Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward

Texas Produced Water Consortium Report to the Texas Legislature 2022

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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Texas Commission on Environmental Quality
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Texas Economic Development and Tourism Office
Texas Parks and Wildlife Department
Texas Water Development Board

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Frequently Used Acronyms

PW – Produced water
TPW – Treated produced water
Bbl/Bbls – Barrel/Barrels
MMbbls – Million barrels
Bbbls – Billion barrels
Bopd – Barrels of oil per day
RRC – Railroad Commission of Texas
TCEQ – Texas Commission on Environmental Quality
TDS – Total Dissolved Solids
PPM – Parts per million
Mg/L – Milligrams per liter
SWD – Salt water disposal
MGD – Million gallons per day
HF – Hydraulic fracturing
Ac-Ft – Acre Foot

Executive Summary

Key Findings

- Due to its overwhelming abundance of produced water relative to other areas of the state, this report currently focuses solely on the Permian Basin.
- The potential for treating produced water could lead to an estimated 2 billion barrels per year (~256,000 ac-ft) of treated produced water, and as high as 4 billion barrels per year (~511,000 ac-ft) that could be available for beneficial use outside of oil and gas operations, depending on treatment capabilities and recovery rates.
- There are existing technologies that can effectively treat water of various quality levels; however, no facility currently exists in the Permian that is treating water to a quality beyond that which is needed for oil and gas operations.
- The lack of an existing facility and the high variability of produced water qualities warrants pilot project facilities to provide treated water samples for analyzing treatment quality capabilities and treated water characterization.
- Treating produced water for beneficial reuse outside of the oil and gas industry is not currently more economical than disposal or reuse within the industry. However, factors such as innovation in technological efficiencies and the potential for future water markets as an economic development tool, or a necessary response to scarcity conditions, will eventually make this an economically viable option.

Report Directives of Senate Bill 601

Now codified into statute, Senate Bill 601 as passed specifically directed the Texas Produced Water Consortium (*TXPWC, Consortium*) as follows:

"Not later than September 1, 2022, the consortium shall produce a report that includes:
(1) suggested changes to laws and administrative rules to better enable beneficial uses of fluid oil and gas waste, including specific changes designed to find and define beneficial uses for fluid oil and gas waste outside of the oil and gas industry;
(2) suggested guidance for establishing fluid oil and gas waste permitting and testing standards;
(3) a technologically and economically feasible pilot project for state participation in a facility designed and operated to recycle fluid oil and gas waste; and
(4) an economic model for using fluid oil and gas waste in a way that is economical and efficient and that protects public health and the environment."[1]

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[1] Texas Education Code § 109.204(a-1).

Consortium Approach

For the past year the Consortium has endeavored to address these four directives with as much specificity as possible, utilizing the expertise of our membership, existing literature, and outside sources. Bi-weekly virtual member subcommittee meetings spanning six different focus areas (policy, standards, technology, economics, membership and legal) along with the ongoing efforts of Consortium staff to take meetings, generate surveys, and draft documents for further member input led up to a full-day seminar in Lubbock to discuss various sections of this report and outstanding issues brought forward by members. In considering how to fulfill the report requirements from SB 601, the Consortium needed to answer the following questions:

1. *How much treated produced water could be available for beneficial use outside of the oil & gas industry?*
2. *Is there a technology, or technologies, that could treat produced water to an adequate quality for beneficial use?*
3. *What set of pilot projects should the Consortium, with state participation, administer to provide proof-of-concept and begin establishing confidence in the ability to treat produced water for beneficial use?*
4. *What are the economics of treating produced water for beneficial use in a manner that is cost-effective, efficient and protective of public health and the environment?*
5. *What legislative and/or regulatory actions need to be considered at this time as a result of answers to these questions?*

These questions form the basis of a tightly interwoven system of produced water treatment that, if not addressed in a careful and considerate manner, could result in setbacks to the industry and the economic driver of the state as a whole. This report will detail those items on which the Consortium was able to provide guidance, but more importantly it outlines those topics where current systemic insufficiencies have made providing definitive answers difficult, and provides a plan for how the Consortium will continue to pursue answers through its research and investigation efforts.

A Tale of Two Challenges

Current & Emerging Water Shortages

Texas is experiencing unprecedented population growth, driven largely by its current economic success due in no small part to the oil & gas industry in the state. Such growth can bring significant challenges, however, and Texas is not immune to the potential for future hardships without proper planning and preparation. Case in point, the Texas Water Development Board's (TWDB) 2022 Texas State Water Plan illustrates a dire need for additional water resource development: under drought of record conditions, the state of Texas could face a 6.9 million acre-feet shortage of water by the year 2070.[2] Putting that into perspective, TWDB further elaborates that if water management strategy projects are not implemented during that time

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[2] Texas Water Development Board. "2022 State Water Plan: Water for Texas." (2022); https://www.twdb.texas.gov/waterplanning/swp/2022/docs/SWP22-Water-For-Texas.pdf .

frame, approximately 25% of Texas' projected 51.5 million population could have *less than half* the municipal water supplies they need during a drought of record.[3] The economic consequences to our state would be significant; modeling for 2020 indicated a potential for $110 billion in losses under those record conditions and up to $153 billion by 2070 without sufficient conservation and water supply development.[4]

Planning for the future of our water resource adequacy is the responsibility of every Texan. Conservation strategies alone represent only 2.2 million of the needed 6.9 million acre-feet by 2070[5]; new sources of water must be identified and developed. The Texas Legislature has made significant progress in prior years to pass legislation aimed at bolstering new water resource development. Texas is fortunate to have access to both seawater and brackish groundwater, and tremendous strides are being made in the field of desalination technology for treating these water sources for public and industrial use. There is, however, another water source that is currently being generated in excess volumes in regions across the state, especially in arid locales who know better than most what it truly means to face a drought: produced water.

Produced Water Management

Produced Water (PW), statutorily defined as "fluid oil & gas waste,"[6] is water generated through oil & gas production operations. The properties of produced water can vary considerably depending on the geographic location of the field, the geologic formation in which production is occurring, and the type of hydrocarbon product being produced.[7] Produced water may contain salts (total dissolved solids [TDS]), organic and inorganic compounds, naturally-occurring radioactive material (NORM), chemical additives, and transformational byproducts, among others.[8] This report focuses on produced water from unconventional-tight oil formation wells (see Appendix A).

It is now more important than ever to find lasting solutions to these two critical issues.

The most common form of managing produced water has historically been through disposal into EPA Class II injection wells, but strides in treatment and use technology and regulatory actions have also enabled treating produced water for reuse within the industry. In a report for the Groundwater Protection Council, it was estimated in 2012 that 99% of produced water in Texas was managed through injection, either for disposal or for enhanced oil recovery.[9] Detailed in that report, it was estimated that 53.5% (approximately 5.3 billion barrels) were disposed that year (this remains consistent with current Consortium driven survey data).[10] Since 2008, unconventional field development in Texas has resulted in an ongoing effort by the RRC to modernize

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[3] *Id.*

[4] *Id.*

[5] *Id.*

[6] Texas Natural Resources Code § 122.001(2).

[7] Groundwater Protection Council. "Produced Water Report: Regulations, Current Practices, and Research Needs." (2019).

[8] *Id.*

[9] Veil, John. "US produced water volumes and management practices in 2012." (2015).

[10] *Id.*

their rules. One of the key areas they have focused on is improving their rules relating to water management to allow operator innovation to recycle produced water by treating to a "clean brine" level, which can then be utilized for hydraulic fracturing and other completion practices.[11] However, as detailed later in the projections section, even if operators were able to utilize treated produced water for 100% of their production activities in the Permian Basin, there would still be millions of barrels of excess produced water generated every day, needing to be disposed or otherwise managed.

How much treated produced water could be available for beneficial use outside of the oil & gas industry?

Focus on the Permian Basin

One of the most important questions regarding treated produced water reuse is that of volume- more specifically, what is the volume of *excess* or *potentially available* treated produced water for beneficial use outside of the oil & gas industry. Answering this question will help to guide the state on the most appropriate locations for emphasizing research, and firmly establishes if/where opportunities may exist to access a new source of water.

While there is no complete picture of produced water amounts at this time, projecting produced water volumes has been the subject of many papers as well as a key component of several third-party analytical platforms. While the volumes contained in these estimates vary, there was one common observation: *the Permian Basin generates the overwhelming majority of oil and produced water in Texas* (see Appendix B). For example, in a 2019 white paper from the Texas Alliance of Energy Producers (TAEP) using data from B3 Insight and Sourcewater, Inc., the percentage of produced water in the Permian compared to the rest of the basins in the state accounted for between 66% and 91% of all produced water in 2017 (the difference in range is attributed to differences in the datasets between specific geographic boundaries).[12]

Volume Projection

There are currently two required methods of reporting to the Railroad Commission of Texas that provide information on produced water volumes in the state: Form W-10, a required annual test of every producing oil well in the state where an operator reports oil, gas, and water production during a 24-hour time period; and Form H-10, a report that is due annually but details the monthly monitoring records of pressure and volume for injection (disposal) wells.[13] These reporting methods are currently the best information available and form the basis for the methodology of many projections.

Projecting produced water volumes is a target moving in several dimensions: volumes not only vary by formation and basin, but they change over time for each producing well as the barrels of water produced to each barrel of oil produced (herein referred to as the Water-to-Oil ratio,

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[11] https://www.currentargus.com/story/opinion/columnists/2022/01/07/shaky-ground-texas-railroad-commission-takes-much-needed-stand-oilfield-earthquakes/9129798002/

[12] Lyons et.al., "Sustainable Produced Water Policy, Regulatory Framework, and Management in the Texas Oil and Natural Gas Industry: 2019 and Beyond," p. 8, 2019.

[13] Railroad Commission of Texas, "Oil & Gas Forms" https://www.rrc.texas.gov/oil-and-gas/oil-and-gas-forms/

or WOR) may increase over the life of the well.[14] Data presented in the TAEP white paper detailed an estimated average 7:1 WOR across Texas; varying from as low as 1:1 in some basins to as high as 10:1 in others.[15, 16] As time progresses, however, new and increased methods of oil recovery and the sliding scale of WOR lends itself to the need for updated projections.

Building upon the need to update volume estimates based on current trends, Texas Tech faculty for the Consortium used produced water information from Enverus, formerly DrillingInfo, paired with RRC data on disposal well volumes and data shared by Consortium members to estimate daily PW volumes for each county within the Permian Basin. This evaluation was focused specifically on unconventional tight oil wells, as other well types, such as conventional or waterfloods, generally consume as much produced water as they generate. Calculations from this data resulted in an estimated WOR for each county, which was then used to generate a weighted average WOR of 4.99 for the Delaware Basin and 2.63 for the Midland Basin. Using these WORs and RRC oil production data, the Consortium estimates that 3.93Bbbls of produced water were generated in 2019. Based on a survey of hydraulic fracturing companies, we can further refine this number by subtracting the average percentage of produced water that is reused by the industry for HF, leaving an estimated 2.76Bbbls of produced water that could have been available to treat for beneficial use in 2019.

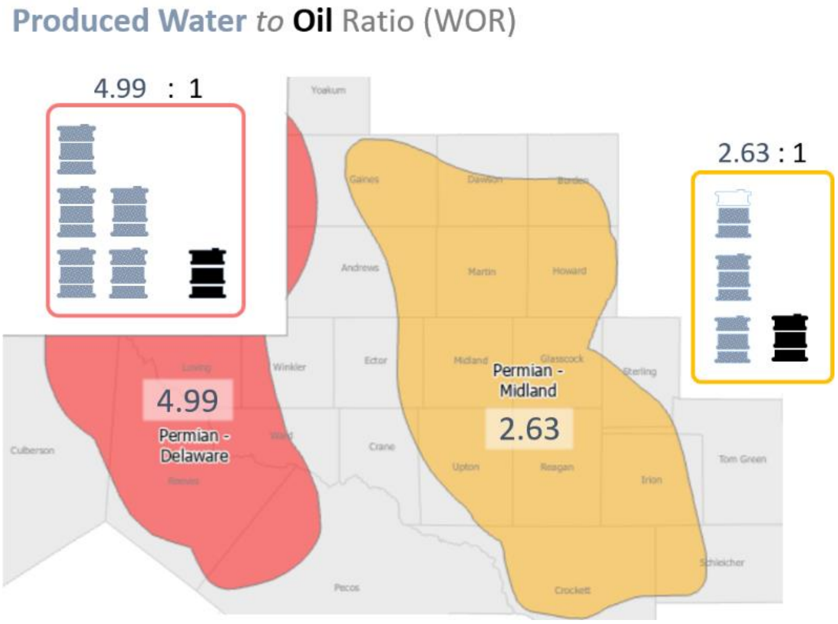

Figure 1. Produced Water to Oil Ratio (WOR), Permian Delaware and Midland Basins.

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[14] Lyons et.al., "Sustainable Produced Water Policy, Regulatory Framework, and Management in the Texas Oil and Natural Gas Industry: 2019 and Beyond," p. 6, 2019

[15] *Id.*

[16] Barclays, "The Water Challenge: Preserving a Global Resource," 2017, p. 23.

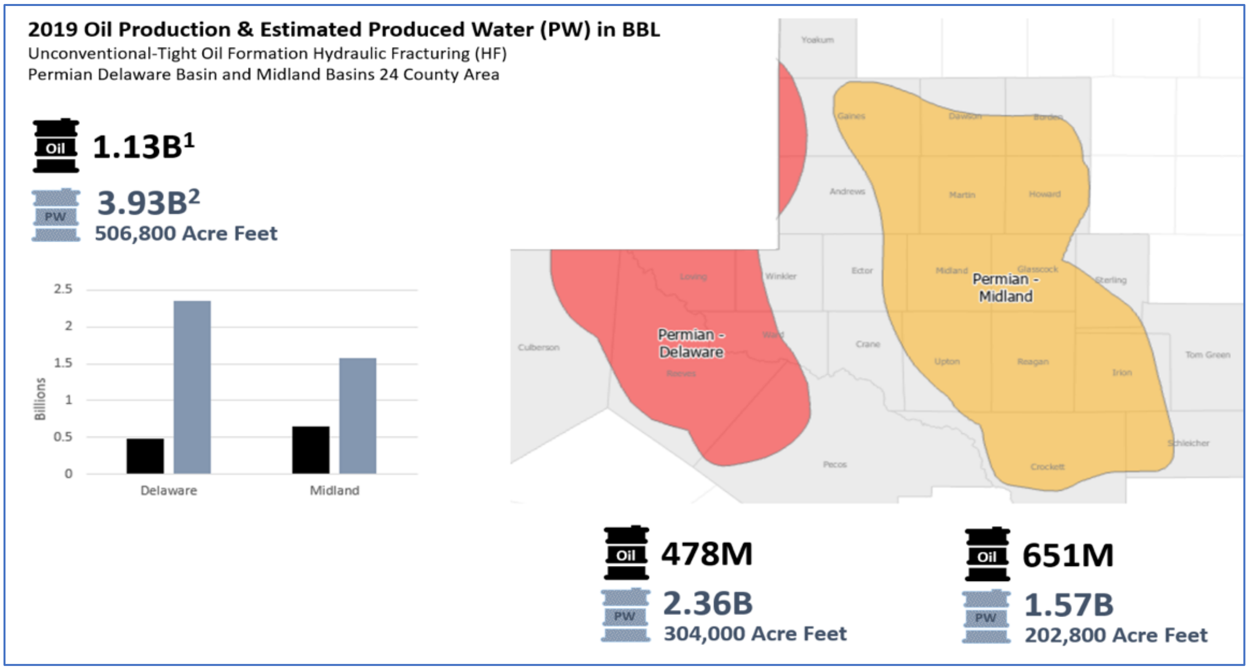
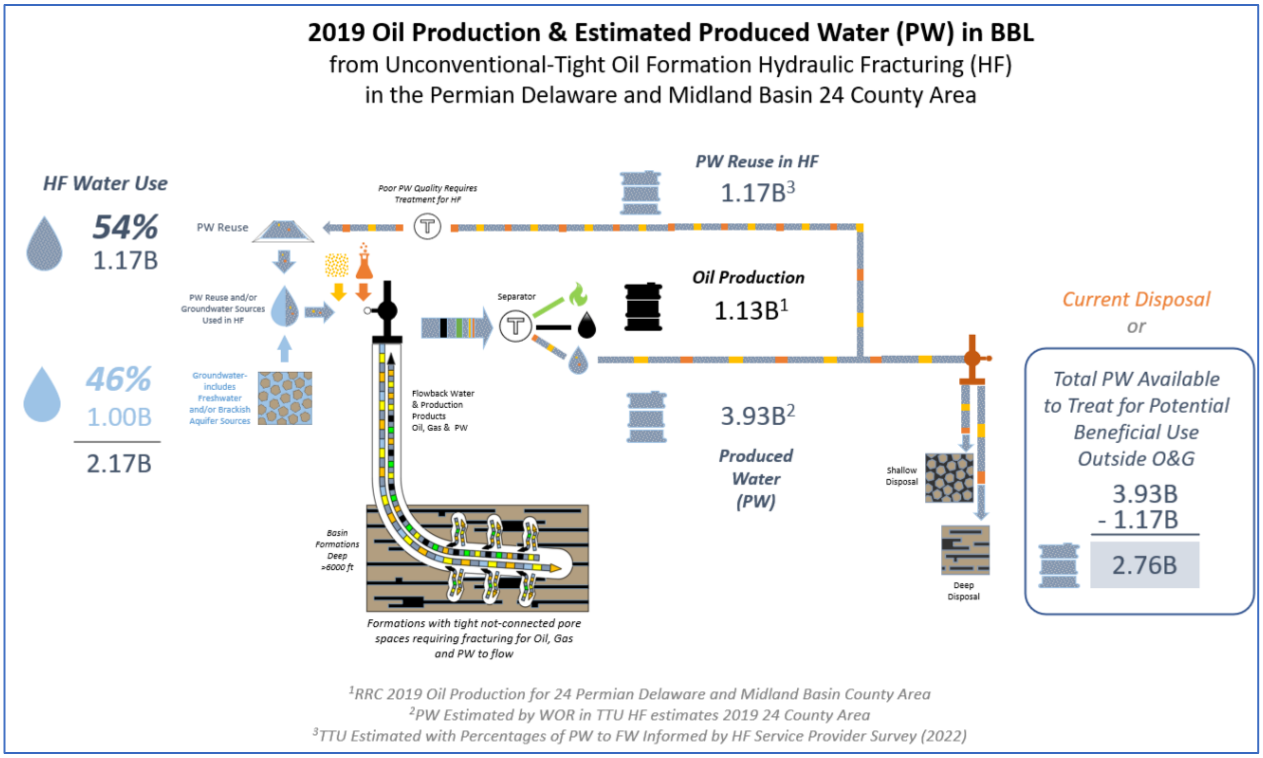

2019 Oil Production & Estimated Produced Water (PW) in BBL
Unconventional-Tight Oil Formation Hydraulic Fracturing (HF)
Permian Delaware Basin and Midland Basins 24 County Area

Figure 2. 2019 Annual Oil Production (Railroad Commission of Texas) and 2019 Estimated Produced Water in 24 County Area in the Permian, and by Delaware and Midland Basins.


2019 Oil Production & Estimated Produced Water (PW) in BBL
from Unconventional-Tight Oil Formation Hydraulic Fracturing (HF)
in the Permian Delaware and Midland Basin 24 County Area

[1] RRC 2019 Oil Production for 24 Permian Delaware and Midland Basin County Area
[2] PW Estimated by WOR in TTU HF estimates 2019 24 County Area
[3] TTU Estimated with Percentages of PW to FW Informed by HF Service Provider Survey (2022)

Figure 3. 2019 Oil Production (Railroad Commission of Texas), Estimated Produced Water (PW) Based on Water to Oil Ratio (WOR) in 24 County Area Permian Delaware and Midland Basins and PW to Groundwater Use for Hydraulic Fracturing (HF) (Survey of HF Service Providers by TxPWC).

Attempting to predict future volumes, the WOR for each county was then used with the reported oil production in each county, using historical and projected oil production volumes, to arrive at a projected average produced water volume over a 38-year horizon of 14MMbbl/day. After accounting for the produced water that is treated and reused by the oil and gas industry, the Consortium developed a 38-year average estimate of ~11MMbbl/day, 4Bbbl/year, or 511,000 ac-ft/year of excess produced water volumes available for beneficial reuse.

Technically Recoverable Volume

The annual excess projection above does not tell the whole story, unfortunately. There is an additional, highly variable piece that must be considered: the technically recoverable volume. There are many factors that may ultimately impact the exact volumes of produced water that are treated, including proximity to end users, transportation and storage logistics, treatment costs, etc. However, the extreme quantity paired with the high salinity of Permian produced water (120,000-130,000 mg/L on average) creates a particularly unique challenge for addressing the mineral byproduct of the treatment processes: put plainly, leftover salt concentrations may exceed manageable quantities under systems that favor high water recovery.

While the Consortium will continue to research treatment technologies that drive increased water recovery rates as it relates to managing these solid byproducts, the simplest approach currently would be to treat water to the point where the product water streams result in one potentially useable treated portion and one concentrated brine portion that would still be diverted to disposal or potentially reused for HF, typically water with a TDS range of 250,000-275,000 mg/L. Since raw Permian produced water, on average, is around 120,000-130,000 mg/L TDS, this means a recovery rate of around 50% treated produced water available for beneficial use.

Therefore, the Consortium’s projected average treated produced water volume available for beneficial use over the next 38 years is approximately 2Bbbl/year or 256,000 ac-ft/year. Put in perspective, the 2022 State Water Plan for Water Planning Region F (covering most of the Permian) indicates an average annual need (potential shortage) of 80,751 ac-ft/year over the next 50 years.

Are there technologies that can treat produced water to an adequate quality for beneficial use?

Just as there is a need for reliable produced water data, so too exists the need for more technology-specific information, particularly as it relates to treating produced water in the Permian Basin as public detailed information on produced water specific to basins/formations is limited at this time. Developing a better understanding of the characteristics of the produced water in a specific region of interest will be integral to achieving an economical and technologically feasible approach to treating produced water for beneficial use that is protective of public health and the environment.

There are several locations across the US that are treating produced water for beneficial use; the North Kern Water Supply District in Kern County, CA blends fresh water with treated produced water from wells that are not hydraulically fractured and uses this for irrigation.[17,18] Eureka Resources commercializes minerals extracted from treated produced water from the Marcellus Shale before discharging the treated effluent into the Susquehanna River in Pennsylvania.[19, 20] There have also been smaller and shorter-term projects in Colorado, Wyoming, and Oklahoma, where treated produced water has been treated and beneficially reused. However, as it has been previously stated and warrants reemphasis, produced water is not uniform in quality. At this time, the Consortium is not aware of any scalable operations treating produced water in the Permian Basin to a quality beyond that necessary for reuse in hydraulic fracturing, more commonly referred to as a "clean brine." Consortium members have unanimously indicated the need for such a facility to generate treated produced water samples that could be tested and analyzed to better understand Permian produced water and to determine achievable water qualities from various technologies in relation to basin-specific sources.

Technology Review

Given the minimal extent of existing operations and the realization that treatment energy costs will largely be driven by the need for desalinating Permian PW high in amounts of total dissolved solids (TDS), Consortium faculty turned to a similar but more developed body of existing treatment technology for comparison: seawater desalination. A list of potential technologies was developed with input from Consortium members that range in technology readiness levels[21] and include established and "novel" technologies to ensure the most efficient and economical technologies continue to be identified. Our goal in this report, however, was to focus on smaller group of promising technologies which could provide the most immediate ability to effectively treat produced water in a scalable and economical manner, and those technologies were as follows:

Reverse osmosis (RO)	Multi-stage flash evaporation (MSF)
Multi-effect distillation (MED)	Mechanical vapor compression (MVC)
Membrane distillation (MD)	

Each of these technologies has strengths and weaknesses in their approach to treating produced water; for instance, membrane-based high pressure reverse osmosis is among the most efficient and cost-effective methods for desalinating brackish water and seawater, but the pressure necessary to treat produced water potentially high in organic concentrations and TDS would likely result in membrane failure and scaling issues and has yet to be successfully

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[17] North Kern Water Supply District, "Produced Water," https://www.northkernwsd.com/produced-water/

[18] California Regional Water Quality Control Board et. al., Food Safety Project White Paper, https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/white_paper/foodsafety_whitepaper.pdf

[19] Eureka Resources, https://www.eureka-resources.com/

[20] Eureka Resources, https://www.eureka-resources.com/

[21] NASA, "Technology Readiness Level," https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

demonstrated. Alternatively, thermal-based processes such as multi-stage flash evaporation can yield high quality product water free of many constituents, but are energy-intensive as thermal processes rely on high temperatures for treatment.

The best approach to treating produced water will likely be a combination of several technologies in a treatment-train process that includes pre-treatment, treatment, post-treatment and polishing. Through pilot projects and ongoing member engagement (including leveraging synergies between the Texas and New Mexico Consortia) the Consortium will continue to evaluate these and other technologies to find the most advantageous treatment system for achieving beneficial use.

What set of pilot projects should the Consortium, with state participation, administer to provide proof-of-concept and begin establishing confidence in the ability to treat produced water for beneficial use?

Project Approach

Undertaking a series of pilot projects will be critical to answer concerns regarding technological capabilities, Permian produced water characteristics, and practical economic information in order to instill public confidence in the beneficial use of treated produced water. Based on these needs and utilizing the information developed for this report, the Consortium has developed two phases of pilot projects for consideration:

Phase 1: Immediate Focus

- Co-location of treatment technology in the Midland Basin at an existing produced water collection site, capable of treating a minimum inflow of 500 BBL/day, necessary to provide treated produced water samples for testing and analysis of constituent characterization and risk and toxicology assessment, and operational costs. Estimated operation: 3-6 months per technology, continuing thereafter as necessary.
- Co-location in the Delaware Basin at an existing produced water collection site, capable of treating a minimum inflow of 500 BBL/day, necessary to provide treated produced water samples for testing and analysis of constituent characterization and risk and toxicology assessment, and operational costs. Estimated operation: 3-6 months per technology, continuing thereafter as necessary.

Phase 2: Operated as Funding and Consortium Member Interest Allows

- Establish bench scale “plug-and-play” testing facility to focus on innovative technologies and treatment-train efficacy research.
- Site analysis of existing non-Texas based produced water treatment facilities.
- Contained and monitored application testing of treated produced water on native rangeland, cotton, and/or regional edible crops to further aid in overall system knowledge regarding human and environmental hazard and risk assessment.

Given Consortium membership desire to develop a better profile of target basin produced water characteristics and treatment capabilities, and the need to identify available, deployable, and scalable technologies (members have indicated that a system that can treat a minimum inflow of 500 barrels per day provides relative assurance of continued scalability), the Phase 1 projects are designed for exactly that purpose. They will also provide analysis of the economics related to their treatment processes as we continue working to develop an economic model for beneficial use. Phase 2 projects provide useful ongoing insight but are currently considered secondary-in-nature given the focus and will of Consortium members. It should also be noted that some members have currently objected to the Consortium operating field-scale application projects citing human health and environmental concerns, while other members have expressed a strong desire to build upon ongoing bench scale crop trials at other Universities and to move forward in conjunction with Phase 1 projects to aid in accelerating paths to beneficial use and help to establish regulatory certainty.

Formation of a request for proposals (RFP) for Phase 1 is already underway, developed upon the guidance of Consortium members and leveraging lessons learned from the New Mexico Produced Water Research Consortium in their pilot project process. The RFP process will likely occur in two parts: a location-based RFP to select volunteer sites with access to existing infrastructure and adequate amounts of produced water, and a technology-based RFP to select technology participants that can meet the specifications of the project need utilizing the infrastructure associated with the selected locations. The Consortium is currently working to have RFP's finalized by November 2022 and projects selected no later than Q2 2023 with start dates pending any state appropriation.

State Participation

Phase 1's focus on generating treated produced water samples will require significant capital for necessary testing and analysis. While we will develop a more accurate projection of the testing costs once members have agreed to the necessary testing and analyses protocols and established RFP's, the current estimated cost for testing is between $180,000-240,000 per project (depending on length of the project and frequency of testing), with that figure dropping over time as constituents are identified and/or ruled out. In attempting to have a minimum of two Phase 1 pilot projects, one in each of the Delaware and Midland Basins, this range is estimated at $362,000-480,000. Funding provided by the state would be a crucial element to this process and would also serve as an indication of the state's continued dedication to identifying and developing new water sources. Additional oversight of the testing process by the Consortium in conjunction with state agencies such as RRC and/or TCEQ would provide an extra layer of confidence and impartiality to the resulting findings.

What are the economics of treating produced water for beneficial use in a manner that is cost-effective, efficient, and protective of public health and the environment?

As practical economic data is derived from the pilot projects discussed above, the Consortium will use the data to continue building an economic model that provides a realistic expectation for the potential of beneficial use of treated produced water through leveraging several known and projected economic inputs. Detailed more in the pages that follow, there are several facets of a potential system of beneficial use that illustrate that, although treating produced water for beneficial use is not currently the most economical method, continued growth in technological efficiencies paired with external constraints such as water shortages and regulatory influences on produced water management could result in market forces that favor a system of beneficial use over other water management strategies.

Disposal vs. Treatment

As established earlier, injection in saltwater disposal (SWD) wells is currently the most prevalent method of managing produced water. As with managing any resource, companies operating in a free market will generally favor those methods that offer the lowest cost and highest reliability; currently that means disposal via injection or treating produced water to a clean brine standard for reuse in hydraulic fracturing and other completion operations. For disposal, literary sources indicate a range for baseline treatment and transportation to disposal of $.55/bbl using pipelines (most common) up to $1.81/bbl in instances when trucking is the only option.[22] Information provided by Consortium members provides a range of $.60-.70/bbl, further clarifying disposal as the most cost-effective method currently.

To be a viable option, treatment costs to achieve a water quality that is suitable for beneficial use and protective of public health and the environment will have to be competitive with the marginal cost of future disposal. Based on input from Consortium members, the targeted marginal treatment cost to be competitive with disposal in the near future needs to average $1/bbl. Depending on variable input costs such as natural gas for energy, members have indicated current assessments of treatment options average $2.55/bbl with some instances as high as $10/bbl.

Value of Water

Helping to balance out the extra cost for treatment is the prospect of selling treated produced water to end users outside of the oil & gas industry. As water markets continue to mature across the state, a clearer picture of the potential that exists for dealing in water trade will lend more credibility to an economic model.

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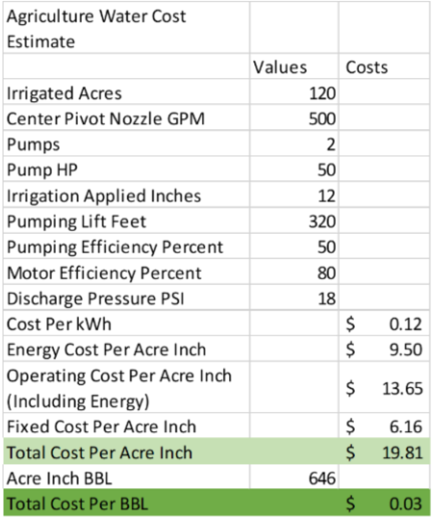
[22] Cooper et.al., “Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges” *ACS ES&T Engineering* 2022 *2* (3), 347-366.

Appendix C illustrates water demand projections from the 2022 State Water Plan for the 24-county area over the Delaware and Midland Basins. The state water plan spells out an undeniable truth: when it comes to water users in and around the Permian, irrigated agriculture tops all others over the next 50 years.[23] Analysis of water value for agriculture indicates a very low cost currently; since groundwater is a private property right, the cost to irrigate equates to the cost of the irrigation system, pump, energy, and maintenance costs required to pump groundwater from an aquifer well. For the summer of 2022 that value was estimated at approximately $.03/bbl.[24]



Agriculture Water Cost Estimate		
	Values	Costs
Irrigated Acres	120	
Center Pivot Nozzle GPM	500	
Pumps	2	
Pump HP	50	
Irrigation Applied Inches	12	
Pumping Lift Feet	320	
Pumping Efficiency Percent	50	
Motor Efficiency Percent	80	
Discharge Pressure PSI	18	
Cost Per kWh		$ 0.12
Energy Cost Per Acre Inch		$ 9.50
Operating Cost Per Acre Inch (Including Energy)		$ 13.65
Fixed Cost Per Acre Inch		$ 6.16
Total Cost Per Acre Inch		$ 19.81
Acre Inch BBL	646	
Total Cost Per BBL		$ 0.03

Table 1: Summer 2022 Estimated Cost Per BBL to Utilize Groundwater for Irrigated Agriculture

The regional plan for the 2022 state water plan from Region F (the TWDB region covering the majority of the Permian) included plans for almost 40 water supply projects spanning the next 50 years, most of which focused on developing groundwater resources. The average cost per barrel across those projects was $.20 while servicing the debt incurred for the project, dropping to $.05/bbl after debt service (calculated in today's dollars). External factors such as future aquifer conditions and potential water shortages could put upward pressure on this resource, however.

Another source of reliable economic data for projecting potential value is municipal water supply rates. In the absence of an established market, these rates can be utilized to illustrate the upper bounds of consumer willingness to pay, particularly for a potable water source. In a survey generated for municipal utilities across the state, respondents were asked to anonymously share their operating costs along with the rates charged to separate customer classes, including ag/irrigation, residential, commercial, and industrial. Of the responses received from Region F, utilities indicated an average cost per barrel of $.22 (treatment, distribution, and administration) while the average rate charged across all rate classes was $.40/bbl.

Other Factors of Consideration

Several other external factors can provide leverage for fostering a system of beneficial use of treated produced water, both voluntary and involuntary in nature. While the increased value of water under continued drought and future shortage conditions is difficult to project, demonstrating other scenarios such as production shut-in from disposal limitations can provide operators, midstream companies, and the state with the revenue implications that could result from a lack of urgency in finding solutions. Lastly, short-term state intervention through financing opportunities or incentives could make treatment options more viable as the overall system becomes more established, provided the pilot projects are successful.

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[23] Texas Water Development Board. "2022 State Water Plan: Water for Texas." (2022); https://www.twdb.texas.gov/waterplanning/swp/2022/docs/SWP22-Water-For-Texas.pdf .

[24] Estimate prepared by Dr. Phil Johnson using summer 2022 values, TTU Department of Agricultural and Applied Economics

Policy Recommendations

Establish a Fund for Pilot Project Testing Needs

The Consortium's approach to pilot projects detailed herein includes the necessity for lab-based testing and analysis of treated produced water. State participation in these projects is crucial to establishing confidence and fostering success, both in the pilot projects and in establishing the state's dedication to securing future resource adequacy.

Creation of a state-appropriated fund used to cover expenses related to the testing and analysis procedures accompanying pilot projects over the next 2 years would greatly assist in the success of these projects as envisioned in SB 601. Through consultation with Consortium members, testing for each project is expected to range from $180,000-240,000, with an anticipated minimum of 2 projects conducted in 2023 and as high as 5 conducted through the biennium ending in 2024, for a testing funding need of $1,000,000-1,200,000.

Require the Texas Produced Water Consortium to Submit a Report to the Legislature on the Status of Pilot Projects by December 31, 2024

Commensurate with the request for funding is a reciprocal need to report back to the state on the status of its potential ongoing investment, but more importantly on the findings of the pilot projects and potential for achieving beneficial use of treated produced water.
Although the Consortium will endeavor to publish and/or review ongoing research as a general function, the Legislature should specifically direct the Consortium to generate a follow-up report on the status of upcoming pilot projects by December 31, 2024, prior to the 89th Texas Legislative Session.

Encourage TWDB and Regional Planning Groups in Oil Producing Regions to Consider Produced Water in Regional Planning Water Supply Projects

If pilot projects are successful in providing proof-of-concept for treating produced water, the next steps to fostering this system involve larger scale planning for transportation and storage needs, likely requiring significant capital to achieve. All funding options will need to be considered, including one of the most prominent and successful water development programs Texas has ever created: the State Water Implementation Fund for Texas (SWIFT). In order to be eligible for SWIFT, however, applicants must be a political subdivision or a nonprofit water corporation and applying for funding for a project that was included in the most recent state water plan.

TWDB's state water planning efforts occur in 5-year cycles, with regional groups submitting their plans the year prior to release of the full state water plan before starting the cycle over. In each cycle the regional planning groups work to identify water supply projects to address their projected future shortages, while reviewing former projects to ensure they are still viable to meet their planning needs in a timely manner. Legislation in recent years has directed the groups to review their existing plans to identify feasibility of proposed projects, and work to update their plans if any projects are deemed infeasible.

While the need to access SWIFT funding for produced water treatment may or may not occur in the future, at a minimum, working with regional groups on the premise of new water resources and the potential need to recharge aquifers for meeting future needs is encouraged, sooner rather later.

RRC and TCEQ Should Consider Processes Necessary for Permitting Produced Water for Beneficial Uses

State agency engagement in the Consortium has been a critical component over the past year, and many challenges and opportunities were brought to light as it relates to jurisdictions and management of produced water regulation in Texas. Based on statute and input from agency participants, the Consortium's current understanding is that the Railroad Commission of Texas would have primacy over every facet of produced water regulation, except in instances of a discharge to surface water body in the state. Such discharges would be under the jurisdiction of TCEQ.

As beneficial use has yet to occur in the Permian, current RRC permitting has not yet considered scenarios of beneficial use (there is a narrowly applied land application permit process occurring in a different basin in south Texas). As pilot projects provide information on achievable qualities, RRC and TCEQ should remain engaged with the Consortium to leverage that information for the benefit of potential future permitting.

There are also unique scenarios that may arise in the course of using treated produced water outside of the oil & gas industry that will require the two agencies to more clearly define their roles of oversight and interaction. For instance, a question of jurisdiction could occur if treated produced water permitted by RRC were sold to a manufacturing or power generation facility that had existing air emission or water discharge permits through TCEQ that had not accounted for the new influent treated produced water stream in their original emission/discharge permit.

In addition to the work that has been done to engage RRC and TCEQ on their authorities for managing extracted water, TXPWC will continue to engage stakeholders that would be the theoretical "receivers" of treated produced water to help identify and engage the regulatory bodies or industry standard developers impacted. This includes agricultural, construction, or industry related trades or organizations among others.

Member Feedback and Future Issues

Many issues pertinent to the future of treating produced water for beneficial use arose over the course of the Consortium's research, and still more are to come. Members were asked to rate their stance on many member-generated topics in a survey by "agreeing," "agreeing with modifications," "disagreeing and proposing an alternative," or "cannot respond based on expertise or knowledge," which followed by asking the members to relay further input or data on each specific topic to help progress the Consortium's research. Utilizing the input of the 29 respondents, some of those issues have been detailed below while other topics are specifically called out in sections throughout this report. These topics likely warrant further discussion and investigation by the Consortium if pilot projects are able to prove that it is possible to treat Permian produced water to a beneficial use quality.

Further Regulatory Clarification

In addition to the need for future permitting consideration, Consortium members detailed many other areas of regulatory clarification that may need to be considered for beneficial use to become more of a reality. Like many topics of consideration, some members indicated it was too premature to discuss this issue in detail prior to having a more developed understanding of produced water, its constituents, technology capabilities, etc., and members detailed the need to develop specific standards for recommendation to regulatory agencies to ensure regulatory certainty above all. In particular, some members indicated first the need to complete an environmental and human health risk assessment framework (detailed in Appendix F) as well as further analyzing the Produced Water Treatment and solid waste stream practices currently under EPA/TCEQ jurisdiction, some members desired more clarity regarding aquifer storage and recharge (ASR) and surface discharge, while others desired increased regulatory oversight of beneficial uses by TCEQ as opposed to the current structure given their experience with reclaimed water. There were also comments directed at further exploring what impacts, if any, might occur to the Resource Conservation and Recovery Act (RCRA) exemption from treating and beneficially using produced water, as well as increasing engagement of the beneficial user groups themselves to aid in developing water quality standard recommendations. Still other members advocated for one regulatory agency of jurisdiction, or at minimum increased sharing of information and resources between agencies (again, aiding in regulatory certainty).

Given the many unique perspectives in the Consortium it is understandable to have several informed but varying ideas on topics like this, and we will continue working towards consensus driven recommendations that may help guide future legislative and regulatory actions.

Ensuring Technical Resources for State Agencies to Evaluate and Establish Standards

Consortium members showed unanimous interest in ensuring that state agencies have sufficient technical resources to evaluate water quality and establish treatment and effluent standards. Many members supported the continued efforts of this Consortium to help arrive at recommended guidance, and some suggestions included looking specifically to other states who have already developed beneficial use standards to learn from and build upon those approaches. Some members outlined that developing standards and maintaining ongoing oversight of beneficial use would require dedicated personnel, so some combination of increased FTE’s and funding to contract with third-party facilities would be critical to the future of this system. Ideas for funding included legislative appropriation as well as voluntary approaches to industry supported funding opportunities.

Policy Frameworks to Address Liability Throughout the Supply Chain

To facilitate treatment of produced water and subsequent beneficial reuse and establish clear lines of custody transfer and liability allocation, members were asked to develop feedback on policy frameworks addressing liability throughout the supply chain. Providing liability limitations for surface/landowners once water has been legally severed and an emphasis on current custody transfer process/liability following only the recipient/physical possessor of treated produced water were among the feedback received. Some members sought delineation between approaches resembling that of RCRA (generator retains liability) and the Clean Water Act (liability transfers with custody), while others indicated that Texas' mudwork framework provides a clear depiction of how waste product liability transfer could be modeled. Other members felt that liability through the supply chain should not be modified unless/until end users have a comprehensive understanding of produced water and the risks and responsibilities associated with its use, and one suggestion was that there should be liability relief once permit parameters are achieved and "purified" water is discharged into a water of the state/US.

Reporting Volumes, Licensed Buyers and Sellers, and Technical Test Results

Another potential topic Consortium members brought forward was a system of reporting on volumes, licensed buyers and sellers, and pre-defined specifications of technical test results. When asked if they agreed with the concept of this type of reporting, 62% of respondents agreed, 10% agreed with some modifications, and 7% disagreed. A number of potential approaches and examples were provided as areas of further consideration, including looking to Pennsylvania's regulatory reporting/tracking and New Mexico's OCD Water Use Report, along with the current structure of reporting associated with wastewater treatment permits. Member ideas also included reporting volumes of produced water and disposal volumes monthly rather than the annual reports currently required, focusing regulatory mandates on agricultural use rather than transactions between industrial users, downstream monitoring and auto-shutdown systems to prevent accidental discharge, requiring single-source tracking to eliminate multiple reporting requirements (i.e. only through the treatment facility), and reporting on transaction volumes, final dispositions, analytical results and transfer chain of water, among others.

Conclusion

The Consortium's current projected recoverable produced water volume, at an estimated 256,000 ac-ft/year in the Permian, represents a significant opportunity for a potential new water source. At this time, we believe the significant amount of produced water in the Permian Basin paired with current disposal issues and future projected regional water needs provides more than enough incentive for both industry and the state to keep working together on a system of treatment and beneficial reuse of produced water. Evidence also exists that treating produced water for beneficial use is occurring in other states, but would require demonstration in the Permian to warrant further confidence and ensure the unique characteristics of that basin are considered and economically viable.

