Caroline Crow

Please see the attached comments submitted by Earthjustice on behalf of Texas Permian Future Generations (Part 1 of 2). Thank you.

June 16, 2026

Via Electronic Filing
https://tceq.commentinput.com/comment/search

Gwen Ricco
MC 205, Office of Legal Services
Texas Commission on Environmental Quality
P.O. Box 13087
Austin, Texas 78711-3087

Re: Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

Dear Ms. Ricco,

Earthjustice on behalf of Texas Permian Future Generations ("Commenters") submits the following comments regarding the Texas Commission on Environmental Quality's ("TCEQ" or "Commission") proposed amendments to 30 Texas Administrative Code Chapter 309, Domestic Wastewater Effluent Limitations and Plant Siting and 30 Texas Administrative Code Chapter 210 (Use of Reclaimed Water), Subchapter E (Special Requirements for Use of Industrial Reclaimed Water) to implement Senate Bill 1145 ("SB 1145"), 89th Regular Texas Legislative Session, which amended Texas Water Code ("TWC"), § 26.131 (Duties of the Railroad Commission), to transfer permitting authority for the land application of produced water that is treated for beneficial use from the Railroad Commission of Texas ("RRC") to TCEQ.

Texas Permian Future Generations was created in 2020 by a group of Permian Basin residents concerned about the effect the oil field was having on the environment around them. The group's goal is a Permian Basin with better workplace protections for people who work in the oil field, better air and water quality, and fewer earthquakes, as well as a more diversified economy with more economic opportunities outside of the oil field.

The Permian Basin produces 6.6 million barrels of oil a day, but only about 13 inches of rain fall here annually.[1] Rich in one resource and lacking in another, this stretch of Texas runs the country while flirting with destruction, existing at the intersection of power and poverty, abundance and drought, salt and sky.[2]

The Permian Basin is a buried sea of black shale.[3] Its surface is so porous the yearly foot of rain falls right through the cracks into the shallow unconfined aquifers just below the surface, like the Pecos Valley Aquifer.[4] Once upon a time, the Basin had a wealth of water to feed the Pecos River—the largest tributary to the Rio Grande River.[5] Now, the Pecos is a threadbare ribbon wrapping across this arid land where it still can. The Pecos' water was always salty, but not saltier than the region could tolerate. Balanced in the salty water was life: pupfish, softshell turtles, and leopard frogs.[6]

In 1985 the first golden algal fish kill occurred.[7] Studies show the algal blooms are a consequence of high levels of salinity, sulfate, and chloride, and can also be caused by brine contamination from oil and gas production.[8] As oil and gas production has increased, the health of the Pecos River and the aquifers it feeds has declined.[9]

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[1] EIA Today in Energy, *EIA Forecasts near term U.S. Crude Oil production will remain near 2025 record*, https://www.eia.gov/TODAYINENERGY/detail.php?id=67045 (Jan. 22, 2026); *and see* Midland Development Corporation, Midland, Texas Climate https://www.midlandtxedc.com/community/climate.

[2] Kevin Crowley, Bloomberg, *Texas Oil Boom Spawns a Toxic Crisis of the Industry's Own Making* (Sept. 16, 2025) https://www.bloomberg.com/graphics/2025-permian-basin-geyser/.

[3] Shi-zhen Li, China Geology, Vol. 7, Issue 3, *Formation, evolution, reconstruction of black shales and their influence on shale oil and gas resource* (July 25, 2024) https://www.sciencedirect.com/science/article/pii/S2096519224001307.

[4] Texas Aquifers Study, Groundwater Quantity, Quality, Flow and Contributions to Surface Water, (Dec. 31, 2016) https://www.twdb.texas.gov/groundwater/docs/studies/TexasAquifersStudy_2016.pdf at 118-20. ("Aquifers Study").

[5] Christopher W. Hoagstrom, Historical and Recent Fish Fauna of the Lower Pecos River, (Nov. 17, 2001) at 91.

[6] U.S. Fish & Wildlife Service, *Pecos Pupfish*, https://www.fws.gov/species/pecos-pupfish-cyprinodon-pecosensis; U.S. Fish & Wildlife, *Endangered and Threatened Species: Threatened Species Status for Pecos Pupfish and Designation of Critical Habitat*, (Nov. 22, 2024) https://www.fws.gov/species-publication-action/endangered-and-threatened-species-threatened-species-status-pecos; U.S. Geological Survey, 2026, *Apalone spinifera emoryi* (Agassiz, 1857): Nonindigenous Aquatic Species Database, Gainesville, FL, https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=1275, Revision Date: 10/21/2019, Peer Review Date: 3/4/2019, Access Date: 6/13/2026; U.S. Geological Survey, 2026, *Lithobates berlandieri* (Baird, 1859): Nonindigenous Aquatic Species Database, Gainesville, FL, https://nas.er.usgs.gov/queries/FactSheet.aspx?speciesID=69, Revision Date: 10/26/2009, Access Date: 6/13/2026.

[7] Texas Parks and Wildlife, Golden Algal: what is it? https://tpwd.texas.gov/landwater/water/environconcerns/hab/ga/.

[8] Ric Jensen, *The Influences of Human Activity on the Pecos River*, Texas Water Resources Institute "TPWDs study concluded that the volume of flow in the river, salinity from natural and man-made sources and contaminants from oil production and agricultural activities influence the aquatic biology of the river.", chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://scispace.com/pdf/the-influences-of-human-activities-on-the-waters-of-the-3uu0n763ln.pdf.

[9] Martha Pskowski, Texas Tribune, *Companies aim to release more treated oilfield wastewater into rivers and streams* (April 29, 2024) https://www.texastribune.org/2024/04/29/texas-treated-produced-water-disposal-discharge-rivers/.

The water waste from hydrocarbon production continues to accelerate. Operators pushed it underground until it produced earthquakes. Understandably, the State now wants to solve the waste and drought problem with one solution: reclaiming the same water that over-salted the ecosystem away. But this wastewater is more than salty—it is toxic. Covering the ground in the same salty, toxic wastewater that altered the balance of the Pecos will bring us new problems: it will seep into every unconfined aquifer in the State, once land applied.

Below, Commenters explain the history of produced water management, including the serious public health concerns, argue for a regulatory framework with numeric/agronomic rigor to protect people and water resources, make recommended changes to the proposed rules, and urge TCEQ to deny the pending Texas Land Application Permits as unprotective until standards for this wastewater can be promulgated.

Figure 1: Principal Rivers of Texas[10]

I. INTRODUCTION

Produced water has always been a part of Texas. It's as old as Texas oil. But now we are producing volumes of produced water that eclipse our oil production. After 100 years of hydrocarbon production and almost 50 years of underground injection, the ground in Texas is swollen in sore.[11]

Drought has also always been a part of Texas. The Texas Water Development Board was created in 1957 following an almost decade-long, record drought.[12] Since 2022, the State of Texas

[10] Texas State Historical Association, Pecos River: Geography, History, and Water Management, (Originally published 1952, Updated April 16, 2016).

[11] State of Texas Railroad Commission of Texas Oil and Gas Division, Class VI UIC Primacy Application (Dec. 2022) at 2. ("Texas received primacy for Class II wells under Section 1425 of Safe Drinking Water Act on April 23, 1982, and designated the Railroad Commission of Texas (RRC) as the lead agency to coordinate the state's SDWA Section 1425 UIC Program.").

[12] Texas Water Development Board, About Page, https://www.twdb.texas.gov/about/.

has been under a standing drought disaster order.[13] This standing order has been amended and renewed every month since. As the drought persists, protecting the groundwater we have is the most important thing the State of Texas can do. But the current rulemaking does just the opposite, threatening the State's limited water resources.

TCEQ seeks to employ the State-only Texas Land Application Permit ("TLAP") program for land application relying on a fiction that *no* produced water will reach the underlying aquifers. As will be explained more below, the Clean Water Act may be a more protective federally back-stopped program better suited for this process. Further, this rulemaking must result in substantive standards for what stands to potentially become one of Texas' largest industrial wastewater streams.

II. LEGAL & FACTUAL BACKGROUND

Since 1982, operators have pumped wastewater from oil and gas production underground. In 2021, the total produced water volume in Texas was over 8.1 billion barrels.[14] According to the SB 1145 analysis, Texas produces an average of 7 barrels of produced water for each barrel of oil—in 2021, 8.1 billion barrels produced water resulted from 1.7 million barrels of hydrocarbon production.[15]

Table 1. Historical Water-Oil Ratio ("WOR") (2014-2023 average) vs Projected WOR (2024-2050 average) for the Delaware Basin (DB) and Midland Basin (MB) in all three forecast cases: low case, base case, and high case.[16]

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

Toxics and Public Health Risks

Produced water includes a complex mixture of naturally occurring constituents, such as total dissolved solids ("TDS"), heavy metals, and radioactive materials, including naturally occurring radioactive material ("NORM") and technologically enhanced naturally occurring radioactive material ("TENORM").[17] More specifically, produced water can contain, among other

[13] Governor Abbott, Drought Disaster Proclamation (May 17, 2026) https://gov.texas.gov/news/post/governor-abbott-amends-renews-drought-disaster-proclamation-in-may-2026.
[14] Groundwater Protection Council, *U.S. Produced Water Volumes and Management Practices in 2021* 88, https://www.gwpc.org/wp-content/uploads/2021/09/2021_Produced_Water_Volumes.pdf.
[15] *Id*. at 88-89; Bill Analysis, Senate Research Center, S.B. 1145 by Birdwell; Sparks, Natural Resources, Enrolled (June 5, 2025) at 1.
[16] Texas Produced Water Consortium, Beneficial Use of Produced Water in Texas (2024), at 88, https://www.depts.ttu.edu/research/tx-water-consortium/TXPWCFINALDRAFT.pdf. ("2024 TXPWC Report").
[17] Groundwater Protection Council, *Produced Water Report: Regulations, Current Practices, and Research Needs*, at 8 (2019) https://www.gwpc.org/wp-content/uploads/2019/06/Produced_Water_Full_Report___Digital_Use.pdf.

constituents, bromide, chloride, sulfate, total suspended solids ("TSS"), barium, potassium, sodium, strontium, benzene, ethylbenzene, radium-226, and radium-228.[18] Chemical additives in fluid used to develop, stimulate, and maintain fracked wells can contain acid, biocide, breaker, clay stabilizer, corrosion inhibitor, crosslinker, friction reducer, gel, iron control, pH adjusting agent, proppant, scale inhibitor, and surfactant.[19] A recent study in Colorado found that fracking fluid contained toxic chemicals banned under state law, including 1,4-Dioxane and 2-Butoxyethanol.[20] Still, this list barely scratches the surface. A review of nearly 130 papers identified approximately 1,200 unique chemicals detected in produced water.[21]

Many of the known constituents within produced water are associated with serious health risks. Numerous studies have found that produced water contains harmful constituents linked to cancer as well as developmental and neurological harms.[22] A study of over 800 wells in California, found toxic compounds in the wastewater of 96% of wells, some in high enough concentrations to pose serious health risks.[23] Research has found that the radioactive materials in produced water can pose significant health risks, including lung cancer and other forms of cancer.[24] Produced water also includes chemical additives like surfactants, biocides, and per- and polyfluoroalkyl substances ("PFAS") that are toxic even in very low concentrations and have been linked to serious health problems including liver and thyroid damage, hormone disruption, and cancer.[25] Produced water can contain tremendous levels of TDS and salt—10 times higher than seawater in some cases—posing significant challenges for treatment, disposal, or reuse.[26]

A 2019 literature review also found "legacy pollutants" are present in produced water and could be reintroduced into the environment through discharges.[27] The study found that produced water contained "endosulfan, an organochlorine insecticide that was banned in the US in 2010,

[18] U.S. EPA, *Hydraulic Fracturing For Oil And Gas: Impacts From The Hydraulic Fracturing Water Cycle On Drinking Water Resources In The United States (Final Report)*, 29–31, (2016) https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=332990.
[19] U.S. EPA, *Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act*, Table 3-1 at 8 (May 2020), https://www.epa.gov/sites/default/files/2020-05/documents/oil-gas-final-report-2020.pdf.
[20] Jennifer Oldham, *Oil and Gas Companies Used Banned Toxic Chemicals Near the Rocky Mountains*, Colorado Newsline (Oct. 21, 2025), https://coloradonewsline.com/2025/10/21/oil-and-gas-companies-used-banned-toxic-chemicals-near-the-rocky-mountains/.
[21] Cloelle Danforth et al., *An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction.*, 134 Env't Int'l 105280 (2020).
[22] *See, e.g.*, Concerned Health Professionals of NY et al., *Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking and Associated Oil and Gas Infrastructure* (8th ed. 2022), available at https://psr.org/resources/fracking-compendium-8/ (collecting research).
[23] Emily A. Chittick & Tanja Srebotnjak, *An Analysis of Chemicals and other Constituents Found in Produced Water from Hydraulically Fractured Wells in California and the Challenges for Wastewater Management* (in Abstract) 204 Part 1 J. Env't Mgmt. (2017), https://www.sciencedirect.com/science/article/abs/pii/S0301479717308630?via%3Dihub.
[24] Amy Mall & Bemnet Alemayehu, *A Hot Fracking Mess: How Weak Regulation of Oil and Gas Production Leads to Radioactive Waste in our Water, Air, and Communities*, at 7, NRDC (2021), https://www.nrdc.org/sites/default/files/fracking-mess-regulation-radioactive-waste-report.pdf.
[25] Ayusha Ariana et al., *Pathways for Potential Exposure to Onshore Oil and Gas Wastewater: What We Need to Know to Protect Human Health*, Genohealth (2025).
[26] *Id*.
[27] Danforth et al., *supra* note 9, at 11.

and tetrachloroethylene, which is a suspected human carcinogen."[28] The study noted that the presence of legacy pollutants in produced water should be assessed as a risk to reusing or discharging produced water in a way that reintroduces it to the environment.[29] This study concluded that more research is needed before updating and expanding produced water discharge programs.[30]

Scientific research has highlighted the particular risks with the reuse of produced water for agriculture and wildlife propagation. A study in California found an increased cancer risk among adults consuming particular crops irrigated with oilfield produced water due to their exposure to arsenic.[31] A recent study by the Colorado Department of Natural Resources focused on coalbed methane produced water quality and found that in addition to issues with TDS and salinity, some harmful chemicals (barium, sodium, chloride, and fluoride) were found to be at high enough concentrations to "warrant caution" for reuse in livestock applications.[32] In addition, PFAS were detected in 6 of 24 samples collected and levels of benzene exceeded the EPA Maximum Contaminant Level ("MCL") in 3% of sample results.[33]

EPA completed a study evaluating discharges of produced water for agriculture and wildlife propagation and anticipates formal publication of a report on the study soon.[34] However, previously, in April 2025, EPA published a report on the study to its website that has since been removed. That report, retrieved by Earthjustice using a web archive, raises serious concerns regarding the discharge of produced water to the environment for agricultural and wildlife uses—including the land application contemplated by this rulemaking. The report states:

> *[T]here is a lack of data for constituents found in produced water related to crop health, ecotoxicology, livestock impacts, and other information that is necessary to make an adequate determination of 'good enough quality' [for use in wildlife and agricultural propagation]. In most cases, produced water … will contain an unpredictable and complex mixture of chemical additives and naturally occurring constituent for which no water quality standards and analytical methods exist. These concerns related to the unknown chemistry of produced water and the limited amount of data regarding treatability of produced water, particularly regarding reduction of toxicity, creates a challenge for regulators to determine treatment approaches and effectiveness. These knowledge gaps further complicate understanding treatment technology effectiveness to address potential human health and aquatic toxicity concerns resulting from discharges.*[35]

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[28] *Id.*
[29] *Id.*
[30] *Id.* at 12.
[31] Jennifer Hoponick Redmon et al., *Is Food Irrigated with Oilfield-Produced Water in the California Central Valley Safe to Eat? A Probabilistic Human Health Risk Assessment Evaluating Trace Metals Exposure*, 2020 Risk Anal. 41(8), 1463, available at https://pmc.ncbi.nlm.nih.gov/articles/PMC8519025/.
[32] Colorado Energy & Carbon Management Commission Department of Natural Resources, *Methane Seepage and Coalbed Methane Produced Water Quality in the Raton Basin, Huerfano and Las Animas Counties, Colorado*, at 10 (2025) *https://ecmc.colorado.gov/data-maps-reports/area-reports/raton-basin*.
[33] *Id*.
[34] EPA, Oil and Gas Extraction Effluent Guidelines, https://www.epa.gov/eg/oil-and-gas-extraction-effluent-guidelines (Jun 2, 2026).
[35] United States Environmental Protection Agency, Study of the Agricultural and Wildlife Water Use Subcategory (40 CFR 435 Subpart E), April 2025, recovered at [1/9/2026 6:26:24 PM].

With this acknowledgment, EPA's report goes on to present a wide-ranging body of literature demonstrating profound and vast adverse impacts to animals, soil, plants, waterbodies, and human health from produced water exposure. Such harms include, among others, the following:

- Soils irrigated with blended produced water had higher concentrations of salts and boron compared to soil from crops irrigated with groundwater and this accumulation is associated with diminished plant health.
- Development exposure to endocrine-disrupting chemicals commonly found in produced water impacted pituitary hormone concentrations, reduced sperm counts, altered folliculogenesis, and increased mammary gland ductal density and preneoplastic lesions and altered energy expenditure, exploratory and risk-taking behavior, and caused impairments to the immune system in mice, and altered basal and antiviral immunity in frogs.
- Increased disinfection biproducts ("DBPs"), including total trihalomethanes, toxic brominated trihalomethanes, iodinated DBPs and haloacetamindes, in drinking water systems impacted by produced water discharges.
- Farmers exposed to produced water contamination reported neurological issues (headache, dizziness, difficulty concentrating, short-term memory loss, skin numbness and tingling, incoordination, seizures, and inability to stand), respiratory issues (burning in nose and throat, difficulty breathing, asthma), vascular issues (nosebleeds, stroke), dermatological issues (hair loss and rashes), and gastrointestinal issues (vomiting, diarrhea, weight loss, weigh gain, cramping).
- Buildup in sediment of salts, alkaline earth metals (strontium, radium, and barium) and organic chemicals (nonylphenol ethoxylates [NPEs] and polycyclic aromatic hydrocarbons).
- Increased risk of soil sodification, groundwater salinization, and to plant health from salt and boron accumulation in the soil even with use of low-saline produced water.
- Stunted growth in wheat and sunflower plants irrigated with mixtures of treated and untreated produced water.
- Decreased rates of seed germination and reductions in biomass in crops irrigated with produced water.
- Deteriorated health and death in birds exposed to produced water.
- Increased incidence of health issues in livestock exposed to produced water, including sudden death, reproductive, neurological, gastrointestinal, musculoskeletal, and upper respiratory issues, and increases in stillbirths in cattle.
- Increased antimicrobial resistance in microbial communities downstream from produced water discharges.
- Altered metabolism, reduced swimming performance, and aerobic scope in fish exposed to produced water.[36]

Overall, a substantial, and growing, body of research establishes numerous health risks associated with produced water and its constituents. This body of research particularly cautions

[36] *Id.* at 25–40.

against reintroducing this waste into the environment for uses such as crop irrigation, livestock watering, and habitat creation.[37]

Unproven Treatment Technologies

Current scientific research does not support the conclusion that produced water can be safely treated for land spreading or discharge. Tailoring an appropriate produced water treatment solution, often referred to as a "fit-for-purpose- treatment train," is a major barrier to large scale operations. Characterizing the constituents of any wastewater is critical to selecting the appropriate treatment technology;[38] however, the complex chemical composition of produced water varies considerably from reservoir to reservoir, between basins, geologic formations, the specific hydrocarbons being produced, the duration of production, and any chemical additives used by the operator.[39] As of today, wastewater treatment technologies are not specifically designed to handle treating highly saline produced water at large scale.[40] The highly complex and variable chemical composition of produced water combined with a lack of detailed produced water characterization means that determining the right fit-for-purpose train remains unsolved.[41]

Further, any treatment or discharge of produced water is complicated by knowledge gaps about its constituents. The oil and gas industry is not required to disclose every chemical used in its extraction activities, leaving many constituents in produced water unknown due to proprietary information and "trade secret" claims. An analysis of data available on FracFocus, a national database for chemical disclosure in fracking operations, found that "proprietary claims have increased from 2014 to 2022 in mass, frequency, and proportion" with "a total of 10.4 billion pounds of chemicals withheld as trade secrets from 2014 to 2022."[42] Even where constituents of produced water are known, there is a lack of toxicity data for these constituents. One study found that of the nearly 1,200 chemicals identified in produced water, 86% lack toxicity data and only 24% can be detected through standard analytical methods.[43]

To date, the history of produced water treatment facilities is rampant with failures, human tragedy, environmental contamination, and taxpayers left to clean-up pervasive industrial harm. Below is a non-exhaustive list of produced water treatment facilities that have discontinued operations and now face legacy environmental concerns:

- **Antero's Clearwater** facility in Doddridge County, West Virginia, claimed that it would turn produced water into fresh water and food-grade salts. The facility idled less than two years after beginning operations in 2017, citing a lack of cost effectiveness. For years, West

[37] *E.g.*, Melissa Troutman & Amy Mall, *California Oil and Gas Waste Report*, Earthworks 16 (Jan. 2021), https://earthworks.org/wp-content/uploads/2021/09/CA-Waste-Report-2021-Final-2-1.pdf.
[38] 2022 TXPWC Report at 14.
[39] 2022 GWPC at 9.
[40] 2022 TXPWC Report at 14–15 (describing that technically recoverable volume is a major challenge due to the high salinity of Permian produced water and that there are no existing scalable treatment operations in the Permian.).
[41] 2022 TXPWC Report at 15.
[42] Vivian Underhill et al., *Increases in Trade Secret Designations in Fracking Fluids and their Potential Implications for Environmental Health and Water Quality*, 351 Journal of Environmental Management 119611 (2024) https://www.sciencedirect.com/science/article/abs/pii/S030147972302399X.
[43] Danforth et al., *supra* note 9.

Virginians had flagged concerns about the radioactivity and toxicity of the waste processed by the facility.[44]

- **Austin Master Services** in Martins Ferry, Ohio was permitted in 2014 to treat oil and gas wastewater. After Martins Ferry residents raised concerns that the facility was illegally stockpiling wastewater and other oil and gas waste, leading to soil and water contamination, the Ohio Department of Natural Resources ordered that the facility shut down in 2022. Ohio taxpayers footed the bill for cleaning up the facility after Austin Master failed to comply with court orders.[45] An Ohio court ultimately ordered the company to pay over $34 million in penalties for mismanagement of oil and gas waste on its property.[46]

- **Eureka Resources** operated three produced water treatment facilities in Pennsylvania. Plagued with environmental violations, hazardous workplace conditions, and a worker death, all three facilities are now closed and undergoing cleanup.[47] The company currently faces criminal charges for oil and gas wastewater leaks and violations of the state's solid waste management laws.[48]

- **Fairmont Brine Processing, formerly AOP Clearwater,** in West Virginia was permitted to treat produced water. The facility was constructed between 2009 and 2010 and apparently operated until 2018. Numerous significant legacy environmental issues exist at the closed facility including TENORM and Resource Conservation and Recovery Act ("RCRA") wastes. Per recent U.S. Environmental Protection Agency ("EPA") documentation (June 2026), 46,200 gallons of RCRA mixed liquids and 72,179 gallons of TENORM liquids have been removed from the site, along with 331 tons of TENORM solids and over 33 tons of TENORM contaminated debris, with over 500 tons of TENORM solids remaining on-site.[49] Former workers at the facility have experienced rare cancers that some believe are attributable to their workplace exposures.[50]

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[44] Justin Nobel, *In West Virginia, Plan to Clean Up Radioactive Fracking Waste Ends in Monster Lawsuit*, DeSmog (Sep. 19, 2023), https://www.desmog.com/2023/09/19/radioactive-fracking-waste-west-virginia-veolia-antero-clearwater/.
[45] Liz Partsch, *ODNR to Clean Up Brine Waste at Austin master Services Facility*, Farm and Dairy (Aug. 1, 2024), https://www.farmanddairy.com/news/odnr-to-clean-up-brine-waste-at-austin-master-services-facility/834871.html.
[46] Joselyn King, *Judge: Austin Master Owes Over $34 Million in Penalties to State of Ohio for Violations at Martins Ferry Frack Waste Facility*, The Intelligencer Wheeling News-Register (Jan. 15, 2026).
[47] Joshua Boaz Pribanic, *"I Turned Blue": Workers Share Horrifying Experiences Treating Fracking Wastewater*, Public Herald (Dec. 10, 2023), https://publicherald.org/i-turned-blue-workers-share-horrifying-experiences-treating-fracking-wastewater-2/; Kiley Bense, *A Company's Struggles Raise Questions About the Future of Lithium Extraction in Pennsylvania*, Allegheny Front (Sep. 19, 2024), https://www.alleghenyfront.org/pennsylvania-fracking-waterwater-lithium-extraction-eureka/.
[48] John Beauge, *Defunct Pa. firm faces criminal charges over fracking waste leaks*, PENNLIVE (Jun. 08, 2026).
[49] U.S. EPA, Fairmont Brine Site, Site Update: Week of 6/8/26.
[50] Justin Nobel, *Radioactive Shadow Workers The treatment of oil and gas field waste is a dirty industry's dirtiest secret*, Sierra (March 24, 2025).

- **Southwestern Energy** received a National Pollutant Discharge Elimination System ("NPDES") permit to discharge produced water into the White River in Arkansas. The facility closed due to high operating costs.[48]

Together these produced water treatment facilities paint a cautionary tale, demanding that TCEQ exercise the utmost rigor in determining a regulatory protocol to oversee land application of produced water.

Texas Produced Water Consortium History & the Pilot Studies

SB 601 from the 87th Legislature created the Texas Produced Water Consortium ("Consortium"). The purpose of the Consortium is to study the economics, technology, and environmental and public health considerations of beneficially using treated oil-and-gas produced water. To accomplish this, the Consortium produced three reports:

- 2022 Report: *Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward.* The first report to the Legislature focused on the Permian Basin, estimated how much produced water could theoretically become available for use outside the oil field, and laid out a "fit for purpose" approach. ("2022 TXPWC Report").
- 2024 Report: *Beneficial Use of Produced Water in Texas.* The second report began a pilot-sampling program and flagged gaps in the existing regulatory framework. ("2024 TXPWC Report").
- 2026 Report: *Produced Water Treatment Pilot Testing: Water Quality Report.* This report presented the results of 5 pilot projects. ("2026 TXPWC Report").

The Pilots were required by legislation, SB 601 (2021) and SB 1047 (2023). Below is a summary of the pilots referenced in the Consortium reports:

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

pretreatment, advanced thermal desalination, polishing and disinfection train process. Inlet raw water quality averaged approximately 120,000 mg/L in TDS. Preliminary analysis indicates the resulting finished water achieved an average quality of 456 mg/L TDS.

