identifies basic energy requirements as well as the most common challenges associated with desalinating the produced water. The Permian Basin can be divided into the Midland Basin which exhibits a median total dissolved solids (TDS) of 129,000 mg/L (based upon a summary of 23,296 samples) and the Delaware Basin which exhibits a median TDS of 71,700 mg/L (based upon 6,182 samples), although some Consortium members indicate portions of the basin that experience similar average salinity to that of the Midland. The lower salinity of the Delaware Basin water provides a greater range of opportunities for desalination including Ultra High Pressure Reverse Osmosis (UHP-RO) as well as thermal desalination. The higher salinity of the Midland Basin suggests that thermal desalination processes are likely to be the only viable technology solutions. Among the thermal desalination processes, mechanical vapor compression/recompression (MVR) is considered the most efficient of the currently commercial technologies and is used in most proposed desalination demonstration plants. This report will summarize the applicability and energy requirements of RO/UHP-RO and MVR for Delaware Basin type waters and for MVR for Midland Basin waters. Key results suggest that slightly acidic feed waters (either naturally or through acid addition) can limit precipitation of scaling compounds such as calcium carbonate as well as dramatically reduce carryover of ammonia by either UHP-RO or MVR.

Future work is expected to focus on additional process modeling to examine trace organic constituent behavior in the MVR system as well as examine, via modeling, potential improvements to the processes. We also expect to undertake experimental evaluation of the UHP-RO process and to evaluate pilot plant data from MVR systems to test the modeling results and to provide field performance data. Our analytical equipment is currently being installed to conduct these analyses. We expect that both modeling and experiment will drive improved understanding as well as help optimize the technologies that may be applied in the Permian Basin.

5.1 Characteristic of Delaware and Midland Basin Produced Water

As noted above the chemistry of the produced water from the Delaware and Midland Basins of the Permian Basis are substantially different. This is due both to formation characteristics as well as the amount of water produced per barrel of oil. The water-oil ratio (WOR) in the Delaware Basin is estimated to be almost double the WOR of the Midland basin (Figure 1).

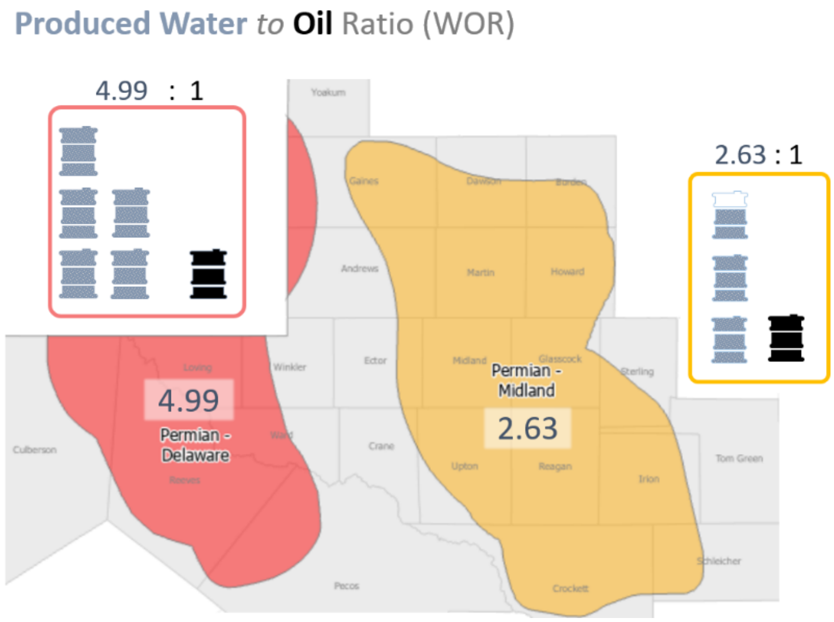

Figure 1: Produced Water-to-Oil ratios in the Permian's Delaware and Midland Basins.

The composition of the Delaware and Midland basins is summarized in Table 1.The much higher WOR in the Delaware Basin is reflected in the lower salinity of the water from this basin. The pH shown in the Table was defined by equilibrium thermodynamics using the observed composition of the waters.

Table 3 Composition of Delaware and Midland Basin produced waters by percentile and comparison to seawater

				Delaware Basin (6,182 samples)			**Midland Basin (23,296 samples)**		
	Water Source (%ile)		**Seawater**	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**
Resistivity,		ohms/m	-	0.066	0.09	0.125	0.045	0.05	0.059
Ionic Strenght		mol/L	0.7	0.9	1.27	1.75	1.97	2.33	2.59
pH			8.15	6.33	6.68	7.02	5.95	6.23	6.69
Hardness,		mg/L	6,345	1,901	3,426	6,716	7,387	9,807	13,095
Calcium	(Ca)	mg/L	400	594	1,064	2,073	2,277	3,066	4,112
Magnesium	(Mg)	mg/L	1,272	98	180	357	388	512	683
Sodium	(Na)	mg/L	10,556	18,920	25,897	34,484	38,528	46,000	50,207
Potassium	(K)	mg/L	380	176	262	386	448	563	684
Barium	(Ba)	mg/L	-	1	1	3	2	3	4
Strontium	(Sr)	mg/L	13	120	188	329	422	576	736
Iron	(Fe)	mg/L	-	5	14	30	25	47	79
Manganese	(Mn)	mg/L	-	0.3	0.5	0.8	0.9	1.4	2.2
Sulfate	(SO4)	mg/L	2,649	362	662	931	271	386	572
Chloride	(Cl)	mg/L	18,980	29,927	42,309	58,000	65,663	77,764	86,532
Bromide	(Br)	mg/L	65	194	255	297	464	588	683
Phosphate	(PO4)	mg/L	-	21	26	37	43	53	69
Boron	(B)	mg/L	4.6	37	45	64	42	50	60
Silica	(SiO2)	mg/L	-	13	15	18	10	13	16
Bicarbonate	(HCO3)	mg/L	140	427	610	830	244	329	439
Carbon Dioxide	(CO2)	mg/L	-	88	154	264	154	264	418
TDS		**mg/L**	**34,400**	**50,980**	**71,700**	**98,100**	**109,000**	**129,000**	**145,000**

The fundamental challenge of desalination is the energy cost of separation of the salts from the water. The ideal energy requirements (i.e. assuming 100% efficiency and no energy losses of any kind) are shown in Figure 2 for seawater and the 25%ile (96,0000 mg/L), 50%ile (122,000 mg/L) and 75%ile (140,000 mg/L) Permian Basin waters (including both Midland and Delaware Basins)

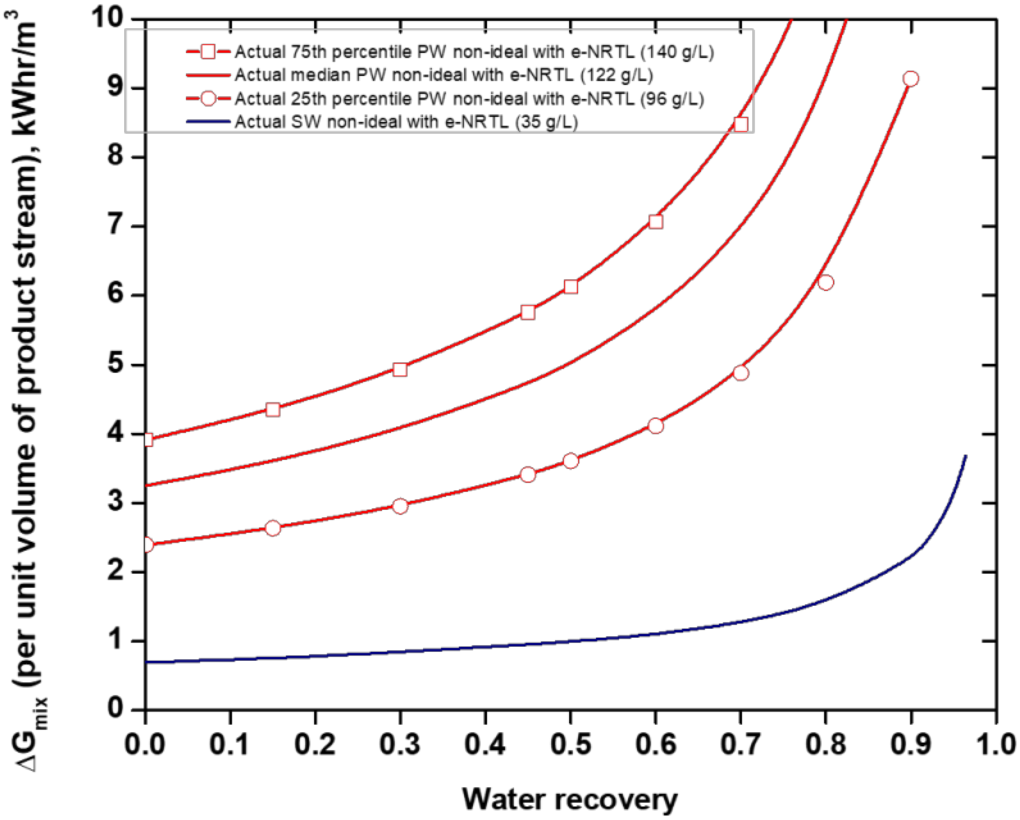

Figure 2: Minimum energy requirements to separate salts from seawater and 25th, 50th and 75th %ile Permian Basin waters

In addition to TDS, important components that affect desalination include the dissolved inorganic carbon (DIC) (distributed between carbonic acid, carbonate, bicarbonate and carbon dioxide depending upon pH) and calcium (which is typically the most important precipitating compound) . There is also concern about trace constituents not identified in Table 1 including volatile organic contaminants (VOCs) such as benzene, toluene, ethylbenzene and xylene (BTEX) and ammonia. Ammonia has been identified as a constituent that may control beneficial use of the treated water and its fate during desalination is especially important here. Concentrations of total ammonia nitrogen (TAN) consisting of ammonia (NH_3) and ammonium (NH_4^+) are often 300-800 mg/L in the raw produced waters. Ammonia is generally viewed as the limiting factor in the beneficial use of the treated water in that the allowed ammonia is typically well below 30 mg/L depending upon final use.

5.2 Desalination of Delaware Basin Produced Water by RO/UHP-RO

Because of the relatively low salinity of the Delaware Basin Water, RO and UH-PRO should be the most cost-effective treatment approach. RO is routinely used for desalination of seawater with a total cost of about $2000/acre-ft of water produced or about $0.26/bbl. All energy requirements and costs in this report are based upon volume of treated water produced and not feed water volume. The specific energy requirements of actual systems are 3-4 kWh/m^3 for seawater desalination (Integrated Membrane Solutions Model, Nitto Hydronautics). At a current Texas average energy cost of $0.15/kWh, this corresponds to $0.45-$0.60/m^3 or $0.07-0.12 /bbl. The balance of the cost per volume water produced is associated with typically required pretreatment and capital costs. Note that drinking water systems are typically prorated over 20-30 years because treated water demand is typically stable or increases.

A simple schematic for a single stage RO system is shown below:

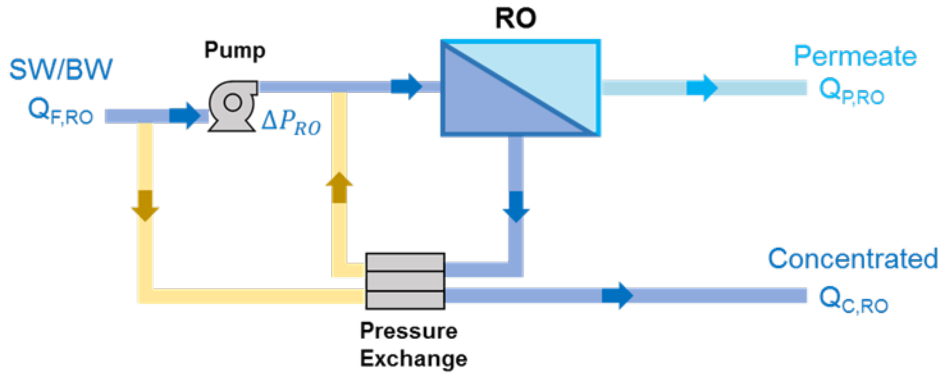

Figure 3: Simplified single stage RO system.

Seawater RO (SWRO) membranes are widely commercially available and can typically operate at pressures up to approximately 1200 lb/in² or approximately 80 bar. Although the salinity of produced water is higher than seawater, there are also Ultra-High Pressure Reverse Osmosis (UHPRO) membranes (*e.g.*, DuPont's FilmTec™ XUS180808) that can operate at pressures of approximately 1,800 lb/in² or approximately 120 bar which is promising for treating PW, especially in the Delaware Basin[96].

The salinity of RO concentrate (C_{conc}) can be approximated by conservation of mass of the feed salinity (C_{feed}), accounting for the volumetric hydraulic recovery (r) and salinity removal (R), according to Equation 1 (*i.e.*, neglecting changes in solution density and mass fraction):

$$C_{conc.} = C_{feed}\left(1 + \frac{rR}{1-r}\right) \qquad \text{Eq. 1}$$

The osmotic pressure of the RO concentrate (π_{conc}) can be estimated with Eq. 2 based on the concentrate salinity (calculated from Equation 1), the universal gas constant (R), the osmostic coefficient (φ, approximated as 1.0), the molar concentration of ions, C_{solI} (approximately the sum of the concentrations of the Na and Cl ions), and (T) the absolute temperature (assumed to be 25 °C or 298 K)

$$\pi_{conc} = \varphi c_{sol} RT \qquad \text{Eq. 2}$$

[96] DuPont. (2023). DuPont™ XUS180808 Reverse Osmosis Element Product Data Sheet. In blob:chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/38f8fe79-1c85-46d3-9c21-650b3903b86b (Ed.): DuPont

Assuming 99% salinity removal (R), the salinity and osmotic pressure of RO concentrate were estimated using Eqs. 1 and 2, respectively, for treating the 25th percentile and 50th percentile salinities of the Delaware Basin with volumetric hydraulic recovery ranging from 30% to 50% (Figure 4). The first quartile salinities could easily be treated by SWRO, and the second quartile could be treated by UHPRO, both with hydraulic recovery up to 50%.

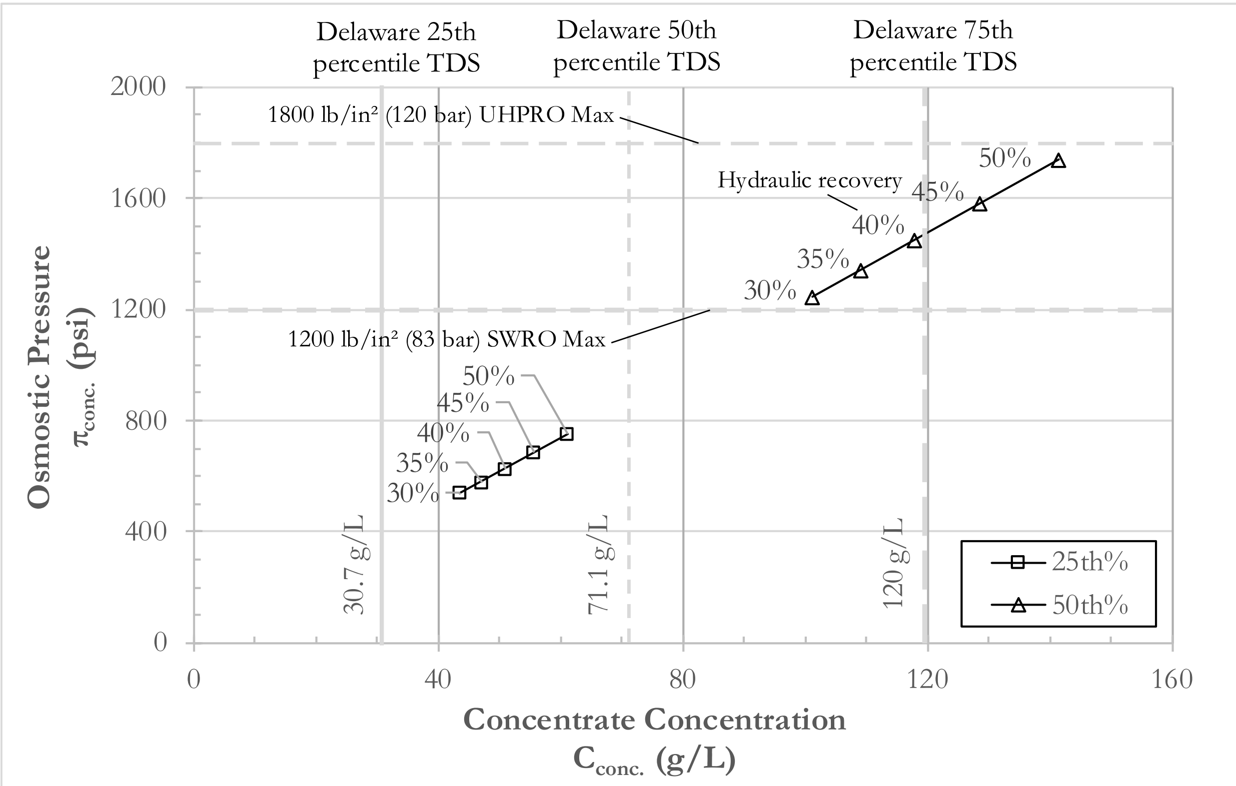

Figure 4: Estimated Delaware RO concentrate osmotic pressures as a function of percent recovery compared to RO limits.

We can expect an energy requirement of 8-10 kWh/m^3 (Integrated Membrane Solutions Model, Nitto Hyrdronautics). This suggests that energy requirements alone correspond to $0.19-0.24/bbl. Assuming that the desalination energy requirements account for 30-50% of the total cost (as with seawater), the expected treatment costs for application of RO to Delaware Basin waters is expected to be $0.50-$0.60 /bbl.

The above analysis suggests that the 25th percentile and 50th percentile salinities of PW from the Permian's Delaware Basin (30.7 g/L and 71.1 g/L) could be treated with SWRO and UHPRO, respectively, with hydraulic recovery up to 50%, which can be achieved with single-stage array design. Note that the presence of sparingly soluble constituents could limit the actual recovery. The 75th percentile salinity of 120 g/L could be treated by UHPRO with a hydraulic recovery of approximately 20% (not shown on Fig. 2). More rigorous modeling should be conducted for more accurate predictions of osmotic pressures for these high salinity brines.

Testing could proceed with a laboratory scale UHPRO system with operators shipping samples of “clean brine” from the Delaware Basin. Considering the temporal variability of PW, pilot testing at a clean brine facility or at a saltwater disposal (SWD) well is critical to evaluate the robustness and longevity of UHPRO membrane elements in this application.

Field demonstration/testing could also evaluate the transport of organics and ammonia through the RO system. It would be expected that most of the organics and any dissolved ammonia (NH_3) would pass through the membrane in the RO/UHPRO while ammonium (NH_4^+) would not. The distribution of TAN between NH_3 and NH_4^+ is a function of pH with acidic pHs reducing the amount of NH_3 that can pass into the treated water. A low pH would also reduce the precipitation of any scaling components such as $CaCO_3$. The effect of pH on treated water quality is addressed in the evaluation of MVC below.

5.3 Desalination of Delaware Basin Produced Water by MVR

Although RO/UHP-RO is likely to be the most efficient desalination approach for Delaware Basin produced waters, it is possible to compare it to a mechanical vapor compression system for these waters. MVR has been demonstrated in pilot facilities for a shale gas water with feed composition very similar to 25%ile Delaware Basin produced water[97]. We will use this demonstration illustrate the applicability of MVR for Delaware Basin quality waters. We also simulated the process in Aspen Plus® process modeling software to allow evaluation of the behavior of carbonates and ammonia through the process. AspenPlus® has incorporated many of the thermodynamic extensions developed over the past decade at Texas Tech to allow prediction of the thermodynamics of concentrated electrolyte solutions. The thermodynamic package in AspenPlus® and developed originally by Dr. Chen at Texas Tech, is the electrolyte non-random two liquid model (e-NRTL). A simplified flowsheet for MVR used in the simulations and depicting the key parts of the process is shown in Figure 5.

[97] Hayes, T. D., Halldorson, B., Horner, P. H., Ewing, J. J. R., Werline, J. R., & Severin, B. F. (2014). Mechanical vapor recompression for the treatment of shale-gas flowback water. *Oil and Gas Facilities*, *3*(04), 54-62.

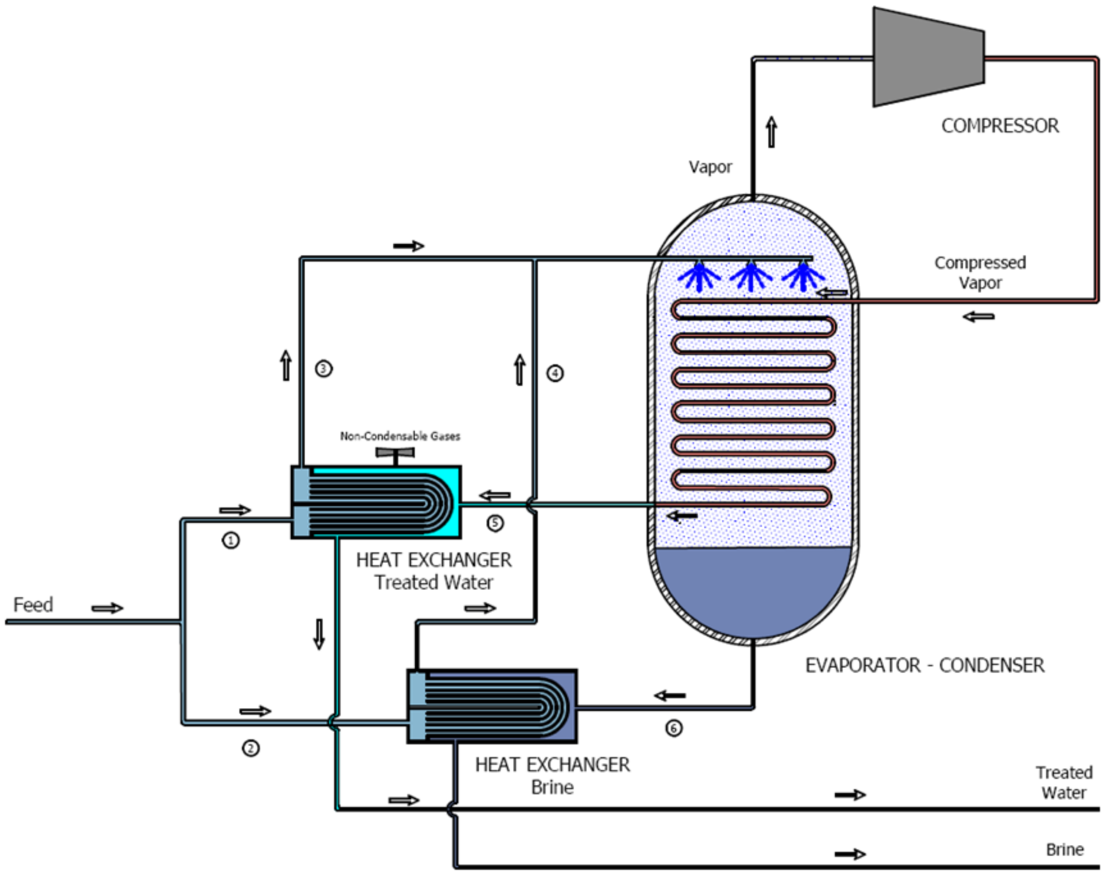

Figure 5: Simplified Flowsheet for MVR

MVR involves low pressure evaporation of the feed brine with the vapor being compressed and heated to supply the necessary latent heat. The feed waters are heated by the product concentrated brine and condensed distillate stream. The primary energy input is the compressor to drive the process.

The feed to the MVR pilot facility contained a median of 44900 mg/L TDS. The pH was adjusted to 10 and then the water was clarified before pH was again lowered before being fed to the evaporation unit. The system was operated at 68% recovery (by mass, 72% by volume) . The compositions of the feed stream, the post-clarifier feed stream to the evaporator and the distillate (product treated water) and condensate (concentrated brine) are summarized in Table 2.

Table 4 Feed and product stream compositions for shale water demonstration MVR[98]

			Influent Water	Post Clarifier	Distillate	Concentrate
TDS	mg/L		44900	46900	103	162000
Calcium	(Ca),	mg/L	2570	2705	0.8	8960
Magnesium	(Mg),	mg/L	291	296	0.1	1055
Sodium	(Na),	mg/L	10700	12100	3.6	39000
Potassium	(K),	mg/L	296	349	0.1	1670
Barium	(Ba),	mg/L	7	7	0.1	5
Strontium	(Sr),	mg/L	467	467	0.1	1735
Iron	(Fe),	mg/L	27	27	0.1	2
Lithium	(Li),	mg/L	11	11	0.1	38
Sulfate	(SO4),	mg/L	316	205	5	793
Chloride	(Cl),	mg/L	-	-	-	-
Phosphate	(PO4),	mg/L	9	6	0.3	18
Boron	(B),	mg/L	18	16	0.4	62
Bicarbonate	(HCO3),	mg/L	-	-	-	-
Carbon Dioxide	(CO2),	mg/L	-	-	-	-
	(CO3),	mg/L	-	-	-	-
Ammonia		mg/L	84	84	64	114
BTEX		mg/L	2.9	2.1	0.1	0

The results show that negligible TDS is found in the distillate stream but were instead Approximately half of the mass of the ammonia in the feed was found in the distillate stream but as we will see below this is a strong function of feed pH as well as temperature. BTEX compounds in that these are not destroyed by the system but the distillate liquids contained almost no BTEX suggesting that most of the BTEX was in the vapor of the distillate and vented.

Process simulations in AspenPlus® were able to reproduce the observed distribution of salts. The simulations were also used to estimate the energy required to achieve the observed separation and the specific energy consumption (SEC) of the process was estimated to be 18.3 kWh/m^3 of treated water produced assuming a 70% efficiency of the compressor. This is at least double the specific energy requirement for UHP-RO. This represents the SEC of the process and any external efficiency losses associated with how the power is generated is not included. For example, Hayes et al. (2014) employed natural gas generators to provide power and based upon natural gas utilization, 40 kWh/m^3 was required to operate the process. They estimated an overall efficiency of 35% in translating this power to desalination. Assuming the 70% compressor efficiency, this translates to an estimated SEC for the process of 20 kWh/m^3, in good agreement with the simulation estimate of 18.3 kWh/m^3. This suggests that the energy requirements of MVR when applied to Delaware Basin waters are 3-4 times that of UHP-RO.

Process simulations were also used to evaluate the distribution of important trace components in the produced water feed including ammonia and $CaCO_3$. The distribution of both

[98] Hayes, T. D., Halldorson, B., Horner, P. H., Ewing, J. J. R., Werline, J. R., & Severin, B. F. (2014). Mechanical vapor recompression for the treatment of shale-gas flowback water. *Oil and Gas Facilities*, *3*(04), 54-62.

of these constituents are a strong function of pH as shown in Figures 6 and 7. Figure 6 shows that the Ca in the feed is entirely associated with the concentrated brine at pH<6. As pH increases between 6 and 7, however Ca is precipitating at $CaCO_3$, potentially causing scale in the process equipment.