To that end, pilot projects will be extremely valuable in providing treated water samples for testing and analysis on a regional basis, with an immediate focus on the Delaware and Midland Basins. This testing and analysis is necessary to derive a more definitive answer on different technology's abilities to treat water characteristics that can vary spatially and temporally across Texas to a level that poses no risk to human or environmental health. Economic data from pilot projects will also take our collective knowledge from the theoretical to the substantiated and allow the Consortium to identify areas where innovation can help make treating produced water for beneficial use a sustainable, cost-effective, and more resilient water resource management strategy in the arid Southwest.

Source of Produced Water and Scope of Study

Source of Produced Water

The focus of this study is on produced water generated from tight oil wells in the Permian Basin (see Appendix A). It must be noted that in this study, the Permian Basin area is represented by 3 Texas state districts: “7C”, “8”, and “8A” (Appendix D).

The sources of Produced Water are grouped into 2 main categories:

- Conventional: most conventional wells in the Permian Basin are typically vertical and typically involve secondary or tertiary oil recovery.
- Unconventional (Tight Oil): Tight/low-permeability formations developed with primarily horizontal wells. We also considered vertical wells in tight oil as well. In this report, they’re interchangeably referred to as “unconventional” or “tight oil”.

Daily water production from these 2 source categories, along with daily total oil production, is shown in Figure 4 between 2014 and 2021 (data from Enverus**)**. We can note that water production from conventional wells has been gradually decreasing between 2014 and 2021, while production from tight oil wells has dramatically increased reaching its peak in 2019. This study does not consider conventional wells’ water production because it is largely reinjected in EOR projects. And not available for treatment and utilization discussed later in the report. The total oil production curve seems very similar to the change in tight-oil water production, suggesting that tight oil wells account for most of the oil production (which is actually the case: 90% between 2018 and 2021). We excluded vertical tight oil wells in our produced water forecast (later in this report) in order to deliver a more accurate amount of produced water available for treatment. It was easier to search, and separate production based on well type, in this case, horizontal versus vertical. Most, if not all, tight oil vertical wells are located in Midland and Delaware basin Trend Area fields designated by the Railroad Commission of Texas (RRC). These wells have been termed as Wolfberry, Wolfbone and Spraberry.

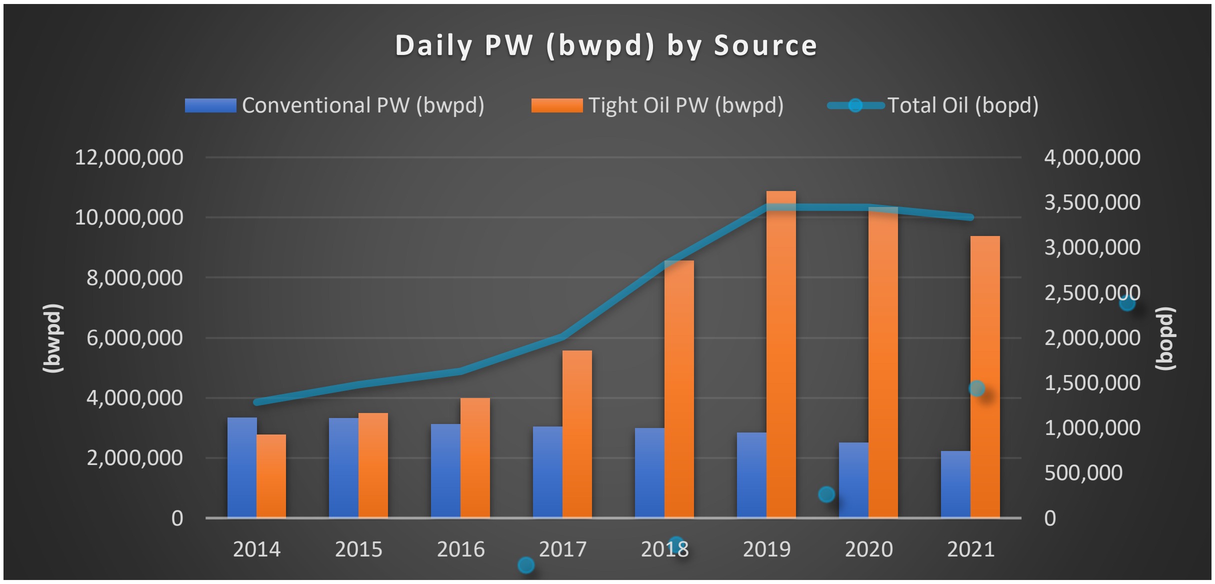


Figure 4. Daily Produced Water, sorted by Source, and Total Oil Production, 2014-2021, Permian Basin (Enverus).

Water Injection Types

We assessed injection, as reported to the state, in order to assess the produced water calculated by Enverus. This is due to the fact Texas does not require water production volumes to be reported. As documented by the RRC, the Underground Injection Control (UIC) specifies 3 main types of injection for water in the oilfield, as listed below:

- Type 1: Disposal into a nonproductive zone (W-14).
- Type 2: Disposal into a productive zone (H-1).
- Type 3: Secondary or Tertiary Recovery.

Targeting Disposal Wells

The purpose of the TXPWC is to find a beneficial use for volumes of produced water. We have not considered volumes used for "Type 3" injection since oil recovery (secondary and tertiary) projects are already utilizing most, if not all, of that volume. Thus, we only assessed wells where produced water volumes are to be injected into disposal wells ("Type 1" and "Type 2). Injection volumes for all three type injection wells are shown in Figure 5. As a side note, volumes in Type 3 are made up of produced water from the various EOR projects plus the makeup water volumes. EOR projects require make up water due to the losses of water injected into the target producing zone plus to make up for the volume of oil produced. In other words, EOR project injection should equal total production of oil, gas and water. We acknowledge that there is nearly a threefold difference in the amount produced versus injected in Type 3 injection wells. Our best explanation is inaccuracies in test reported, or lack thereof, in EOR projects.

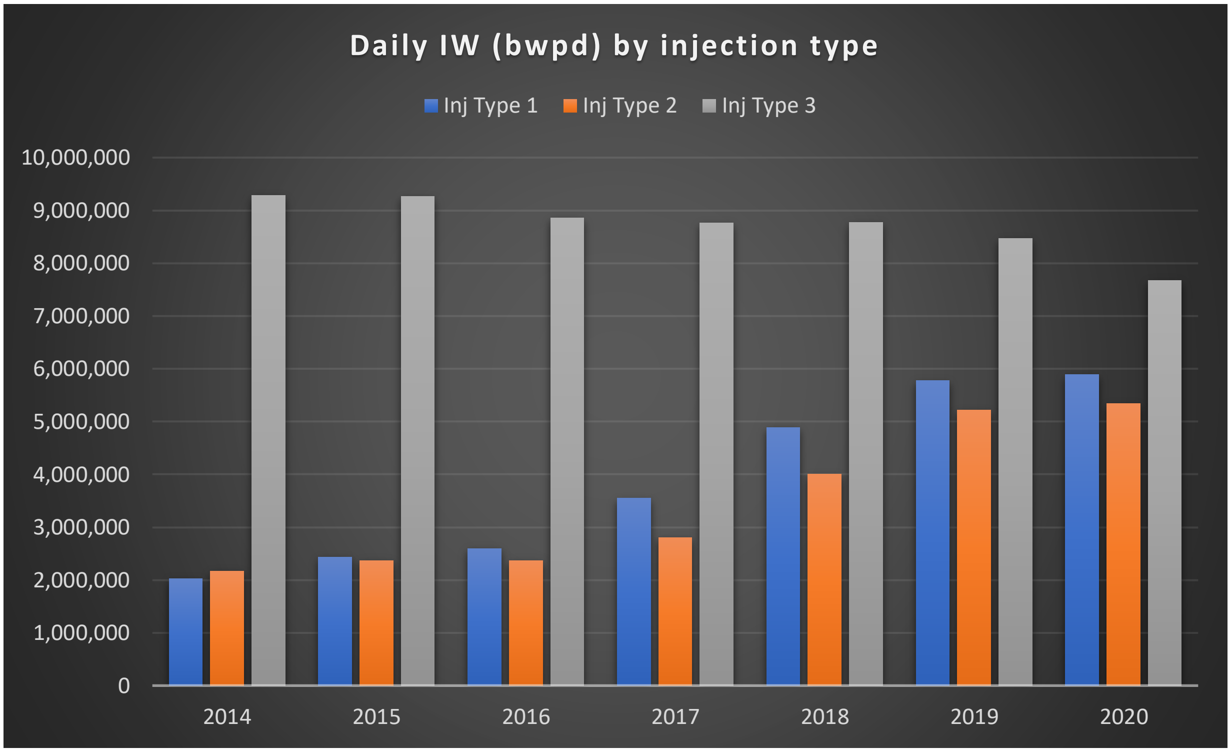


Figure 5. Daily injected water, sorted by injection well type, 2014-2020, Permian Basin (Railroad Commission of Texas).

It is assumed in this study that oil recovery is mostly used in fields with conventional vertical wells. The main interest of TXPWC in this type of field would be assessing the volumes of freshwater (FW) used as makeup water in recovery methods. To conserve FW, we would desire to replace these volumes with produced water. Assuming injected freshwater (from H-10 reports) is only used for oil recovery, the contribution of freshwater towards makeup water has shown to be around 2.8% between 2014 and 2020 (Figure 6). Also, reported freshwater injection seems to be significant in only 4 main counties that contributed to 92% of total injection between 2014 and 2020 (Figure 7).

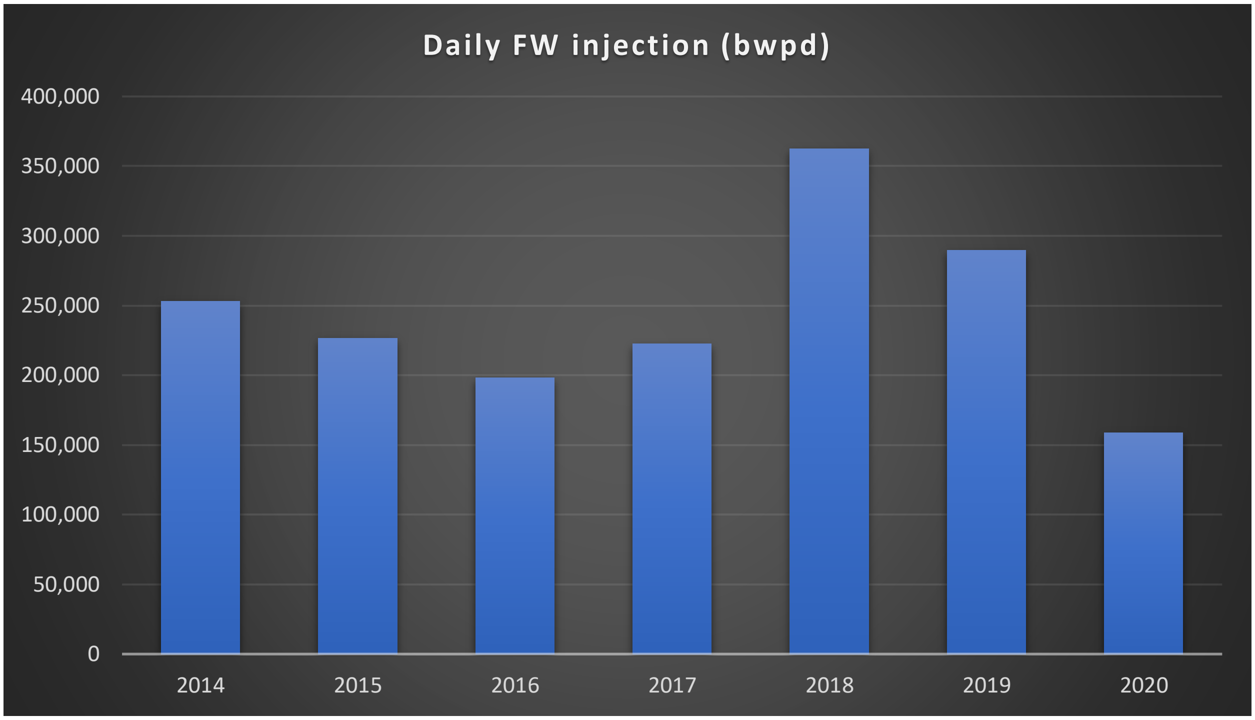


Figure 6. Daily freshwater injection, 2014-2020, Permian Basin (Railroad Commission of Texas).

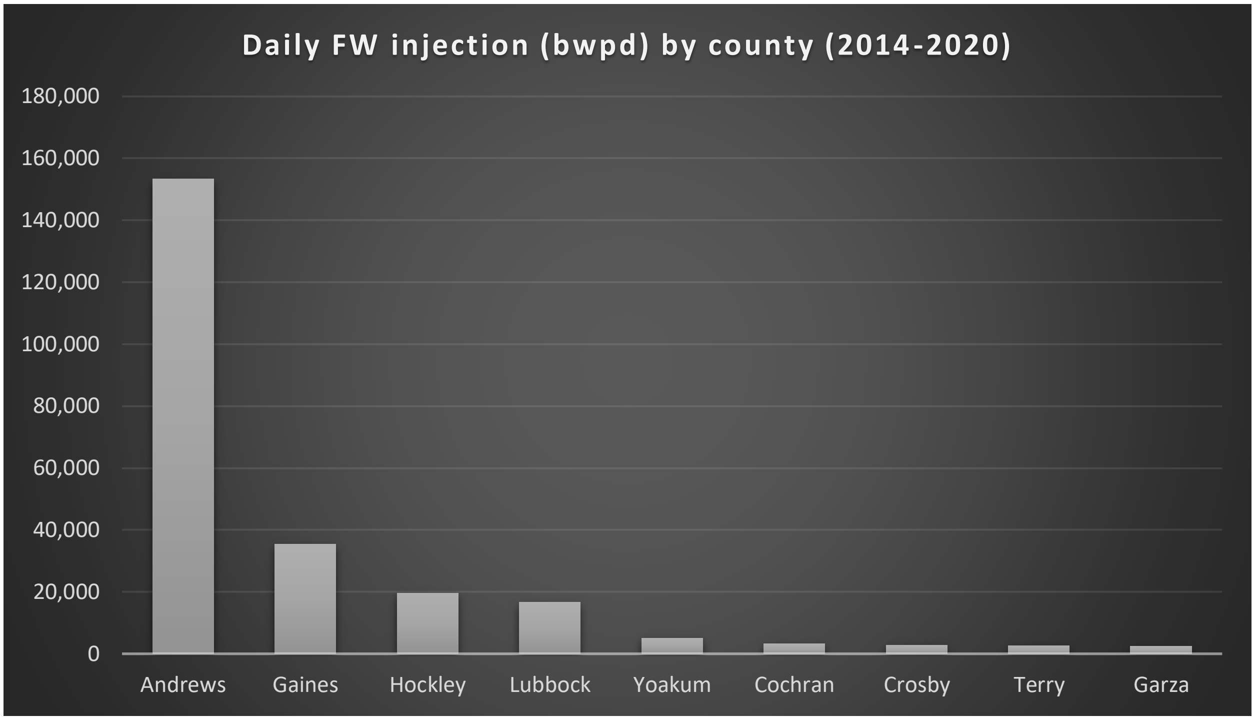


Figure 7. Daily freshwater injection, sorted by county, 2014-2020 (Railroad Commission of Texas). The displayed counties contributed to 98.6% of total freshwater injection in the Permian Basin.

Produced Water from Tight Oil Wells

Water production, as reported by Enverus, is calculated rather than a measured value. The calculated water volume is based on an annual well test, reported by the operator to the Railroad Commission of Texas. This is done by taking the measured 24-hour oil and water rates and calculating a water-oil ratio (WOR). The RRC gets a once a year well test which Enverus calculates a WOR for each well. The RRC also gets monthly oil and gas production on a lease basis for oil wells which, Enverus allocates oil back to each well on the lease based on annual test. Finally, Enverus then calculates monthly water production on a well-by-well basis based on the test calculated WOR. This method may result in an error in the calculated volumes since the WOR might not remain constant all throughout a year. As for injection, volumes are reported monthly and measured, and not calculated. We believe that the calculated volumes of water are reliable for use in our study. This is based on the injection-production comparison shown in Figures 8 and 9. As shown in Figure 8, water production from tight oil wells only is relatively similar to and trends the same as water injection into disposal wells (Types 1 & 2). As horizontal tight oil wells became dominant in 2018 (Figure 4), the difference between production and injection volumes becomes insignificant for the purpose of our study. Additionally, based on the foregoing statement, we assessed production and injection volumes on a county basis for the period of 2018 through 2020. As shown in Figure 9, the volumes reasonably match in the major tight-oil-producing counties. Injection may include water produced from New Mexico but, we are unable to assess that volume from the RRC.

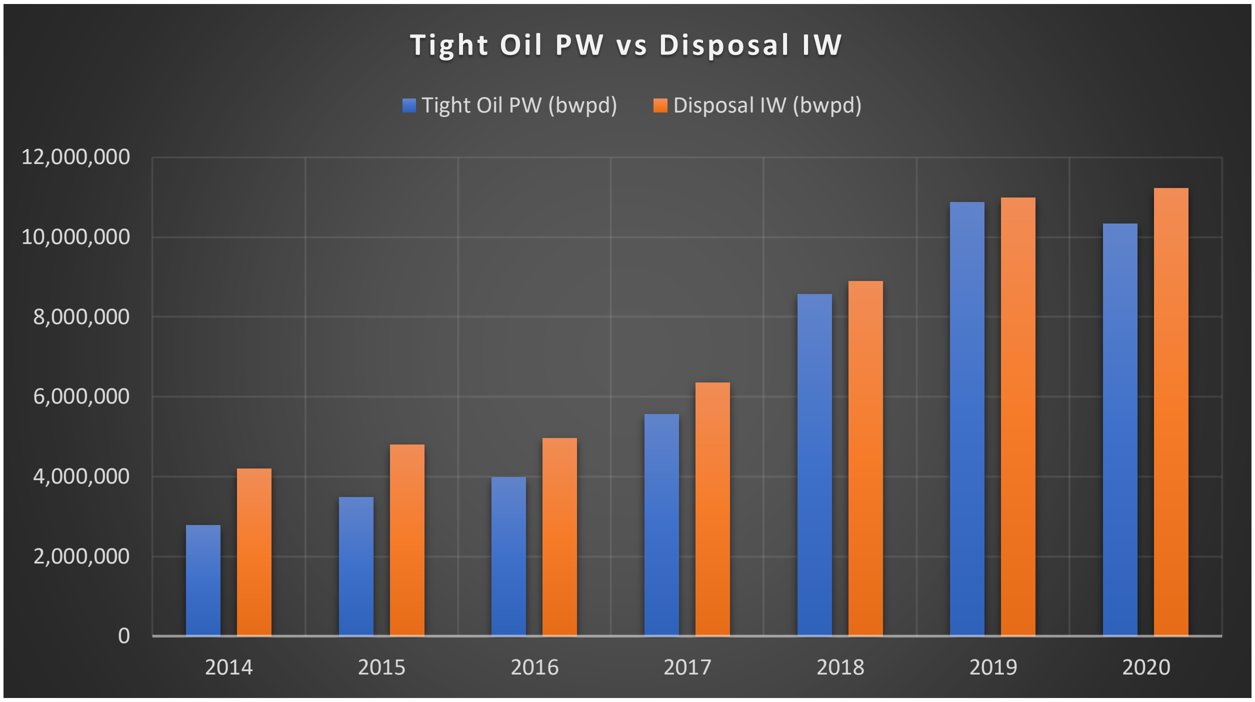


Figure 8. Water production from tight oil wells (Enverus) vs Water injection into disposal wells (Railroad Commission of Texas), 2014-2020, Permian Basin.

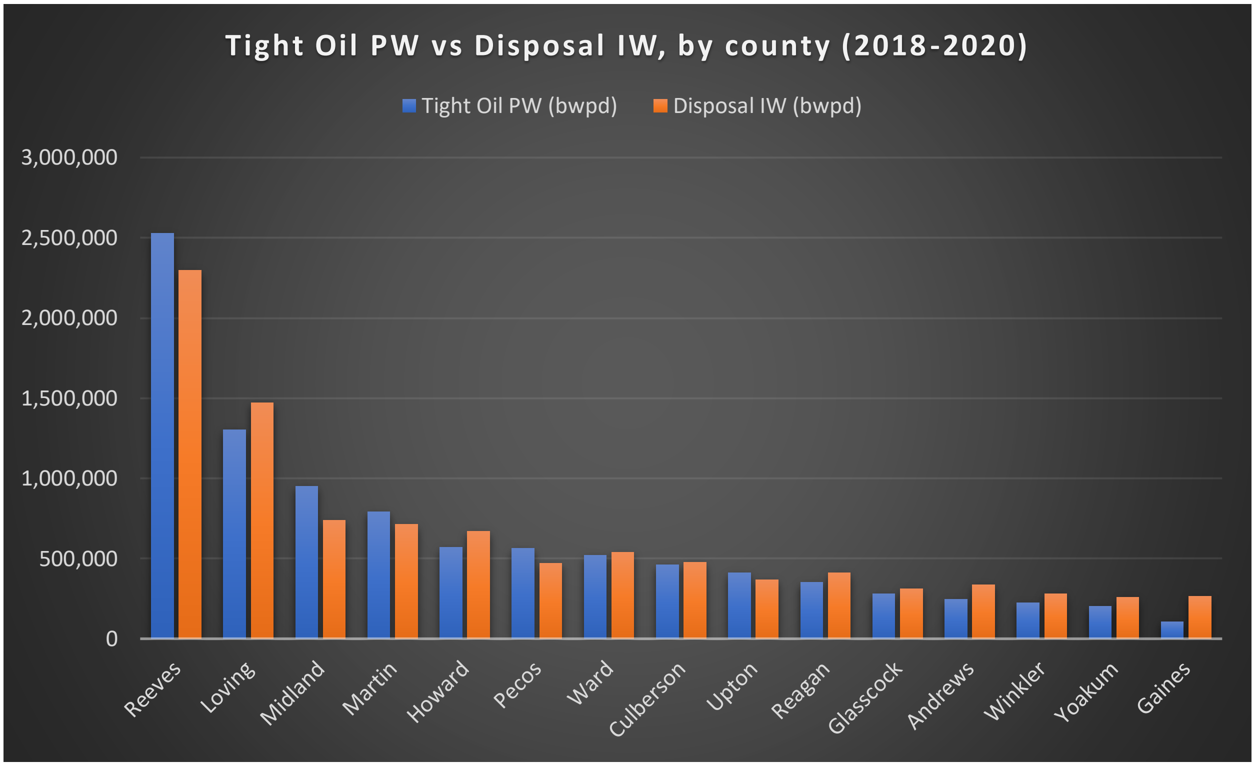


Figure 9. Water production from tight oil wells (Enverus) vs Water injection into disposal wells (Railroad Commission of Texas), 2018-2020, Permian Basin, sorted by county (the displayed counties contribute to 95% of water production).

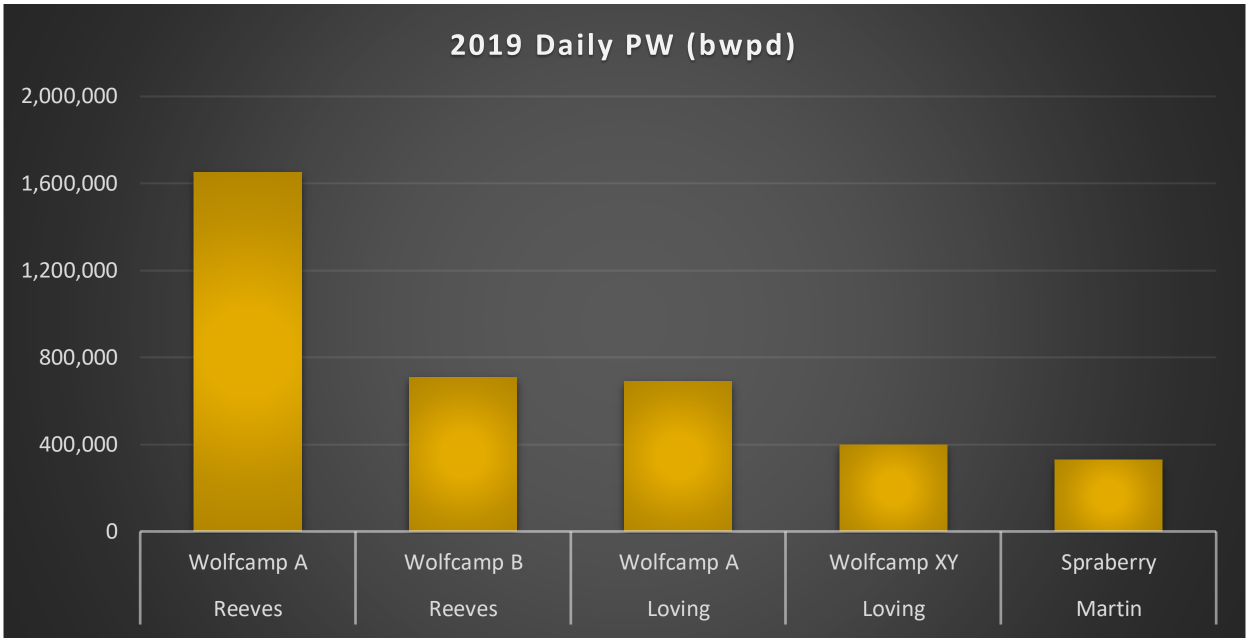


Figure 10. Major water producing sources from tight oil formations and counties in 2019 (Enverus). Displayed sources contribute to 35% of the total water production.

Due to the covid-19 pandemic, the production numbers had dropped in 2020 and 2021. Thus, we assumed that the 2019 production numbers are representative of the current/near-future production. The major water-producing counties and formations in 2019 can be seen, respectively in Figures 11 and 12. The chart in Figure 13 displays the major tight oil sources contributing to 80% of water production. Each source is defined by county, formation and daily water production in **Error! Reference source not found.**.

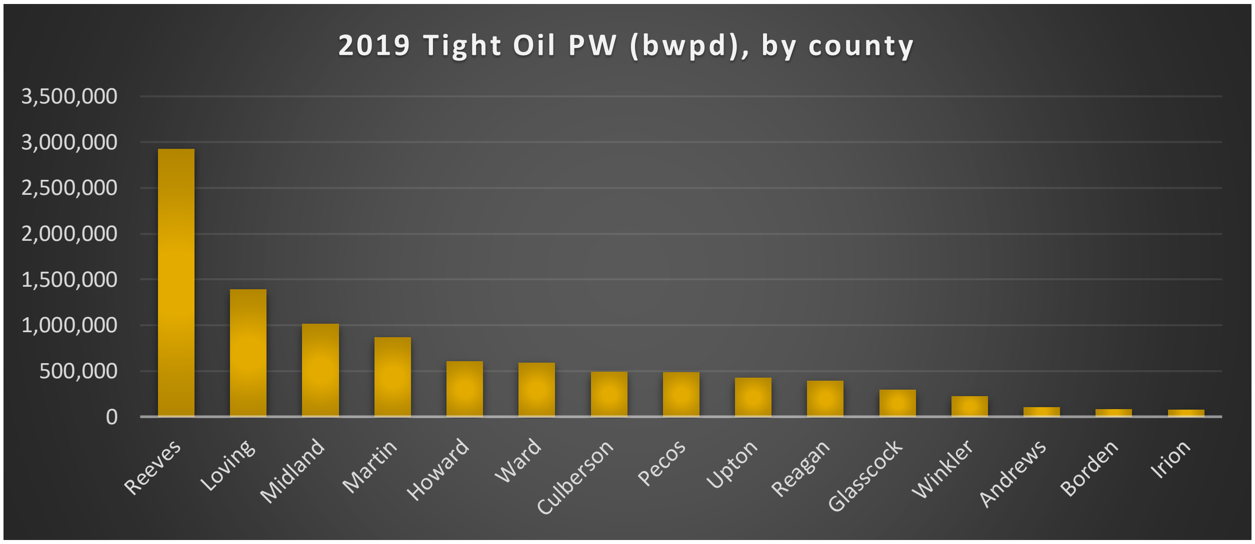


Figure 11. Water production from tight oil wells (Enverus) in 2019, Permian Basin, sorted by county (the displayed counties contribute to 91% of water production).

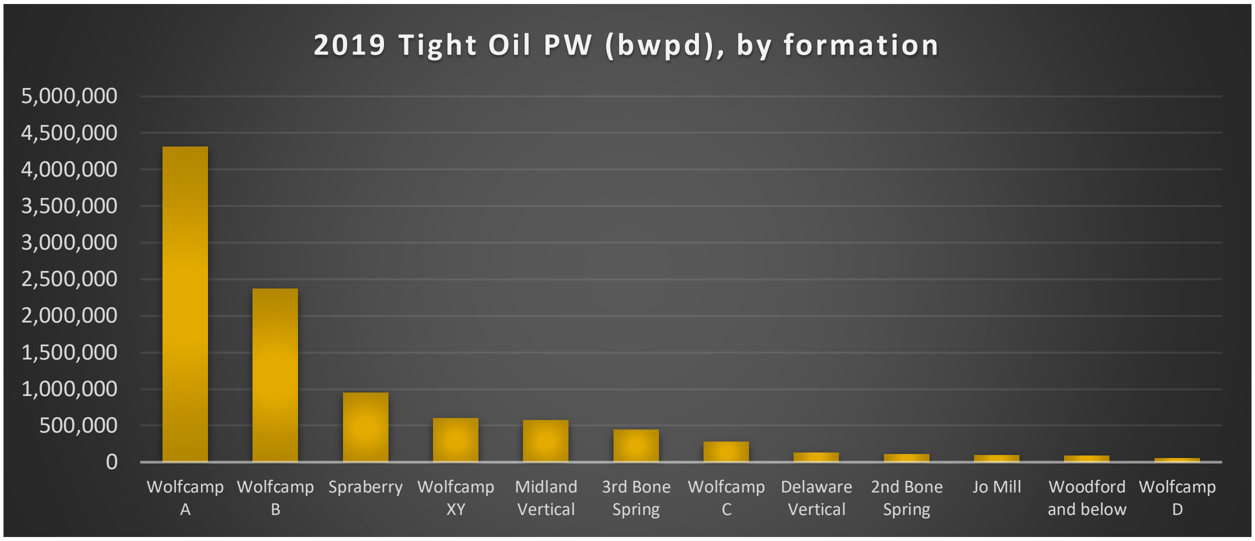


Figure 12. Water production from tight oil wells (Enverus) in 2019, Permian Basin, sorted by formation (the displayed counties contribute to 92% of water production).

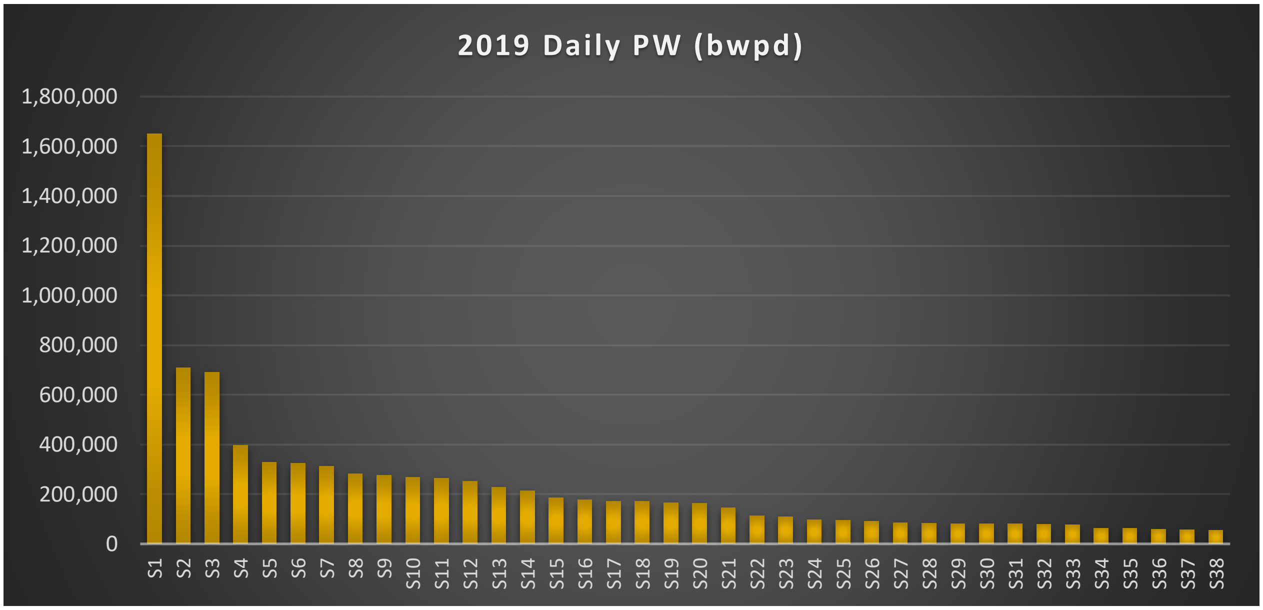


Figure 13. Water production from tight oil formations in different counties in 2019 (displayed data represents 80% of the total production). Sources S1 through S38 are described in ***Error! Reference source not found.****.*

Table 2: Water production from tight oil formations in different counties (displayed data represents 80% of the total production). Source: Enverus.

Source	County	Formation	2019 Daily PW (bwpd)
S1	Reeves	Wolfcamp A	1,651,128
S2	Reeves	Wolfcamp B	709,583
S3	Loving	Wolfcamp A	691,675
S4	Loving	Wolfcamp XY	397,640
S5	Martin	Spraberry	329,169
S6	Midland	Wolfcamp B	323,832
S7	Howard	Wolfcamp A	313,132
S8	Ward	Wolfcamp A	282,652
S9	Culberson	Wolfcamp A	275,479
S10	Midland	Spraberry	269,189
S11	Upton	Wolfcamp B	264,099
S12	Midland	Wolfcamp A	252,899
S13	Reagan	Wolfcamp B	228,851
S14	Pecos	Wolfcamp A	214,785
S15	Howard	Spraberry	185,785
S16	Martin	Wolfcamp B	177,367
S17	Reeves	3rd Bone Spring	172,154
S18	Martin	Wolfcamp A	171,834
S19	Ward	Wolfcamp B	165,232
S20	Reeves	Wolfcamp XY	162,582
S21	Glasscock	Wolfcamp A	144,912
S22	Pecos	Wolfcamp B	113,237
S23	Loving	3rd Bone Spring	109,739
S24	Reagan	Wolfcamp A	97,009
S25	Martin	Midland Vertical	95,515
S26	Midland	Midland Vertical	91,574
S27	Loving	Wolfcamp B	84,793
S28	Winkler	Wolfcamp A	82,253
S29	Reeves	Woodford and below	81,623
S30	Winkler	Wolfcamp B	81,312
S31	Culberson	Wolfcamp C	81,082
S32	Reeves	Wolfcamp C	80,046
S33	Ward	3rd Bone Spring	76,910
S34	Culberson	Wolfcamp B	63,160
S35	Borden	Wolfcamp A	62,572
S36	Glasscock	Wolfcamp B	58,377
S37	Irion	Wolfcamp B	57,299
S38	Martin	Jo Mill	55,118

Produced Water Reuse for Hydraulic Fracturing

The purpose of this section is to assess how much produced water (PW) is used for hydraulic fracturing in the Permian Basin. This was accomplished by sending out a survey to all the known fracturing service providers active in the Permian Basin. The use of PW for fracturing is a choice made by the operator, not the service company. Based on our survey, we estimate that roughly 54% of the water used for fracturing is PW. The results of our survey are as follows:

Total Jobs Reported per Month (Job Count):	347 jobs
Average Water Volume per Job:	521,497 bbls/job
Monthly Water Pumped:	180,953,341 bbls
Percentage of jobs using FW:	46%
Percentage of jobs using PW:	54%
Average Daily use of FW:	2,703,232 bbls/day
Average Daily use of PW:	3,229,664 bbls/day

A "job" is all the fracturing treatments on one horizontal well. One well may have 20 to 100 stages of fracturing treatments. The survey represents the use of FW and PW in a particular frac job. This does not imply that the 2 types are mixed as jobs are done with either all FW or all PW.
We believe that the survey represents a super majority of the jobs being pumped (greater than 90%) in the Permian Basin. This is based on the combination of rig count and the average number of days to drill a well, which gives an estimate of 340 drilled wells per month. The survey also matches closely with frac job data reported by Enverus (Figure 14), when comparing Total Jobs Reported per Month and Monthly Water Pumped.

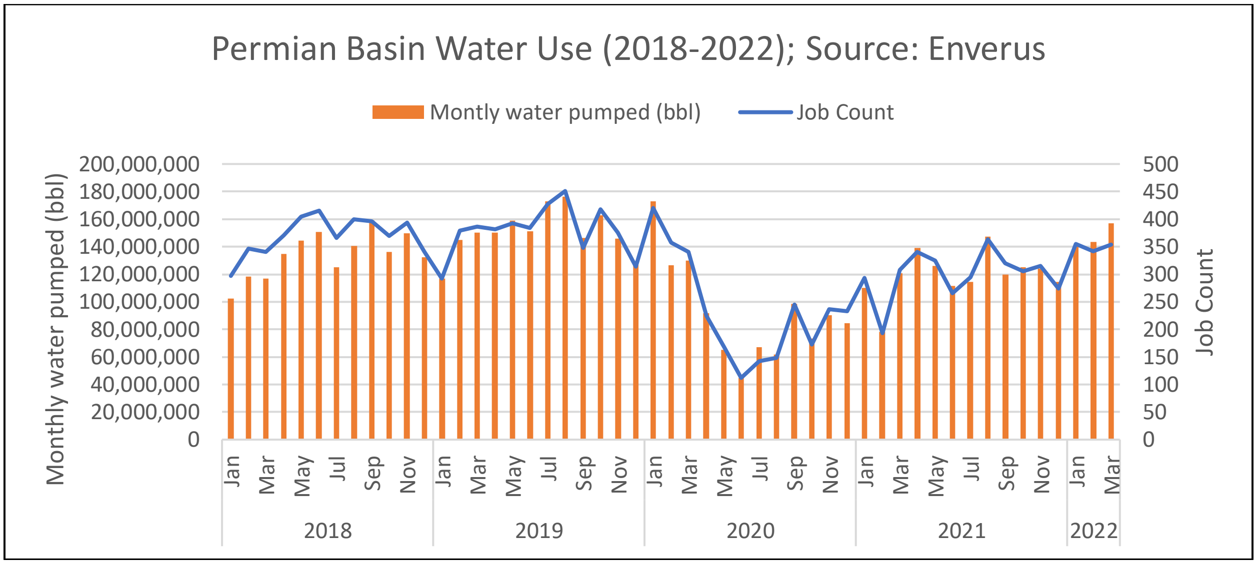


Figure 14. Frac Job Data reported by Enverus (January 2018 through March 2022)

Produced Water Projection

The main goal of this section is to forecast water production in oil-producing RRC districts 8, 8A, and 7C (see Appendix D) at the County levels for an economic evaluation. We have only accessed future development in the basin areas where tight oil is been developed or drilled. In addition, only existing horizontal production is included in the projection. We did not include conventional production, which was primarily waterfloods, nor did we include tight oil vertical wells because tight oil vertical production is no longer significant. This is because drilling of tight oil vertical wells has fallen drastically since 2017 and the volume of the production from the existing vertical tight oil wells is insignificant i.e., about 5.4% of produced water volume as of 2020 and falling. Therefore, the forecast includes only tight oil horizontal wells.

Generally, water production is tied to hydrocarbon production; hence the production projection methodology covers the oil, gas, and water forecast. Projected water production, which covers both the current wells and future wells was based on decline curve analysis (Arp's equation). Arp’s equation is an industry-accepted practice used to estimate future production. It is a function of initial production rates and Arp’s parameters – which are the initial nominal decline rate Di and b-factor. These parameters are determined from the production data trend of a well, reservoir, or field. The initial decline rate is the initial steepness (or rate of decline) at the beginning of production of the curve while the b-factor determines the rate at which the decline rate deteriorates (or reduces in value with time). In other words, the rate of a well may fall 80% in the first year from 1000 to 200 BOPD, but in the second year on fall 40% from 200 to 120 BOPD. And in the third decline at 30% and so on. Type curves were generated for each county based on their production history and Arp’s parameter determined. Future wells production projection is based on these Arp’s parameters generated from the type curves. Figures 15 and 16 show the oil and water production forecast for all existing tight horizontal wells and future drilling in tight formations. At a maximum annual rate of 4.3MMbbl/D of oil, and 14.1MMBBL/D of water, the cumulative production predicted over 38 years is 45.2Bbbl and 145Bbbl respectively.

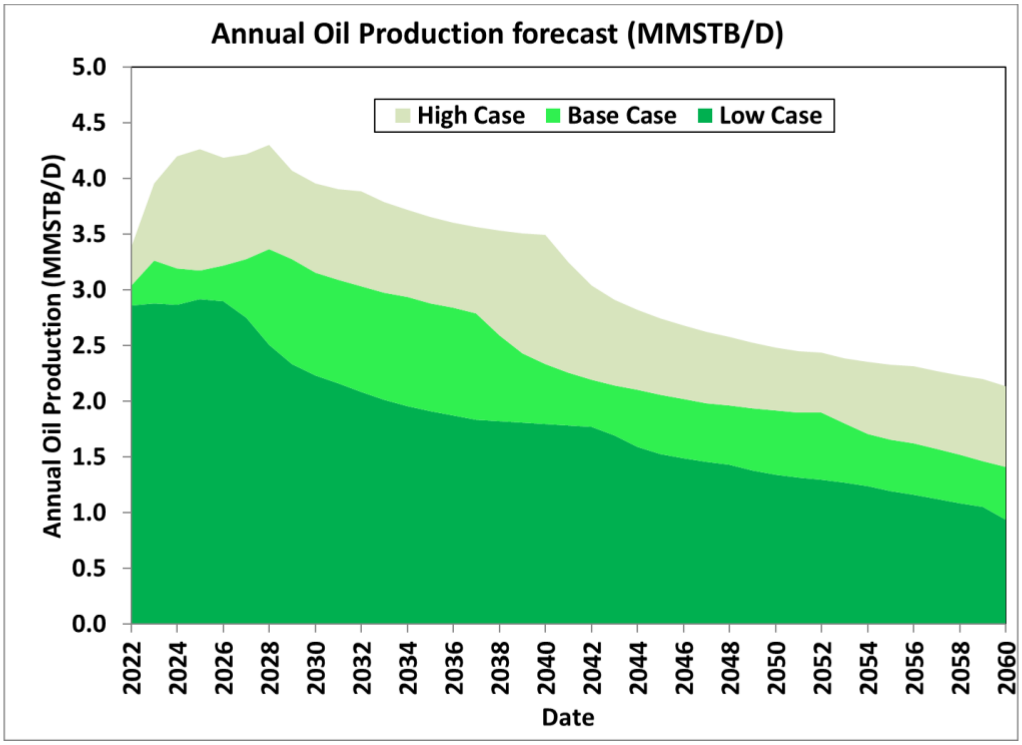


Figure 15: Annual Oil Production Forecast for Districts 8, 8A, and 7C.