5. **Pilot E: Midland basin collection.** Pilot operation began in Fall 2023 at a site near Colorado City, TX at a scale of approximately 132 BPD. The system is comprised of multiple reverse osmosis processes. Inlet raw water quality averaged approximately 55,000 mg/L in TDS. Preliminary analysis indicates the resulting finished water achieved an average quality of 179 mg/L TDS.[51]

The most recent Consortium conclusions are based on the limited pilot studies listed above. After analyzing 60 samples obtained from the five pilot testing projects between August 2024 and June 2025, the Consortium concluded that the pilot treatment systems effectively removed more than 99% of salinity, organics, and radioactivity.[52] Commenters attach a report authored by toxicologist George Woodall, PhD summarizing methodology issues, gaps, and recommendations related to the Consortium Reports.

To the extent that TCEQ is depending on the deficient Consortium Reports to justify land applying produced water for beneficial use, Commenters urge the Commission to pause until adequate technology is identified, studied and implemented, and to cure the identified gaps in the Consortium Reports before any land application permits for produced water can safely issue. Additionally, Commenters urge the Commission to partner with the Consortium and re-run the Pilots for sufficient time to prove the resulting conclusions could be consistently achieved, without creating cumulative adverse consequences.

III. COMMENTS ON RULEMAKING

A. The Texas Land Application Permit Program is Deficient.

Commenters applaud the legislature's foresight in requiring that produced water land application jurisdiction be moved from the Railroad Commission to TCEQ, but Commenters urge that the land application of produced water be permitted under the State's delegated Clean Water Act authority—rather than through the TLAP program. Importantly, SB 1145 did not dictate the regime TCEQ must use but left that to TCEQ's discretion as the permitting authority. As will be explained below, the State of Texas should consider requiring permits for the land application of produced water to be permitted under the State's delegated authority to administer the National Pollutant Discharge Elimination Program. Alternatively, the State should implement a regulatory scheme specifically designed to safely manage produced water's land application.

1. The Federal Clean Water Act

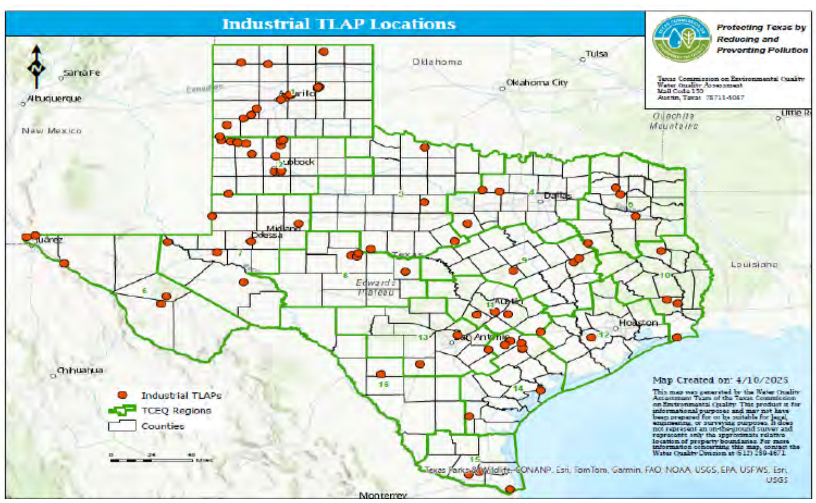
Federal law has historically recognized that states should approach produced water with caution. For nearly 50 years, produced water has been a prohibited category of point source discharge.[53] In its 1979 rulemaking, however, EPA did create an exception to the zero discharge standard for *some* wells in the western United States through 40 C.F.R., Part 435, Subpart E: a

[51] 2024 TXPWC Report at 10–11.
[52] 2026 TXPWC Report at iv.
[53] 40 C.F.R. Part 435.

beneficial use subcategory for wastewater produced west of the 98th meridian "for which the produced water has a use in agriculture or wildlife propagation when discharged into navigable waters."[54] The rule requires wastewater to be of "good enough quality" to be used for wildlife or livestock watering or other agricultural uses, and requires it to actually be used for such purposes.[55] The only federal effluent limitation guidelines ("ELGs") for oil and gas wastewater discharged for agricultural and wildlife propagation uses are a daily limit of 35 mg/L for oil and grease and the undefined "of good enough quality" standard.[56] EPA has announced its intention to revise these ELGs, but is yet to release a proposed rule.[57]

Figure 2: Map of Produced Water Discharge Rules[58]

Figure 3: Active TLAP Permits in Texas[59]



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[54] *See* 40 C.F.R. Subpart E, §§ 435.50–435.52.
[55] *Id*. § 435.51(c).
[56] *Id*. § 435.52(b).
[57] U.S. Environmental Protection Agency, *EPA Will Revise Wastewater Regulations for Oil and Gas Extraction to Help Unleash American Energy (ELGs: Oil and Gas)*, (Mar. 12, 205) https://www.epa.gov/newsreleases/epa-will-revise-wastewater-regulations-oil-and-gas-extraction-help-unleash-american.
[58] Martha Pskowski, Inside Climate News, *Standards Still Murky for Disposing Oilfield Wastewater in Texas Rivers*, (Aug. 17, 2023), https://insideclimatenews.org/news/17082023/texas-permitting-produced-water-disposal/.
[59] TCEQ, Texas Land Application Permits Industrial Wastewater Presentation.

The federal Subpart E exception exists related to discharge within the federal Clean Water Act framework.[60] Under the federal Clean Water Act, a "point source" is "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture."[61]

"Point Source" has been more explicitly defined and interpreted by the Courts—as has the agricultural exemption. The most current interpretations would, at the very least, require a Clean Water Act permit for the land application of produced water. Point source is consistently defined broadly as a "discernable" "conveyance."[62] And, Courts have "routinely" found that "land application systems, spray head sprinklers, and trucks constitute point sources when used to spread treated wastewater and manure on land."[63]

The agricultural exemption in the Point Source definition cannot be properly invoked here. Very recently, a federal court interpreted the agricultural exemption and reasoned that when "irrigation activities" did not concern "water obtained from a natural source to irrigate crops" that is later "returned to its source"—then the agricultural exemption would not be satisfied.[64] When the activities in question concerned "a state-mandated and state-designed land treatment vegetation system" this "intentional drainage of industrial wastewater *does not fall* within the purview of the *agricultural return flows exclusion*."[65] Thus, under the federal regime, a Clean Water Act permit would be required for the land application of produced water.

Given this context, the Commission must address, in this Rulemaking, whether the land application of produced water that will likely reach waters of the United States—via the hydrologically connected groundwater documented in Texas—constitutes a discharge that is the functional equivalent of a direct discharge.[66]

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[60] *Id.*
[61] 33 U.S.C. § 1362(14).
[62] *Id; and see Grand Traverse Band of Ottawa & Chippewa Indians v. Burnette Foods, Inc.*, 813 F. Supp. 3d 748, 764 (W.D. Mich. 2025) quoting *County of Maui, Hawaii v. Hawaii Wildlife Fund*, 590 U.S. 165, 182, (2020) (statute "does not say 'directly' from or 'immediately' from"; approving the statutory construction adopted by the plurality in *Rapanos v. United States*, 547 U.S. 715, 743, (2006) (opinion of Scalia, J.)); *see also United States v. W. Indies Transp., Inc.*, 127 F.3d 299, 309 (3d Cir. 1997) ("Congress intended a broad definition of 'point source'") (citing *United States v. Earth Sciences, Inc.*, 599 F.2d 368, 373 (10th Cir. 1979)); *United States v. Lucas*, 516 F.3d 316, 332–34 (5th Cir. 2008) (collecting cases, including *Rapanos*, supporting the proposition that a point source need only convey a pollutant to navigable waters).
[63] *Grand Traverse Band of Ottawa & Chippewa Indians*, 813 F. Supp. 3d at 764 (collecting cases); *see, e.g., Peconic Baykeeper, Inc. v. Suffolk Cnty.*, 600 F.3d 180, 188–89 (2d Cir. 2010) (spray applicators are point source); *see also* pending TLAP Application Package for WQ Permit No. WQ0005522000 at 82 of 175 ("Application of the treated PW will be through stationary, high-efficiency irrigation sprayers (guns). The guns will be located strategically to take advantage of the terrain and ensure complete coverage of the application area. Subsurface piping will distribute the effluent to the guns. The system will include controls that will allow independent operation of zones, consisting of up to 5 guns each, on a controlled schedule."); *see also* pending TLAP Application for WQ0005515000 at 22 of 205 (effluent will be distributed on land by sprinklers).
[64] *Grand Traverse Band of Ottawa & Chippewa Indians*, 813 F.Supp. 3d at 765.
[65] *Id.* (emphasis added).
[66] *See generally, County of Maui v. Hawaii Wildlife Fund*, 590 U.S. 165 (2020).

Commenters respectfully request that the Commission resolve this question in favor of requiring TPDES permits for land application of produced water. In the alternative, Commenters request that TCEQ revise the TLAP program to implement the expanded monitoring specific to produced water and implement agronomic rigor required under a TPDES permit.

2. Texas Pollution Discharge Elimination System

Turning next to the State's delegated authority to administer the National Pollution Elimination Discharge System, Commenters urge the Commission to use this Program to permit the land application of produced water.

To control and limit water pollution, in 1998, EPA delegated authority to Texas to administer the State's National Pollutant Discharge Elimination System ("NPDES") program.[67] Texas' program is referenced as the Texas Pollutant Discharge Elimination System ("TPDES") program. EPA premised delegation upon Texas' procedures and requirements as set forth in the statutes and regulations in place at the time, as well as representations made by the Texas Attorney General.

After HB 2771 from the 86th Legislature, Texas was prompted to seek additional delegation from the EPA related to produced water. And it was not until very recently—in 2021—that EPA delegated Texas the authority to discharge produced water.

Historically, the Railroad Commission oversaw land application of produced water and allowed application of produced water with a low chloride content.[68] In 2025, SB 1145 from the 89th Legislature, transferred permitting authority of the land application of produced water from the RRC to TCEQ. This legislation required TCEQ to adopt standards for the land application of produced water that has been treated for beneficial use.[69] Specifically, the Act required those land application standards to "prevent the pollution of surface and subsurface water."[70]

Regardless of which program is used—TLAP or TPDES— the same produced water may reach surface and subsurface water—just by two very different permitting regimes. In Texas "waters of the state" include "groundwater, percolating, or otherwise," meaning, produced water that seeps into an aquifer has reached "waters of the state."[71] TCEQ must implement the most protective program to preserve Texas' finite water resources. While SB 1145 did not specify the program or method of implementation for TCEQ to use in carrying out its mandate, federal law makes clear that the permitting of land application of produced water is appropriately done through TCEQ's delegated authority under the Clean Water Act; this is also the permitting regime most effective, enforceable, and protective of Texas' limited water resources.

Under Texas law, based on the current definitions of "Point Source", "Discharge", and "Waters of the state", the proposed land application of produced water will constitute a point source discharging to "waters of the state." Thus, the land application of produced water is most appropriately permitted under TCEQ's TPDES program.

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[67] 63 FR 185 (Sept. 24, 1998).
[68] *See Application Information for a Permit to Land Apply Produced Water or Gas Plant Effluent,* Tex. R.R. Comm'n, (providing guidance of a land apply permit application).
[69] S.B. 1145, Section 1(e).
[70] *Id.*
[71] Tex. Water Code § 26.001, (20).

The Texas Water Code defines point source as:

> *any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants or wastes are or may be discharged into or adjacent to any water in the state.*[72]

Discharge includes:

> *deposit, conduct, drain, emit, throw, run, allow to seep, or otherwise release or dispose of, or to allow, permit, or suffer any of these acts or omissions.*[73]

While "waters of the state" includes:

> *groundwater, percolating or otherwise, lakes, bays, ponds, impounding reservoirs, springs, rivers, streams, creeks, estuaries, wetlands, marshes, inlets, canals, the Gulf of Mexico, inside the territorial limits of the state, and all other bodies of surface water, natural or artificial, inland or coastal, fresh or salt, navigable or nonnavigable, and including the beds and banks of all watercourses and bodies of surface water, that are wholly or partially inside or bordering the state or inside the jurisdiction of the state.*[74]

According to these foundational definitions in the Texas Water Code, the produced water seepage into groundwater that may occur through land application means these discharges should be permitted under the State's TPDES Program.[75] Not just according to the definitions and hydrology basics, (as is explained more below in Section D), but also because, according to the State's legislatively mandated Aquifers Study[76]: "**All aquifers contribute some groundwater to the baseflow of streams and rivers in Texas**."[77] Thus, the TLAP program is insufficient to account for the impacts to surface waters and may violate the States' federally delegated authority to implement the Clean Water Act.

Additionally, the TPDES architecture provides *potentially* more safeguards when dealing with a varied and unknown waste stream, like produced water. Under a TPDES framework, produced water would be subject to the following:

- submitting "additional information, such as treatment processes and analyses for an enhanced list of pollutants"[78]

[72] Tex. Water Code § 26.001(21).
[73] Tex. Water Code § 26.001(20).
[74] Tex. Water Code § 26.001(5).
[75] Tex. Water Code § 26.001(5), (20), (21).
[76] HB 12332 directed the Texas Water Development Board to study the State's confined and unconfined aquifers.
[77] Aquifers Study at 22 (emphasis added).
[78] Texas Produced Water Consortium Report (2024) at 20–21.

- "draft permits will include acute and chronic Whole Effluent Toxicity (WET) testing"[79]
- Water quality standards[80]
- Antidegradation review[81]
- Public discharge monitoring reports[82]
- Citizen Suit enforcement[83]

Therefore, the TPDES program is likely the more protective permitting regime for the land application of produced water and the one TCEQ should employ to best protect the State's limited water resources. Whatever regulatory program is chosen, TCEQ must make protecting Texas' water resources the priority.

3. Texas Land Application Permit Program

In contrast to the TPDES scheme, TLAP regulates land application, but the produced water regulated is still destined for waters of the state. The State-only TLAP program is based on a fiction that *no* produced water will be discharged into waters of the state. As explained throughout this comment, this is simply not the case.

Still more concerning, the TLAP program does not have a set of corresponding regulations defining its "origin, scope, or minimum standards required."[84] Additionally, there has been no TLAP rulemaking for this state-only program and it evidently lacks a federal backstop. It has no history of public adoption, nor can TCEQ explain its authority to require a facility to obtain a TLAP permit.[85] Given these regulatory gaps, relying on the TLAP program as the sole permitting program for produced water land application will not be protective of human health and Texas' precious water resources.[86]

Ultimately, permitting produced water's land application through the TLAP program may also conflict with federal law. Specifically, the TLAP permitting program does not carry the geographic boundary prescribed by the federal regulations, which only allow discharge of produced water west of the 98th meridian. If produced water's land application for beneficial use

[79] *Id.*
[80] 30 Tex. Admin. Code Chapter 307 (Texas Surface Water Quality Standards).
[81] 30 Tex. Admin Code § 307.3 (antidegradation).
[82] 33 U.S.C. § 1365.
[83] *See* HB49 (amends the Texas Natural Resources Code to shield individuals or entities that possess treat and subsequently use, or transfer produced water for beneficial use from liability in tort for (1) consequences of the treatment or subsequent use of treated water, (2) exposure to the produced water or any byproduct generated in the treatment process; and (3) personal injury, death or property damage arising from exposure to produced water, treated water or any byproduct of treatment. These protections have two exceptions for gross negligence or negligence combined with violations of a regulatory requirement for the treatment, generation, use or disposal of produced water.).
[84] Timothy A. Wilkins, Texas Environmental Law Journal, A Regulator's Reach Exceeds its Grasp: The Quiet Expansion of the TCEQ's Water Code Jurisdiction (March 2016) at 32–33.
[85] *Id.* at 34.
[86] *See also* Modern Engineering Solutions, https://mod-eng.com/land-application-permits-in-texas-a-faster-path-to-wastewater-approval-for-developers/, (Explaining TLAP Permits as follows: "TCEQ's review does not include receiving water analysis, anti-degradation review, or EPA coordination for standard domestic applications. That narrower scope is what makes TLAP approvals faster and less contentious than TPDES permits for qualifying sites.").

qualifies as a discharge under the federally delegated TPDES program, and it is now allowed across the entire State (and not just west of the 98th meridian) this will violate federal law's current prohibition on the same.[87] Figures 2 and 3 illustrate this problem. Further, as explained above, any discharge of produced water reaching waters of the state must under federal and state law have a TPDES permit.

B. EPA and the Legislature Required the Commission to Establish Numerical Standards.

In November 2020, TCEQ applied to EPA for authority under the NPDES Program to discharge produced water, hydrostatic test water, and gas plant effluent.[88] When EPA approved TCEQ's program, EPA conditioned this approval on TCEQ promulgating standards.[89]

SB 1145 directs TCEQ to both assume permitting authority *and* adopt standards that prevent the pollution of surface and subsurface water.[90] The proposed rules do not accomplish this. Instead, the rules simply (1) extend Chapter 309's existing location/siting standards for land application of domestic wastewater to now include industrial wastewater and produced water, and (2) add produced water (40 C.F.R. 435 and 437) to the list of process wastewaters eligible for reuse authorization under Texas Water Code Section 210.54.

The preamble states that produced water "will be permitted as industrial wastewater" and acknowledges that the minimum requirements for land application of industrial wastewater "have historically been applied . . . on the basis of best professional judgment." The rules, as proposed, fail to establish water-specific numeric effluent limits, monitoring parameters, or end-use criteria.

Recommendation: The Commission should create a mandatory analyte list and numeric limits for produced water. These analytes should include toxic contaminants across produced water sample sets. For those contaminants with drinking water standards, the numeric standards should be *at least as stringent* as those applied to drinking water.[91] The mandatory analyte list and numeric limits for produced water should include at least the following analytes: Acidity, Alkalinity (Total as CaCO3), Aluminum, Ammonia Nitrogen, Arsenic, Barium, Benzene, Beryllium, Biochemical Oxygen Demand, Boron, Bromide, Cadmium, Calcium, Chemical Oxygen Demand, Chlorides, Chromium, Cobalt, Copper, Ethylene Glycol, Gross Alpha, Gross Beta, Hardness (Total as CaCO3), Iron – Dissolved, Iron – Total, Lead, Lithium, Magnesium, Manganese, MBAS (Surfactants), Mercury, Molybdenum, Nickel, Nitrite-Nitrate Nitrogen, Oil & Grease, PFAS/PFOAs, pH Phenolics (Total), Radium 226, Radium 228, Selenium, Silver, Sodium, Specific Conductance, Strontium, Sulfates, Thorium, Toluene, Total Dissolved Solids, Total Kjeldahl Nitrogen, Total Suspended Solids, Uranium, and Zinc.

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[87] *See* 40 C.F.R. Subpart E, §§ 435.50–435.52.
[88] 85 F.R. 229, (Nov. 27, 2020); *and see* 86 F.R. 28 (Feb. 12, 2021).
[89] In January 2021, the EPA approved Texas' application to issue NPDES discharge permits from oil and gas operations, which includes produced water. Fed. Reg. Doc. 2021-02895 (Feb. 5, 2021), https://www.federalregister.gov/documents/2021/02/12/2021-02895/approval-of-the-application-by-the-state-of-texas-for-partial-national-pollutant-discharge.
[90] S.B. 1145, Section 1(e).
[91] *See* 2026 TXPWC Report at iv (Commenters propose TCEQ utilize it's 101 drinking water limits because those are the same limits that the Consortium reports relied on to measure the efficacy of treatment of produced water.).

C. The Domestic Wastewater Framework Is Insufficient for Produced Water.

The existing regulatory framework for domestic wastewater never contemplated incorporating produced water, and it is ill-suited to regulate produced water. In TCEQ's proposed revisions to Chapter 309, "industrial wastewater" is defined as "non-domestic or non-municipal wastewater,"[92] while produced water is defined as "all wastewater associated with oil and gas exploration, development, and production activities . . ."[93] Each one of these, as defined, includes a variety of pollutants that require thoughtful limits to be safely applied to land.

Under current Texas regulations, domestic wastewater has specific definitions. For example, the RRC defines it as: "wastewater that originates primarily from kitchen, bathroom, and laundry sources, including waste from food preparation, dishwashing, garbage, grinding, toilets, baths, showers, and sinks of a residential dwelling."[94] TCEQ defines domestic wastewater as including waterborne human waste and waste from washing, bathing and food preparation.[95] On the other hand, produced water contains persistent toxic constituents that do not typically appear in domestic wastewater. The effluent limitations for domestic wastewater cannot be expected to protect the human environment from the constituents of produced water. Nor can the associated treatment criteria.

Historically, TCEQ has, through the TLAP program, allowed land application as a method for disposing domestic wastewater, particularly in areas where the discharge may be restricted by watershed protection rules.[96] Produced water and domestic sewage, however, have very different constituents of concern. The primary constituents of concern with domestic sewage include: pathogens, nutrients, (more recently) PFAS and Perfluorooctane sulfonic acid ("PFOS"), nitrogen, etc.[97] Extending this framework to hypersaline industrial fluid with radioactive isotopes and remnants of countless proprietary chemicals without requiring strict standards for constituent identification and corresponding safe limits poses substantial risks to human health, safety, and threatens Texas' precious water resources.

Recommendation: Commenters urge TCEQ to create a specific regulatory framework for produced water with specific numerical limits and monitoring designed for produced water. Some produced water specific regulatory additions may include: numerical baseline limits, monitoring and mandatory reporting, and prescriptive disclosure from water resources with corresponding distance limitations to ensure human health and safety. All the existing distance limitations for domestic wastewater must also be reconfigured to address contaminants in produced water and to guard against produced water's vertical migration and seepage into groundwater. Numeric limits, monitoring, and mandatory reporting must include at least the following analytes: Acidity, Alkalinity (Total as CaCO3), Aluminum, Ammonia Nitrogen, Arsenic, Barium, Benzene, Beryllium, Biochemical Oxygen Demand, Boron, Bromide, Cadmium, Calcium, Chemical

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[92] The proposed rule defines industrial wastewater in reference to 30 Tex. Admin. Code § 210.52(9).
[93] The proposed rule defines produced water in reference to 30 Tex. Admin. Code § 305.541(b).
[94] Texas Railroad Commission, *Recycling Treated Domestic Wastewater and Mobile Drinking Water Treatment System Wastewater* (July 15, 2022) https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/environmental-permit-types/recycling/dww-recycling/.
[95] 30 Tex. Admin. Code § 222.5(5).
[96] See 30 Tex. Admin Code § 213 and 30 Tex. Admin. Code § 311.
[97] U.S. EPA, *Sources and Solutions: Wastewater*, (Nov. 12, 2025) https://www.epa.gov/nutrientpollution/sources-and-solutions-wastewater; U.S.EPA, *Per- and Polyfluoroalkyl Substances (PFAS) in Sewage Sludge*, (Aug. 15, 2025) https://www.epa.gov/biosolids/and-polyfluoroalkyl-substances-pfas-sewage-sludge.

Oxygen Demand, Chlorides, Chromium, Cobalt, Copper, Ethylene Glycol, Gross Alpha, Gross Beta, Hardness (Total as CaCO3), Iron – Dissolved, Iron – Total, Lead, Lithium, Magnesium, Manganese, MBAS (Surfactants), Mercury, Molybdenum, Nickel, Nitrite-Nitrate Nitrogen, Oil & Grease, PFAS/PFOAs, pH Phenolics (Total), Radium 226, Radium 228, Selenium, Silver, Sodium, Specific Conductance, Strontium, Sulfates, Thorium, Toluene, Total Dissolved Solids, Total Kjeldahl Nitrogen, Total Suspended Solids, Uranium, and Zinc.

D. The Proposed Rules Threaten Texas Water Resources.

As referenced above, House Bill 1232, passed by the 84th Texas Legislature, directed the Texas Water Development Board ("TWDB") to conduct a comprehensive, statewide study on the hydrology and geology of confined and unconfined aquifers. In December 2016, the Texas Aquifers Study ("Aquifers Study") was published and, as required by legislation, determined the following:

> 1. *the quantity and quality of groundwater in those aquifers,*
> 2. *whether those aquifers are tributary or non-tributary,*
> 3. *the contribution of those aquifers to any surface flow of any water in this state, and*
> 4. *the contribution of those aquifers to any other aquifer in this state.*[98]

The Aquifers Study summarized much of the information about "waters of the State" that is highly relevant to this Rulemaking. The following relevant information is summarized and cited from the Aquifers Study.