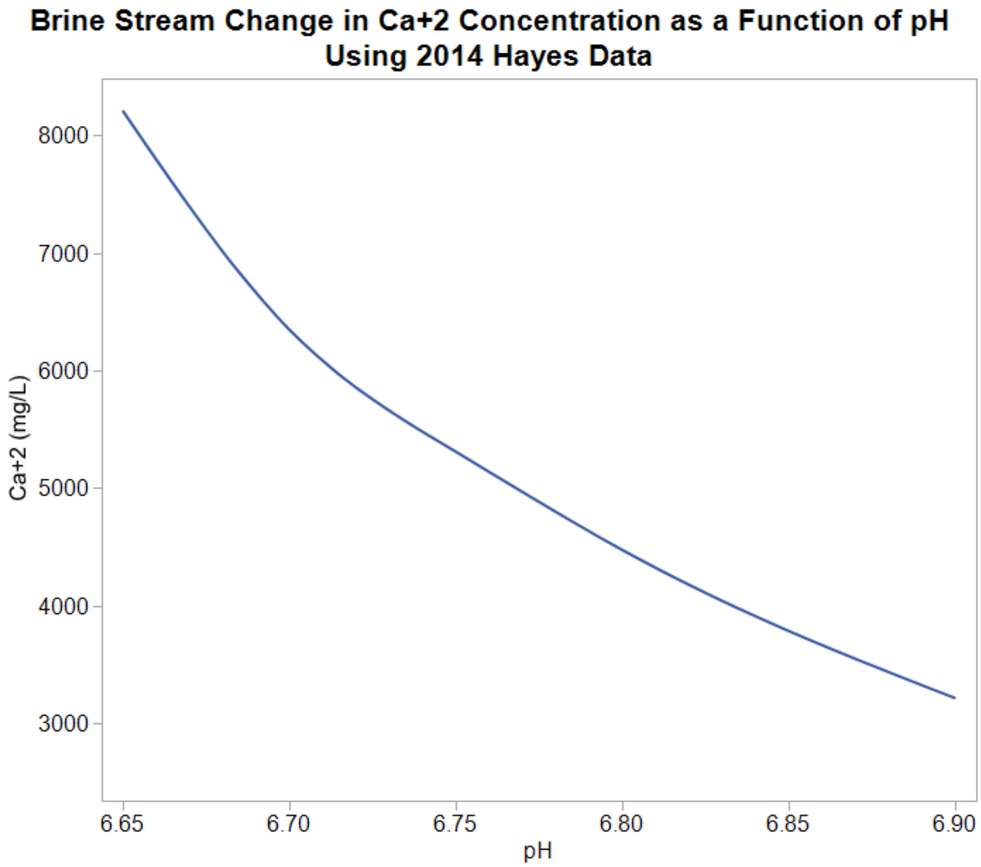

Figure 6: Calcium precipitation as a function of pH feed to the evaporator

In Figure 7, the total ammonia nitrogen in both the treated water and in the concentrated brine is shown as a function of pH. At low pH (pH<5.5), essentially all of the total ammnia nitrogen is in the form of NH_4^+ and stays with the concentrated brine. As pH increases to near neutral conditions, however, the bulk of the nitrogen is in the form of NH_3 and is found in the distillate stream and ultimately, the treated water or in the vapor in the evaporator overheads. This illustrates that perhaps the easiest means of controlling both $CaCO_3$ participation and ammonia carryover into the desalinated water is to maintain the feed pH well below 6. The specific pH will vary depending upon the concentrations of ammonia and calcium in the feed water, temperature and the desired concentrations in brine and/or distillate streams. Note that maintaining an acidic pH would also benefit an RO/UHP-RO in that there would be little $CaCO_3$ precipitation or ammonia in a form capable of migrating through the RO membrane.

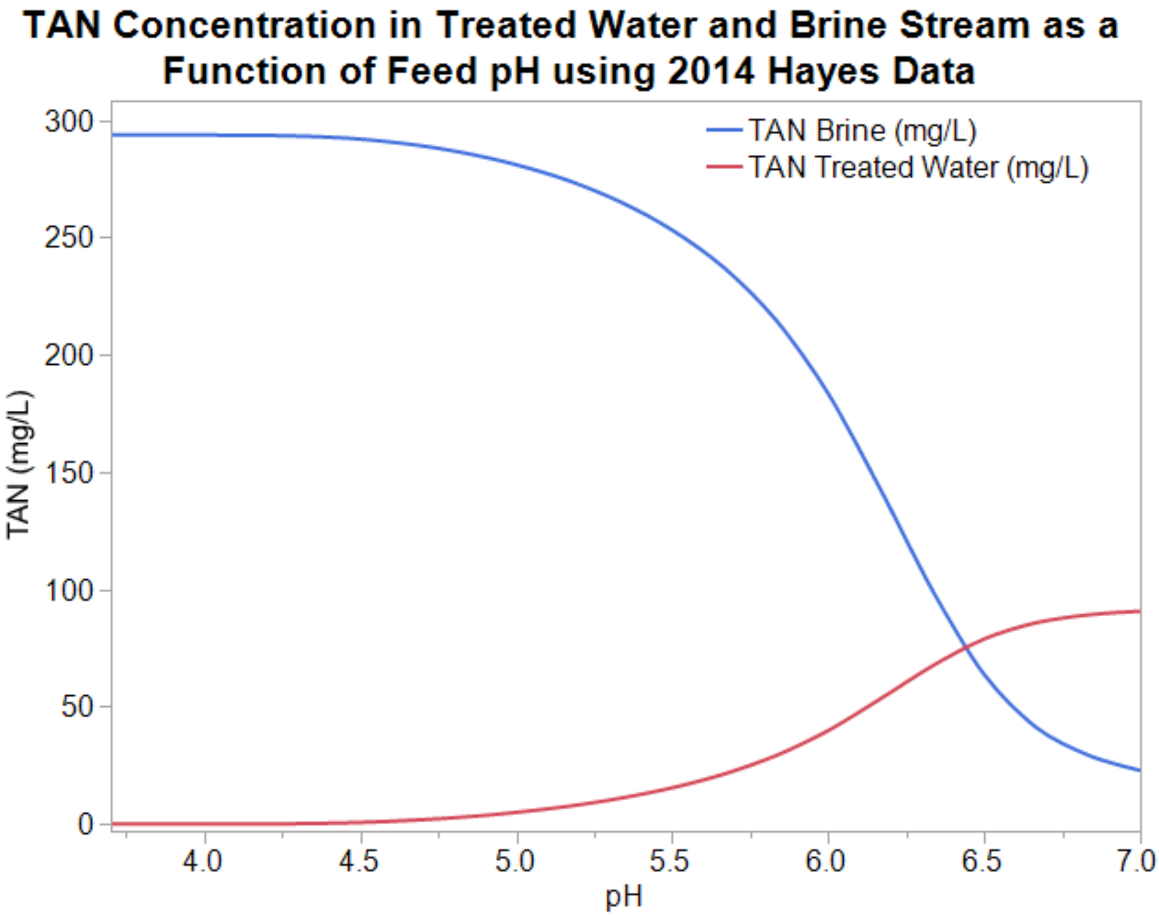

Figure 7: Total Ammonia Nitrogen as a function of feed pH

5.4 Conclusions for Delaware Basin

The above discussion suggests that the best option for desalination of Delaware Basin produced water is RO/UHP-RO given the lower energy requirements in the range of 4-6 kWh/m^3 (just desalination step). Maintaining an acidic feed water is also likely to eliminate any $CaCO_3$ scale on the membrane or process equipment and enhance ammonia rejection by the membrane, reducing requirements for other pre or post treatment of the feed water. The use of MVR for Delaware Basin produced waters will likely require 3-4 times the energy of RO/UHP-RO under ideal conditions and thus is much less favored for use with these waters.

Desalination of Midland Basin Produced Water by MVR

The much higher salinity and therefore osmotic pressure of Midland Basin produced water suggests that RO/UHP-RO is not a viable desalination approach with current membrane technology. Instead, thermal technologies and MVR are likely to be the optimum choice for desalination. AspenPlus® was again employed to simulate process performance of MVR for desalination of Midland basin waters. Here we will focus on the median waters and evaluate the sensitivity of performance of the system to variations in input water composition.

At NaCl concentrations above 300 g/L (300,000 mg/L), salts will precipitate leading to a solids handling problem. In order to avoid this, the operation is limited to a recovery of about

50% based upon mass for the median Midland Basin produced waters. The concentrated brine which will remain a slurry with only trace precipitates can then be sent for deep well disposal. We will focus on performance up to the maximum recovery of about 50%. Although significant volumes will still need to be disposed of via deep well injection, the recovery will cut the volume requiring disposal approximately in half and reduce pressure on potentially overstressed injection zones.

A key factor in system performance is the presence of dissolved inorganic carbon (DIC) in the form of carbonate, bicarbonate and carbon dioxide (CO_2). High carbonate concentrations can lead to precipitation of scaling solids, particularly calcium carbonate. In addition, carryover of the volatile CO_2 to the distillate fraction ensures the formation of a non-condensable phase which reduces the energy efficiency as well as reduces the amount of desalinated condensed water that can be produced. The effect of dissolved inorganic on SEC for the MVR process was simulated and the results are shown in Figure 8. The higher salt content of the Midland Basin produced water increases the SEC over the simulations with Delaware Basin water (20-30 kWh/m^3 for 50% recovery depending on DIC content). The SEC is at a minimum in the range of 20-25% recovery but this does not maximize the amount of treated water produced. The SEC increases up to the maximum of about 50% recovery and increases with DIC in the feed water.

In Figure 8, the SEC associated with desalination produced water with only NaCl and no DIC present is also shown to illustrate the effect of DIC. The influence of DIC on SEC is most pronounced at low recovery rates where the effects of the noncondensable CO_2 significantly affect the amount of treated water produced.

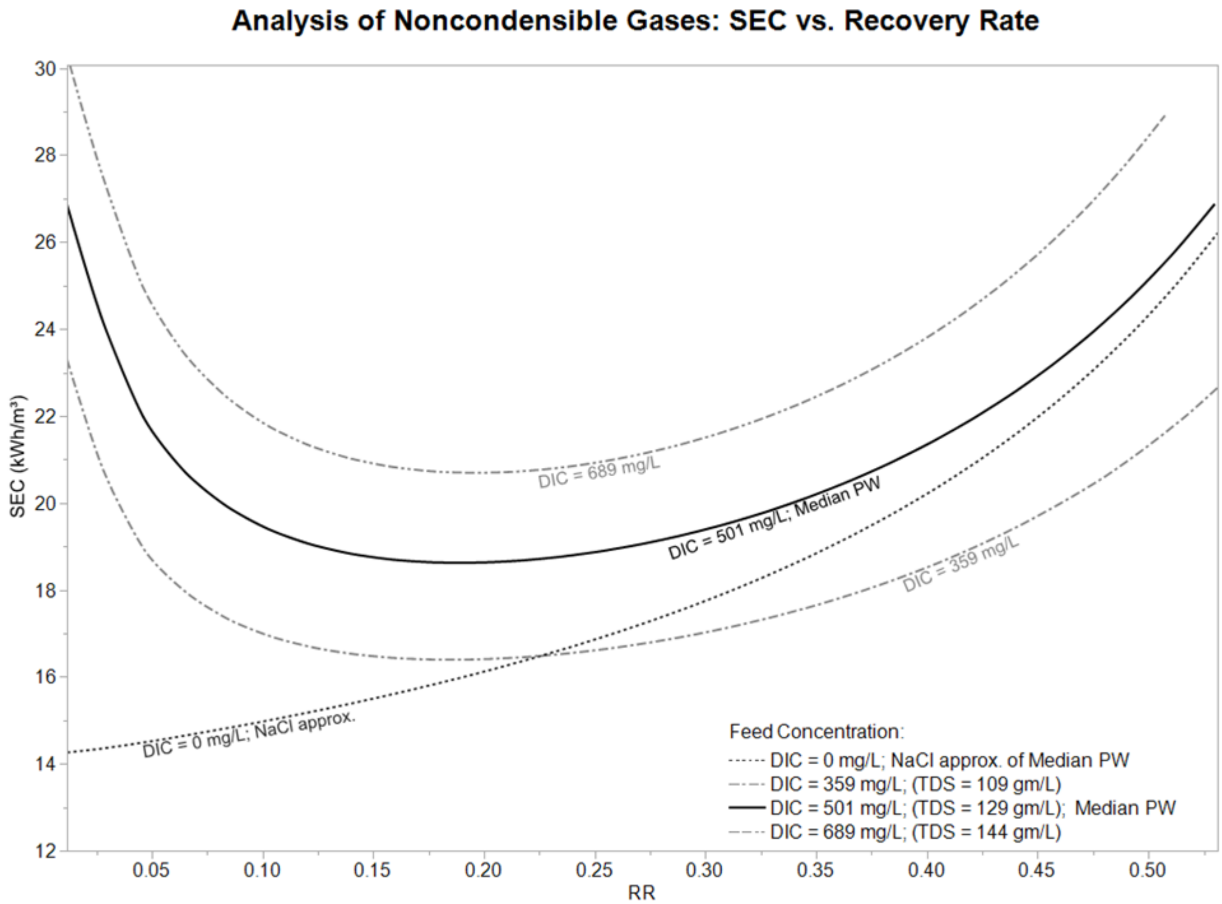

Figure 8: SEC versus recovery for DIC of 25%ile, median and 75%ile Midland Basin produced water. NaCl at TDS of median water also shown to reflect of SEC when there are no non-condensable gases in the overhead.

The SEC can also be influenced by process conditions. Key process variables include the evaporator temperature and the final temperature difference between the condensing treated water phase compared to the evaporator temperature. The latter represents the efficiency in transferring heat from the condensing , compressed vapor to the evaporating liquid feed. Table 3 summarizes the SEC estimated for 50% recovery as a function of these two key process variables. As expected, improvements in evaporator/condenser design to maximize the heat transfer between the two phases provides the most benefits in reducing energy requirements.

Evaporator temperature has a modest effect with higher temperatures requiring somewhat more energy for the desalination.

Table 5 SEC as a function of evaporator temperature and the final temperature difference between the evaporator and the condensed desalinated water. All simulations for median Midland Basin produced water and 50% recovery

SEC in kWh/m³ by Evaporator Temperature				
ΔT	60 C	70 C	80 C	90 C
1 C	18.9	19.2	19.6	19.9
2 C	21.8	22.0	22.2	22.4
3 C	24.8	24.9	24.9	25.0
4 C	27.8	27.7	27.7	27.7

The process simulations were also used to estimate the distribution of TAN and DIC between the concentrated brine and the treated water as a function of the feed pH. The SEC and percentage of non-condensable vapor in the evaporator overhead stream changes very little as a function of feed pH. The distribution of DIC and TAN, however change dramatically.

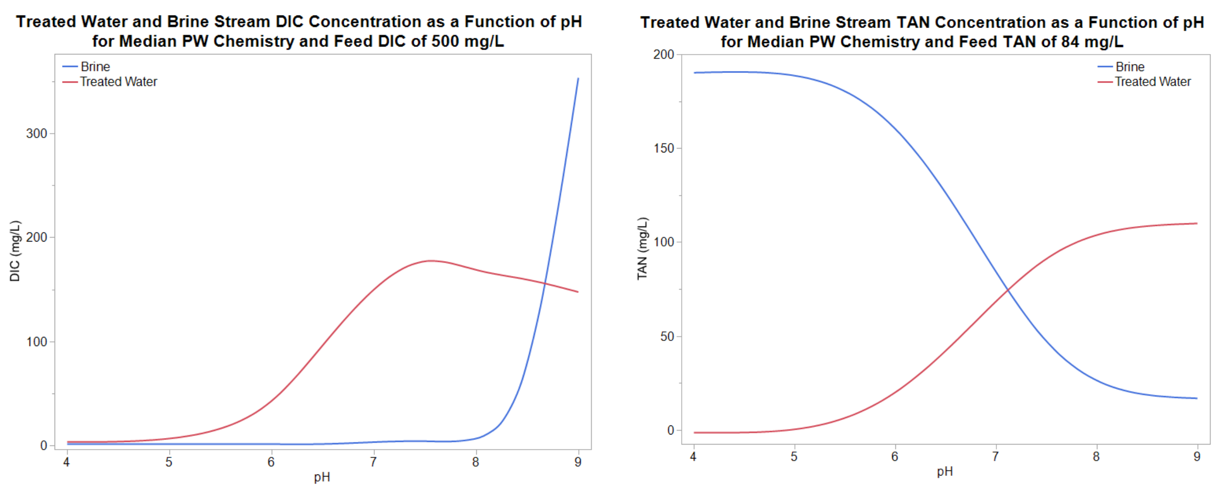

Figure 9: DIC (carbonates and CO2) and TAN distribution as a function of feed pH for Midland Basin median produced water

DIC in Figure 9 is shown as the sum of carbonate, bicarbonate and CO_2 in the liquid phase. Figure 9 shows that at pH below 6 the CO_2 is largely driven out of the liquid into the vapor and is not included in the figure. The mass of CO_2 in the overhead from the evaporator remains a relatively small fraction of the total vapor stream (which is more than 90% water vapor) and does not significantly affect the SEC of the overall process although it will contribute to some carryover of carbonates into the condensed desalinated water stream. As pH increases above 8, the amount of carbonates in the concentrated brine increases dramatically due to precipitation (e.g. of calcium carbonate).

TAN follows a very similar behavior to that predicted for the pilot demonstration of Hayes et al. 2014[99]. That is, below pH 6, all of the ammonia nitrogen is in the concentrated brine while at more neutral and basic pH of the feed, the ammonia nitrogen becomes an important contaminant of the condensed treated water stream.

The presence of significant ammonia in the condensed treated water stream is problematic in that it limits beneficial uses of the water. Post-treatment is required to remove the ammonia for many beneficial uses. Moderate acidification of the feedwaters, however, will ensure very little carryover of ammonia and ammonia is not of concern in the concentrated brine to be sent for disposal.

VOC distribution can also be estimated through the process simulations. VOCs are not sensitive to pH but their presence in the overhead stream is largely a function of their volatility from water. Those compounds with high aqueous volatility will be carried overhead and partition between the overhead vapor phase the condensed treated water stream. Benzene, for example, would be largely carried into the overhead from the evaporator while a greater proportion of high molecular weight polyaromatic hydrocarbons would be carried with the concentrated brine. The carryover of organics will be evaluated more completely in future analyses.

5.5 Conclusions for Midland Basin

MVR can be viewed as an efficient desalination approach for Midland Basin water. Adjustment to an acidic pH as a pretreatment step can have significant benefits in terms of reducing $CaCO_3$ scale and, most importantly, reducing the carryover of ammonia into the treated water. This may be a far more cost-effective solution for ammonia than treatment of the desalinated product water. Post-treatment may still be needed, however, for the management of VOCs that will be examined in more detail in the coming year.

[99] Hayes, T. D., Halldorson, B., Horner, P. H., Ewing, J. J. R., Werline, J. R., & Severin, B. F. (2014). Mechanical vapor recompression for the treatment of shale-gas flowback water. *Oil and Gas Facilities*, *3*(04), 54-62.

6 Upcoming Research Project: Guayule Latex Production Using Produced Water

6.1 Introduction

Produced water, a byproduct of oil and gas production operations, contains various production chemicals. It accounts for up to 80% of the waste generated by these operations[100]. In 2019, the oil and gas industries in northern and western Texas produced over 3.9 billion barrels of produced water[101]. Due to its high salinity (120,000-130,000 mg/L total dissolved solids (TDS)) and other contaminants, untreated produced water is generally unsuitable for crop production[102]. Some studies have reported TDS concentrations as high as 400,000 mg/L[103]. Sodium and chloride ions are the most prevalent components, but arsenic, boron, silica, benzene, ethylbenzene, toluene, and phenol are also common. The composition of produced water varies depending on factors such as geology, depth, and chemical additives, making regional differences significant. However, most produced water is composed of various inorganic salts, metals, radioisotopes, and organic hydrocarbons[104].

A study by Benko & Drewes assessed geologic basins for coproduced water and its quality, classifying the Permian Basin as having very low potential for treatment due to high TDS concentrations and large volumes of water[105]. However, this study did not consider factors such as agricultural activity and infrastructure. The Consortium previously estimated that the volume of treated produced water potentially available for use could be as high as 2 billion barrels per year depending on the technological recovery rate[106]. This could significantly contribute to agricultural production, particularly during droughts and extreme heat. However, there is hesitation to use produced water for edible crop production due to concerns about the accumulation of harmful compounds in plant tissues. Public perception also plays a role, as many people prefer that desalinated or treated water not be used in food production[107]. These perceptions could negatively impact the purchase, consumption, and production of agricultural crops, particularly food crops. Therefore, identifying and evaluating non-edible crops that can tolerate produced water is important.

The High Plains region, a highly productive agricultural area with significant oil and gas activities, is also one of the most important cotton-producing regions in Texas. Irrigation is

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100 Neff, J., Lee, K., & DeBlois, E. M. (2011). Produced Water: Overview of Composition, Fates, and Effects. In Produced Water (Issue July). https://doi.org/10.1007/978-1-4614-0046-2_1

101 Texas Produced Water Consortium. (2022). Beneficial Use of Produced Water in Texas: Challenges, Opportunities, and the Path Forward.

102 Texas Produced Water Consortium. (2022). Beneficial Use of Produced Water in Texas: Challenges, Opportunities, and the Path Forward.

103 Benko, K. L., & Drewes, J. E. (2008). Produced water in the Western United States: geographical distribution, occurrence, and composition. Environmental Engineering Science, 25(2), 239–246.

104 Neff, J., Lee, K., & DeBlois, E. M. (2011). Produced Water: Overview of Composition, Fates, and Effects. In Produced Water (Issue July). https://doi.org/10.1007/978-1-4614-0046-2_1

105 Benko, K. L., & Drewes, J. E. (2008). Produced water in the Western United States: geographical distribution, occurrence, and composition. Environmental Engineering Science, 25(2), 239–246.

106 Texas Produced Water Consortium. (2022). Beneficial Use of Produced Water in Texas: Challenges, Opportunities, and the Path Forward.

107 Theodori, G. L., Avalos, M., Burnett, D. B., & Veil, J. A. (2011). Public Perception of Desalinated Produced Water From Oil and Gas Field Operations: a Replication. Journal of Rural Social Sciences, 26(1), 92–106. http://www.ag.auburn.edu/auxiliary/srsa/pages/Articles/JRSS 2011 26 1 92-106.pdf

needed to increase yields and profits[108]. While cotton remains a staple crop, alternative crops are being explored. Among these, guayule (*Parthenium argentatum* Gray) stands out as a unique alternative rubber crop. Native to the semi-arid regions of the U.S. and Mexico, guayule is a proven natural rubber latex (NRL) producing alternative to Hevea rubber trees. Guayule is a perennial shrub from the Chihuahuan desert that produces natural rubber (NR) and NRL with properties similar, and in some cases superior, to Hevea NR and NRL[109]. For over 100 years, guayule has been used intermittently as a source of NR during global crises, but post-crisis, small-scale production of guayule NR (GNR) struggled to compete with Hevea NR[110]. However, recent advances in guayule research, including efficient methods for aqueous GNRL extraction, improved germplasm, and the development of high-margin markets like allergy-safe medical devices, have made sustainable production feasible[111] [112] [113] [114].

Guayule can be harvested throughout the year, supporting constant GNR production and minimizing the size and cost of processing facilities[115]. It has been successfully grown for its NRL and NR in Texas, New Mexico, Arizona, and California and is known for its low water usage, making it a sustainable option for U.S. national NRL and NR security[116] [117]. In contrast, the NR industry relies solely on clonal Hevea trees, which are vulnerable to disease and climate change, resulting in widespread rubber insecurity[118] [119] [120]. Hevea rubber trees, grown in tropical regions, are susceptible to fungal pathogens, pests, and other diseases, which can devastate these clonal monocultures. Significant impacts on NR production have been observed in South

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108 Nair, S., Wolfskill, A., Burton, C., Reck, K., & Weyand, K. (2016). Crop Yield and Profitability Trends in Southern High Plains of Texas. Beltwide Cotton Conferences, 562–566.

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119 Nyaka Ngobisa, A. I. C., Zainal Abidin, M. A., Wong, M. Y., & Wan Noordin, M. W. D. (2013). Neofusicoccum ribis associated with leaf blight on rubber (Hevea brasiliensis) in Peninsular Malaysia. Plant Pathology Journal, 29(1), 10–16. https://doi.org/10.5423/PPJ.OA.07.2012.0110

120 Thailand's rubber industry. (2019). www.boi.go.th

America and Southeast Asia due to diseases like South American Leaf Blight (SALB) and extreme weather events, leading to a 10% loss of NR production in 2020[121] [122] [123].

Guayule offers several advantages over traditionally produced crops, including reduced water use and management inputs, as well as the creation of a stable ecosystem for pollinators between harvests[124]. Guayule is a low-input perennial crop that requires minimal fertilization and pest management, as its high terpene content is a potent insect deterrent[125] [126] [127]. GNRL could become a key supplemental cash crop in areas struggling with water availability or quality, contributing to a sustainable production system based on ecosystem and resource conservation. Additionally, each hectare of guayule sequesters about 43 tons of CO_2, adding future value in the form of carbon credits[128] [129] [130]. While guayule has a lower carbon footprint than synthetic polymers, Hevea NRL is associated with a higher carbon footprint due to importation and unsustainable production practices[131] [132]. Reducing the use of high input and intensive crops promotes sustainability in regions affected by climate change and offers ecosystem benefits to native insect populations and wildlife. Furthermore, guayule can be harvested year-round, ensuring consistent income for farmers and supporting constant GNRL production. The ability to harvest year-round also minimizes the size and cost of extraction facilities, which could be co-located with available facilities.

However, rubber and latex yield are related to plant nutrition and photosynthetic capacity, which are influenced by planting date and management practices. Severe drought conditions may irreversibly convert latex to solid rubber within the plant, and little is known about how salinity or osmotic stress affects NRL production and quality[133]. Guayule lines selected for increased

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yields have been in development for many years, and research is extensive[134 135 136]. These selected lines need to be re-evaluated in the High Plains through greenhouse experiments and field trials. While GNR and GNRL yields vary according to location and management, improved selections generally perform better than older lines in multiple locations[137 138]. Although environmental factors affect rubber content, we hypothesize that the relative performance should remain fairly consistent.

Guayule is more drought-resistant than other crops, but irrigation does affect GNRL production[139 140]. While guayule establishes reliably via transplants, high-quality water (<1 dS/m) is essential for the stand establishment of seedlings. However, after establishment, guayule can tolerate higher salinity (4.5 dS/m)[141]. As mentioned previously, there are large stores of treated and untreated produced water originated from oil and gas operations in northern and western Texas which is unsuitable for crop production due to high salinity and contaminants. However, there is growing interest in desalinating produced water, with a target of 50% recovery, potentially providing up to 250,000 acre-feet of treated water[142]. Thermal and membrane desalination technologies are being piloted in the Permian Basin, generating high-quality water for agriculture[143 144 145]. Guayule could potentially be grown with this desalinated produced water, or blended formulations thereof, though this remains unproven. Therefore, it could be an ideal crop for benefiting from produced water. However, no known studies have verified this. Research is crucial to assess the salinity tolerance of newer guayule accessions in semi-arid West Texas and determine how alternative water sources can impact GNRL production and quality. In this project, a series of greenhouse trials will be conducted to test the hypothesis that treated and blended produced water can be successfully used to grow guayule.