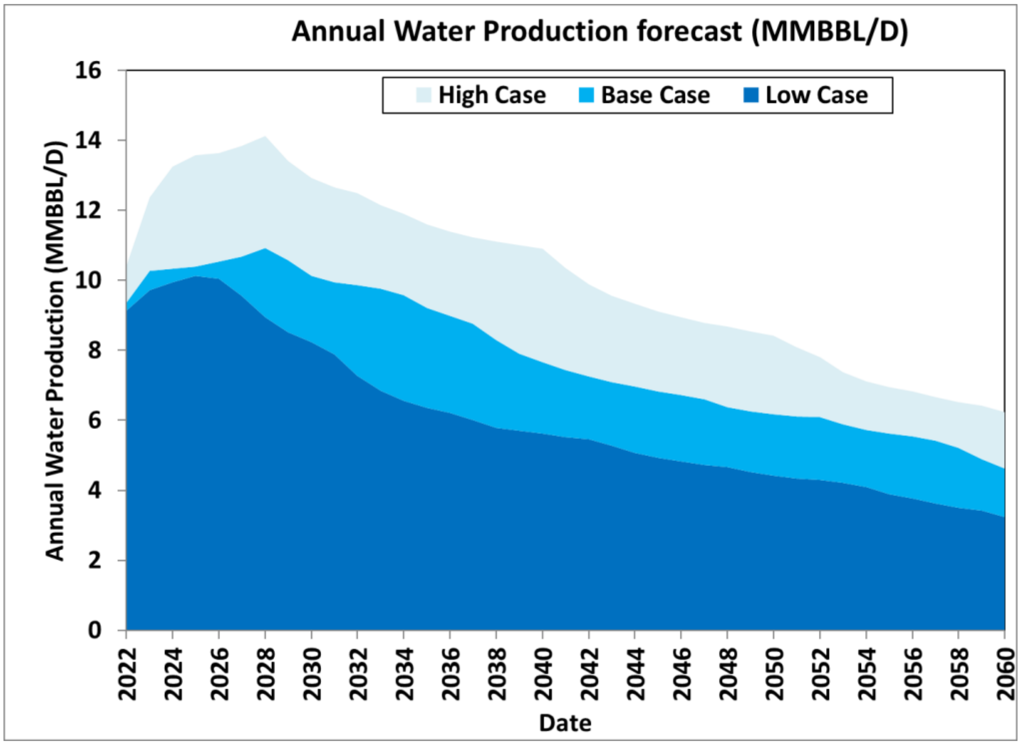


Figure 16: Annual Water Production Forecast for Districts 8, 8A, and 7C.

Assumptions

- Existing horizontal and Future horizontal wells development were covered in this analysis, however wells currently classified as Shut-in wells or Drill Uncompleted (DUC) were not considered.
- All wells drilled prior to 2016 were evaluated with one DCA per county.
- Type curves were established using only wells drilled in 2017 for each county because most of the horizontal drilling technology appeared to have developed to a point where only the length of the lateral was changing.
- Well drilled from 2017 to 2021 were evaluated individually as a group drilled during those years as the initial decline rate is substantially different for each of those years. This was accomplished by using the 2017 type curve generated above. The current predominant lateral length may not be accurately representative however, it is deemed reasonable for the purpose of this report.
- Specifically, the b-factor values of the type curves were used for all cases. For the 2021 forecast, due to the paucity of data, both the b-factors and an initial nominal decline rate from the type curves were used.
- A 5% minimum decline rate (Dm) was assumed for the projection i.e., the rate at which the curves change from using a hyperbolic model to the exponential model. Typically, the range of Dm is 2-10% (John Wright) depending on the type of reservoir. This value is usually established by analysis of production reservoirs that have reached the end of life. To prevent the overestimation of reserves, Dm is applied to limit the reduction of the decline rate. Not limiting the decline rate reduction results in a highly optimistic forecast.
- An economic limit of 5 BOPD per well is assumed for the existing wells based on analogue well performance in this area.
- To capture varying rig count over time, low, base, and high case realization was determined and applied in determining the number of wells to be drilled yearly based on the estimated drainage area to be drilled. The basis for the estimate considers both current and past rig utilization plus current industry media reports on outlooks for drilling. One point to emphasize is that with the current high oil process, the industry is reluctant to drill at rates previously seen in the basin plus there are current constraints on both labor and oilfield tubulars.

Most of the production data at the county level indicate that there is no decline because new wells are being drilled concurrently. For example, Figure 17 indicates the increasing oil, gas, and water production from Midland County. To analyze this, the wells were grouped on a yearly basis to capture the declining trends i.e., 2017-2021. Figure 18 shows the forecast trend for each group.

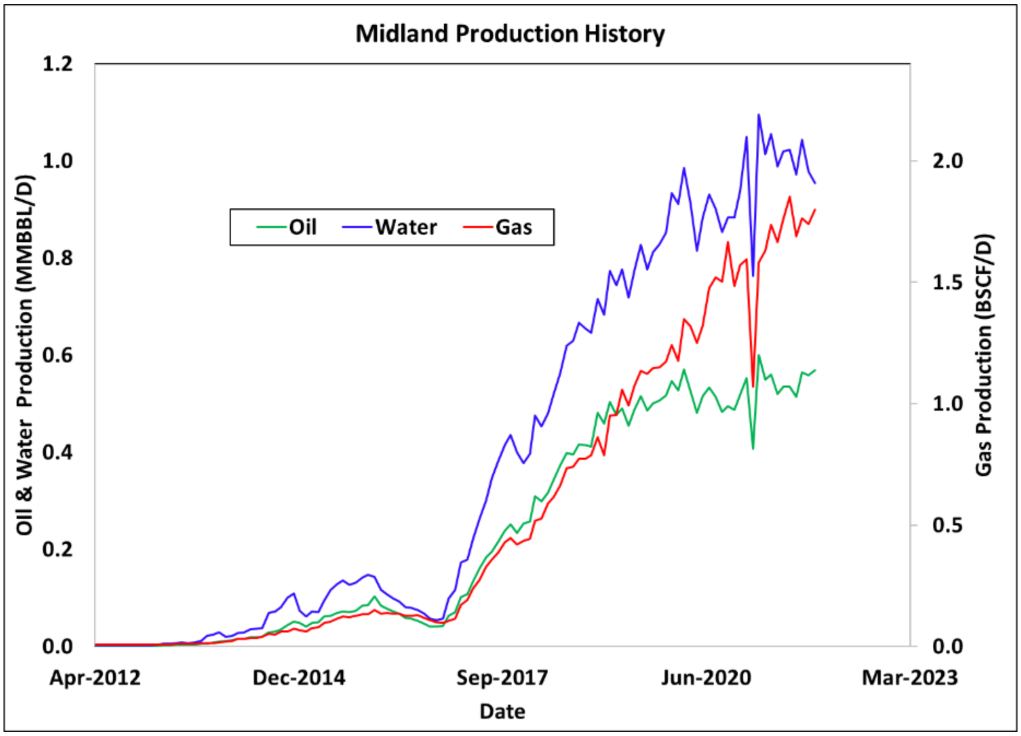


Figure 17: Typical production showing continuous incremental oil and gas production.

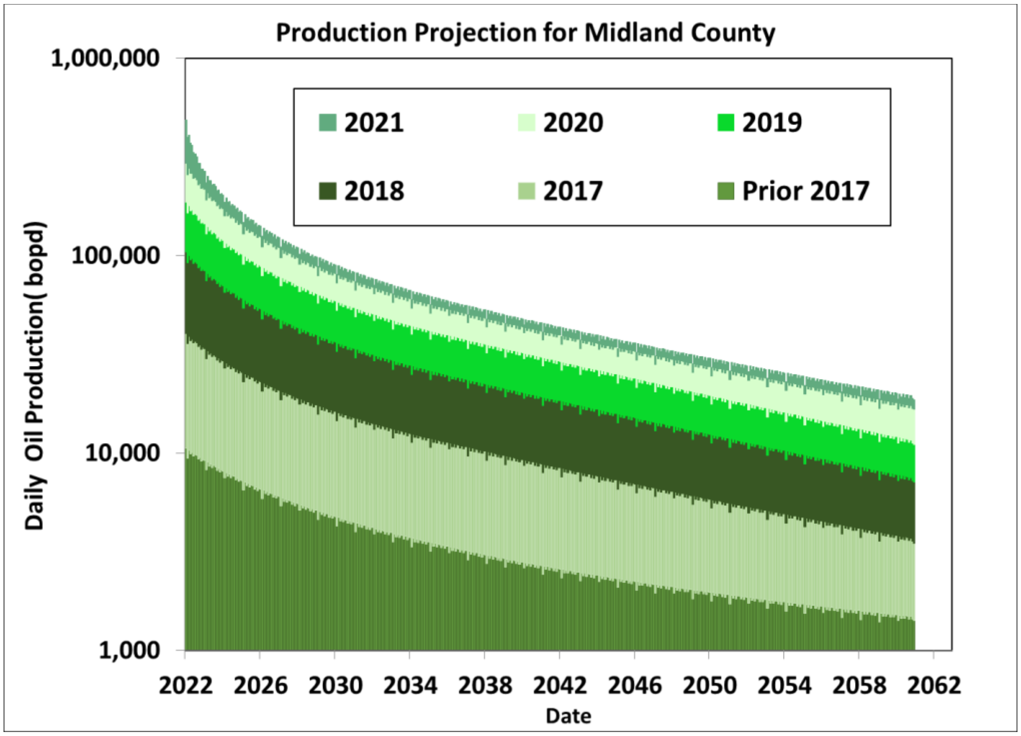
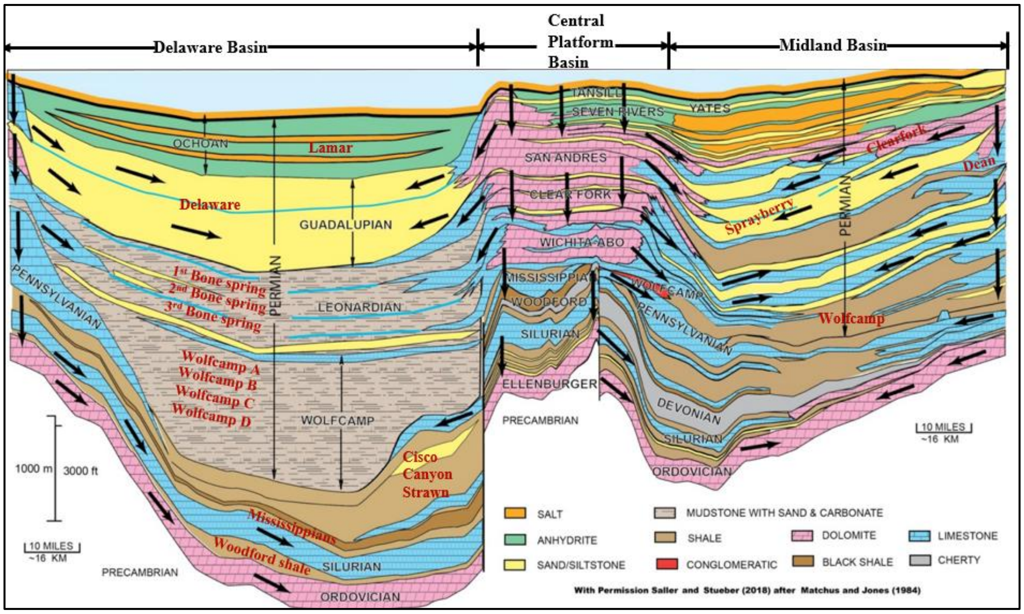


Figure 18: Production Forecast for Midland County current well.

New Drills

For future drills, projection is based on the area available within the target basins and considering the areas, the existing well spacing, well count, the rig count, and lateral lengths of wells. The analysis does not include the central basin platform, North/Northwest, and Eastern shelf because conventional wells contribute little produced water in the Permian basin that needs to be disposed of in saltwater disposal wells. This is because most of the water from these conventional wells is utilized within Enhanced Oil recovery (EOR) projects in these areas. In addition, there is minimal drilling development remaining in these areas, therefore new drill projections were limited to Midland and Delaware basins only. Furthermore, the Parent-Child interaction effect was not considered in this report.



With Permission Saller and Stueber (2018) after Matchus and Jones (1984)

Figure 19: A cross-section of the Delaware, Central Platform, and Midland basins.

Target Area for Drilling and Well Count

A polygon drawn around the target area of the existing horizontal wells was used to estimate the total development area that was considered in this evaluation (Figure 20). In this assessment, we had to deal with around 8 different layers for horizontal well development such as, Bone Spring, Spraberry, Wolfcamp A, B, C, D, etc., shown in Figure 19. From the geologic map, there may be a high density of horizontal wells, but they are not landed in one layer hence, it is difficult and tedious to determine the number of horizontal wells for each layer. To handle this, a reasonable assumption was made to handle the development of multiple layers by estimating a general well density that encompasses drilling all horizons. These well densities range from 4-20 wells per section (640 acres) on average. This was accessed this by focusing on the area with the greatest concentration of horizontal wells to estimate well density for all layers combined. The high cases are based on the maximum number of well density observed, the base case is the number of the predominant well density per section, and the low case is based on either the minimum or average minimum well density per section. Additionally, we utilized the weighted average lateral length combined with wells density noted above to ascertain an empirical drainage area per well

(Figures 21-23). (Width X length= empirical drainage area). The target area, the number of wells per section and the total drainage area, the undrained area, and the required well number to drain these regions were calculated. For example, if we have 20 wells per section, that will give about 264ft spacing between wells (i.e., 5280ft/20). This combined with a 10,000ft lateral length gives an empirical drainage area of 2,640,000ft^2 (60acres). The total number of wells that can be drilled to drain the target area was determined and then the number of wells for future drilling was estimated by removing the number of existing wells from the total. For instance, If the Target area is 120,000 acres and the existing number of wells are 1200, and the total ultimate number of wells drilled are estimated to be 2000 wells (120,000 acres/60 acres per well), then, the future number of wells to drill are 800 wells.

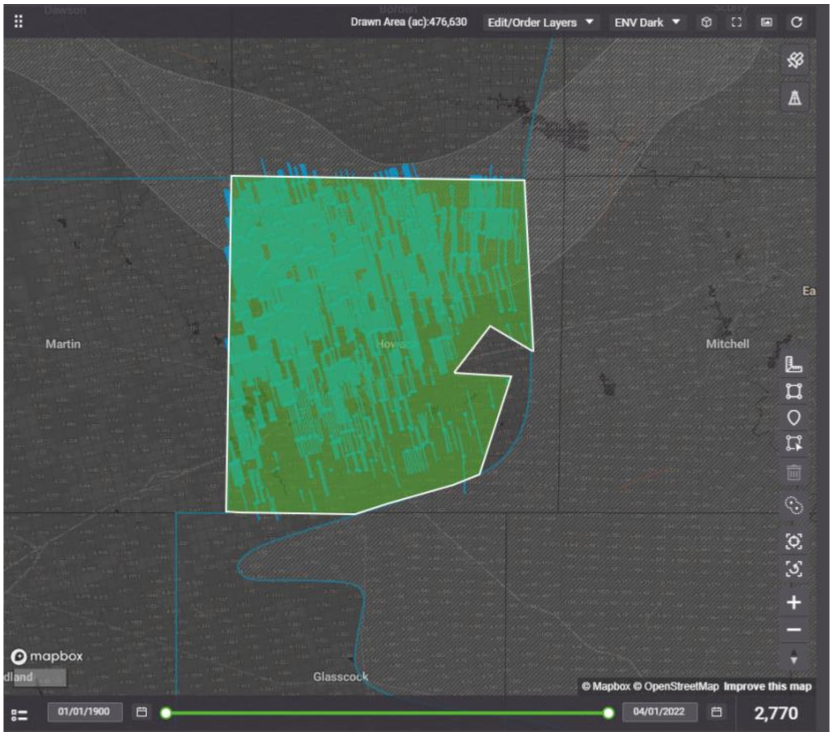


Figure 20: A typical example of Drainage Area estimation for Howard County.

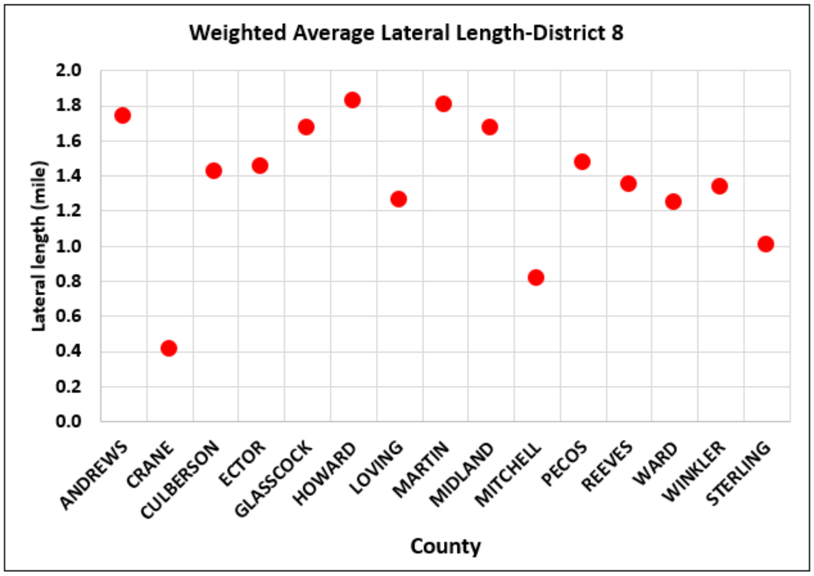


Figure 21: Lateral length of the existing wells for district 8 between 2016 and 2017.

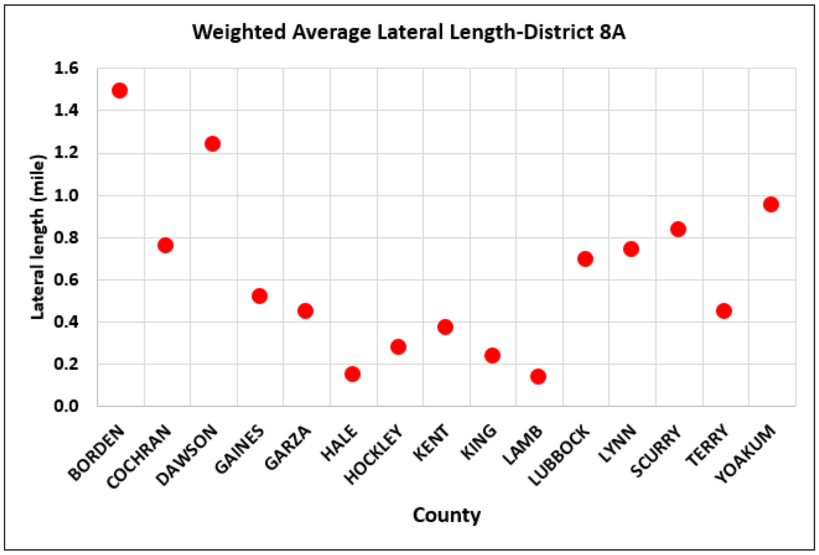


Figure 22: Lateral length of the existing wells for district 8A between 2016 and 2017.

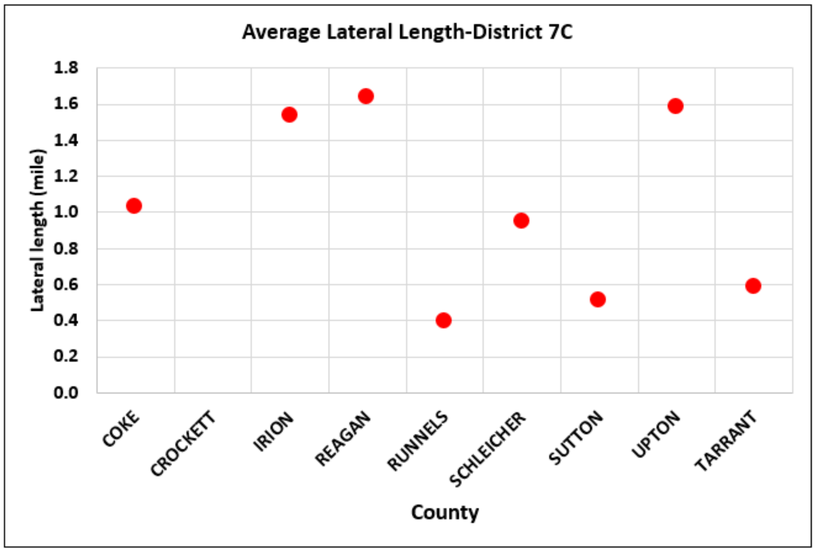


Figure 23: Lateral length of the existing wells for district between 2016 and 2017.

Rig Count and Drilling Rate

Three realizations (low, base, and high cases) were considered to capture the changes associated with rig count with time. Based on the data from Baker Hughes, Figure 24 indicates that for the three districts (8, 8A, and 7C), the rig count could be as high as 350, 45, and 100 respectively. The current rig count (as of April 2022) is used as the low and base cases projections, while the high cases are the average rig count from 2009 to date as shown in Figure 24. Table 3 summarizes the rig count assumptions for the low, base, and high cases. For the drilling rate assumptions, we polled multiple operating oil companies in the Permian Basin. That poll resulted that the drilling rate of 3 miles of horizontal wells ranges from 15 to 20 days per well. An average value of 18 days per well is used in this analysis.

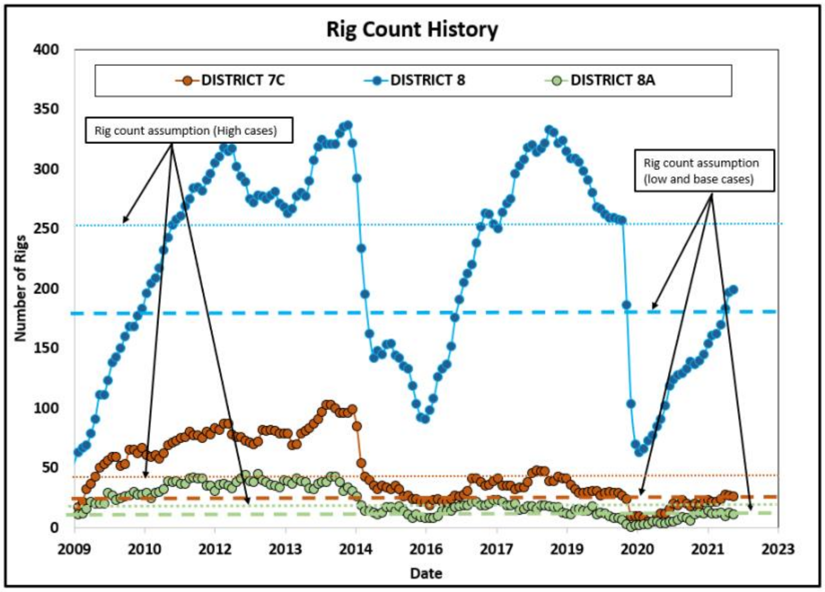
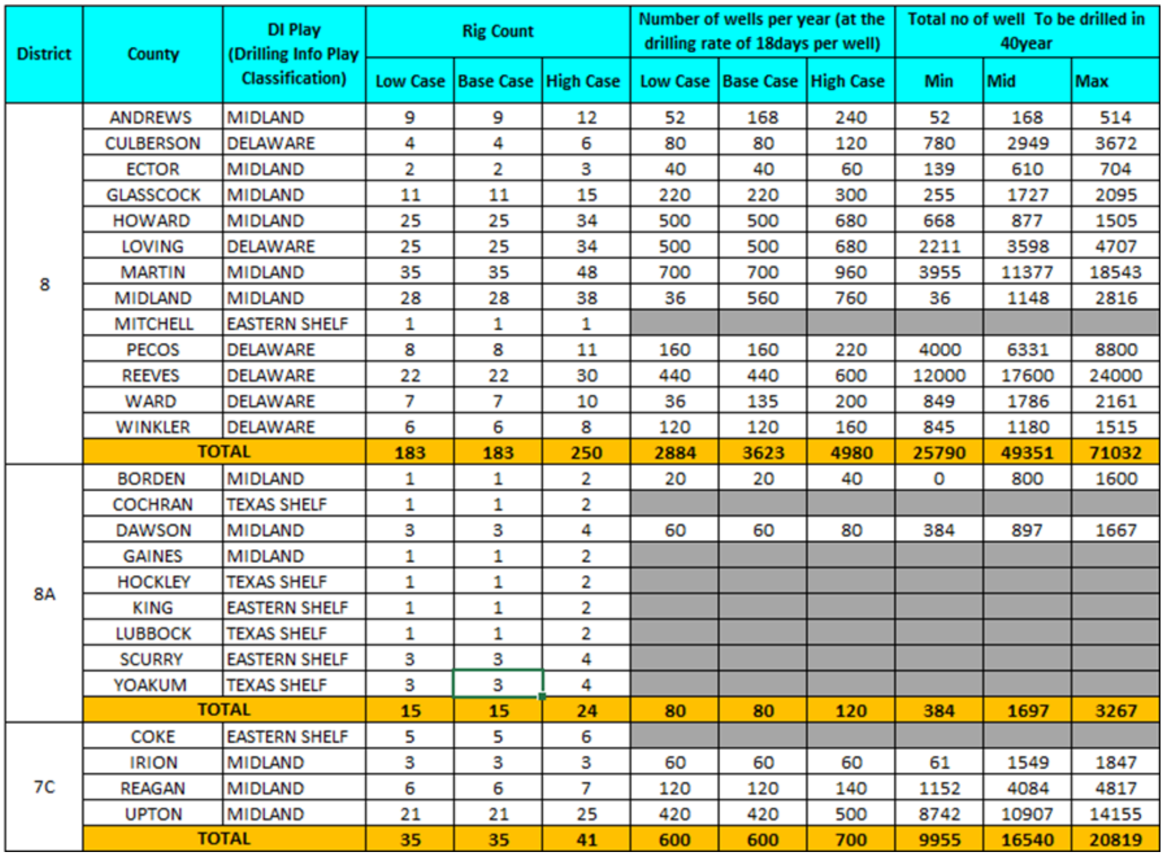


Figure 24: Rig count assumptions for district 8, 8A and 7C.

Table 3: Summary of the rig count and wells count projection per year and the total number of wells to be drilled in 40yrs.



District	County	DI Play (Drilling Info Play Classification)	Rig Count			Number of wells per year (at the drilling rate of 18days per well)			Total no of well To be drilled in 40year		
			Low Case	Base Case	High Case	Low Case	Base Case	High Case	Min	Mid	Max
8	ANDREWS	MIDLAND	9	9	12	52	168	240	52	168	514
	CULBERSON	DELAWARE	4	4	6	80	80	120	780	2949	3672
	ECTOR	MIDLAND	2	2	3	40	40	60	139	610	704
	GLASSCOCK	MIDLAND	11	11	15	220	220	300	255	1727	2095
	HOWARD	MIDLAND	25	25	34	500	500	680	668	877	1505
	LOVING	DELAWARE	25	25	34	500	500	680	2211	3598	4707
	MARTIN	MIDLAND	35	35	48	700	700	960	3955	11377	18543
	MIDLAND	MIDLAND	28	28	38	36	560	760	36	1148	2816
	MITCHELL	EASTERN SHELF	1	1	1						
	PECOS	DELAWARE	8	8	11	160	160	220	4000	6331	8800
	REEVES	DELAWARE	22	22	30	440	440	600	12000	17600	24000
	WARD	DELAWARE	7	7	10	36	135	200	849	1786	2161
	WINKLER	DELAWARE	6	6	8	120	120	160	845	1180	1515
	TOTAL		**183**	**183**	**250**	**2884**	**3623**	**4980**	**25790**	**49351**	**71032**
8A	BORDEN	MIDLAND	1	1	2	20	20	40	0	800	1600
	COCHRAN	TEXAS SHELF	1	1	2						
	DAWSON	MIDLAND	3	3	4	60	60	80	384	897	1667
	GAINES	MIDLAND	1	1	2						
	HOCKLEY	TEXAS SHELF	1	1	2						
	KING	EASTERN SHELF	1	1	2						
	LUBBOCK	TEXAS SHELF	1	1	2						
	SCURRY	EASTERN SHELF	3	3	4						
	YOAKUM	TEXAS SHELF	3	3	4						
	TOTAL		**15**	**15**	**24**	**80**	**80**	**120**	**384**	**1697**	**3267**
7C	COKE	EASTERN SHELF	5	5	6						
	IRION	MIDLAND	3	3	3	60	60	60	61	1549	1847
	REAGAN	MIDLAND	6	6	7	120	120	140	1152	4084	4817
	UPTON	MIDLAND	21	21	25	420	420	500	8742	10907	14155
	TOTAL		**35**	**35**	**41**	**600**	**600**	**700**	**9955**	**16540**	**20819**

Decline Rate

The type-curves generated are based on the weighted average lateral well length of existing wells for 2016-2017 for each County. The weighted average lateral length is the sum of the product of well count and the lateral length of horizontal wells completed in each layer divided by the total well count. The methods assumed that the weighted average lateral length of the existing wells is also going to be the lateral length of the new drills. Tables 4-6 shows the summary of the type curve parameters underlining the forecast. The purpose was to determine Arp's parameters, which are the initial nominal decline rate, Di, and b-factor.

Table 4: District 8 type curve parameters for oil, gas, and water decline.

County	2017 Horizontal wells					
	b-factors			Initial decline rate, Di (/yr)		
	Gas	oil	water	Gas	oil	water
ANDREWS	0.48	0.95	0.99	0.82	3.90	2.60
CRANE	2.50	1.40	0.50	6.08	2.81	0.24
CULBERSON	1.85	1.21	0.56	2.09	2.40	1.14
ECTOR	0.65	1.38	1.75	0.33	4.18	6.40
GLASSCOCK	2.20	1.08	1.15	0.95	5.00	6.33
HOWARD	2.76	1.25	1.42	2.51	6.25	5.59
LOVING	1.23	1.19	1.23	2.78	5.20	2.99
MARTIN	1.94	1.13	1.07	1.31	4.65	3.52
MIDLAND	1.94	1.06	1.09	1.05	4.71	5.43
MITCHELL	0.52	1.38	1.08	0.81	13.30	11.90
PECOS	1.62	1.23	1.05	2.27	3.54	2.67
REEVES	0.95	0.75	0.44	0.98	1.54	1.01
STERLING	0.46	1.27	1.04	0.22	6.99	6.44
WARD	2.40	2.13	1.52	5.80	9.99	4.30
WINKLER	1.44	1.57	0.99	1.49	2.94	1.72

Table 5: District 8A type curve parameters for oil, gas, and water decline.

County	2017 Horizontal wells					
	b-factors			Initial decline rate, Di (/yr)		
	Gas	oil	water	Gas	oil	water
BORDEN	2.50	1.73	1.17	3.81	14.22	8.35
COCHRAN	1.00	1.85	1.44	2.40	4.35	3.19
DAWSON	0.98	1.74	1.67	2.48	7.63	14.67
GAINES	0.50	1.25	2.50	0.12	0.27	0.90
HALE	2.64	0.97	0.10	1.37	0.89	10.70
HOCKLEY	0.16	1.50	0.50	1.89	2.95	0.59
KENT	0.63	0.93	1.43	0.73	0.94	0.56
KING	0.50	1.50	1.84	2.05	0.20	0.34
LAMB	0.00	0.56	1.10	0.01	0.45	0.26
LUBBOCK	1.37	2.47	1.30	0.82	0.75	0.01
LYNN	0.97	1.27	1.02	2.20	5.80	1.02
SCURRY	2.53	1.47	0.84	1.80	2.72	4.45
TERRY	0.78	1.94	0.50	0.11	0.62	0.04
YOAKUM	2.50	1.88	1.46	0.12	3.13	3.00

Table 6: District 7C type curve parameters for oil, gas, and water decline.

County	**2017 Horizontal wells**					
	b-factors			**Initial decline rate, Di (/yr)**		
	Gas	**oil**	**water**	**Gas**	**oil**	**water**
COKE	**1.50**	**1.02**	**1.50**	**2.07**	**1.15**	**8.10**
CROCKETTS	**2.19**	**1.10**	**0.30**	**1.05**	**12.91**	**1.29**
IRION	**2.71**	**0.99**	**1.04**	**0.73**	**6.90**	**8.40**
REAGAN	**2.97**	**1.13**	**1.02**	**0.55**	**5.04**	**2.26**
RUNNELS	**0.63**	**0.63**	**0.66**	**4.40**	**4.40**	**4.50**
SCHLEICHER	**0.22**	**1.50**	**1.36**	**0.19**	**1.56**	**0.68**
SUTTON	**0.50**	**1.02**	**1.44**	**0.33**	**1.45**	**6.41**
TERRELL	**1.40**	**1.19**	**2.05**	**2.10**	**8.40**	**4.60**
UPTON	**0.54**	**1.07**	**1.13**	**2.00**	**4.49**	**6.82**

Production Forecast

The combination of all the production from district 8, 8A and 7C for all wells are shown in Figures 25-27. This represents production from existing horizontal wells, and the future wells. At a maximum annual rate of 20.6BSCF/D of gas, 4.3MMbbl/D, of oil and 14.1MMBBL/D of water, the cumulative production predicted over 38 years is 264TSCF, 45.2Bbbl and 145Bbbl respectively. In this aggregate forecast, the dominance of district 8 forecast can clearly be seen.

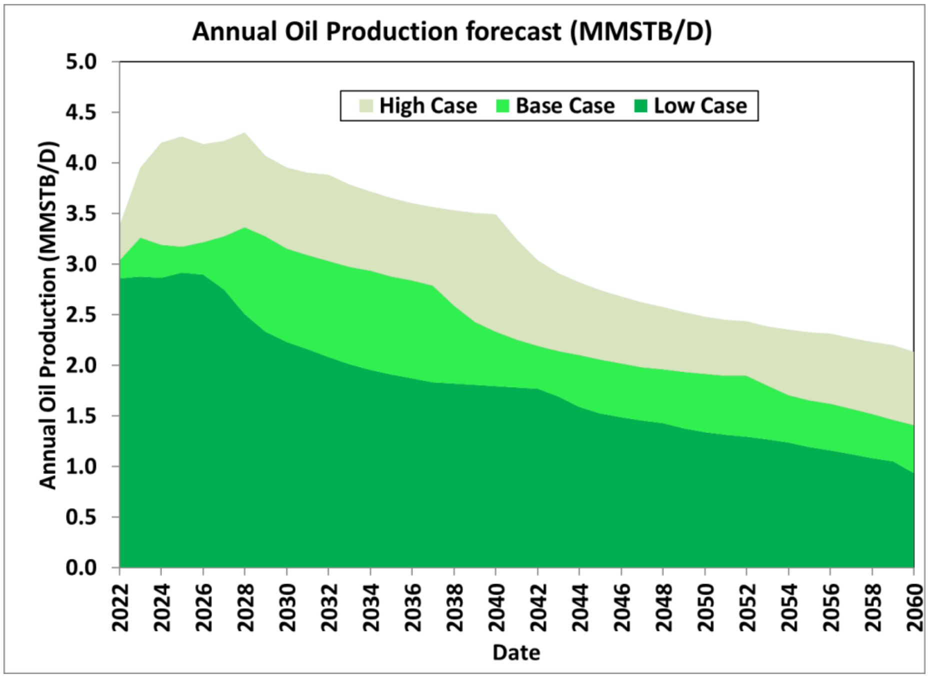


Figure 25: Annual Oil Production Forecast for District 8, 8A, and 7C.

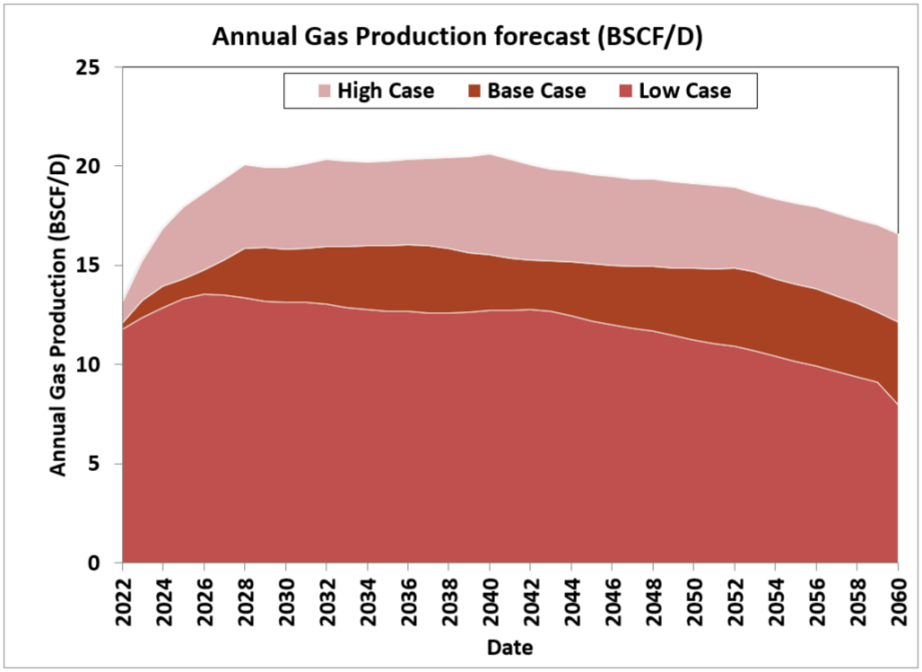


Figure 26: Annual Gas Production Forecast for District 8, 8A, and 7C.

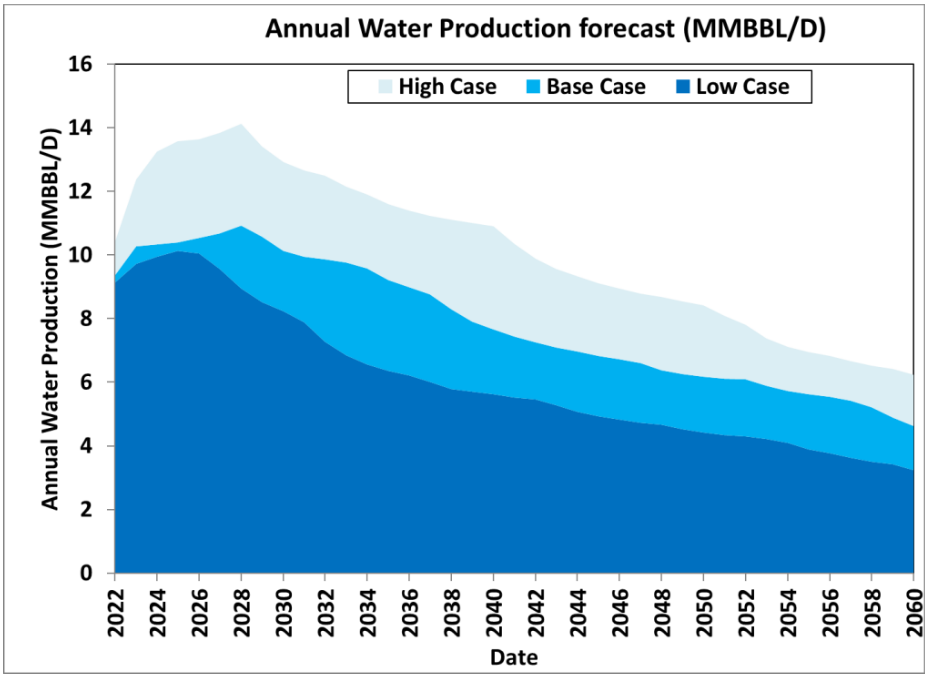


Figure 27: Annual Water Production Forecast for District 8, 8A, and 7C.

District 8

The Railroad Commission (RRC) Oil producing District 8 consist of 15 counties. The production forecast on the district level is shown in the Figs. 25-27which indicate a maximum annual oil, gas, and water production rate of 3.7MMbbl/D, 16.2BSCF/D, and 12.3MMBBL/D respectively. This amount to a cumulative production of 35.2Bbbls, 194.6TSCF and 122.1Bbbl over the period of 38 years.

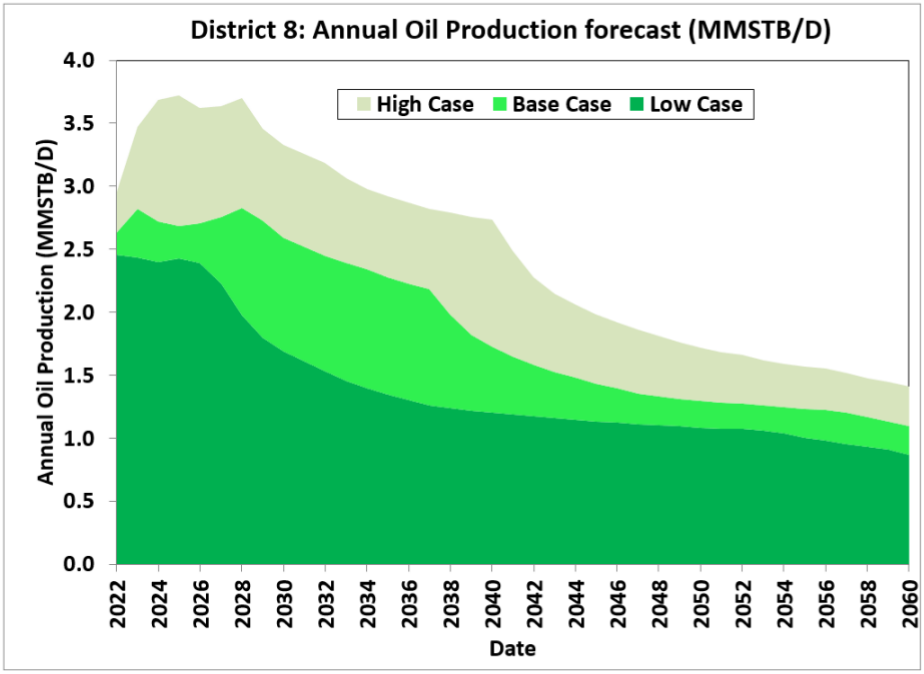


Figure 28: Annual Oil Production Forecast for District 8.

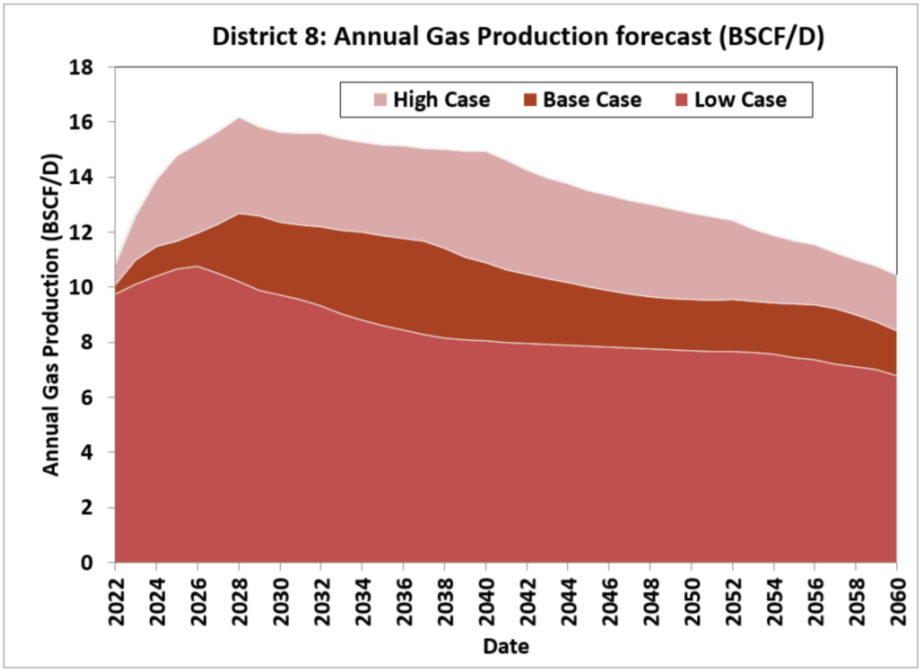


Figure 29: Annual Gas Production Forecast for District 8.