More than 60 percent of the water used in Texas comes from groundwater found in our 9 major and 21 minor aquifers.[99] Major and minor characterize the amount of freshwater in the State's aquifers. Most groundwater in the major and minor aquifers is fresh, with total dissolved solids concentrations less than 1,000 milligrams per liter.[100] Among the major and minor aquifers—some are confined, and others are unconfined.[101] Unconfined aquifers are especially sensitive because there is no confining layer between the surface and the water table.[102] By contrast, confined aquifers may not readily transmit groundwater. Still other aquifers (not major or minor) also contribute significant sources of local groundwater.[103] These aquifers extend beneath 81 percent of Texas.[104]

Permeability is a measure of how easily water can flow through rocks and soil. Aquifers are comprised of different materials and have varying degrees of permeability. For example, water moves through cemented sandstone slowly, so it is said to have low permeability.[105] Shales

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[98] Texas Aquifers Study, Groundwater Quantity, Quality, Flow and Contributions to Surface Water, (Dec. 31, 2016) https://www.twdb.texas.gov/groundwater/docs/studies/TexasAquifersStudy_2016.pdf at i, 3. ("Aquifers Study").
[99] *Id.* at i, 3.
[100] *Id.*
[101] *Id.*
[102] *Id.* at 5–6, 117–18.
[103] *Id.*
[104] *Id.*
[105] *Id.* at 4.

typically restrict water movement and have low permeability.[106] Aquifer materials like gravel have high permeability.[107]

Many aquifers in Texas are highly permeable. In fact, the Ogallala, Gulf Coast, and Carrizo-Wilcox aquifers, are some of the largest and also some of the most permeable—consisting of "sedimentary rocks with intergranular porosity."[108] Edwards (Balcones Fault Zone) Aquifer, is a limestone aquifer, and it traps water in crevices and caverns, which is caused largely by the dissolution of limestone by groundwater.[109] In West Texas, the Igneous Aquifer is another example of an aquifer where groundwater flows through all the tiny cracks and fractures found in its igneous and volcanic rocks.[110]

Figure 4: Major Aquifers of Texas[111]

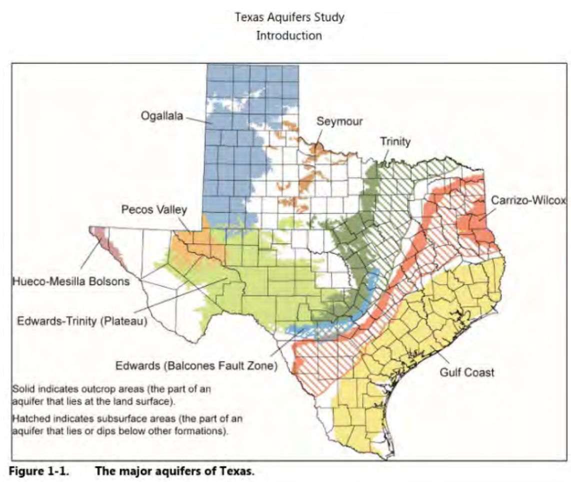
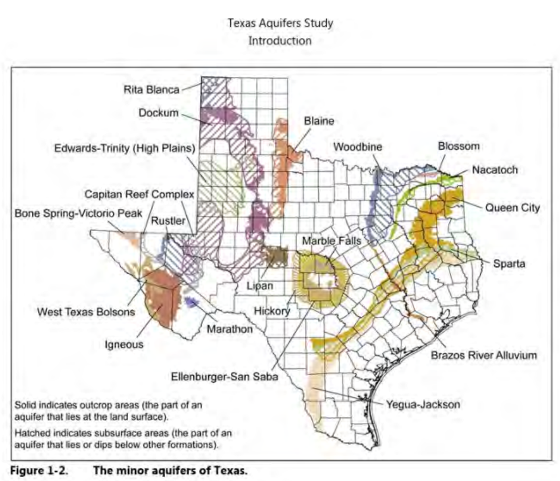


Figure 5: Minor Aquifers of Texas[112]



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[106] *Id.*
[107] *Id.*
[108] *Id.*
[109] *Id.*
[110] *Id.*
[111] Texas Almanac, Aquifers of Texas, https://www.texasalmanac.com/articles/aquifers-of-texas.
[112] *Id.*

The Aquifers Study made important categorical findings that should influence the Commission in making necessary revisions to the rules for the health and safety of both the people and water of Texas. First, the Aquifers Study found that—"*All* aquifers contribute *some* groundwater to the baseflow of streams and rivers in Texas."[113] The Study follows this conclusion with "strictly speaking, groundwater in nearly every aquifer in Texas has some degree of movement into or out of surface water and could be considered a tributary."[114] Generally, tributary groundwater is "groundwater that discharges into surface water"—the definition is otherwise silent on criteria to define boundaries between tributary and non-tributary aquifers.[115] Of the aquifers evaluated, the Study determined all but one to be tributaries to the surface waters of the state.[116]

Figure 6: Tributary and Non-Tributary Aquifers[117]

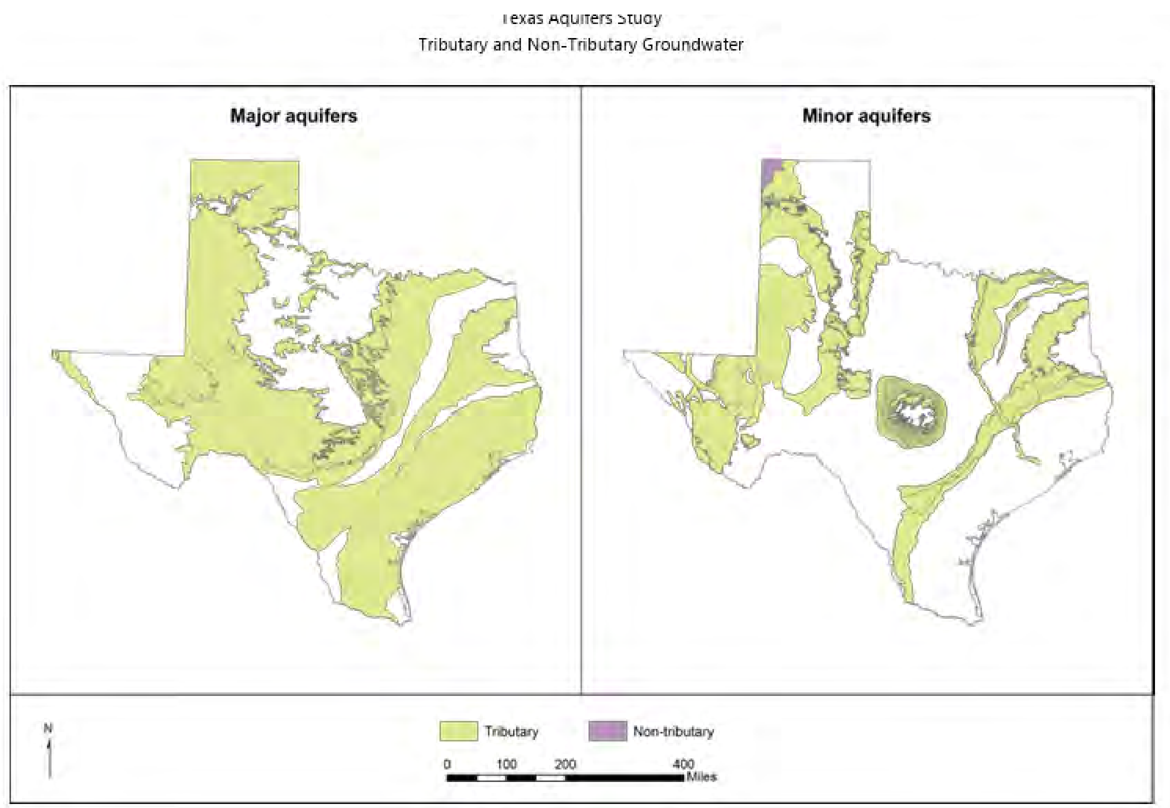

Figure 4-2. Tributary and non-tributary aquifers of Texas.

[113] Aquifers Study at 22.
[114] Aquifers Study at 33–34.
[115] Aquifers Study at 33.
[116] Aquifers Study at Table 4-1, Figure 4-2; *and see* at vi (Rita Blanca contributes zero percent to streamflow and is classified as non-tributary).
[117] Aquifers Study at 37.

According to this conclusion that all aquifers will contribute to the baseflow of streams and rivers in Texas, [118] any land application will discharge into "waters of the state,"[119] and "Waters of the United States."[120]

Importantly, federal law has never treated produced water's agricultural destination as a basis for relaxed scrutiny. Since 1979, a facility that was permitted under the Clean Water Act to discharge produced water for livestock watering or other agricultural use west of the 98th meridian has been a regulated "Point Source" within the Oil and Gas Extraction Point Source Category under the federal NPDES Program. This category of discharge is subject to numeric effluent limitations.[121] Permitting these uses through the TLAP program, as is proposed, with no numeric effluent numeric limitations contravenes Texas Legislation and requirements under the Clean Water Act.[122]

The Pecos Valley Aquifer is illustrative of the problem that land applying inadequately treated produced water may cause. This aquifer is unconfined and the "top of the aquifer is exposed at the ground surface over the entire extent of the aquifer."[123] Return flows from the Pecos River water applied for irrigation are estimated at over 50% of the total recharge to the aquifer.[124] Additionally, this aquifer ranks second statewide in surface water connectivity.[125] Notably, the Pecos Valley aquifer is already impacted—"oil field brines and agricultural runoff have significant effect on the groundwater quality of the Pecos Valley aquifer."[126] Moreover, it is hydraulically connected to underlying minor aquifers.[127] Accordingly, contaminants introduced at the surface will reach the underlying aquifer.

Currently, there is a pending Texas Pacific TLAP Application for WQ0005522000 that intends to drench the ground above the Pecos Valley Aquifer—which poses a serious threat if the produced water is not adequately cleaned and treated beforehand. In a region accustomed to 11 inches of rainfall *annually*, this Application asks to discharge 1 inch of produced water *daily*.[128] This level of land application would be significantly more water than the area is accustomed to, and the produced water would certainly drain into the unconfined aquifer, introducing contaminants. The pending application additionally proposes no groundwater monitoring.[129] Because produced water that is land applied at the surface will enter the hydrologic cycle, TCEQ must promulgate rules that (1) recognize this reality; and (2) adjust to protect whatever regional

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[118] Aquifers Study at 22.
[119] Tex. Water Code § 26.001.
[120] U.S. EPA, *Definition of Waters of the United States under the Clean Water Act*, (Nov. 12, 2025) https://www.epa.gov/cwa-404/definition-waters-united-states-under-clean-water-act.
[121] 40 C.F.R. Part 435; *see also* 44 FR 22075 (Apr. 13, 1979).
[122] *Id.*
[123] Aquifers Study at 118.
[124] Aquifers Study at 118.
[125] Aquifers Study at 120; *see e.g.* Table 4-1 (70% of overlying streamflow is groundwater).
[126] Aquifers Study at 123–24.
[127] Aquifers Study at 120.
[128] Woodall Report at 6; *and see* Texas Pacific TLAP Application Package PDF at 4 of 175 (May 1, 2026) ("Texas Pacific TLAP Application").
[129] Texas Pacific TLAP Application at 66 of 175.

unconfined aquifer may be affected.[130] Any contamination introduced to an aquifer from produced water may eventually flow to an adjacent one.[131]

Commenters additionally introduce and a report by geologist, Nathan Wiser, to support and further explain the problem posed by introducing water above unconfined aquifers. Specifically, that over time, the volumes of produced water and any associated contaminants will accumulate in the State's aquifers.[132]

Recommendation: Commenters request that TCEQ require TPDES permits with stringent limits on contaminants if the land application is over an unconfined aquifer. Including all the contaminants previously named in Commenter's recommendations throughout this comment. Additionally, Commenters urge TCEQ to implement regular groundwater monitoring to protect water resources.

E. The 100-foot setback is arbitrary and unprotective.

Proposed Section 309.13(c)(6) would require a wastewater treatment plant unit, or land where irrigation using effluent occurs, to be located a minimum of 100-feet from a water in the state. The rule proposal plans to carry over the existing insufficient domestic wastewater distances. These distances are *not* informed by produced water's composition—such as its high salinity and persistent constituents including radioactive isotopes. Given that treated produced water may retain certain toxic characteristics, a 100-foot buffer from surface water is insufficient.

Additionally, a 100-foot setback does nothing to address the potential for this water to be transported vertically to an unconfined aquifer whose top is exposed at the land's surface. In the Pecos Valley—a lateral distance to a creek may be helpful but does not resolve the threat of additional contamination to that region's groundwater. The Pecos Valley Aquifer is open to the surface and already salt-stressed.[133] A horizontal setback cannot guard the aquifer against additional potential harm. Specifically, the surface applied water will reach the water table in that case. For example, as already discussed, return flows from irrigation water applied at the surface are estimated to be over 50% of the recharge to the Pecos Valley aquifer.[134] Water applied at the surface *will* percolate down.

[130] Wiser Report (June 16, 2026) at 1.
[131] Wiser Report at 5.
[132] Wiser Report at 9.
[133] Aquifers Study at 118.
[134] Aquifers Study at 118.

Recommendation: Commenters request that TCEQ:

(1) explain the technical basis for the 100-foot setback as applied to produced water, specifically[135];
(2) require groundwater monitoring to comply with SB 1145's requirement to "prevent the pollution of surface and subsurface water."[136] This is particularly important over and near aquifer recharge zones addressed in Section 309.13(d);[137]
(3) increase the setback from waters of the state;
(4) create a vertical setback over aquifers or other sensitive geographic areas where water can easily migrate; and
(5) account for and protect against the vertical transfer of produced water, salt, and other pollutants into unconfined aquifers.

F. TCEQ must ensure the final rule does not conflict with federal and state requirements for the generation, transport, handling, treatment, storage, and disposal of solid and hazardous waste and hazardous material.

As detailed in Section II, a robust and growing body of literature shows produced water contains hazardous and toxic constituents that can threaten both human health and the environment. While the oil and gas industry has long enjoyed an exemption from regulation as hazardous waste under the Resource Conservation and Recovery Act ("RCRA") for its exploration and production wastes, this exemption is not without limitation, and TCEQ must ensure the proposed rule does not take it as such.

Facilities receiving and processing produced water will generate, transport, handle, and dispose of treatment residuals, concentrates, sludges, scales, and other materials, some of which are likely to meet hazardous waste and hazardous material characteristics under federal law. Produced water itself may also in some cases meet RCRA hazardous waste characteristics and/or qualify as hazardous material under the federal Hazardous Materials Transportation Act and its implementing regulations.

Recommendation: The proposed rule should require applications for the land application of produced water to specify all waste streams associated with the land application operation, including whether materials received by, generated, handled, treated, stored, or offered into transport by the facility meet RCRA hazardous waste characteristics and whether any material offered into transport constitutes hazardous material under the federal Hazardous Materials Transportation Act and its implementing regulations or state transportation regulations. At the very least, the rule must clarify that any state permit for land application does not waive or in any way insulate permittees from applicable federal and state requirements pertaining to the generation,

[135] Notably, Commenters made two different public information requests (PIR No. 114850 dated April 24, 2026 and PIR No. 115043 dated April 30, 2026) seeking the technical basis of the 100-foot setback, but no documents were provided during the comment period. Commenters' email exchange with the TCEQ related to the requests is attached.
[136] S.B. 1145, Section 1(e).
[137] 30 Tex. Admin. Code § 309.13(d).

treatment, storage, transport, and disposal of solid and hazardous waste and the transport of hazardous materials.

G. TCEQ must ensure the final rule does not exacerbate ongoing issues with underground injection control wells in the state of Texas, further endangering underground sources of drinking water.

While many are holding land application out as a means of mitigating the ongoing harms caused by underground injection of oil and gas waste in Texas, it is critical to remember that operators treating produced water for land application still plan to rely on underground injection to dispose of the waste stream created during the treatment process. This waste stream will be rich in toxic and corrosive produced water constituents, including radioactive isotopes. Introducing this new highly concentrated waste stream into underground injection wells is likely to come with its own problems. Further, this waste—removed from primary field operations—is likely better suited to disposal in Class I injection wells.

Recommendation: TCEQ must ensure that any waste generated during produced water treatment is properly characterized prior to any disposal in underground injection wells and that waste is disposed of in Class I injection wells as applicable. Any waste streams exceeding 60 pCi/L combined radium-226 and radium-228 must be sent to Class I injection wells.[138]

H. Definitions in the Proposed Rules are Lacking.

1. Best Professional Judgment

The preamble of the proposed rules states that the minimum requirements for land application of industrial wastewater "have historically been applied . . . on the basis of best professional judgment." Under these proposed rules, produced water will be permitted as industrial wastewater, and industrial wastewater land application will be determined case-by-case using Best Professional Judgment ("BPJ").[139] This is problematic for two reasons. First, employing BPJ admits TCEQ has failed to comply with the legislative mandate to promulgate standards.[140] And, second, it means there are no substantive standards for what could become the largest industrial wastewater stream in Texas. From both a public health and regulatory certainty perspective, this is insufficient.

The concept of Best Professional Judgment exists under the Federal Clean Water Act. According to the EPA's website it means: "the method used by permit writers to develop technology-based NPDES permit conditions on a case-by-case basis using all reasonably available and relevant data to establish technology-based limits or determine other appropriate means to

[138] 40 C.F.R § 146.3; ENV'T PROT. AGENCY, OFF. OF WATER, A REGULATORS' GUIDE TO THE MANAGEMENT OF RADIOACTIVE RESIDUALS FROM DRINKING WATER TREATMENT TECHNOLOGIES 19 (2005); Justin Nobel & Megan M. Hunter (2025), What Lies Beneath: Is America's Most Common Method for Disposing of Oilfield Wastewater Legal? VERMONT JOURNAL OF ENVIRONMENTAL LAW, Vol. 26, 313–351, https://vjel.vermontlaw.edu/wp-content/uploads/2025/07/Hunter_Nobel_VJEL-Vol.-26_Issue-4_Final.pdf.
[139] TCEQ Interoffice Memorandum Docket No. 2026-0018-RUL, (Apr. 10, 2026) at 2 ("The minimum requirements for land application of treated effluent established under Chapter 309 have historically been applied to land application of industrial wastewater on the basis of best professional judgement.").
[140] S.B. 1145, Section 1(e).

control its discharge."[141] Texas has borrowed this specialized term for use in the TLAP program without importing the federal discipline that makes the term legitimate. According to the State's delegated authority to implement the TPDES, when specific regulations do not apply to a particular discharge, "the Permit requirements will be considered on a case-by-case basis and on best professional judgment in accordance with 40 CFR §125.3 as adopted by 30 TAC §308.1."[142]

Under the Clean Water Act, Best Professional Judgment is bounded. Where BPJ is allowed, it still employs technology-based limits. For example, it is used only where guidelines do not exist, and it is governed by codified decision factors under 40 C.F.R. Section 125.3(d). Critically, discharges subject to technology based effluent limits developed through best professional judgment under the Clean Water Act remain subject to the additional NPDES standards protecting water quality, including water quality standards and antidegradation provisions, while the proposed rules under the TLAP program lack such fundamental protections. Below, Figure 7 illustrates how Best Professional Judgment could operate.

Figure 7: Tools for Developing Technology Based Effluent Limits Using Best Professional Judgment[143]

Exhibit 5-22 Tools for developing case-by-case TBELs using BPJ

Permit file information
- Current and previous NPDES application forms.
- Previous NPDES permit and fact sheet.
- Discharge monitoring reports.
- Compliance inspection reports.

Information from existing facilities and permits
- NPDES Individual and General Permits for other NPDES permits issued to facilities in the same region or state, or that include case-by-case limitations for the same pollutants.
- Toxicity reduction evaluations for selected industries.
- Other media permit files (e.g., Resource Conservation and Recovery Act [RCRA] permit applications and Spill Prevention Countermeasure and Control [SPCC] plans.
- ICIS-NPDES <https://icis.epa.gov/icis> data.
- Literature (e.g., technical journals and books).

Effluent guidelines development and planning information
- Industry experts within EPA headquarters, EPA Regions, and states <www.epa.gov/guide/contacts.html>.
- Development Documents, CWA section 308 questionnaires, screening and verification data, proposed and final regulations, contractor's reports, and project officer contacts <www.epa.gov/guide>.
- EPA's Technical Support Documents <www.epa.gov/guide/304m> and records supporting EPA's biennial effluent guidelines program plans also provide additional useful information. In particular, such resources provide a sample of the current limitation and latest developments in industrial pollutant prevention, water conservation, and wastewater treatment. The Technical Support Documents also identify industrial sectors not currently regulated by effluent guidelines.

Statistical guidance
- Effluent Guidelines Technical Development Support Documents, such as the Development Document for Final Effluent Limitations Guidelines and Standards for the Iron and Steel Manufacturing Point Source Category <www.epa.gov/guide/>.

Economics guidance
- *Protocol and Workbook for Determining Economic Achievability for NPDES Permits*[9] <www.epa.gov/npdes/pubs/protocol_npdespermits.pdf> and <www.epa.gov/npdes/pubs/workbook_econ_permits.pdf>.
- *BCT Cost Test Guidance* <www.epa.gov/npdes/pubs/owm0009.pdf>.

Guidance for BMP-based limitations
- *Guidance Manual for Developing Best Management Practices (BMPs)*[10] <www.epa.gov/npdes/pubs/owm0274.pdf>.
- *Storm Water Management for Industrial Activities: Developing Pollution Prevention Plans and BMPs*[11] <www.epa.gov/npdes/pubs/contents_indguide.pdf>.
- National Menu of Stormwater Best Management Practices <www.epa.gov/npdes/stormwater/menuofbmps>.

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[141] EPA, *Learn about Effluent Guidelines*, https://www.epa.gov/eg/learn-about-effluent-guidelines (July 25, 2025).
[142] Memorandum of Agreement between the Texas Natural Resource Conservation Commission and the U.S. Environmental Protection Agency, Region 6 Concerning the National Pollution Discharge Elimination System (Sept. 14, 1998) at 20.
[143] EPA, NPDES Permit Writers' Manual, Chapter 5 at 5-48 (2010) https://www.epa.gov/npdes/npdes-permit-writers-manual (updated Sept. 22, 2025).

Moreover, while produced water is not a new waste stream—it is highly variable. Historically, the Railroad Commission was responsible and allowed application of produced water with a low chloride content. The passage of SB 1145 moved the authority to apply produced water to TCEQ. The current rules allow produced water to not only be applied to land—but introduce the concept of "beneficial use." Legislation to create the Texas Produced Water Consortium was only passed in 2018. So, any treatment technology and corresponding standard to be derived from those technologies are also new. Accordingly, no one at the TCEQ is likely to possess the judgment required to effectively execute best professional judgment in a manner that will be protective of public health and water resources.

Case-by-case permitting—without adopting more stringent BPJ requirements from the Clean Water Act—yields an unstructured permitting regime lacking regulatory certainty. Permitting decisions born from so much discretion will leave the regulatory community and the public without judicial recourse. Further, State discretion should not be allowed to shield a State operator from federal liability when the no-discharge fiction fails.[144]

Recommendation: TCEQ should adopt methodology—similar to EPA's presented above—and incorporate that into the rule as a defined process to implement Best Professional Judgment.

2. Beneficial Use

SB 1145 permits land application only of produced water "that has been treated for beneficial use."[145] Problematically, however, beneficial use is not defined, and there is no quality threshold that produced water has to meet, either. Without a definition, the rule cannot control the quality of the produced water that will be applied to land. Failing on every front, the proposed rules lack regulatory certainty and fail to protect the human environment. Where one operator may carefully treat produced water for a specific purpose to a quality fit for agronomic use, another may use raw, or minimally treated, produced water and spray it on land as a disposal method. The two pending applications are a good example of this problem.

- Texas Pacific Application for Permit No. WQ0005522000 describes "polished desalinated" produced water that will have undergone "advanced treatment using desalination, reverse osmosis, and granulated activated carbon."[146] This treated produced water will "land applied for beneficial use (rangeland restoration)."
- Brymer Application for Permit No. WQ0005515000 will land apply produced water on "fenced in dry ranchland with low to no bearing vegetation mixed with coastal grass and cacti."[147] "Discharges from the facility are expected to contain no pollutants, Fresh wastewater."[148]

Recommendation: Commenters urge TCEQ to adopt a definition of "beneficial use" that, at a minimum, requires (1) a numeric salinity and Total Dissolved Solids ceiling that is directly

[144] 33 U.S.C. § 1311 (Federal effluent limitations and requirement that discharges comply with the same.).
[145] Tex. Water Code § 26.131(e).
[146] Texas Pacific TLAP Application at 51 of 175.
[147] Brymer TLAP Application Package PDF at 35 of 205 (March 19, 2026) ("Brymer TLAP Application").
[148] Brymer TLAP Application at 35 of 205.

tied to the receiving soil and crops; (2) constituent limits for the organics, metals, boron, ammonia, nitrogen, and radioactive isotopes; (3) demonstrates Whole Effluent Testing ("WET") to ensure non-toxicity; and (4) the use is clearly identified, remains agronomic, and mirrors the federal requirement at 40 C.F.R. § 435.51(c) that the treated produced water must be "put to such use" as a condition.

I. The Pending Permits Should Be Denied.

The two pending TLAP applications cannot result in issued permits for several reasons. First, TCEQ has yet to promulgate any standards, despite being required to do so by SB 1145. Both pending TLAP applications are asking for approval before any land application standards exist. Two, as was discussed above, the other problems with the current rules mean that there is no regulatory certainty for the operators, and issuing those same operators permits without a fleshed out regulatory scheme would be premature. Finally, the reality that the land application of produced water may in many situations reach waters of the state—requires TCEQ to revisit the permitting programs prior to approving these permits.

IV. EXHIBIT LIST

The below-listed exhibits supporting these comments are attached for the Commission's review and consideration.

NO.	DESCRIPTION
1	Texas Produced Water Consortium Report (2022)
2	Texas Produced Water Consortium Report (2024)
3	Texas Produced Water Consortium Report (2026) Appendices available for download here: https://www.depts.ttu.edu/research/tx-water-consortium/2026-water-quality-report.php
4	Texas Aquifers Study (2016)
5	George Woodall, PhD Report
6	Nathan Wiser, Geologist Report
7	U.S Environmental Protection Agency Study of the Agricultural and Wildlife Water Use Subcategory
8	Commenters' Emails with TCEQ related to Public Information Requests

V. CONCLUSION

Commenters urge TCEQ to adopt a more stringent regulatory framework with numeric/agronomic rigor to protect people and water resources, implement Commenters' recommended changes to the proposed rules, and deny the pending TLAP permits as unprotective until standards for this wastewater can be promulgated.

We thank you in advance for your consideration of our comments.

Sincerely,

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Texas Permian Future Generations

Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

EXHIBIT 1

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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Current TXPWC Membership

Apache Corporation
Aris Water Solutions
B3 Insight
Back Flow Fluids
Bureau of Economic Geology at University of Texas
Blackbuck Resources
Bobcat Group, LLC
BPX Energy (BP)
Carollo
Chesapeake Energy
Chevron
ConocoPhillips
CrownQuest Operating, LLC
Crystal Clearwater Resources
Deep Blue
Diamondback Energy
Endeavor Energy Resources
Environmental Disposal Systems
Energy Makers Advisory Group
Environmental Defense Fund
ExxonMobil
Fasken Oil & Ranch
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Meadows Center for the Environment
NGL Energy Partners
NGL Water Solutions
New Mexico Produced Water Research Consortium
Occidental Oil & Gas Corporation
PearlSnap Midstream
Permian Basin Petroleum Association
Pioneer Natural Resources
Pyote ClearWater Logistics
Resource West
Select Energy Services
Sierra Club Lone Star Chapter
Solaris Midstream Holdings
Steven Walden Co.
Texas & Southwestern Cattle Raisers
Texas 2036
Texas Alliance of Energy Producers
Texas Desalination Association
Texas Independent Producers & Royalty Owners Association
Texas Land & Mineral Owners Association
Texas Oil & Gas Association
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WaterBridge
Western Midstream Partners
Westward Environmental & Engineering Excellence
William Mitchell
XRI

State Agency Partners

General Land Office
Railroad Commission of Texas
State Energy Conservation Office
Texas Commission on Environmental Quality
Texas Department of Agriculture
Texas Economic Development and Tourism Office
Texas Parks and Wildlife Department
Texas Water Development Board

Table of Contents

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]

[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

[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).

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

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

[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.

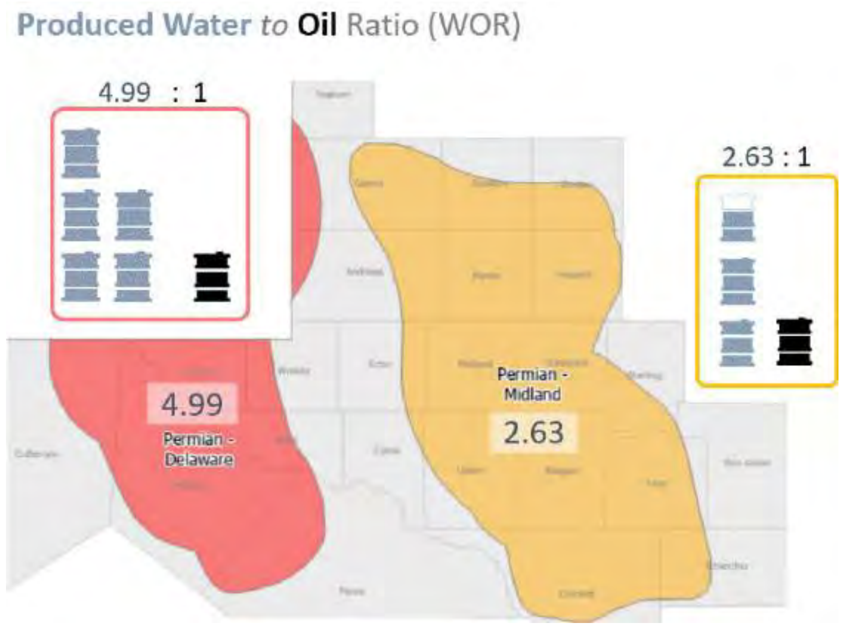

Figure 1. Produced Water to Oil Ratio (WOR), Permian Delaware and Midland Basins.