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140 Rasutis, D., Soratana, K., Mcmahan, C., & Landis, A. E. (2015). A sustainability review of domestic rubber from the guayule plant. Industrial Crops and Products, 70, 383–394. https://doi.org/10.1016/j.indcrop.2015.03.042

141 Foster, M. A., Coffelt, T. A., & Petty, A. K. (2011). Guayule production on the southern high plains. Industrial Crops and Products, 34(3), 1418–1422. https://doi.org/10.1016/j.indcrop.2011.04.019

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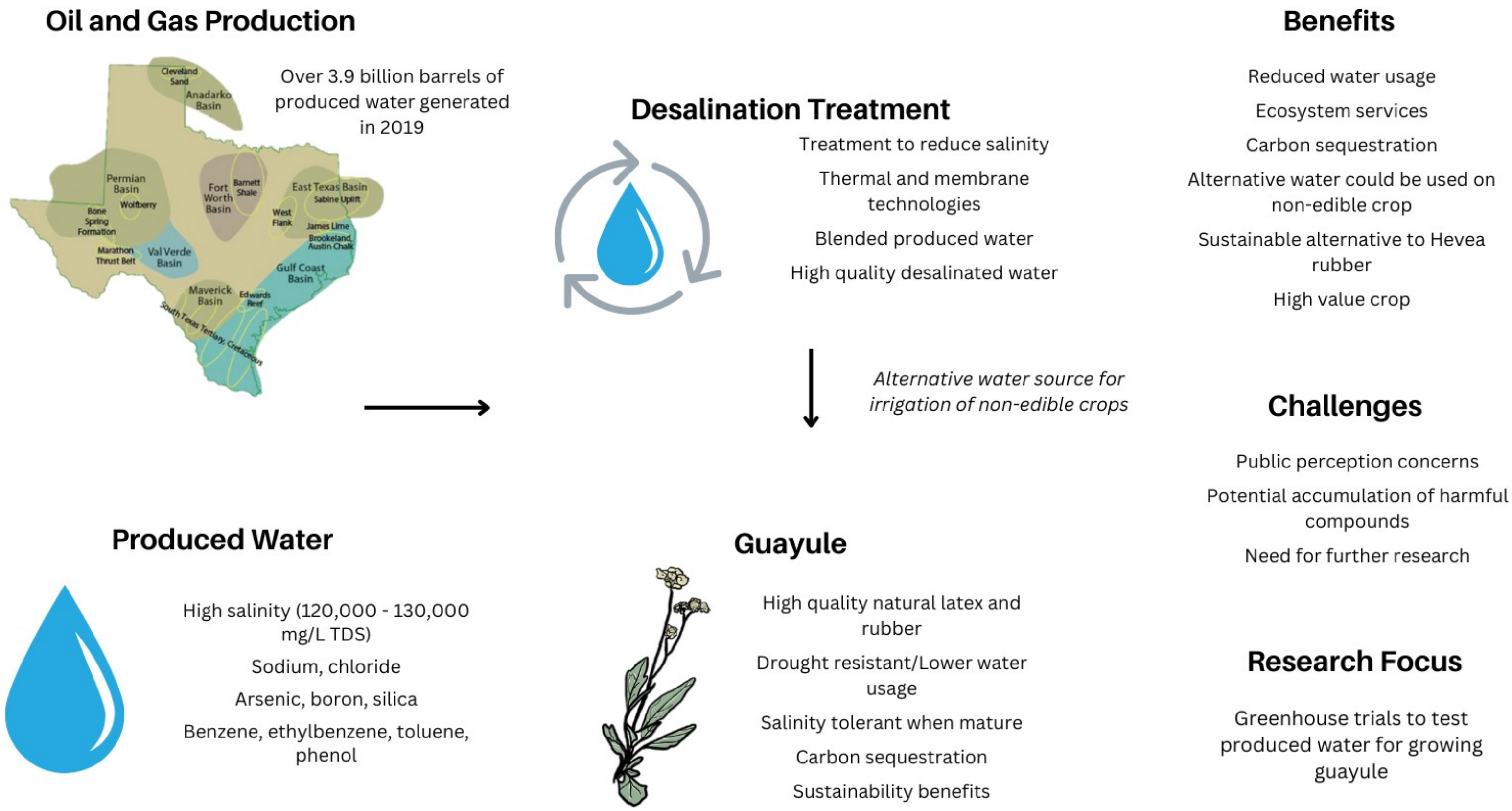

Figure 10: Project visual summary and justification for using produced water for guayule production in the Southern High Plains.

6.2 Work plan

Produced water studies on guayule latex will take place in the greenhouse and garden complex of Texas Tech University. Latex yields, properties, plant physiology, water use efficiency, nutritional status, and overall plant biomass will be identified over a period of one year.

6.2.1 Experimental setup

We will evaluate three factors: genotype (2 lines) and water quality (RO water, treated produced water, and blended produced water) using 7 biological replicates in a randomized complete block design. We will propagate approximately 42 plants of each line and then transplant them into 5 gal pots. Plants will be grown for 6 weeks under well-watered, well-drained, and fertilized conditions to ensure healthy growth before applying treatments. Fertilization will be applied using a soluble fertilizer at a rate equivalent to 65 kg ha^{-1} N (0.23 g/30 cm container). Soil moisture will be kept at field capacity (~20-30% volumetric water content (VWC)) throughout the trial and monitored using soil sensors (Teros 12, Meter Group).

Produced water will be obtained from local sources and stored in 50-gallon containers in the Texas Tech University Gardens and Greenhouse Complex in Lubbock, TX. Prior to use, it

will be sent for quality and heavy metal concentrations (nitrate, phosphorus, potassium, calcium, magnesium, sodium, chloride, sulfate, boron, carbonate, bicarbonate, pH, conductivity, total dissolved solids, sodium absorption ratio, E. coli, and Coliform bacteria counts) at the Waters Agricultural Laboratory (Camilla, GA). Two lines of guayule that have been provided by EnergyEne will be selected for the experiments. We currently have an agreement to experiment on lines developed by them, but details are confidential. Produced water treatments will consist of a) treated produced water, b) untreated produced water blended to an electrical conductivity (EC) of 3 dS/m, along with a RO water control will be used. Irrigation will then commence using the treatments described above. Plants will be irrigated with the same volume of water throughout the trial using an automated irrigation system, and data will be collected as follows.
<u>Environmental measurements</u> - Soil sensors will be installed in 18 pots to monitor soil EC, VWC, and temperature throughout the trials. The greenhouse environment will also be recorded using a HOBO datalogger with a quantum sensor (Onset). Water application volume data will also be collected, and water used from storage containers will be monitored to ensure accurate WUE calculations.
<u>Plant growth and development</u> – Plant height and canopy circumference will be recorded every 3 weeks. Chlorophyll content, photosynthesis/ C assimilation (CIRAS 3), and trunk diameter will be measured once per month. Photosynthesis measurements will only take place after plants have matured (about 6 months) due to the size and number of leaves. We will use infrared thermometers to measure canopy temperature and monitor the plant's response to treatments over time. All physiological traits will be measured using young, fully expanded leaves. Growth rate and relative growth rates (normalized for variance in initial plant heights) will be calculated to compare performance among lines and the effects of water treatments. The relative water content will be determined using fresh, turgid, and dry tissues, according to (Soltys-Kalina et al., 2016). Proline will also be analyzed according to methods by (Lee et al., 2018) and modified by the Simpson lab using a microplate spectrophotometer. Plant health rating based on visual appearance of canopy fullness, dieback, leaf color, pest/disease, and overall characteristics will be assessed with a 0-5 value. With 0 indicating a dead plant and 5 indicating a visually healthy plant. Mortality will then be evaluated for each line and treatment to determine if salinity tolerance varies by line.

<u>Nutritional analysis</u> - Nutritional analyses (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, zinc, manganese, iron, and copper) will be performed 4 times (once per quarter) by collecting and drying tissue samples and then sending them to a testing laboratory (Waters Agricultural Laboratories). Additionally, heavy metal testing will be performed to ensure accumulation of toxic ions is not occurring. Specifically, lead, barium, cadmium, arsenic, and selenium will be analyzed by Waters Agricultural Laboratories (Camilla, GA).

<u>Latex/rubber harvest and analysis</u> - Woody tissue samples will be collected, and latex will be extracted every 3 months throughout the experiment. Guayule is a 2-year crop, and therefore, the whole plant cannot be harvested for overall yields within the one-year experiment. Water use efficiency (WUE) will also be assessed as the ratio of latex/rubber yield to water applied. Latex quality and characterization will then be contracted to Ohio State University or the Chemical Engineering department at TTU. Latex quality evaluation will consist of particle size analysis (light scattering), total solids, and dry rubber content.

7 Upcoming Research Project: Critical Mineral Assessment & Recovery

7.1 Introduction

A Texas Tech University research team led by Dr. Mahdi Malmali from the Department of Chemical Engineering – with support from Texas Produced Water Consortium – submitted a grant proposal to U.S. Department of Energy's Fossil Energy and Carbon Management office titled "Developing a Regional Evaluation and Assessment of Critical Minerals – Gulf Coast and Permian Basin (DREAM-GCPB)". This proposal was led by the University of Texas at Austin. The Texas Tech University team will lead the proposed efforts under Thrust 1 (Produced Water). The core goal in Thrust 1 is to characterize and assess critical mineral resource potential in oil and gas industry waste, produced water and subsurface brines. Additional objectives include linking these mineral resources to manufacturing of high-value products to enhance economic growth and job creation, planning the development of a Technology Innovation Center (TIC), and stakeholder outreach and education to support economic development. The details of the efforts are elaborated under Subtasks 3.1, 4.1, and 6.1, as well as Task 5.

The primary objective of this study is to catalyze economic growth and job creation by identifying resource potential in the Gulf Coast and Permian Basin (Region 5) areas. The project will characterize and assess critical mineral resource potential in oil and gas industry waste. Additional objectives include linking these mineral resources to manufacturing of high-value products to enhance economic growth and job creation, planning the development of a Technology Innovation Center, and stakeholder outreach and education to support economic development. Our recent assessment from limited number of produced water samples in the Gulf Coast and Permian Basin region show some of the highest concentrations of CMs in brines in the United States. Through developing feasible separation and purification technologies, a large market for REEs and CMs recovered from such resources and waste streams is envisioned that can drive economic growth, reduce energy costs, enhance the security fossil fuel energy with less carbon footprint, accelerate job creation, and eventually improve environment and public health in Region 5 (and in the national scale).

This proposed study will focus on Region 5, including the Gulf Coast and Permian Basin, extending across the states of Alabama (AL), Mississippi (MS), Louisiana (LA), Texas (TX) and southern New Mexico (NM). The Gulf Coast and Permian Basin provide an ideal system to conduct this study. The following summarizes many of the favorable aspects of the Gulf Coast and Permian Basin in terms of produced water:

1. Since 2007, the State of Texas has annually produced ~10 Bbbl of produced water, contributing to approximately 41% of the produced water collected in the U.S. Including other states in Region 5 (New Mexico: 1 Bbbl, Louisiana: 1 Bbbl, Mississippi: 171 Mbbl, and Alabama: 63 Mbbl), roughly 50% of the US produced water is collected in this region, which places produced water at the focal point of CORE-CMin Region 5.
2. Approximately, 50% of the produced water is reinjected for enhanced oil recovery, while the other 50% is either injected to class II wells (45%) for disposal or surface discharged (5%).

3. Management of produced water in the Permian basin is a +$4 billion business. Currently, the disposal of PW into class II wells costs more than $2 billion, annually. Recovering REEs and CMs can transform produced water management practices, while reducing the water environmental impact of fracturing practices.
4. Data on CM and REE potential in produced water in the Gulf Coast basin is even more limited, while there are encouraging, but scattered, concentrations of CMs reported. For instance, elevated Li levels (>80ppm) are reported in specific locations, such as Smackover Formation brines in AR, TX, LA, and MS.
5. Oil and gas industries have current (and future) large investments for handling produced water and are expanding technologies, transportation, and infrastructure that can be repurposed for potential REE and CM recovery from produced water.

8 ADDENDUM: Project PARETO—DOE's Produced Water Optimization Initiative

The **P**roduced Water **A**pplication for Beneficial **R**euse, **E**nvironmental Impact and **T**reatment **O**ptimization (PARETO) project is the United States Department of Energy's (DOE) produced water optimization initiative. The project is a collaboration among the National Energy Technology Laboratory (NETL), the Lawrence Berkeley National Laboratory (LBNL), and the Ground Water Protection Council (GWPC). The initiative is committed to developing open-source decision-support software for the broader produced water (PW) community. The PARETO suite of tools facilitates cost-effective, resource-efficient, and environmentally sustainable PW management decisions using mathematical optimization tools. The tools have been designed with input and feedback from O&G (oil and gas) industry stakeholders since the project's inception and support all major stages of well operation, PW treatment, disposal, and beneficial reuse. Figure 1 illustrates the complexity of produced water management problems that decision makers face every day (e.g., how to move water, when and how to treat water, reuse vs. injection).

Project PARETO established a collaboration with the Texas Produced Water Consortium (TxPWC) for mutual support and to further the goals of both entities. The Project PARETO team is committed to collaborating with TxPWC and its members, initially by offering workshops and presentations at TxPWC meetings.

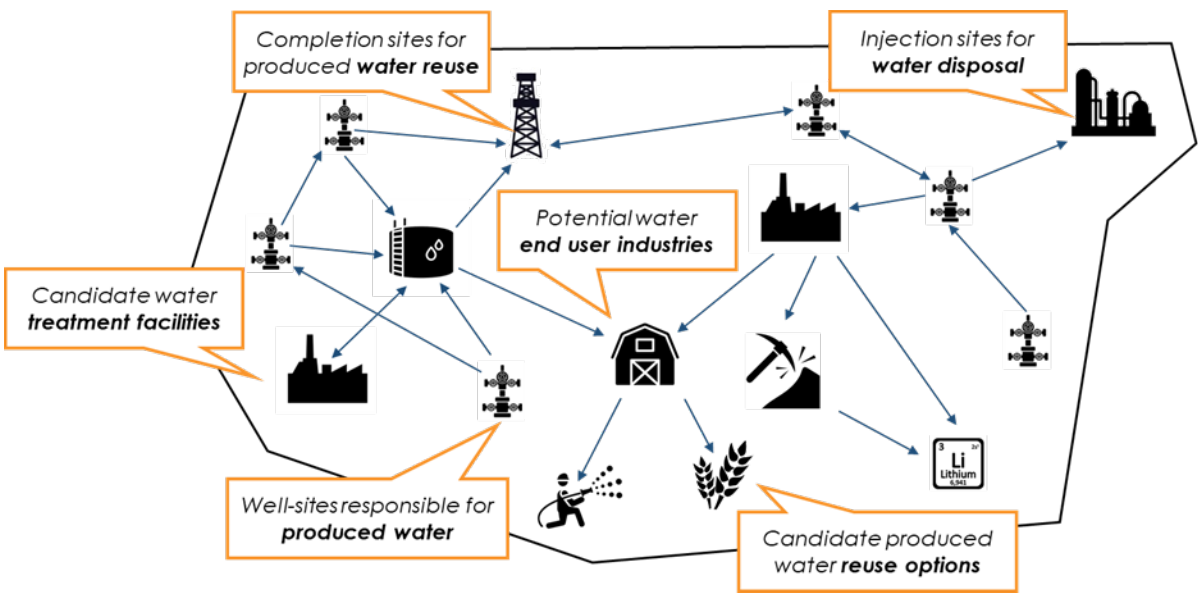

Figure 11: Illustration of the targeted scope of Project PARETO.

Project PARETO was originally launched in 2021 with its first official software release in 2022. Following that release, development continued with a major focus on beneficial reuse in 2023 and PW sharing tools in 2024. Other features such as rigorous hydraulics support and critical minerals recovery have been added as modules as well. This article summarizes the resources that have been made available under the Project PARETO umbrella. More information can be found at the following links or by directly contacting the development team at PARETO@netl.doe.gov:

- Project PARETO website: https://www.project-pareto.org/[1]
- PARETO GitHub page: https://github.com/project-pareto[2]
- PARETO documentation: https://pareto.readthedocs.io/en/latest/

PARETO framework paper[146]: https://rdcu.be/cYZ5S

8.1 Introduction to the PARETO Suite

Project PARETO provides decision-support tools for PW management that can make recommendations on water transportation (piping vs. trucking), pipeline infrastructure buildout, storage and treatment facility sizing and location, disposal well site selection, and beneficial reuse options. Additional PARETO extensions consider hydraulics, rare earth element/critical mineral (REE/CM) recovery, subsurface risks induced by injection of PW, and identification of PW sharing and trading opportunities.

The PARETO suite consists of several computational optimization models. PARETO leverages mathematical programming tools, algorithms, and solvers widely used in complex logistical problems, supply chain scheduling, and infrastructure planning problems (among other applications). Optimization models comprise four components:

1. **Objective function:** What goal should be accomplished? The objective function takes the form of a mathematical expression to be either maximized or minimized.
    - Examples: Minimize the total annualized cost of water management or maximize reuse of PW for a network given the water demand over a planning horizon.
2. **Decision Variables:** What decisions can be made?
    - Examples: Flowrates, inventory levels, water injection rates at disposal wells.
3. **Mathematical Constraints:** What limitations must be considered?
    - Examples: Completions pads water demand must be met at a given time, a maximum flowrate enforced within a pipeline.
4. **Parameters:** What fixed data must be considered? Parameters are values that cannot be changed by the optimization algorithm.
    - Examples: Disposal costs at a specific disposal site, the maximum flow rate within a specific pipeline, flowback/production forecasts of water from production pads over time.

Optimization algorithms find values of the decision variables that maximize (or minimize) the value of the objective function. PARETO provides multiple objectives for users to select from (e.g., cost minimization, water reuse maximization). Users can select the objective function that is best suited for their needs to obtain appropriate recommendations.

The general workflow for using PARETO tools to build and solve optimization models is described below:

1. The user provides **input data**.

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146 Drouven, M. G., Caldéron, A. J., Zamarripa, M. A., & Beattie, K. (2023). PARETO: An open-source produced water optimization framework. *Optimization and Engineering, 24*, 2229-2249.

- Typical data include lists of network components (e.g., well pads, pipelines, disposal sites, treatment options) and all required parameter data (e.g., flowback and completions demand forecasts, treatment and disposal costs, connections between network elements).

2. The software builds an **optimization model**.
    - This process is fully automated, but the user can change settings that affect different aspects of the final model (e.g., whether hydraulics should be considered in the model).
    - PARETO models are built using Pyomo, a Python-based, free and open-source optimization modeling framework[147 148].
3. The software runs an **optimization algorithm**.
    - PARETO leverages Pyomo as an interface to advanced numerical optimization solvers. PARETO can be used with open-source and commercial mathematical programming solvers (e.g., CBC, IPOPT, CPLEX, Gurobi). The numerical optimization algorithm determines the optimal solution of the PW network optimization problem.
4. The software returns specific **recommendations**.
    - PARETO provides several tools to "unpack" the results from the solver. Using Python methods and tools, PARETO's built-in aids help visualize, study, and analyze the proposed actions from the optimization solution.

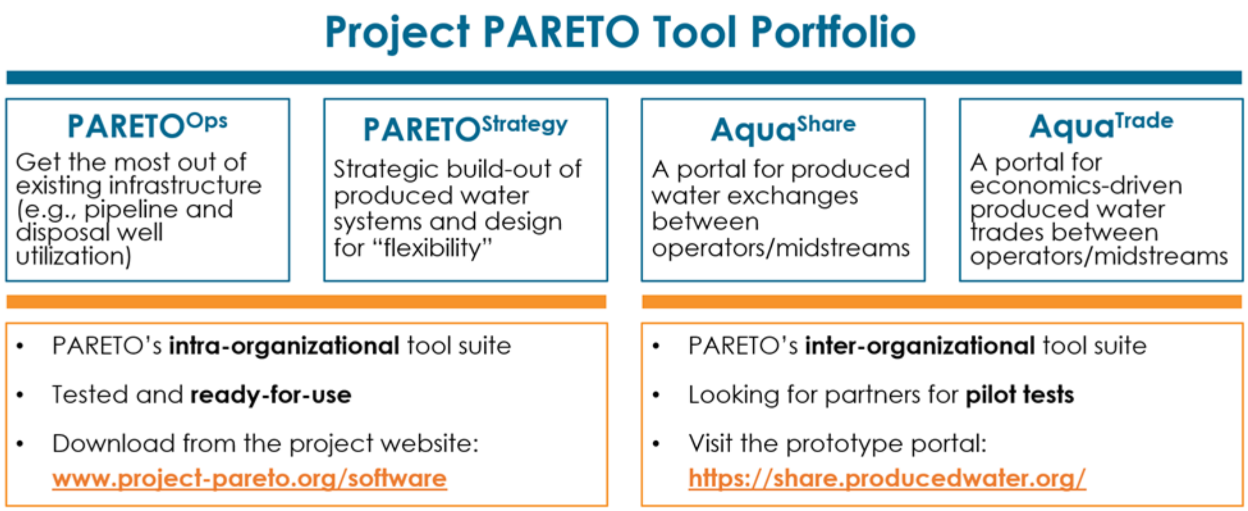

Figure 12: Overview of the Project PARETO tool portfolio.

The PARETO Suite currently comprises the tools shown in Figure 2 and described below:

- **PARETO^{Ops}:** PARETO's operational model helps users make the most of existing infrastructure. Users enter data describing the disposition of their assets (e.g., pipelines, well pads, disposal options, storage sites) along with water forecasts, and PARETO^{Ops}

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147 Bynum, M. L., Hackebeil, G. A., Hart, W. E., Laird, C. D., Nicholson, B. L., Siirola, J. D., . . . Woodruff, D. L. (2021). *Pyomo — Optimization Modeling in Python* (3rd ed., Vol. 67). Springer Science & Business Media.

148 Hart, W. E., Watson, J.-P., & Woodruff, D. L. (2011). Pyomo: modeling and solving mathematical programs in Python. *Mathematical Programming Computation, 3*(3), 219-260.

determines the best PW management decisions possible to minimize costs. PARETO$^{\text{Ops}}$ is geared to provide insights into how to improve day-to-day operations in water management.

- **PARETO$^{\text{Strategy}}$:** PARETO's strategic model builds upon the features of PARETO$^{\text{Ops}}$, adding infrastructure buildout options to the decision-making problem (expansion of pipelines, placement/sizing of disposal wells, storage sites, and treatment plants). PARETO$^{\text{Strategy}}$ is geared toward analysis of longer time horizons compared to PARETO$^{\text{Ops}}$, aiming to provide insight into the best opportunities for investment in the mid-long term. PARETO$^{\text{Strategy}}$ also includes other features lacking in PARETO$^{\text{Ops}}$ (described in the PARETO$^{\text{Strategy}}$ section).
- **Aqua$^{\text{Share}}$**: PARETO's initial prototype PW exchange web portal, Aqua$^{\text{Share}}$, is designed to facilitate mutually beneficial PW exchanges between operators. With PW recycling becoming common practice, and operators negotiating exchanges to take advantage of PW availability within the local community, the PARETO team developed a web portal to help operators make free, mutually beneficial PW exchanges to reduce sourced water needs and disposal volumes.
- **Aqua$^{\text{Trade}}$**: This tool is an extension of Aqua$^{\text{Share}}$ based on feedback from project stakeholders. Aqua$^{\text{Trade}}$ consists of a PW trading tool that adapts market clearing algorithms used in electricity markets to develop a PW trading model. This PW trading portal is under development at NETL and will allow operators to bid to provide or accept PW volumes, resolving PW exchanges through an auction process.
- The remainder of the article focuses on highlighting PARETO$^{\text{Strategy}}$ and its graphical user interface (via a case study), the PARETO water sharing/trading portals (Aqua$^{\text{Share}}$ and Aqua$^{\text{Trade}}$), and the project's stakeholder engagement and community outreach efforts.

8.2 PARETOStrategy – Industrial Case Study Demonstration

- This section highlights PARETO$^{\text{Strategy}}$, demonstrating how a basic case study is set up using the PARETO UI graphical user interface. The installer for the latest version of PARETO UI may be downloaded here: https://www.project-pareto.org/software/. The workflow for solving a case study with PARETO$^{\text{Strategy}}$ follows the same pattern described in the previous section; Figure 3 illustrates the major elements of the workflow.

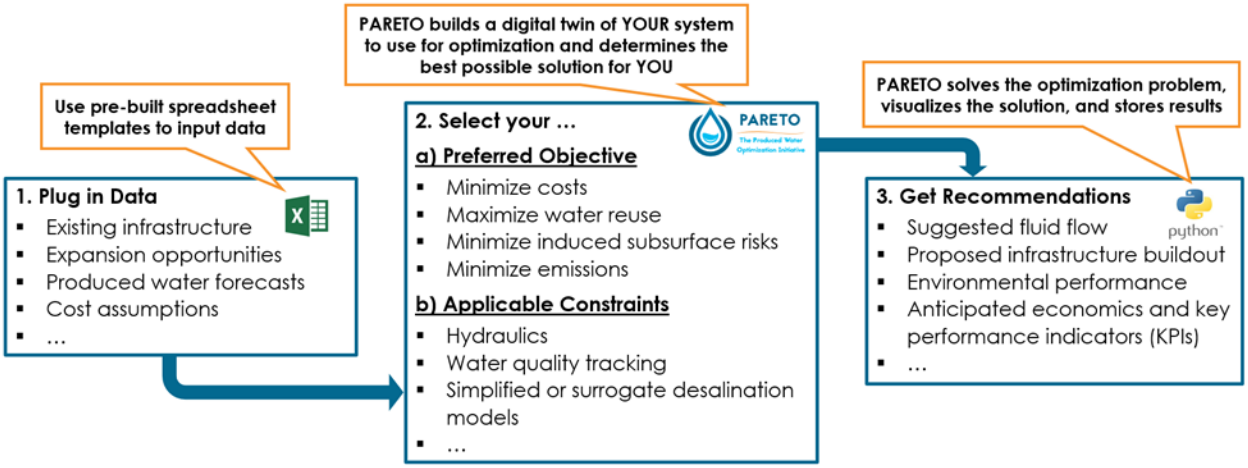

Figure 13: PARETOStrategy optimization workflow.

PARETO uses Microsoft Excel spreadsheets as the format to input data for PARETO$^{\text{Strategy}}$ and PARETO$^{\text{Ops}}$. The Project PARETO team developed several example case studies that users can use as starting points:

- Documentation of case studies can be found here: https://pareto.readthedocs.io/en/latest/case_studies/index.html
- Case study input files are hosted in the project-pareto repository on GitHub: https://github.com/project-pareto/project-pareto/tree/main/pareto/case_studies

8.3 Industrial Case Study

The PARETO team developed a representative industrial case study (motivated by realities in the Permian Basin). A schematic of this case study network is shown in Figure 4.

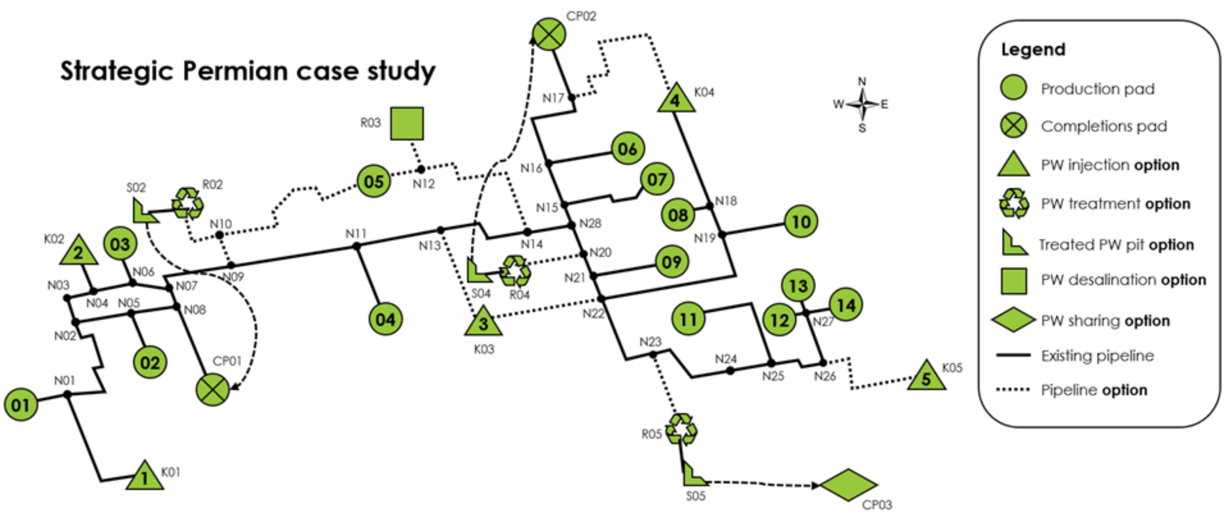

Figure 14: Strategic Permian case study schematic.

The case study is characterized by the following details:

- **Planning horizon:** 52 weeks
- **Resolution of time:** 1 week
- **Network nodes:** 28 (e.g., N01, N02, N03)
- **Production pads:** 14 (e.g., PP01, PP02, PP03)
- **Completions pads:** 3 (CP01, CP02, CP03)
- **External completions pads:** 1 (CP03)
    - External completions pads can be used to model opportunities for water sharing outside of the main network. For these pads, meeting the completions demand is optional instead of required.
- **Disposal sites:** 5 (e.g., K01, K02, K03)
    - Disposal expansion is allowed for K03 and K05 (these locations start with zero initial disposal capacity—in other words, they are candidate locations for new wells).
- **Storage sites:** 3 (S02, S04, S05)
    - All storage sites start with zero initial capacity and can be expanded if necessary.
- **Treatment sites:** 4
    - Non-desalination sites: R02, R04, R05
    - Desalination site: R03
    - All treatment sites have zero initial treatment capacity
- **Economics:**
    - Default discount rate: 8%
    - Default capital expenditure lifetime: 20 years

In addition to the existing pipelines and pipeline options shown in Figure 4, PW can also be transported by truck if necessary. Figure 5 through Figure 7 summarize the production and flowback forecasts and the completions pad demand over time. Figure 5 shows flowback rates over the planning horizon, with completions pad CP01 providing most of the flowback volume. Figure 6 displays production forecasts for the 14 production pads. PARETO$^{\text{Strategy}}$ functions to find a use for all this PW; if it cannot find a solution, it will return an infeasible status. Figure 7 illustrates completions demand. There is significant overlap between the flowback, production, and demand forecasts, providing ample opportunity for PW reuse. This example illustrates how PARETO can aid users in creating effective water management plans, identify opportunities for PW exchanges, and mitigate uncertainties around future operating schedules.