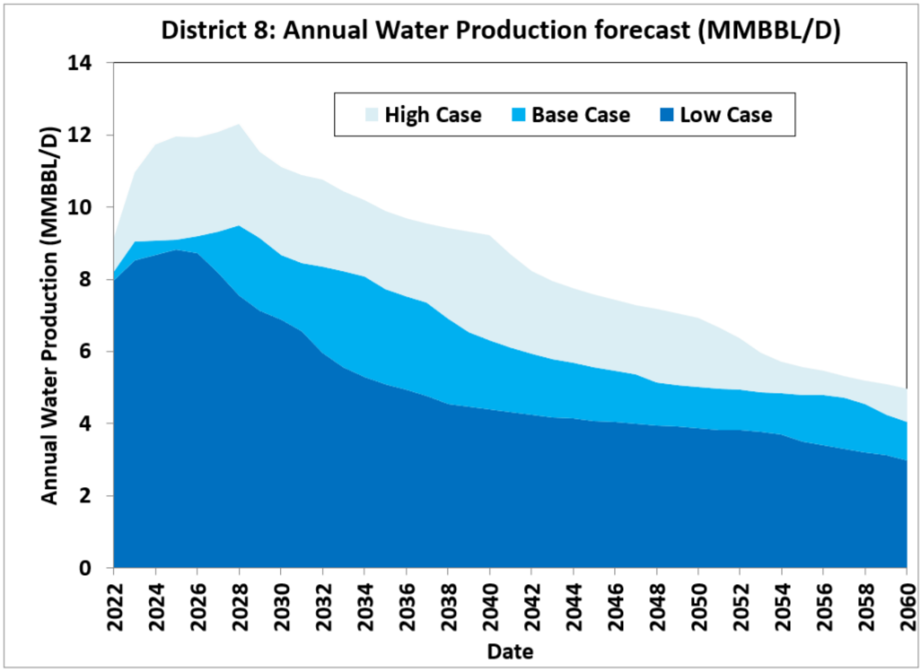


Figure 30: Annual Water Production Forecast for District 8.

District 8A

The RRC Oil producing District 8A consist of 19 counties. The production forecast on the district level is shown in the Figs. 28-30 which indicate a maximum annual oil, gas, and water production rate of 0.11MMbbl/D, 0.16BSCF/D, and 0.94MMBBL/D respectively. This amount to a cumulative production of 1.2Bbbl, 1.5TSCF, and 8.2Bbbl over the period of 38 years.

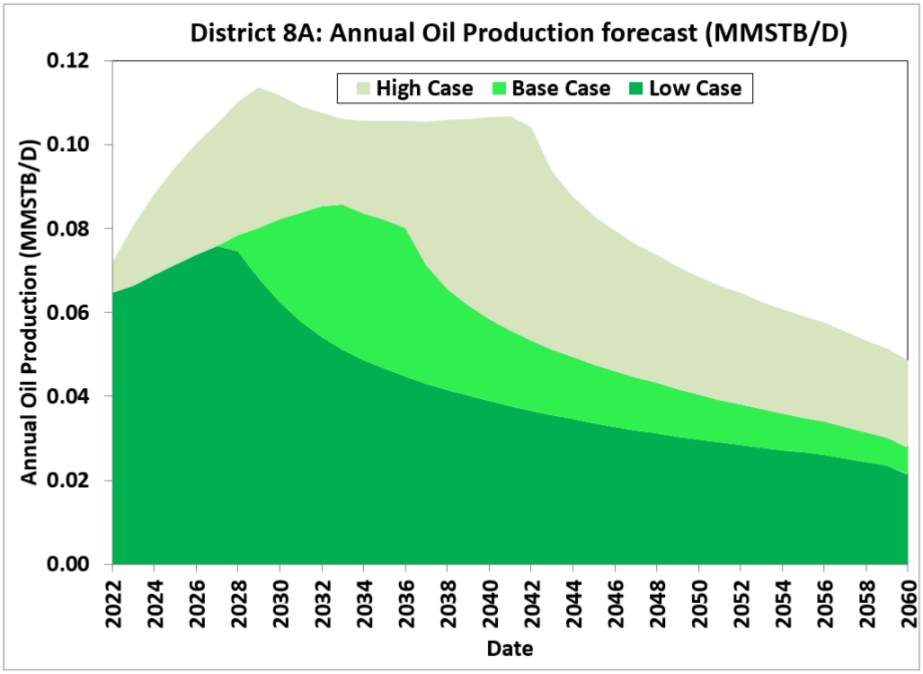


Figure 31: Annual Oil Production Forecast for District 8A.

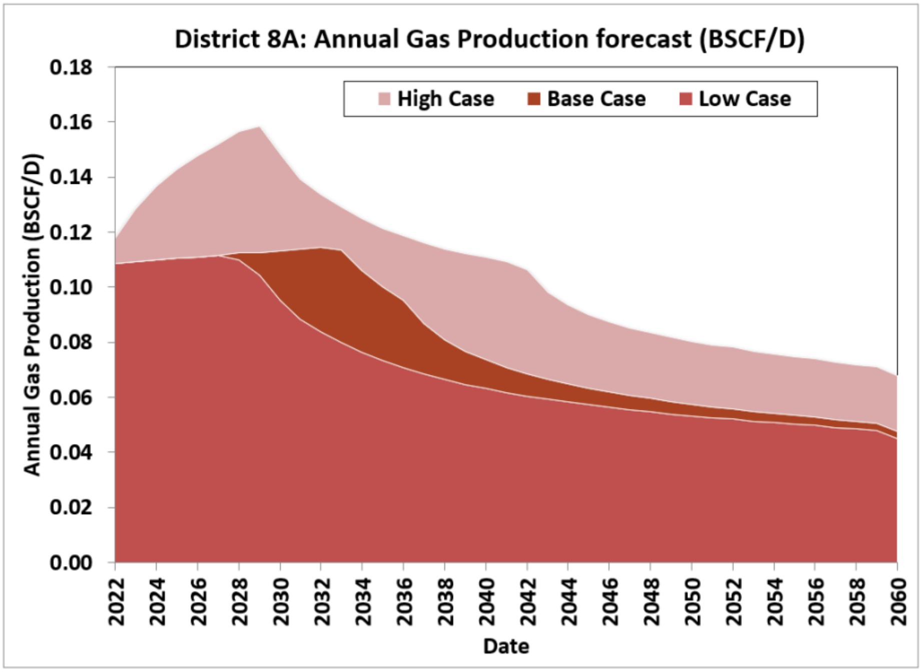


Figure 32: Annual Gas Production Forecast for District 8A.

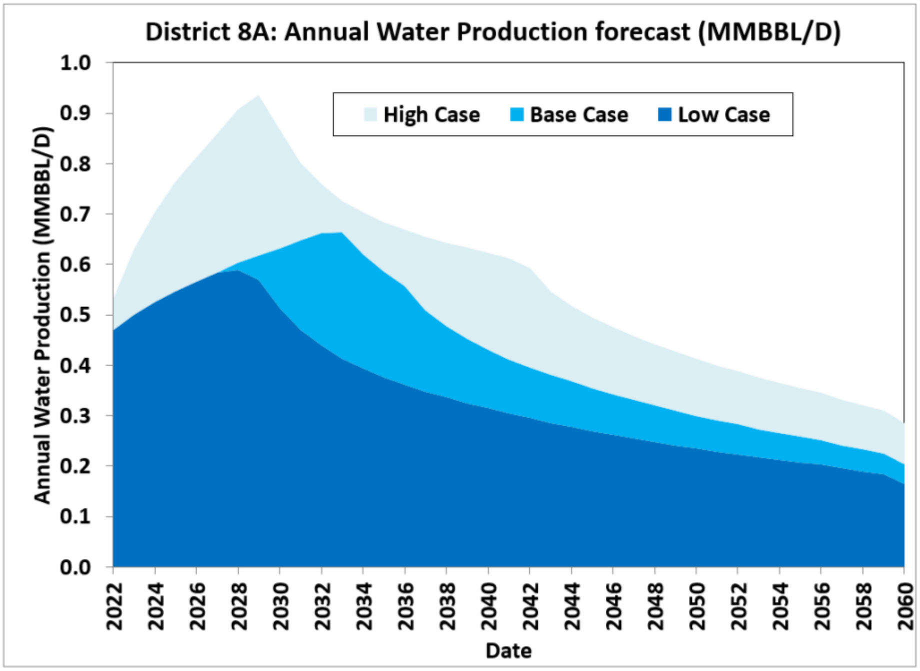


Figure 33: Annual Water Production Forecast for District 8A.

District 7C

The RRC Oil producing District 7C consist of 13 counties. The production forecast on the district level is shown in the Figs. 31-33 which indicate a maximum annual oil, gas, and water production rate of 0.71MMbbl/D, 6.26BSCF/D, and 1.06MMBBL/D respectively. This amount to a cumulative production of 8.8Bbbl, 69.7TSCF and 14.1Bbbl over the period of 38 years.

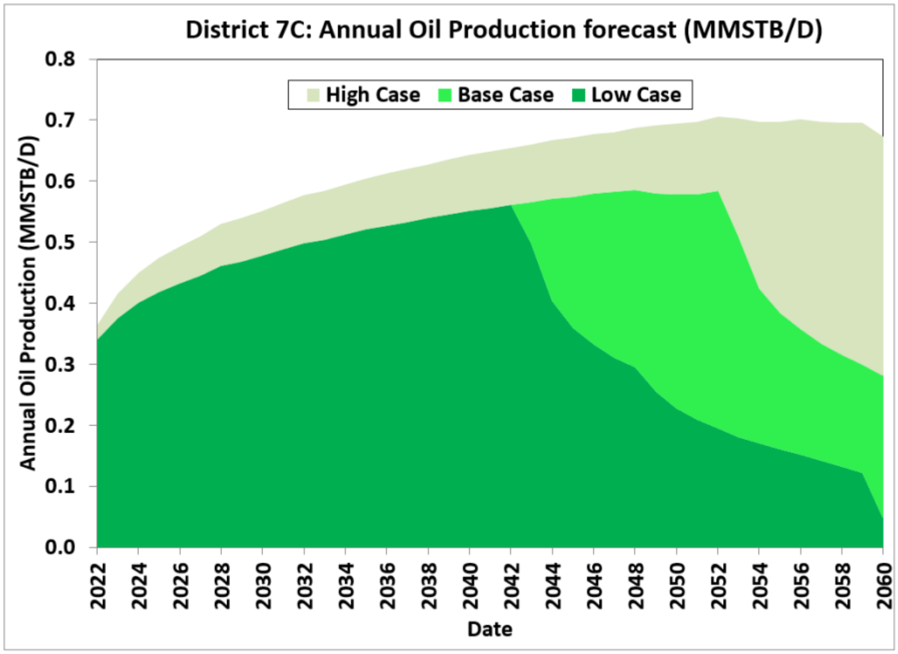


Figure 34: Annual Oil Production Forecast for District 7C.

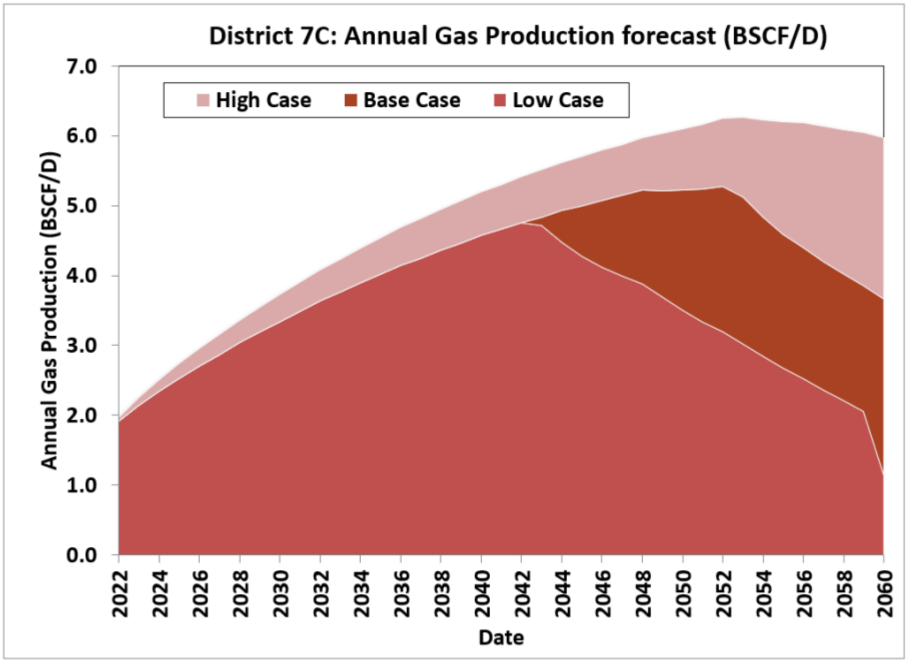


Figure 35: Annual Gas Production Forecast for District 7C.

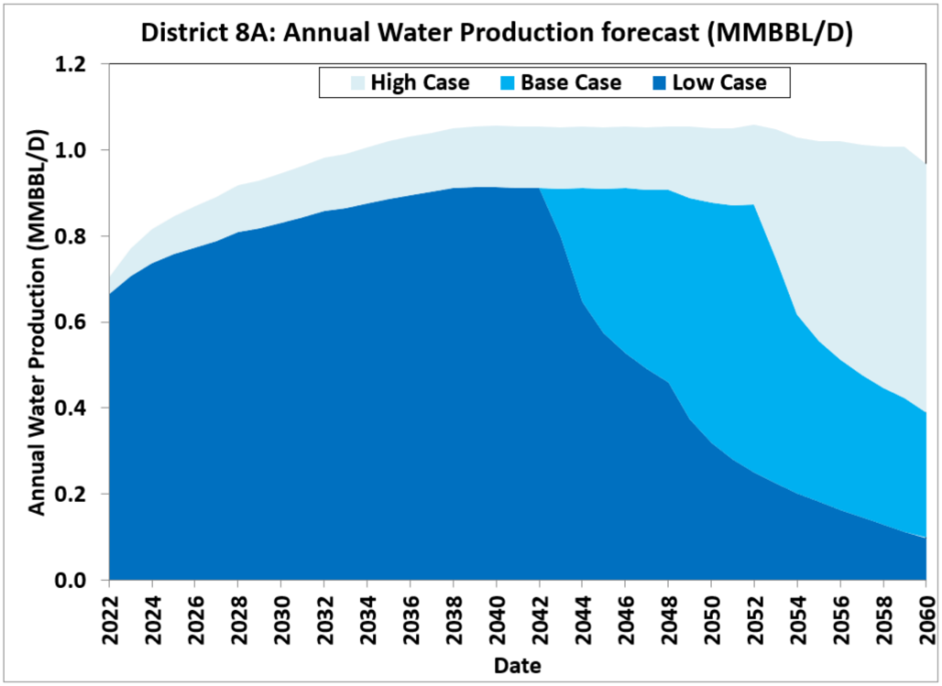


Figure 36: Annual Water Production Forecast for District 7C.

Technology

Beneficial use of treated produced water in Texas, especially from the Permian Basin, may be possible once constituents which pose potential risk (including organics, inorganics, and potentially radionuclides) and dissolved solids (salts), are removed from the water. As will be discussed in the subsequent sections, the efficacy, efficiency, and estimated cost of treatment to achieve appropriate removal is not currently well defined as few potentially applicable technologies have been evaluated or demonstrated at scale for highly saline produced water such as that found in the Permian and Delaware basins of Texas. The TXPWC can encourage and facilitate the development of these technologies through both research and assistance in overcoming barriers to implementation of the technologies. The technologies will require demonstration at pilot scale to evaluate energy requirements and costs, realistic operations and maintenance costs, as well as identify pretreatment and post-treatment requirements and potential effectiveness and reliability of treatment technologies for produced water applications. A variety of technology developers and vendors would likely be interested in developing and demonstrating potentially applicable technologies, but an appropriate testing facility would be an important requirement to advance these evaluations. In addition to encouraging and facilitating the development of technologies for treating produced water the TXPWC could also provide third party oversight and monitoring of the demonstrations themselves. Any demonstrations at the facility would be more credible if there were third party oversight and monitoring.

A demonstration facility could be built around a centralized produced water collection and management facility such as one designed for recycling water within the industry. Such a facility would have access to large volumes of produced water of different qualities and characteristics and be permitted for managing and recycling produced water. Pilot technologies could be built or brought to the facility and produced water could be treated and returned to the facility without having project specific treatment and disposal permits. Co-location with an existing permitted treatment and disposal facility minimizes the costs required to properly handle pilot testing effluents.

A variety of technologies for desalination of produced water have been outlined in a report by the Groundwater Protection Council although the report does not attempt to estimate the cost of treatment.[25] These technologies either alone or in combination might be appropriate for testing and evaluation. The energy costs associated with treatment of produced water is likely to be dominated by the removal of salts due to the high dissolved solid content of produced water from the Permian Basin. As a result, several candidate technologies for produced water treatment can be identified from those used to desalinate seawater. Several salt-removal technologies were subjected to a techno-economic evaluation to illustrate their potential applicability using as a basis the detailed information available on energy requirements and costing available for seawater desalination applications. The primary goal of this evaluation was

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[25] Produced Water Report: Regulations, Current Practices, and Research Needs. Groundwater Protection Council, 2019 https://www.gwpc.org/sites/gwpc/uploads/documents/Research/Produced_Water_Full_Report___Digital_Use.pdf Accessed on August 2022

to illustrate that there are demonstrated technologies that could be employed for treatment of produced water and an estimate of their energy requirements and operating costs. The goal of the evaluation was not to determine the final configuration or to set detailed cost estimates of the technologies nor to assess required pretreatment and post-treatment for any beneficial use of the treated water. The focus was on the energy costs of implementing such technologies for desalination of produced water because capital costs are largely unavailable and often driven by pre- and post-treatment technologies that are not yet defined. The concept underlying the current analysis is that if the technologies are unlikely to be economically viable or technically feasible even disregarding pre- or post-treatment technologies, then there is little reason to pursue those technologies. The technologies evaluated included:

- Reverse osmosis (RO)
- Multi-stage flash evaporation (MSF)
- Multi-effect distillation (MED)
- Mechanical vapor compression (MVC)
- Membrane distillation (MD)

A short summary of each of the technologies can be found as appendices (see Appendices G-K). These summaries are designed to provide a short primer on these technologies for those unfamiliar with them as opposed to a detailed description of how they might be applied to produced water treatment. These processes were selected due to their widespread use (RO), the ability to efficiently treat high salinity waters and high technology readiness level (MSF, MED and MVC) and a promising produced water technology although not yet at a high technology readiness level (MD). Fouling is a common challenge in the application of any membrane technologies to the treatment of produced water. In general, thermal technologies are more efficient at high salinities which is why the primary focus is on these technologies. Thermal technologies can also take advantage of waste heat where available, thereby reducing operating cost. Other technologies that are not considered here but potentially applicable to produced water desalination and might be evaluated in pilot studies, include forward osmosis (FO), osmotically assisted reverse osmosis (OARO), humidification-dehumidification (HDH) and freeze based thermal desalination. This discussion will also focus on the primary desalination technologies to evaluate their potential applicability and not pre-and post-treatment, hybrids or combination technologies whose evaluation is likely to be the subject of pilot scale demonstrations.

Technology Evaluation

Assumptions

The produced water that may be available for beneficial use varies significantly in quality and volume. In this section, potentially viable desalination technologies will be described and evaluated. These technologies will be identified based upon their potential applicability for treating produced water.

Essentially all beneficial uses will require significant removal of total dissolved solids (TDS) through desalination. The economics of desalination will generally be more favorable if feed volumes can be maintained for substantial periods of 10 years of more. Efficient produced water treatment will require transportation and collection of the produced water to a central treatment facility. There has been significant growth in centralized treatment facilities, and this will be important in developing treatment systems for beneficial uses. The treated low salinity waters will also require transportation to the location of the beneficial use. Due to the wide range of potential produced water collection systems as well as the equally wide range of potential beneficial uses and locations, this will not be evaluated in this section. Instead, *the technologies will be evaluated on the basis of their operating cost, excluding costs of transport to and from a treatment facility, pre and post treatment which may be required to effectively and reliably achieve a higher level of effluent quality, as well as storage at the treatment facility. Further the profit and return that may be required to induce investment will not be considered nor will taxes.*

Higher values may be placed on water in particular conditions (e.g. a community without access to other sources of water) but will require further research to determine the likelihood of these conditions to drive investment in widespread treatment of produced water. *The potential value of the treated water is not included in this analysis of potentially applicable technologies, but is discussed in the economics section.*

Valuable products such as rare earths, lithium or salts such as calcium carbonate or concentrated brines may improve process economics and the demonstration and testing of these technologies at pilot scale should be encouraged. The ability to extract these products from Permian Basin produced water, however, has not been demonstrated and are *not considered in this section*.

For the purposes of this analysis, capital costs were *not* estimated for produced water treatment facilities. Capital costs for seawater treatment are included for reference and a summary of available capital costs for produced water treatment costs are tabulated in this report. The available data on capital costs of produced water treatment facilities, however, is limited and focused primarily on pilot scale or small treatment facilities. *Driving down the capital costs of produced water treatment facilities through scale and design is a major objective of the TXPWC and the proposed pilot plant testing.*

The evaluation of treatment costs here is limited to operating cost and *reported on a basis of volume of treated product water*. The capital costs are likely to show economies of scale but the operating costs on a per unit volume of treated product water basis are largely independent of plant size. All operating costs were evaluated on the basis of a feed water volume of 2 MGD (0.048 MMbopd). A variety of cost factors that were included in the analysis are summarized below.

- Capital costs are shown only for seawater desalination where costing is available.[26] Capital costs are corrected to 2022 chemical engineering process cost index.

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[26] Bhojwani, S.; Topolski, K.; Mukherjee, R.; Sengupta, D.; El-Halwagi, M. M., Technology review and data analysis for cost assessment of water treatment systems. *Science of The Total Environment* **2019,** *651*, 2749-2761.

- Feed water volume of 2 MGD (0.048 MBD) is shown although the operating cost per volume treated product water is essentially identical at larger and smaller flows using the simplified assumptions applied here.
- 100% plant availability.
- Electrical costs at $0.06/KWh.
- Thermal energy costs at $6/MMBTU.
- Labor costs at \$0.025-0.05/m^3 of water produced.[27] These were corrected to 2022 with the chemical engineering process cost index.
- Chemical costs for seawater were used as a basis.[28, 29] This was corrected for high TDS waters by assuming chemical costs were linear in TDS and corrected to 2022 using the Federal Reserve Consumer Price Index for commodity chemicals.
- Energy requirements and capital costs for seawater facilities were used as a basis.[30] Capital costs were only estimated for seawater facilities since these are the only facilities for which reliable costing data could be identified. These were corrected to 2022 with the chemical engineering process cost index.
- Process efficiency estimates were based upon data from seawater facilities and estimates of minimum energy requirements to achieve the desired desalination.[31, 32]

The potentially applicable treatment technologies will normally produce water with 100 mg/L total dissolved solids (TDS) or less. For the purposes of this analysis the product water will be assumed freshwater with negligible TDS. It is also expected that salts will not normally be cost-effective to recover, and the baseline analysis will assume that the concentrate stream will be disposed of by saltwater disposal wells. This would normally be expected to limit the TDS in the concentrate stream to 250-275 g/L (250,000—275,000 mg/L) to avoid difficulties with pumping and disposing of this stream. For this reason, brine concentration and crystallization technologies are not considered.

Produced Water Chemistry

The range of produced water chemistry that will likely require desalination was based upon a database of more than 17,000 individual samples provided by an industry partner. This database included 14,814 samples from tight oil wells, split between the Delaware and Midland Basins (2,265 samples and 11,036 samples, respectively), ranging from 2014 to 2022. From this database a median produced water TDS as well as 25th percentile and 75th percentile chemistry was determined. The median dissolved solids concentration in the database was 123 g/L (123,000 mg/L), while the 25th percentile was 95.2 g/L (95,200 mg/L) and the 75th percentile was 142 g/L (142,000 mg/L). The Delaware basin samples contained significantly less dissolved solids with a median concentration of 71.1 g/L (71,100 mg/L). Xu and Hightower from the New

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[27] Mistry, K. H.; Lienhard, J. H., An economics-based second law efficiency. *Entropy* **2013,** *15* (7), 2736-2765.

[28] Bhojwani, S.; Topolski, K.; Mukherjee, R.; Sengupta, D.; El-Halwagi, M. M., Technology review and data analysis for cost assessment of water treatment systems. *Science of The Total Environment* **2019,** *651*, 2749-2761.

[29] Najafi, F. T.; Alsaffar, M.; Schwerer, S. C.; Brown, N.; Ouedraogo, J. In *Environmental impact cost analysis of multi-stage flash, multi-effect distillation, mechanical vapor compression, and reverse osmosis medium-size desalination facilities,* ASEE Annual Conference & Exposition*, 2016.*

[30] Al-Karaghouli, A.; Kazmerski, L. L., Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews* 2013, 24, 343-356.

[31] Lin, S., Energy Efficiency of Desalination: Fundamental Insights from Intuitive Interpretation. *Environmental Science & Technology* 2019

[32] Thiel, G. P. Desalination systems for the treatment of hypersaline produced water from unconventional oil and gas processes. Massachusetts Institute of Technology, 2015.

Mexico Produced Water Research Consortium have reported a similar level of TDS (Average of 3,800 samples in the Permian Basin of 118 g/L).[33] Not measured in the samples included in the database evaluated here is organic matter and Xu and Hightower reported an average of about 120 mg/L (TOC) with a maximum of 184 mg/L in their produced water samples. The presence and levels of potential organic constituents of concern are an important factor in evaluating treatment technology efficacy and potential beneficial uses of the treated effluent. However, for the current evaluation and development of rough treatment cost estimates for desalination treatment technologies, the focus is on the inorganic constituents.

For the purposes of this technology evaluation, we considered waters for four different TDS concentrations as summarized in Table 7. These included the 25, 50 and 75%ile produced water concentrations from the entire database and seawater as relatively high-quality produced water “end-member” (e.g. produced water from Delaware basin)
Based on a concentrated stream limit of about 250 g/L (250,000 mg/L), the recovery of the median produced water in a desalination system is limited to about 50% and this was used in the evaluation of the technologies. Various technologies may have their own limits to recovery, and these will be noted in the discussion of those technologies.

Table 7: Assumed chemical composition of produced water for treatment based on 17,000+ samples from the Midland and Delaware basins (* Na was adjusted slightly where necessary to achieve electroneutrality).

	Concentration (mg/L)			
Species	Seawater	25th Percentile	50th Percentile	75th Percentile
Calcium (Ca)	408	1,723	2,728	3,794
Magnesium (Mg)	1,298	299	464	640
Sodium (Na)*	10,768	34,417	43,336	49,458
Potassium (K)	396	359	501	643
Barium (Ba)	-	1	2	3
Strontium (Sr)	-	293	506	691
Iron (Fe)	-	17	36	68
Manganese (Mn)	-	0.6	1.1	1.9
Total cations	12,870	37,122	47,592	55,325
Sulfate (SO_4)	2702	282	421	690
Chloride (Cl)	19364	57,012	73,586	84,843
Bromide (Br)	67	401	549	674
Phosphate (PO_4)	-	32	48	66
Boron (B)	-	40	49	61
Silica (SiO_2)	5	10	13	17
Bicarbonate (HCO_3)	146	256	366	525
Carbon Dioxide (CO_2)	9.19	110	220	374
Total anions	22,284	58,033	75,035	86,880
Total TDS	35,154	95,155	122,627	142,204
Alkalinity (as mg/L $CaCO_3$)	120	210	300	431

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[33] Xu, P.; Hightower, M., Characterization of Produced Water and Surrounding Surface Water in the Permian Basin. In *Produced Water Society Seminar* 2022, Houston TX, 2022.

An additional limitation on desalination processes is that a minimum energy is required to achieve the separation of salts from water. Figure 37 illustrates the minimum energy required for seawater (SW) and 25, 50 and 75th percentile produced water (PW) based upon the composition in Table 7. The e-NRTL model as developed and updated at TTU[34] [35, 36, 37] was used to evaluate non-ideal solution behavior which has an important effect on the required minimum energy. The minimum energy considering non-ideal solution effects is 1.5-2 times greater for the produced water cases than based upon the assumption of an ideal solution. The effect of non-ideality on the seawater case is minimal.

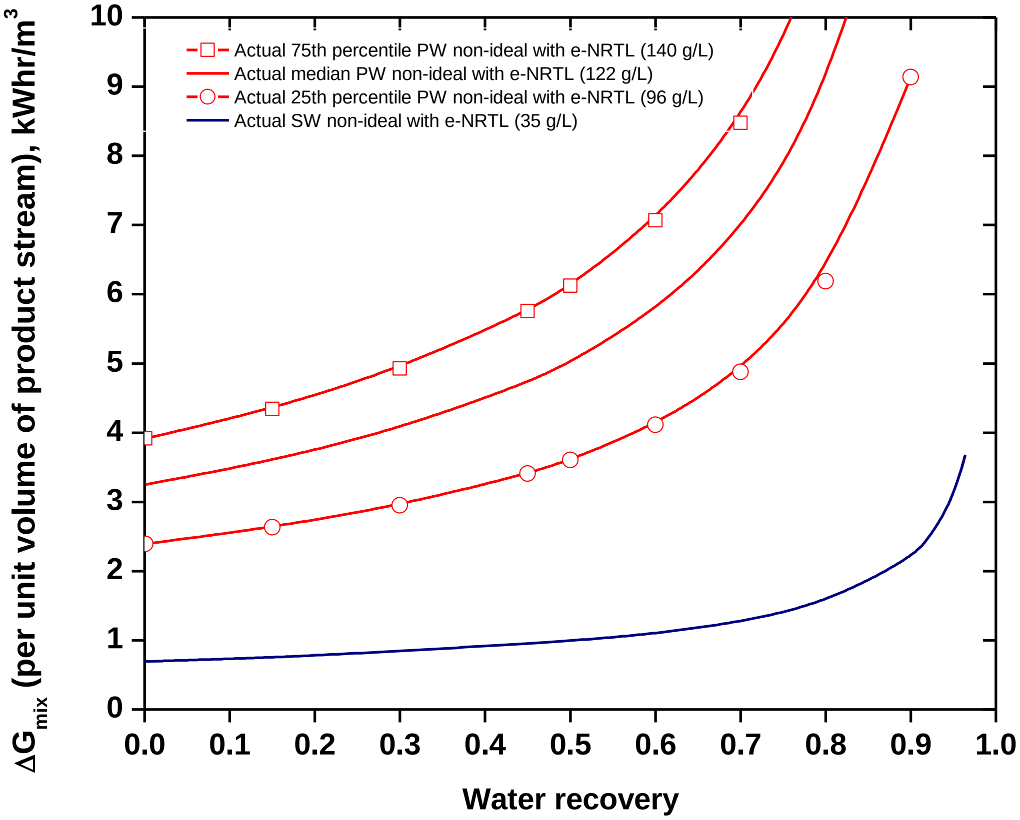

Figure 37. Comparison of thermodynamic minimum energy requirements to desalinate seawater (SW) and 25, 50 and 75 Percentile produced water (PW) as a function of fresh water recovery.

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[34] Song, Y.; Chen, C.-C., Symmetric electrolyte nonrandom two-liquid activity coefficient model. *Industrial & Engineering Chemistry Research* 2009, 48 (16), 7788-7797.

[35] Honarparvar, S.; Saravi, S. H.; Reible, D.; Chen, C.-C., Comprehensive thermodynamic modeling of saline water with electrolyte NRTL model: A study on aqueous Ba2+-Na+-Cl−-SO42− quaternary system. *Fluid Phase Equilibria* 2017, 447, 29-38.

[36] Honarparvar, S.; Saravi, S. H.; Reible, D.; Chen, C.-C., Comprehensive thermodynamic modeling of saline water with electrolyte NRTL model: A study of aqueous Sr2+-Na+-Cl−-SO42− quaternary system. *Fluid Phase Equilibria* 2018, 470, 221-231.

[37] Chen, T.; Honarparvar, S.; Reible, D.; Chen, C.-C., Thermodynamic modeling of calcium carbonate scale precipitation: aqueous Na+-Ca2+-Cl−-HCO3−-CO32−-CO2 system. *Fluid Phase Equilibria* 2022, 552, 113263.

Reverse Osmosis (RO)

Reverse osmosis is the *de facto* standard desalination technology for brackish water and seawater. Water is forced through a membrane by pressurizing above the osmotic pressure and reversing normal osmotic flow. The primary advantage of RO is its efficiency and relatively low operating cost. Table 8 summarizes our estimated treatment cost for seawater and of treating produced water at 25% ile[38]. As with all technologies in this document, seawater desalination is used as a basis for the produced water desalination estimates subject to the assumptions defined above. Because only seawater desalination data is available, the evaluation of RO for high salinity (>100,000 mg/L) produced water treatment is not currently possible as the membrane systems necessary to achieve desalination have not been demonstrated.

Table 8: Costs of treating seawater and produced water (25% ile TDS) by RO (assuming 50% recovery).

Reverse Osmosis

Feedflow	**Feedflow**	**Recovery**	**Product flow**	**Capital Cost**	**Operating Cost**		**Operating Cost per volume water**			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	8.6	0.3	0.8	0.25	0.55	0.04	0.09
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		0.9	2.4	0.68	1.71	0.11	0.27

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[38] Bhojwani, S.; Topolski, K.; Mukherjee, R.; Sengupta, D.; El-Halwagi, M. M., Technology review and data analysis for cost assessment of water treatment systems. *Science of The Total Environment* **2019,** *651*, 2749-2761.

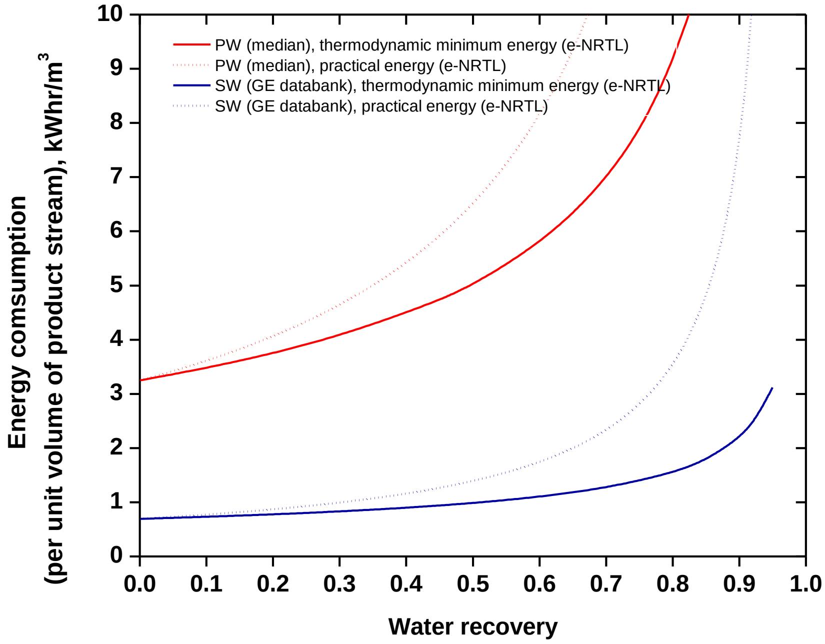

Figure 38. Comparison of thermodynamic minimum energy requirements to desalinate seawater (SW) and 25, 50 and 75 Percentile produced water (PW) as a function of fresh water recovery.

Multi-stage Flash Evaporation (MSF)

Multi-stage flash evaporation is a relatively mature technology that involves a series of stages under partial vacuum in which a portion of the feed water evaporates yielding a product water essentially free of dissolved solids and salinity. It is energy intensive in that feed water needs to be heated to 90-110 °C. Heat is recovered from the vapors at each stage to assist in this process. It can be applied to highly saline waters although scaling on heat transfer surfaces can be problematic. The technology is most efficient for large volume water treating. The primary limitation of multistage flash evaporation is that the recovery for existing facilities is limited to 20%. This is not a serious limitation for treating seawater at the coast in that feed volume can be increased to meet desired treated water targets. For produced water, however, this limitation means that MSF reduces the volume of produced water that must sent for deep well disposal by only 20%. This may not be a sufficient disposal volume to encourage large scale investment despite a relatively low cost. The estimated costs of MSF for various size facilities assuming 20% freshwater recovery are shown in Table 9.

The primary resource for capital cost is Bhojwani et al.[39] A low- and a high-cost range is shown with the primary difference being assumed process efficiencies. For seawater, the typical range

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[39] Bhojwani, S.; Topolski, K.; Mukherjee, R.; Sengupta, D.; El-Halwagi, M. M., Technology review and data analysis for cost assessment of water treatment systems. *Science of The Total Environment* **2019,** *651*, 2749-2761.

of gained output ratio defined as kg of product treated water/kg steam is 8-15.[40] For produced water, the low range operating cost is defined by the higher expected thermodynamic efficiency for highly saline systems (20%) while the high range operating cost is defined by the lower efficiency of seawater MSF desalination (about 4%).[41] Like all of these technologies, practical information obtained through pilot projects will be critical to the development of realistic cost data. Members have noted that extrapolating costs from seawater desalination can result in projected CAPEX and OPEX deficiencies, particularly through materials for construction, the loss of convenient heat sink of seawater for vapor condensing, impact of scaling/cleaning, and impact of ability to recover.

Table 9: Estimated costs of multi-stage flash evaporation for seawater and various quality produced waters assuming 20% recovery of the feedwater.

Multi-stage Flash										
Feedflow MBD	**Feedflow** MGD	**Recovery** % (v/v)	**Product flow** MGD	**Capital Cost** M$	**Operating Cost** M$/yr		**Operating Cost per volume water** $/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	Seawater									
0.048	2	20	0.40	7.98	0.6	1.1	1.05	2.02	0.17	0.32
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	20	0.40		0.8	3.4	1.42	6.08	0.23	0.97
Case	**Produced water - 50th Percentile TDS**									
0.048	2	20	0.40		1.0	4.5	1.85	8.10	0.29	1.29
Case	**Produced water - 75th Percentile TDS**									
0.048	2	20	0.40		1.2	5.4	2.20	9.71	0.35	1.54

Multi-Effect Distillation (MED)

Multi-effect distillation is also a relatively mature technology that produces freshwater at slightly lower temperatures than multi-stage flash. The system can be operated in a forward feed mode in which all streams move through stages in the same direction, backward feed when the vapors and feed move in opposite directions, and parallel feed where feed water is fed to all stages simultaneously. Recovery is typically higher than with multi-stage flash including up to 67% in some applications. However, like MSF scaling on heat transfer surfaces are an issue for produced water.

As with multi-stage flash, the primary resource for capital costs is Bhojwani et al.[1] For seawater, the typical range of gained output ratio defined as kg of product treated water/kg steam is 10-16[4]. For produced water the high range operating costs assumes the same gain output ratio as seawater case while the low range is defined by a higher thermodynamic efficiency (20%).[6] Operating costs are summarized in Table 10 for a recovery of 50%.

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[40] Al-Karaghouli, A.; Kazmerski, L. L., Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews* 2013, 24, 343-356.

[41] Thiel, G. P. Desalination systems for the treatment of hypersaline produced water from unconventional oil and gas processes. Massachusetts Institute of Technology, 2015.

Table 10: Estimated costs of multi-effect distillation for seawater and various quality produced waters assuming 50% recovery of the feedwater.

Multi-effect distillation

Feedflow	Feedflow	Recovery	Product flow	Capital Cost	Operating Cost		Operating Cost per volume water			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	7.6	1.3	2.2	0.97	1.57	0.15	0.25
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		2.4	7.2	1.75	5.20	0.28	0.83
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		3.3	9.8	2.35	7.06	0.37	1.12
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		3.9	11.8	2.82	8.52	0.45	1.35

Mechanical Vapor Compression

Mechanical vapor compression desalination uses pressure rather than temperature as the primary tool to achieve evaporation. It operates at relatively low temperatures for an evaporative technology, increasing its efficiency. The water vapor from the evaporator/condenser gets compressed producing a superheated fluid which provides the heat for the vaporization of the pre-heated feed. Relatively high recoveries (up to 40-50% are possible).

As with multi-stage flash, the primary resource for capital costs is Bhojwani et al.[42] A low and a high operating cost range is shown with the primary difference being assumed process efficiencies. Overall efficiencies range from 8-14% [5], Costs are summarized in Table 11 for a recovery of 50%. Only the lowest flowrates evaluated for other processes are shown because this technology has not been demonstrated for higher flowrates. Higher flowrates are achieved by multiple MVC systems in parallel.

Table 11: Estimated costs of MVC for seawater and various quality produced waters assuming 50% recovery of the feedwater.

Mechanical Vapor Compression

Feedflow	Feedflow	Recovery	Product flow	Capital Cost	Operating Cost		Operating Cost per volume water			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	4.90	0.7	1.2	0.49	0.88	0.08	0.14
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		1.7	4.1	1.21	2.95	0.19	0.47
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		2.3	5.6	1.66	4.05	0.26	0.64
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		2.8	6.8	2.01	4.91	0.32	0.78

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[42] Bhojwani, S.; Topolski, K.; Mukherjee, R.; Sengupta, D.; El-Halwagi, M. M., Technology review and data analysis for cost assessment of water treatment systems. *Science of The Total Environment* **2019,** *651*, 2749-2761.

Membrane distillation (MD)

Membrane distillation is a promising but less mature technology than those evaluated above. The membrane is hydrophobic allowing only vapor to pass ensuring that salts dissolved in the liquid phase are not passing through the membrane. The membrane typically has larger pores than with RO and the lack of water flux avoids some fouling issues. Condensation of liquids on the product sides slow vapor transport. Various configurations exist to correct this problem including air-gap membrane distillation which has stagnant air between the sides of the membrane and sweeping air membrane distillation minimizes vapor condensation on the membrane. Vacuum membrane distillation also ensure that condensation does not occur on the membrane surface.

Tavakkoli et al.[43] conducted a technoeconomic evaluation of MD for Marcellus produced water which typically exhibits higher salinities than Permian water. They estimated that an 1893 m^3/day facility producing 1263 m^3/day of freshwater (7944 barrels per day, 0.33 MGD) would cost $1.58 /barrel.