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.

[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.

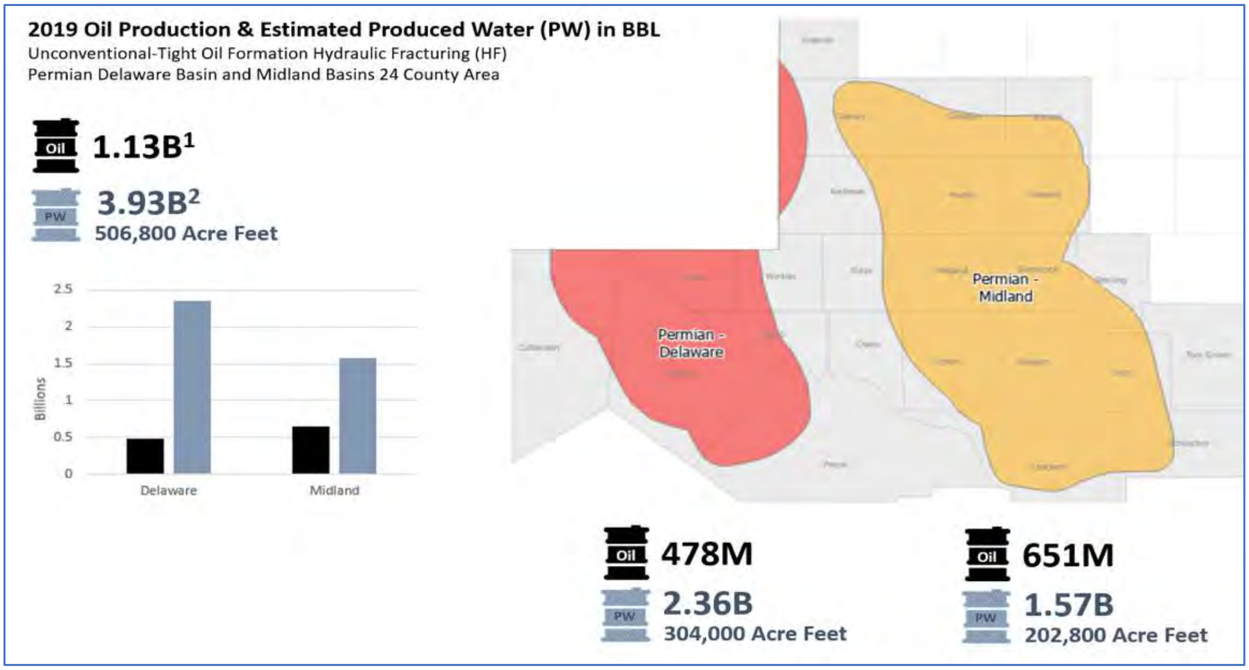

Figure 2. 2019 Annual Oil Production (Railroad Commission of Texas) and 2019 Estimated Produced Water in 24 County Area in the Permian, and by Delaware and Midland Basins.

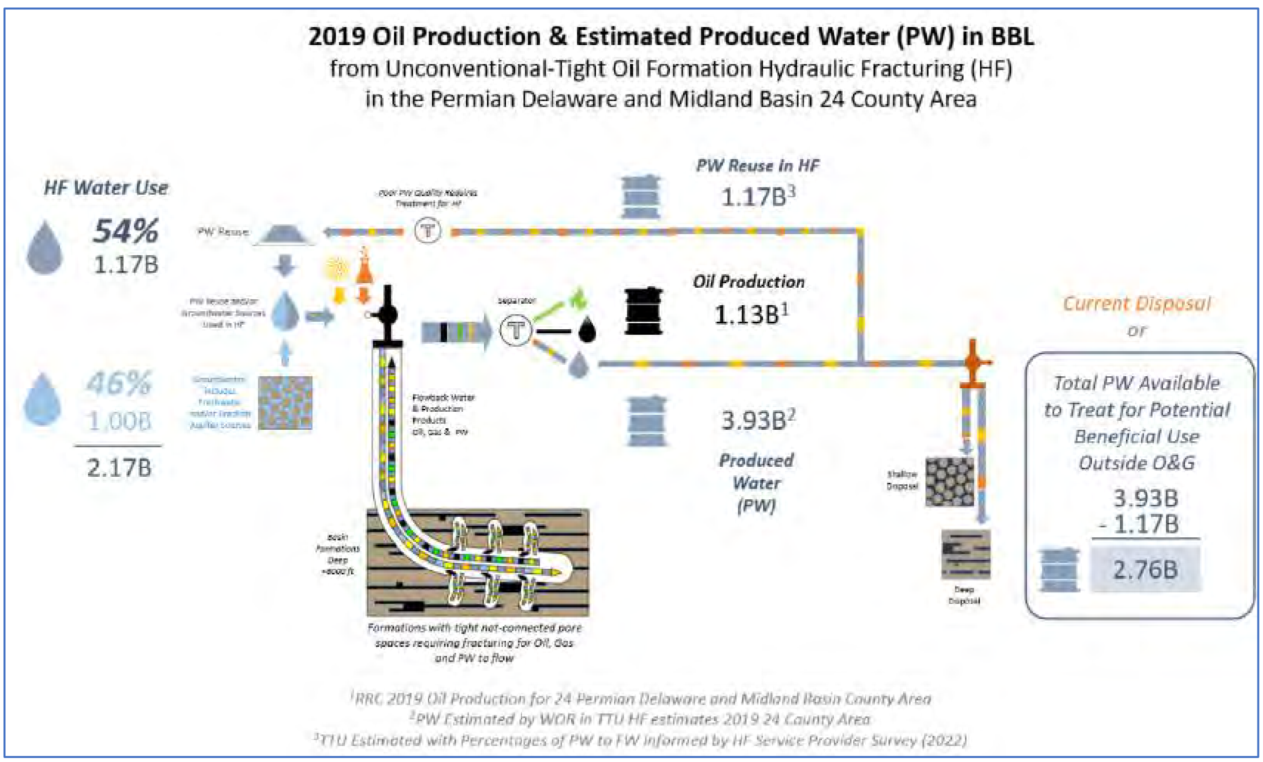

Figure 3. 2019 Oil Production (Railroad Commission of Texas), Estimated Produced Water (PW) Based on Water to Oil Ratio (WOR) in 24 County Area Permian Delaware and Midland Basins and PW to Groundwater Use for Hydraulic Fracturing (HF) (Survey of HF Service Providers by TxPWC).

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

[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.

[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.

[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 89^{th} 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.

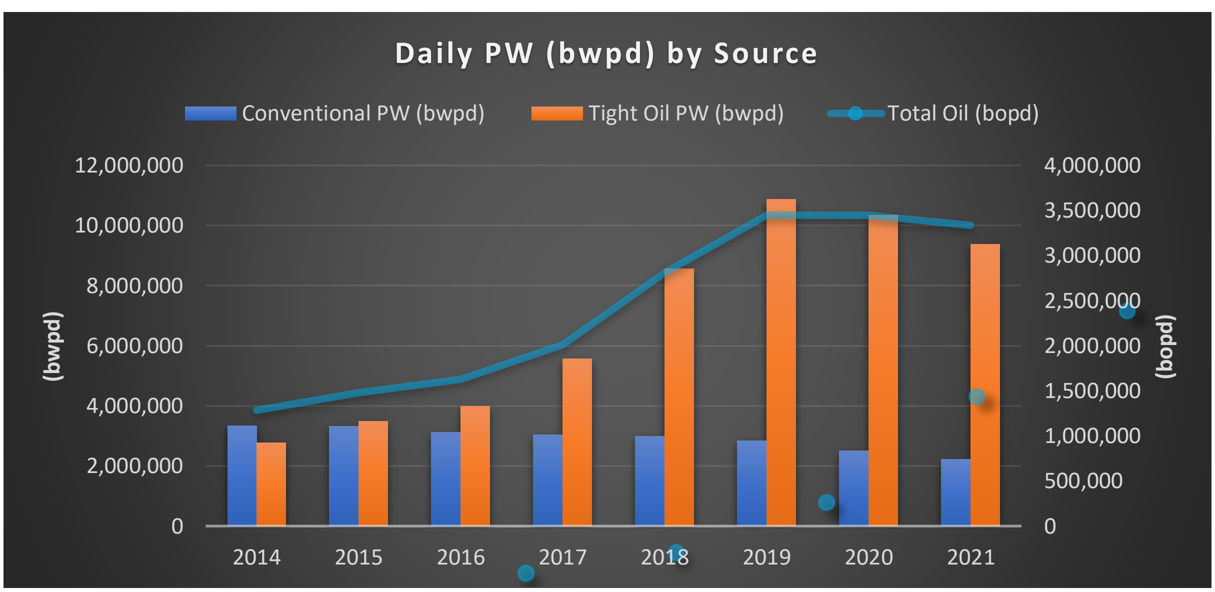

Figure 4. Daily Produced Water, sorted by Source, and Total Oil Production, 2014-2021, Permian Basin (Enverus).

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.

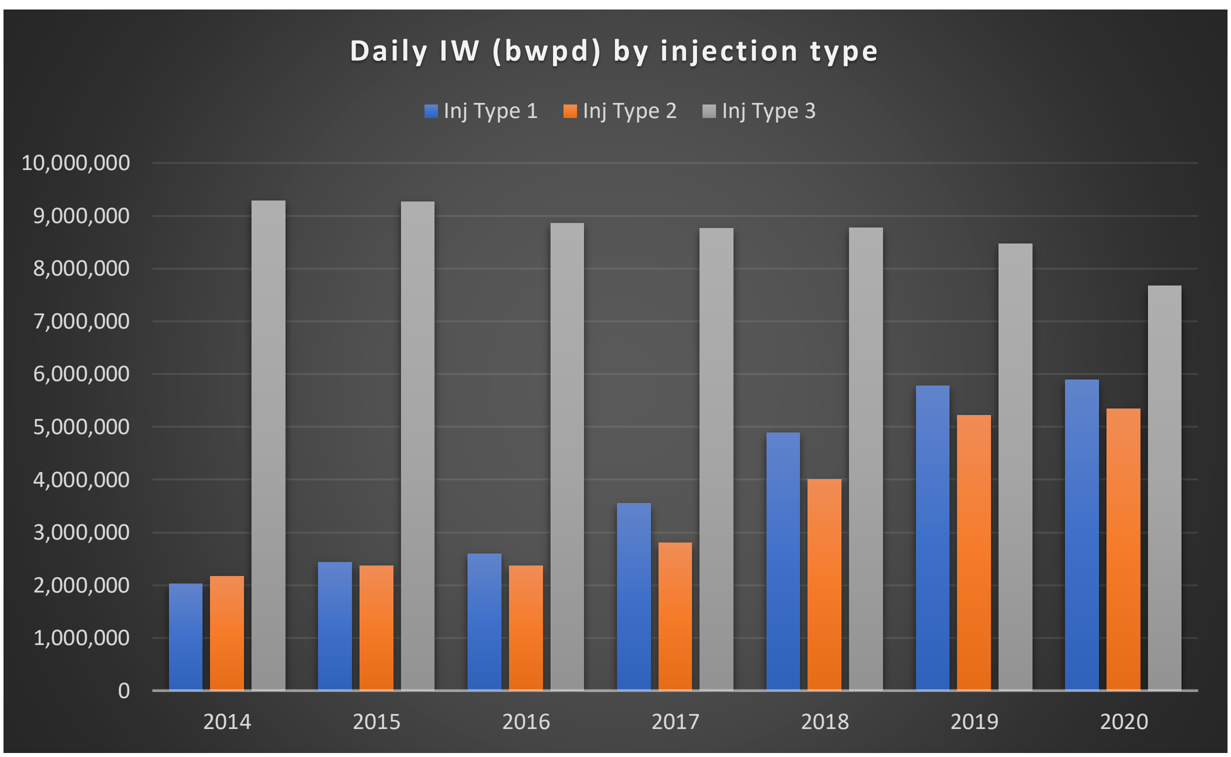

Figure 5. Daily injected water, sorted by injection well type, 2014-2020, Permian Basin (Railroad Commission of Texas).

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).

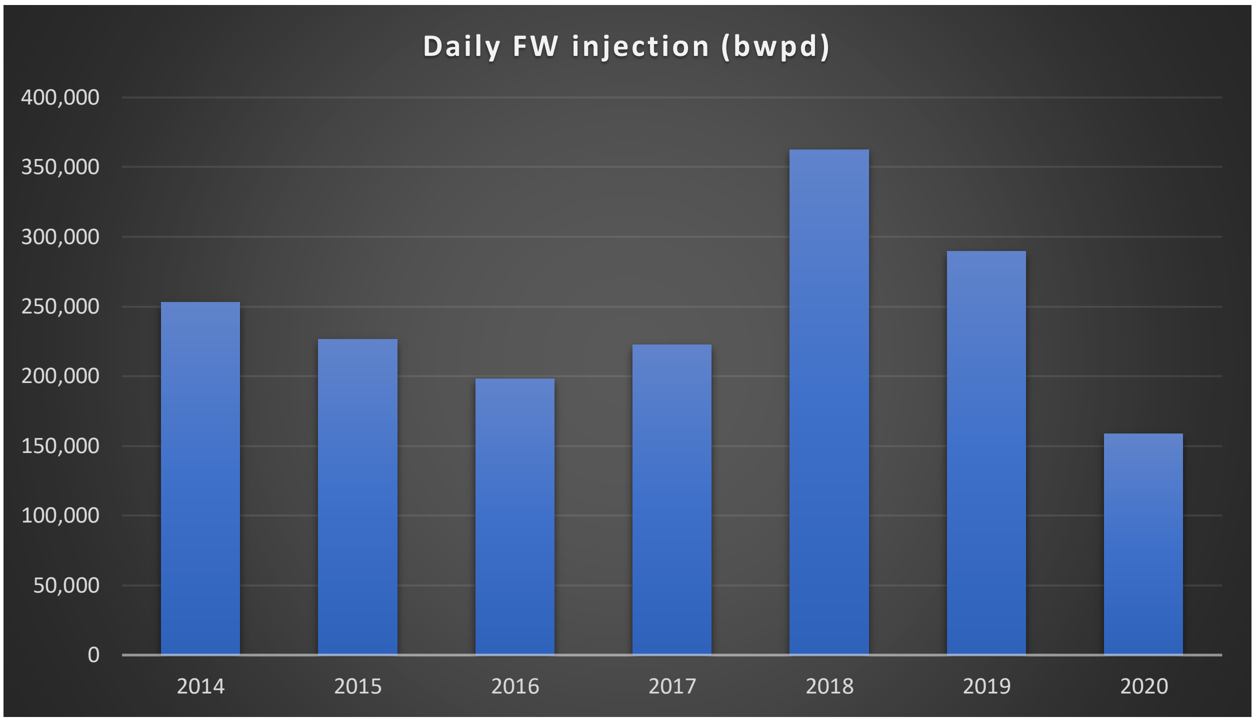

Figure 6. Daily freshwater injection, 2014-2020, Permian Basin (Railroad Commission of Texas).

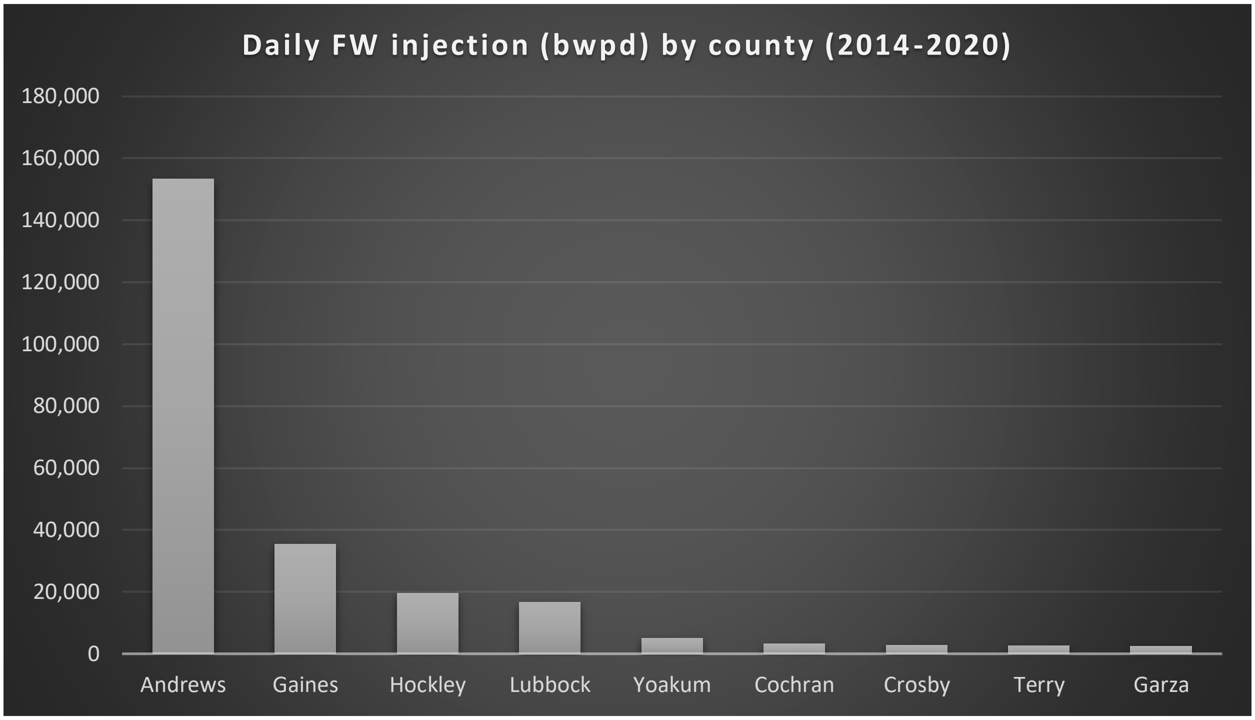

Figure 7. Daily freshwater injection, sorted by county, 2014-2020 (Railroad Commission of Texas). The displayed counties contributed to 98.6% of total freshwater injection in the Permian Basin.

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.

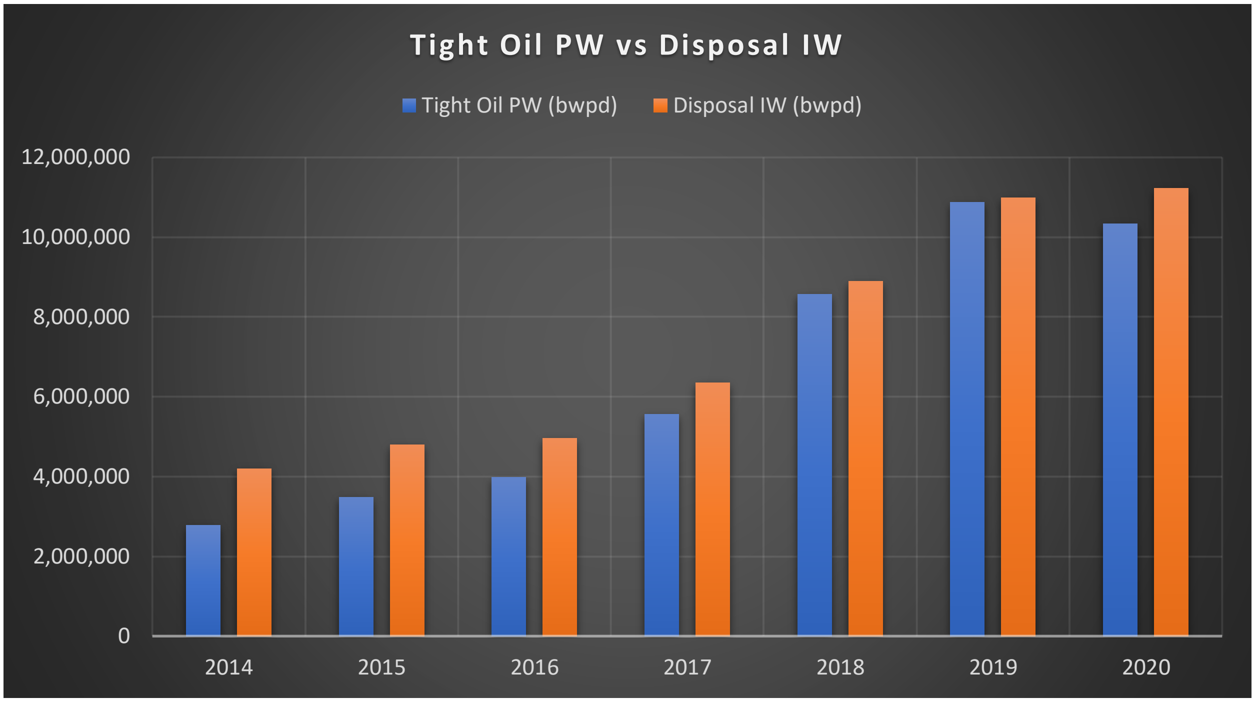

Figure 8. Water production from tight oil wells (Enverus) vs Water injection into disposal wells (Railroad Commission of Texas), 2014-2020, Permian Basin.

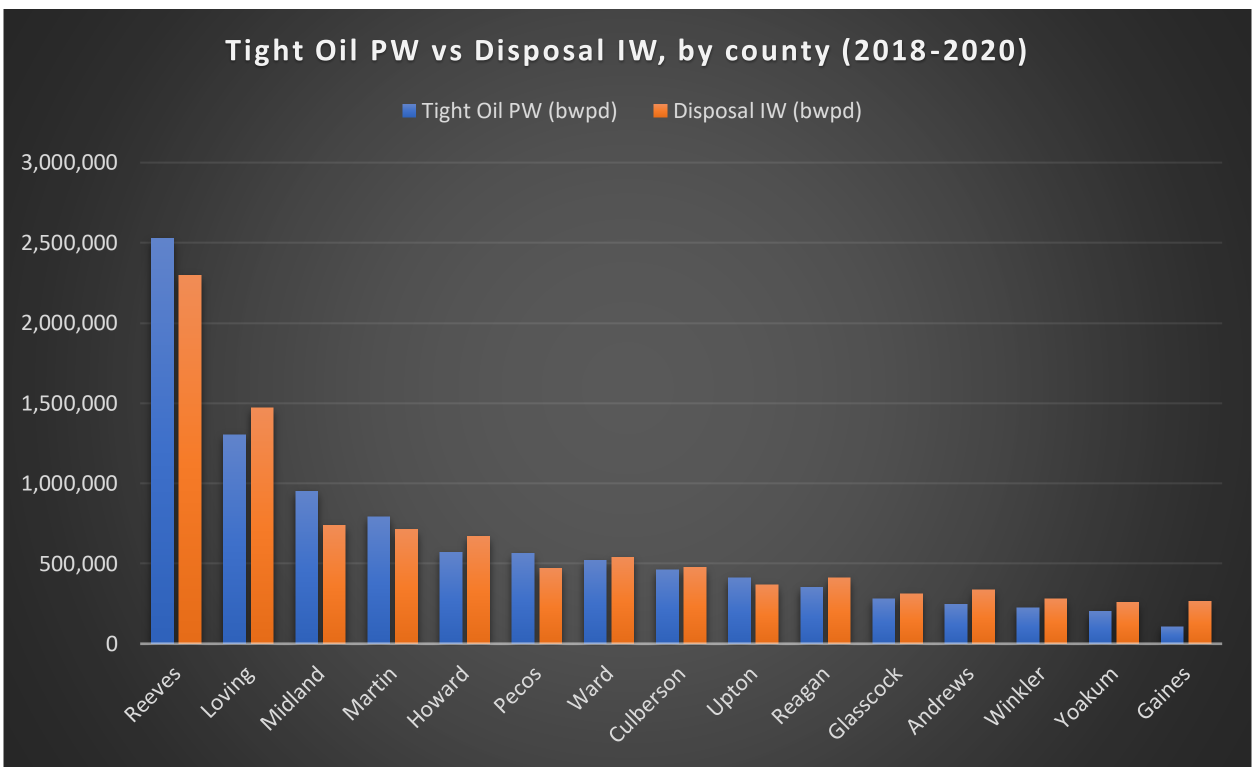

Figure 9. Water production from tight oil wells (Enverus) vs Water injection into disposal wells (Railroad Commission of Texas), 2018-2020, Permian Basin, sorted by county (the displayed counties contribute to 95% of water production).

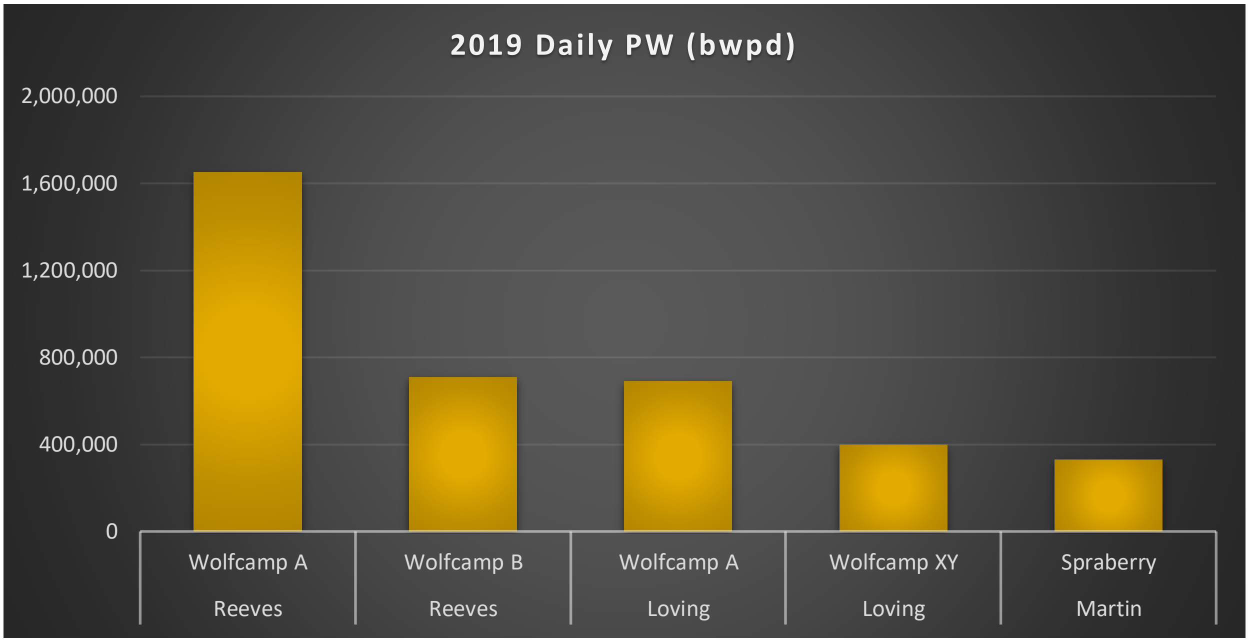

Figure 10. Major water producing sources from tight oil formations and counties in 2019 (Enverus). Displayed sources contribute to 35% of the total water production.

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.**.