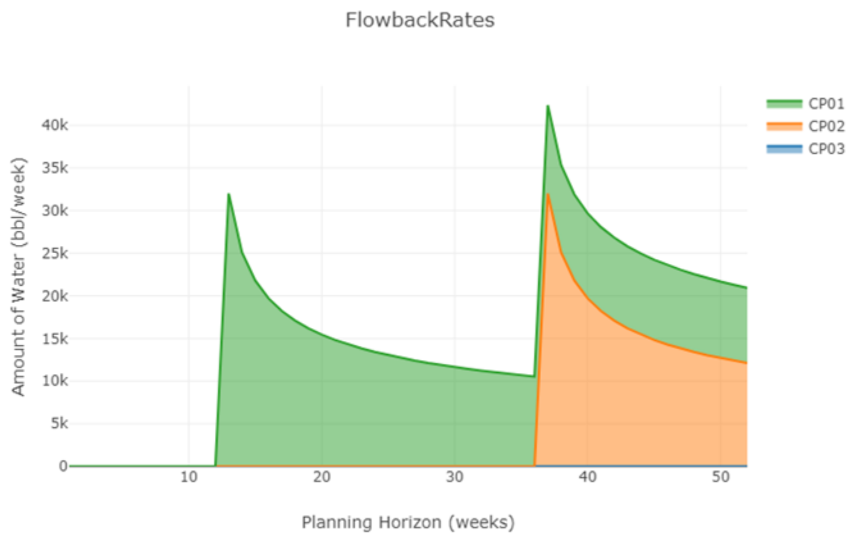

Figure 15: Flowback forecast over time. It is important to note that PARETO is designed so that it MUST "find a home" for every barrel of flowback that is coming into the respective PW system. If it cannot do so, the tool will return an "infeasible status".

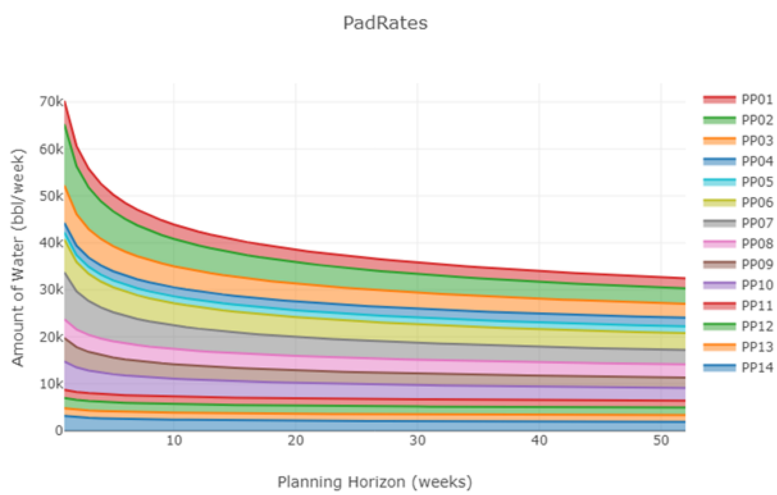

Figure 16: Production forecast over time. It is important to note that PARETO is designed so that it MUST "find a home" for every barrel of production that is coming into the respective PW system. If it cannot do so, the tool will return an "infeasible status".

Figure 17: Completions demand over time. It is important to note that PARETO is designed so that it MUST meet every barrel of demand that has been specified at the respective completions pads. If it cannot do so, the tool will return an "infeasible status".

8.4 Industrial Case Study Results

Figure 11 shows the Model Results screen, which summarizes the results and high-level key performance indicators and provides graphical tools to analyze the problem.

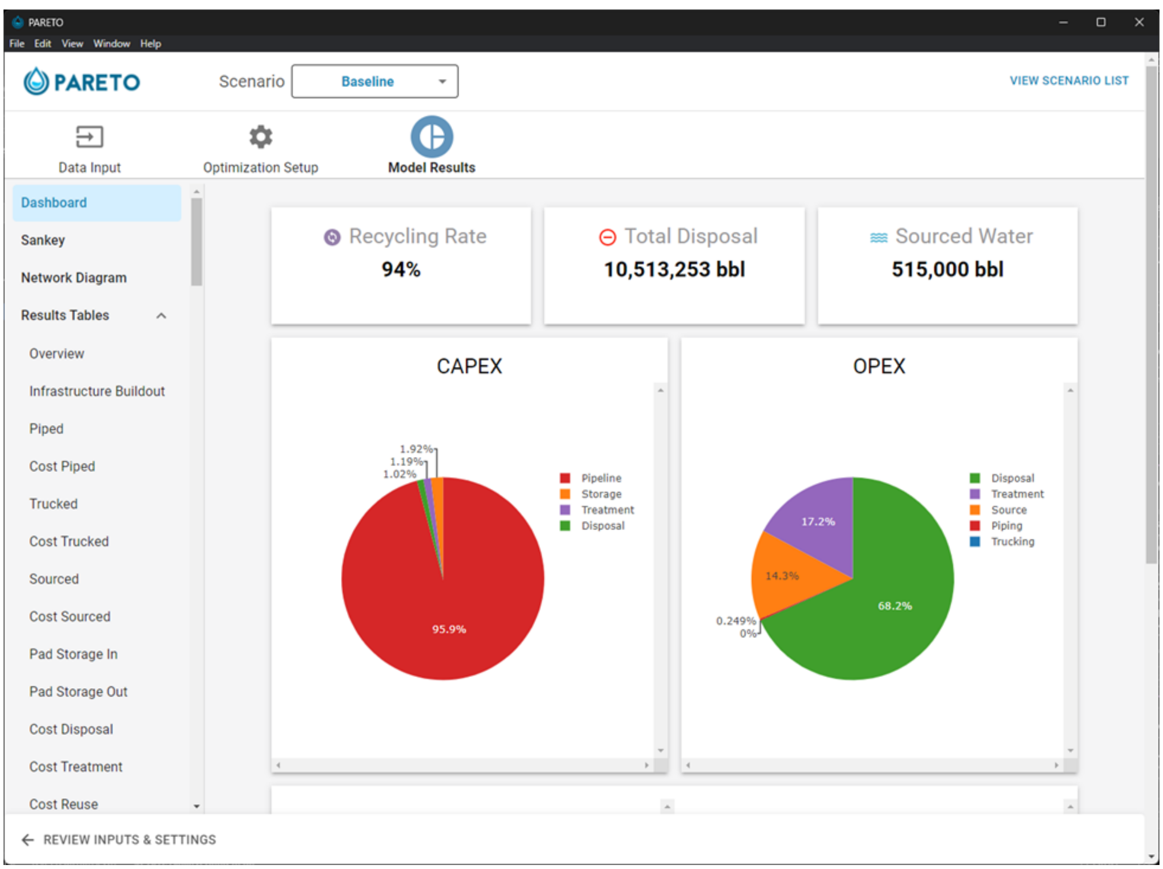

Figure 18: PARETO UI Model Results screen.

The Model Results screen has the following tabs on the left:

- **Dashboard:** Displays high-level key performance indicators (KPIs), breakdown of capital expenditure (CAPEX) and operational expenditure (OPEX), and plots of trucked and piped water deliveries.
- **Sankey:** Shows a Sankey diagram of water flow throughout the network. Includes filters for times and locations.
- **Network Diagram:** Allows the user to upload a picture of the network being modeled.
- **Results Tables:** All tabs in this section contain the detailed results of the model.
    - **Overview:** Displays a list of high-level KPIs for the solution.
    - **Infrastructure Buildout:** Summarizes the infrastructure buildout and expansion decisions in the solution.
    - **Remaining tabs:** Correspond to the variables within the optimization model and can be viewed as necessary.

For this case study, PARETO^{Strategy} recommends several new pipelines to be constructed along with two treatment facilities, two water storage sites, and two disposal wells. Several options for infrastructure buildout, and the external water sharing option, are not executed. The infrastructure buildout results for the case study are summarized in the schematic shown in Figure 12. Among all the possible decisions that could be made, PARETO^{Strategy} has determined that this subset results in the lowest overall cost.

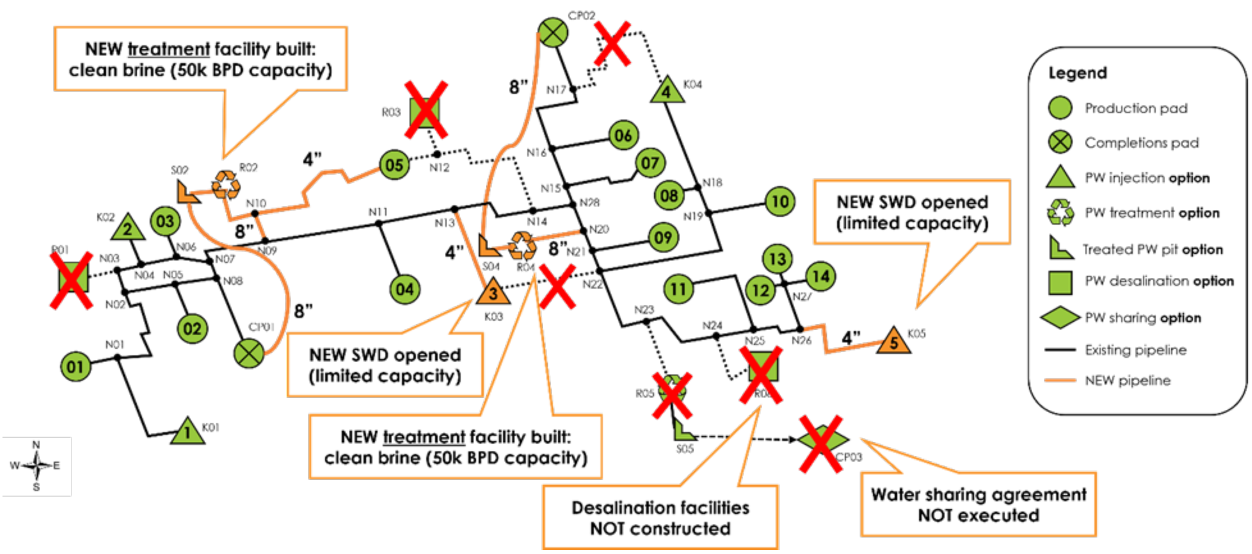

Figure 19: Strategic Permian case study – results.

8.5 Advanced Features

The PARETO Suite provides advanced features that have not been explicitly highlighted above:

- **Quality propagation:** Given the concentrations of quality components in water sources, PARETO models can track the concentration of the components throughout the network over time. This calculation is performed post-optimization.

- **Treatment:** PARETO allows different technology selections for treatment sites. Given the importance of PW desalination for beneficial reuse, PARETO draws an explicit distinction between desalination and non-desalination treatment options. Desalination sites can be represented by either linear costing correlations or surrogate models. Surrogate models for desalination technologies like mechanical vapor compression (MVC) and membrane distillation (MD) are based on detailed process models and have been created using machine learning techniques for model training using WaterTAP model libraries[149] and the IDAES Integrated Platform[150].
- **Beneficial reuse:** Produced water beneficial reuse options can be included in the model as downstream sinks for treated water and/or concentrated brine. The PARETO tool's beneficial reuse feature identifies the best reuse options, accounting for seasonal demand variations, ensures minimum volume commitments, fine-tunes water quality, and customizes flow-specific costs and credits. It also optimizes the locations for reuse and upstream desalination centers.
- **Hydraulics:** A hydraulics module to incorporate hydraulics calculations into the PW network model is included. This module includes estimation of pressure drop due to friction and elevation, limiting pressures in the network to the maximum allowable operating pressure, and recommendations for the optimal locations of compression stations (i.e., booster pumps).
- **Objective functions:** PARETO supports the following objective functions:
    - Minimize total annualized cost. This option is the default.
    - Maximize the total reuse of water.
    - Minimize the total subsurface risk. This option encourages the model to avoid using the disposal wells, which are determined to be the likeliest to result in induced seismicity or other adverse effects. Note that subsurface risk calculations can also be performed and analyzed even if this option is not selected for the objective function.
    - Minimize the total emissions (e.g., CO_2, NO_x) resulting from water management activities (e.g., transportation, water treatment).
- **Multi-objective optimization:** Tradeoffs among the available objective functions can be explored using multi-objective optimization algorithms.
    - Note that this feature is not currently supported in PARETO UI and at present must be accessed via Python code. The following Jupyter notebook provides a demonstration: https://github.com/project-pareto/project-pareto/blob/main/pareto/examples/multiobjective_optimization/seismicity_vs_cost_MOO.ipynb
- **Infrastructure timing:** Given the expected time required to complete infrastructure expansion and buildout projects, this feature indicates the time at which construction should begin so that expanded infrastructure is ready when it is needed. These calculations are performed post-optimization.

[149] WaterTAP contributors. (n.d.). WaterTAP: An open-source water treatment model library. Version 0.6. Sponsored by California Energy Commission, National Alliance for Water Innovation, and USDOE. Available at https://github.com/watertap-org/watertap.

[150] Lee, A., Ghouse, J. H., Eslick, J. C., Laird, C. D., Siirola, J. D., Zamarripa, M. A., . . . Miller, D. C. (2021). The IDAES process modeling framework and model library—Flexibility for process simulation and optimization. *Journal of Advanced Manufacturing and Processing, 3*(3). Retrieved from https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/amp2.10095

- **Infrastructure override:** PARETO UI allows infrastructure buildout decisions to be overridden to easily examine results other than the optimal solution. This feature makes it easy for users to pose and analyze "what-if" questions about infrastructure buildout.
- **Scenario copying and comparison:** The scenario list in PARETO UI makes it easy to copy a scenario, which can then be modified as desired. Furthermore, the scenario comparison feature provides a specialized dashboard that makes it easy to compare two different scenarios.
- **GIS integration:** Geographical information systems (GIS) files (Keyhole Markup Zip [KMZ] or Keyhole Markup Language [KML]) can be loaded into PARETO UI to ease the data entry process. Specifically, PARETO UI creates a customized Excel input template based on the GIS file that the user may download and populate. Once populated, the Excel input file may then be loaded into PARETO UI to begin optimization.
- **Critical minerals screening tool:** This tool evaluates whether a given PW network has the potential for critical mineral recovery. It evaluates whether existing infrastructure facilities either enhance or hinder critical mineral recovery opportunities and provides insights into the optimal location to install treatment facilities.

Note that this feature is not currently supported in PARETO UI and at present must be accessed via Python code. The following Jupyter notebook provides a demonstration: https://github.com/project-pareto/project-pareto/blob/main/pareto/examples/CM_screening_tool/CM_screening_tool.ipynb

8.6 AquaShare and AquaTrade

Two recent additions to the PARETO suite of PW management tools, Aqua^{Share} and Aqua^{Trade}, grew from a desire to facilitate the exchange of PW between operators (inter-operator water exchange) and have become a major focus of ongoing PARETO development. Motivated by O&G sector operators who adopted practices of inter-operator PW exchange to mitigate sourcing and disposal costs, DOE and GWPC partnered to create tools that could facilitate these practices and assist operators in this beneficial practice.

Produced water recycling has emerged as a common practice in the O&G industry. Operators able to recycle PW as a fracturing fluid benefit from two cost reductions: the cost of sourcing water for fracturing and the cost of disposing of the PW. In this way, PW can be recycled multiple times to keep operating costs low. The limitation to this practice is logistical; it is generally not feasible to store PW long-term, and so operators need to have their fracturing schedules set up to take advantage of PW as it becomes available. When fracturing logistics fail to align, or volumes do not match, disposal frequently becomes the seemingly only option for managing produced fluids.

Inter-operator water sharing emerged as a practice in the O&G industry as a means of overcoming logistical limitations to PW recycling. Coordinating with a larger peer group (typically other operating companies within the same reservoir), operators can find a greater number of opportunities to recycle PW, overcoming logistical limitations within their own fracturing schedules. This practice typically takes the form of ad hoc water exchange in which two operators will work out exchange arrangements by phone, text, or email. Both parties benefit from the exchange; one saving on sourcing costs, and the other on disposal, and so the practice has become common. Figure 13 lays out a simple schematic illustrating the major elements of this practice: two operators with a midstream providing transportation services.

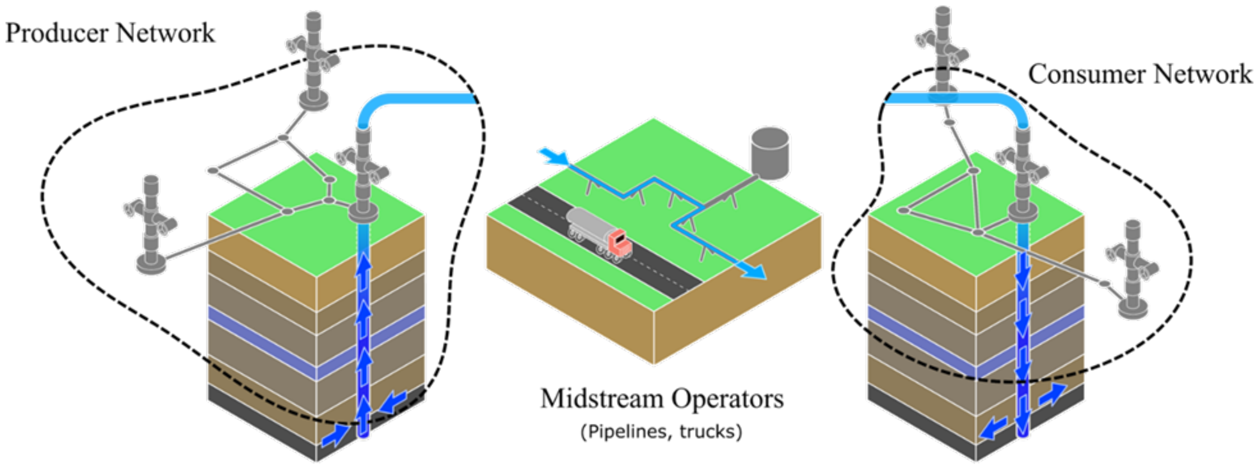

Figure 20: Schematic representation of two operator networks with a midstream operator providing transportation infrastructure. O&G operators have adopted practices of PW exchange for mutual benefit.

In addition to the cost benefits, there are indirect benefits associated with PW recycling. Reduced water injection and sourcing (specifically freshwater sourcing) are important environmental benefits. Therefore, the O&G industry can provide energy with a reduced impact on water supplies, ecosystems, and communities. In addition, inter-operator water exchanges have the potential to reduce the total PW transport required to do business (a competitor in the same basin is typically—though not always—closer than a disposal well, favoring pipeline utilization in places like the Permian and reducing long haul trucking in places like Appalachia). This outcome is a public relations benefit for operators working near human populations, who typically have negative perceptions of PW transport vehicles.

These observations motivate DOE's and GWPC's ongoing development of PW exchange tools. These tools are designed around a use case in which operators have unexpected water surpluses or shortages and are unable to resolve a recycling solution within their own networks. Rather than trying to arrange a solution on an ad hoc basis, operators can submit information to the water exchange portal, which will attempt to find suitable recycling opportunities. There are two water exchange portals in development, each based on a different strategy: Aqua^{Share} and Aqua^{Trade}.

8.6.1 Aqua^{Share}

Aqua^{Share} is a PW exchange portal centered on the concept of water sharing. Operators using Aqua^{Share} are willing to exchange water at no additional cost. The Aqua^{Share} algorithm matches users by maximizing the volume of PW recycled subject to minimizing the travel distance of the matched operators. This algorithm aligns with DOE's and GWPC's objectives by maximizing recycling and minimizing exchange distance. This approach makes a tradeoff: users have no ability to influence the algorithm, meaning that it always finds the "best" match for a user with no alternative. Nevertheless, Aqua^{Share} guarantees that transport distances will be reduced, meaning that operators can trust that the tool will help them make improvements in related KPIs. Figure 14 and Figure 15 show elements of the functional Aqua^{Share} prototype: the request form and the match dashboard. The tools are designed around a data-light philosophy and require minimal information to execute the matching algorithm. Outputs are returned to users on the match dashboard.

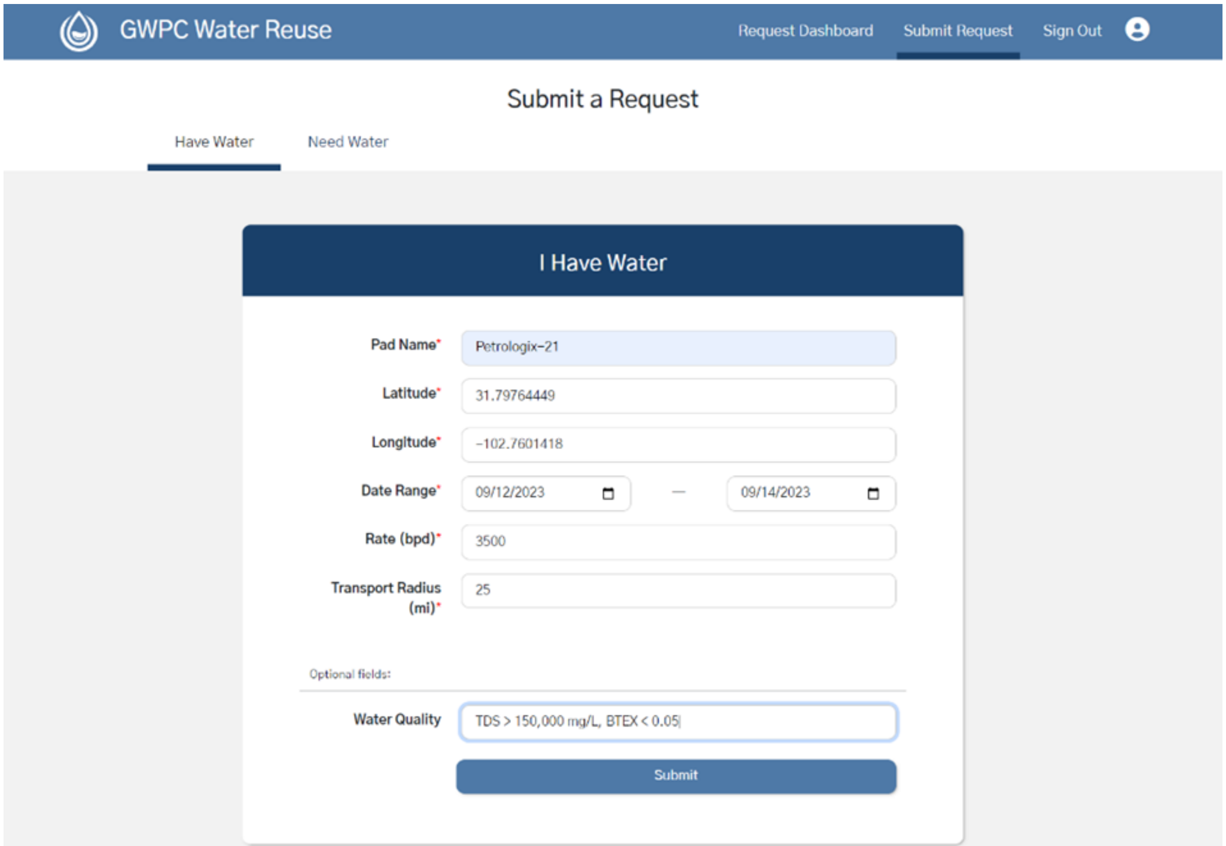

Figure 21: AquaShare request entry form. Part of a functional prototype.

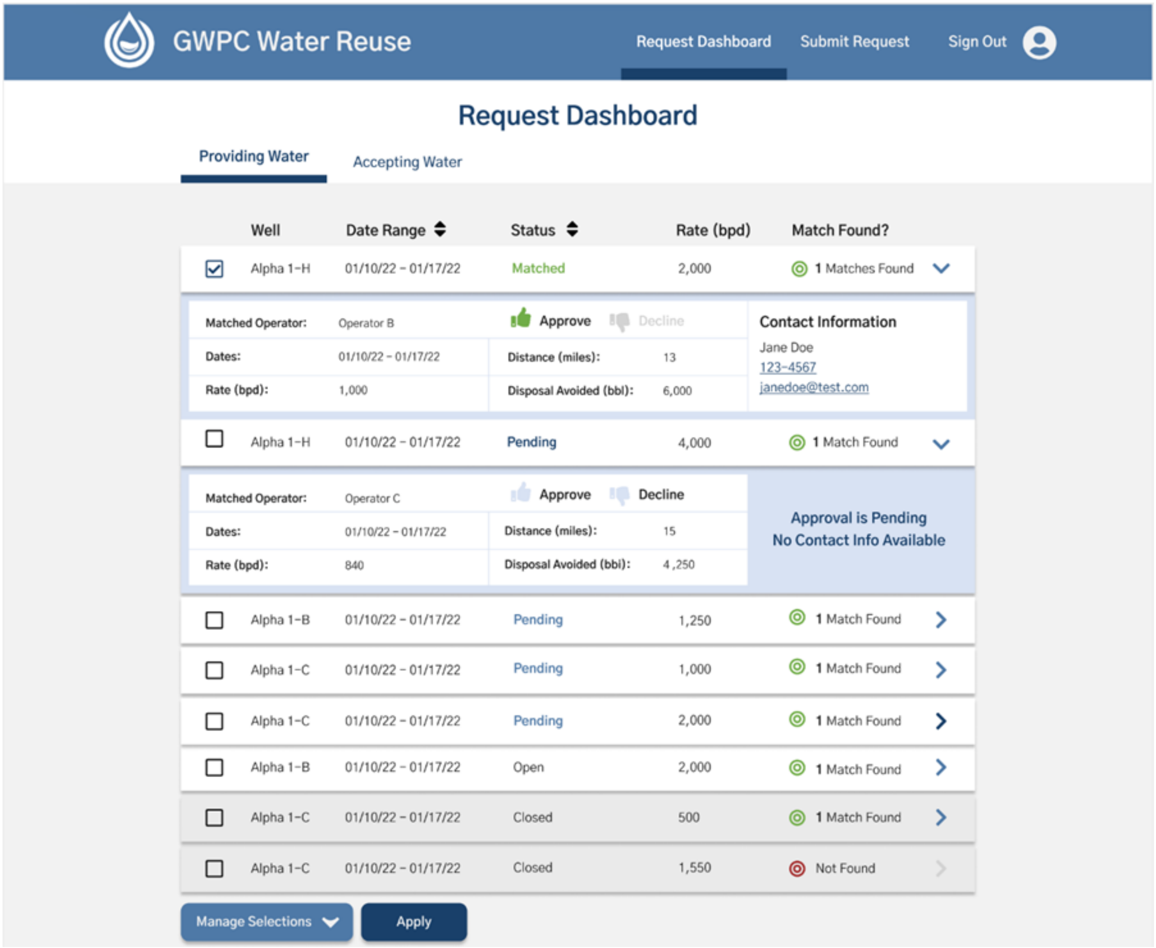

Figure 22: AquaShare match dashboard. Part of a functional prototype.

8.6.2 Aqua^{Trade}

As an expansion of Aqua^{Share} development and capabilities, Aqua^{Trade} takes a different approach to water exchanges. Rather than providing the "best" match, Aqua^{Trade} enables users to influence algorithmic outcomes by introducing an auction mechanic. Drawing on algorithms used in electricity markets, Aqua^{Trade} provides a bidding system to users. While this approach trades off guarantees of minimized transport distance, test groups have demonstrated positive reactions to the additional level of influence that the bidding system grants. Figure 16 shows a mock-up of the proposed Aqua^{Trade} request dashboard.