Table 12 summarizes our estimates for costs to treat Permian basin produced water. Note that MD has only been demonstrated at small pilot plant level scales and extrapolation to high flowrates is not supported.

Table 12: Estimated costs of MD for seawater and various quality produced waters assuming 50% recovery of the feedwater.

Membrane Distillation										
Feedflow	**Feedflow**	**Recovery**	**Product flow**	**Capital Cost**	**Operating Cost**		**Operating Cost per volume water**			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	8.9	1.5	4.7	1.11	3.41	0.18	0.54
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		6.0	16.5	4.31	11.91	0.69	1.89
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		8.3	22.8	5.97	16.46	0.95	2.62
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		10.1	27.8	7.28	20.04	1.16	3.19

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[43] Tavakkoli, S.; Lokare, O. R.; Vidic, R. D.; Khanna, V., A techno-economic assessment of membrane distillation for treatment of Marcellus shale produced water. *Desalination* 2017, 416, 24-34.

Other technologies

A variety of other technologies have been proposed for desalination. Panagopoulos[44] compared the actual energy consumption and treated product water cost for several processes including

- Membrane based processes
    - Electrodialysis metathesis (EDM)
    - Reverse osmosis (RO)
    - Nanofiltration (NF)
    - High pressure reverse osmosis (HPRO)
    - Forward osmosis (FO)
    - Electrodialysis (ED) and electrodialysis reversal (EDR)
    - Osmotically assisted reverse osmosis (OARO)
    - Membrane distillation
    - Membrane crystallization
- Thermal processes
    - Multi-effect distillation (MED)
    - Multi-stage flash evaporation (MSF)
    - Brine concentrator (BC)
    - Spray dryer (SD)
    - Eutectic freeze crystallization (EFC)
    - Brine crystallizer (BCr)

It is difficult to directly compare the analysis in Panagopoulos to those herein due to different assumptions about feed water quality, but the energy and costs reported in the manuscript can provide some indication of the relative behavior of the processes as well as provide some additional rationale for the processes evaluated in this report.

Figure 39 shows the actual energy consumption estimated by Panagopoulos for the various technologies. Although the energy consumption of the membrane processes are relatively low, they are, in general, not applicable to highly saline water streams. Intermediate in energy requirements are the thermal processes (including MSF and MED considered in this report). These processes have the advantage of being capable of addressing highly saline waters. The 5 relatively high energy processes are, except for MD, brine concentration or crystallization approaches which are not part of the current analysis.

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[44] Panagopoulos, A.; Haralambous, K. J.; Loizidou, M., Desalination brine disposal methods and treatment technologies - A review. *Sci Total Environ* 2019, 693, 133545.

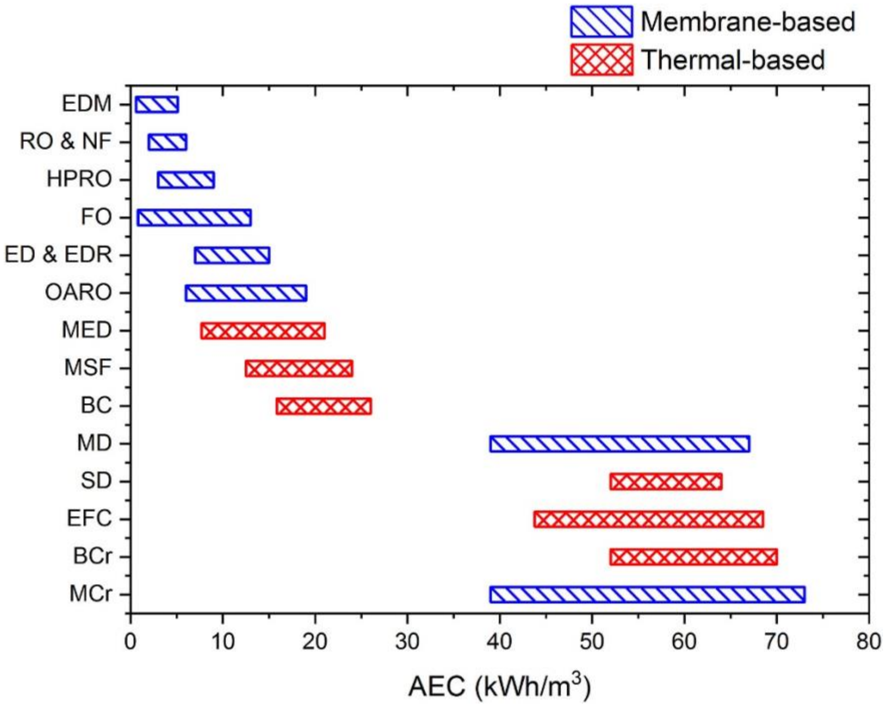

Figure 39 Actual energy consumption (AEC) for various processes from Panagopoulos[45]

Figure 40 shows the estimated costs of the treated water produced for the various processes from Panagopoulos. The only processes considered that are neither membrane-based processes nor brine concentatrion/crystallizaiton processes are MSF, MED and MD. These other processes may be appropriate for specialized applications in the future and should be considered for demonstration and evaluation for those applications. The processes discussed in this report, however, remain the processes most likely to be applicable to broad based treatment of highly saline waters with the concentrate phase remaining a liquid for deep well disposal.

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[45] *Ibid.*

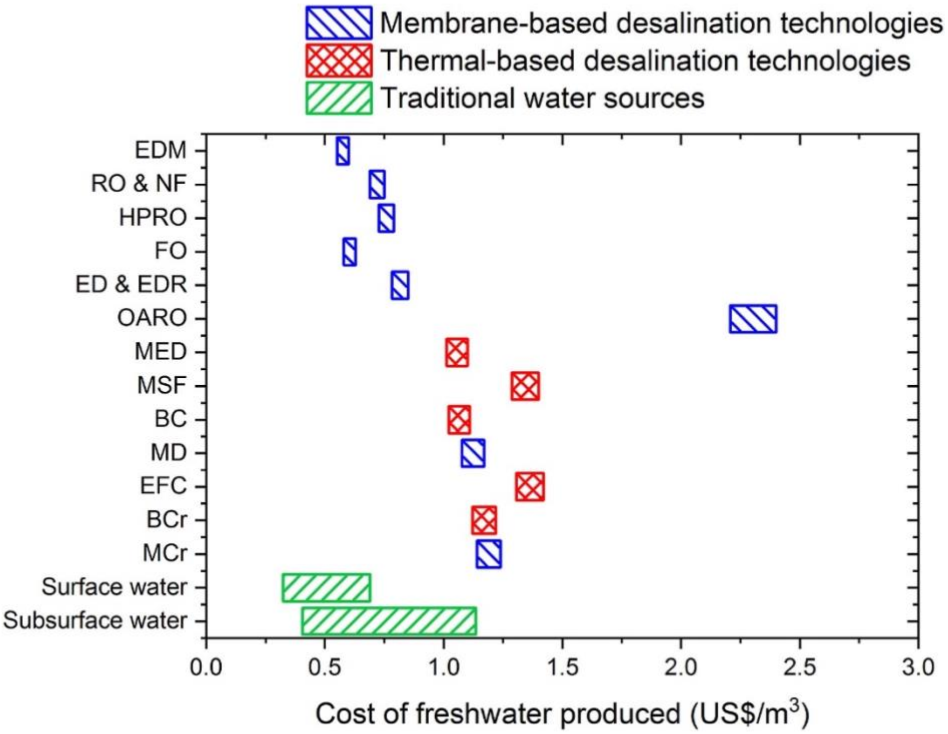

Figure 40 Cost of treated freshwater (<800 mg/L TDS) produced by the various processes from Panagopoulos[46]

Existing Produced Water Treatment Facilities

The data and analyses presented above is largely an effort to extrapolate from existing data on seawater desalination facilities to compare basic facilities for produced water desalination on a common basis (no pre- or post-treatment, no storage or transportation, no hybrid or combination technologies and operating costs only). There are existing produced water treatment facilities at both full and pilot scale which can also provide information, and most are thermal (evaporation/condensation) technologies as were the focus of the discussion here. These facilities have mostly been constructed and operated in oilfield basins other than the Permian and thus may have different economic and regulatory drivers. In the Marcellus Shale, for example, there are few disposal wells, the amount of water generated is relatively low compared to the Permian and the TDS concentration is high (i.e., greater than the Permian basin medium TDS). The latter characteristics could be viewed as a negative, but it allows the facilities to produce more easily salts and high value products such as lithium which can partially offset the cost of desalination. Thus, many of the plants that are currently operating include solids management and recovery or produce a valuable concentrated brine which are not considered in the analyses herein. These facilities also tend to exhibit higher water recoveries since one of the goals is to recover as much as possible from the produced water feed stream. Thus, the overall costs and energy requirements are typically higher than those evaluated here.

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[46] Panagopoulos, A.; Haralambous, K. J.; Loizidou, M., Desalination brine disposal methods and treatment technologies - A review. *Sci Total Environ* 2019, 693, 133545.

Although the assumptions are different the summaries provided by EPA are instructive as to the energy requirements and costs of such facilities. Table 13 compares energy requirements form mechanical vapor compression technologies by this work and operating facilities summarized by EPA 2018.[47] Although there is no perfect comparison, EPA reported energy requirements of 22-94 kWh/m^3 of treated product water using produced water 60-130 g/L, MVC-based technologies, and recoveries of 50-95%. The range we report for MVC technology treating Permian Basin produced water (90-140 g/L) and 50% recovery is 18-75 kWh/m^3 of treated product water. Higher energy requirements are associated with higher TDS and higher recovery. Although energy requirements are similar, operating costs reported by EPA tend to be significantly higher due to different assumptions about unit energy costs as well as the cost of money and return on investment which are not included in our analyses.

Table 13: Comparison of PW energy requirements in this work to that reported by EPA, 2018 for mechanical vapor compression.

ENERGY COMSUMPTION COMPARISON FOR MVC DESALINATION

	Feed TDS		Energy (KWh/m^3-product)		Reference
Type	(g/L)	Recovery	Low	High	
Theoretical estimate	35	50	7.0	12.0	This study
Theoretical estimate	95.6	50	18.0	44.0	This study
Theoretical estimate	122	50	25.1	61.3	This study
Theoretical estimate	140.1	50	30.6	74.8	This study
Vendor/Field study/Reports	110-130	50	81.8	94.35	EPA 2018
Vendor/Field study/Reports	60-80	60-90	38.6		EPA 2018
Vendor/Field study/Reports	<128	60-95	22.0	30.4	EPA 2018

We were not able to include capital costs of produced water treatment facilities in our evaluation. EPA has summarized costs for existing facilities, and these are included in Table 14[48]. Note that these facilities are relatively small (only one exceeds 0.5 MGD) and may have normalized costs that exceeds large scale operational facilities that may be developed in the future. A major goal of the TXPWC and pilot projects is to reduce this normalized treatment cost through a combination of scale and design.

Table 14: Capital Costs of PW treatment facilities (EPA, 2018).

CAPITAL COSTS

Technology Type	Feed TDS (g/L)	Capacity (MGD)	Capital cost ($/gpd)	Total Capital cost (in million $)	Total cost ($/bbl)	Cost type	Reference
MVR	45-80	0.32	NA	NA	2.57-4.5	Purchase	EPA 2018
MVR	NA	0.11	38	4.0	5.0-6.0	Purchase	EPA 2018
MVR	NA	0.05	22-44	1.7	2.0-3.0	Purchase	EPA 2018
MVR	<128	0.07	34	2.4	2.5-6.5	Purchase	EPA 2018
Evaporative	25.3-195	NA	8	NA	5.24	Purchase	EPA 2018
NA	100	NA	NA	NA	6.3-8.25	NA	EPA 2018
NA	100	NA	NA	NA	6.5-10.0	NA	EPA 2018
NA	15-230	4.2	NA	22-95	3.6-7.5	NA	Oklahoma PWWG, 2017

MVR- Mechanical Vapor Recompression

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[47] US EPA, *Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes*, EPA-821-R-18-004, 2018.

[48] *Id.*

Member Feedback and Future Issue

Establishing Bonding and Process Safeguards

Another important issue that will need to be considered if beneficial use outside of oil & gas becomes a reality: establishing bonding and process safeguards to ensure resources are available to address potential hazards and/or facility abandonment. 76% of survey respondents agreed in whole or in part with this concept, while 7% disagreed that such measures need to be established. Among the concepts for further discussion members offered ideas such as creating an industry funded treated produced water reclamation fund to insure against future liability, evaluating Pennsylvania's tiered annual renewal fee for covering releases and abandonments, and reviewing existing RRC reclamation, road base manufacturing plant bonding, commercial vs. non-commercial fluid recycling and CCUS programs along with Natural Resource Code 91.109. Some members recommended lowering the dollar value requirements for existing water recycling operations, while others indicated the existing disposal regulation bonding and safeguard processes are a good place to start. Other potential existing programs to model include RCRA and CERCLA, the John Graves General Permit through TCEQ, RRC SWR 3.1 and 3.78, and existing bonding requirements for gas processing plants and water treatment facilities in other states. There was also feedback related to going beyond just accidental releases to include any potential impacts associated with intentional reuse, and a desire to further clarify who/what is required to carry such bonding.

Summary

An analysis of a variety of potentially applicable treatment technologies leads us to the following conclusions.

- Based on theoretical evaluation using minimum energy for salt separation processes combined with estimated range of thermodynamic efficiencies for given desalination processes, there are potentially applicable technologies that may reduce disposal volume by a factor of 2 and with individual operating costs less than $1/ bbl on the basis of evaluating salts removal.
- Costs and necessity of pre- and post-treatment for further organic and inorganic treatment are a significant unknown and will increase the operating cost per barrel accordingly.
- Storage and distribution to users likely controls the economic viability of beneficial use.
- Thermal (Evaporation/Condensation) technologies can be viable options depending on configuration, waste heat availability and water recovery.
- Membrane technologies are continuing to develop but currently have limited applicability due to high osmotic pressure and scaling challenges. They may be appropriate as part of an overall treatment train.
- There is a need for pilot projects of potentially applicable technologies to determine their full potential, define efficient hybrid/combination approaches and evaluate pre and post treatment requirements.

Pilot Projects

One of the most important next steps for this Consortium is to undertake a series of pilot projects to develop and improve understanding of economically viable production scalable treatment technologies or treatment trains. While the Consortium is working to develop exact parameters for the project RFP's by the end of 2022, ideally the projects would require technology capable of treating average Permian TDS between 120,000-130,000 mg/L. The Consortium is also working to establish standards targets and/or to identify testing and analytical programs, including sampling and analysis plans and quality control/quality assurance, that will be utilized in the subsequent testing and analysis phase with treated produced water samples. The following are the proposed pilot projects:

Phase 1: Immediate Focus

- Minimum 500 barrel/day output of treatment technology equipment co-located in the Midland Basin at an existing produced water collection site, designed to provide treated produced water samples for testing and analysis of constituent characterization and risk and toxicology assessment, and operational costs. Estimated operation: 3-6 months per technology, continuing thereafter as necessary.
- Minimum 500 barrel/day output of treatment technology equipment co-located in the Delaware Basin at an existing produced water collection site, designed to provide treated produced water samples for testing and analysis of constituent characterization and risk and toxicology assessment, and operational costs. Estimated operation: 3-6 months per technology, continuing thereafter as necessary.

Phase 2: Operated as Funding and Consortium Member Interest Allows

- Establish bench scale "plug-and-play" testing facility to focus on innovative technologies and treatment-train efficacy research.
- Site analysis of existing non-Texas based produced water treatment facilities.
- Contained and monitored application testing and analysis of treated produced water on native rangeland, cotton, and/or regional edible crops to further aid in overall system knowledge regarding human health and environmental hazard and risk assessment.

Structure

Utilizing Consortium member participation and oversight, Phase 1 pilot projects will be selected and operated on their ability to treat a minimum of 500 bopd of average quality Permian Basin PW (120,000-130,000 mg/L TDS) to <1000 mg/L. The RFP process will be split into two phases. The first RFP will be location-based to find volunteer facilities with the capability to accept a third-party treatment system or containing their own treatment system, minimum of one facility in each of the Delaware and Midland basins. The second RFP will be technology based to solicit companies who can warrant they are able to meet the requirement established in the RFP. Additional considerations for pilot projects may include:

- Access to a PW volume necessary for direct feed or storage and feed to a technology or technology system.
- Access to disposal of liquids and solid wastes.
- Energy required by the treatment technology or treatment system.
- Access for testing and monitoring.

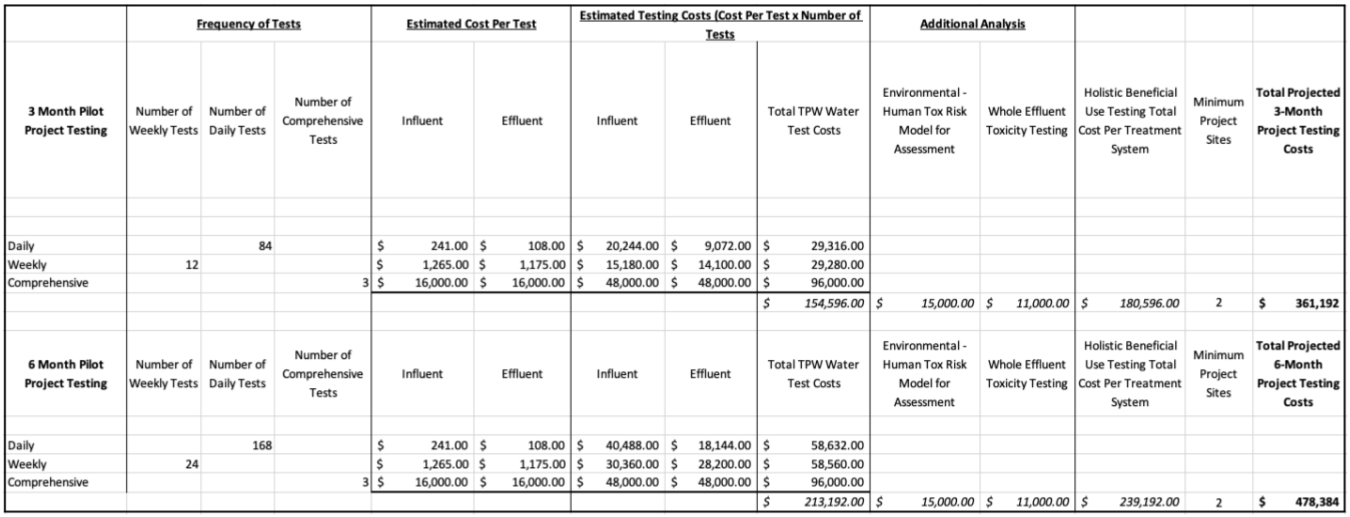
These Phase 1 Pilot Projects aim to leverage knowledge gained through NMPWRC bench scale projects to test production capacity of a treatment technology (or treatment train) to understand complete costs (CAPEX & OPEX), waste volumes and qualities, and treated produced water quality achieved. Pilot projects will require a Consortium determined set of monitoring, measuring, testing, analyzing, and reporting methods. Current Consortium member input, published papers, and existing permit requirements offer a wide range of options for monitoring and testing methods including sampled testing for analytes, WET (Whole Effluent Toxicity) testing, and Liquid Chromatography High Resolution Mass Spectrometry (qTOF) methods in addition to the risk assessment framework developed by the GWPC (see Appendix F). As mentioned previously, there has been some disagreement between members on the exact approach to testing and analysis at this time, and we are working to develop guidelines prior to releasing an RFP.

Projects in Phase 1 are designed to find the most technologically ready and scalable technology (members have indicated that a system that can reliably treat a minimum inflow of 500 barrels per day provides relative assurance of continued scalability) for achieving beneficial use. Additionally, bench scale testing ensures innovative technologies that may drive further efficiencies and/or better economics are still appropriately considered. Once membership is willing, the Consortium would aim to also test and analyze treated produced water application on soil, plants (rangeland & crops), and animals (wildlife & livestock) in contained and monitored environments to aid in the continued understanding of any potential human health and environmental impacts. These tests would at minimum be administered according to all applicable regulations and permitting requirements, along with any other necessary membership approved containment protocols to prevent and/or limit off-site exposure and transmission risks.

State Participation Needs: Funding for Testing

With such a critical focus on providing proof-of-concept through the scalable pilot projects, the associated testing and analysis of the treated water will be the lynch pin to the whole system. Funding for Phase 1 project testing will vary as Consortium members set the parameters and frequency for testing in the coming months. Proposed methods of testing and associated costs have been developed through member input and with the help of cost analysis from NMPWRC to provide an estimate. Currently one of the most expansive approaches includes a series of comprehensive analyte testing on influent and effluent water streams, potentially accompanied by daily and weekly monitoring tests and sampling. This is another area where some members are split, with other members contending that if no process or influent water quality in the treatment system is changed (which may not be feasible if located at a centralized/shared facility), daily and weekly testing should be minimized as it is likely redundant. Table 15 provides a breakdown of the potential range of cost estimates that can be adjusted depending on which method Consortium members choose (also included in Appendix L):

Table 15: Potential Testing Costs for 3- and 6-Month Pilot Projects.



	Frequency of Tests			Estimated Cost Per Test		Estimated Testing Costs (Cost Per Test x Number of Tests			Additional Analysis				
3 Month Pilot Project Testing	Number of Weekly Tests	Number of Daily Tests	Number of Comprehensive Tests	Influent	Effluent	Influent	Effluent	Total TPW Water Test Costs	Environmental - Human Tox Risk Model for Assessment	Whole Effluent Toxicity Testing	Holistic Beneficial Use Testing Total Cost Per Treatment System	Minimum Project Sites	**Total Projected 3-Month Project Testing Costs**
Daily		84		$ 241.00	$ 108.00	$ 20,244.00	$ 9,072.00	$ 29,316.00					
Weekly	12			$ 1,265.00	$ 1,175.00	$ 15,180.00	$ 14,100.00	$ 29,280.00					
Comprehensive			3	$ 16,000.00	$ 16,000.00	$ 48,000.00	$ 48,000.00	$ 96,000.00					
								$ 154,596.00	*$ 15,000.00*	*$ 11,000.00*	*$ 180,596.00*	2	**$ 361,192**
6 Month Pilot Project Testing	Number of Weekly Tests	Number of Daily Tests	Number of Comprehensive Tests	Influent	Effluent	Influent	Effluent	Total TPW Water Test Costs	Environmental - Human Tox Risk Model for Assessment	Whole Effluent Toxicity Testing	Holistic Beneficial Use Testing Total Cost Per Treatment System	Minimum Project Sites	**Total Projected 6-Month Project Testing Costs**
Daily		168		$ 241.00	$ 108.00	$ 40,488.00	$ 18,144.00	$ 58,632.00					
Weekly	24			$ 1,265.00	$ 1,175.00	$ 30,360.00	$ 28,200.00	$ 58,560.00					
Comprehensive			3	$ 16,000.00	$ 16,000.00	$ 48,000.00	$ 48,000.00	$ 96,000.00					
								$ 213,192.00	*$ 15,000.00*	*$ 11,000.00*	*$ 239,192.00*	2	**$ 478,384**

As you can see from the table, administering testing for two pilot projects over 3-6 months is estimated to run between $362,000-480,000. Attempting to operate several sets of pilot projects within a year could reach and exceed $1,000,000 for the first year, likely declining once the Consortium is comfortable with the achieved characterization and risk analysis of the initial trials' produced water samples.

Timeline

Depending on the finalization of RFP's and selected location and technology-based applicants, the Consortium would ideally like to have projects selected no later than Q2 2023 with start dates pending any state appropriation. Consortium members will also decide on length of project trials, currently identified between 3-6 months per project.

Critical Components of RFP

Members have added several ideas for RFP inputs that will continue to be considered, including ensuring zero-discharge, uptime expectations, focusing on determining full-treatment costs (including operations and maintenance, energy, and appropriate solids management), utilizing grid electricity or natural gas as the most reliable forms of energy as opposed to waste heat, and making sure that certain standards targets are established prior to adoption of an RFP.

Water Quality Standards

This chapter discusses the water quality requirements for typical non-oil and gas sector water uses. It also presents a discussion on current data gaps, future research and application directions that are necessary for establishing water quality standards for various end uses.

Introduction

Over 400,000 acre-feet of produced water is disposed annually using deep well injection methods within the Permian Basin region of Texas.[49] Being a semi-arid region with limited water resources, this water has the potential to mitigate some of the current and projected water deficits in West Texas.[50] The disposal of produced water has also contributed to increased seismic activity in recent times.[51,52] Therefore, reuse of produced water outside of the oil and gas industry could be beneficial if it can be proven that treatment technologies can efficiently and economically treat water to a quality that is acceptable for other end users and is protective of human health and the environment.

While there is a growing interest in reusing produced water in non-oil and gas applications, doing so is not without challenges. The quality of Permian produced water will require additional treatment prior to its use. Additional consideration should be given to constituents within the produced water that may pose risks to human health and the environment, not only for their potential presence in treated effluents, but also from risks or spills that may occur while raw water is transported and stored prior to any treatment. In addition, there could be residual constituents in the produced water (even after treatment) whose impacts on an intended use may not fully be known at this stage. All these factors are important when reuse of produced water is considered in any given sector.

Water quality standards (WQS) are provisions of state, territorial, authorized tribal or federal law approved by EPA that describe the desired condition of a water body and the means by which that condition will be protected or achieved.[53] This definition implies that standards mainly focus on evaluating whether a water source is fit for a given purpose. As stated earlier, treatment technologies are often required to make the source water fit for a given purpose. In addition, if the source water contains constituents of concern, additional care must be taken to ensure that the source water is stored and transported properly. The treatment of produced water will result in generation of concentrated brine that may include elevated levels of many constituents of concern. Therefore, disposal of waste concentrate is also an important aspect of overall produced water reuse.

The primary focus of this chapter is to better understand what is known or available in current standards or guidelines that could inform the ongoing discussion between Consortium

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[49] Railroad Commission of Texas, https://www.rrc.state.tx.us/, 2022

[50] Br.Scanlon,https://www.researchgate.net/publication/339307492_Will_Water_Issues_Constrain_Oil_and_Gas_Production_in_the_US

[51] Railroad Commission of Texas, "Seismicity Response," https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response/

[52] Texas Seismological Network, https://earthquake.usgs.gov/data/comcat/contributor/tx/ 2022.

[53] EPA, "What are water quality standards?" https://www.epa.gov/standards-water-body-health/what-are-water-quality-standards#:~:text=Water%20quality%20standards%20(WQS)%20are,will%20be%20protected%20or%20achieved

members in developing recommended guidance on water quality standards that would be necessary to treat produced water to a quality that is fit for a given use.

Caveats, Assumptions and Limitations

While there is a growing interest in reusing treated produced water in many sectors, much of the work carried out to-date is still at laboratory or small-scale piloting stages.[54] As such, the potential impacts of reusing produced water at field scale is largely unknown for most applications. The lack of hazard and risk assessment is perhaps the most significant limitation of this study. The Texas Produced Water Consortium will continue to track efforts in this area and update this document as more studies become available and when it is possible and necessary to do so.

The reuse of treated produced water for numerous variable end-uses to address challenges associated with drought and dwindling water resources facing many Texas water users is certainly an ideal end-goal. However, questions still exist with regards to a detailed characterization of the produced water and the likely risks to human health and the environment posed by constituents within the produced water.[55,56,57,58,59,60] Based on the feedback from the stakeholders of the Texas Produced Water Consortium, given the current state-of-the-knowledge, and the constraints of time, both direct and indirect potable reuse were not considered in this study. Therefore, no attempt was made to study the water quality standards for potable water use. The consortium will continue to engage with its stakeholders and other researchers and regulatory agencies to address this issue in the future.

It may be more practical to treat produced water for certain applications, such as industrial use or agricultural applications, which are discussed in this report below. Members have also expressed interest in studying the possible effects of potential ammonia concentrations in treated produced water and their possible application for irrigated agriculture use. Studies on the blending of saline (brackish and seawater) and fresh waters in other provide insight to the potential for conjunctive use of treated produced water and freshwater to minimize potential

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[54] NAE, *Flowback and produced waters: opportunities and challenges for innovation: proceedings of a workshop of the National Academies of Sciences Engineering and Medicine and others*. National Academies Press, 2017.

[55] P. Xu, Y. Zhang, W. Jiang, L. Hu, X. Xu, K. C. Carroll, and N. Khan, *CHAR- ACTERIZATION OF PRODUCED WATER IN THE PERMIAN BASIN FOR POTENTIAL BENEFICIAL USE NM WRRI Technical Completion Report No.398*. ”New Mexico Water Resources Institute, 2022.

[56] R. V. Emmons, G. S. Shyam Sunder, T. Liden, K. A. Schug, T. Y. Asfaha, J. G. Lawrence, J. R. Kirchhoff, and E. Gionfriddo, “Unraveling the complex composi- tion of produced water by specialized extraction methodologies,” *Environmental Science & Technology*, vol. 56, no. 4, pp. 2334–2344, 2022.

[57] C. Danforth, J. McPartland, J. Blotevogel, N. Coleman, D. Devlin, M. Olsgard, T. Parkerton, and N. Saunders, “Alternative management of oil and gas produced water requires more research on its hazards and risks,” *Integrated environmental assessment and management*, vol. 15, no. 5, pp. 677–682, 2019.

[58] P. Xu, Y. Zhang, W. Jiang, L. Hu, X. Xu, K. C. Carroll, and N. Khan, *CHAR- ACTERIZATION OF PRODUCED WATER IN THE PERMIAN BASIN FOR POTENTIAL BENEFICIAL USE NM WRRI Technical Completion Report No.398*. ”New Mexico Water Resources Institute, 2022.

[59] R. V. Emmons, G. S. Shyam Sunder, T. Liden, K. A. Schug, T. Y. Asfaha, J. G. Lawrence, J. R. Kirchhoff, and E. Gionfriddo, “Unraveling the complex composi- tion of produced water by specialized extraction methodologies,” *Environmental Science & Technology*, vol. 56, no. 4, pp. 2334–2344, 2022.

[60] C. Danforth, J. McPartland, J. Blotevogel, N. Coleman, D. Devlin, M. Olsgard, T. Parkerton, and N. Saunders, “Alternative management of oil and gas produced water requires more research on its hazards and risks,” *Integrated environmental assessment and management*, vol. 15, no. 5, pp. 677–682, 2019.

crop yield losses and prolong the useful life of scarce and nonrenewable freshwater resources such as the Ogallala Aquifer.[61,62] The Consortium is also aware of a number of bench-scale trials currently evaluating produced water and produced water blended with fresh water on crops, specifically cotton, in Texas and Colorado. These are questions the Consortium will continue to study through pilot projects and the input of users across the stakeholder spectrum.

While the focus of this chapter is on water quality standards that may be required for various end-uses, it is important to be clear that the Texas Produced Water Consortium does not have the regulatory authority to set standards. Therefore, this section is aimed at compiling existing standards and a foundational understanding of the end use needs of various applications. The Consortium will continue to utilize this baseline information with data gathered from produced water treatment pilot projects to validate or identify recommendation for fit-for-purpose treated produced water quality standards for various uses that protect public health and the environment. Another purpose here is to document data and knowledge gaps that currently exist that may limit the use of produced water as an alternative source of water for meeting water needs outside of the oil and gas industry. The purpose here is to document what is currently known and the likely concerns associated with current water quality guidelines that are available. **The research presented here must not be construed to represent treatment level requirements for produced water in totality or as being endorsed as appropriate end use standards by the authors of this report or the Texas Produced Water Consortium.**

In the remainder of this chapter, water quality considerations for various common applications are discussed with a goal of identifying and tabulating generally acceptable criteria based on existing knowledge and practices for commonly used waters. To the extent possible, a short discussion of how the constituents of the produced water can affect the intended use is also presented to place the standards in perspective.

Water Quality - Construction Activities

Water is an essential ingredient in construction activities. It is primarily used for mixing concrete, curing concrete, cleaning sands to wash out low strength materials such as clays and in general improve the workability characteristics of materials, especially slurries of cement and concrete. Water is also used for making asphalt emulsions and there is a growing interest in using cold and warm asphalt mixes to reduce high carbon emissions associated with the hot mix process.[63, 64]

The primary goals of construction activities include - 1) The constructed structure must withstand the design loads and not fail prematurely; 2) The structure must not alter the environment by causing unwanted emissions and exposures; examples include organic

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[61] K. F. I. Murad, A. Hossain, O. A. Fakir, S. K. Biswas, K. K. Sarker, R. P. Rannu, and J. Timsina, "Conjunctive use of saline and fresh water increases the productivity of maize in saline coastal region of Bangladesh," *Agricultural Water Management*, vol. 204, pp. 262–270, 2018.

[62] P. Gowda, R. Bailey, I. Kisekka, X. Lin, and V. Uddameri, "Featured series introduction: Optimizing Ogallala aquifer water use to sustain food systems," 2019.

[63] M. E. Abdullah, K. A. Zamhari, R. Buhari, S. K. A. Bakar, N. H. M. Kamarud- din, N. Nayan, M. R. Hainin, N. A. Hassan, S. A. Hassan, and N. I. M. Yusoff, "Warm mix asphalt technology: a review," *Jurnal Teknologi*, vol. 71, no. 3, 2014.

[64] S. Jain and B. Singh, "Cold mix asphalt: An overview," *Journal of Cleaner Production*, vol. 280, p. 124378, 2021.

emissions in indoor air and infiltration of contaminants from road surfaces during rainfall events; and 3) The materials used for construction, particularly surfaces that interact with the natural environment and living beings (e.g., pavements), must not exhibit excessive wear and tear than what is to be typically expected. Excessive repairs and rehabilitation of constructed structures are not only expensive, but can lead to hazardous conditions, cause unwanted inconveniences, and affect the overall quality of life within a region. In addition, potential short- and long-term exposures to workers at construction sites arising from the use of water is also an important factor to consider when evaluating the reuse of produced water in construction activities.

The efforts by the construction industry to reduce its environmental footprint, enhanced emphasis on recycling and scarcity of freshwater are some of the factors that promote the use of less quality waters in construction activities. In particular, understanding the impacts of using saline water on construction material strength has been an active area of research. Much of the interest in using highly saline water or understanding salinity impacts on construction are driven by activities in coastal areas and potential interactions of road construction materials with road salts in cold climates as well as structures built to store high salinity waters (e.g., cooling towers). The literature focused on using produced water from oil and gas operations is extremely sparse. One study on the use of produced and brackish water in concrete mixtures out of Oman provides useful insights related to how the use of high salinity water affects construction activities, and therefore can help better understand the water quality requirements of the construction industry.[65]

Cement, concrete, steel and asphalt are the most common construction materials used for large-scale construction. Therefore, the focus of this study will be the likely impacts of using produced water in construction with these materials.

Cement

Special grades of cement have been developed for use in structures that interact with highly saline waters. In particular, the API Grade G and Grade H cements are used for construction of boreholes and wells in the oil and gas industry. These cements can withstand waters of high salinity. The ordinary portland cement (OPC) typically used for general construction does not exhibit higher durability when used with saline waters. However, the strength of the cement can be improved by using it in conjunction with other materials (e.g., fly-ash) to create geopolymers.[66, 67] The presence of clays and microbial growth also affect the strength properties of cement mixes, especially when they are mixed with waters of higher salinity.[68]

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[65] R. A. Taha, A. S. Al-Harthy, and K. S. Al-Jabri, “Use of production and brackish water in concrete mixtures,” *International Journal of Sustainable Water and Environmental System*, vol. 1, no. 2, pp. 39–43, 2010.

[66] H. M. Giasuddin, J. G. Sanjayan, and P. Ranjith, “Stress versus strain behav ior of geopolymer cement under triaxial stress conditions in saline and normal water,” *Development*, vol. 2, no. 3, p. 12, 2013.

[67] P. Thirumakal, M. Nasvi, and K. Sinthulan, “Comparison of mechanical be- haviour of geopolymer and opc-based well cement cured in saline water,” *SN Applied Sciences*, vol. 2, no. 8, pp. 1–17, 2020.

[68] S. Horpibulsuk, W. Phojan, A. Suddeepong, A. Chinkulkijniwat, and M. D. Liu, “Strength development in blended cement admixed saline clay,” *Applied clay science*, vol. 55, pp. 44–52, 2012.

Cement mixes made with saline water typically exhibit lower compressive strength and may take longer times to cure. The presence of salts can also cause chemical interactions that reduce the strength of the cement compared to cements mixed with normal water.[69] As a rule-of-thumb, in purely cement-based construction, water of any salinity can be used as long as the strength reductions are likely to be within 10% of that obtained using high quality water.[70]

Concrete

Concrete is the second most used material in the world after water. It is an ad-mixture of cement, coarse grained particles (gravel) and fine-grained particles (sands) of varying proportions. The quality of water used to prepare concrete has a profound influence on its structural properties and the failure modes a structure can experience.[71, 72, 73] In the US, the American Society of Testing and Materials (ASTM), prescribes certain water quality requirements ASTM C94-1996 for ready mix concrete and ASTM 1602M-06 for the production of hydraulic cement concrete. The water quality requirements from these documents are summarized in Table 16.[74]

Table 16: ASTM Specifications for Ready-Mix Concentrate.

Constituent	Requirement	Remarks
Total Dissolved Solids (TDS)	≤ 50000	mg/L
pH	4.5 - 8.5	≥ 6 preferred
Total Alkalinity	≤600	mg/L as $CaCO_3$
Sulfate (SO_4^{2-})	≤3000	mg/L
Chloride (Cl^-)	≤4000	mg/L
Total Suspended Solids (TSS)	≤ 2000	mg/L
Oil and Grease (mineral oil)	2%	by wt of concrete
Total Iron	2%	by wt of concrete

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[69] H. M. Giasuddin, J. G. Sanjayan, and P. Ranjith, “Stress versus strain behav-ior of geopolymer cement under triaxial stress conditions in saline and normal water,” *Development*, vol. 2, no. 3, p. 12, 2013.

[70] F. Saleh, R. Rivera, S. Salehi, C. Teodoriu, and A. Ghalambor, “How does mixing water quality affect cement properties,” in *SPE International Conference and Exhibition on Formation Damage Control*, OnePetro, 2018.

[71] O. A. Qasim, B. H. Maula, H. H. Moula, and S. H. Jassam, “Effect of salinity on concrete properties,” in *IOP Conference Series: Materials Science and Engineering*, vol. 745, p. 012171, IOP Publishing, 2020.

[72] R. A. Taha, A. S. Al-Harthy, and K. S. Al-Jabri, “Use of production and brackish water in concrete mixtures,” *International Journal of Sustainable Water and Environmental System*, vol. 1, no. 2, pp. 39–43, 2010.

[73] T. Dhondy, Y. Xiang, T. Yu, and J.-G. Teng, “Effects of mixing water salinity on the properties of concrete,” *Advances in Structural Engineering*, vol. 24, no. 6, pp. 1150–1160, 2021.

[74] D. G. Daniel and C. L. Lobo, *User’s Guide to ASTM Specification C-94 on Ready-mixed Concrete*. ASTM International, 2005.

Reinforced Concrete, Steel, Other Metals

Concrete as a material offers excellent compressive strength but does not do well under tensile loads. Therefore, reinforcements are added to improve the tensile strength of concrete. The most common reinforcement material is steel but other materials such as fiber-reinforced plastics (FRP) are also used. The risk of corrosion damage is the most important factor that limits the use of produced water with steel construction. Higher grade stainless steel is expensive and while it may used in small scale applications such as oil-water separators and produced water treatment, its use in large-scale construction will be cost prohibitive. The water quality requirements for use with steel reinforced cement concrete (RCC) tends to be more stringent with regards to the presence of total dissolved solids (TDS), sulfates and chlorides as compared to water use in concrete without steel reinforcements.

Table 17: ASTM Specification for Steel Reinforced Cement Concentrate[75]*.*

Constituent	Requirement	Remarks
Total Dissolved Solids (TDS)	≤ 2000	mg/L
pH	4.5 - 8.5	≥ 6 preferred
Total Alkalinity	≤400	mg/L as $CaCO_3$
Sulfate (SO^{2-}) 4	≤400	mg/L
Chloride (Cl^{-})	≤500	mg/L
TSS	≤ 2000	mg/L
Oil and Grease (mineral oil)	2%	by wt of concrete
Total Iron	2%	by wt of concrete

While the construction of steel structures does not involve the use of water, the corrosion of steel due to prolonged exposure to water is of concern. Typically, steel structures that are likely to come in contact with water are coated with hydrophobic substances (water repellents) to prevent direct contact with water and thus minimize the risks of corrosion.

Aluminum alloys are also widely used in construction applications as it offers higher resistance to corrosion compared to steel. However, these alloys can undergo local corrosion effects due to material defects and imperfections. One study suggests that aluminum alloys with magnesium (Mg) and zinc (Zn) can undergo biocorrosion caused by the presence of fungi such as *A. Nigher* which are fairly ubiquitous in saline environments.[76] This biocorrosion can be both uniform and localized depending upon the attachment characteristics of the microbes. The excretion of organic acids was noted to be the primary cause of corrosion which led to reductions of pH. While the study was conducted under controlled conditions and focused on inorganic salinity, the presence of organic acids in produced water and those arising during its treatment could pose problems in the use of produced water with construction materials based

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[75] D. G. Daniel and C. L. Lobo, *User's Guide to ASTM Specification C-94 on Ready-mixed Concrete*. ASTM International, 2005.

[76] J. Wang, F. Xiong, H. Liu, T. Zhang, Y. Li, C. Li, W. Xia, H. Wang, and H. Liu, "Study of the corrosion behavior of aspergillus niger on 7075-t6 aluminum alloy in a high salinity environment," *Bioelectrochemistry*, vol. 129, pp. 10–17, 2019.

on aluminum alloys. Additional insights from oil and gas producers with regards to the use of storage structures constructed from aluminum alloys could be useful to evaluate the performance of these materials that come in contact with produced water.

Asphalt

Asphalt is another widely used material in construction of roads and pavements. Asphalt is a naturally occurring material (also called bitumen) and combined with sand and gravel to create asphalt concrete. Bitumen, serves as the binding agent and is particularly useful to create water repellent, smooth surfaces, two characteristics that improve the safety of the drivers and the quality of the driving experience.

Hot mix asphalt (HMA) is the most common method for producing construction grade asphalt concrete. The fugitive emissions associated with this procedure has led to preparation techniques such as the warm mix asphalt (WMA) which is now used in about 30% of road construction activities in the US. Experiments are currently underway to create cold mix asphalt.[77,78] However, water use in asphalt-based construction, especially in HMA and WMA, is fairly low. Elevated ions in the water can interfere with the asphalt binding process and reduce the adhesion between the asphalt and the rock mixtures due to reduced interfacial tension.[79, 80]

Major Findings

The use of treated produced water in construction may be feasible when the construction largely involves cement concrete. The ASTM standards suggest that the quality of water used for mixing and curing concrete can be lower than typical freshwater as long as the loss in strength is within 10% of what would be obtained using fresh water. Some experimentation may be necessary to ascertain if such is the case, prior to any use. The use of treated produced water is more problematic with steel and asphalt materials as they have higher water quality requirements and the general recommendation is to use potable water with these applications.