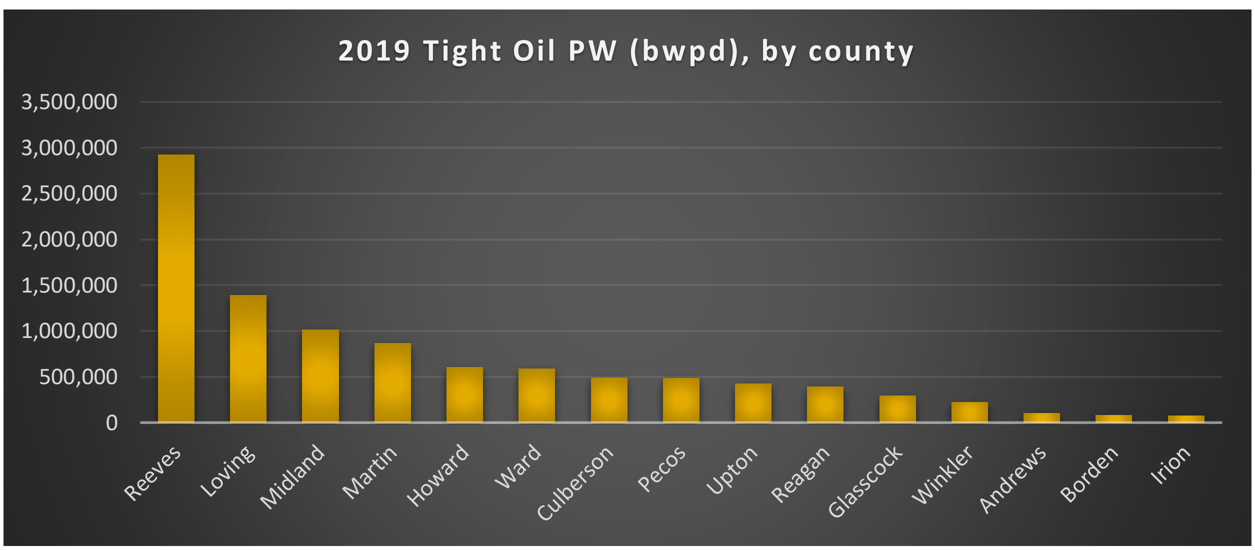

Figure 11. Water production from tight oil wells (Enverus) in 2019, Permian Basin, sorted by county (the displayed counties contribute to 91% of water production).

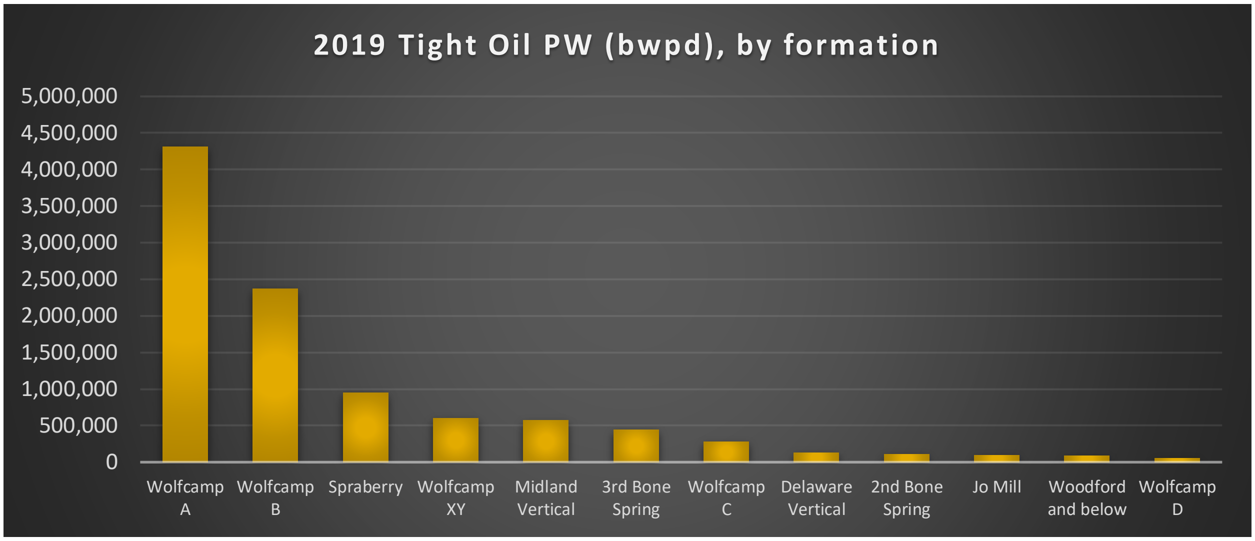

Figure 12. Water production from tight oil wells (Enverus) in 2019, Permian Basin, sorted by formation (the displayed counties contribute to 92% of water production).

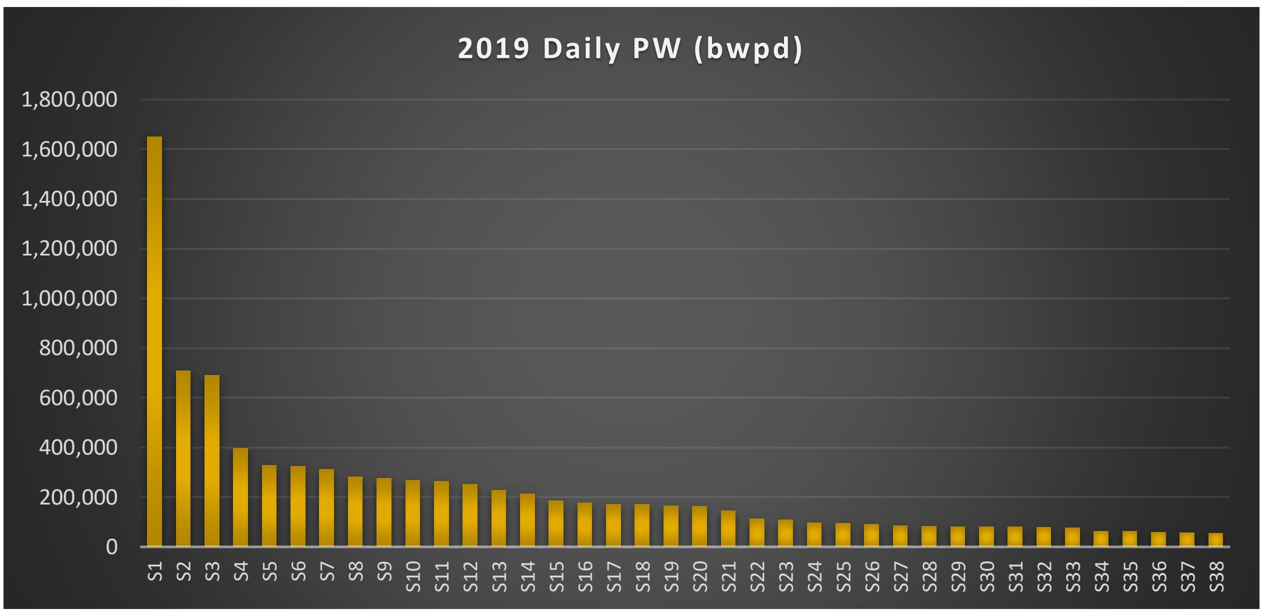

Figure 13. Water production from tight oil formations in different counties in 2019 (displayed data represents 80% of the total production). Sources S1 through S38 are described in ***Error! Reference source not found.****.*

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.

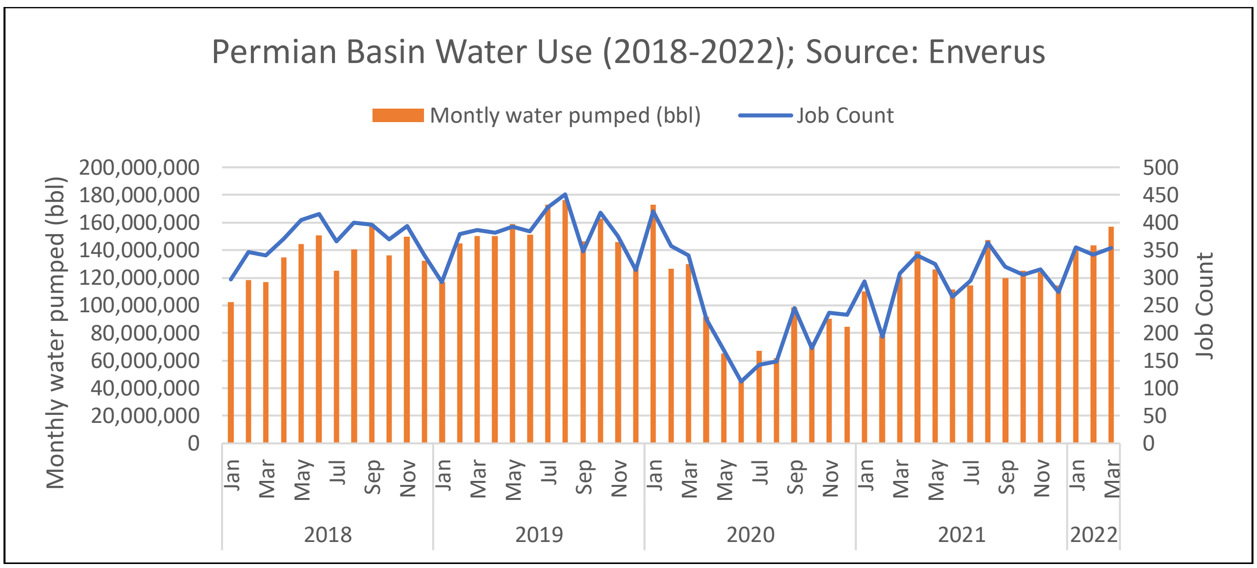

Figure 14. Frac Job Data reported by Enverus (January 2018 through March 2022)

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.

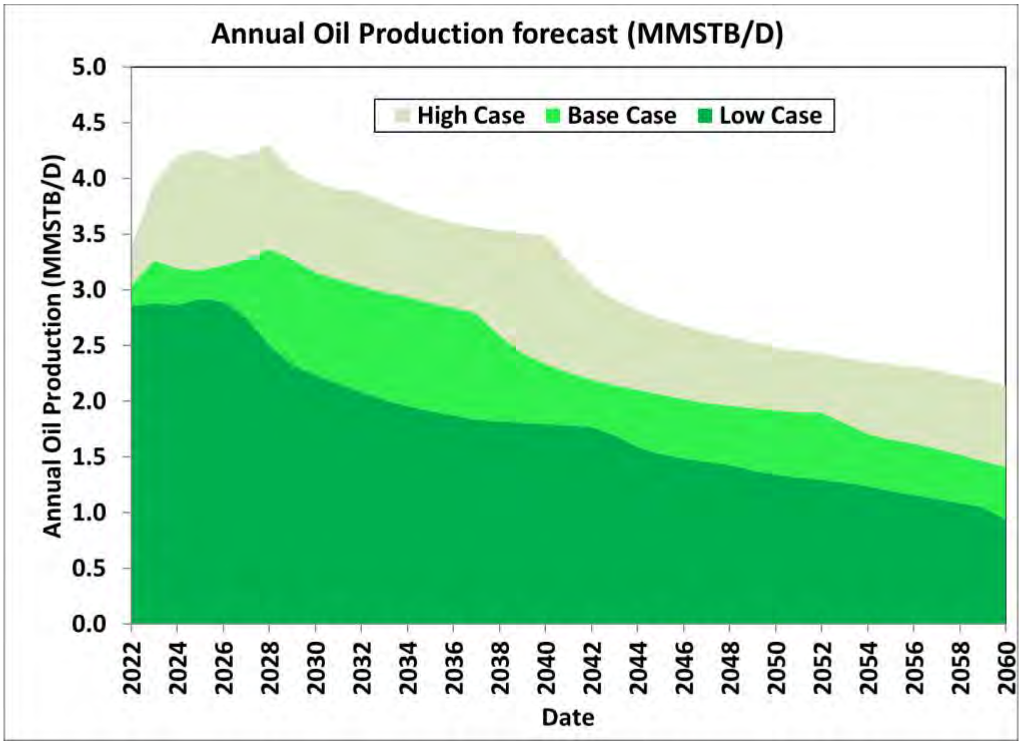

Figure 15: Annual Oil Production Forecast for Districts 8, 8A, and 7C.

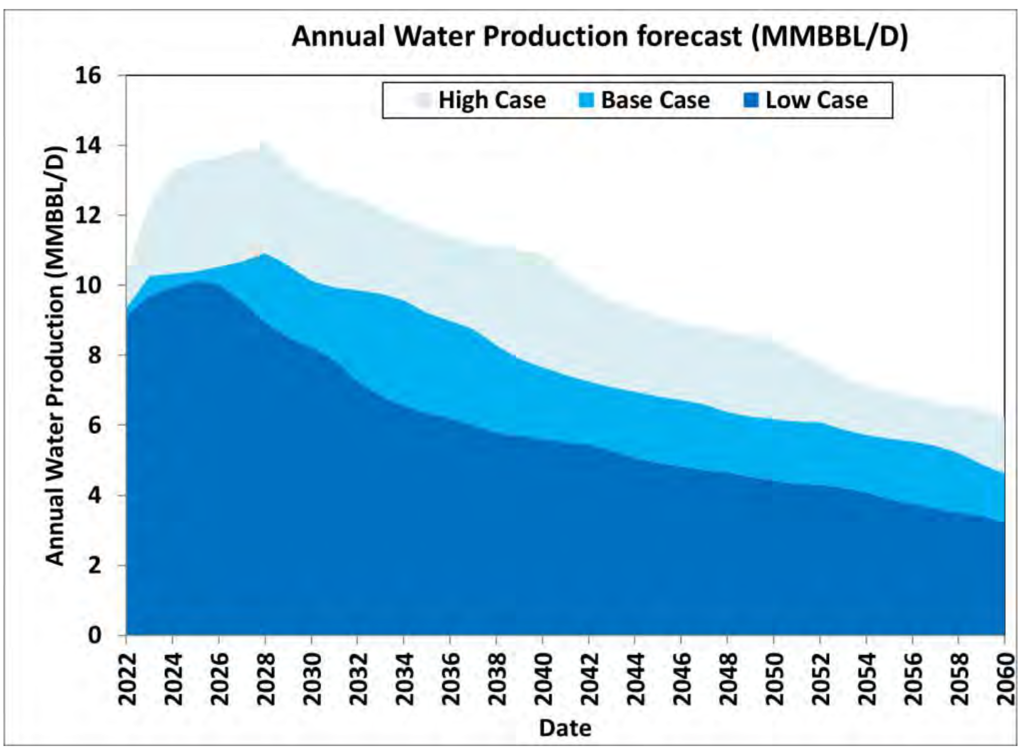

Figure 16: Annual Water Production Forecast for Districts 8, 8A, and 7C.

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.

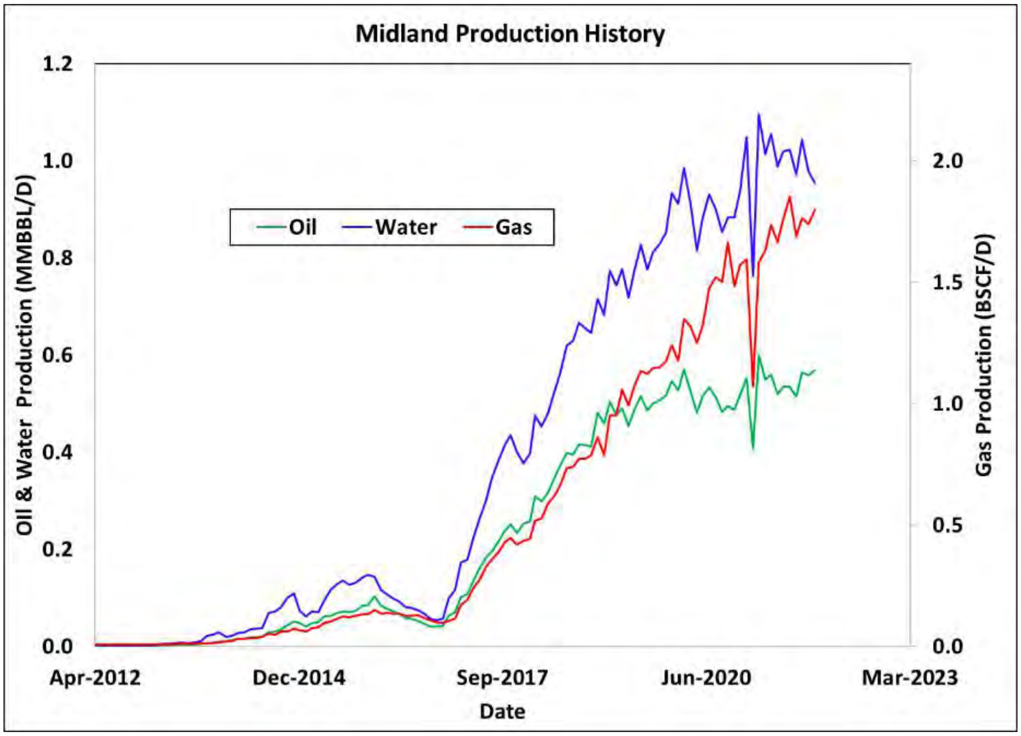

Figure 17: Typical production showing continuous incremental oil and gas production.

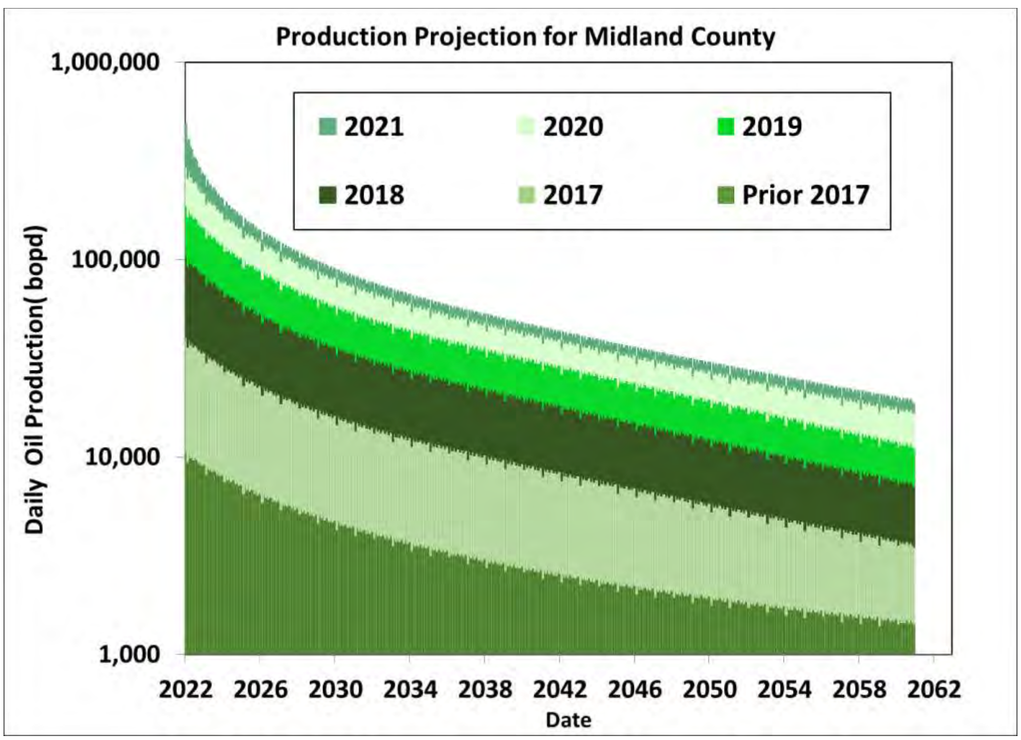

Figure 18: Production Forecast for Midland County current well.

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.

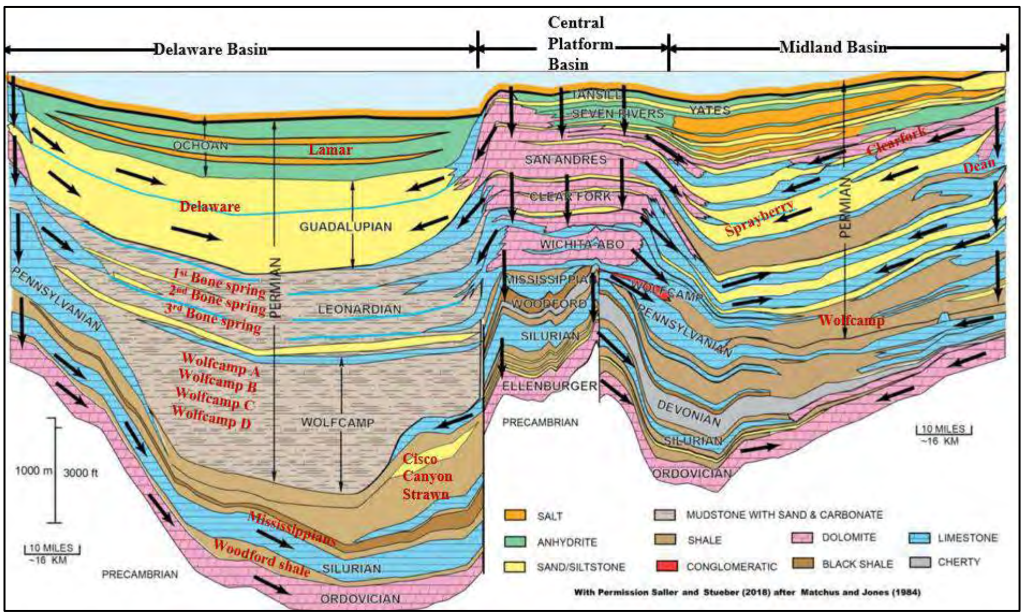

Figure 19: A cross-section of the Delaware, Central Platform, and Midland basins.

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.

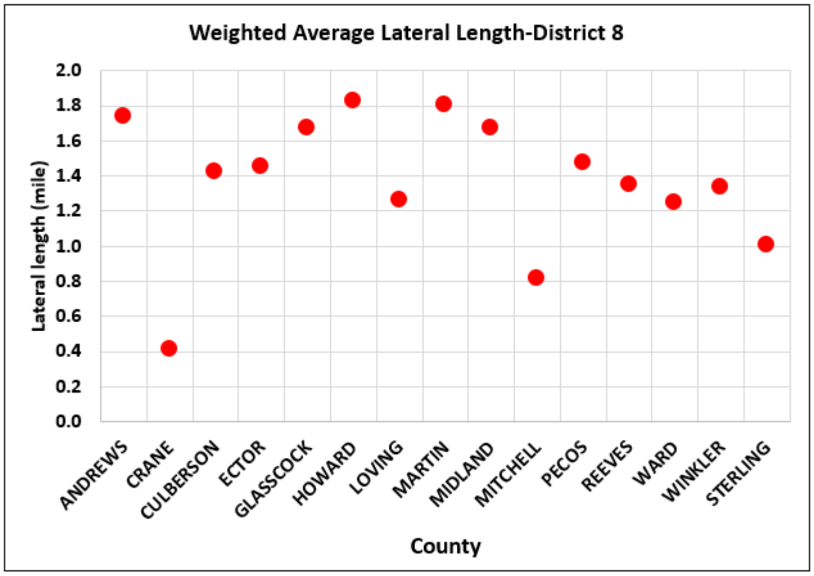

Figure 21: Lateral length of the existing wells for district 8 between 2016 and 2017.

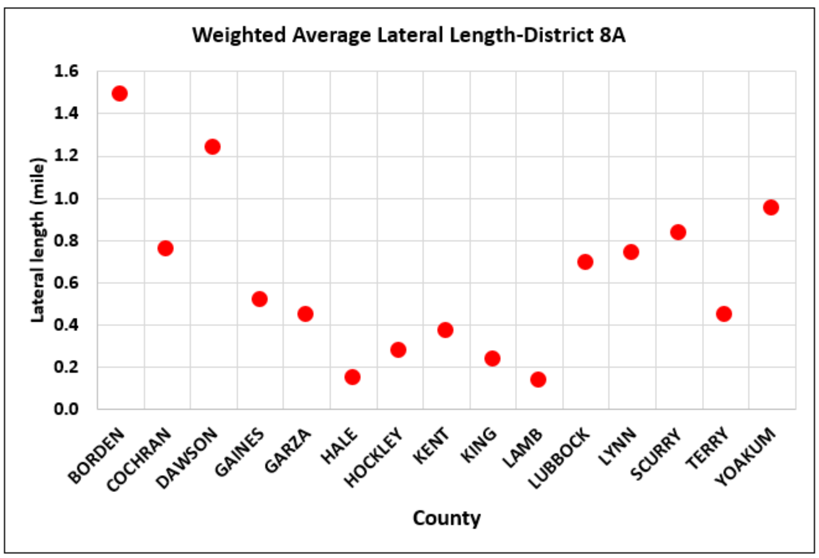

Figure 22: Lateral length of the existing wells for district 8A between 2016 and 2017.

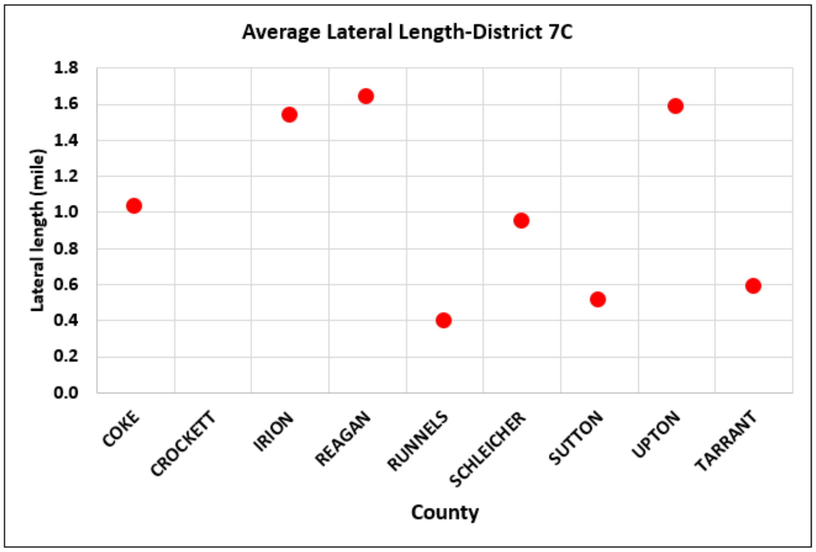

Figure 23: Lateral length of the existing wells for district between 2016 and 2017.

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.

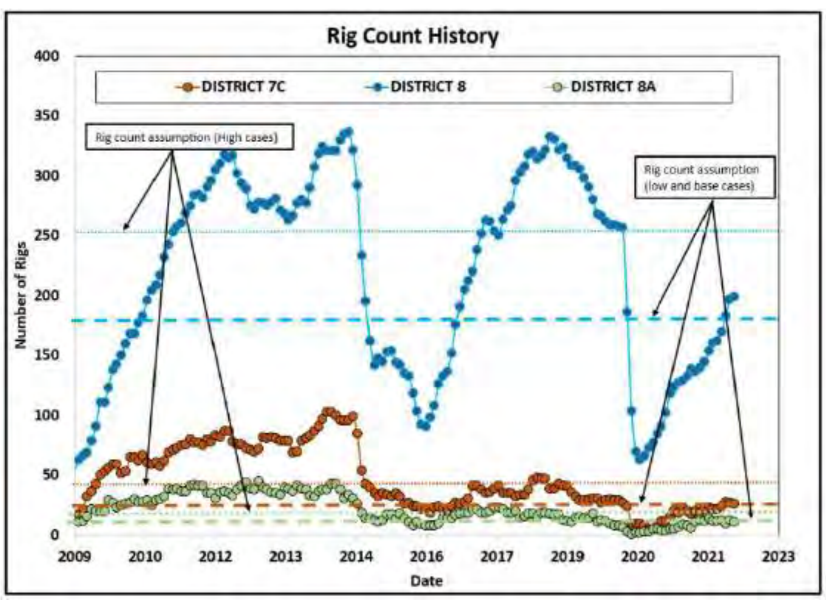

Figure 24: Rig count assumptions for district 8, 8A and 7C.