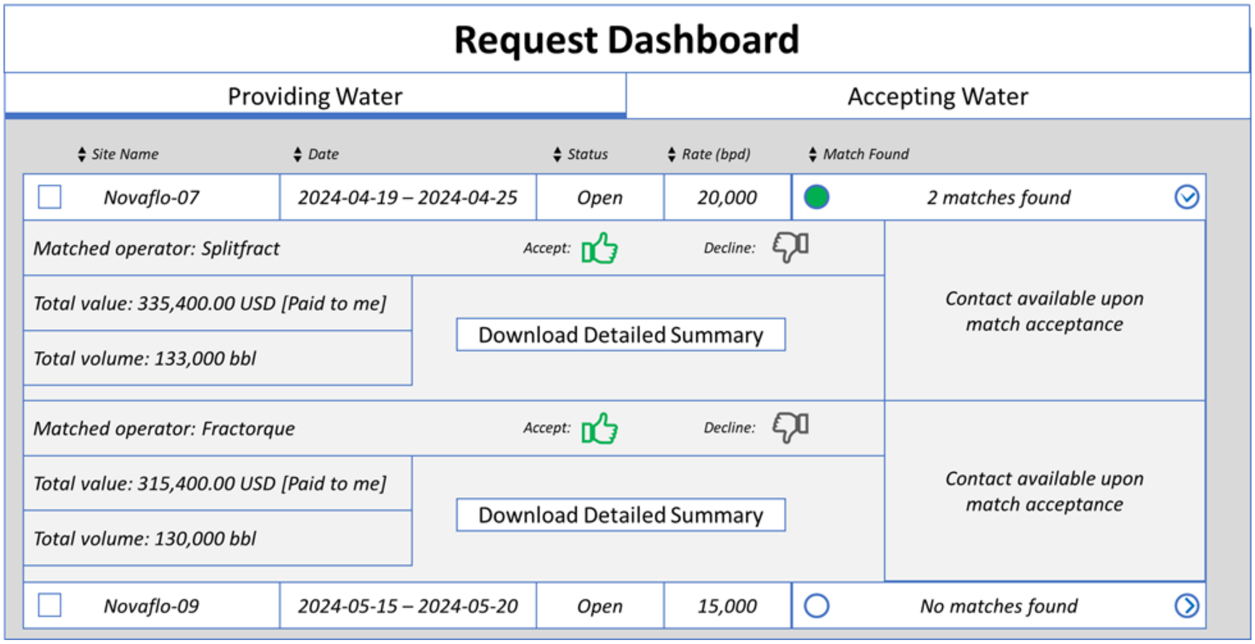

Figure 23: A mock-up of the proposed AquaTrade request dashboard.

8.7 Stakeholder Engagement and Community Outreach

A major element of Project PARETO is its stakeholder board. Created at the advent of the project in 2021, the board has helped inform and shape the direction of the project and the development of the tools in the framework. The stakeholder board comprises members from throughout the O&G and PW ecosystem, with representatives from operators, advocacy groups, and governing organizations. The stakeholder board provides a forum for DOE to communicate development progress and updates to interested parties, and more importantly, to collect feedback from present and future users. Feedback from the stakeholder board has been invaluable in managing changes during development, as the team has added and modified features to be consistent with operator experiences, industry needs, and stakeholder desires. Input from the board has also helped the Project PARETO team to keep in mind opportunities for future commercialization of the software.

Until now, the stakeholder board has primarily focused on PARETO software and case study development, but going forward, the stakeholder board intends to focus more broadly on issues related to onshore produced water management across the U.S. Anyone interested in joining the stakeholder board, or anyone having questions or wanting more information, should contact the Project PARETO team via email at PARETO@netl.doe.gov.

8.8 Disclaimer

This project was funded by the Department of Energy, National Energy Technology Laboratory an agency of the United States Government, through a support contract. Neither the United States Government nor any agency thereof, nor any of their employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately

9 ADDENDUM
Volumetrics: Origin, Quantity, Forecast and Management

9.1 Area of study

Within the West Texas region, the PW requiring management emanates from the Midland Basin (MB) and the Delaware Basin (DB), two sub-basins of the Permian Basin. The two sub-basins (herein basins) account for 87% of the region's saltwater disposal (SWD) and 98% of the hydraulic fracturing water use (HFW)[151 152]. Other parts of the region involve conventional hydrocarbon production where PW is reinjected for enhanced oil recovery. Within the two basins, a large portion of PW originated from tight-oil formations and is thereafter disposed into SWD wells or recycled in hydraulic fracturing. The PW requiring management is mainly herein referred to as tight-oil produced water (TPW). The Permian Basin, the two basins and the intersecting counties are mapped in Figure 24.

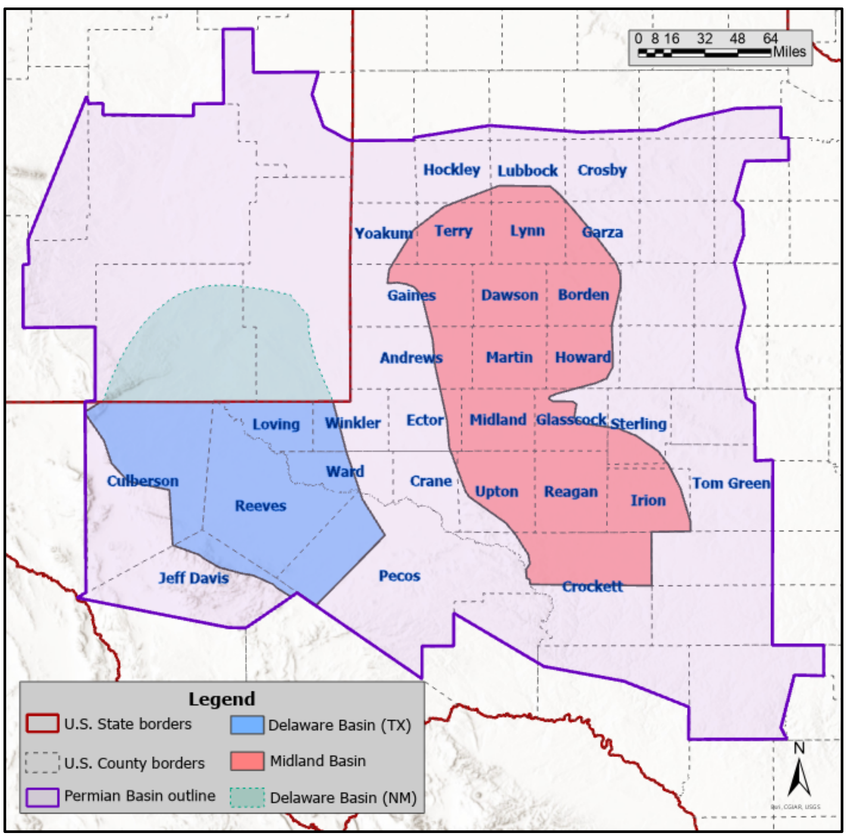

Figure 24. 2D map showing the Delaware Basin and Midland Basin, 2 sub-basins of the Permian Basin, along with the intersecting Texas counties.

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151 FracFocus (2024) FracFocus - Data Download. In: FracFocus. https://fracfocus.org/data-download. Accessed 20 Oct 2023

152 Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

9.2 Dataset for Produced Water

In the state of Texas, PW is not reported by the O&G operators[153]. This report uses PW data as calculated by Enverus[154]. Oil and gas production are reported monthly to the state on a lease basis. Within a lease, each well requires an annual well test which provides information on daily oil, gas and water production. Enverus uses the annual well test data to determine contribution of each well to oil and gas production in the lease, and subsequently monthly oil and gas production of each well. The well test is also used by Enverus to calculate the water-oil ratio (WOR) for each oil wells and water-gas ratio for each gas well and determine monthly water production per well.

The Enverus dataset can be considered valid enough for a spatiotemporal analysis that identifies the main locations and geological intervals of TPW in the Delaware and Midland basins. In fact, the dataset proves reliable for the Midland Basin as in 2023 as TPW exceeded the reported SWD[155] by 1.77 MMbwpd (Figure 25), a volume difference equaling 47% of the basin's HFW[156]. The estimated recycling percentage of 47% is close to the 53% estimated by B3 Insight for the basin in 2023[157]. Whereas in the Delaware Basin (Texas), the reported SWD exceeded the Enverus-calculated TPW by 2.16 MMbwpd (Figure 25). This volume difference is explained by an excess of SWD volume originating from New Mexico estimated at 2.3 MMbwpd in 2023 and set to reach 3.9 MMbwp by 2034[158]. Indeed, Figure 26 shows that SWD exceeds TPW considerably in Reeves, Loving and Culberson, 3 counties on the TX-NM border. If a 2.3 MMbpwd SWD excess indeed emanated from New Mexico in 2023, then the remaining of DB's TPW after SWD would have only accounted for 10% of the HFW[159], much less than the 51% estimated by B3 Insight[160]. The noted discrepancy in recycling percentage could be due to lack of WOR data with the delay in initial well testing for some wells in the Delaware Basin. Nonetheless, WOR remains roughly constant for both basins with a coefficient of variance of 7.18% for the Delaware Basin and 7.98% for the Midland Basin between 2014 and 2024 (Figure 27). This aspect of the WOR supports the validity of the TPW calculation method used by Enverus. We evaluated WOR in the two basins as since 2020, 91% of TPW emanated from oil wells and 8% from liquid-rich gas wells (producing from the same formations as the oil wells)[161].

153 Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

154 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

155 Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

156 FracFocus (2024) FracFocus - Data Download. In: FracFocus. https://fracfocus.org/data-download. Accessed 20 Oct 2023

157 B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

158 B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

159 FracFocus (2024) FracFocus - Data Download. In: FracFocus. https://fracfocus.org/data-download. Accessed 20 Oct 2023

160 B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

161 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

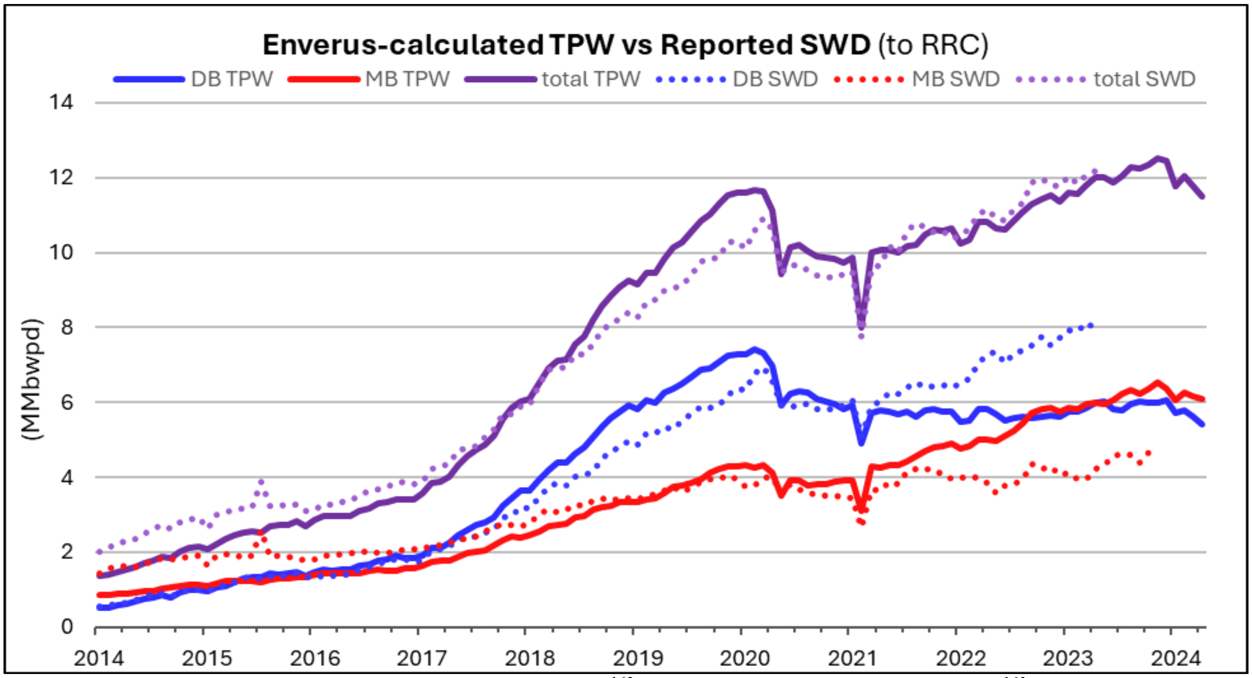

Figure 25. Enverus-calculated tight-oil produced water (TPW)[162] vs reported saltwater disposal (SWD)[163]

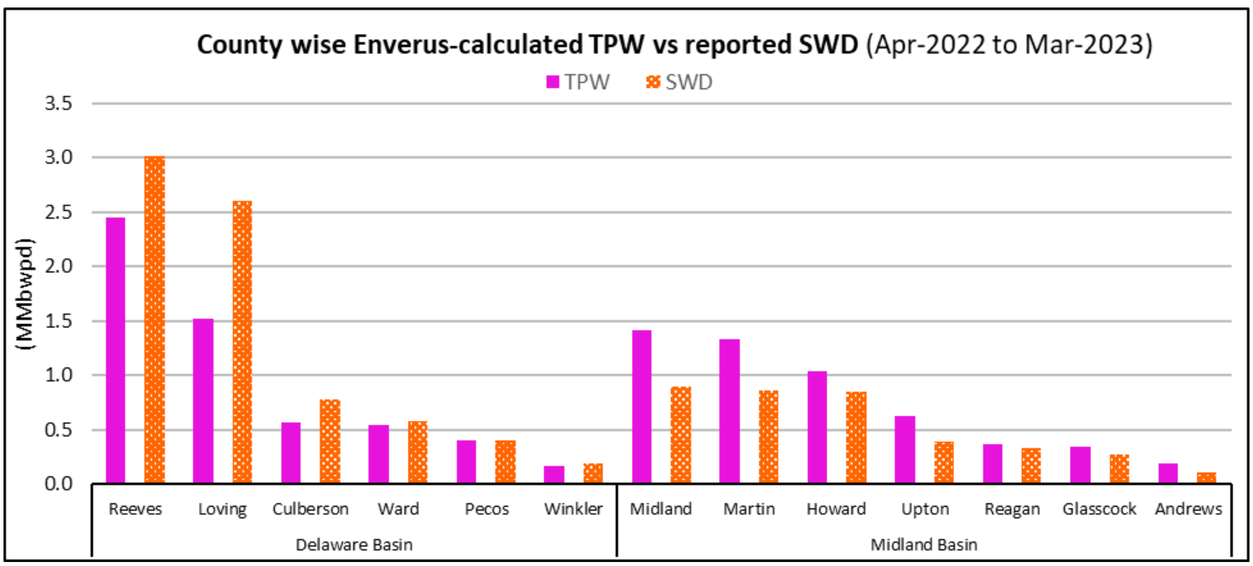

Figure 26. County wise Enverus-calculated tight-oil produced water (TPW)[164] vs reported saltwater disposal (SWD)[165], Apr-2022 to Mar-2023. The major TPW/SWD counties are displayed.

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162 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

163 Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

164 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

165 Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

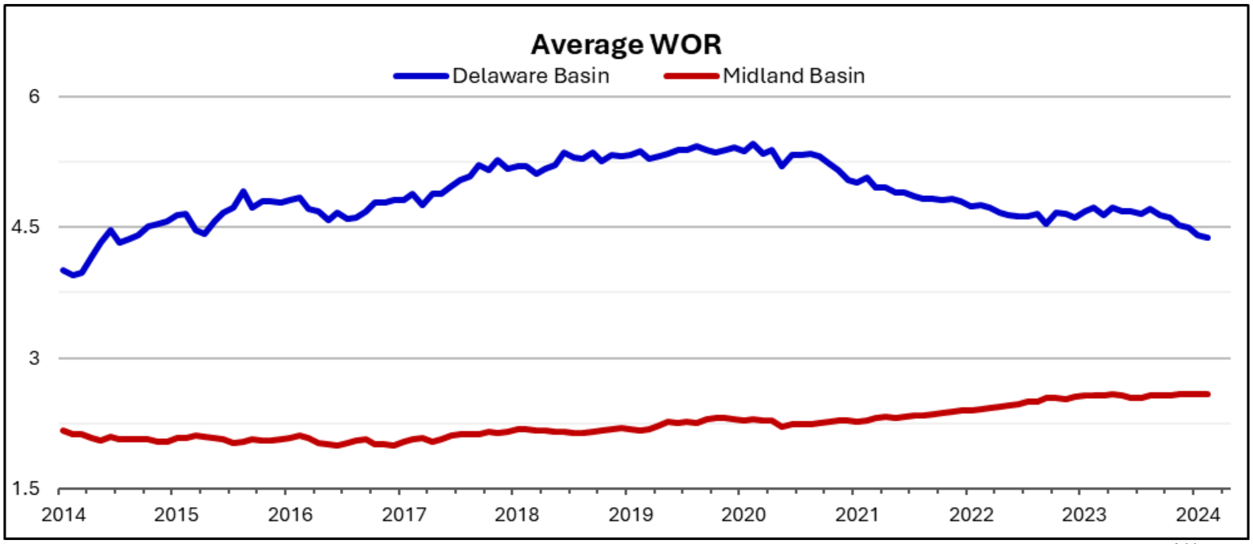

Figure 27. Average basin-wide monthly water-oil ratios (WOR) from tight-oil formations in West Texas, 2014-2024[166]

Noteworthy is at the time of data collection, SWD was reported in the Midland Basin until November 2023 and in the Delaware Basin until April 2023. This 7-month difference is due to the different SWD report due dates for fields in the two basins (Figure 0.1).

Table 6 shows the results of a survey we sent to service companies concerning use of PW in frac jobs within the Texas part of the Permian Basin. The companies reported on 70 jobs in the Delaware Basin and 120 jobs in the Midland Basin. The survey results show a PW recycling percentage of 66% in the Delaware and 62% in the Midland. These percentages are higher than those surveyed for the 2022 TxPWC report (54%) and align with the B3 Insight data which predicts PW recycling will increase steadily over the next 10 years[167]. Moreover, the survey suggests that a frac job requires 21 million gallons in both basins, which agrees with FracFocus data since 2022 (21.1 million gallons in DB and 22.4 million gallons in MB)[168].

Table 6. Survey on recycling produced water (PW) in hydraulic fracturing jobs, covering around 59% of the frac jobs in the Permian Basin (68% of the Delaware Basin (TX), 55% of the Midland Basin).

Basin	2023 monthly job count (FracFous)	monthly jobs studied in our survey , mid-2024	total HFW of surveyed jobs (bwpd), mid-2024	PW recycling % in surveyed jobs, mid-2024
Delaware Basin	103	70	1,145,970	66%
Midland Basin	209	115	1,844,589	62%

9.3 Historical origin and quantity of Produced Water in the area of study

In this work, we did not consider the formation reported by operators to be the source of TPW or oil as we believe it could be erroneous. Instead, we defined the considered main intervals as a group of geological interval(s) designated by Enverus, herein termed Layer(s) or 'Enverus

[166] Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

[167] B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

[168] FracFocus (2024) FracFocus - Data Download. In: FracFocus. https://fracfocus.org/data-download. Accessed 20 Oct 2023

Interval(s)' (Table 7). Enverus determines the geological interval from which each well produces, based on well depth and geographical location[169]. Our report's considered intervals of tight-oil formations (hereafter intervals) have been mapped in recent literature[170] [171] [172] and can be seen in Figure 28. The Enverus dataset provides monthly water production for each well allowing us to evaluate monthly volumes by interval and location. TPW for the year 2023 is shown sorted by basin and geological interval in Figure 29, and by county and interval in Figures 30 and 31. As a matter of interest, the distribution of initial rates relative to Layers is shown in Figure 0.2 and Figure 0.3.

Table 7. List of the geological intervals considered in this work and specified as groups of Enverus-defined geological intervals. Note: 'Delaware Vertical' and 'Midland Vertical' involve vertical wells producing from different formation intervals in the Delaware Basin and Midland Basin respectively, through commingling of multiple intervals. Usually, 'Delaware Vertical' refers to Wolfbone[173] and 'Midland Vertical' to Wolfberry[174].

Interval abbreviation	Geological Interval considered by TxPWC	Enverus Interval (Layer)
Avl	Avalon	Above Upper Avalon
		Lower Avalon
		Middle Avalon
		Upper Avalon
BS1	1st Bone Spring	1st Bone Spring
BS2	2nd Bone Spring	2nd Bone Spring
		2nd Bone Spring Sand
BS3	3rd Bone Spring	3rd Bone Spring
		3rd Bone Spring Sand
Dn	Dean	Dean
DV	Delaware Vertical	Delaware Vertical
JM	Jo Mill	Jo Mill
LPM	Lower Pennsylvanian & Mississippian	Lower Pennsylvanian & Mississippian
MV	Midland Vertical	Midland Vertical
SB	Spraberry	Above Upper Spraberry
		Lower Spraberry
		Middle Spraberry
		Upper Spraberry
WCA	Wolfcamp A	Wolfcamp A

169 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

170 Eyitayo SI, Watson MC, Kolawole O, et al (2023) Novel systematic approach for produced water volume quantification applicable for beneficial reuse. Environmental Science: Advances 2:508–528. https://doi.org/10.1039/d2va00282e

171 Saller AH, Stueber AM (2018) Evolution of formation waters in the Permian Basin, United States: Late Permian evaporated seawater to Neogene meteoric water. Am Assoc Pet Geol Bull 102:401–428. https://doi.org/10.1306/0504171612517157

172 Shale Experts (2024) Permian Basin Overview. In: Shale Experts. https://www.shaleexperts.com/plays/permian-basin/Overview. Accessed 14 Apr 2024

173 Lohoefer D, Keener B, Snyder DJ, Ezeldin S (2014) Development of the Wolfbone Formation Using Open Hole Multistage Vertical Completion Technology. Society of Petroleum Engineers - SPE Hydraulic Fracturing Technology Conference 2014 844–853. https://doi.org/10.2118/168643-MS

174 U.S. Energy Information Administration (2022) Permian Basin, Part 2: Wolfcamp and Spraberry Shale Plays of the Midland Sub-Basin. In: U.S. Energy Information Administration. https://www.eia.gov/maps/pdf/Permian-p2_Spraberry_Midland.pdf. Accessed 28 Apr 2024

		Wolfcamp A Lower
		Wolfcamp A Upper
WCB	Wolfcamp B	Wolfcamp B
		Wolfcamp B Lower
		Wolfcamp B Upper
WCC	Wolfcamp C	Wolfcamp C
WCD	Wolfcamp D	Wolfcamp D
WFB	Woodford & below	Woodford & below
WXY	Wolfcamp XY	Wolfcamp XY

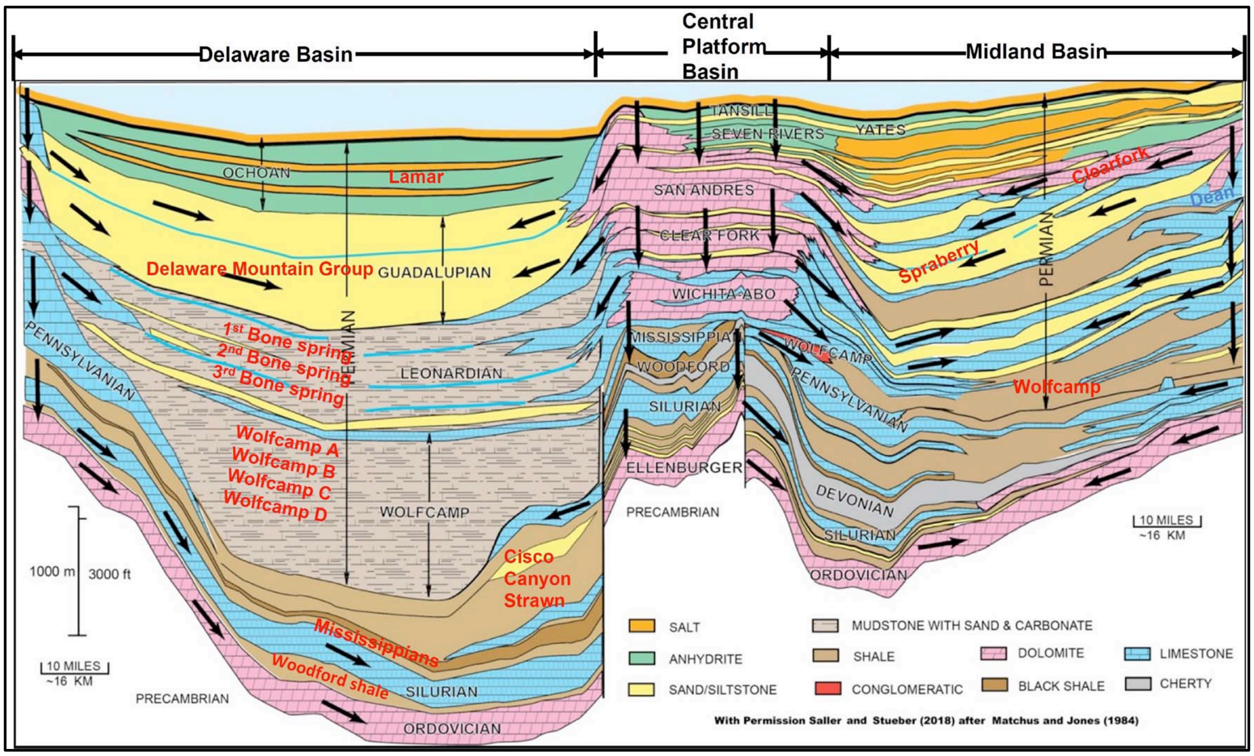

Figure 28. A cross-section of the Delaware Basin, Central Platform Basin, and Midland Basins: three sub-basins of the Permian Basin, displaying the geological intervals considered in our study[175]. We only considered the intervals within the Delaware and the Midland.

175 Eyitayo SI, Watson MC, Kolawole O, et al (2023) Novel systematic approach for produced water volume quantification applicable for beneficial reuse. Environmental Science: Advances 2:508–528. https://doi.org/10.1039/d2va00282e

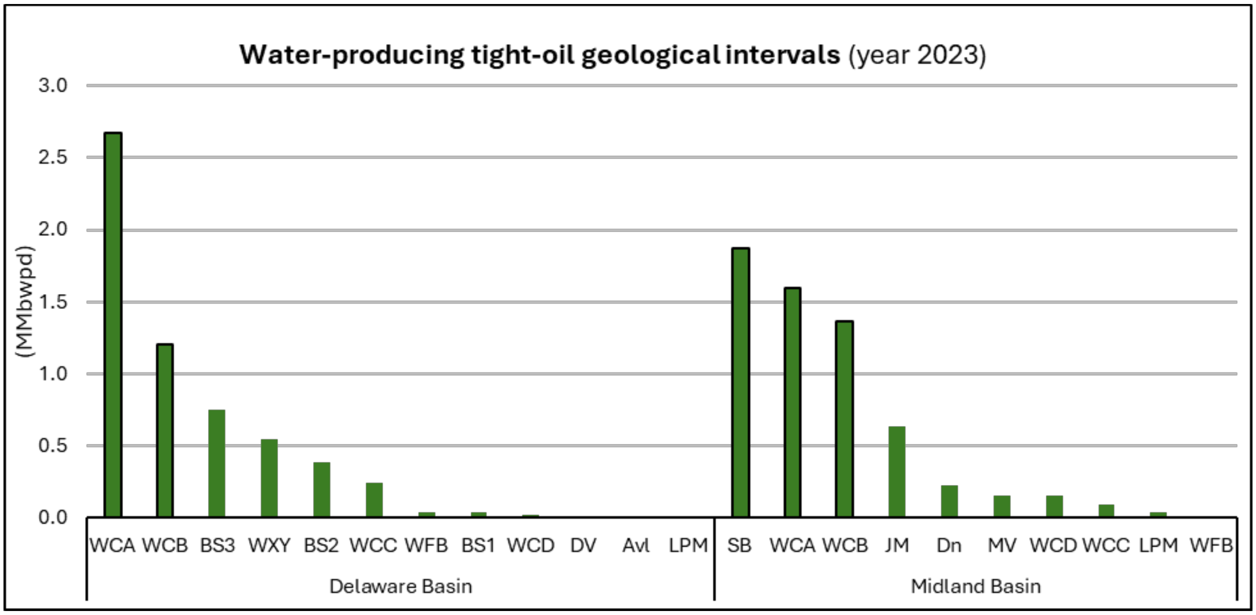

Figure 29. Water production from the water-producing tight-oil geological intervals considered by TxPWC in 2023[176].