Thermoelectric Uses

The US thermoelectric sector is the largest (non-consumptive) user of water. Water is largely used as a coolant to remove waste heat that is generated as part of the electric generation process and may then be discharged to surface waters in compliance with Clean Water Act (CWA) National Pollutant Discharge Elimination System permits (NPDES) issued by EPA or states.[81] Co-location of desalination and power plants is noted to be advantageous as the waste heat can be used to reduce the energy and carbon footprint associated with the desalination

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[77] M. E. Abdullah, K. A. Zamhari, R. Buhari, S. K. A. Bakar, N. H. M. Kamarud- din, N. Nayan, M. R. Hainin, N. A. Hassan, S. A. Hassan, and N. I. M. Yusoff, "Warm mix asphalt technology: a review," *Jurnal Teknologi*, vol. 71, no. 3, 2014.

[78] S. Jain and B. Singh, "Cold mix asphalt: An overview," *Journal of Cleaner Production*, vol. 280, p. 124378, 2021.

[79] N. Baldino, R. Angelico, P. Caputo, D. Gabriele, and C. O. Rossi, "Effect of high water salinity on the adhesion properties of model bitumen modified with a smart additive," *Construction and Building Materials*, vol. 225, pp. 642–648, 2019.

[80] N. Voutchkov, "Seawater desalination costs cut through power plant co-location," *Filtration & separation*, vol. 41, no. 7, pp. 24–26, 2004.

[81] EPA, "Steam Electric Power Generating Effluent Guidelines," https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines.

process.[82, 83] In particular, direct contact membrane distillation (DCMD) was reported to effectively utilize waste heat and recover about 65% of water regardless of the produced water concentration using a calibrated modeling study.[84]

In determining a potential fit-for-purpose quality of treated produced water for thermoelectric uses there are considerations arising specifically from salt concentrations that must be taken into account. Infrastructure modifications may effectively handle issues of scaling and corrosion, but dissolved salts lower the vapor pressure of water which in turn causes a decrease in thermal efficiency. This reduced thermal efficiency will in turn result in a bigger cooling tower to achieve same cooling as with freshwater and also increases the power consumption. It is estimated that there will be a decrease in performance efficiency of about 1.1% for every 10,000 mg/L of TDS in the water or about 5% decrease in the overall efficiency for a 50,00 mg/L water.[85, 86]

While it may be possible to use treated produced water for cooling applications, the variability in water quality, the availability of water on a steady basis and potential loss of efficiencies must be taken into account and further evaluated prior to making a recommendation. While specific standards have not been prescribed, some problematic constituents are noted to be - calcium (Ca^{+2}), sulfate (SO_4^{2-}); chloride (Cl^-) and ammonium (NH_4^+) and pH <6.5 (acidic solutions cause corrosion). In addition, the presence of microbes in the water can also lead to biofouling (biocides may aid in controlling this issue). Accidental exposures from organic compounds present in the produced water could also be a concern, especially if their concentrations are at an elevated level (above permissible indoor air quality standards).

Agricultural Uses

Irrigated agriculture is the largest user of water in the world. With increasing water scarcity, there is a growing interest in using produced water for meeting crop water needs. Results to date have largely been mixed. A greenhouse study evaluated the potential beneficial reuse of produced water to grow wheat using various dilutions of produced water.[87] The results from this study indicated that irrigation with even 5% produced water dilution led to decreases in soil health, microbial diversity and crop yields. Another study concluded that the treatment of produced water (specific to that region) for agricultural standards was feasible and cost effective compared to certain disposal costs in Colorado.[88] In a simulation study in Qatar, produced water was blended with treated sewage (municipal wastewater) for irrigation of

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[82] *Id.*

[83] K. Elsaid, E. T. Sayed, B. A. Yousef, H. Rabaia, Malek Kamal, M. Abdelkareem, and O. Ali, "Recent progress on the utilization of waste heat for desalination: A review," *Energy conversion and management*, vol. 221, p. 113105, 2020.

[84] O. R. Lokare, S. Tavakkoli, G. Rodriguez, V. Khanna, and R. D. Vidic, "In- tegrating membrane distillation with waste heat from natural gas compressor stations for produced water treatment in pennsylvania," *Desalination*, vol. 413, pp. 144–153, 2017.

[85] J. Maulbetsch, M. DiFilippo, and C. Performance, "Environmental effects of saltwater cooling towers," *California Energy Commission, PIER Energy-related Environmental Research Program, Berkeley, CA*, 2008.

[86] C. Harto, M. Finster, J. Schroeder, and C. Clark, *Saline water for power plant cooling: challenges and opportunities*. Argonne National Lab.(ANL), Argonne, IL (United States), 2014.

[87] H. Miller, K. Dias, H. Hare, M. A. Borton, J. Blotevogel, C. Danforth, K. C. Wrighton, J. A. Ippolito, and T. Borch, "Reusing oil and gas produced water for agricultural irrigation: Effects on soil health and the soil microbiome," *Science of the Total Environment*, vol. 722, p. 137888, 2020.

[88] F. C. Dolan, T. Y. Cath, and T. S. Hogue, "Assessing the feasibility of using produced water for irrigation in colorado," *Science of The Total Environment*, vol. 640, pp. 619–628, 2018.

sugar beet (a salt tolerant crop).[89] While this theoretical study identified produced water as a potential alternative source of irrigation water, the conditions in Qatar (i.e., the extreme water scarcity) is not directly applicable to this study.

Agriculture is a major water user in West Texas and accounts for nearly 90% of the total water use. The major crops grown in this area include cotton, corn, sorghum and winter wheat. Peanut farming is localized to areas in Gaines County where the soils are sandy (a requirement for peanut crop). Of the major crops, cotton and sorghum exhibit higher tolerances to water quality compared to corn. The water requirements for corn are also high and its production in West Texas is not possible without irrigation. Smaller aquifer depths and higher levels of depletion has limited corn production in southern parts of the High Plains of Texas.

Water quality requirements of irrigation are not standardized and can vary due to several factors, which include - 1) The plant cultivar, 2) The water availability in the region; 3) the farmers tolerance of yields and lower revenues 4) precipitation patterns in the region, especially the timing of rainfall events that can help limit the amount irrigation water needed and 5) water markets and other alternatives that can be profitable compared to irrigated agriculture (e.g., selling water for oil and gas production, placement of land into conservation reserve program).

As the need for new water sources increases, produced water isn't the only new resource being evaluated. The large availability of brackish groundwater in geological units underlying the Ogallala and other major aquifers has led to a renewed interest in exploring the potential of using lower quality waters in agriculture.[90,91,92] In particular, there has been a growing interest in producing cotton using brackish and produced water at various freshwater blended ratios.[93, 94, 95,96,97] Further research is being conducted to determine if cotton lint yields are comparable by water quality and may indicate potential for reusing treated produced water for non-edible crop production.[98]

Elevated levels of salt in irrigation water affects plant growth in many ways. The application of the saline water causes changes to the soil structure and affects its permeability. The ion-exchange between water and soil minerals cause these changes. The reduction of permeability

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[89] A. Echchelh, T. Hess, and R. Sakrabani, "Agro-environmental sustainability and financial cost of reusing gasfield-produced water for agricultural irrigation," *Agricultural Water Management*, vol. 227, p. 105860, 2020.

[90] S. Kalaswad, B. Christian, and R. Petrossian, "Brackish groundwater in TexasTexas,-"*The future of desalination in Texas*," vol. 2, 2004.

[91] J. E. Meyer, M. R. Wise, and S. Kalaswad, *Pecos Valley aquifer, West Texas: structure and brackish groundwater*. Citeseer, 2012.

[92] V. Uddameri and D. Reible, "Food-energy-water nexus to mitigate sustain- ability challenges in a groundwater reliant agriculturally dominant environment (grade)," *Environmental Progress & Sustainable Energy*, vol. 37, no. 1, pp. 21–36, 2018.

[93] K. Wei, J. Zhang, Q. Wang, Y. Guo, and W. Mu, "Irrigation with ionized brackish water affects cotton yield and water use efficiency," *Industrial Crops and Products*, vol. 175, p. 114244, 2022.

[94] G. Yang, F. Li, L. Tian, X. He, Y. Gao, Z. Wang, and F. Ren, "Soil physicochemical properties and cotton (gossypium hirsutum l.) yield under brackish water mulched drip irrigation," *Soil and Tillage Research*, vol. 199, p. 104592, 2020.

[95] I. Sharif, S. Aleem, J. Farooq, M. Rizwan, A. Younas, G. Sarwar, and S. M. Chohan, "Salinity stress in cotton: effects, mechanism of tolerance and its management strategies," *Physiology and Molecular Biology of Plants*, vol. 25, no. 4, pp. 807–820, 2019.

[96] K. Lewis, J. Moore, and B. Weathersby, "Agricultural Reuse of Treated Produced Water." https://www.owrb.ok.gov/2060/PWWG/Resources/Lewis_Katie.pdf, 2022.

[97] Id.

[98] Id.

limits the amount of water reaching the root zone and affects the water use efficiency. Salts present in the water are also expelled initially in the root zone (a process similar to membrane desalination). The accumulation of these salts however reduces the water uptake in the long run (i.e., over the growing season). Elevated salts in water taken up by the plants can affect the pH, cause sodium toxicity as well as other physiological impacts that stunt the plant growth and cause yield reductions.[99] Recent research indicates that while cotton cultivars can tolerate up to 6000 ppm of dissolved solids in water, there were noticeable yield reductions and sustained use of such water for irrigation purposes was not optimal.[100, 101] Even with low salinity produced water the risks of sodium toxicity and elevated boron concentrations were noted to be higher compared to groundwater in California.[102]

The reductions of leaf areas and a plants ability to expand its leaf are both affected by salinity stresses. The reduction of average leaf area leads to reductions of net photosynthesis while the reduction in the ability to expand the overall leafy biomass led to diminished total photosynthesis. While the reductions of average leaf area were noted for elevated levels of salinity in sorghum, the impacts of total leaf biomass were noted with lower salinity levels as well.[103] The use of highly saline water had bigger impacts on the germination and early growth stages of sorghum than crop yield losses at maturity.[104, 105] Salinity in general was noted to reduce carbon dioxide absorption from the atmosphere and reductions in plant evapotranspiration due to inefficient stomatal conductance, which not only affect plant growth but can also affect greenhouse gas emissions and affect long-term precipitation dynamics both within the region as well as on a larger regional scale.[106, 107, 108]

The interaction between soil texture and salinity also plays an important role in determining the effects of saline water irrigation on plant growth. Field studies indicate that salinity effects on corn and soybean yields was less in sandy loam soil compared to those in silty loam.[109] Calcium (Ca) is noted to play a major role in fighting salinity stresses as it helps maintain the integrity of the root membrane. In- creased ionic strength can cause calcium displacement from cell membranes and lead to salinity stresses. In addition to the more common sodium (Na) and

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[99] I. Sharif, S. Aleem, J. Farooq, M. Rizwan, A. Younas, G. Sarwar, and S. M. Chohan, "Salinity stress in cotton: effects, mechanism of tolerance and its management strategies," *Physiology and Molecular Biology of Plants*, vol. 25, no. 4, pp. 807–820, 2019.

[100] K. Wei, J. Zhang, Q. Wang, Y. Guo, and W. Mu, "Irrigation with ionized brackish water affects cotton yield and water use efficiency," *Industrial Crops and Products*, vol. 175, p. 114244, 2022.

[101] G. Yang, F. Li, L. Tian, X. He, Y. Gao, Z. Wang, and F. Ren, "Soil physicochemical properties and cotton (gossypium hirsutum l.) yield under brackish water mulched drip irrigation," *Soil and Tillage Research*, vol. 199, p. 104592, 2020.

[102] A. J. Kondash, J. H. Redmon, E. Lambertini, L. Feinstein, E. Weinthal, L. Cabrales, and A. Vengosh, "The impact of using low-saline oilfield produced water for irrigation on water and soil quality in California, "*Science of The Total Environment*," vol. 733, p. 139392, 2020.

[103] G. W. Netondo, J. C. Onyango, and E. Beck, "Sorghum and salinity: Ii. gas exchange and chlorophyll fluorescence of sorghum under salt stress," Crop science, vol. 44, no. 3, pp. 806–811, 2004.

[104] E. Maas, J. Poss, and G. Hoffman, "Salinity sensitivity of sorghum at three growth stages," *Irrigation Science*, vol. 7, no. 1, pp. 1–11, 1986.

[105] H. Esechie, "Interaction of salinity and temperature on the germination of sorghum," *Journal of Agronomy and Crop Science*, vol. 172, no. 3, pp. 194–199, 1994.

[106] K. J. Harding and P. K. Snyder, "Modeling the atmospheric response to irrigation in the great plains. part ii: The precipitation of irrigated water and changes in precipitation recycling," *Journal of Hydrometeorology*, vol. 13, no. 6, pp. 1687– 1703, 2012.

[107] A. DeAngelis, F. Dominguez, Y. Fan, A. Robock, M. D. Kustu, and D. Robinson, "Evidence of enhanced precipitation due to irrigation over the great plains of the United States," *Journal of Geophysical Research: Atmospheres*, vol. 115, no. D15, 2010.

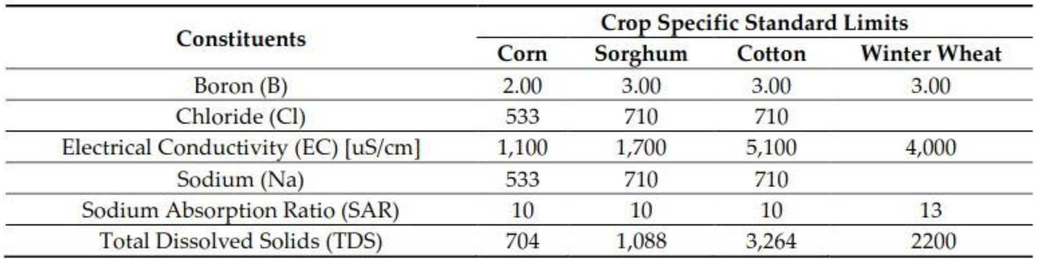
[108] P. W. Keys, M. Porkka, L. Wang-Erlandsson, I. Fetzer, T. Gleeson, and L. J. Gordon, "Invisible water security: Moisture recycling and water resilience," *Water security*, vol. 8, p. 100046, 2019.

[109] K. Butcher, A. F. Wick, T. DeSutter, A. Chatterjee, and J. Harmon, "Corn and soybean yield response to salinity influenced by soil texture," *Agronomy Journal*, vol. 110, no. 4, pp. 1243–1253, 2018.

potassium (K), other monovalent cations such as lithium (Li), cesium (Cs) and rubidium (Rb) can also affect the integrity of root uptake and increase salt stresses in corn.[110]

Removal of salts leaching from the use of salt-enriched water leads to salinization of the soil both at the surface (enhanced by soil evaporation) as well as at depth (due to rejection of salts by the roots and presence of clays that retard the downward movement of salts. Low moisture contents in the deeper vadose zones also impede the flow of water due to low relative hydraulic conductivities). Salt drainage structures (e.g., tile drains) are crucial to avoid soil salinization risks, but most fields in West Texas do not have them installed as they use center-pivot irrigation systems. The use of saline water in center-pivot and drip irrigation systems can also lead to salt accumulations in and around the nozzle which lead to clogging and decreased irrigation application efficiencies. The elevated levels of sodium (Na) especially in comparison to calcium (Ca) increases the sodium absorption ratio (SAR). Technologies that reduce the concentrations of sodium and chloride in irrigation water, calcium amendments to reduce sodium absorption ration may become necessary.

Table 18: Water Quality Requirements for Major Crops in West Texas.



Constituents	Crop Specific Standard Limits			
	Corn	Sorghum	Cotton	Winter Wheat
Boron (B)	2.00	3.00	3.00	3.00
Chloride (Cl)	533	710	710	
Electrical Conductivity (EC) [uS/cm]	1,100	1,700	5,100	4,000
Sodium (Na)	533	710	710	
Sodium Absorption Ratio (SAR)	10	10	10	13
Total Dissolved Solids (TDS)	704	1,088	3,264	2200

The water quality requirements for major crops in West Texas presented in Table 18 were compiled from regional-specific literature and in consultation with extension agents and other agricultural experts in the region based on the potential use of brackish water.[111]
In addition, general crop water quality requirements are presented in a Food and Agricultural Organization (FAO) irrigation paper and serve as a standard reference for acceptable limits for various trace elements and other constituents typically present in water.[112]

Summary

Depending on the concentration, salinity and other constituents present in produced water can have deleterious effects both on crops and the soil. Therefore, use of treated produced water must be further studied to ensure constituents that may impact the specific end-use irrigated product, soils, or workers are appropriately removed or reduced.

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[110] J. Lynch, G. R. Cramer, and A. Lauchli, "Salinity reduces membrane-associated calcium in corn root protoplasts," *Plant Physiology*, vol. 83, no. 2, pp. 390–394, 1987.

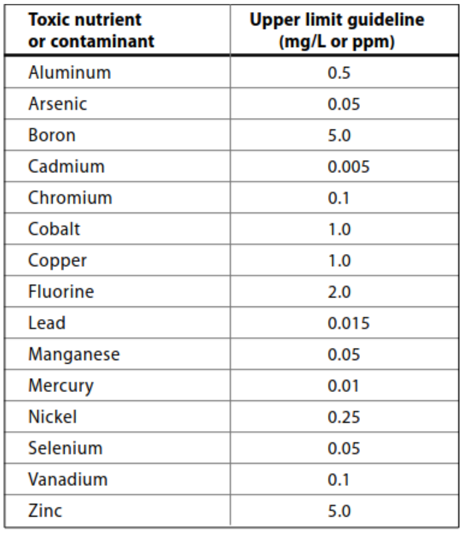
[111] A. Karim, M. Gonzalez Cruz, E. A. Hernandez, and V. Uddameri, "A gis-based fit for the purpose assessment of brackish groundwater formations as an alternative to freshwater aquifers," *Water*, vol. 12, no. 8, p. 2299, 2020.

[112] FAO, "Water Quality for Agriculture," https://www.fao.org/3/t0234e/t0234e00.htm

Livestock Use

Brackish water has been used as a water supply source for livestock use in many arid and semi-arid regions especially during periods of drought. A study found that increased levels of salinity in drinking water (up to 10,000 mg/L) with "otherwise harmless water quality" had no negative impact on the health of young bulls.[113] However, the use of high salinity water for livestock use can result in reduced water intake by animals which in turn also leads to lower feed intake and as such loss of cattle biomass and reduced milk and meat yields. While lower water can be tolerated by cattle for shorter periods of time, especially in the absence of other sources, there are noticeable health effects (e.g., diarrhea) when total dissolved solids (TDS) is greater than 7000 ppm and must be avoided when possible. In addition, waters with TDS below 5000 ppm are recommended for pregnant and lactating cattle. Generally speaking, older ruminants have greater tolerance for salinity than younger cattle.[114] Sulfate levels below 500 ppm is considered safe for all cattle, but high sulfate concentrations in water can cause some sporadic cases of polio.[115,116] In addition, water with sulfates greater than 3000 mg/L is not recommended for lactating and confined cattle.[117]

Nutrient guidelines for dairy cattle have been prescribed by National Research Council and are commonly used by FAO and extension services to derive general water quality guidelines that are presented in Figure 41.[118]



Toxic nutrient or contaminant	Upper limit guideline (mg/L or ppm)
Aluminum	0.5
Arsenic	0.05
Boron	5.0
Cadmium	0.005
Chromium	0.1
Cobalt	1.0
Copper	1.0
Fluorine	2.0
Lead	0.015
Manganese	0.05
Mercury	0.01
Nickel	0.25
Selenium	0.05
Vanadium	0.1
Zinc	5.0

Figure 41: Cattle Water Quality Guidelines from National Research Council.

Summary

Brackish water with TDS up to 7000 ppm or higher with has been used in cattle operations especially in the short-term. However, prolonged use of saline water can result in reduced yields and affect animal health. In addition, bioaccumulation of organic compounds in beef and dairy products and their subsequent transfer to humans cannot be ruled out and warrants further study.[119] The nature and extent of treatment required to make produced water compatible with the needs of the cattle industry has not been studied well. Given these limitations, it is recommended that treated produced water not be used in the cattle industry at this point in time.

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[113] C. Visscher, S. Witzmann, M. Beyerbach, and J. Kamphues, "Watering cattle (young bulls) with brackish water–a hazard due to its salt content?," *Tierarztliche Praxis Ausgabe G: Großtiere/Nutztiere*, vol. 41, no. 06, pp. 363–370, 2013.

[114] D. Breede, "Evaluation of water quality and nutrition for dairy cattle," in *High Plains Dairy conference*, 2006.

[115] *Id.*

[116] South Dakota State University Extension, "How Do Sulfates in Water Affect Livestock Health?" https://extension.sdstate.edu/how-do-sulfates-water-affect-livestock-health

[117] *Id.*

[118] N. R. Council *et al.*, *Nutrient requirements of dairy cattle: 2001*. National Academies Press, 2001.

[119] M. S. McLachlan, G. Czub, M. MacLeod, and J. A. Arnot, "Bioaccumulation of organic contaminants in humans: a multimedia perspective and the importance of biotransformation," *Environmental science & technology*, vol. 45, no. 1, pp. 197–202, 2011.

Other Considerations

The water quality standards and recommendations discussed above provide an initial assessment of end-use needs for various sectors where produced water may potentially be reused. Large water users such as agriculture and thermoelectric users will require guarantees that produced water will be available when needed and at a firm yield for extended periods of time (particularly for thermoelectric uses). While the standards described above provide at least pre-liminary guidelines for treatment, it is important to recognize that produced water will contain other constituents of concern, whose prolonged exposure can cause harm to human health and the environment.

Most desalination processes have the ability to remove many classes of chemicals. However, the concentrations of many constituents, especially those whose toxicity characteristics are known, should also be considered as part of the water quality monitoring requirements until it is determined that treatment technologies reduce the levels of these concentrations such that they have no observable health or environmental effects.[120]

Exposure assessment of chemicals that are either accidentally or intentionally released into the environment as part of the produced water reuse is also an essential next step in refining the guideline criteria presented here. Fate and transport models and exposure assessment protocols have been established for many chemical classes across different exposure pathways and can be adopted for site-specific evaluations with treated produced water.[121, 122, 123, 124]

Human and environmental health risk assessment associated with produced water constituents also continues to be an active area of research. The New Mexico Produced Water Research Consortium (NMPWRC) has several ongoing studies focused on comprehensive characterization of human health and environmental risks associated with produced water. The Groundwater Protection Council has also developed a risk assessment framework that is under consideration by the TXPWC to identify data gaps and inform research needs to improve risk-based decision making, shown in Appendix F. If Consortium members decide to adopt this approach to risk assessment, it would include first characterizing treated produced water with a set of defined constituents and research on the diverse options to control or remove those constituents. The Consortium will continue interfacing with NMPWRC to better understand their approach to comprehensive risk assessment as we develop our own approach to setting standards targets for pilot projects and beyond.

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[120] E. J. Folkerts, G. G. Goss, and T. A. Blewett, "Investigating the potential toxicity of hydraulic fracturing flowback and produced water spills to aquatic animals in freshwater environments: a north american perspective," *Reviews of Environ- mental Contamination and Toxicology Volume 254*, pp. 1–56, 2020.

[121] P. J. Rice, P. J. Rice, E. L. Arthur, and A. C. Barefoot, "Advances in pesticide environmental fate and exposure assessments," *Journal of agricultural and food chemistry*, vol. 55, no. 14, pp. 5367–5376, 2007.

[122] J. A. Berry and P. G. Wells, "Integrated fate modeling for exposure assessment of produced water on the sable island bank (Scotian shelf, Canada)," *Environmental Toxicology and Chemistry: An International Journal*, vol. 23, no. 10, pp. 2483– 2493, 2004.

[123] M. D. Lurdes Dinis and A. Fiuza, "Exposure assessment to heavy metals in the environment: measures to eliminate or reduce the exposure to critical receptors," in *Environmental heavy metal pollution and effects on child mental development*, pp. 27–50, Springer, 2011.

[124] L. A. Klinchuch and J. M. Waldron, "Fate and transport modeling with American petroleum institute decision support system applied in a site assessment for residual crude oil in unconsolidated sediments: Case study in Kern county, California," *Environmental Geosciences*, vol. 2, no. 2, pp. 85–94, 1995.

Member Feedback and Future Issues

Industry Support to Help Develop a Broad Understanding of Produced Water Constituents

As we move forward on the charge to develop guidance on recommendations for standards for beneficial use, an overwhelming 90% of member survey respondents indicated that the Consortium should continue working with industry partners to develop a broad understanding of constituents contained in produced water. When asked how the industry could best support a system of collection, sampling, and data generation/analysis members indicated a robust and wide range of options. Members suggested various methods of public and private reporting utilizing existing or in-development sources, with examples such as FracFocus, TEXNET, Water Star in New Mexico, and data sourced from and in coordination with state agencies such as RRC and TCEQ. Members indicated an interest in studying sub-basins, formations, and life-of-well effects (temporal variation), and a few members also suggested reporting be mandated by legislation. The Consortium will continue discussing and working on consensus recommendations on this and other issues.

Regulating End Product vs Intermediates

With an eye towards the future of treated produced water, members were interested in discussing whether or not at some point only the treated produced water product could be regulated as opposed to any intermediary stages. 48% of respondents agreed with only regulating the end product, 14% agreed with modifications, and 10% disagreed. Member responses included suggesting looking to existing models (such as industrial wastewater permits that have numerical discharge criteria), relying on any forthcoming risk assessments to determine the need for intermediary monitoring, mirroring other permits like NPDES which only monitors at the “outfall,” ensuring permit writers and permits allow for the encapsulation of present or potentially present constituents to foster a more holistic understanding throughout the process, and ensuring that intermediates are regulated to take into account the possibility of spills, leaks, and other accidental discharges. As we learn more about the characteristics of produced water the Consortium will continue to develop guidance on this issue.

Conclusions

There is still a need for continued and advanced testing and analysis of treated produced water samples utilizing various treatment technologies before verifying or recommending their application for beneficial use outside of the oil & gas industry. With the proper analysis of constituents in treated produced water along with associated risk assessment for beneficial uses, the potential for reuse of treated produced water may exist in many sectors.

The basic guidelines collected above define some minimum end use requirements of water and provide an initial depiction of the quality required for a given purpose. These requirements guide the type of treatment that may be necessary for making produced water fit for a given purpose. Just like many other sources, produced water is also a mixture of many constituents. It is not possible to fully characterize all constituents within produced water, but there are advanced tools available today that can gather comprehensive and detailed information that would inform a pilot study’s effluent analysis program to ensure it assesses removal or reduction of most constituents of potential concern.

Two other important questions arise when setting standards for produced water use: 1) Do constituents within produced water affect the fitness of treated produced water for a given use? and 2) Even when there is effect on the fitness, does produced water use lead to unacceptable levels of human health and environmental risks? These factors must also be ascertained for safe use of produced water. Therefore, site specific exposure assessments are recommended in addition to meeting existing or future water quality guidelines. Understanding the composition of the produced water, development of new analytical methods for characterization of unknown constituents and the risks these constituents can pose are all important topics and active areas of research that the Consortium will continue to take into account in its future research and pilot work. While we are not recommending new specific standards for non-oil & gas uses in this report, water quality guidelines must be approached with a dynamic lens and be reviewed as more information becomes available.

Economics of Produced Water

Overview

Along with the need of pilot projects to produce treated water samples for further testing and analysis, there is a parallel and equally important need to extract economic data from these pilot projects in order to build any future economic model with confidence. As mentioned in the previous section, these projects can provide crucial information as it relates to the efficacy of treatment technologies in achieving various water quality levels through any combination of processes and it is through these efforts that we may also derive the most economical and efficient approach to treating produced water for various fit-for-purpose beneficial uses that still protects public health and the environment.

In considering the approach to modeling the economics of a beneficial reuse system for treating produced water, this section illustrates various economic factors that impact that system, including current disposal costs, potential treatment costs, estimated water values using regional water planning cost analysis of water supply projects, and potential impacts to oil and gas production revenues based on production disruptions from disposal limitations. Among these there are certain factors that we can determine with a fair amount of accuracy currently (disposal costs), factors that will vary greatly over time and lend themselves to forecasting (future value of water), and other factors that will need further proof-of-concept (such as treatment technology economics).

Disposal Costs

As you will see illustrated, disposal through EPA Class II injection wells, or wells regulated by the Railroad Commission of Texas for injection of fluids associated with oil and natural gas production, is currently the most cost-effective method of managing excess volumes of produced water by a significant margin.[125] This is largely due to significantly lower treatment requirements for disposal compared to beneficial uses and availability of facilities across the Permian Basin that can dispose of produced water. However, external factors could continue to decrease this margin over time and influence the model, such as future water scarcity conditions driving increased water valuation and seismic events leading to further disposal disruptions such as those currently being experienced in the Permian Basin.[126]

In their 2021 paper titled “Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges,” Carolyn Cooper et. al. used the modeling system Water Techno-Economic Assessment Pipe-Parity Platform (WaterTAP3) to estimate levelized cost of water in dollars per cubic meter across three fit-for-purpose treatment train approaches, as well as to analyze costs for utilizing saltwater disposal facilities in the Permian.[127] The WaterTAP3 analysis showed a baseline disposal cost of $.18/bbl before adding in conveyance, which can range from an

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[125] EPA, “Class II Oil and Gas Related Injection Wells,” https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells.

[126] Seismicity Response, Railroad Commission of Texas https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response/

[127] Cooper, Carolyn M., et al. "Oil and Gas Produced Water Reuse: Opportunities, Needs, and Challenges." ACS ES&T Engineering 2.3 (2021): 347-366.

additional \$.37/bbl for pipeline and up to \$1.64/bbl if trucking is required.[128] This would give us an approximate range of \$.55-\$1.81/bbl for SWD. As pipeline conveyance is the more economical and more widely used method, input from Consortium membership on average disposal fees utilizing pipelines allows us to narrow that range down to \$.60-\$.70/bbl in most instances.

Projected Treatment Costs

To be a viable option, treatment costs to achieve a water quality that is suitable for beneficial use and protective of public health and the environment will have to be competitive with disposal; based on input from Consortium members the targeted cost to be competitive is \$1/bbl of recovered treated water. Depending on variable input costs such as natural gas for energy, members have indicated current assessments of treatment options average \$2.55/bbl with some instances as high as \$10/bbl.

Theoretical treatment costs using WaterTAP3 software were developed for the treatment technologies reviewed by the Consortium and are included in the technology section as well as the appendices. While these estimates show that the cost for treatment technology alone may rival that of disposal, they do not account for transportation, storage, or the potential need to run pre- and post-treatment and/or polishing to achieve certain qualities.

Potential Water Values

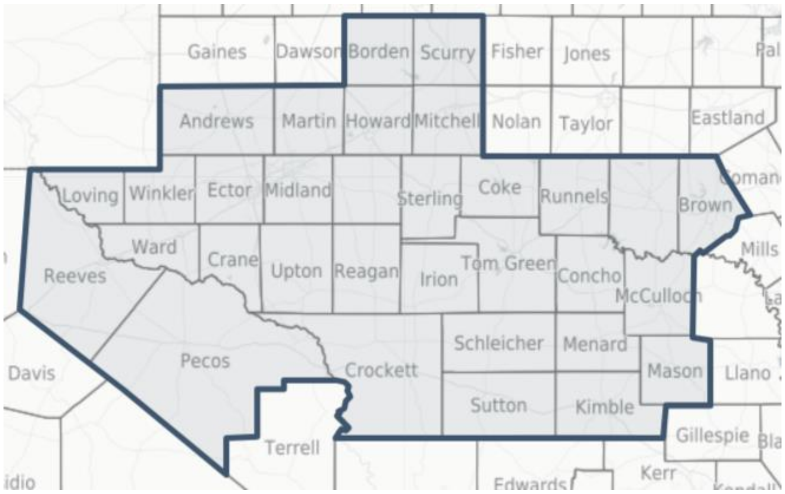

Figure 42: TWDB Planning Region F (Texas Water Development Board).

Among the toughest factors to determine is the potential value produced water may hold to a purchasing end user outside of the oil and gas industry. There are several factors that will come into play with valuing this water, many of which cannot be ascertained at the time of this report, such as: increases in water values due to future scarcity events, legislative or regulatory changes impacting new or existing water supplies, and the potential need for discounting new sources of water (such as direct or indirect potable reuse, produced water, etc.) based on public perception and confidence in the source.

The approved 2021 Region F Water Plan (which includes the vast majority of the Permian Basin) details several water supply projects and their associated costs, including numerous projects

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[128] *Id.*

aimed at developing new and existing groundwater resources.[129] The plan provides a projected annualized cost per 1,000 gallons, both before and after servicing the debt associated with capital costs of the supply projects. Taking the cost of the water after debt service provides an excellent snapshot of the current willingness to pay (value) for groundwater resources in this region of Texas. After adjusting the figures for barrels rather than gallons, the average cost before debt service of 40 proposed supply projects for this region is $.23/bbl, with values ranging from $.02/bbl to $.87/bbl, and the average cost after debt service is $0.07/bbl, with values ranging from less than $.01/bbl up to $.43/bbl. Of note, there are outliers with this data set, noted in the graphs in the appendices, that are seemingly not groundwater-development based projects. Rather, they are projects aimed at potable reuse, aquifer storage and recovery, and even city-to-city purchase of treated water.

Produced Water Disposal/Management Limitations

In December 2021, in response to seismic activity in the Gardendale Seismic Response Area (SRA), the Railroad Commission of Texas indefinitely suspended "injection into deep geologic strata – below the top of the Strawn Formation and especially the Ellenburger Formation."[130] RRC continues to monitor this and other SRA's for seismic activity and methods of disposal, but the economic reality of limited disposal options for produced water provides a necessity and opportunity to pursue greater innovation in treatment and beneficial reuse options.

Members have indicated under these circumstances a number of options that are or will be explored. More data and modeling will help us to determine the optimal option or set of options that operators and midstream companies would likely choose, but these options include transporting produced water into other areas or basins for disposal (increasing transportation cost per barrel) or exploring injection into available strata.

In extreme circumstances, production may also be disrupted if other disposal or management methods are not viable. The calculation that an operator needs to make in order to determine the true value of treatment options versus disposal methods in a scenario where disposal options are limited can better illustrate the value of beneficial reuse. We can derive the potential value per barrel of treatment technology alternatives by finding the revenue lost on unrealized oil production due to halting production and dividing by the number of barrels of excess water with no alternative disposal method. For example, let's suppose an operator needs to dispose of 100,000 barrels of PW per day. Due to a limitation on disposal, they can only dispose of 70,000 barrels per day. This leaves 30,000 barrels of excess produced water with no viable disposal option, thus creating the need to halt production once 70,000 barrels of PW are achieved. For the purposes of this example we will assume a 7:1 pw to oil ratio on production (operators would likely shut-in their highest water producing wells first) and an average spot price of $65/bbl (based on the average of the last 5 years oil Cushing, OK WTI Spot Price[131]). With these assumptions, the amount of oil that would theoretically not be produced

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[129] https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/index.asp

[130] https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response/

[131] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rwtc&f=m

on those 30,000 barrels of excess water is roughly 4,286 bbls. The revenue lost on those unrealized barrels of production would amount to approximately $278,590 per day, and therefore the breakeven price in treating a barrel of pw is now $9.29/bbl:

(4,286 bbls oil per day unrealized) x ($65/bbl) = $278,590 lost revenue per day
($278,590) /(30,000 bbls pw) = $9.29/bbl breakeven cost

Regional Impact

Beyond revenue losses to industry operators and state coffers, impacts to an entire region such as the Permian when there are production issues can be devastating. To illustrate the current vibrancy of their economy and what is really at stake, several graphs in Appendix N detail 2021 Bureau of Labor Statistics data for the Permian. In summary, the 24 counties comprising the Permian contain over 12,000 businesses employing 152,000 people, representing over $11 billion in wages. Businesses (establishments), employment, and wages are concentrated in higher population counties with larger municipalities in the 24 Permian Delaware and Midland Basin County Area. The $11B in 2021 Annual Wages is impressive when compared to other non-major metro areas in the state.

Member Feedback and Future Issues

Prioritizing Movement of Treated Produced Water

Another critical component to the economics of potential beneficial use is the movement of produced water- the more it costs to transport and utilize treated produced water the more expensive and difficult it will be to foster its use outside of oil & gas. As noted previously, pipelines are by far the most cost-effective method for transporting produced water by a factor of more than 3x over trucking. 62% of respondents agreed that prioritizing the most efficient method of transportation would deliver cost-effective economics and further utilization, 14% agreed with modifications and 3% disagreed. Responses offered that colocation of generation and point of use will be highly unlikely although prioritizing uses closest to the generation should occur, meeting a quality of water that would allow for partnering with municipal service companies would be highly beneficial, creating tax reduction incentives for the creation of pipeline networks to help the prioritization of movement, and carefully considering how transportation and pipelines need to preserve private property rights through landowner notifications and fair compensation, while another respondent simply indicated it was too early in the process to determine.

Key Aspects of a Holistic Economic Model

Further member input on other key aspects to consider as a holistic economic model continues to be developed include the social cost of GHG emissions (current federal government consideration) and an assigned value of water for replenishing aquifers, ongoing consideration for the potential to commercialize byproducts extracted from produced water, quantitative ESG analysis, a continued focus on an economic model that protects pubic heath and the environment, and understanding the impacts and changes to CapEx on a cost-per-barrel throughput capacity as systems are scaled in size.

Economic Benefits of Continued O&G Operations in an Environment of Increased Injection Disposal Restrictions

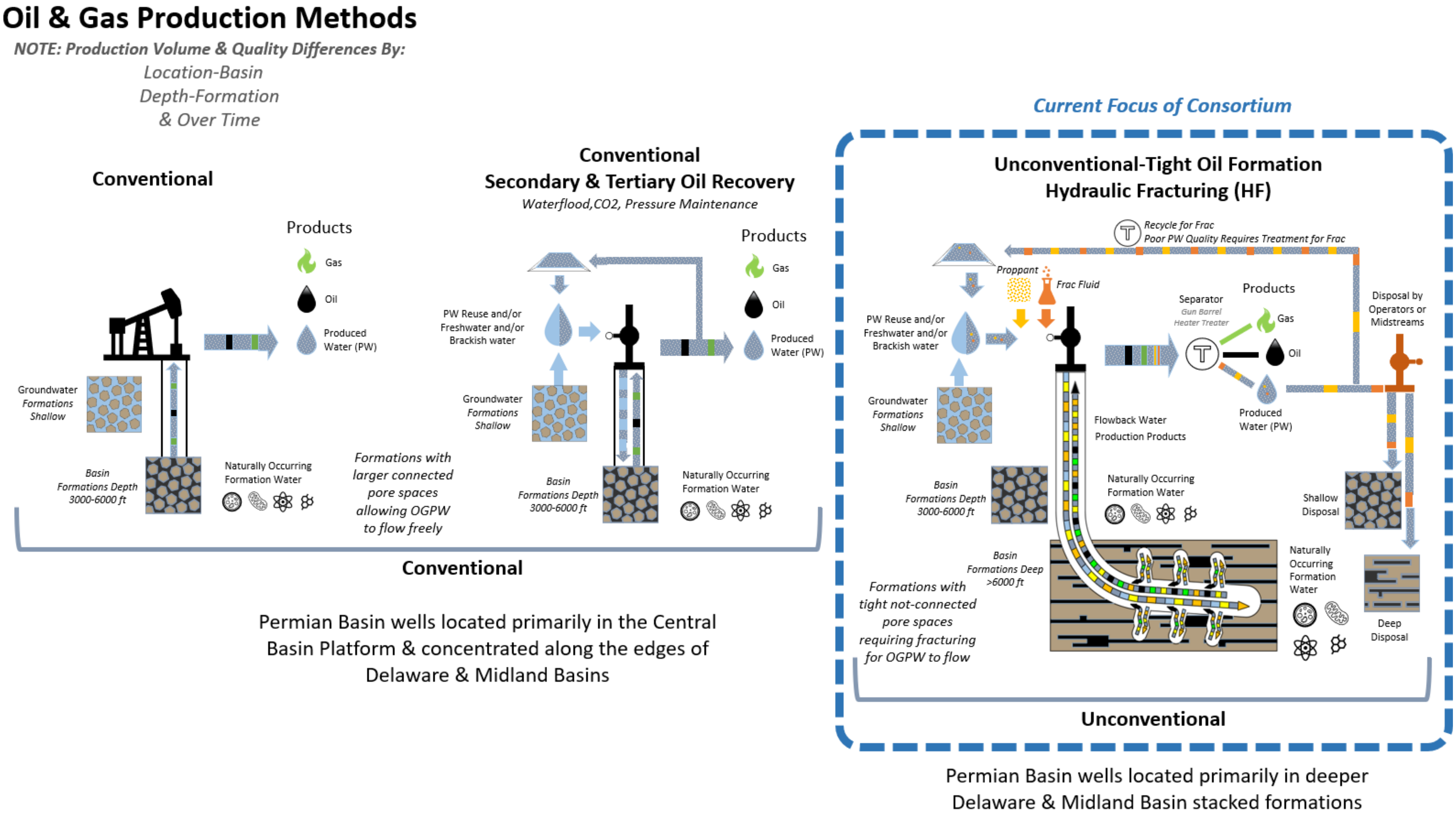
Along with the potential economics of shut-in production, members provided feedback on encapsulating the value that other produced water reuse options would provide for preserving oil & gas operations in an environment of increased injection disposal restrictions. Some members wanted to focus on the "highest cost to dispose of produced water," (i.e. rather than assuming production would shut-in, exploring the cost to transport to a different basin still allowing for disposal) and better evaluating the impact of water usage increasing and replenishment decreasing.

Conclusion

More concrete information is vital to developing an economic model for treating produced water for beneficial use, particularly in the form of practical technology evaluation and projected future water values. The gap between low disposal costs ($.60-70/bbl) and estimated treatment costs (member reported average of $2.55/bbl) is too significant when considering the need to deal with millions of barrels of produced water every day. Efficiencies in technology will drive that cost down, regulatory actions in response to potential seismicity may limit disposal options causing increased costs, and future water shortages may lead beneficial end users outside of the oil & gas industry to be willing to pay higher premiums for water. Like any economic system facing such external pressures, there is a breakeven point in the future where all these inputs will likely result in treated produced water reuse as a viable option; however, we cannot risk affecting the economic engine of a region and a state waiting on increasing problems to force markets into submission.