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.

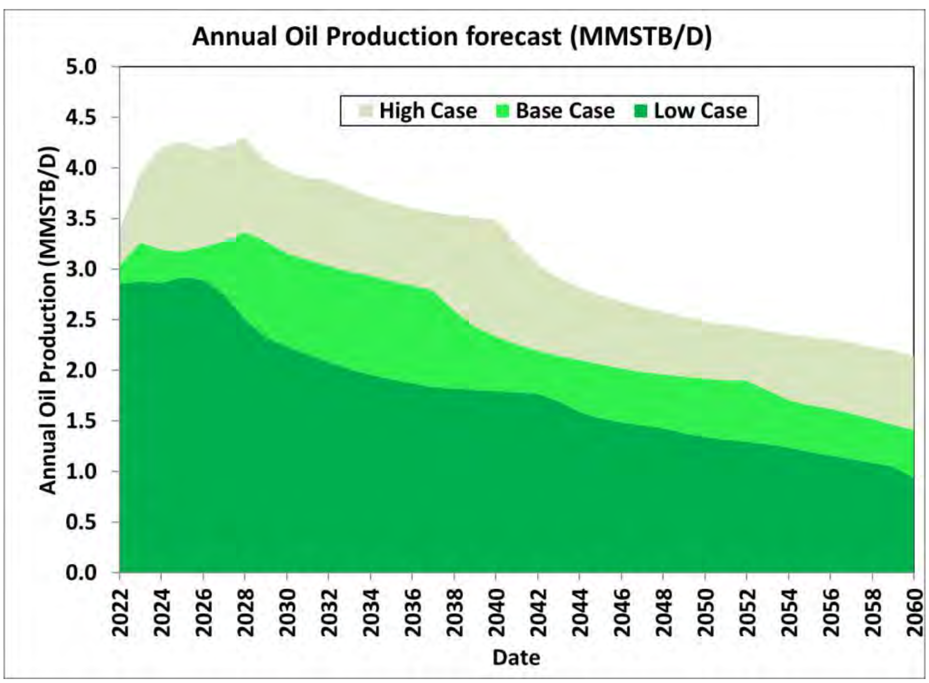

Figure 25: Annual Oil Production Forecast for District 8, 8A, and 7C.

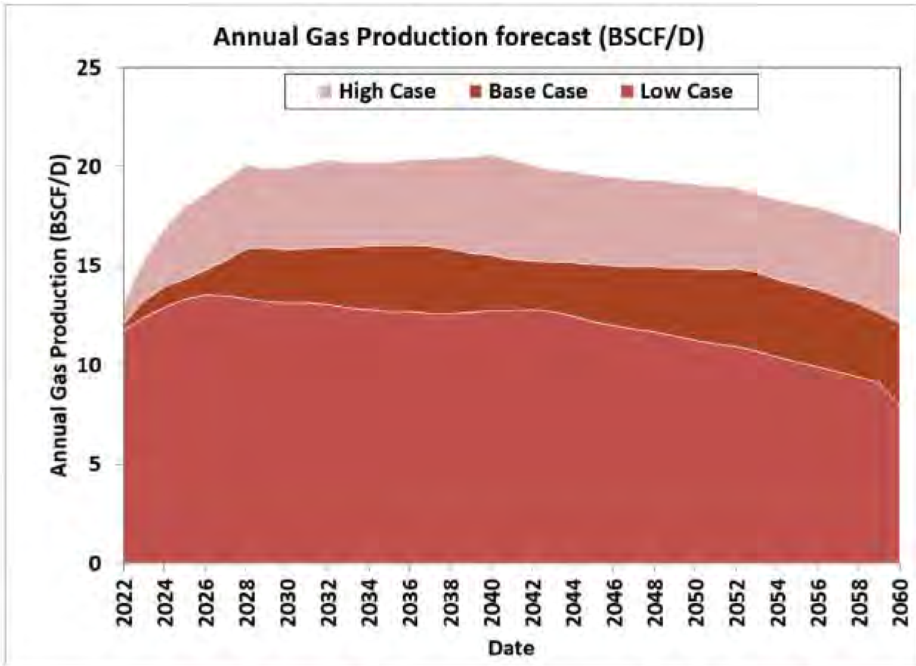

Figure 26: Annual Gas Production Forecast for District 8, 8A, and 7C.

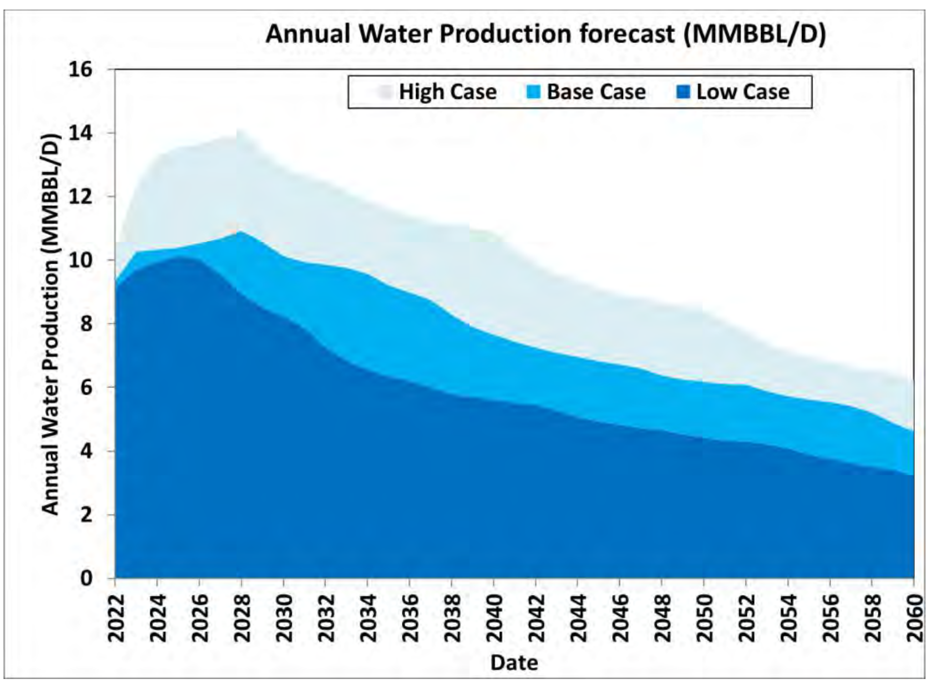

Figure 27: Annual Water Production Forecast for District 8, 8A, and 7C.

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.

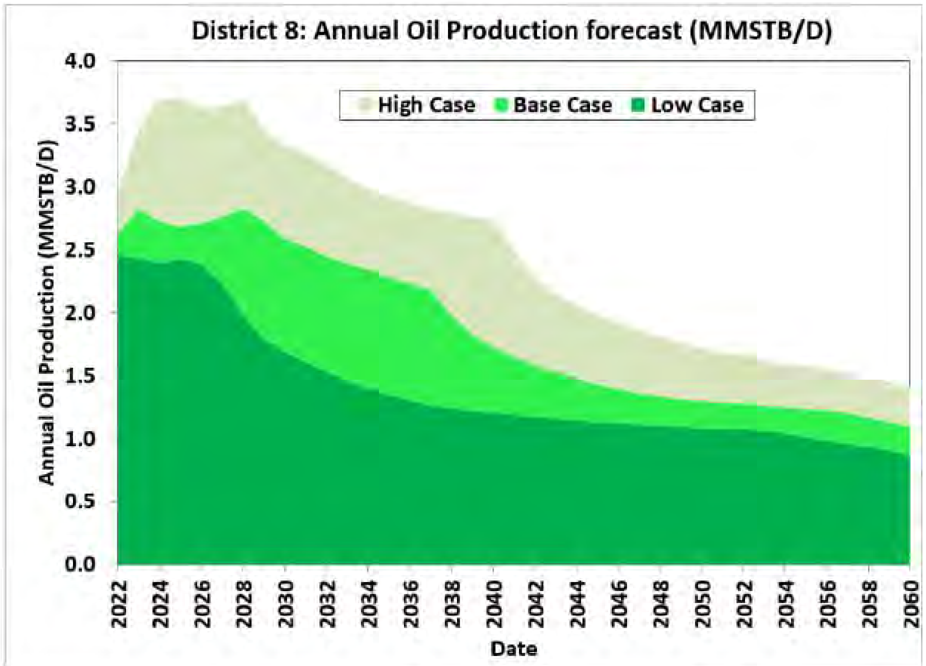

Figure 28: Annual Oil Production Forecast for District 8.

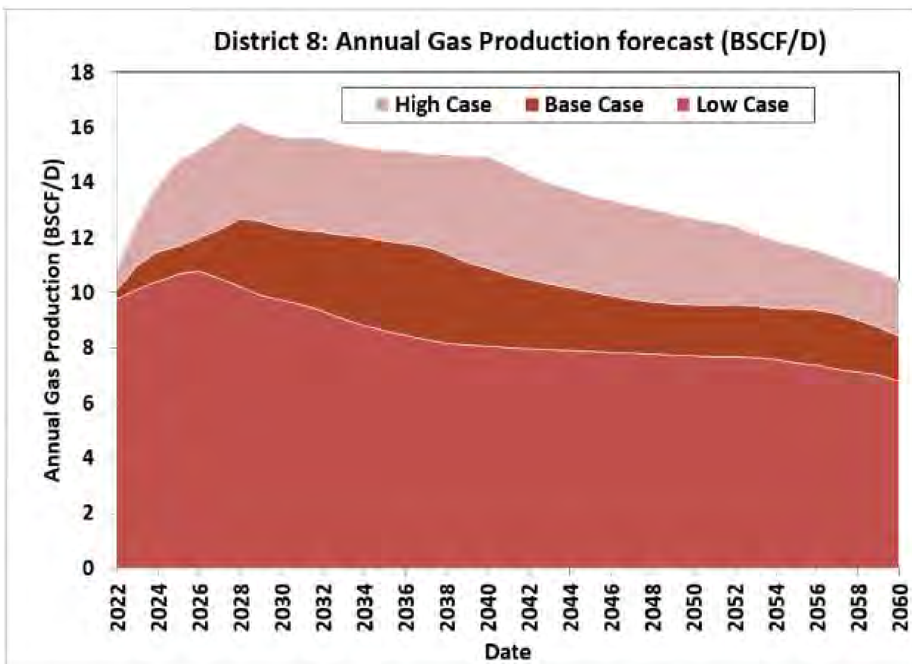

Figure 29: Annual Gas Production Forecast for District 8.

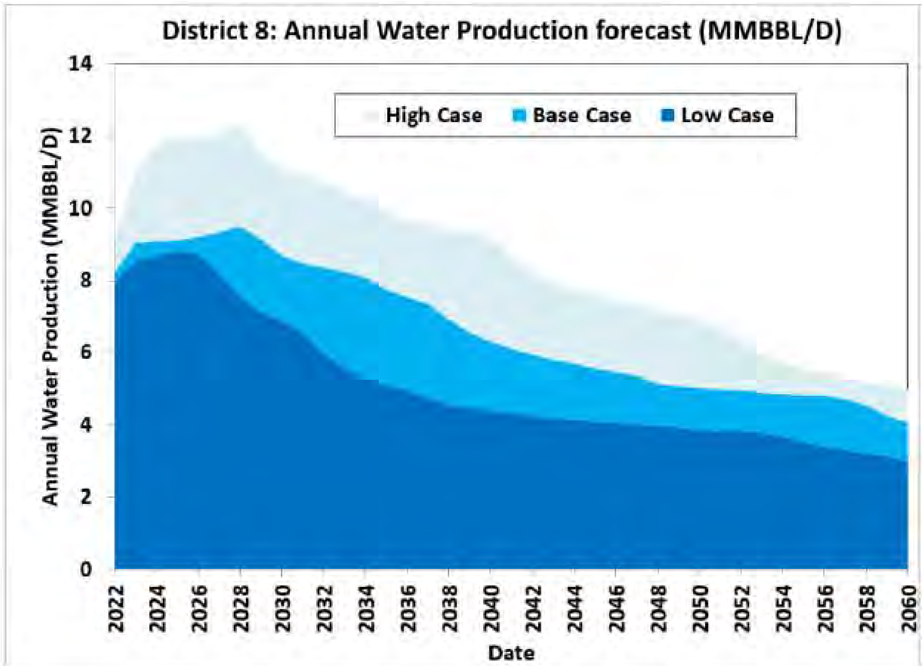

Figure 30: Annual Water Production Forecast for District 8.

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.

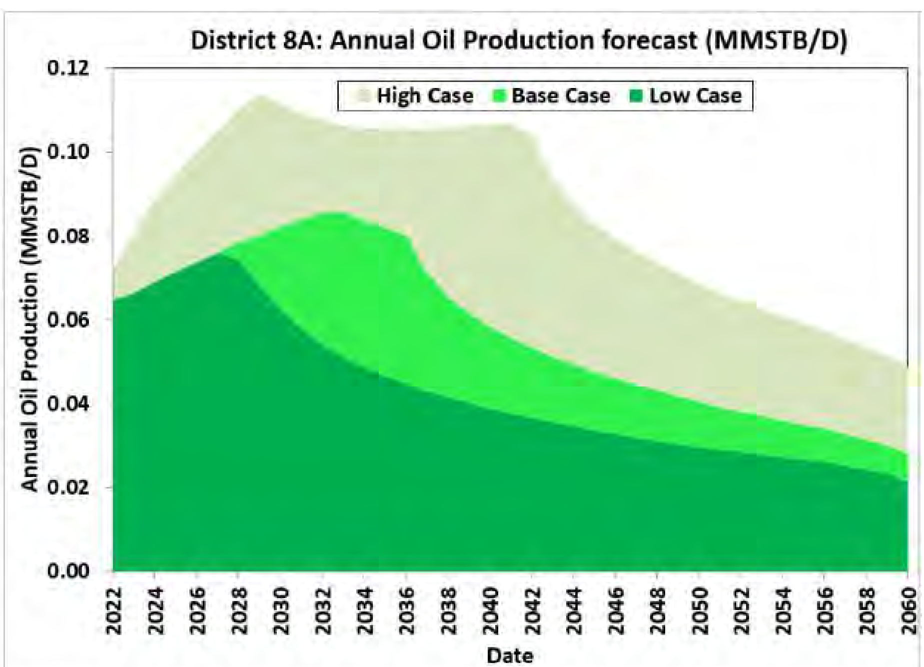

Figure 31: Annual Oil Production Forecast for District 8A.

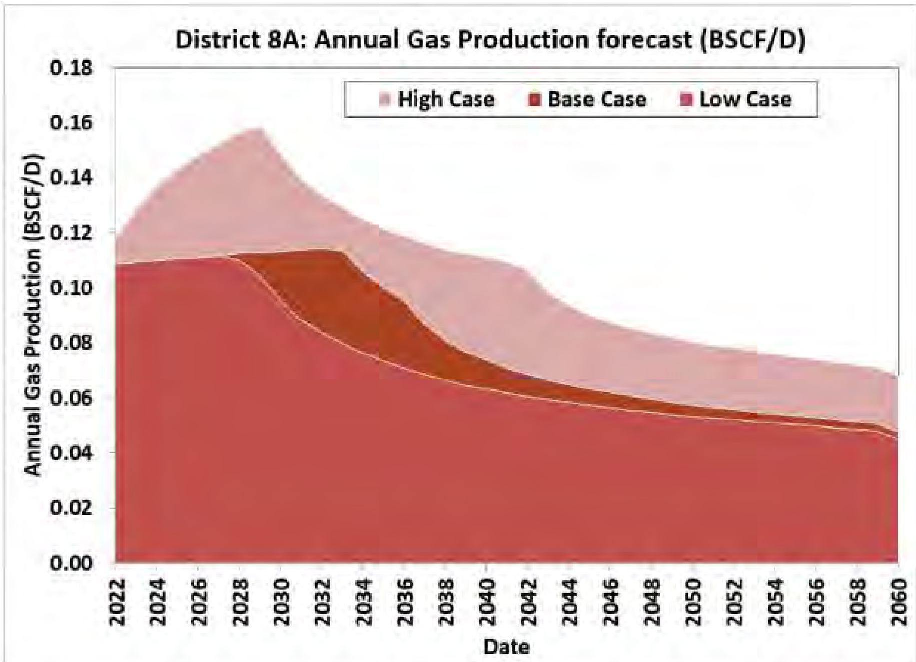

Figure 32: Annual Gas Production Forecast for District 8A.

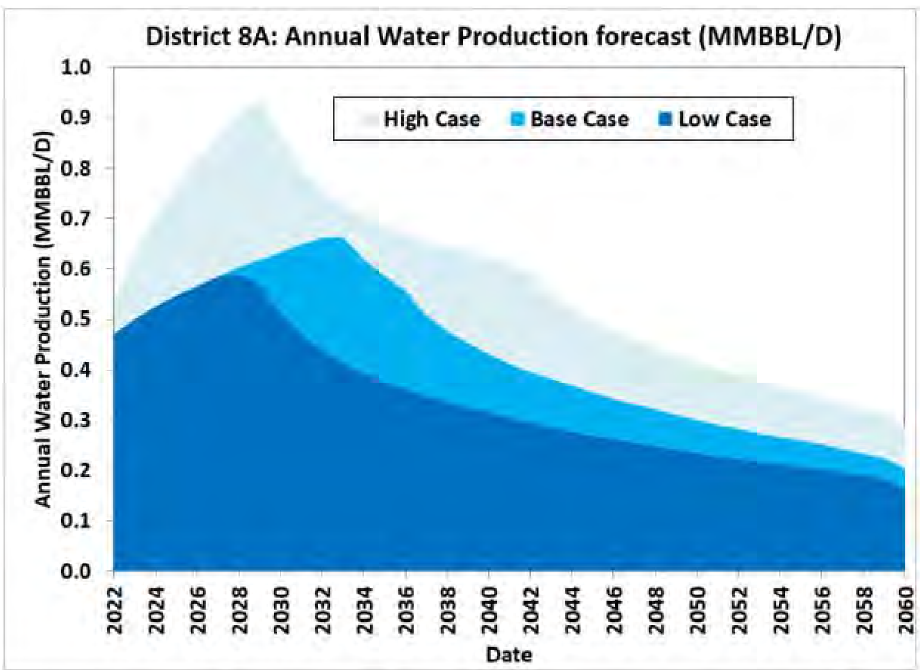

Figure 33: Annual Water Production Forecast for District 8A.

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.

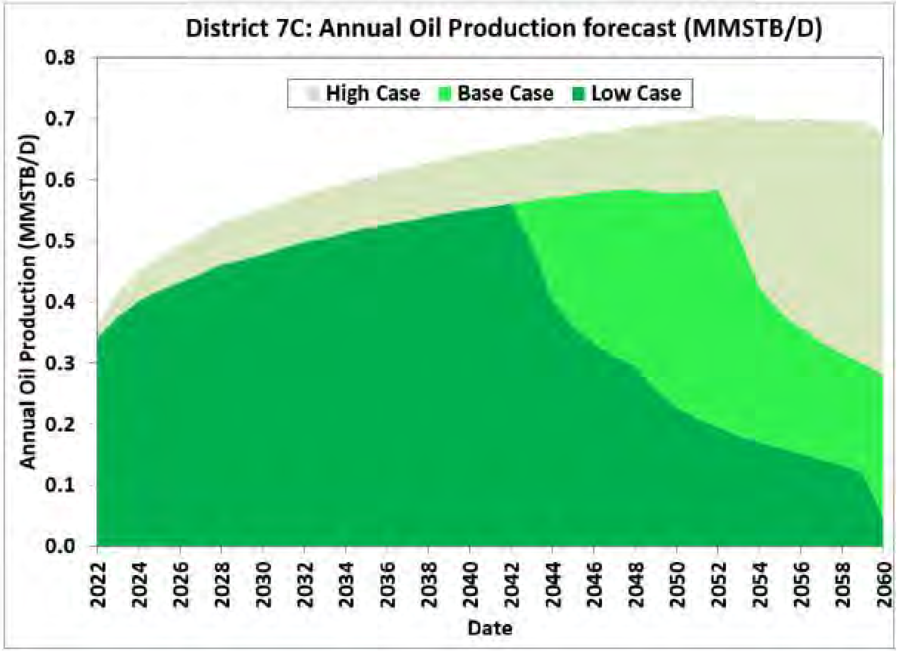

Figure 34: Annual Oil Production Forecast for District 7C.

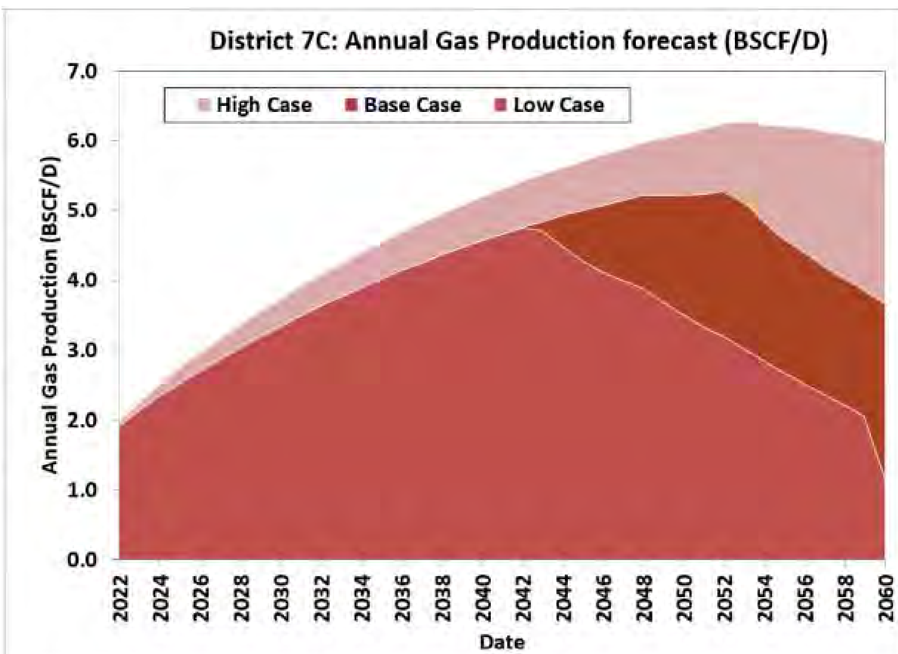

Figure 35: Annual Gas Production Forecast for District 7C.

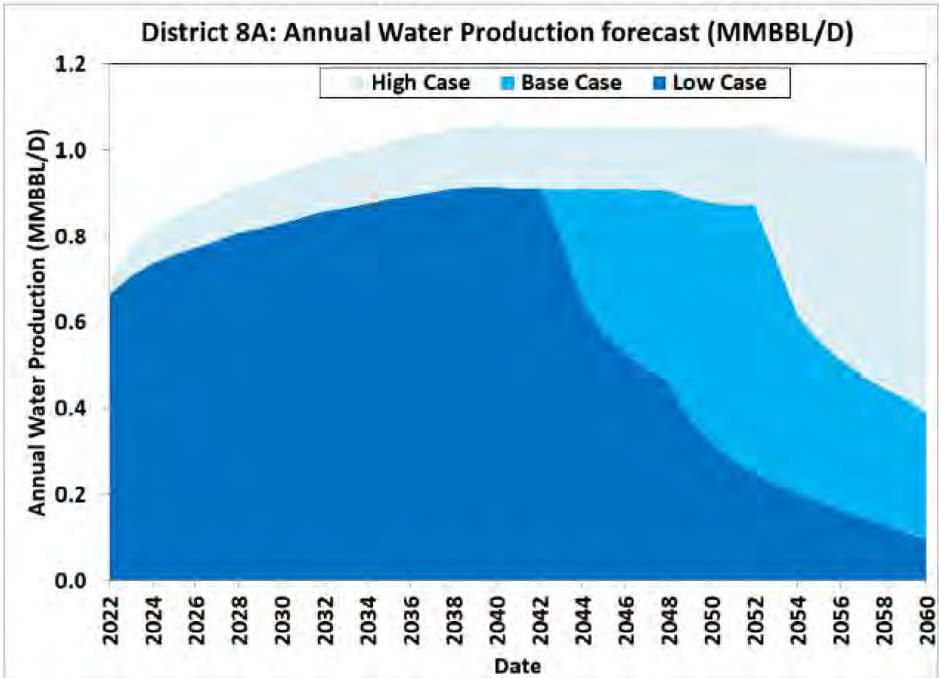

Figure 36: Annual Water Production Forecast for District 7C.

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

[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.

[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

[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

[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.

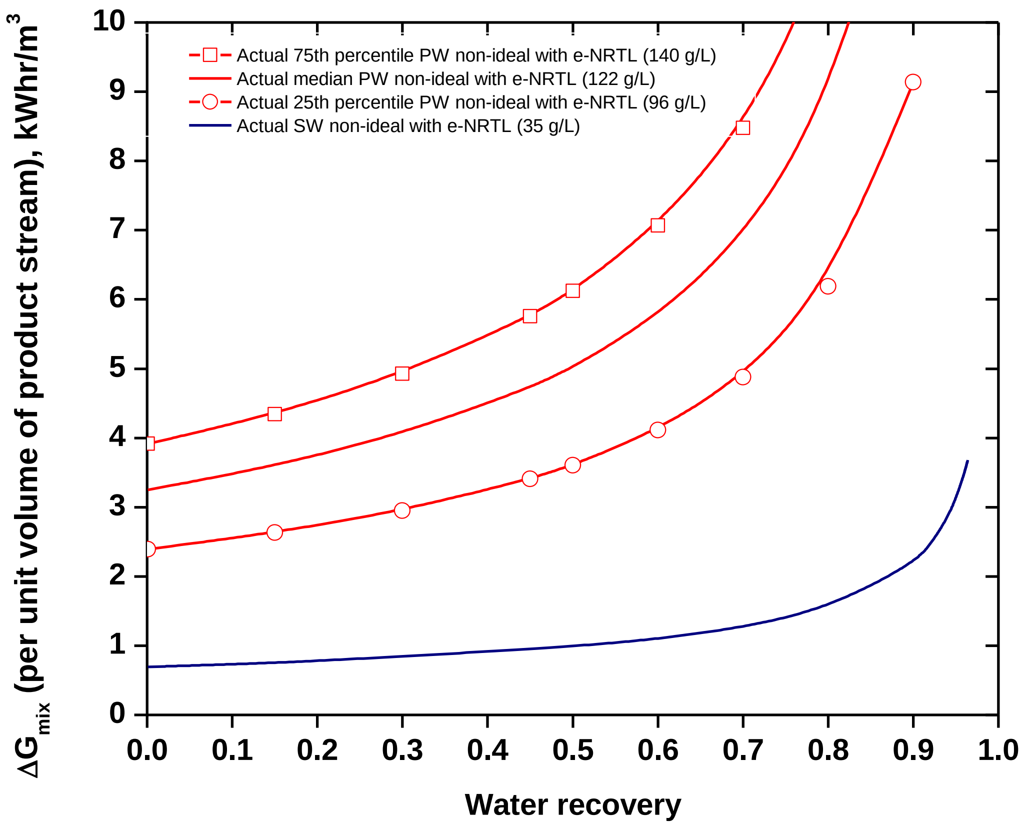

Figure 37. Comparison of thermodynamic minimum energy requirements to desalinate seawater (SW) and 25, 50 and 75 Percentile produced water (PW) as a function of fresh water recovery.