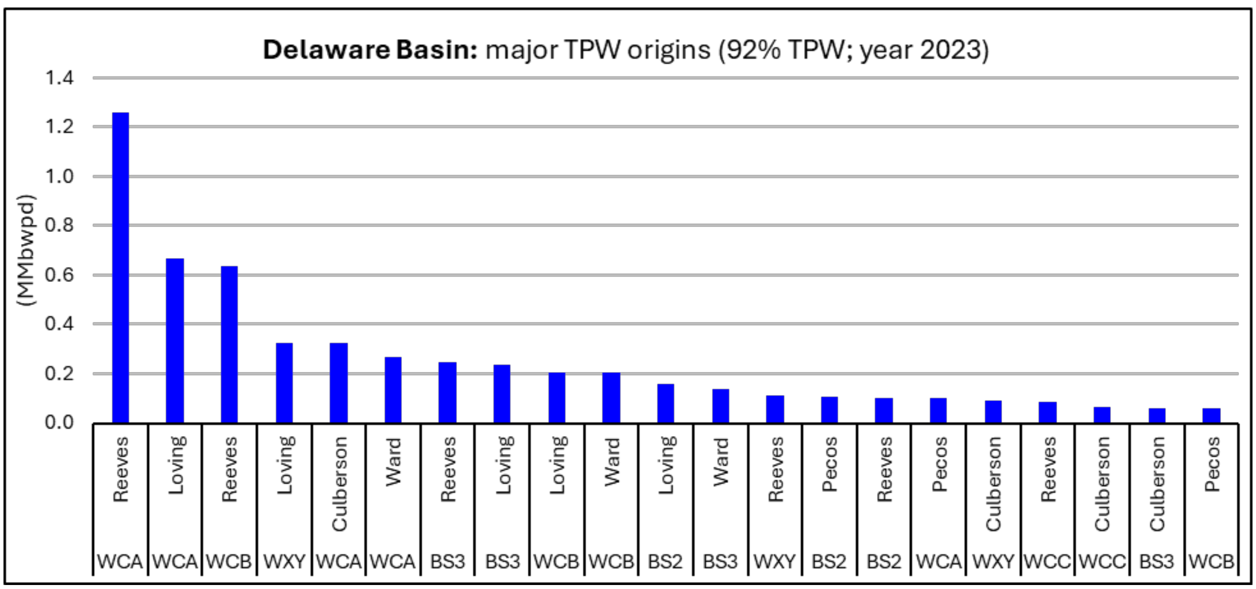

Figure 30. Water production from the major origins of tight-oil produced water (TPW) within the Delaware Basin in 2023. Geological interval and county are shown for each origin, with intervals abbreviated according to Table 7.

176 Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

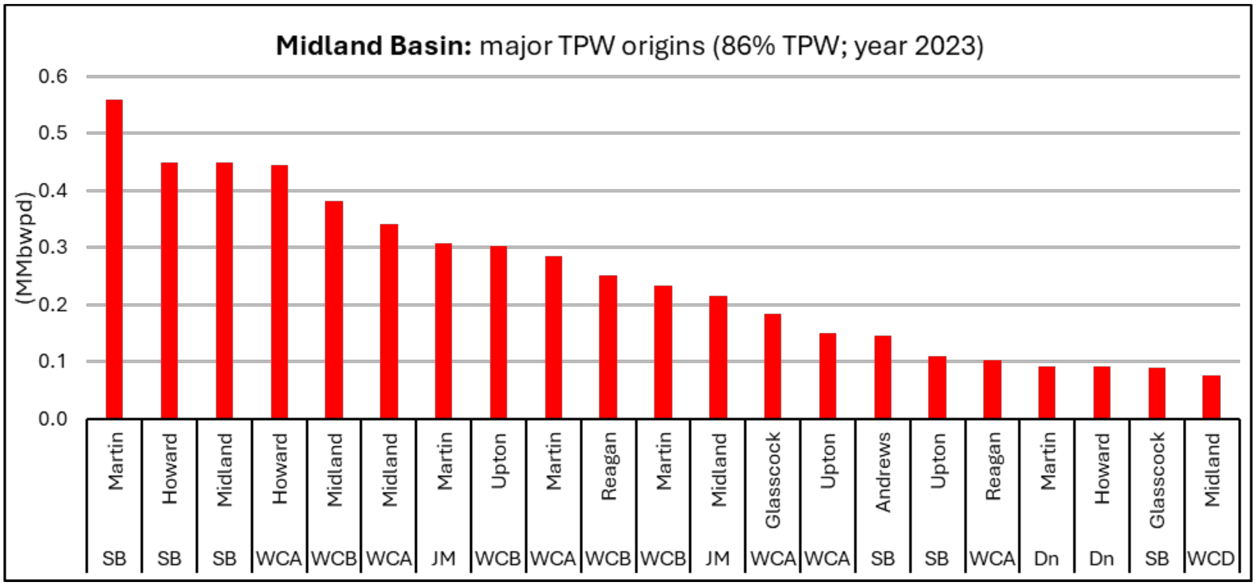

Figure 31. Water production from the major origins of tight-oil produced water (TPW) within the Midland Basin in 2023. Geological interval and county are shown for each origin, with intervals abbreviated according to Table 7.

Figure 32 shows the geospatial distribution of TPW (within 9-mi^2 subdivisions) in 2023 noting a concentration in volume in the Delaware Basin near the TX-NM border and in spread-out parts of the Midland Basin. Had PW been the sole source for HF, the excess PW would have been mainly found in the Delaware Basin, which suggests the need for larger water management in said basin (Figure 33). As seen in Figures 34 and 35, despite greater oil production in the Midland Basin, the higher WOR in the Delaware can be more concerning for water management.

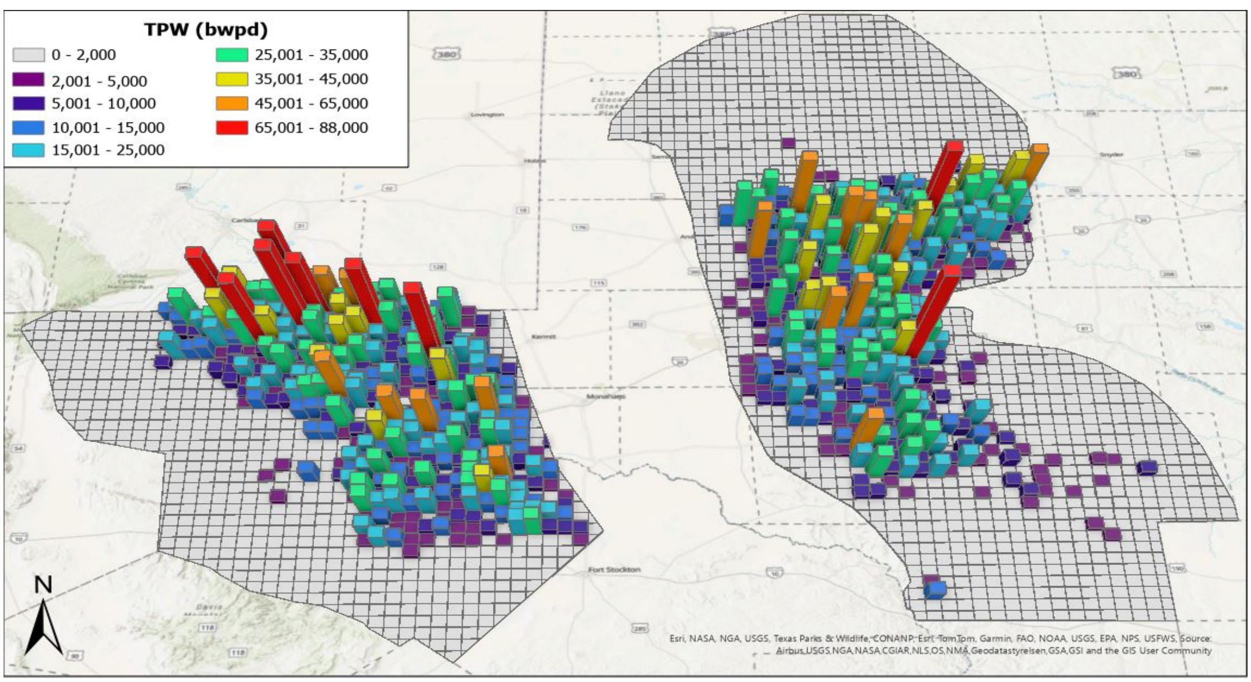

Figure 32. 3D map of tight-oil produced water (TPW) in 9-mi2 subdivisions of the Delaware and Midland basins for the year 2023.

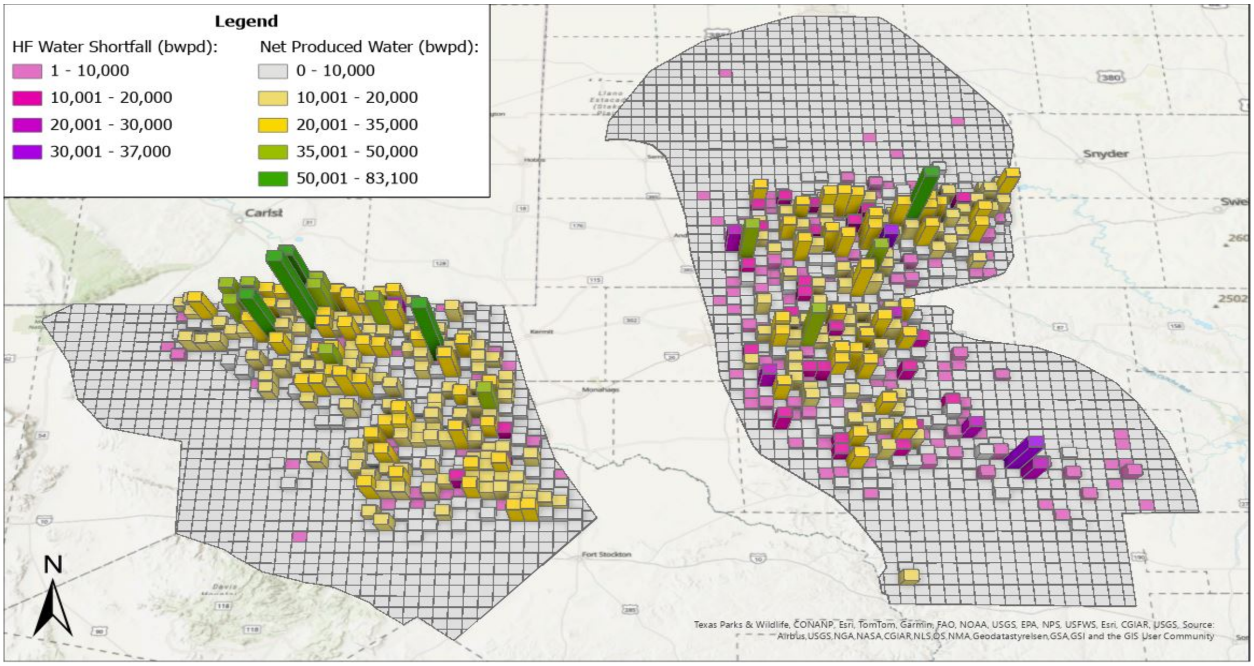

Figure 33. Net produced water (NPW) with Hydraulic Fracturing Reuse (2023). This map assumes that in each 9-mi2 subdivision, the largest possible volume of tight-oil produced water (TPW) is used for hydraulic fracturing (HF). It is determined accordingly whether a subdivision has an excess volume of TPW or an HF water shortfall ($V_{NPW} = V_{TPW} - V_{HF\_total}$).

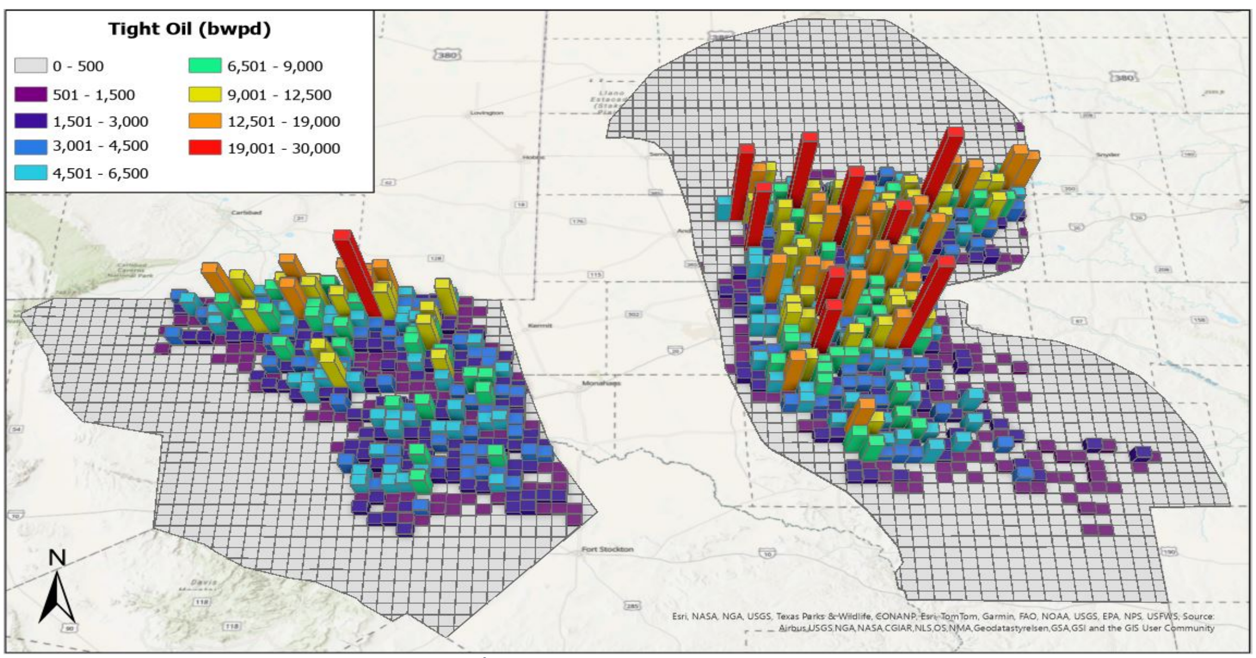

Figure 34. 3D map of tight oil production in 9-mi^2 subdivisions of the Delaware and Midland basins for the year 2023.

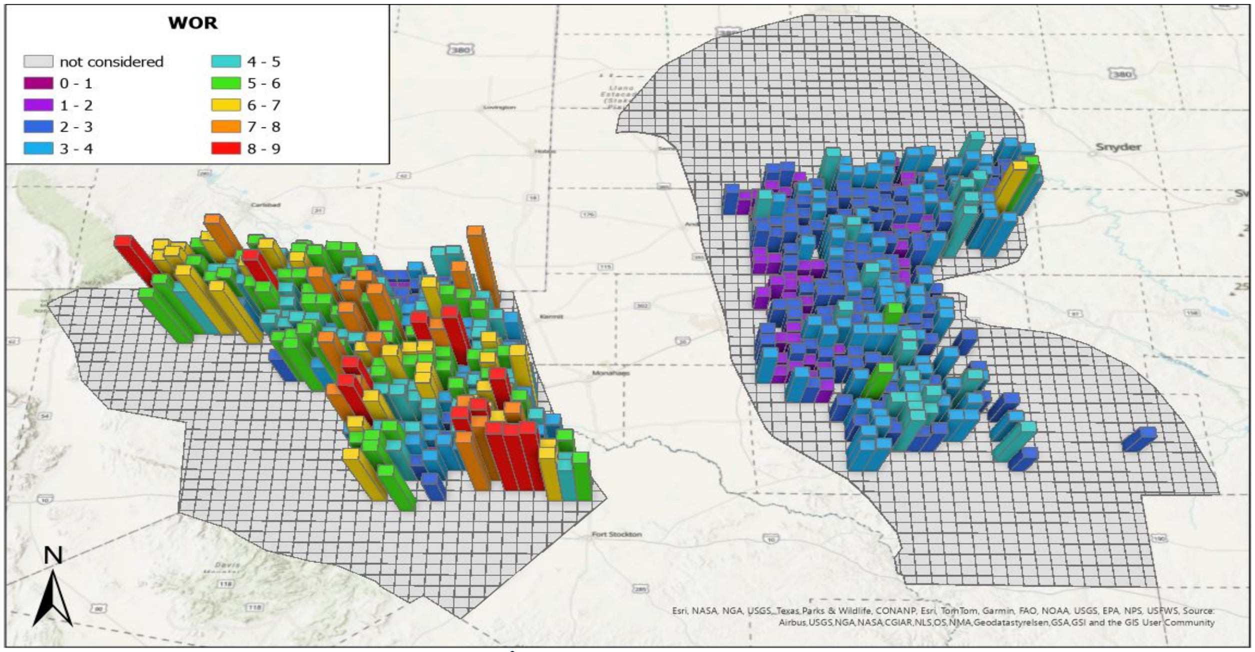

Figure 35. 3D map of water-oil ratio (WOR) in 9-mi² subdivisions for 2023: (WOR<=9) and (TPW>=5000 bwpd). Subdivisions with WOR>9 only represented 4.3% of the tight-oil produced water (TPW). Subdivisions producing less than 6,000 bwpd represented 7.2% of the TPW. The areas with high WOR produce minimal amounts of oil and water. This is reasonable given that high-WOR wells are not commercially viable.

9.4 Effect of Lateral Distance on Hydraulic Fracturing and Production

In this section, we evaluate the effect of a well's lateral distance (or length) on HF water use and production. As shown in Figure 36, Operators increased both the lateral length and fracturing fluid intensity in both basins, thus resulting in a greater demand for hydraulic fracturing water. By assessing Figures 27, 36, 37 & 38, we have concluded the following:

- Midland Basin
  - Oil and water productivity (rate per unit length) increased with increased fracture fluid intensity.
  - Oil productivity (rate per unit length) did not change with longer laterals.
  - Water productivity (rate per unit length) increased with longer laterals.
  - WOR increased with longer laterals.
- Delaware Basin
  - Oil and water productivity (rate per unit length) increased with increased fracture fluid intensity.
  - Oil productivity (rate per unit length) decreased with longer laterals.
  - Water productivity (rate per unit length) decreased with longer laterals.
  - WOR decreased with longer laterals.

We have based future production and well development on the recent well lateral lengths (2 to 3 miles) and fracturing fluid intensity.

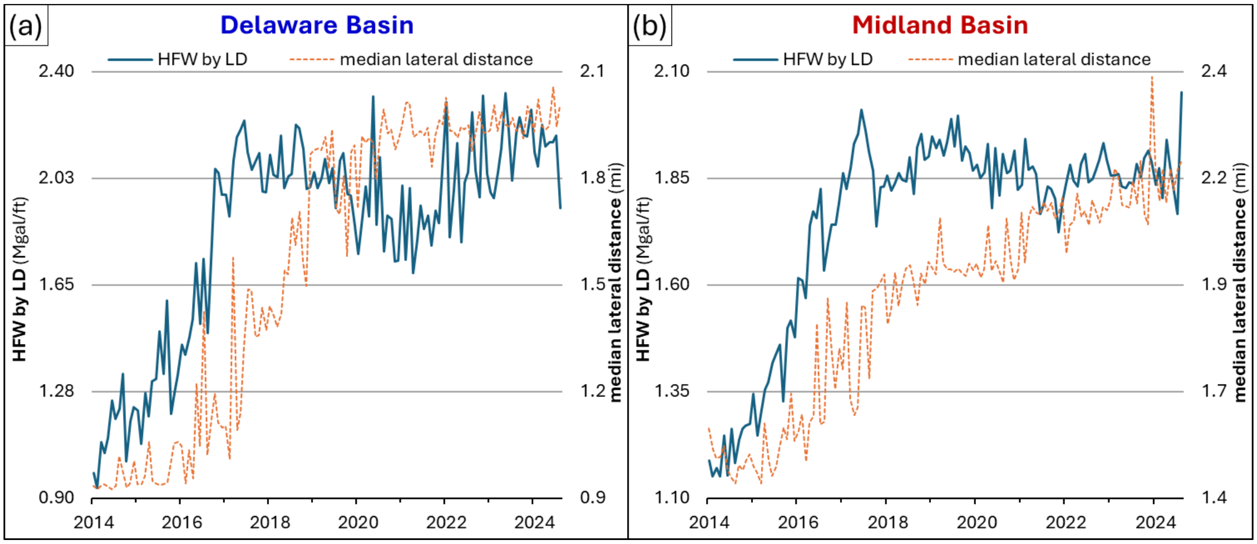

Figure 36. Monthly change in median lateral distance and in hydraulic fracturing water use by lateral distance (HFW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that were completed in said month.

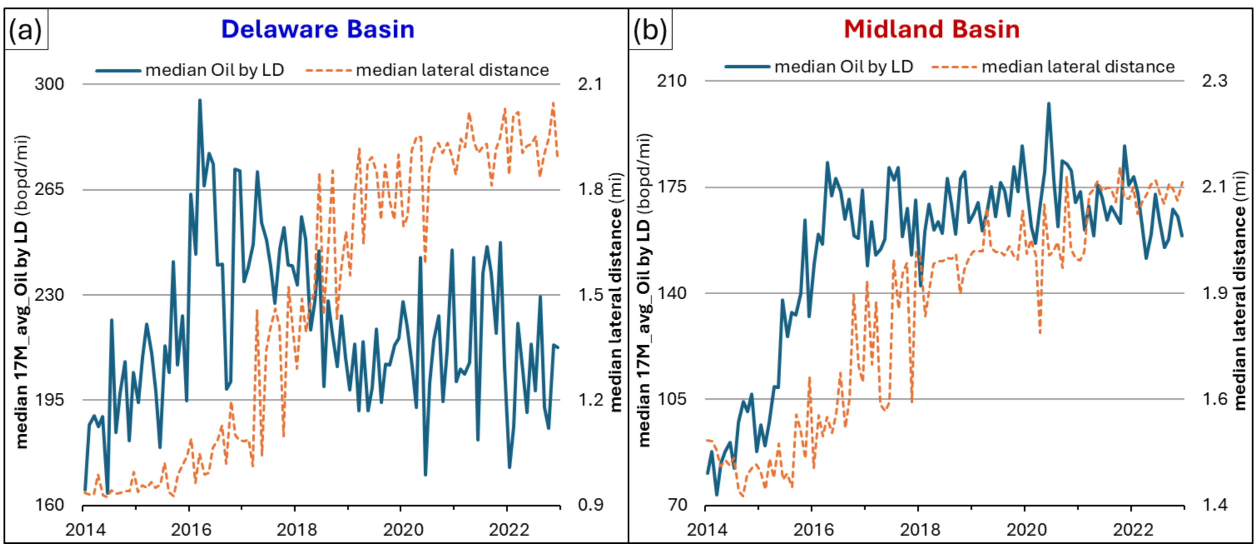

Figure 37. Monthly change in median lateral distance and in the Oil average of the first 17 producing months divided by lateral distance (median 17M_avg_PW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that started producing in said month.

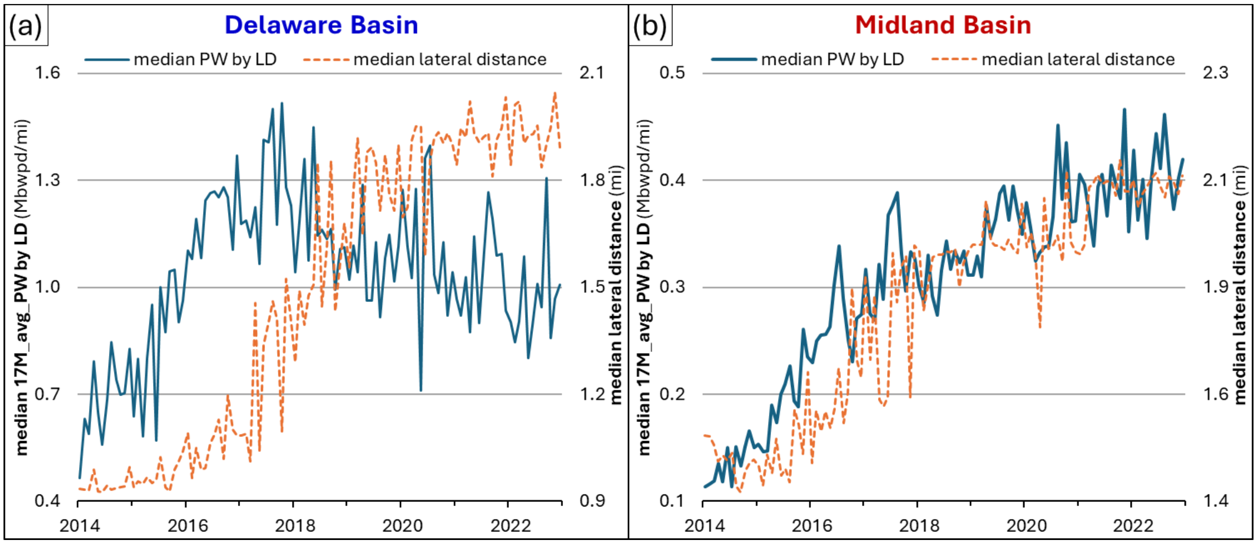

Figure 38. Monthly change in median lateral distance and in the PW average of the first 17 producing months divided by lateral distance (median 17M_avg_PW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that started producing in said month. The plotted PW is that produced from tight-oil formations.

9.5 Forecast of produced water, oil production and hydraulic fracturing water use

We forecasted production from existing and future drilled wells based on existing and available data to Texas Tech University (TTU). There is a great deal of uncertainty when projecting drilling activity and detailed geology given that TTU does not have access to Permian Basin Operators' plans, budgets, internal technical data, and financial capabilities. In addition, there is also a great deal of regulatory and economic uncertainty such as seismicity/SWD, oil prices, cost of goods and services, etc. Therefore, TTU does not warrant the accuracy of the projected production of water or oil.

The forecast for the existing active horizontal wells within each county involves grouping the historical Oil and Water data by wells drilled in different time periods (pre-2019, 2019-2022, and post-2022), and projecting an Arps decline curve for the associated decline for each time period, similarly to the 2022 TxPWC report[177] [178]. The production forecast of the existing wells is added to that of future horizontal wells to be drilled (prospective wells). Among the existing wells, we only forecasted production from horizontal wells as such wells accounted for 99% of tight-oil produced water in 2023 and 98% of the drilling activity in the two basins since 2019[179].

Below are the updates to the production forecast method of the previous TxPWC report[180] [181]:

177 Smith R, Bernard E, Watson M, et al (2022) Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward. In: Texas Produced Water Consortium. https://www.depts.ttu.edu/research/tx-water-consortium/2022-report.php. Accessed 28 Apr 2024

178 Eyitayo SI, Watson MC, Kolawole O, et al (2023) Novel systematic approach for produced water volume quantification applicable for beneficial reuse. Environmental Science: Advances 2:508–528. https://doi.org/10.1039/d2va00282e

179 Baker Hughes (2024) Rig Count Overview & Summary Count. In: Baker Hughes. https://rigcount.bakerhughes.com/. Accessed 24 Sep 2024

180 Smith R, Bernard E, Watson M, et al (2022) Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward. In: Texas Produced Water Consortium. https://www.depts.ttu.edu/research/tx-water-consortium/2022-report.php. Accessed 28 Apr 2024

181 Eyitayo SI, Watson MC, Kolawole O, et al (2023) Novel systematic approach for produced water volume quantification applicable for beneficial reuse. Environmental Science: Advances 2:508–528. https://doi.org/10.1039/d2va00282e

- For each county within the DB & MB, the maximum number of prospective wells was determined by considering the major producing tight-oil Enverus Intervals (Layers) within the county (2020-2024) (see Table 7) and well spacing, i.e. the maximum lateral well density per Layer (lateral length per area of the Layer's geographical extent). This assumes that the maximum lateral well density would be eventually accomplished throughout all the county's Layers (those considered for forecast) before drilling is halted. Also assumed is that an existing horizontal well has drained/is draining an area proportional to its lateral length and inversely proportional to the county's maximum lateral well density per Layer. The prospective wells (within a county) would be horizontal, all with the same lateral length (2 to 3 mi) and type curve which are derived from the county's latest completion and production techniques (2018-2024)[182]. All prospective wells would eventually drain the same area throughout the county, regardless of the producing Layer. Given the lack of geologic, parent-child well relationship and reservoir detail, we made a simplifying assumption that oil and water production from a prospective well would be the same for all the different Layers of a county. Only the existing horizontal wells are taken into consideration when accounting for the historically drained area.
- The incorporated geographical extents of Layers were determined by Enverus in 2024 by evaluating rock viability and the proven economic extent of each Layer[183]. The maximum lateral well density per Layer is determined by subdividing each county into (2mi x 1mi) subdivisions and assessing the lateral well density in every producing Layer within each subdivision. The process involved assessing the intersection of all laterals of existing wells with the subdivisions (Figure 0.4). The dimensions of a subdivision (2mi x 1mi) were chosen based on the recent 2-mile lateral lengths across both basins.
- The rig count (for each county) was updated based on more recent data from 2022 through 2024[184]. As suggested by recent drilling activity, we used an average value of 18 days per well for the Midland Basin and 22 days per well for the Delaware.
- For counties that are within the basins' geographical extents of Layers but do not currently have a rig, a one-rig availability assumption is made and type curves from neighboring counties are assumed.