APPENDICES

Appendix A – Oil and Gas Production Methods



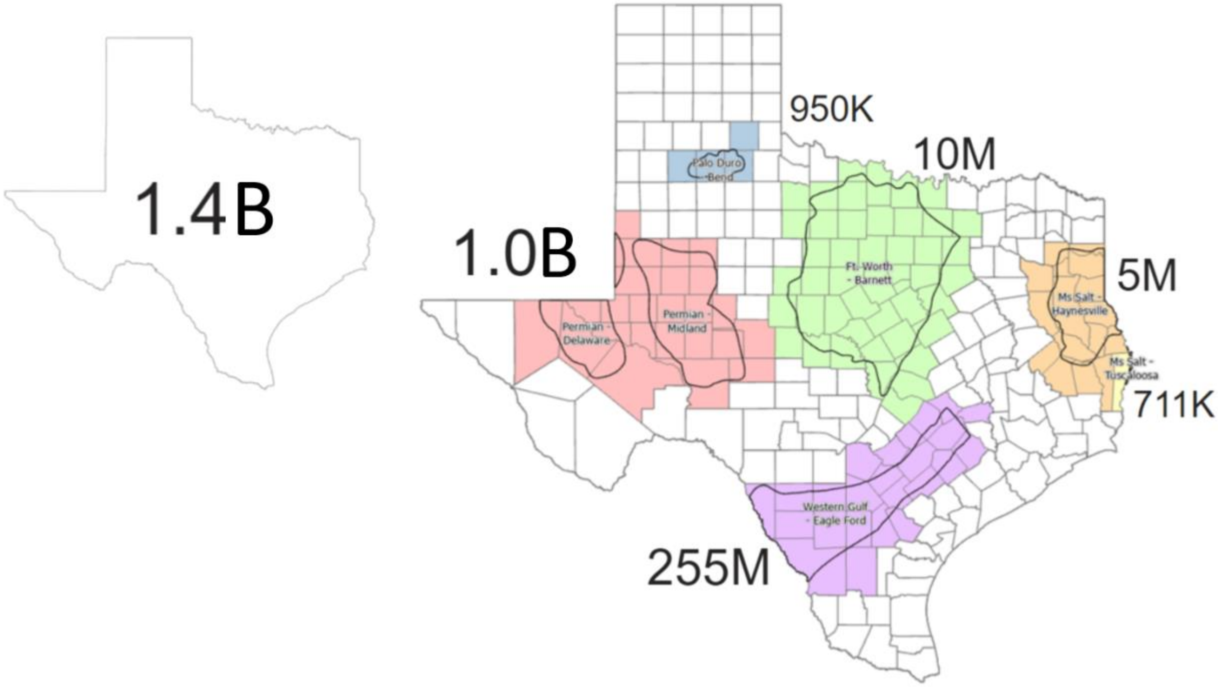
Permian Basin wells located primarily in the Central Basin Platform & concentrated along the edges of Delaware & Midland Basins

Permian Basin wells located primarily in deeper Delaware & Midland Basin stacked formations

Appendix B – 2021 Texas Shale Play Oil Production

2021 Annual Oil Production in BBL- RRC County Reports

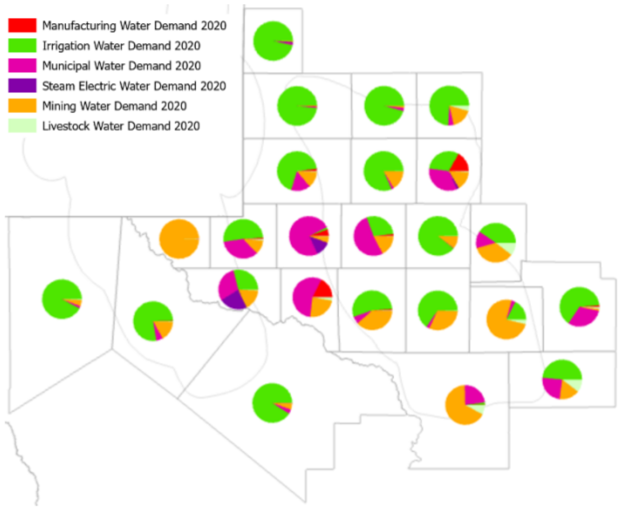
Total for Counties atop Unconventional-Tight Oil Formation Hydraulic Fracturing (HF) Shale Plays



Appendix C – 2022 Texas Water Plan Overview for 24 County Area

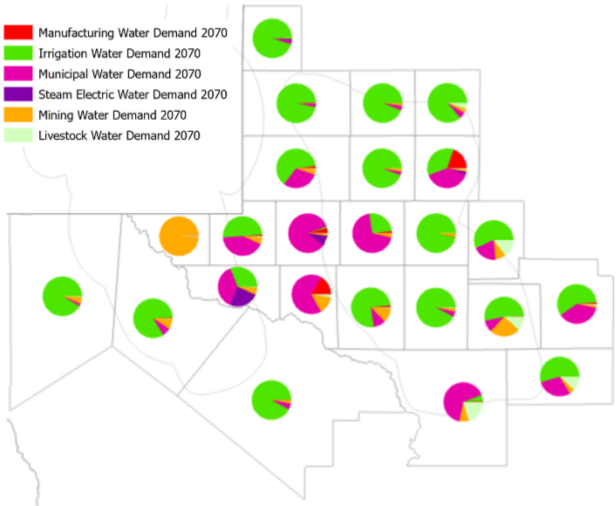
2020 Total Water Demand

Permian Delaware & Midland Basin Counties (24)



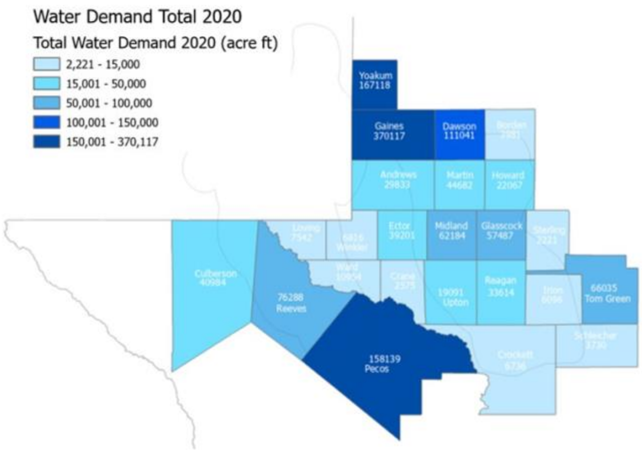
2070 Total Water Demand

Permian Delaware & Midland Basin Counties (24)



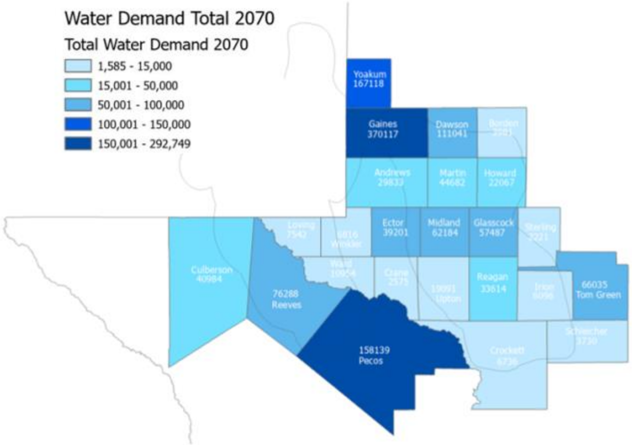
2020 Total Water Demand

Permian Delaware & Midland Basin Counties (24)



2070 Total Water Demand

Permian Delaware & Midland Basin Counties (24)

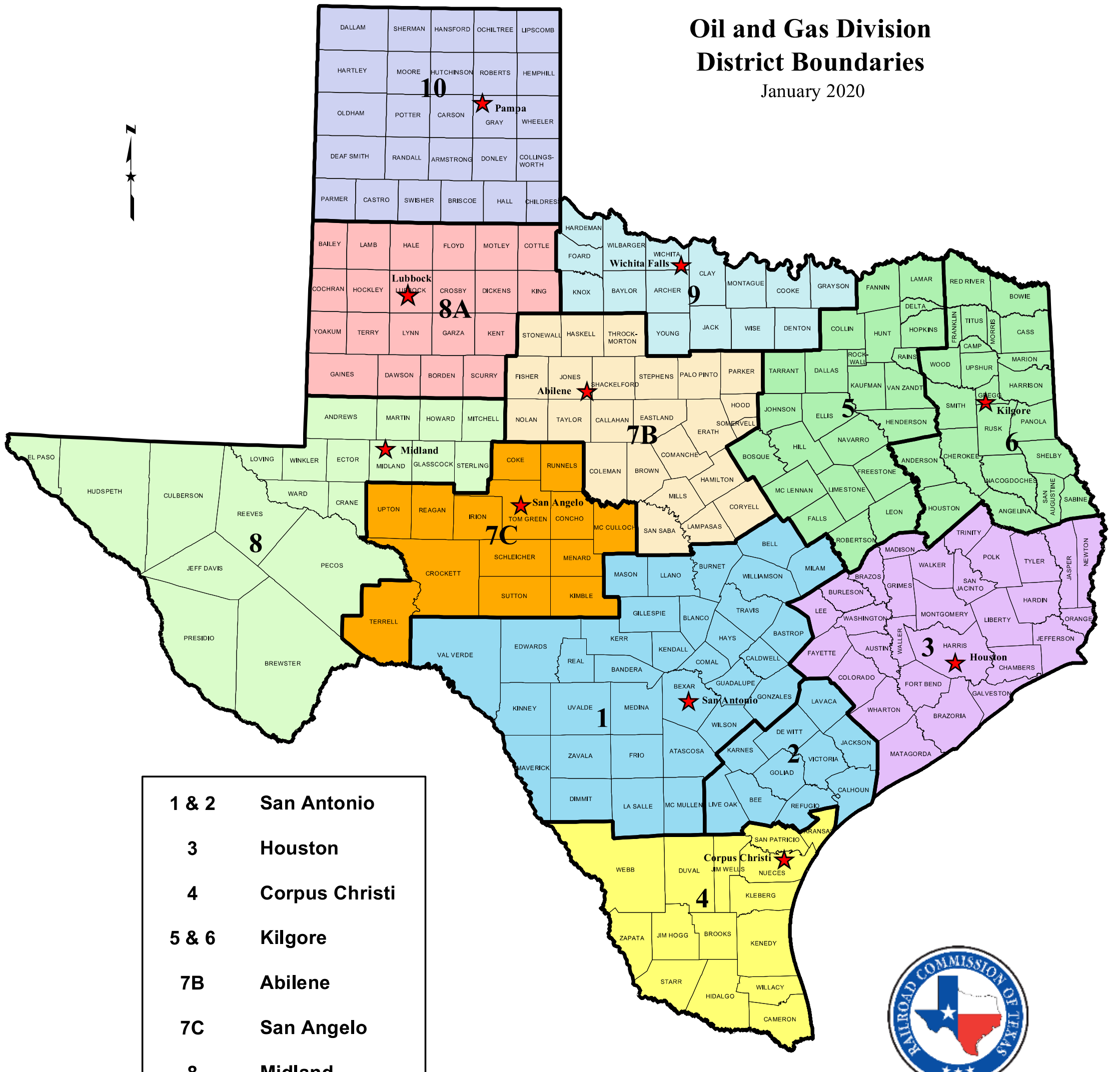


Appendix D – Railroad Commission of Texas Oil and Gas Division District Boundaries

RAILROAD COMMISSION of TEXAS

Oil and Gas Division
District Boundaries

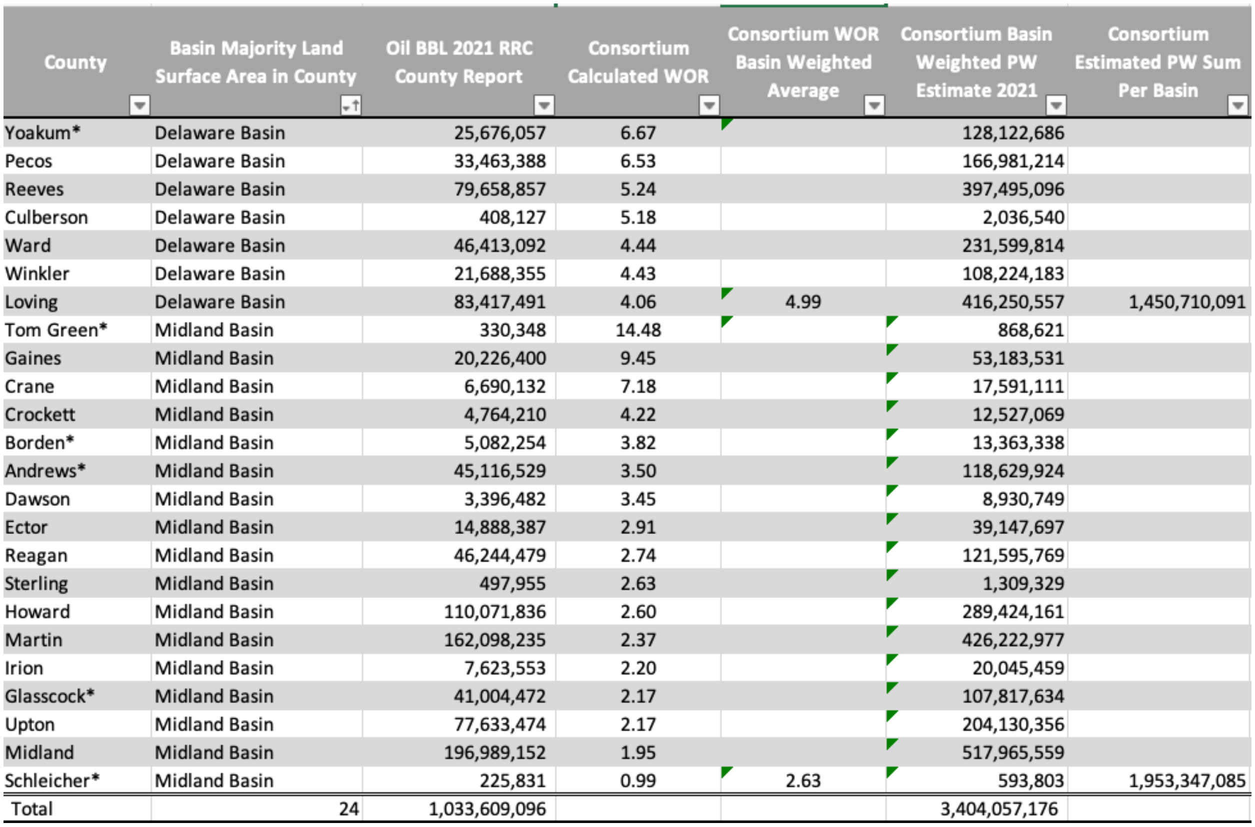
January 2020



1 & 2	San Antonio
3	Houston
4	Corpus Christi
5 & 6	Kilgore
7B	Abilene
7C	San Angelo
8	Midland
8A	Lubbock
9	Wichita Falls
10	Pampa

PREPARED BY
RAILROAD COMMISSION OF TEXAS
OIL AND GAS DIVISION
January 2020

Appendix E – WOR Calculations



County	Basin Majority Land Surface Area in County	Oil BBL 2021 RRC County Report	Consortium Calculated WOR	Consortium WOR Basin Weighted Average	Consortium Basin Weighted PW Estimate 2021	Consortium Estimated PW Sum Per Basin
Yoakum*	Delaware Basin	25,676,057	6.67		128,122,686	
Pecos	Delaware Basin	33,463,388	6.53		166,981,214	
Reeves	Delaware Basin	79,658,857	5.24		397,495,096	
Culberson	Delaware Basin	408,127	5.18		2,036,540	
Ward	Delaware Basin	46,413,092	4.44		231,599,814	
Winkler	Delaware Basin	21,688,355	4.43		108,224,183	
Loving	Delaware Basin	83,417,491	4.06	4.99	416,250,557	1,450,710,091
Tom Green*	Midland Basin	330,348	14.48		868,621	
Gaines	Midland Basin	20,226,400	9.45		53,183,531	
Crane	Midland Basin	6,690,132	7.18		17,591,111	
Crockett	Midland Basin	4,764,210	4.22		12,527,069	
Borden*	Midland Basin	5,082,254	3.82		13,363,338	
Andrews*	Midland Basin	45,116,529	3.50		118,629,924	
Dawson	Midland Basin	3,396,482	3.45		8,930,749	
Ector	Midland Basin	14,888,387	2.91		39,147,697	
Reagan	Midland Basin	46,244,479	2.74		121,595,769	
Sterling	Midland Basin	497,955	2.63		1,309,329	
Howard	Midland Basin	110,071,836	2.60		289,424,161	
Martin	Midland Basin	162,098,235	2.37		426,222,977	
Irion	Midland Basin	7,623,553	2.20		20,045,459	
Glasscock*	Midland Basin	41,004,472	2.17		107,817,634	
Upton	Midland Basin	77,633,474	2.17		204,130,356	
Midland	Midland Basin	196,989,152	1.95		517,965,559	
Schleicher*	Midland Basin	225,831	0.99	2.63	593,803	1,953,347,085
Total	24	1,033,609,096			3,404,057,176	

Appendix F – GWPC Risk Assessment Framework

Produced Water Report: Regulations, Current Practices, and Research Needs

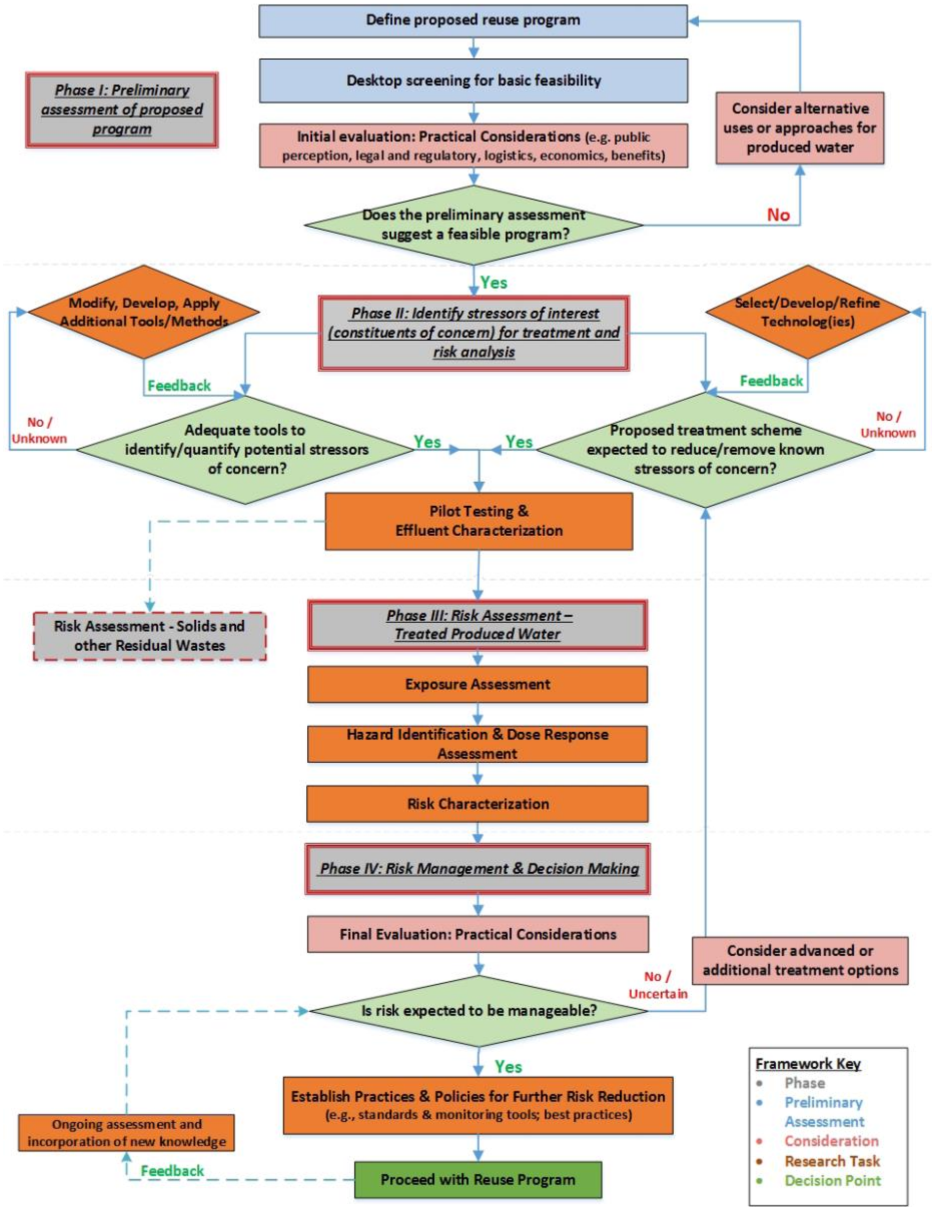


Figure 3-9: Framework for Research, Evaluation and Decision-Making

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Appendix G – Mechanical Vapor Compression (MVC)

Description of the technology

Mechanical Vapor Compression (MVC), also referred to as Mechanical Vapor Recompression (MVR), is a thermal technology relying on the thermodynamic principle where decrease in pressure results in lowering of boiling point temperature enabling it to operate at lower temperatures (70^{o}C [1]). MVC is one of two Vapor Compression (VC) desalination technologies, the other being Thermal Vapor Compression (TVC). MVC typically consists of a compressor coupled to an evaporator/condenser and heat exchangers to pre-heat feed water (Figure 43). The water vapor from the evaporator/condenser gets compressed producing a superheated fluid which provides the heat for the vaporization of the pre-heated feed [2]. It can be set up as a single or double evaporation system, the single evaporation system being the one mostly used. The single evaporation system does the compression in one stage while the double evaporation system does in two. Both systems can be with or without brine recirculation. The compressor unit of MVC is typically the most energy intensive part of the system.

Thermal technologies rely on evaporating part of the feed water creating a brine stream of higher salt concentration than the feed. Due to the increase in boiling point elevation with salinity and the energy needed for evaporation, a higher salt concentration leads to higher energy demand in the system. Double evaporation MVC addresses this by pre-evaporating part of the solution, that is at a lower salt concentration, in the first stage and the rest in the second. This setup has shown to be efficient in treating high salinity water [3]. Further, implementing brine recirculation increases the efficiency of the system by 25% regardless of the system setup. With brine recirculation, the heat transfer coefficient increases, decreasing the transfer area required [2].
For seawater total annual cost including both annualized capital cost and operating cost can be as low as \$0.25 – \$0.34/bbl.

Process description

A process schematic is shown Figure 43.

1. The incoming feed water is split in equal proportions and passed through regenerators where the feed gets heated up before entering the evaporator.
2. The feed water is then sprayed in the evaporator/condenser onto hot tubes causing evaporation.
3. Then the vapor is pulled into the compressor where it gets compressed becoming a superheated fluid.
4. The superheated fluid from step 3. passes through tubes inside the evaporator/condenser where its latent heat of condensation is used to evaporate the feed water.

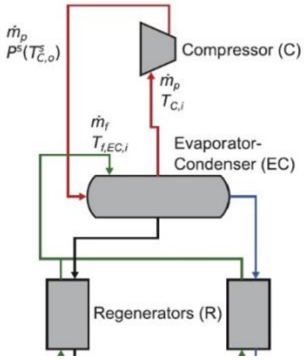

Figure 43: SCHEMATIC OF SINGLE-EVAPORATION MVC PROCESS FLOW [4]

Pretreatment required

Removal of oil and suspended solids (SS).
Scale inhibitors.

Limitations

Small capacity
Energy intensive (electrical energy).
Restricted implementation due to possible volatile components (legislative restraints) [5].

Product water (Salinity, Other quality measures, Recovery)

Distillate, recovery up to 40% [1].

Potential Application

Used to produced potable water.

Technology Readiness

Commercial application - up to 3000 m^3/day for a single unit. Multiple units can be used to increase desalination capacity.
Incorporated in various hybrid setups.

Economics

Mechanical Vapor Compression

Feedflow MBD	**Feedflow** MGD	**Recovery** % (v/v)	**Product flow** MGD	**Capital Cost** M$	**Operating Cost** M$/yr		**Operating Cost per volume water** $/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	4.90	0.7	1.2	0.49	0.88	0.08	0.14
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		1.7	4.1	1.21	2.95	0.19	0.47
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		2.3	5.6	1.66	4.05	0.26	0.64
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		2.8	6.8	2.01	4.91	0.32	0.78

Table 19: Literature summary of energy consumption and costs (product water basis) to desalinate seawater.

	Electrical Energy consumption [kWh_e/m^3]	Capacity [m^3/day]	Utility cost- ($/bbl)	Total cost ($/bbl)	References
Seawater	7 – 12	<100 – 3,000*	0.07 -0.10 Δ	0.13-0.32 Δ	[2, 5-7]

Produced water	10 - 30	468	0.7 – 2.1	0.95 – 1.75	[8]

** 100 – 1,000 m^3/day is a medium size MVC treatment plant*

Δ Cost ranges are representative for seawater being sensitive to primary utility cost, treatment efficiencies and capacities should not be considered exhaustive.

Table 20: Pros and Cons related to MVC.

Advantages	Disadvantages
Shown to be suitable for higher seawater feed salinities [1, 4]. Compact unit with small foot-print compared to MSF and MED [1]. High thermodynamic efficiency [2]. No external heat source required [2]. Coupled with other desalination techniques as hybrid systems (e.g., MED-MVC).	Increase in energy demand with the increase of salinity feed [a]. Volatile components if such are present in the feed stream can have adverse effect on performance [5]. Not flexible for varying flow rates [1]. High level of skill needed to operate [1].

a. With concentrating the feed, the increase in salinity results in the increase of boiling point which in turn means a higher energy input is needed to maintain the heat-transfer difference [3].

Technology Path Forward for PW treatment:

- Research the applicability of the dual-evaporator MVC for PW treatment.
- Design efficient compressors with high capacities and low capital cost.

Uncategorized References

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2. Jamil, M.A. and S.M. Zubair, *On thermoeconomic analysis of a single-effect mechanical vapor compression desalination system.* Desalination, 2017. **420**: p. 292-307.
3. Liang, L., et al., *Treatment of high-concentration wastewater using double-effect mechanical vapor recompression.* Desalination, 2013. **314**: p. 139-146.
4. Thiel, G.P., et al., *Energy consumption in desalinating produced water from shale oil and gas extraction.* Desalination, 2015. **366**: p. 94-112.
5. Osipi, S.R., A.R. Secchi, and C.P. Borges, *Cost assessment and retro-techno-economic analysis of desalination technologies in onshore produced water treatment.* Desalination, 2018. **430**: p. 107-119.
6. Al-Karaghouli, A. and L.L. Kazmerski, *Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes.* Renewable and Sustainable Energy Reviews, 2013. **24**: p. 343-356.

7. Karagiannis, I.C. and P.G. Soldatos, *Water desalination cost literature: review and assessment.* Desalination, 2008. **223**(1-3): p. 448-456.
8. Bartholomew, T.V., N.S. Siefert, and M.S. Mauter, *Cost optimization of osmotically assisted reverse osmosis.* Environmental science & technology, 2018. **52**(20): p. 11813-11821.

Appendix H – Multi-Effect Distillation (MED)

Description of the technology

Multi-Effect Distillation (MED) is a thermal desalination technology that has been applied in seawater desalination. The vapor from a stage is used to heat subsequent stages, thus achieving a high gain to output ratio (GOR), defined as the ratio of the mass of distillate to the mass of the input steam (Al-Karaghouli and Kazmerski [2]). This is also the definition of the Performance Ratio (PR)T in Bhojwani, Topolski [3]. Typical GOR values for MED range from 10 to 16 kg-distillate/kg-steam corresponding to an energy input of 230 MJ/m^3 to 145 MJ/m^3, respectively[2].

The process relies on three main parameters that influence thermal energy consumption i.) the average enthalpy of evaporation ii.) liquid specific heat iii.) boiling point elevation across the effects [1]. As with other thermal desalination technologies MED becomes more efficient if a waste heat source is readily available. MED operates at a top brine temperature (TBT) range of 65^{o}C – 90^{o}C, the typical operating temperature being 70^{o}C (60^{o}C – 70^{o}C) which is lower than the TBT for MSF (110^{o}C – 120^{o}C). The average recovery ratio of MED is around 35% with a reported range of 20% to 67% [4]. Due to its relatively low operating temperature compared to MSF, MED is a highly versatile technology and is adaptable to a wide range of heat sources [5, 6]. Efficient implementation of MED is dependent on balancing capital and operational cost with the energy source available.

Several variations of MED exist, all with the primary goal of lowering energy input while maintaining or increasing output. Variations of MED are based on the direction of flow. Forward feed MED is a configuration where all streams (feed, product, and vapor) flow in the same direction. This configuration can operate at high TBT and is the most resistant to scaling. These specifications make Forward Feed MED ideal for treating waters with high TDS. However, this configuration is rarely used due to its complexity which in turn means a higher cost of product water. Backward feed MED vapor and feed move in opposite directions, achieving high thermal efficiency but requiring more electrical energy for pumping. Parallel feed MED, the simplest and most used out of the mentioned configurations, is a configuration where the feed water is evenly distributed throughout stages using a single pump. Due to higher TBT than other configurations, parallel feed MED has a higher propensity for scaling than other configurations. The benefit of this configuration is that it uses one pump to move the brine, and for vapor flow between stages no pump is needed as the process uses pressure potential between stages [6].

For seawater total annual cost including both annualized capital cost and operating cost can be as low as $0.10 – $0.34/bbl [7].

Process description

A process schematic is shown in Figure 44.

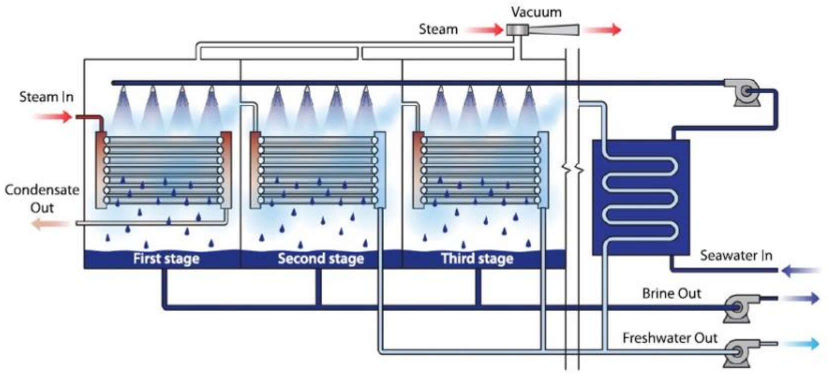

Figure 44 SCHEMATIC OF CONVENTIONAL MED PROCESS FLOW [2]

1. In the first stage/effect, product water is pumped into the hot side of the evaporator, at the same time, the feed stream is dispersed in the cold side of the evaporator. The feed stream is passed through the condenser where it is pre-heated before entering the first stage. Due to the low pressure in the stage, water in the feed stream evaporates at relatively low temperatures.
2. The produced stream then passes through a demister, then condensing on the hot side of the evaporator in the second effect becoming the product stream. The excess heat from condensation heats the feed stream feed of the second stage. The remaining liquid from the first effect is drained off as brine.
3. These steps are repeated in the subsequent stages with the steam from the final stage cooled by the feed stream in a condenser.
4. The remaining liquid from each stage is drained into the brine stream, collected and either disposed of or further treated depending on the design.

Pretreatment required

Removal of oil and suspended solids (SS).
Addition of antiscalants.

Limitations

Deterioration of supporting equipment due to high TDS (pumps).

Product water (Salinity, Other quality measures, Recovery)

Distillate, typical recovery ranges from 20% to 35% with higher recoveries up to 67% noted in some cases for seawater [4].

Potential Application

Used to produce potable water.

Technology Readiness

Mature technology for seawater desalination.

Economics

Multi-effect distillation

Feedflow MBD	**Feedflow** MGD	**Recovery** % (v/v)	**Product flow** MGD	**Capital Cost** M$	**Operating Cost** M$/yr		**Operating Cost per volume water** $/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	7.6	1.3	2.2	0.97	1.57	0.15	0.25
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		2.4	7.2	1.75	5.20	0.28	0.83
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		3.3	9.8	2.35	7.06	0.37	1.12
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		3.9	11.8	2.82	8.52	0.45	1.35

Table 21: Literature summary of energy consumption and costs (product water basis) to desalinate seawater.

Electrical Energy consumption [kWh_e/m^3]	Thermal energy consumption in electricity equivalents (corresponding thermal range) [kWh_e/m^3]	Capacity [m^3/day]	Utility cost- ($/bbl)	Total cost ($/bbl)	References
2 – 2.7	10 – 21.4 (120 – 257 MJ/m^3)	10,000 – 500,000*	0.06 – 0.11 $^{\Delta}$	0.10-0.34 $^{\Delta}$	[2, 7, 8]

** 12,000 – 55,000 m^3/day is a medium size MED treatment plant [2]*

Δ Cost ranges are representative for seawater being sensitive to primary utility cost, treatment efficiencies and capacities and should not be considered exhaustive.

Table 22: Pros and Cons related to MED.

Advantages	Disadvantages
Well established technology, widely researched and implemented for desalination. More stable energy consumption under partial load operation than MSF [5].	Not flexible for varying water flow rate [4]. Prone to scaling and equipment deterioration with increase in recovery.

Lower operating temperature than MSF (MSF operating temperature ~120°C while for MED its <70°C) [9]. Easily coupled with different renewable energy sources (Solar, geothermal).	Using variations of MED, although more energy efficient, increase the complexity of the system as well as capital cost. Complex setup increasing the cost of labor as it necessitates high skilled labor [4].

Technology Path Forward for PW treatment:

- Effective and low-cost pre-treatment technologies to remove scale forming components.
- Designing efficient heat exchangers and evaporators with low capital cost.

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Appendix I – Multi-Stage Flash (MSF)

Description of the technology

Multi-stage Flash is one of the two most well-established thermal technologies for water desalination and involves a series of stages under partial vacuum in which a portion of the feed water evaporates yielding a product water essentially free of dissolved solids and salinity. The vapor from each stage is condensed to form the product water and to provide heat to increase the temperature of the incoming feed. The feed water needs to be heated to a temperature to allow flashing at the first stage, typically requiring a top brine temperature (TBT) of 90-110 °C. As an energy intensive process, it is usually employed in conjunction with a source of waste heat. The waste heat is usually in the form of a low pressure (1 to 3 bars) steam that can be utilized to heat the incoming brine, lowering the energy demand of the process[2].

The performance of the MSF is largely controlled by the TBT. The efficiency and number of stages is determined by the temperature difference between TBT and the temperature of the feed water. As a result efficiency can change between winter and summer due to changes in the feed water temperature[3]. A higher TBT results in higher water recovery but also may lead to higher risks of scaling and corrosion. Corrosion inhibitors are necessary whose price and availability is also a determining factor in determining TBT [4].

MSF is generally limited to low recoveries (<20%[5]) and so is typically only employed for seawater due to the need for large amounts of feed water to meet target product water flowrates. For seawater total costs including both annualized capital cost and operating costs can be as low as $0.11-$0.45/bbl [2].

Process description

A process schematic is shown in Figure 45.

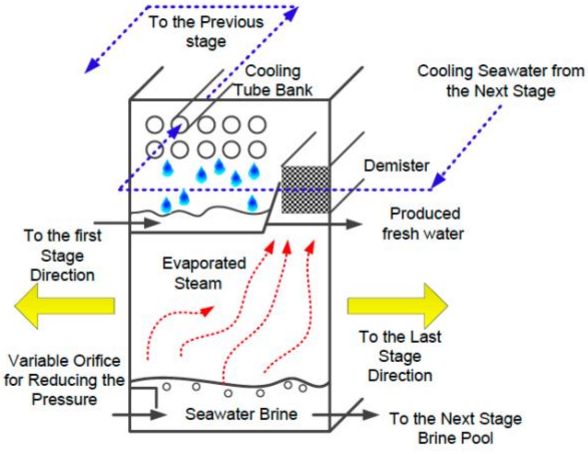

Figure 45 SCHEMATIC OF MSF PROCESS FLOW [1]

1. The feed comes from the brine heater to the first stage evaporator. It passes through the cooling tube bank (or feed heater) exiting each stage. There it gets gradually heated while also serving as a coolant for vapor condensation.
2. After the last stage the feed enters the bottom of the evaporator which is called the brine pool.
3. A part of the brine flashes due to it's a vacuum in the stage, passing through the demister, and finally condensing on the surface of the cooling tubes.
4. The remainder of the brine goes to the next stage where the process is repeated. This sequence ends after the final stage after which the concentrated brine is disposed of.
5. The final stage typically connected to vapor compressors (e.,, thermal vapor compressor) to control and maintain pressure drop in the stages and discharge non-condensable gas present in the system [1].

Pretreatment required

Screening and rough filtration to remove solids.

Scaling inhibitors cost and availability.

Limitations

Not economically feasible as a small-scale plant.

Feed water quality along with scaling inhibitor cost and availability can cap TBT which governs output quantity and recovery of product water.

For the technology to be a viable option, the plant must be placed adjacent to a waste heat source.

Product water (Salinity, Other quality measures, Recovery)

Water typically containing from 2 to 10 mg/L TDS with water recovery typically between 10 - 20%

Potential Application (within the oil field, agricultural irrigation, agricultural livestock, industrial, domestic non-potable, potable water)

With suitable post treatment high water quality is achievable including potable water.

Technology Readiness (commercial, pilot scale, bench scale)

Mature technology with commercial units available at multiple scales.

Economics

Multi-stage Flash

Feedflow	**Feedflow**	**Recovery**	**Product flow**	**Capital Cost**	**Operating Cost**		**Operating Cost per volume water**			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	Seawater									
0.048	2	20	0.40	7.98	0.6	1.1	1.05	2.02	0.17	0.32
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	20	0.40		0.8	3.4	1.42	6.08	0.23	0.97
Case	**Produced water - 50th Percentile TDS**									
0.048	2	20	0.40		1.0	4.5	1.85	8.10	0.29	1.29
Case	**Produced water - 75th Percentile TDS**									
0.048	2	20	0.40		1.2	5.4	2.20	9.71	0.35	1.54

Table 23: Literature summary of energy consumption and costs (product water basis) to desalinate seawater.

Electrical Energy consumption [kWh_e/m^3]	Thermal energy consumption in electricity equivalents (corresponding thermal range) [kWh_e/m^3]	Capacity [m^3/day]	Utility cost- ($/bbl)	Total cost ($/bbl)	References
2.5-5	15.8 – 23.5 (190 – 282 MJ/m^3)	5000 - > 500,000*	0.07-0.13$^{\Delta}$	0.11-0.45$^{\Delta}$	[2, 6, 7]

** 50,000-75,000 m^3/day is considered a typical sized MSF*

$^{\Delta}$ Cost ranges are representative for seawater being sensitive to primary utility cost, treatment efficiencies and capacities and should not be considered exhaustive.

Table 24: Pros and Cons related to MSF.

Advantages	Disadvantages
Suitable for treating high salinity feeds (> 55 000 mg/L) [8]. Well established and used technology for water treatment. High treatment capacity (>500 000 m^3/day) [1]. Long plant lifecycle (>30 years). Less pre-treatment than membrane technologies. Adaptable to highly varying water quality. High Product water quality [5]. Robust and reliable[4].	Economically viable as a large-scale treatment plant. Low recovery ratio compared to other technologies. High salinity feed increases the boiling point elevation, meaning that more energy is required for treatment. Less energy efficient than MED (Second Law of Efficiency: 3.8% compared to 5.1% for MED) [8]. Rigid system. Efficiency depending on flow (constant hydraulic head in the brine pool) [1]. High thermal energy demand[4].

Technology Path Forward for PW treatment:

- Research and develop new materials with higher resistivity to scaling that could be implemented in the design.
- Explore pretreatment options with the goal of reducing scaling potential thus increasing TBT (produced water output).
- Develop site and feed water specific setup (implementing renewable energy sources, waste heat streams, power generation, energy recovery, etc..).
- Evaluate possible uses of the product water in industries requiring water of high purity.

References:

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2. Al-Karaghouli, A. and L.L. Kazmerski, *Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes.* Renewable and Sustainable Energy Reviews, 2013. **24**: p. 343-356.
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Appendix J – Membrane Distillation (MD)

Description of the technology

Membrane distillation (MD) is a crossover of both thermal and membrane technology. It is driven by thermal energy evaporating water and a porous hydrophobic microfiltration membrane that allows only water vapor molecules to pass through. The hydrophobicity is based on the surface tension forces of the membrane, not allowing molecules in a liquid state to pass through. The flux of the water vapor molecules is driven by the vapor pressure difference across the membrane which is a direct result of the temperature difference between the hot and cold sides of the membrane.

MD operates at a temperature range of 60°C – 90°C which is a temperature range comparable to that of Multi-Effect Distillation (60°C – 70°C). The reported range for thermal energy required by the system is 56 kWh/m^3 – 100 kWh/m^3 with a GOR of up to 11.2 [2]. As with all membrane technologies, membrane fouling is a key consideration in its efficient operation. Compared to RO, MD membranes have larger pores which have lower fouling propensities. As the technology relies primarily on its membrane's hydrophobicity (surface tension), the presence of surface-active components can cause wetting of the membrane leading to decreased effectiveness. Proper pretreatment of feed stream is crucial for its successful implementation [3].

Different configurations of MD exist which are mainly based on methods for maintaining vapor pressure difference across the membrane and condensation of the permeated vapor. Direct contact membrane distillation (DCMD) is the simplest of its configuration. Here, the feed is in direct contact with the hot side of the membrane. Evaporating at the membrane interface the vapor condenses on the cold side of the membrane leading to an increase in sensible heat loss.[132] Air-gap membrane distillation (AGMD) is another MD configuration addressing this effect. Distinguishable by an air gap of stagnant air between the hot and cold side of the membrane. The generated vapor additionally must pass through the air gap before it condenses. By introducing this additional step, the conductive heat transfer resistance increases, accompanied by an increase in mass transfer resistance which in turn decreases the permeate flux. To mitigate this effect, a cold inert gas can be applied to sweep the water vapor molecules thus the condensation occurs away from the surface of the membrane. Sweeping gas membrane distillation (SGMD) is a configuration that utilizes said configuration. Another MD configuration addressing the sensible heat loss is the Vacuum membrane distillation (VMD) configuration. In this configuration, a vacuum, that is lower than the saturation pressure of pure water, is applied to the permeate side. Same as in SGMD, condensation occurs away from the membrane. In this configuration, the applied vacuum cannot exceed the liquid entry pressure of the pores as wetting might occur. The liquid entry pressure is a function of the feed's surface tension and the membrane's physical properties such as pore size, material, etc. [3]. A variation on DCMD is the Permeate Gap Membrane Distillation (PGMD). This configuration differs from DCMD in that it integrates energy recovery into the membrane

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[132] The increase of sensible heat loss directly relates to conductive heat loss. In the case of DCMD, this causes a decrease in thermal energy on the hot side of the membrane that is available to generate water vapor i.e., cooling of the membrane.

module eliminating the air gap. With this integration, the mass transfer resistance between the two sides of the membrane is reduced [4].

Process description

A process schematic for PGMD configuration is shown in Figure 46.