[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 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	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

[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.

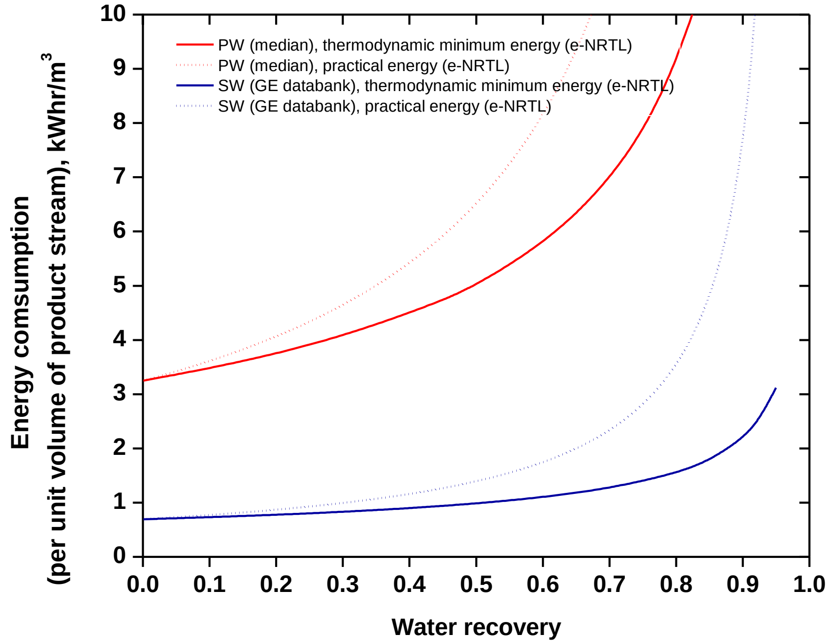

Figure 38. Comparison of thermodynamic minimum energy requirements to desalinate seawater (SW) and 25, 50 and 75 Percentile produced water (PW) as a function of fresh water recovery.

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

[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%.

[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

[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

[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.

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

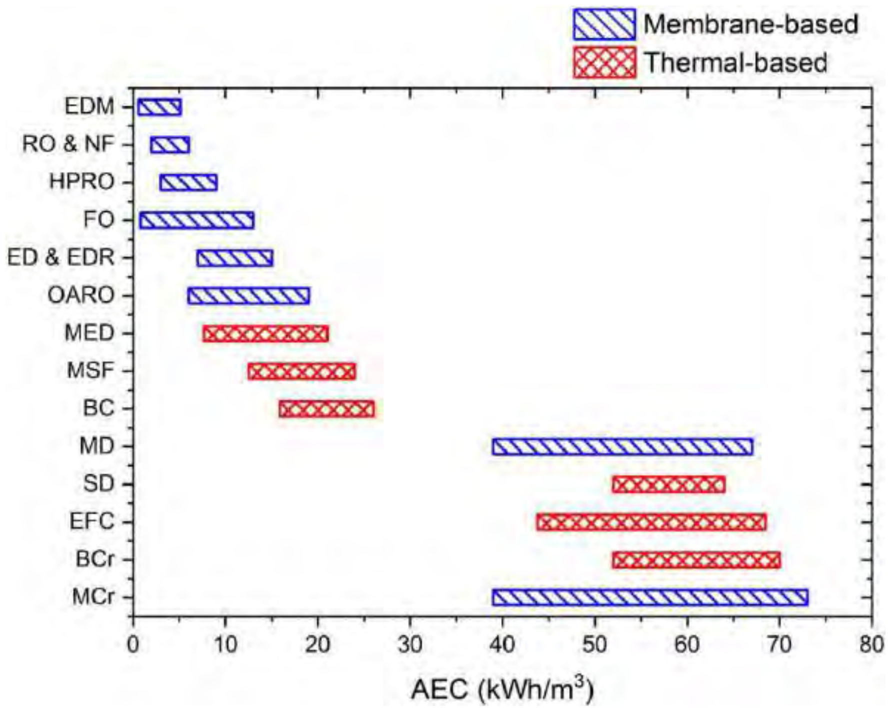

Figure 39 Actual energy consumption (AEC) for various processes from Panagopoulos[45]

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.

[45] *Ibid.*

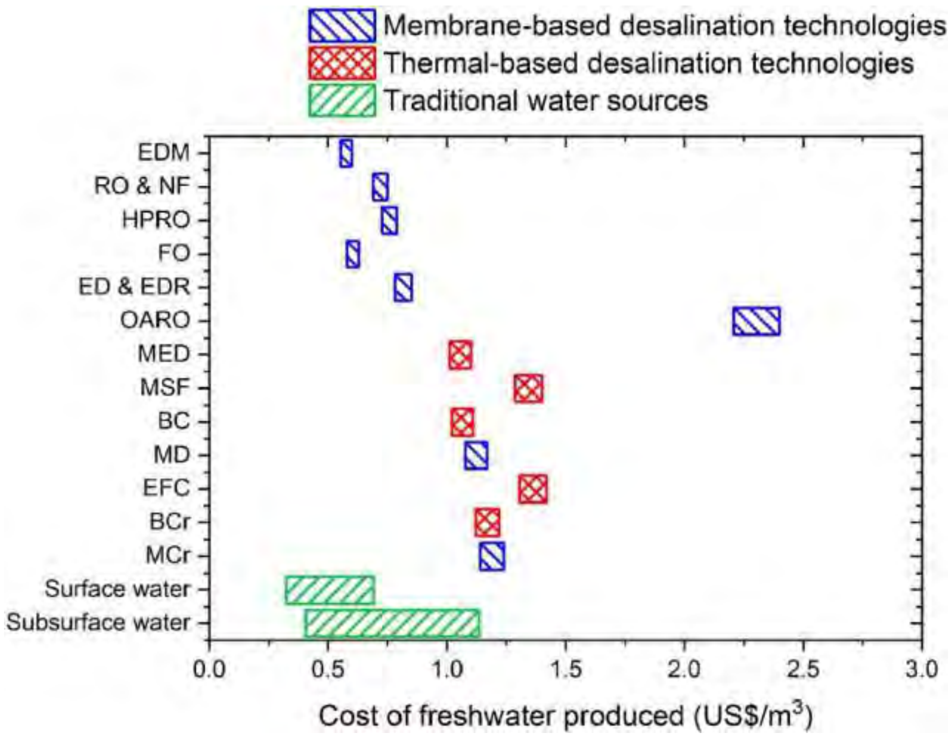

Figure 40 Cost of treated freshwater (<800 mg/L TDS) produced by the various processes from Panagopoulos[46]

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.

[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

Type	Feed TDS (g/L)	Recovery	Energy (KWh/m^3-product) Low	High	Reference
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

[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

[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 c onditions 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

[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_4^{2-})	≤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

[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

[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

[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

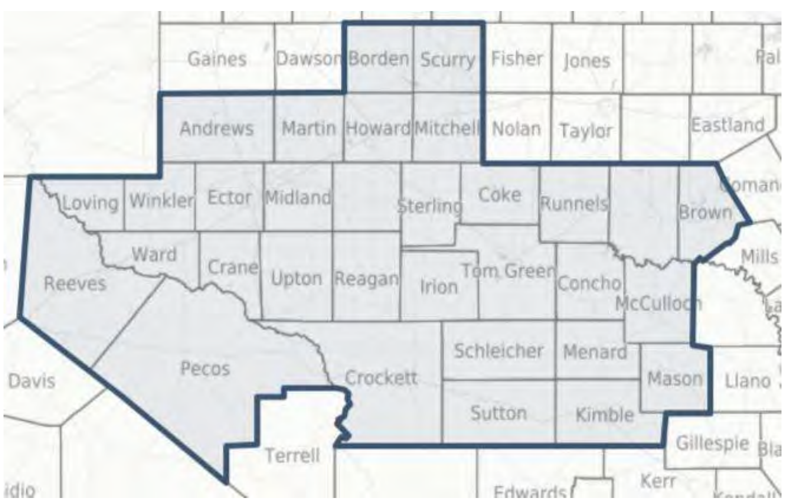


Figure 42: TWDB Planning Region F (Texas Water Development Board).

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

[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

[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

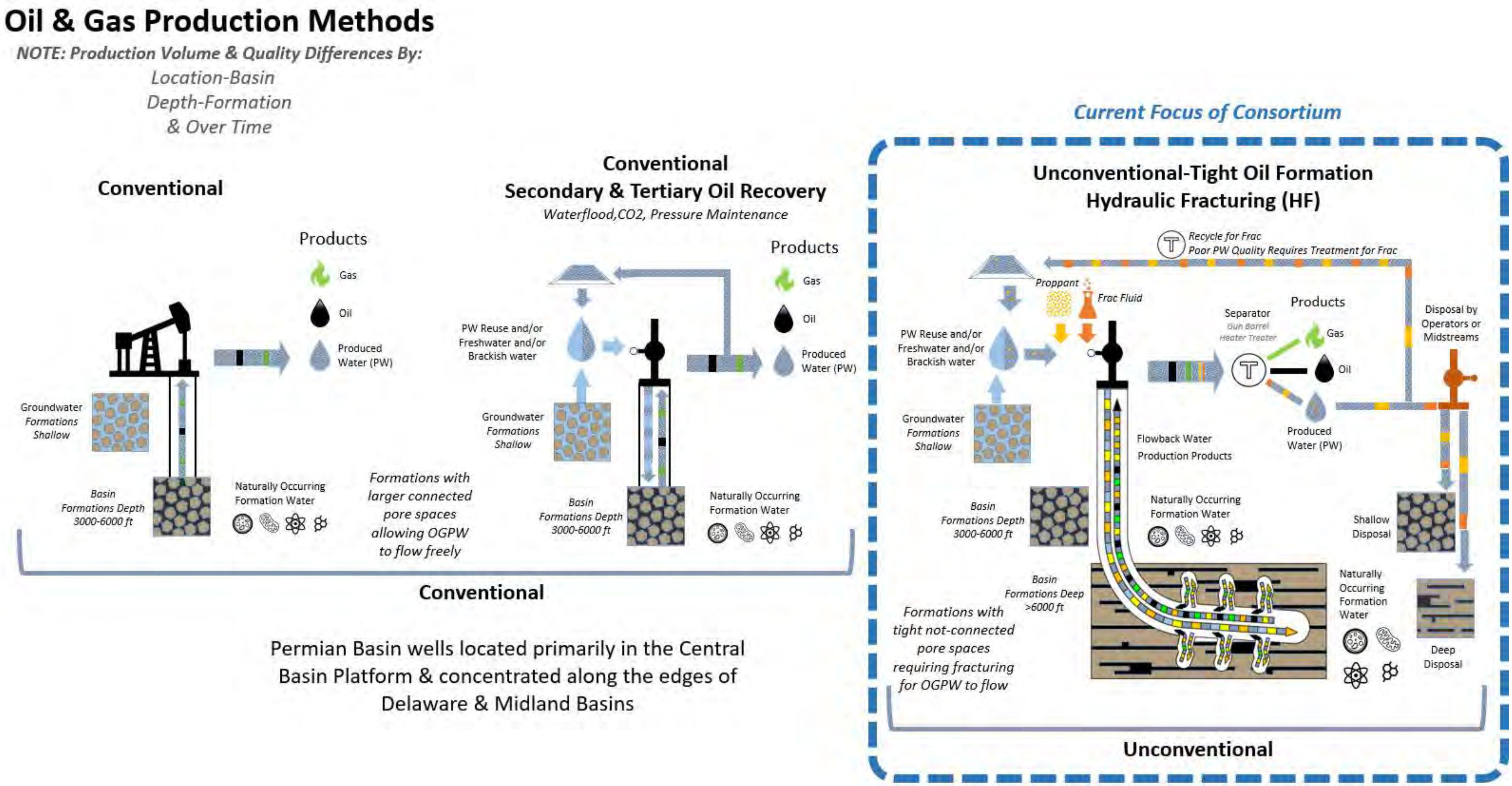
Along with the potential economics of shut-in production, members provided feedback on encapsulating the value that other produced water reuse options would provide for preserving oil & gas operations in an environment of increased injection disposal restrictions. Some members wanted to focus on the "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

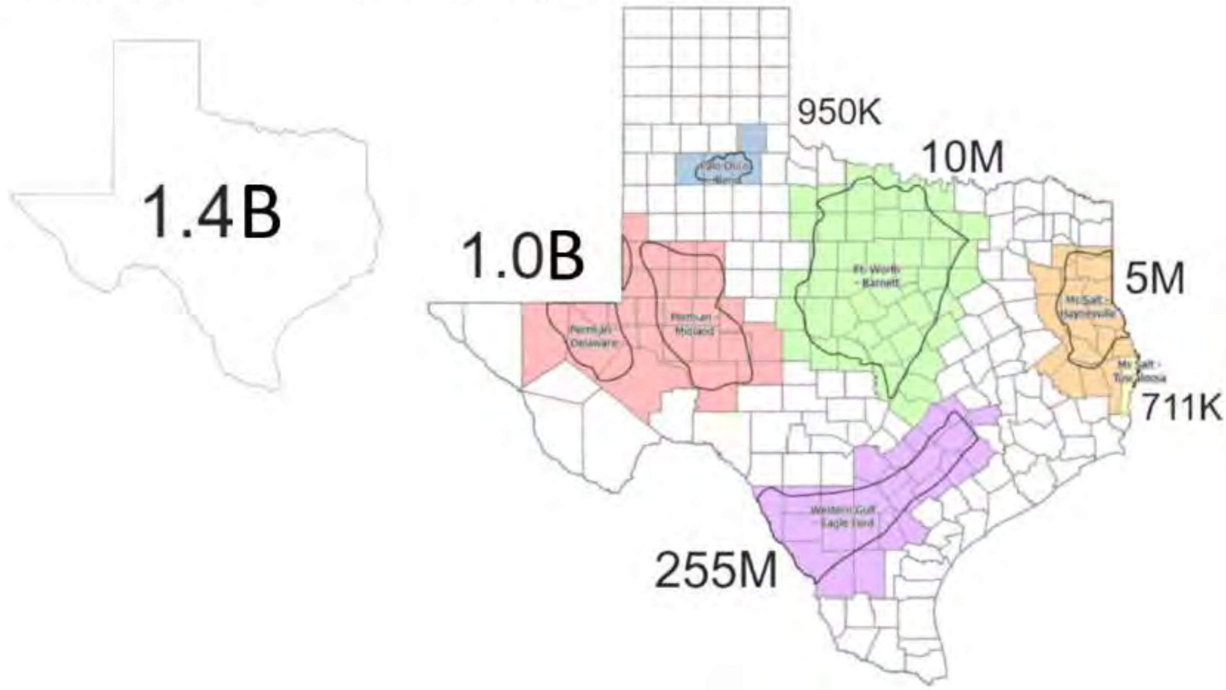


Permian Basin wells located primarily in deeper Delaware & Midland Basin stacked formations

Appendix B – 2021 Texas Shale Play Oil Production

2021 Annual Oil Production in BBL- RRC County Reports

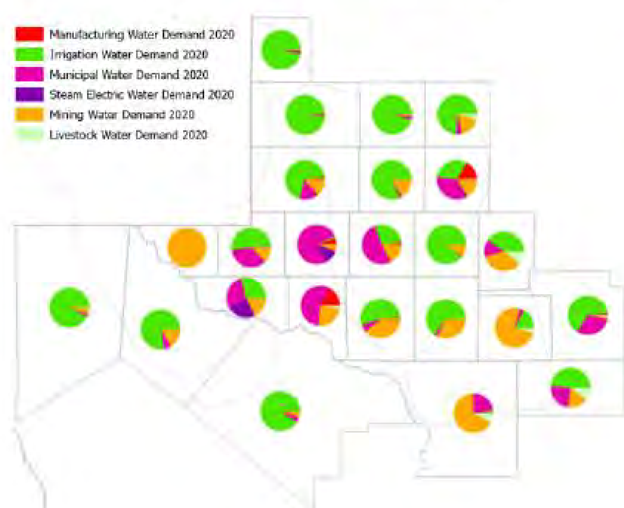
Total for Counties atop Unconventional-Tight Oil Formation Hydraulic Fracturing (HF) Shale Plays



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

2020 Total Water Demand

Permian Delaware & Midland Basin Counties (24)

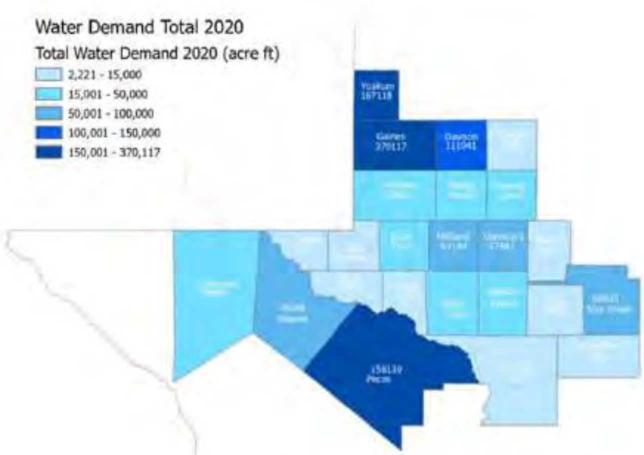


2070 Total Water Demand

Permian Delaware & Midland Basin Counties (24)

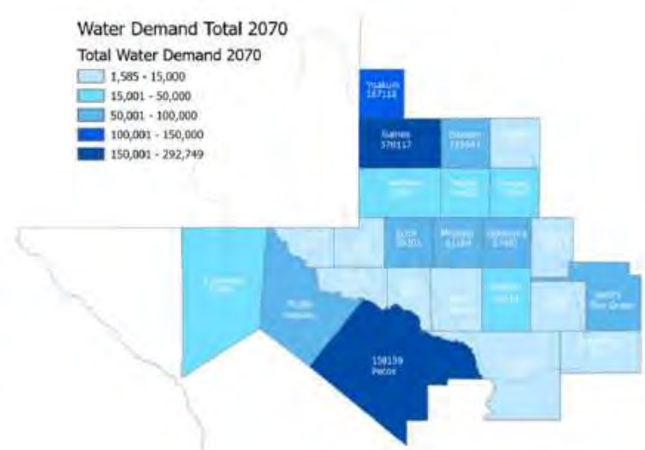
2020 Total Water Demand

Permian Delaware & Midland Basin Counties (24)

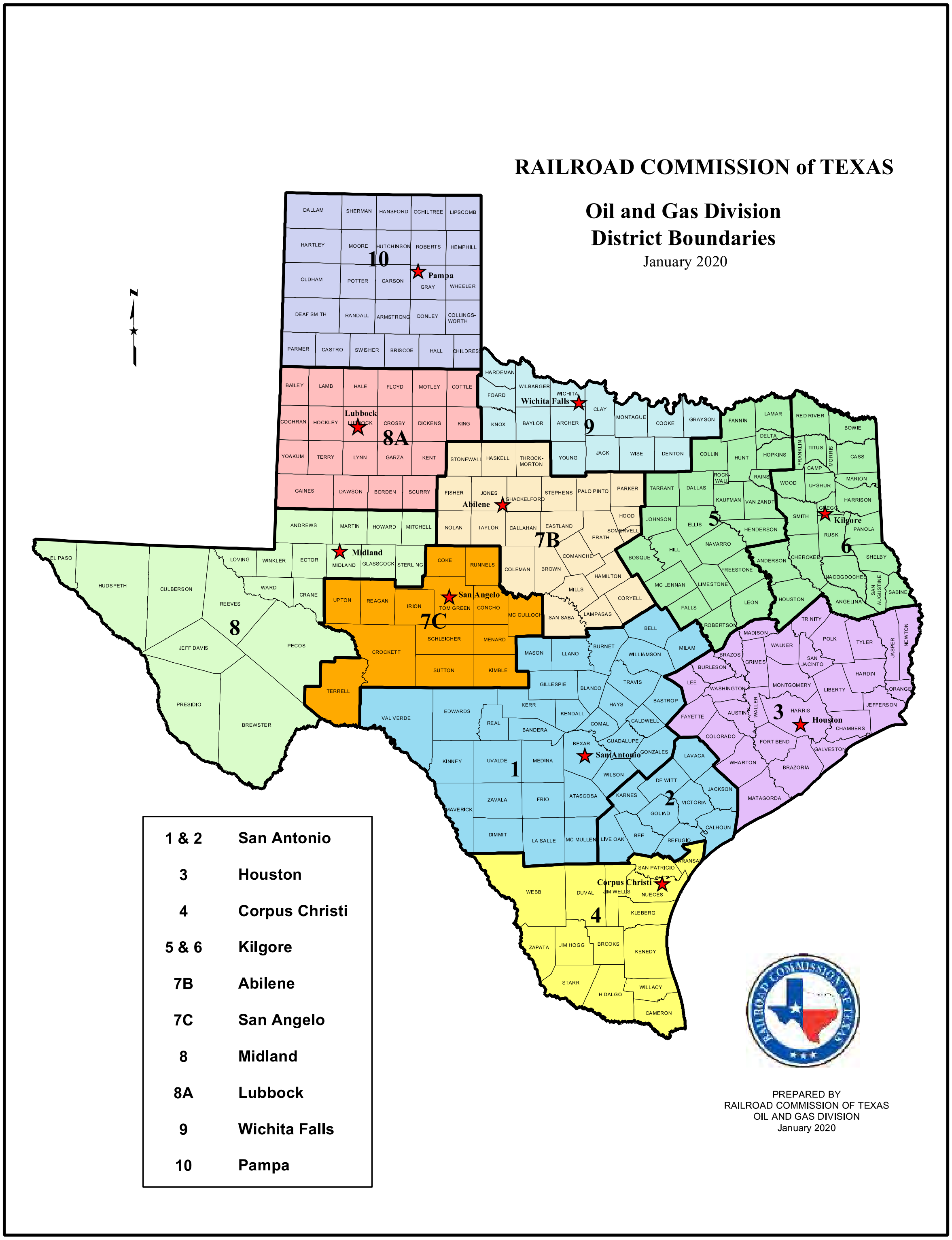


2070 Total Water Demand

Permian Delaware & Midland Basin Counties (24)



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



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

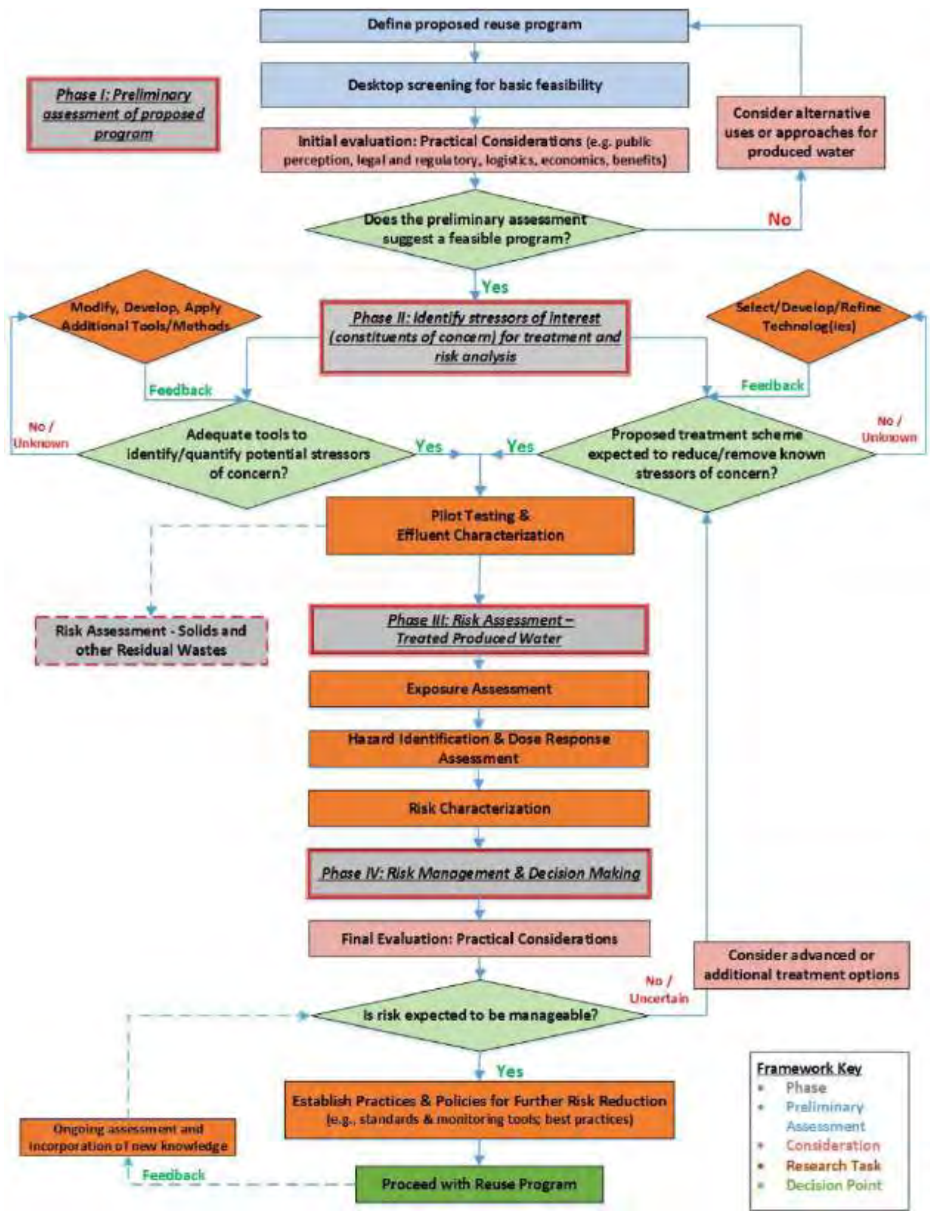


Figure 3-9: Framework for Research, Evaluation and Decision-Making

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°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.

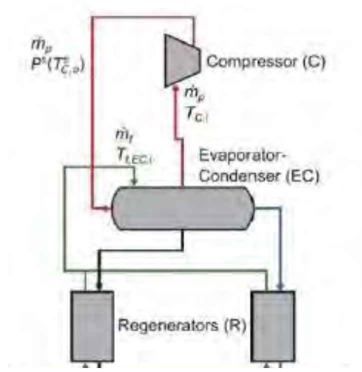


Figure 43: SCHEMATIC OF SINGLE-EVAPORATION MVC PROCESS FLOW [4]

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	**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

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$^{\Delta}$	0.13-0.32$^{\Delta}$	[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.