The historical production data of horizontal wells drilled after 2017 is used to generate a type curve for each county's oil and water production. The future projections for wells are then based on said type curve behavior. Table 0.1 lists the type curve Arps parameters underlining the forecast, which are the b-factor, the initial nominal decline rate D_i, and the production rate Q_i[185]. Table 8 shows the maximum wells to be drilled in each county by the end of 2050 in 3 different cases: low case (LC), base case (BC) and high case (HC). The production forecast shows a maximum daily rate of 6.3 MMbopd and 19.4 MMbwpd in 2040 (around 1.7 times the current production) (Figures 39, 40 & 41) before production decreases in the Midland Basin. The WOR is projected to change by less than 13% from historical WOR (Table 9): increasing in the Midland Basin and decreasing in the Delaware Basin. The water demand for hydraulic fracturing (HFW) is determined for each county by multiplying the new drill count by the historical water demand for the most recent

[182] Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

[183] Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

[184] Baker Hughes (2024) Rig Count Overview & Summary Count. In: Baker Hughes. https://rigcount.bakerhughes.com/. Accessed 24 Sep 2024

[185] Sun H (2015) Advanced Production Decline Analysis and Application. Elsevier

completions (2019-2024)[186]. In total, a maximum of 381,000 AFY would be required for hydraulic fracturing (Figures 40 & 41). In both basins (high and base case), the amount of produced water relative to HFW demand will increase over time. In the low case, the amounts of produced water and HFW demand remain roughly constant.

Table 8. Number of wells used for the new drills in Delaware Basin and the Midland Basin. Counties in Blue are within the Delaware Basin and counties in Red within the Midland Basin. Units are in bopd for oil bwpd for water.

County	considered producing Layer(s)	maximum lateral well density per Layer (ft/acre)			rig count			pospective wells drilled by the end of 2050		
		LC	BC	HC	LC	BC	HC	LC	BC	HC
Culberson	5	37	49	62	3	4	6	1,353	1,804	2,706
Jeff Davis	1	41	51	60	1	1	1	0	99	236
Loving	7	49	59	69	16	25	34	7,216	11,275	15,334
Pecos	8	28	37	46	5	8	11	2,255	3,608	4,961
Reeves	6	41	51	60	15	22	30	6,765	9,922	13,530
Ward	6	27	34	41	5	7	10	2,255	3,157	4,510
Winkler	6	22	31	39	4	6	8	1,076	2,220	3,608
Andrews	5	64	91	117	6	9	12	3,312	4,968	6,624
Borden	2	39	46	54	1	1	2	466	552	806
Crane	2	33	50	66	1	1	1	36	55	74
Crockett	2	38	47	56	1	1	1	552	552	552
Dawson	3	19	29	38	2	3	4	254	570	988
Ector	4	24	30	37	1	2	3	552	784	1,032
Gaines	1	25	41	58	1	1	2	0	21	60
Glasscock	4	82	100	119	7	11	15	3,864	6,072	8,280
Howard	5	72	81	90	16	25	34	7,936	9,800	11,798
Irion	2	57	89	122	2	3	3	1,104	1,656	1,656
Lynn	1	12	23	33	1	1	1	3	18	41
Martin	6	74	97	119	23	35	43	12,696	19,320	23,736
Midland	6	75	106	138	19	28	38	10,488	15,456	20,976
Mitchell	1	72	81	90	1	1	1	178	200	222
Reagan	3	56	74	92	3	6	7	1,656	3,312	3,864
Sterling	3	19	26	34	1	1	1	14	552	552
Terry	1	18	27	35	1	1	1	101	226	397
Upton	5	44	52	60	12	21	25	6,216	8,883	11,875
Total					**150**	**227**	**298**	**70,348**	**105,082**	**138,418**

186 FracFocus (2024) FracFocus - Data Download. In: FracFocus. https://fracfocus.org/data-download. Accessed 20 Oct 2023

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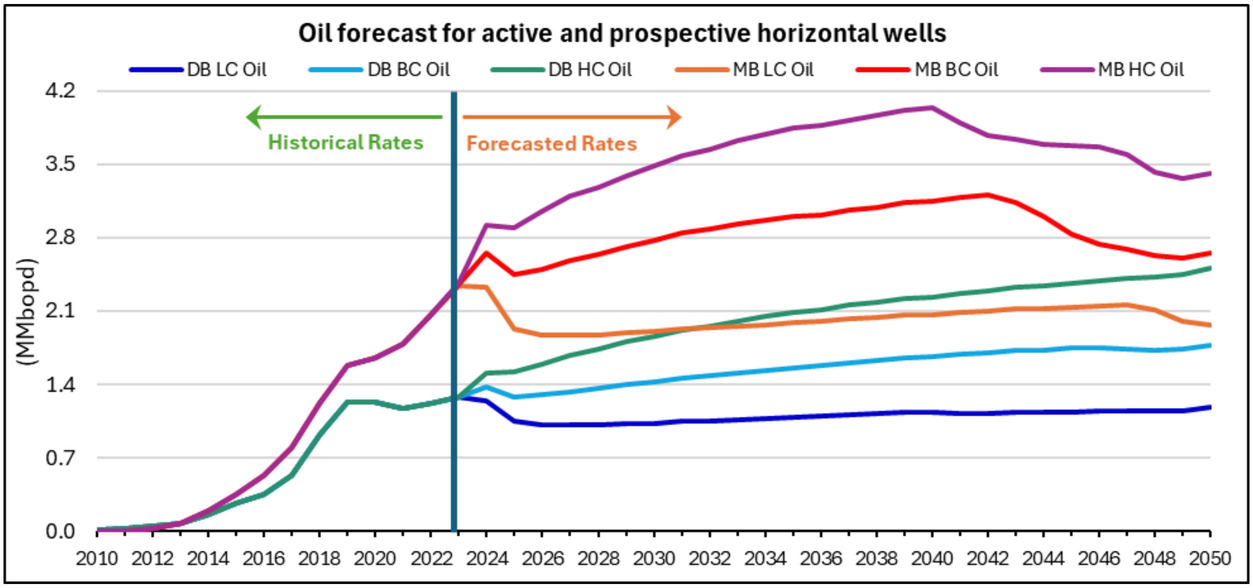

Figure 39. Forecast of Oil Production from active and future-producing horizontal wells, for both the Delaware Basin (DB) and Midland Basin (MB). Three cases are considered for each basin: low case (LC), base case (BC), and high case (HC).

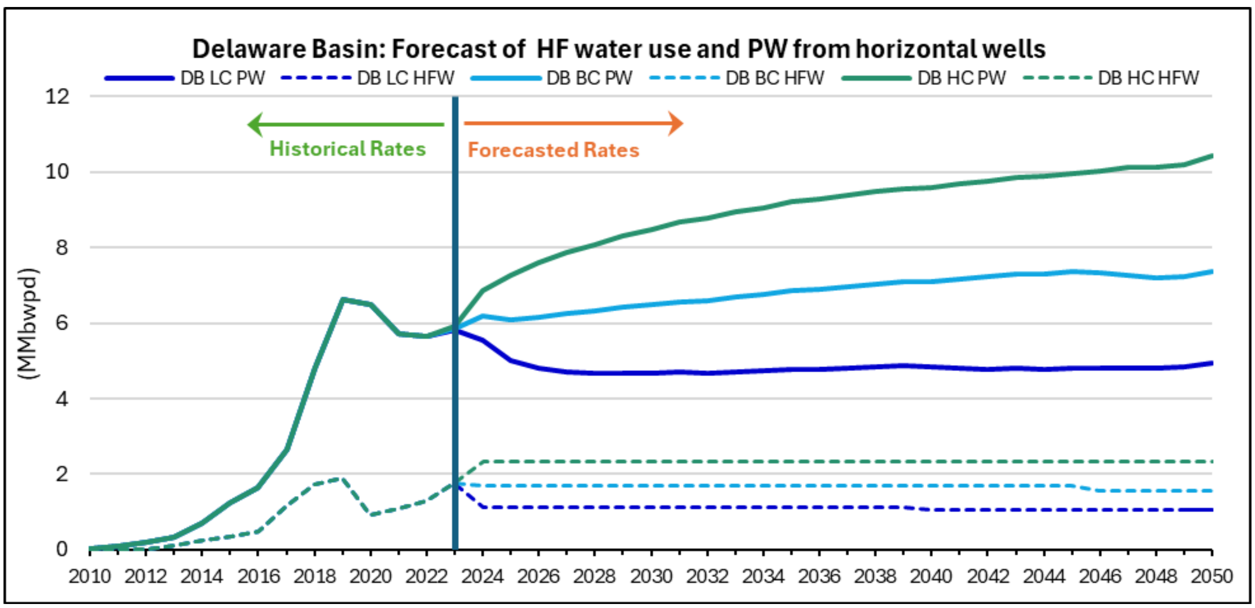

Figure 40. Forecast of produced water (PW) from active and future-producing horizontal wells, and hydraulic fracturing water use (HFW), for the Delaware Basin (DB). Three cases are considered for each basin: low case (LC), base case (BC), and high case (HC).

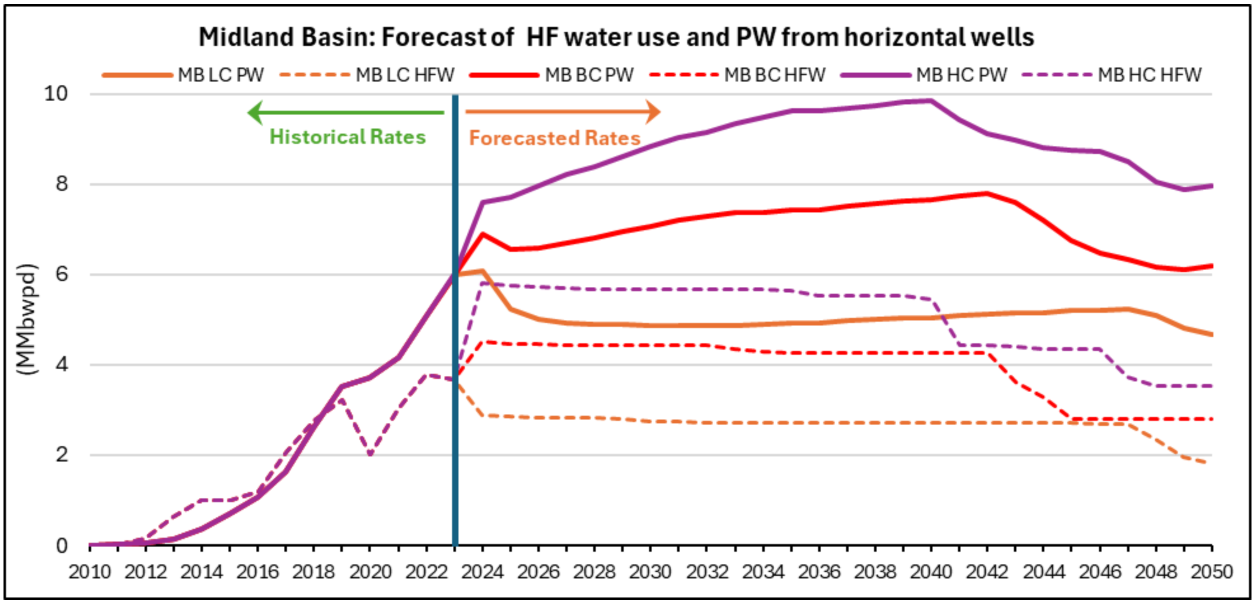

Figure 41. Forecast of produced water (PW) from active and future-producing horizontal wells, and hydraulic fracturing water use (HFW), for the Midland Basin (MB). Three cases are considered for each basin: low case (LC), base case (BC) and high case (HC).

Table 9. Historical WOR (2014-2023 average) vs Projected WOR (2024-2050 average) for the Delaware Basin (DB) and Midland Basin (MB) in all three forecast cases: low case, base case, and high case.

	Low Case		Base Case		High Case	
	DB	MB	DB	MB	DB	MB
Historical WOR (2014-2023)	4.95	2.31	4.96	2.31	4.96	2.31
Projected WOR (2024-2050)	4.37	2.49	4.36	2.47	4.37	2.47
WOR change %	-12%	+8%	-12%	+7%	-12%	+7%

When comparing our forecast findings to a recent water balance forecast of the West Texas region[187], we note that our work's High Case for both the Delaware Basin and for the Midland closely match the projections set by B3 Insight for both PW and HFW (Figure 42). The Midland Basin HF water demand is shown to be 20% higher than B3 Insight's projection, despite a lower water production (13% less). Whereas in the Delaware Basin, HF water demand is 3% lower than that of B3 Insight despite a water production higher by 7%. We conclude that our projection calls for less water management through 2034 than B3 Insight suggests, if PW remains increasingly used in hydraulic fracturing.

[187] B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

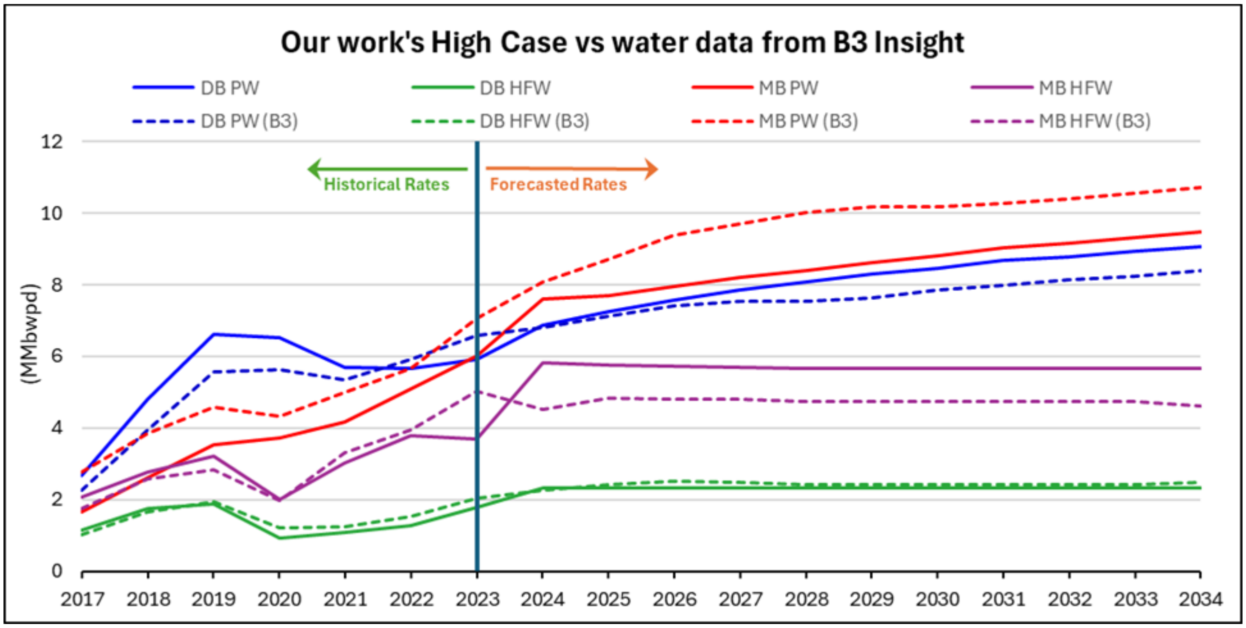

Figure 42. Comparison between our work's high case (HC) for the Delaware Basin (DB) and the Midland Basin (MB), and B3 Insight[188], concerning produced water (PW) and hydraulic fracturing water use (HFW). B3 Insight is referred to as B3 in this graph.

9.6 Suggested Water Management for Irrigation Shortages

B3 Insight suggests that a current PW recycling percentage in completions would increase from 58% in 2024 (DB: 55%, MB: 60%) to 87% in 2034 (DB: 88%, MB: 86%)[189] (B3 Insight 2024). In this work, we assume this percentage to reach 91% by 2050. We adopted the percentages estimated through the year 2034 by B3 Insight and slightly increased the percentage until 2050. This results in the net produced water (NPW), i.e., the water remaining after use of PW in HF operations. We calculated NPW for each production case and compared against the irrigation water shortage of the West Texas region (Figures 43 & 44). The Texas Water Development Board provides projections for water demand and shortage for each Texas county, in different beneficial reuse categories[190]. Water scarcity is a major issue of the West Texas region projected to experience an average annual water demand of 3.35 million AFY; and an average annual water shortfall of 1.05 million AFY**,** 87% of which is attributed to irrigation, leading up to 2070[191] [192] (Texas Water Development Board 2022a, b). The region is projected to account for 30% of Texas' water shortfall in irrigation through 2070. Groundwater accounts for 90% of the Region's total water supply and it could decrease by 43% by 2070 essentially due to irrigation. The region's

[188] B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

[189] B3 Insight (2024) Water Market Trends and Forecast Report. In: B3 Insight. https://www.b3insight.com/. Accessed 3 Sep 2024

[190] Texas Water Development Board (2022a) Statewide Summary | 2022 Texas State Water Plan. In: Texas Water Development Board. https://texasstatewaterplan.org/statewide/. Accessed 28 May 2023.

[191] Texas Water Development Board (2022a) Statewide Summary | 2022 Texas State Water Plan. In: Texas Water Development Board. https://texasstatewaterplan.org/statewide/. Accessed 28 May 2023.

[192] Texas Water Development Board (2022b) 2021 Regional Water Plan, Water Demand Projections by County for 2020-2070 in Acre-Feet. https://www3.twdb.texas.gov/apps/reports/Projections/2022%20Reports/demand_county. Accessed 10 Jan 2023.

irrigation activity is set to account for 45% of Texas' projected shortage in groundwater supply through 2070[193].

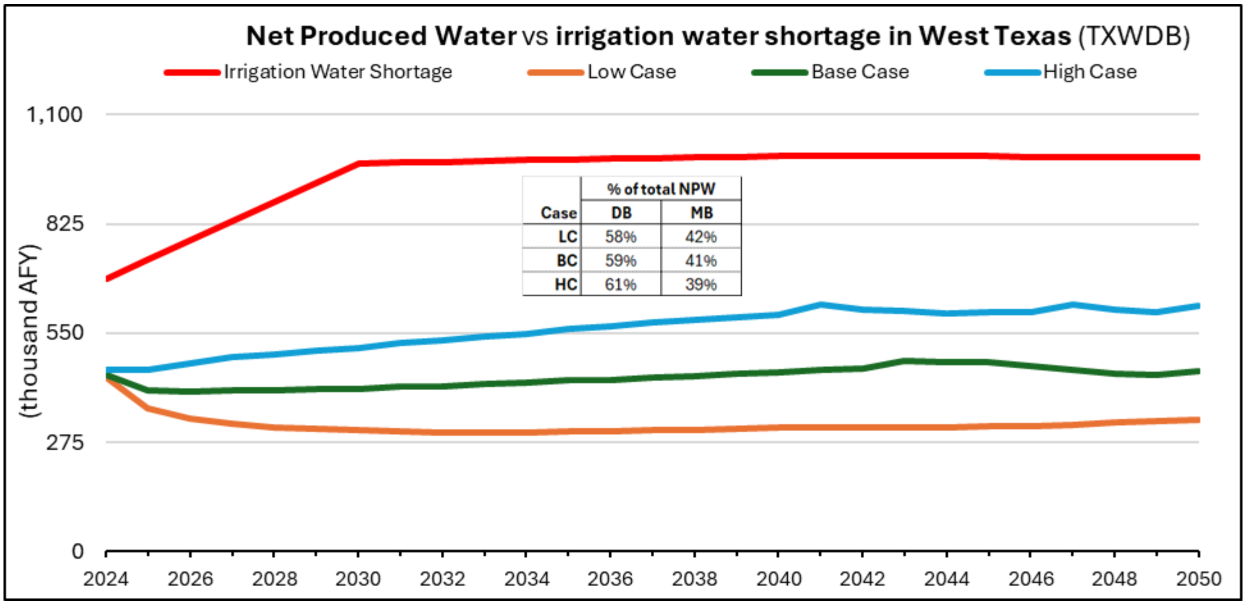

Figure 43. Net Produced Water (NPW) vs Irrigation Water Shortage through 2050. Three cases are considered for production: Low Case (LC), Base Case (BC) and High Case (HC). For each case, NPW is calculated by subtracting the PW recycled in HF from water production and the contribution of each of the Delaware Basin (DB) and Midland Basin (MB) to NPW is weighed. An average recycling water percentage of 83% is assumed through 2050 for both basins.

[193] Texas Water Development Board (2022a) Statewide Summary | 2022 Texas State Water Plan. In: Texas Water Development Board. https://texasstatewaterplan.org/statewide/. Accessed 28 May 2023.

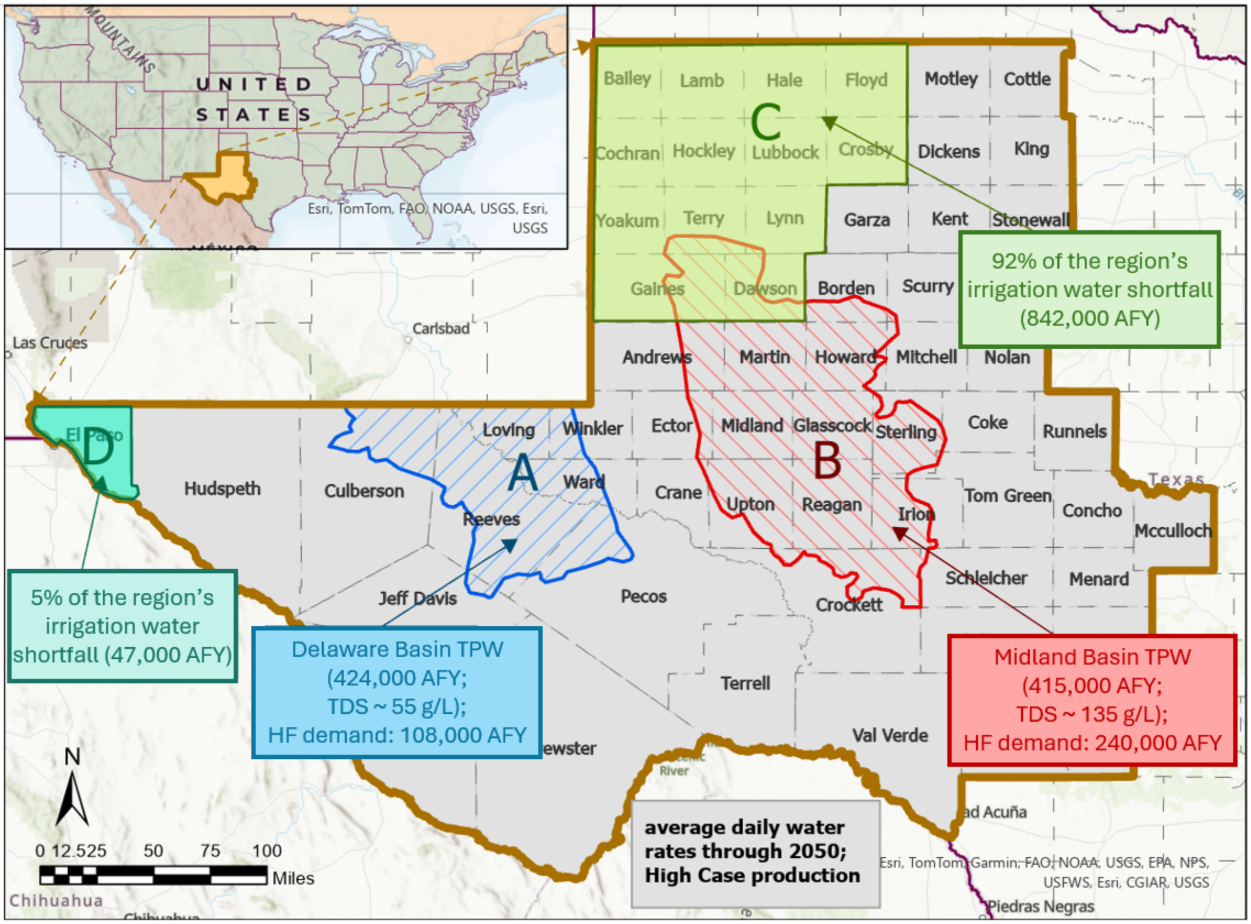

Figure 44. 2D map of the West Texas region showing the geographical extents of the Delaware Basin (area A), the Midland Basin (area B) and the areas with major irrigation water shortfall through 2050 (C and D). The High Case production is considered. The geographical extents are determined from geologic interval data provided by Enverus[194].

As seen in Figure 43, we predict NPW to reach 67% of the irrigation water shortage in 2041, under high case production (620,000 AFY). Around 60% of NPW would originate from the Delaware Basin: a scenario which might prove convenient for treatment as we initially reported in 2022 that the Delaware has a lower TPW salinity (71 g/L) than the Midland (130 g/L)[195] [196]. Recent water analysis (samples collected between 2022 and 2024 by Aegis Chemical Solutions) further supports the claim that the Delaware Basin seems more suitable for water treatment (medians of total dissolved solids: 55 g/L in DB and 135 g/L in MB) (Table 0.5)[197]. Based on

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[194] Enverus (2024) PRISM. In: Enverus. https://www.enverus.com/solutions/energy-analytics/ep/prism/. Accessed 20 Nov 2022

[195] Smith R, Bernard E, Watson M, et al (2022) Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward. In: Texas Produced Water Consortium. https://www.depts.ttu.edu/research/tx-water-consortium/2022-report.php. Accessed 28 Apr 2024

[196] Bechara E, Watson M, Arbad N (2024) Unlocking Sustainability: Transforming Tight-Oil Produced Water into a Lifeline for West Texas. Environmental Processes 11:26. https://doi.org/10.1007/s40710-024-00704-8

[197] Aegis Chemical Solutions (2024) Overview of Aegis Chemical Solutions. In: Aegis Chemical Solutions. https://www.aegischemical.com/. Accessed 28 Apr 2024

current water treatment technology efficiency (50%)[198 199 200 201], treated water would meet 16.7% to 29.5% of the irrigation water shortage through 2050. However, the major producing counties have minimal irrigation water shortage (9,600 AFY) compared to NPW (HC average: 550,000 AFY) through 2050. The two basins' geographical extents 'A' and 'B' are substantially distant from areas with high water shortage, 'C' and 'D' (Figure 44). Correspondingly, further study is needed to address the feasibility of developing a pipeline system to transport treated produced water from the major producing counties to areas 'C' and 'D'. The counties within the Delaware Basin seem more suitable for treatment given the lower salinity, despite the larger distance from area 'C'.

An alternative management plan to using pipelines to move treated water to areas 'C' and 'D' would be addressing the considerable water demand in the two basins to conserve groundwater. Within Area 1, i.e. the area consisting of counties listed in Table 10 (in the Delaware Basin), treated water (50% recovery) would surpass the water irrigation demand, as well as the total water demand of 144,000 AFY (72% irrigation), under high case production. Within Area 2, i.e. the area consisting of counties listed in Table 11 (in the Midland Basin), treated water (50% recovery) would surpass the water irrigation demand, under high case production. Excess treated water could be used to address the other beneficial reuse options in Area 2. The treated water could address 53% of Area 2 total water demand through 2050 (180,000 AFY). In Table 12, we suggest a water balance requiring further investigation of feasibility.

Table 10. "Area 1": comparison between average net produced water (NPW) high case production treated at 50% recovery and the projected average irrigation water demand on a county basis in the Delaware Basin[202], through 2050. The listed counties would account for 88% of the Delaware Basin's tight-oil produced water (TPW) and require 87% of the basin's hydraulic fracturing water. Units are in AFY. Maximum PW recylcing perecentage: 82%.