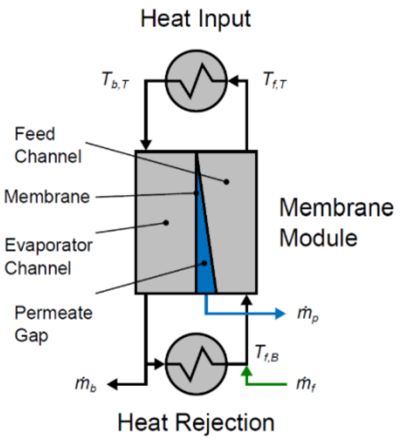

Figure 46. SCHEMATIC OF PGMD PROCESS FLOW [1]

6. The feed enters the membrane on the hot side where it is heated to the designed temperature ($T_{f,T}$) .
7. The heated feed enters the evaporator passing over the hydrophobic membrane permeable to vapor but not the liquid phase.
8. The cold side of the membrane is in contact with the permeate stream and the temperature difference creates a water vapor pressure difference causing evaporation on the hot side while condensation on the cold side of the membrane.

Pretreatment required

Removal of organics, suspended solids, and hydrocarbons.

Removal of hydrophobic components that may cause wetting (alcohols, oil).

Limitations

Fouling at high recovery ratios.

The presence of surfactants affects the efficiency of the hydrophobic membrane [5].

Product water (Salinity, Other quality measures, Recovery)

Distillate, recovery ratio up to 50% [6].

Potential Application (within the oil field, agricultural irrigation, agricultural livestock, industrial, domestic non-potable, potable water)

Production of potable water [7].

Technology Readiness (commercial, pilot scale, bench scale)

So far to the best of our knowledge, the technology has been used on a pilot scale and small capacity field scales (< 100 m^3/d).

Economics

Membrane Distillation										
Feedflow	**Feedflow**	**Recovery**	**Product flow**	**Capital Cost**	**Operating Cost**		**Operating Cost per volume water**			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	8.9	1.5	4.7	1.11	3.41	0.18	0.54
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		6.0	16.5	4.31	11.91	0.69	1.89
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		8.3	22.8	5.97	16.46	0.95	2.62
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		10.1	27.8	7.28	20.04	1.16	3.19

Table 25: Literature summary of energy consumption and costs (product water basis).

Feed water	Electrical Energy consumption [kWh_e/m^3]	Thermal energy consumption in electricity equivalents (corresponding thermal range) [kWh_e/m^3]	Capacity [m^3/day]	Utility cost- ($/bbl)	Total cost ($/bbl)	References
Seawater	0.13 -2	43 – 800†	3.6 – 26.4*	0.09 – 0.27$^{\Delta}$	0.10-0.8	[6-10]
Produced Water	1.9	173	1263	1.1	1.4	[11]

† AGMD pilot project Solarspring in Germany has a energy consumption of 200 – 800 kWh/m^3, treating a feed stream of 240,000 mg/L TDS with an output of 128 mg/L TDS, GOR is reported as 3.64 [6].

** Values represent data from pilot projects.*

Δ Cost ranges are representative of seawater being sensitive to primary utility cost, treatment efficiencies, and capacities and should not be considered exhaustive.

Produced water cost is based on simulation of a hypothetical single stage DCMD plant operating at 0.5 MGD feed capacity at 67 % recovery and inlet TDS of 100 g/L

Table 26: Pros and Cons related to Membrane Distillation.

Advantages	Disadvantages
Lower operating pressures than RO (MD up to a few bars compared to RO that can be more than 80 bars [3]). Ability to utilize low-grade heat [3].	Poor energy efficiency compared to other technologies [1]. Low flux compared to other technologies (MD: 1 – 4 L/m^3, RO: 12 – 17 L/m^3) [12]. Not energy efficient in a single stage [1].

Membrane has a lower propensity to fouling due to large membrane pores and the absence of applied hydraulic pressure [3].	Not suitable to remove paraffins and TOC/VOCs [5]. Currently not implemented as a full-scale treatment option.

Technology Path Forward for PW treatment:

- Membrane research increasing resistance to wettability and increasing the membrane flux.
- Pilot scale using PW is necessary to determine its applicability. Efficiency might be increased by researching configurations utilizing:
  - brine recirculation
  - Multi-pass systems
  - Waste heat sources

References:

1. Thiel, G.P., et al., *Energy consumption in desalinating produced water from shale oil and gas extraction.* Desalination, 2015. **366**: p. 94-112.
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Appendix K – Reverse Osmosis (RO)

Description of the technology

Reverse Osmosis (RO) is one of several membrane-based water treatment technologies and is the standard technology for separating low salinity (seawater and below) streams. Osmosis is the process of water movement from solutions of lower salinity solution (low osmotic pressure) to the higher salinity solutions (high osmotic pressure). In RO, pressure to the feed is applied to the feed using a pump, the pressurized feed is then passed through the membrane in the opposite direction to the osmotic potential. To maintain such a flow, the applied pressure must exceed the osmotic pressure of the higher salinity solution.

RO systems are evaluated on their Specific Energy Consumption (SEC). This metric is defined as the ratio of energy consumption to the volume of permeate. SEC is a function of pressure on both the feed and permeate side, and the recovery ratio. Recovery ratio is, as its name implies, the ratio of the permeate (produced) water to the feed. Further, recovery ratio influenced by the feed salinity, temperature, parts efficiency (pump, energy recovery device). Apart from the concentrate increasing osmotic pressure thus also the energy demand, temperature effects consequently do the same. With the increase in temperature, both salt and feed permeability coefficient increase resulting in inconsistent effects on SEC.

RO operates at a feed pressure of 6 – 30 bar for brackish water while 55 – 80 bar for seawater. The salt rejection for both waters is higher than 95%. A single RO system around 45% of the feed becomes permeate, and around 55% as the brine stream. With the addition of a second stage, the permeate increases to 60% and the brine drops to around 40% [2].

In a two-stage setup, the brine from the first stage gets pressurized to overcome the osmotic pressure of that stream. Called the top stage pressure, this design parameter is correlates to the salinity of the feed being treated before entering the stage. From this we can ascertain that salinity is a controlling variable for the energy consumption of the system [1].

The least work of separation represents the base line of the energy required by the system under ideal conditions. For produced water Thiel, Tow [1] stipulates that the least work of separation is approximately five times that of seawater for a recovery of 50%. The higher osmotic pressure of high salinity produced water significantly increases the pressure required to force water through the membrane in RO and the use of RO to desalinate waters much more than seawater is considered impractical both due to the cost of producing the required high pressure and the fact that membranes are not designed to handle the required pressures.
For seawater total annual cost including both annualized capital cost and operating cost can be as low as \$0.11 – \$0.22/bbl.

Process description

A process schematic is shown in Figure 47.

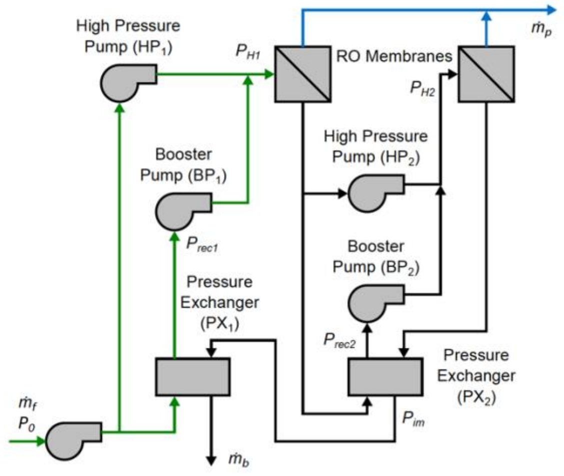

Figure 47 SCHEMATIC OF TWO STAGE HYPOTHETICAL HIGH SALINITY RO PROCESS FLOW [1]

1. The feed stream enters the low-pressure pump pressurizing the feed to a low pressure such as 2 bar. A portion is diverted to the first high-pressure pump (HP_1). There it is pressurized to the designed pressure of the first RO stage.
2. From the first stage, the feed moves along the membrane while being concentrated. This feed, as in step 1. is split into two streams where one is directed to the second high pressure pump (HP_1), pressurized to the design pressure of the second RO stage.
3. The brine from the second RO stage proceeds to the pressure exchanger (PX) where it pressurizes the influent feed.
4. The booster pumps pressurize the second feed stream and the brine from the PX to the pressure required before the RO membrane [1].

Pretreatment required

Removal of oil and suspended solids (SS).
Filtration depending on contained particle size (microfiltration, ultrafiltration, nanofiltration)
Addition of antiscalants.

Limitations

Unproven for salinities above 7% [1].
Deterioration of supporting equipment due to high TDS (pumps).
Membrane fouling and pressure limitations are defined by structural integrity.

Product water (Salinity, Other quality measures, Recovery)

Distillate, with a recovery ratio of 35% – 50% for seawater, 50% - 85% for rakish [2].

Potential Application

Used to produce potable water from seawater and lower salinity waters.
Used to treat lower salinity waters from coal bed methane production [1].

Technology Readiness

Mature technology for seawater desalination and distillation of solutions with lower salinities.

Economics

Reverse Osmosis

Feedflow	Feedflow	Recovery	Product flow	Capital Cost	Operating Cost		Operating Cost per volume water			
MBD	MGD	% (v/v)	MGD	M$	M$/yr		$/m3		$/bbl	
					Low	High	Low	High	Low	High
Case	**Seawater**									
0.048	2	50	1.00	8.6	0.3	0.8	0.25	0.55	0.04	0.09
Case	**Produced water - 25th Percentile TDS**				Low	High	Low	High	Low	High
0.048	2	50	1.00		0.9	2.4	0.68	1.71	0.11	0.27
				Hypothetical Cases (RO not demonstrated at these salinites)						
Case	**Produced water - 50th Percentile TDS**									
0.048	2	50	1.00		1.3	3.2	0.91	2.31	0.14	0.37
Case	**Produced water - 75th Percentile TDS**									
0.048	2	50	1.00		1.5	3.9	1.08	2.78	0.17	0.44

Table 27: Literature summary of energy consumption and costs (product water basis) to desalinate seawater.

Electrical Energy consumption [kWh_e/m^3]	Capacity [m^3/day]	Utility cost- ($/bbl)	Total cost ($/bbl)	References
2.5 - 6	250 – 500,000*	0.04 – 0.10 $^{\Delta}$	0.11- 0.22 $^{\Delta}$	[2, 3]

** 60,000 m^3/day is an average size RO treatment plant [4].*

Δ Cost ranges are representative for seawater being sensitive to primary utility cost, treatment efficiencies and capacities and should not be considered exhaustive.

Table 28: Pros and Cons related to RO.

Advantages	Disadvantages
Small footprint compared to thermal based technologies [3]. Applicable for a wide range of TDS [3]. Extensively researched thus continuously adding new and innovative approaches (Closed circuit desalination, removal of ~99.6% TDS & ~89% DOC [5]) High ion rejection rates (>99% [1]) Membrane more foulant resistant than FO (e.g. more than 5 times [6]). Energy costs can be reduced by implementing energy recovery [7]. Successful pilot scale project for oilfield low salinity produced water treatment in Bakersfield, California [7].	Pretreatment based on types of solutes and their concentration [2]. Concentration polarization while treating high saline solutions [2]. [a] Propensity for fouling. Not resistant to organic foulants (e.g. flux decline ~46% [8]). High energy demand for treating high TDS feeds [1].

a. Due to the convective flow of bulk fluid to the membrane, salt concentration increases at the surface of the membrane causing a boundary layer. The salt concentration in the boundary layer exceeds that of the bulk solution which leads to the diffusion of solutes away from the membrane.

Technology Path Forward for PW treatment:

- Develop methods of determining the most effective pretreatment based on water chemistry.
- Designing membranes more resistant to fouling while keeping low capital cost.

References:

1. Thiel, G.P., et al., *Energy consumption in desalinating produced water from shale oil and gas extraction.* Desalination, 2015. **366**: p. 94-112.
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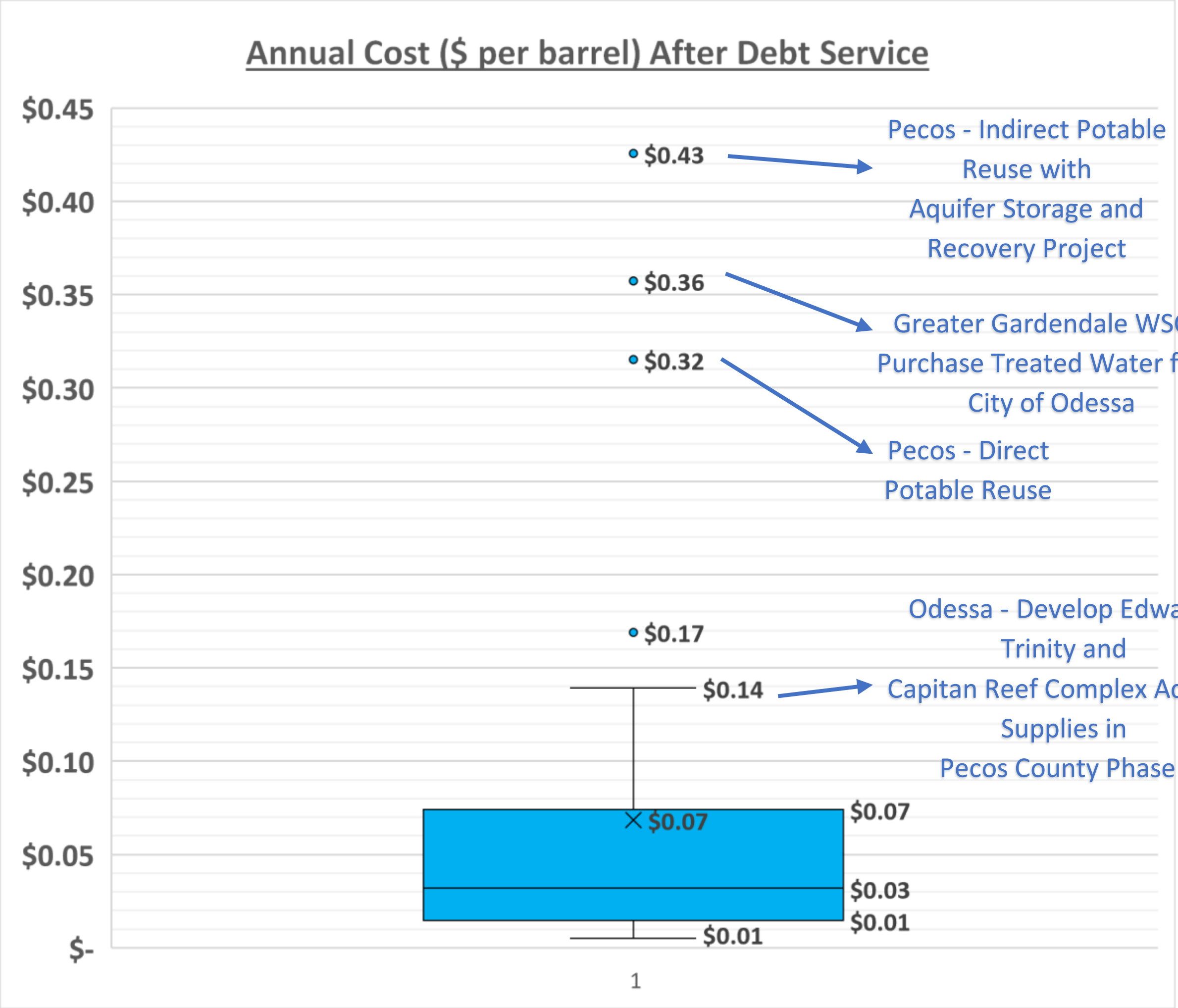
8. Tow, E.W., et al., *Comparison of fouling propensity between reverse osmosis, forward osmosis, and membrane distillation.* Journal of membrane science, 2018. **556**: p. 352-364.

Appendix L – Estimated Pilot Project Testing Costs

	Frequency of Tests			**Estimated Cost Per Test**		**Estimated Testing Costs (Cost Per Test x Number of Tests**			**Additional Analysis**				
3 Month Pilot Project Testing	Number of Weekly Tests	Number of Daily Tests	Number of Comprehensive Tests	Influent	Effluent	Influent	Effluent	Total TPW Water Test Costs	Environmental - Human Tox Risk Model for Assessment	Whole Effluent Toxicity Testing	Holistic Beneficial Use Testing Total Cost Per Treatment System	Minimum Project Sites	**Total Projected 3-Month Project Testing Costs**
Daily		84		$ 241.00	$ 108.00	$ 20,244.00	$ 9,072.00	$ 29,316.00					
Weekly	12			$ 1,265.00	$ 1,175.00	$ 15,180.00	$ 14,100.00	$ 29,280.00					
Comprehensive			3	$ 16,000.00	$ 16,000.00	$ 48,000.00	$ 48,000.00	$ 96,000.00					
								$ 154,596.00	*$ 15,000.00*	*$ 11,000.00*	*$ 180,596.00*	2	**$ 361,192**
6 Month Pilot Project Testing	Number of Weekly Tests	Number of Daily Tests	Number of Comprehensive Tests	Influent	Effluent	Influent	Effluent	Total TPW Water Test Costs	Environmental - Human Tox Risk Model for Assessment	Whole Effluent Toxicity Testing	Holistic Beneficial Use Testing Total Cost Per Treatment System	Minimum Project Sites	**Total Projected 6-Month Project Testing Costs**
Daily		168		$ 241.00	$ 108.00	$ 40,488.00	$ 18,144.00	$ 58,632.00					
Weekly	24			$ 1,265.00	$ 1,175.00	$ 30,360.00	$ 28,200.00	$ 58,560.00					
Comprehensive			3	$ 16,000.00	$ 16,000.00	$ 48,000.00	$ 48,000.00	$ 96,000.00					
								$ 213,192.00	*$ 15,000.00*	*$ 11,000.00*	*$ 239,192.00*	2	**$ 478,384**

Appendix M – Region F Water Supply Projects



Pecos - Indirect Potable Reuse with Aquifer Storage and Recovery Project

Greater Gardendale WSC – Purchase Treated Water from City of Odessa

Pecos - Direct Potable Reuse

Odessa - Develop Edwards Trinity and Capitan Reef Complex Aquifer Supplies in Pecos County Phase I

Appendix N – 2021 Bureau of Labor Statistics Overview

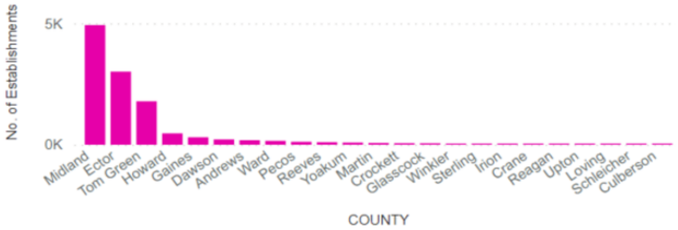
2021 BLS Establishments, Employment, Wages

Permian Delaware & Midland Basin Counties (24)

12K

Establishments

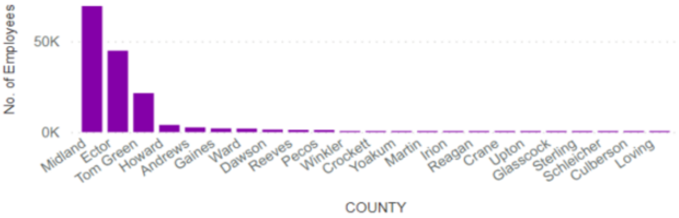
2021 Annual Establishments by County



152K

Employment

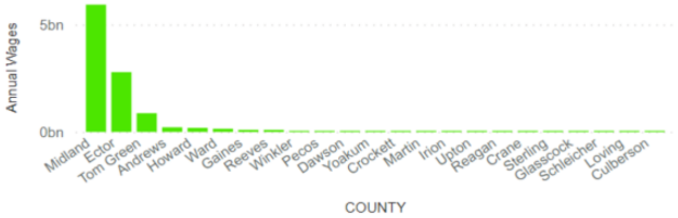
2021 Annual Average Employment by County



$11B

Wages

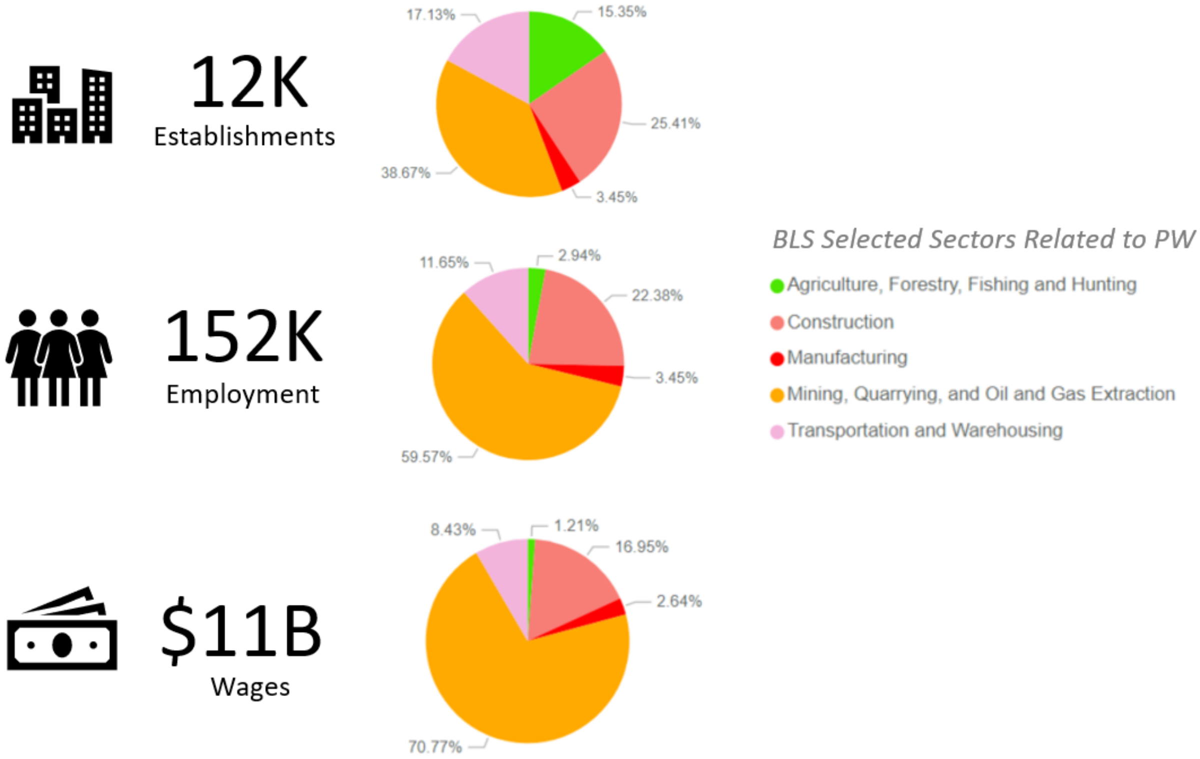
2021 Total Annual Wages by County



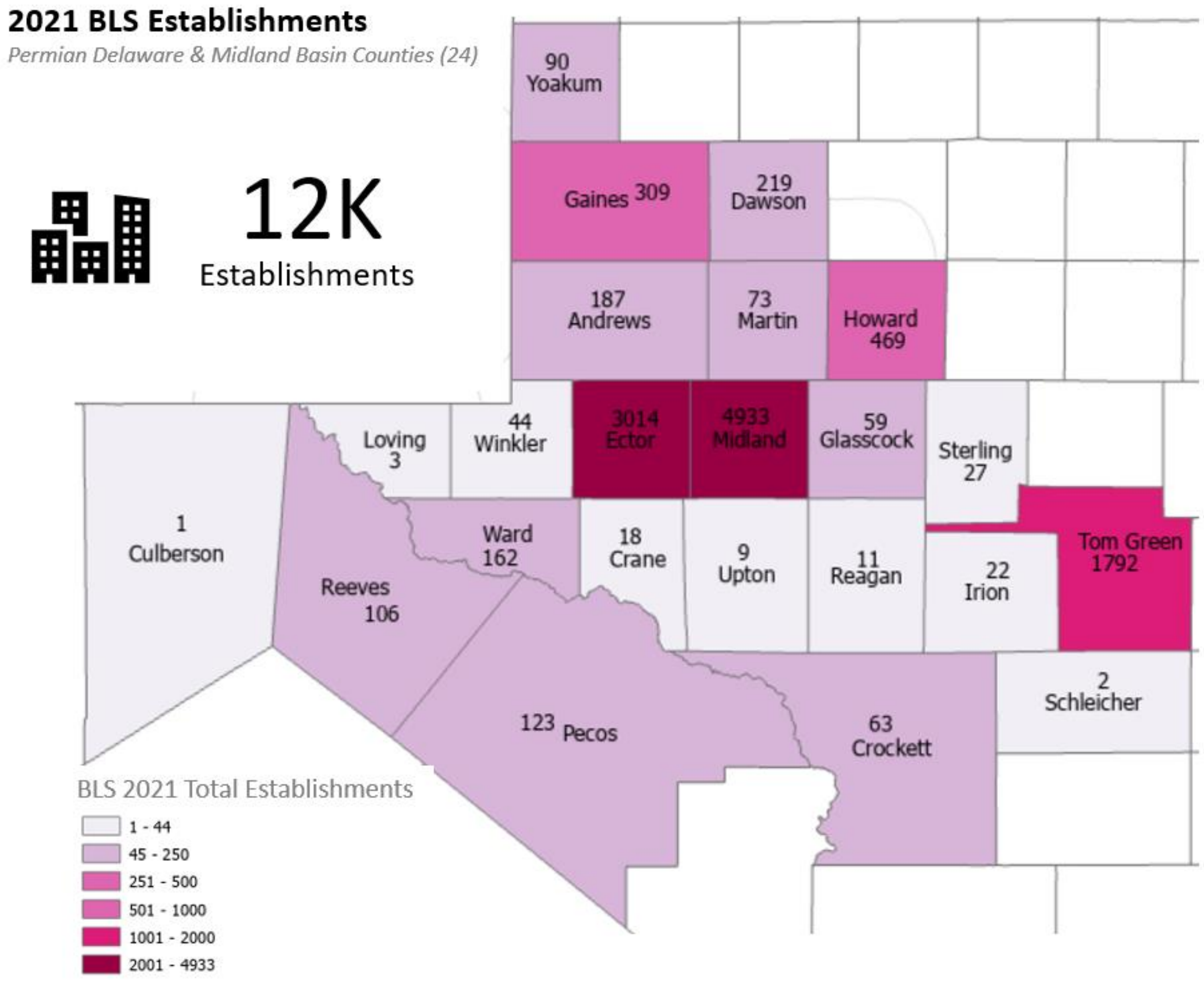
US Bureau of Labor Statistics (BLS) 2021 Total Establishments, Employment and Wages for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.

2021 BLS Establishments, Employment, Wages

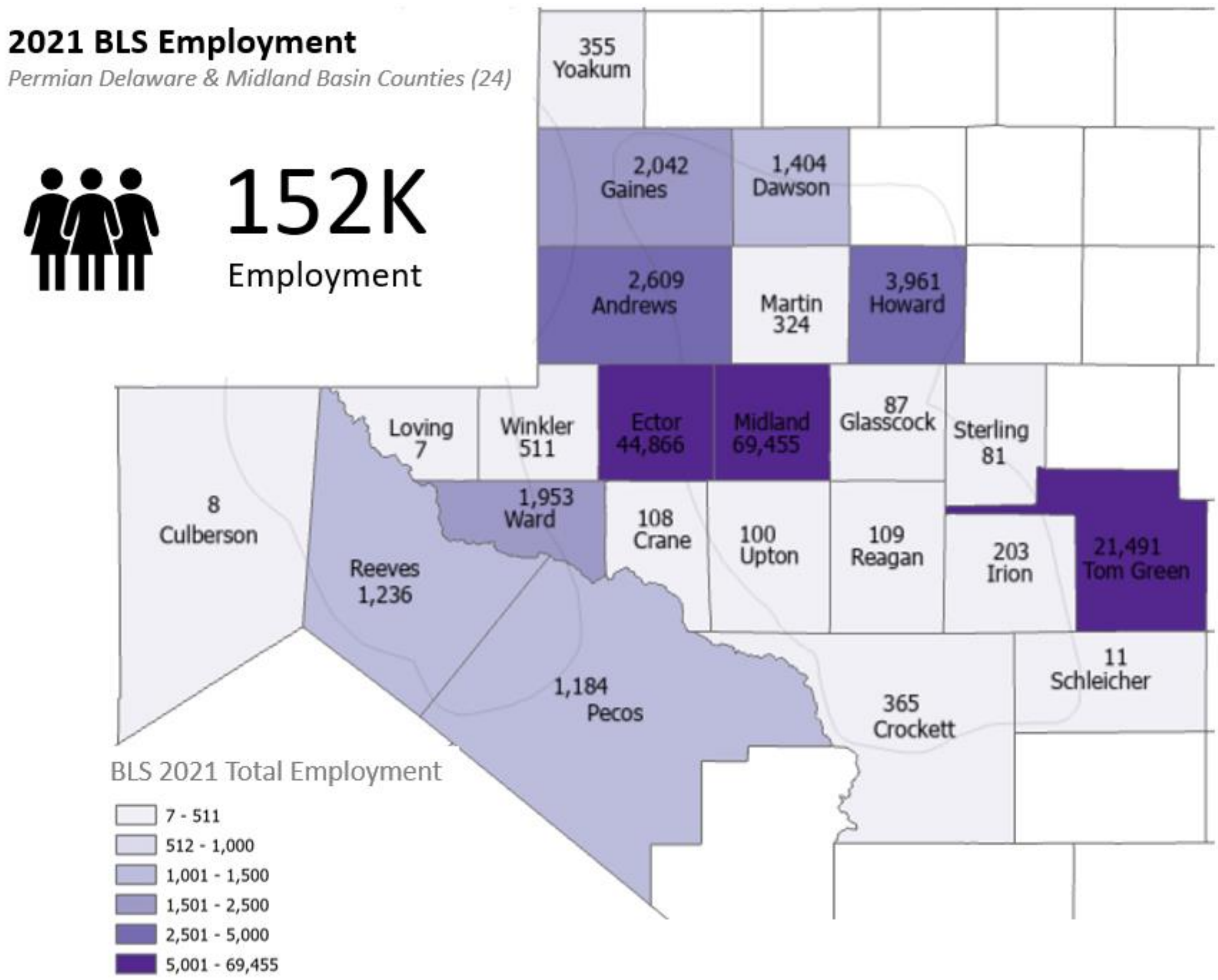
Permian Delaware & Midland Basin Counties (24)



US Bureau of Labor Statistics (BLS) 2021 Total Establishments for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.



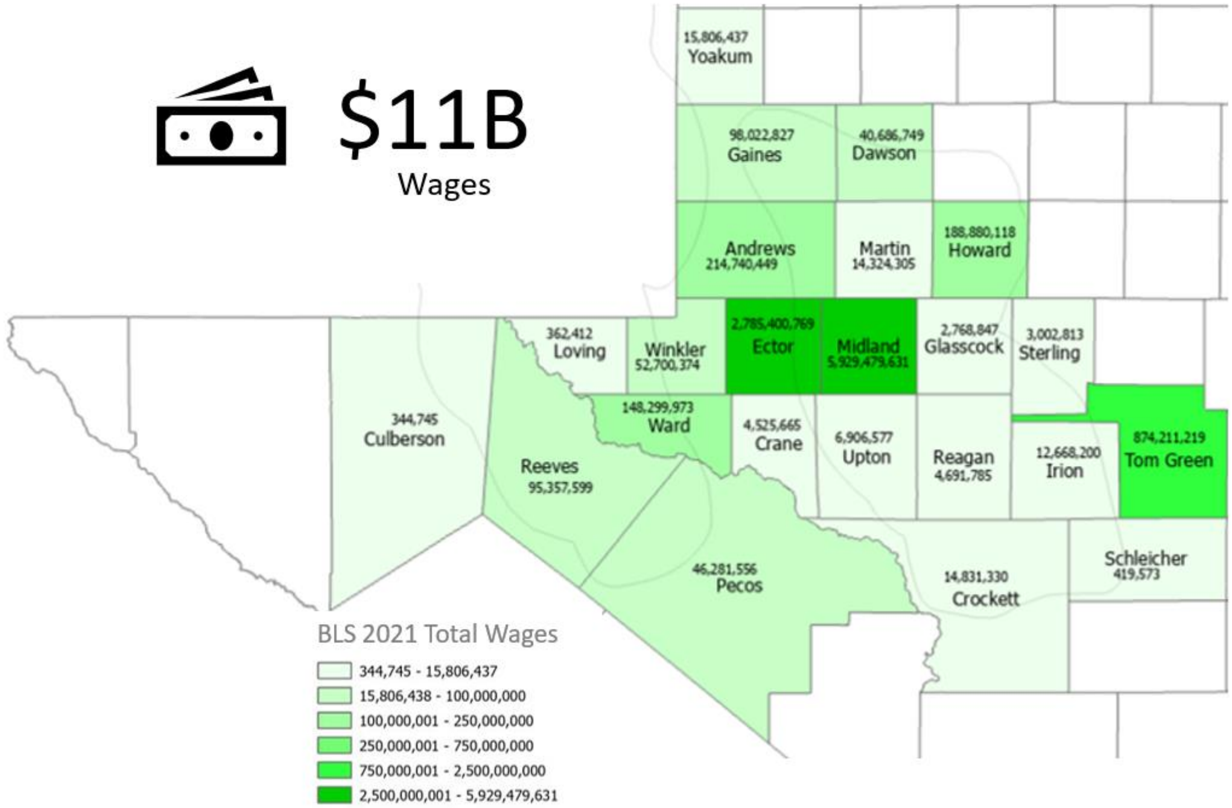
US Bureau of Labor Statistics (BLS) 2021 Total Employment for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.



US Bureau of Labor Statistics (BLS) 2021 Total Wages for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.

2021 BLS Wages

Permian Delaware & Midland Basin Counties (24)



US Bureau of Labor Statistics (BLS) 2021 Total Wages for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.

Glossary and Current Working Terms

Term	Acronym	Definition
Agriculture or Agricultural		Any of the following activities: (A) cultivating the soil to produce crops for human food, animal feed, or planting seed or for the production of fibers; (B) the practice of floriculture, viticulture, silviculture, and horticulture, including the cultivation of plants in containers or non-soil media by a nursery grower; (C) raising, feeding, or keeping animals for breeding purposes or for the production of food or fiber, leather, pelts, or other tangible products having a commercial value; (D) raising or keeping equine animals; (E) wildlife management; (F) planting cover crops, including cover crops cultivated for transplantation, or leaving land idle for the purpose of participating in any governmental program or normal crop or livestock rotation procedure; and (G) aquaculture as defined in Texas Agriculture Code, §134.001, which reads "'aquaculture' or 'fish farming' means the business of producing and selling cultured species raised in private facilities. Aquaculture or fish farming is an agricultural activity."
Aquifer		A geological formation, group of formations, or part of a formation that is capable of yielding a significant amount of water to a well or spring.
Barrel	BBL	In the energy industry, a barrel is 42 U.S. gallons measured at 60 ° Fahrenheit.
Barrels of Water per Day	BWPD	Measure of Barrels of Water Per Day.
Basin		A large, natural depression on the Earth’s surface in which sediments, generally brought by water, accumulate.
Beneficial Use		Use of the amount of water which is economically necessary for a purpose authorized by this chapter, when reasonable intelligence and reasonable diligence are used in applying the water to that purpose and shall include conserved water.
Beneficial Use		Use of the amount of water which is economically necessary for a purpose authorized by law, when reasonable intelligence and reasonable diligence are used in applying the water to that purpose and shall include conserved water.

British Thermal Unit	BTU	The amount of heat required to raise the temperature of one pound of water by one degree F.
Clean Water Act	CWA	Federal Clean Water Act
Discharge		Deposit, conduct, drain, emit, throw, run, allow to seep, or otherwise release or dispose of any pollutant, or to allow, permit, or suffer any of these acts or omissions.
Disposal		Engaging in the act of discharging, depositing, injecting, dumping, spilling, leaking, or placing of any oil and gas NORM waste into or on any land or water, or causing or allowing any such act, so that such waste, or any constituent thereof, may enter the environment or be emitted into the air or discharged into any waters, including subsurface waters. For purposes of this subchapter, disposal of oil and gas NORM waste includes its management at the site (e.g., lease, unit, or facility) where disposal will occur when undertaken for the explicit purpose of facilitating disposal at that site. The term does not include decontamination activities, except for in-place mixing of oil and gas NORM waste to remedy historical contamination of the land surface and decontamination of equipment and facilities that become contaminated solely through disposal operations. In addition, the term does not include activities, including processing or treatment, that occur at a location other than the disposal site.
Disposal Well		Well used for disposal of saltwater into an underground formation.
Dispose		To engage in any act of disposal subject to regulation by the commission including, but not limited to, conducting, draining, discharging, emitting, throwing, releasing, depositing, burying, landfarming, or allowing to seep, or to cause or allow any such act of disposal.
Drinking Water		All water distributed by any agency or individual, public or private, for the purpose of human consumption or which may be used in the preparation of foods or beverages or for the cleaning of any utensil or article used in the course of preparation or consumption of food or beverages for human beings. The term "drinking water" shall also include all water supplied for human consumption or used by any institution catering to the public.
Enhanced Oil Recovery	EOR	The use of any process for the displacement of oil from the reservoir other than primary recovery.
Environmental Protection Agency	EPA	The United States Environmental Protection Agency
Fluid oil and gas waste		Waste containing salt or other mineralized substances, brine, hydraulic fracturing fluid, flowback water, produced water, or other fluid that arises out of or is incidental to the drilling for or production of oil or gas.

Fresh Water		Water having bacteriological, physical, and chemical properties which make it suitable and feasible for beneficial use for any lawful purpose.
Groundwater		Any water that is located beneath the surface of the ground and is not under the direct influence of surface water.
GWPC		Ground Water Protection Council.
Hydraulic Fracturing Fluid		The fluid, including the applicable base fluid and all additives, used to perform a particular hydraulic fracturing treatment.
Industrial Use		The use of water in processes designed to convert materials of a lower order of value into forms having greater usability and commercial value, including the development of power by means other than hydroelectric, but does not include agricultural use.
Injection Well		Well used to inject fluids (usually water) into a subsurface formation by pressure.
Irrigation		The use of water for the irrigation of crops, trees, and pasture land, including, but not limited to, golf courses and parks which do not receive water through a municipal distribution system.
Lease		(A) The tract of land included in the proration units of a well(s).(B) A legal document executed between landowner or lessor that grants the right to exploit the premises for minerals or other products.
Million British Thermal Units	MMBTU	The amount of heat required to raise the temperature of one pound of water by one degree F.
National Pollutant Discharge Elimination System	NPDES	The National Pollutant Discharge Elimination System under which the Administrator of the United States Environmental Protection Agency can delegate permitting authority to the State of Texas in accordance with Section 402(b) of the Federal Water Pollution Control Act.
NORM	NORM	Naturally occurring radioactive material.
NPDES Permit		A permit issued by the regional administrator under the authority of the Federal Clean Water Act, §402, Title 33, United States Code, §1342. NPDES permits can either be individual or general permits.

Occupational Safety and Health Administration	OSHA	U.S. Department of Labor, Occupational Safety and Health Administration
Oil Well		Any well which produces one barrel or more crude petroleum oil to each 100,000 cubic feet of natural gas.
Operator		A person, acting for himself or as an agent for others and designated to the commission as the one who has the primary responsibility for complying with its rules and regulations in any and all acts subject to the jurisdiction of the commission.
Operator		Means a person who assumes responsibility for the physical operation and control of a well as shown by a form the person files with the commission and the commission approves. The commission may not require a person to assume responsibility for a well as a condition to being permitted to assume responsibility for another well. In the event of a sale or conveyance of an unplugged well or the right to operate an unplugged well, a person ceases being the operator for the purpose of Section 89.011 only if the well was in compliance with commission rules relating to safety or the prevention or control of pollution at the time of sale or conveyance and once the person who acquires the well or right to operate the well: (A) specifically identifies the well as a well for which the person assumes plugging responsibility on forms required and approved by the commission; (B) has a commission-approved organization report as required by Section 91.142; (C) has a commission-approved bond, letter of credit, or cash deposit under Sections 91.103-91.107 covering the well; and (D) places the well in compliance with commission rules.
Potable Water		Water that has been treated for public drinking water supply purposes.
Product		Includes refined crude oil, crude tops, topped crude, processed crude petroleum, residue from crude petroleum, cracking stock, uncracked fuel oil, fuel oil, treated crude oil, residuum, casinghead gasoline, natural gas gasoline, gas oil, naphtha, distillate, gasoline, kerosene, benzine, wash oil, waste oil, blended gasoline, lubricating oil, blends or mixtures of petroleum, and/or any and all liquid products or by-products derived from crude petroleum oil or gas, whether hereinabove enumerated or not.

Productive Zone		Any stratum known to contain oil, gas, or geothermal resources in commercial quantities in the area.
Recycle		To process and/or use or re-use oil and gas wastes as a product for which there is a legitimate commercial use and the actual use of the recyclable product for the purposes authorized in this subchapter or a permit. 'Recycle,' as defined in this subsection, does not include injection pursuant to a permit issued under §3.46 of this title (relating to Fluid Injection into Productive Reservoirs).
Reservoir		A porous and permeable underground formation containing a natural accumulation of producible oil and/or gas that is confined by impermeable rock or water barriers and is individual and separate from other reservoirs.
Reuse		The authorized use for one or more beneficial purposes of use of water that remains unconsumed after the water is used for the original purpose of use and before that water is either disposed of or discharged or otherwise allowed to flow into a watercourse, lake, or other body of state-owned water.
Safe Drinking Water Act	SDWA	Federal Safe Drinking Water Act
Saltwater Disposal		All of the produced water from the well is being directed towards a salt-water disposal to get rid of it.
Saltwater Disposal Well	SWD	A well used for the purpose of injecting produced water back into the ground.
Secondary Recovery		Hydrocarbons produced in one well bore by increasing reservoir pressure with water in another well bore.
Tertiary Recovery		An enhanced recovery process that goes beyond water or gas flooding. It may involve steam, fire, chemicals, miscible gases, bacteria or other techniques.
Texas Commission on Environmental Quality	TCEQ	Texas Commission on Environmental Quality

Texas Railroad Commission	RRC	Texas Railroad Commission
Total Dissolved Solids	TDS	Conductivity test of ions in the water. The combined dry weight of dissolved materials, both organic and inorganic, expressed in ppm that are contained in the water.
Transportation or To Transport		The movement of any crude petroleum oil or products of crude petroleum oil or the products of either from any receptacle in which any such crude petroleum or products of crude petroleum oil or the products of either has been stored to any other receptacle by any means or method whatsoever, including the movement by any pipeline, railway, truck, motor vehicle, barge, boat, or railway tank car. It is the purpose of this definition to include the movement or transportation of crude petroleum oil and products of crude petroleum oil and the products of either by any means whatsoever from any receptacle containing the same to any other receptacle anywhere within or from the State of Texas, regardless of whether or not possession or control or ownership change.
Treatment Facility		Any plant, disposal field, lagoon, incinerator, area devoted to sanitary landfills, or other facility installed for the purpose of treating, neutralizing, or stabilizing waste.
Water Flood		An improved oil recovery technique that involves injecting water into a producing reservoir to enhance movement of oil to producing wells.
Water injection	WI	The injection of water in order to maintain reservoir pressure and boost production.
Water Oil Ratio	WOR	The ratio of produced water to produced oil.