County	HC TPW	HC HFW	HC NPW (max 82% recycling)	HC NPW treated at 50% recovery	Projected average irrigation water demand	Excess of treated NPW (+) / Water need (-)
Reeves	145,465	34,102	117,496	58,748	58,937	-189
Loving	144,455	33,380	117,077	58,539	0	+58,539
Ward	28,943	11,943	19,148	9,574	3,160	+6,414
Culberson	28,280	6,937	22,590	11,295	37,863	-26,568
Winkler	27,340	8,001	20,778	10,389	3,507	+6,882
Jeff Davis	2,541	591	2,080	1,040	665	+375
Total	**377,023**	**94,955**	**299,168**	**149,584**	**104,132**	**+45,452**

[198] Pawar R, Zhang Z, Vidic RD (2022) Laboratory and pilot-scale studies of membrane distillation for desalination of produced water from Permian Basin. Desalination 537:115853. https://doi.org/10.1016/J.DESAL.2022.115853

[199] Ricceri F, Giagnorio M, Farinelli G, et al (2019) Desalination of Produced Water by Membrane Distillation: Effect of the Feed Components and of a Pre-treatment by Fenton Oxidation. Sci Rep 9:. https://doi.org/10.1038/s41598-019-51167-z

[200] Scanlon BR, Reedy RC, Xu P, et al (2020) Can we beneficially reuse produced water from oil and gas extraction in the U.S.? Science of the Total Environment 717:. https://doi.org/10.1016/j.scitotenv.2020.137085

[201] Smith R, Bernard E, Watson M, et al (2022) Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward. In: Texas Produced Water Consortium. https://www.depts.ttu.edu/research/tx-water-consortium/2022-report.php. Accessed 28 Apr 2024

[202] Texas Water Development Board (2022a) Statewide Summary | 2022 Texas State Water Plan. In: Texas Water Development Board. https://texasstatewaterplan.org/statewide/. Accessed 28 May 2023

Table 11. "Area 2": Comparison between average net produced water (NPW) from high case production treated at 50% recovery and the projected average irrigation water demand on a county basis in the Midland Basin[203], through 2050. The listed counties would account for 84% of the Midland Basin's tight-oil produced water (TPW) and require 79% of the basin's hydraulic fracturing water. Units are in AFY. Maximum PW recylcing perecentage: 84%.

County	HC TPW	HC HFW	HC NPW (max 84% recycling)	HC NPW treated at 50% recovery	Projected average irrigation water demand	Excess of treated NPW (+) / Water need (-)
Martin	103,313	57,581	55,095	27,547	36,491	-8,944
Midland	88,537	52,810	44,314	22,157	18,107	+4,050
Howard	65,950	28,882	42,648	21,324	6,883	+14,441
Upton	63,534	33,412	35,875	17,937	10,403	+7,534
Andrews	26,755	15,961	13,389	6,694	20,365	-13,671
Total	**348,089**	**188,645**	**191,321**	**95,660**	**92,249**	**+3,411**

Table 12. Suggested management of produced water for 'Area 1' and 'Area 2', under high case production.

area	Basin	Recylcing in Hydraulic Fracturing	Saltwater disposal	Beneficial use within the area	Excess treated water
Area 1	Delaware Basin	20.9%	39.7%	38.2%	1.5%
Area 2	Midland Basin	45.0%	27.5%	27.5%	-

203 Texas Water Development Board (2022a) Statewide Summary | 2022 Texas State Water Plan. In: Texas Water Development Board. https://texasstatewaterplan.org/statewide/. Accessed 28 May 2023

9.7 Volumetrics Appendices

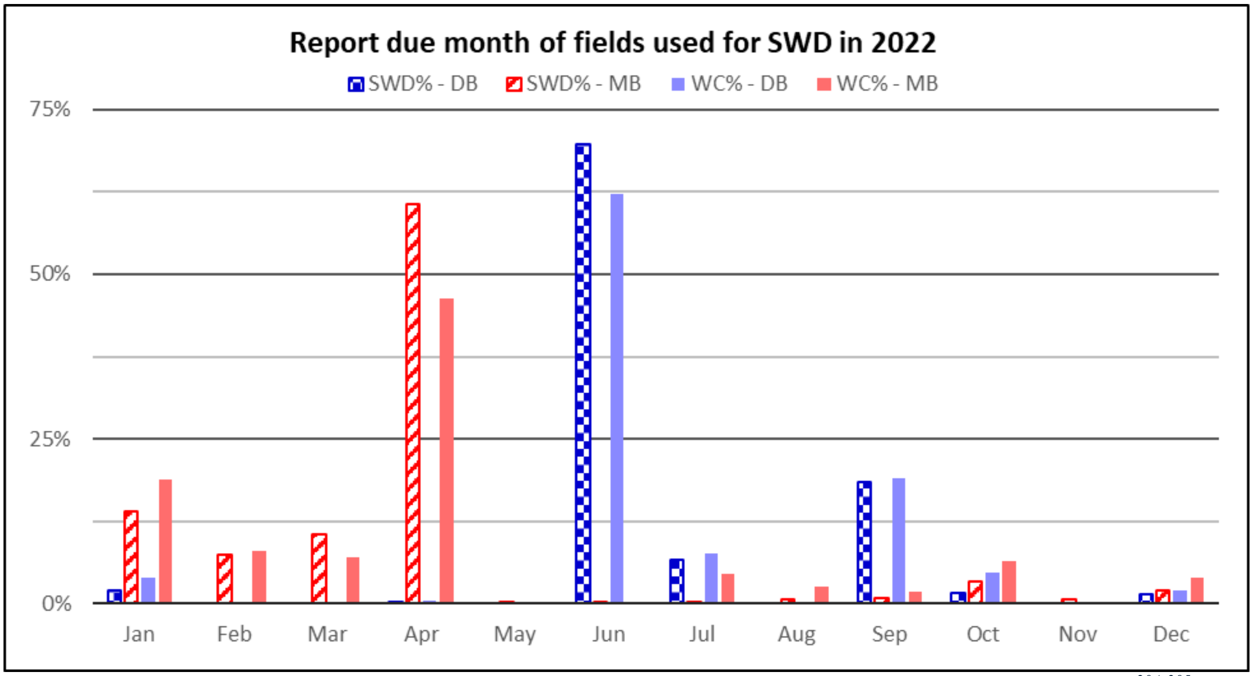

Figure 0.1. Due Months of field used for SWD throughout the Delaware Basin (DB) and Midland Basin (MB) in 2022[204] [205]. WC: Well Count.

[204] Railroad Commission of Texas (2024a) Data Sets Available for Download. In: Railroad Commission of Texas. https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Accessed 20 Nov 2022

[205] Railroad Commission of Texas (2024b) H10 Filing system. In: Railroad Commission of Texas. https://webapps.rrc.texas.gov/H10/publicSearchCycle.do?fromMain=yes. Accessed 3 Sep 2024

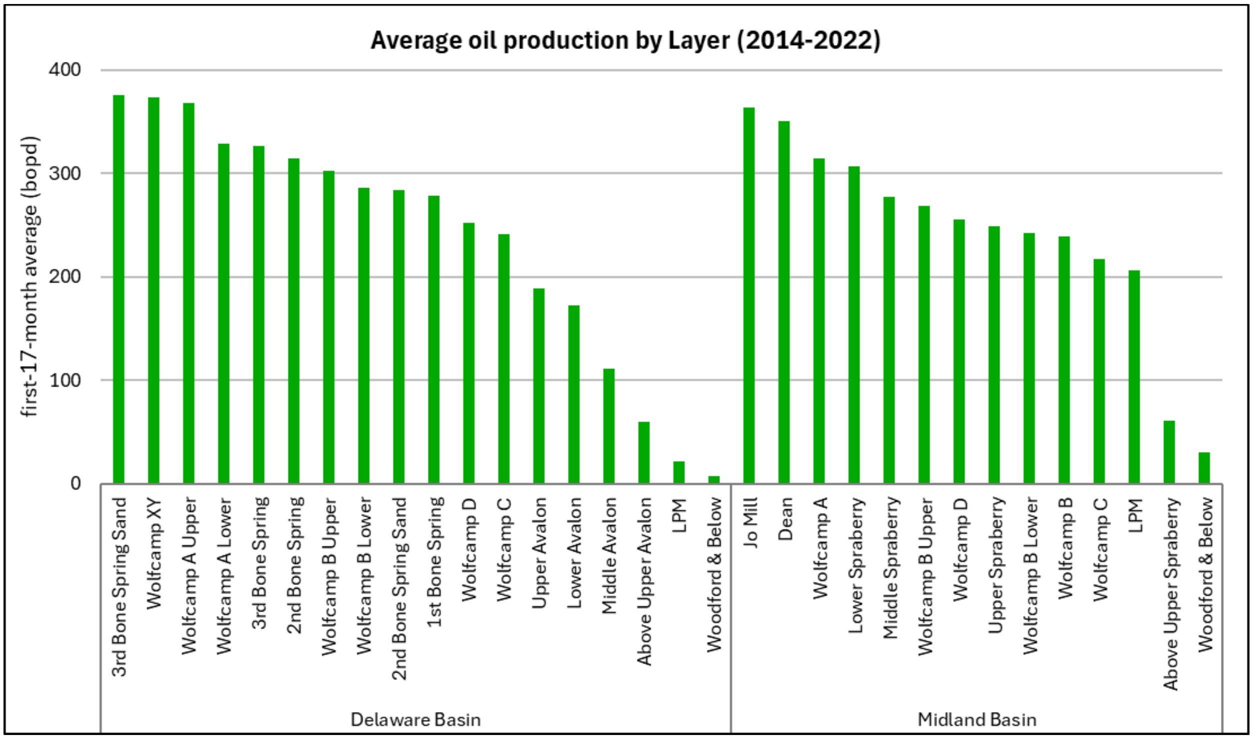

Figure 0.2. Average oil production by Layer (2014-2022): first-17-month average.

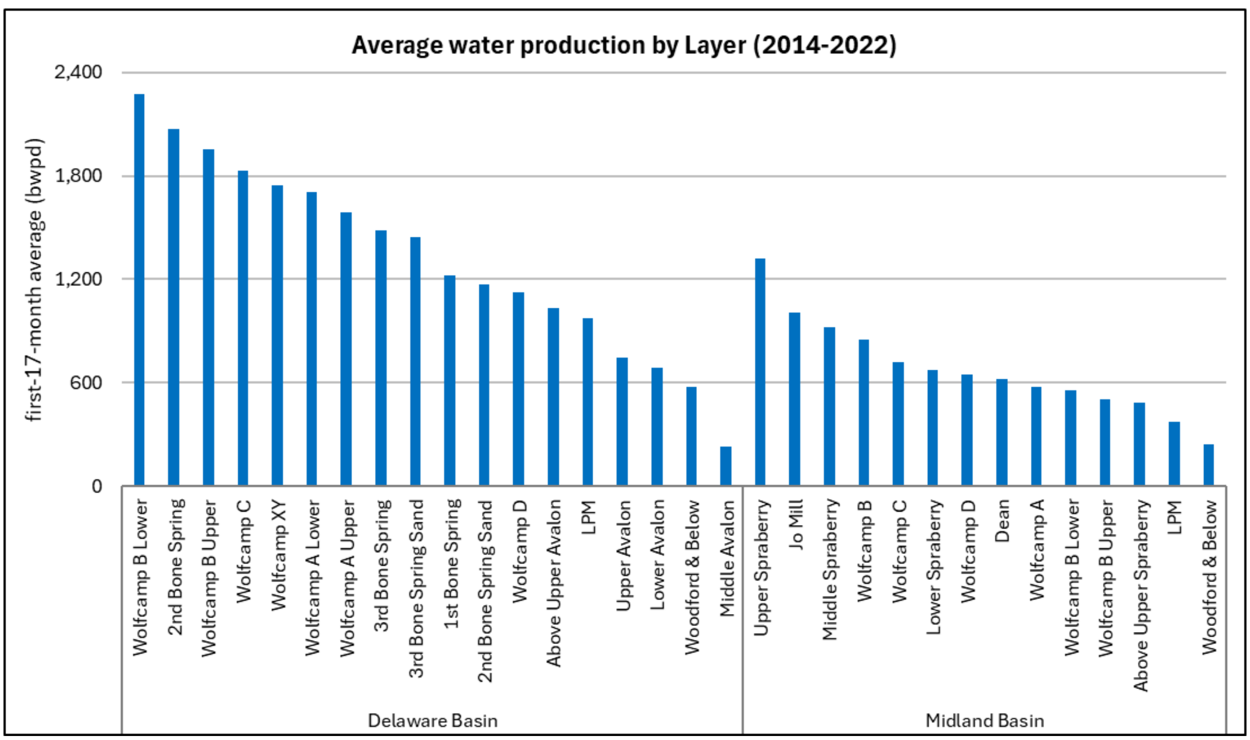

Figure 0.3. Average water production by Layer (2014-2022): first-17-month average.

Figure 0.4. Basis for selecting the maximum lateral well density per Layer for a county: herein shown the selection for Midland County (138 ft/acre in the geographical extent of the Spraberry). Only displayed are the laterals of the wells producing from the Lower Spraberry and intersecting with Midland County. Lateral well density per Layer is determined by examining (2mix1mi) subdivisions: laterals are segmented by subdivision to assess the total lateral length within each subdivision; the total lateral length is then divided by the subdivision's area to calculate its lateral well density per Layer.

Table 0.1. Type curve parameters used for oil and water decline. Counties in Blue are within the Delaware Basin and counties in red within the Midland Basin. Units are in bopd for oil bwpd for water.

County	Horizontal wells completed after 2017					
	b-Factor		Initial decline rate, Di (/yr)		Initial production rate, Qi (bwpd/well)	
	Oil	Water	Oil	Water	Oil	Water
Culberson	0.85	0.77	1.97	1.61	610	3,410
Loving	1	0.81	2.35	1.9	970	3,740
Pecos	1.29	1	3.51	2.59	730	4,430
Reeves	1.06	0.86	3.22	2.21	870	4,260
Ward	1.17	0.78	2.81	2.1	650	2,600
Winkler	1.2	1	2.23	2.35	640	2,970
Andrews	0.7	0.95	1.43	2.3	670	1,640
Borden	0.88	0.86	2.26	2.12	670	1,870
Crane	1	1	3	3	840	2,260
Crockett	1.23	1	5.6	4.61	220	670
Dawson	1.5	0.86	5.81	1.98	620	3,040
Ector	1.2	0.65	3.51	3.58	740	1,690
Gaines	1.5	0.86	5.81	1.98	620	3,040
Glasscock	0.92	0.95	3.51	3.91	840	2,130
Howard	1	0.95	3.51	3	860	2,230
Irion	0.81	0.88	3.51	4.2	360	770
Lynn	1.5	0.86	5.81	1.98	440	3,040
Martin	0.98	0.97	3.96	3.51	1,040	2,230
Midland	0.94	0.89	3.1	2.81	940	1,970
Mitchell	1	0.95	3.51	3	860	2,230
Reagan	0.96	0.9	3.1	3.91	510	1,520
Sterling	0.96	0.9	3.1	3.91	510	1,520
Terry	1.5	0.86	5.81	1.98	440	3,040
Upton	1	1	3	3	840	2,260
Yoakum	2	0.9	4.61	3.31	100	1,050

Table 0.2. Low Case Production: Oil and Water by County. Counties in Blue are within the Delaware Basin and counties in Red within the Midland Basin. Units are in bopd for oil bwpd for water. PW: produced water from horizontal tight-oil wells; HFW: hydraulic fracturing water demand; NPW: net produced water.

	averages through 2050					year 2050				
County	Oil	PW	HFW	recycling	NPW	Oil	PW	HFW	recycling	NPW
Culberson	57,921	354,225	73,724	60,466	293,759	55,399	333,428	73,724	67,636	265,792
Jeff Davis	-	-	-	-	-	-	-	-	-	-
Loving	431,750	1,579,202	333,876	273,835	1,305,367	478,715	1,683,605	333,876	306,307	1,377,298
Pecos	99,318	534,725	142,393	116,787	417,938	119,893	623,173	142,393	130,636	492,538
Reeves	343,799	1,759,703	362,417	297,243	1,462,460	358,611	1,766,328	362,417	332,491	1,433,837
Ward	105,545	358,035	126,922	104,098	253,938	113,141	337,442	126,922	116,442	221,000
Winkler	62,402	224,979	50,511	40,228	184,751	30,630	87,679	-	-	87,679
Andrews	136,060	301,391	169,624	142,044	159,347	148,852	346,579	169,624	152,662	193,917
Borden	19,127	55,694	23,702	19,592	36,102	10,580	29,828	-	-	29,828
Crane	1,617	3,416	1,965	1,041	2,375	343	666	-	-	666
Crockett	6,595	16,442	25,438	16,373	69	6,695	16,239	25,438	16,552	-
Dawson	13,317	51,890	15,017	10,746	41,145	5,442	12,032	-	-	12,032
Ector	22,597	25,017	31,606	24,191	826	26,683	25,072	31,606	25,600	-
Gaines	-	-	-	-	-	-	-	-	-	-
Glasscock	135,191	337,135	211,900	177,446	159,689	143,705	353,972	211,900	190,710	163,261
Howard	322,460	940,877	414,124	343,986	596,891	241,775	676,625	-	-	676,625
Irion	15,498	31,396	61,201	31,042	353	15,330	31,138	61,201	31,756	-
Lynn	88	533	-	-	533	32	109	-	-	109
Martin	532,391	1,288,110	654,625	548,184	739,926	579,066	1,369,583	654,625	589,162	780,421
Midland	472,924	1,064,221	561,228	469,974	594,248	500,389	1,072,161	561,228	505,105	567,055
Mitchell	7,061	19,394	9,033	6,746	12,648	2,024	5,242	-	-	5,242
Reagan	57,729	143,991	104,342	87,376	56,615	49,795	114,446	104,342	93,908	20,538
Sterling	350	787	606	267	520	75	141	-	-	141
Terry	2,933	18,762	5,844	4,061	14,701	960	4,159	-	-	4,159
Upton	273,186	734,253	371,936	309,978	424,274	281,796	757,074	-	-	757,074
Total	**3,119,858**	**9,844,180**	**3,752,035**	**3,085,703**	**6,758,477**	**3,169,930**	**9,646,721**	**2,859,297**	**2,558,967**	**7,089,214**

Table 0.3. Base Case Production: Oil and Water by County. Counties in Blue are within the Delaware Basin and counties in Red within the Midland Basin. Units are in bopd for oil bwpd for water. PW: produced water from horizontal tight-oil wells; HFW: hydraulic fracturing water demand; NPW: net produced water.

	averages through 2050					year 2050				
County	Oil	PW	HFW	recycling	NPW	Oil	PW	HFW	recycling	NPW
Culberson	71,647	436,508	98,298	80,621	355,887	72,262	433,237	98,298	90,182	343,055
Jeff Davis	4,716	23,540	5,188	3,371	20,169	1,314	4,935	-	-	4,935
Loving	632,378	2,324,777	521,682	427,867	1,896,910	733,964	2,589,858	521,682	478,605	2,111,253
Pecos	150,420	820,532	227,829	186,859	633,673	188,540	985,041	227,829	209,017	776,024
Reeves	464,055	2,381,362	531,544	435,956	1,945,406	511,908	2,527,161	531,544	487,653	2,039,508
Ward	136,895	460,891	177,691	145,737	315,154	154,479	460,424	177,691	163,019	297,406
Winkler	110,403	404,326	104,498	87,223	317,103	76,089	228,267	-	-	228,267
Andrews	196,832	435,028	254,436	213,066	221,962	221,541	514,440	254,436	228,993	285,447
Borden	20,571	59,824	28,068	23,504	36,320	21,945	62,366	28,068	25,261	37,104
Crane	2,467	5,215	3,111	1,838	3,377	537	1,043	-	-	1,043
Crockett	6,595	16,442	25,438	16,373	69	6,695	16,239	25,438	16,552	-
Dawson	25,053	108,924	34,000	25,722	83,202	11,418	27,916	-	-	27,916
Ector	34,922	36,630	44,841	32,659	3,971	20,053	7,028	-	-	7,028
Gaines	840	3,928	1,083	650	3,278	298	779	-	-	779
Glasscock	199,482	492,996	332,986	278,843	214,153	222,007	544,663	332,986	299,688	244,975
Howard	408,442	1,176,520	510,456	416,120	760,399	184,421	507,301	-	-	507,301
Irion	21,544	43,555	91,801	43,588	-	22,426	45,625	91,801	46,532	-
Lynn	547	3,363	878	527	2,837	194	666	-	-	666
Martin	766,789	1,832,783	996,168	834,193	998,590	868,412	2,043,579	996,168	896,551	1,147,028
Midland	654,273	1,451,512	827,073	692,593	758,919	724,020	1,544,556	827,073	744,366	800,190
Mitchell	7,889	21,675	10,169	7,711	13,964	2,347	6,085	-	-	6,085
Reagan	91,354	222,402	208,685	174,753	47,649	91,423	208,408	208,685	187,816	20,592
Sterling	11,208	26,137	31,111	24,899	1,238	13,908	31,458	31,111	28,000	3,458
Terry	6,273	40,880	13,321	10,294	30,586	2,920	11,254	-	-	11,254
Upton	396,338	1,066,186	530,793	435,398	630,788	206,328	553,662	-	-	553,662
Total	**4,421,935**	**13,895,935**	**5,611,150**	**4,600,365**	**9,295,603**	**4,359,447**	**13,355,992**	**4,352,812**	**3,902,234**	**9,454,979**

Table 0.4. High Case Production: Oil and Water by County. Counties in Blue are within the Delaware Basin and counties in Red within the Midland Basin. Units are in bopd for oil bwpd for water. PW: produced water from horizontal tight-oil wells; HFW: hydraulic fracturing water demand; NPW: net produced water.

	averages through 2050					year 2050				
County	Oil	PW	HFW	recycling	NPW	Oil	PW	HFW	recycling	NPW
Culberson	99,099	601,075	147,447	120,932	480,144	105,987	632,853	147,447	135,272	497,581
Jeff Davis	10,682	54,002	12,572	9,784	44,218	3,979	15,406	-	-	15,406
Loving	833,007	3,070,353	709,487	581,899	2,488,453	989,214	3,496,111	709,487	650,903	2,845,209
Pecos	201,523	1,106,338	313,265	256,931	849,408	257,188	1,346,908	313,265	287,398	1,059,510
Reeves	601,490	3,091,830	724,833	594,486	2,497,344	687,105	3,396,685	724,833	664,982	2,731,703
Ward	183,919	615,173	253,844	208,195	406,978	216,486	644,898	253,844	232,884	412,014
Winkler	156,765	581,104	170,066	139,483	441,622	200,946	707,890	170,066	156,023	551,867
Andrews	257,605	568,665	339,249	284,087	284,578	294,229	682,301	339,249	305,324	376,977
Borden	31,501	90,993	40,950	33,459	57,535	13,416	37,593	-	-	37,593
Crane	9,935	21,002	4,256	2,862	18,140	2,220	4,316	-	-	4,316
Crockett	6,595	16,442	25,438	16,373	69	6,695	16,239	25,438	16,552	-
Dawson	39,946	182,686	59,188	46,202	136,483	20,271	52,298	-	-	52,298
Ector	46,035	47,632	58,959	41,811	5,821	23,614	7,459	-	-	7,459
Gaines	2,399	11,239	3,264	2,020	9,218	862	2,253	-	-	2,253
Glasscock	263,773	648,857	454,072	380,241	268,616	300,310	735,354	454,072	408,665	326,689
Howard	490,513	1,401,756	613,885	495,279	906,477	196,497	536,153	-	-	536,153
Irion	21,544	43,555	91,801	43,588	-	22,426	45,625	91,801	46,532	-
Lynn	1,244	7,679	2,252	1,434	6,245	454	1,561	-	-	1,561
Martin	923,055	2,195,898	1,223,863	1,024,865	1,171,032	1,061,310	2,492,910	1,223,863	1,101,477	1,391,433
Midland	855,772	1,881,834	1,122,457	939,947	941,887	972,499	2,069,440	1,122,457	1,010,211	1,059,229
Mitchell	8,704	23,923	11,307	8,688	15,235	2,693	6,990	-	-	6,990
Reagan	102,562	248,538	243,465	203,878	44,660	105,331	239,866	243,465	219,119	20,747
Sterling	11,208	26,137	31,111	24,899	1,238	13,908	31,458	31,111	28,000	3,458
Terry	10,017	67,944	23,551	19,219	48,725	6,989	29,851	-	-	29,851
Upton	501,788	1,350,407	710,161	587,900	762,507	340,975	916,578	-	-	916,578
Total	**5,670,681**	**17,955,062**	**7,390,746**	**6,068,464**	**11,886,632**	**5,845,602**	**18,148,995**	**5,850,401**	**5,263,340**	**12,886,875**

Table 0.5. Chemical composition of produced water for treatment based on 7,024 TPW samples collected between Jan-2022 and Jan-2024 from 1,952 wells in the Delaware Basin and Midland Basin. 75% of the samples were collected more than 1,200 days after a well's first production date, hence the dataset likely represents formation water rather than completion flowback.

Chemical Property	Delaware Basin (2,693 samples; 601 wells)			Midland Basin (4,331 samples; 1,351 wells)		
	25th percentile	50th percentile	75th percentile	25th percentile	50th percentile	75th percentile
Total Dissolved Solids (mg/L)	34,418	54,964	83,929	115,334	134,925	149,165
days between first production and sample collection	1,256	1,870	3,504	1,208	2,006	3,246
Resistivity (ohms/m)	0.08	0.12	0.19	0.04	0.05	0.06
Ionic Strength (mol/L)	0.60	0.97	1.50	2.09	2.44	2.69
pH	6.48	6.90	7.26	6.20	6.52	6.85
Specific Gravity (mg/L)	1.02	1.04	1.06	1.08	1.09	1.10
Total Hardness (as CaCO3)	842	2,203	5,057	7,647	10,205	13,101
Calcium (mg/L)	276	698	1,567	2,402	3,215	4,154
Magnesium (mg/L)	36	110	284	392	516	674
Sodium (mg/L)	12,831	20,103	30,263	40,585	47,504	53,069
Potassium (mg/L)	120	187	299	426	536	638
Barium (mg/L)	1	2	8	2	3	3
Strontium (mg/L)	93	157	299	436	584	732
Iron (mg/L)	1	6	21	28	52	85
Manganese (mg/L)	0.1	0.3	0.7	1	1.5	2.3
Sulfates (mg/L)	172	288	662	230	329	467
Chlorides (mg/L)	19,891	32,443	50,165	69,594	81,595	90,375
Phosphorous (mg/L)	25	52	159	39	74	241
Sulfur	59	102	236	85	121	179
Boron	38	53	67	38	44	52
Silicon	11	15	18	7	12	15
Lithium	8	10	13	15	18	22
Bicarbonates (mg/L)	476	647	854	244	317	403
CO_2 in Brine (mg/L)	66	110	220	176	242	330
Dissolved O_2 (mg/L)	0.2	0.4	0.6	0.2	0.3	0.4
Calcite SI	-0.7	-0.4	-0.1	-1.3	-1.1	-0.8
Barite SI	0.3	0.6	0.9	0.2	0.3	0.4
Gypsum SI	-2.0	-1.5	-1.1	-1.3	-1.1	-0.9
Hemihydrate SI	-1.9	-1.5	-1.1	-1.3	-1.1	-0.9
Anhydrite SI	-2.2	-1.7	-1.3	-1.4	-1.2	-0.9
Celestite SI	-0.4	-0.2	0.0	-0.1	0.1	0.2

9.8 Nomenclature

AFY – Acre-foot(feet)/year
bopd – Million Barrel(s) of Oil per Day
bopd/mi – Barrel(s) of Oil per Day, per Mile
bwpd – Barrel(s) of Water per Day
ft – foot (feet)
ft/acre – foot (feet) per acre
HF – Hydraulic Fracturing
HFW – Hydraulic Fracturing Water Demand/Use

Mbwpd/mi – Thousand Barrel(s) of Water per Day, per Mile
mg/L – milligrams per liter
Mgal/ft – Thousand Gallon(s) per Foot
mi – mile(s)
mi^2 – square mile(s)
MMbopd – Million Barrel(s) of Oil per Day
MMbwpd – Million Barrel(s) of Water per Day
NPW – Net Produced Water
RRC – The Railroad Commission of Texas
SI – Saturation Index
SWD – Saltwater Disposal
TDS – Total Dissolved Solids
TPW – Tight-oil Produced Water, i.e., water produced from tight-oil formations
TxPWC – The Texas Produced Water Consortium
UIC – Underground Injection Control
WOR – Water-oil Ratio