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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.

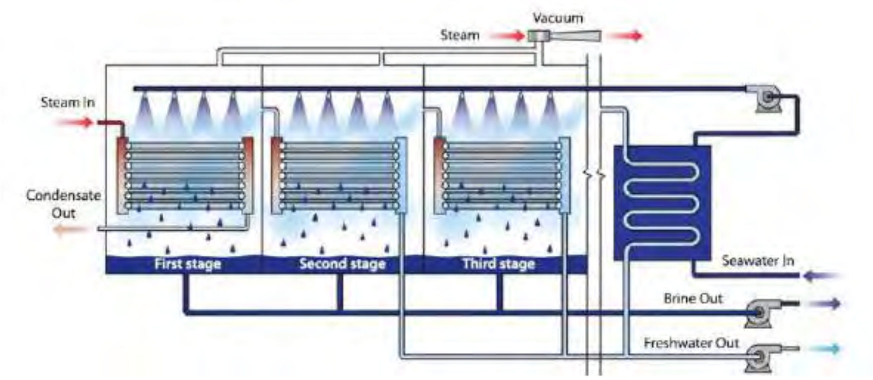

Figure 44 SCHEMATIC OF CONVENTIONAL MED PROCESS FLOW [2]

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$/yr Low	Operating Cost M$/yr High	Operating Cost per volume water $/m3 Low	$/m3 High	$/bbl Low	$/bbl 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 Δ	0.10-0.34 Δ	[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.

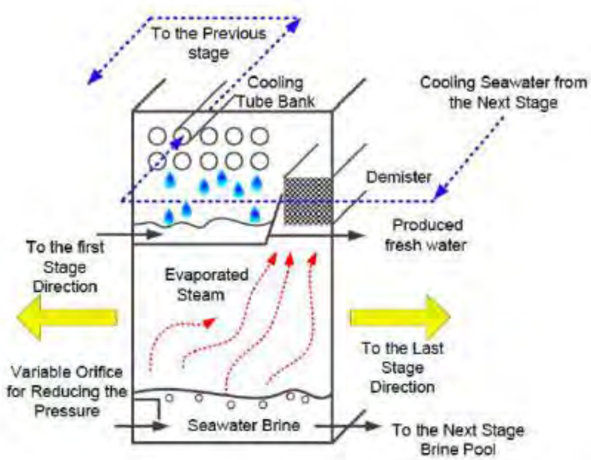

Figure 45 SCHEMATIC OF MSF PROCESS FLOW [1]

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.g., 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.

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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^{o}C – 90^{o}C which is a temperature range comparable to that of Multi-Effect Distillation (60^{o}C – 70^{o}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

[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.

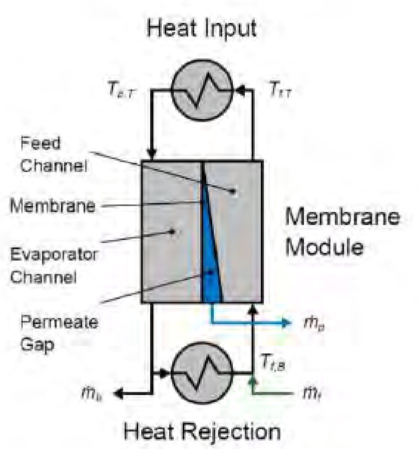

Figure 46. SCHEMATIC OF PGMD PROCESS FLOW [1]

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 Δ	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/m³, 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/m³, RO: 12 – 17 L/m³) [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

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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.

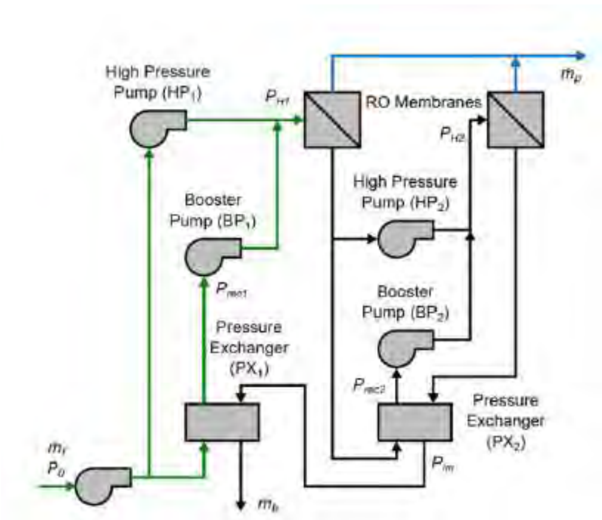

Figure 47 SCHEMATIC OF TWO STAGE HYPOTHETICAL HIGH SALINITY RO PROCESS FLOW [1]

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 Δ	0.11-0.22 Δ	[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.
2. Marc, A.R. and F. Aida, *Sustainable Energy Technologies for Seawater Desalination*. 2022, [N.p.]: Academic Press. 11.
3. Bhojwani, S., et al., *Technology review and data analysis for cost assessment of water treatment systems.* Science of the Total Environment, 2019. **651**: p. 2749-2761.
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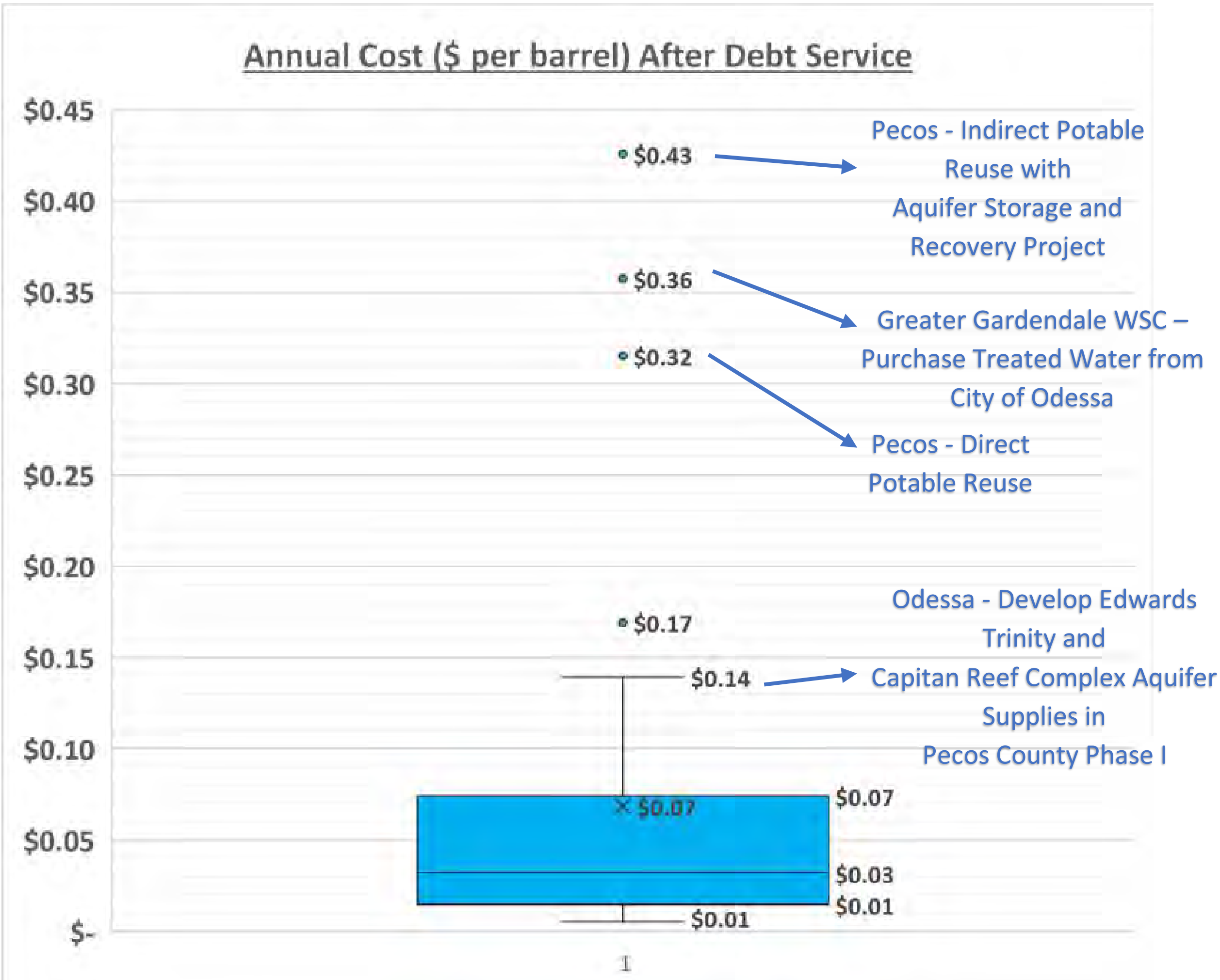
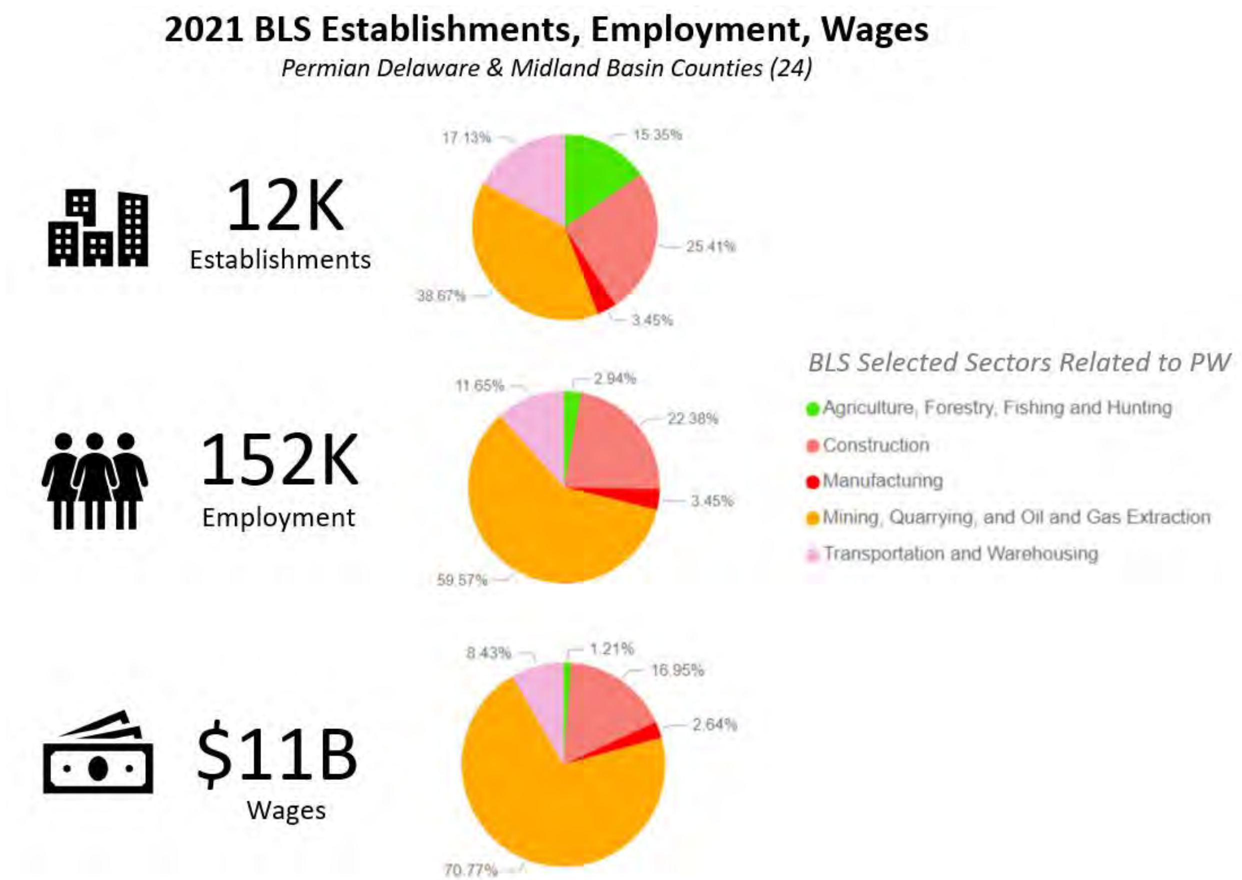
Appendix L – Estimated Pilot Project Testing Costs

	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**

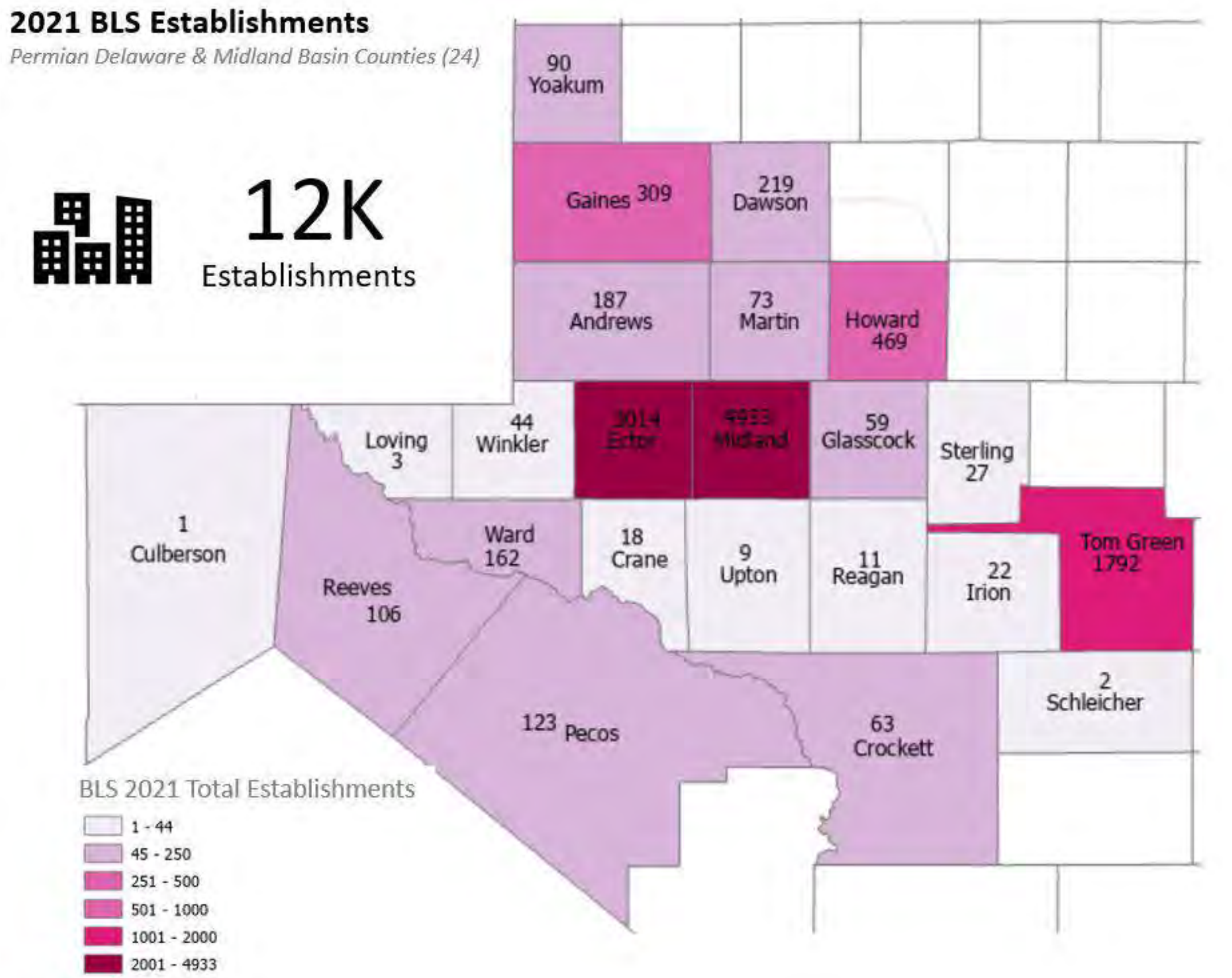

Annual Cost ($ per barrel) After Debt Service
$0.45
$0.40
$0.35
$0.30
$0.25
$0.20
$0.15
$0.10
$0.05
$-
$0.43
$0.36
$0.32
$0.17
$0.14
$0.07
$0.07
$0.03
$0.01
$0.01
1
Pecos - Indirect Potable Reuse with Aquifer Storage and Recovery Project
Greater Gardendale WSC – Purchase Treated Water from City of Odessa
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

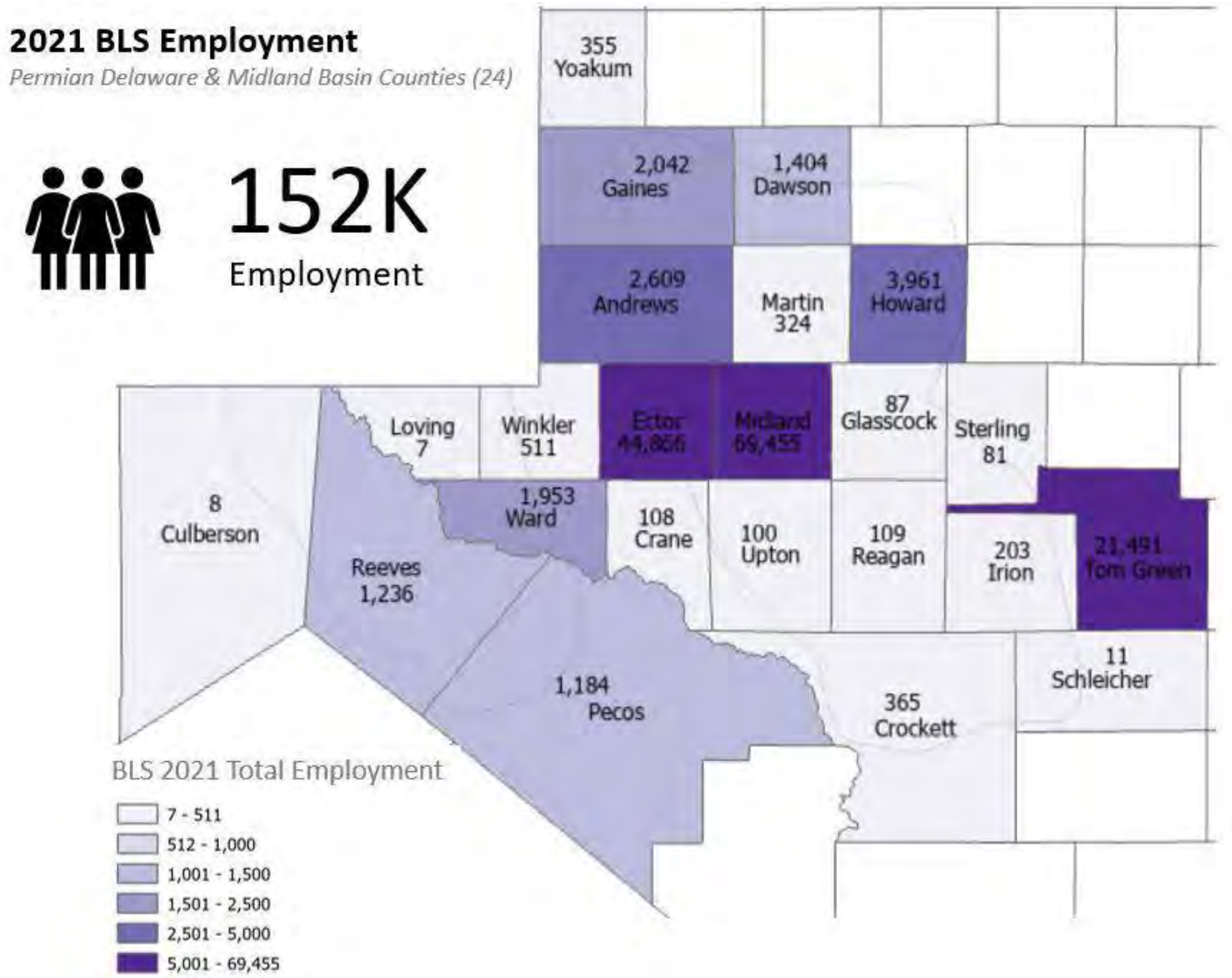
US Bureau of Labor Statistics (BLS) 2021 Total Establishments, Employment and Wages for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.



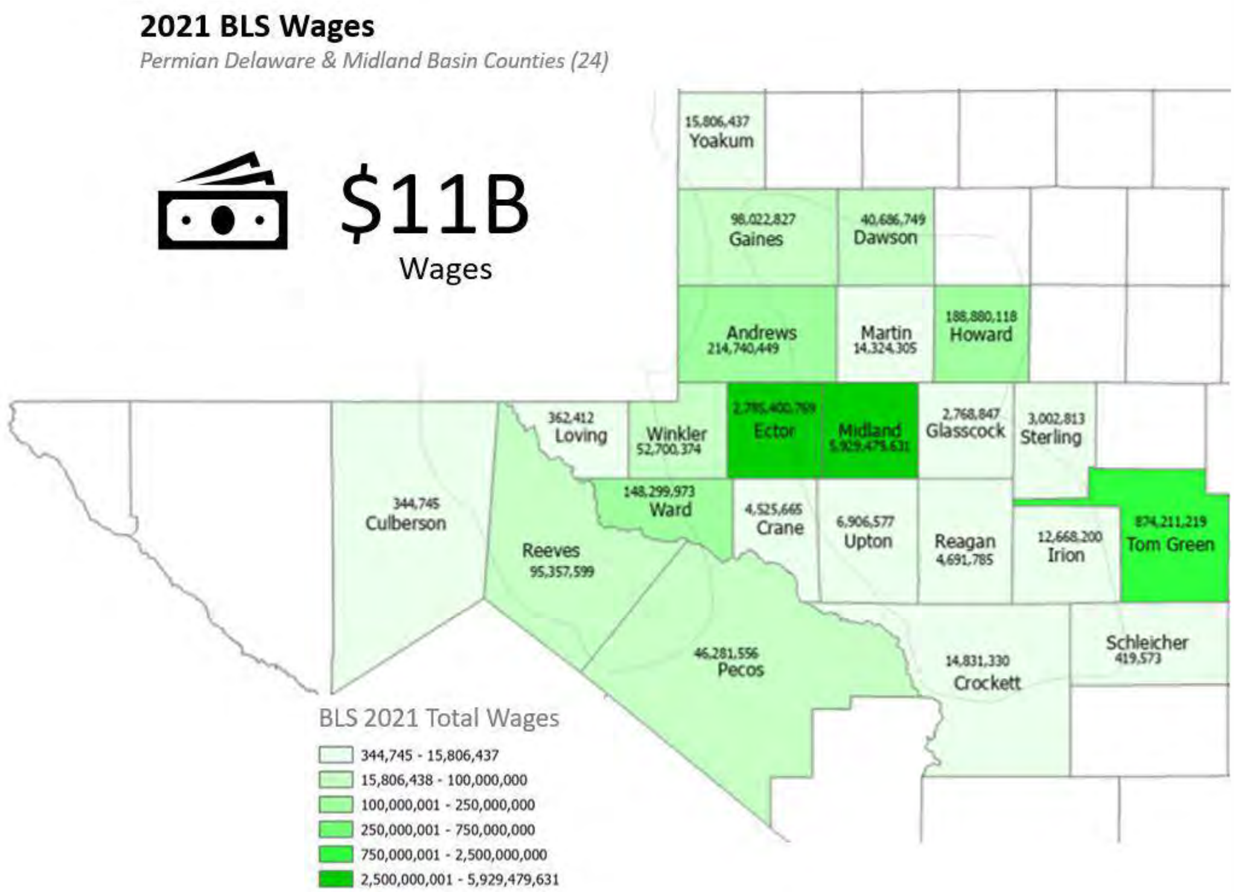
US Bureau of Labor Statistics (BLS) 2021 Total Establishments for the Permian Delaware and Midland Basin 24 County Area. Source data BLS prepared by TXPWC.



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.



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.

Texas Permian Future Generations

Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

EXHIBIT 2

Beneficial Use of Produced Water in Texas

Texas Produced Water Consortium Report to the Texas Legislature 2024

Texas Produced
Water Consortium

Acknowledgment

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

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

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Karlo Rasporic
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2023-2024 TxPWC Membership & Partners
American Water Works - Texas Section
Apache Corporation
Aris Water Solutions
B3 Insight
Baywater Operating
Bureau of Economic Geology at University of Texas
BPX Energy (BP)
Chevron
ConocoPhillips
Devon Energy
Diamondback Energy
Dr. Catherine Brown
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Environmental Defense Fund
ExxonMobil
Gulf Coast Authority
H2O Midstream
Layne Water Midstream
Meadows Center for the Environment
Natura Resources
NGL Energy Partners
NGL Water Solutions
New Mexico Produced Water Research Consortium
Occidental Oil & Gas Corporation
Permian Basin Petroleum Association
Pilot Pure, Inc.
Pilot Water Solutions, LLC
Pioneer Natural Resources
Renovo Resources
Resource West
Select Energy Services
Sierra Club Lone Star Chapter
Steven Walden Co.
TETRA Technologies
Texas 2036
Texas Alliance of Energy Producers
Texas Land & Mineral Owners Association
Texas Oil & Gas Association
Texas Pacific Water Resources
Texas Tech University
Texas Tech Center for Water Law & Policy
WaterBridge
Western Midstream Partners
William Mitchell
William Scott

State Agency Partners
General Land Office
Railroad Commission of Texas
State Energy Conservation Office
Texas Commission on Environmental Quality
Texas Department of Agriculture
Texas Economic Development and Tourism Office
Texas Parks and Wildlife Department
Texas Water Development Board

Table of Contents

1 Executive Summary

1.1 Legislative Updates Since the 2022 Report

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

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

1.2 Pilot Projects

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

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

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

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

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

1.3 Standards

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

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

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

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

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

1.4 Economics

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

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

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

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

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

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

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

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

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

1.5 Technologies & Volumes

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

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

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

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

1.6 Upcoming Research Projects

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

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

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

2 Update on Pilot Projects

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

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

Project information is as follows:

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

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

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

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

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

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

Depending on the application, use of treated produced water in the State of Texas may be governed by standards and permitting processes by:

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

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

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

3.1 Federal Standards: Clean Water Act

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

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[9] Amy Hardberger. (2024) The Challenges and Opportunities of Beneficially Reusing Produced Water, 34 *Duke Environmental Law & Policy Forum* 1-48
Available at: https://scholarship.law.duke.edu/delpf/vol34/iss1/1, accessed 2024-SEP-01

[10] United States Code, Title 33 Navigation and Navigable Waters, §1251, available at https://www.govinfo.gov/link/uscode/33/1251, accessed 2024-AUG-27

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

3.1.1 40 CFR Chapter I, Subchapter D Water Programs

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2 Texas Standards

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

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

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

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

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

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

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

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

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

3.2.1 Railroad Commission (RRC) of Texas

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

From the RRC website[27]:

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

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

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

3.2.1.1 RRC Pilot study for land application of treated produced water

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2.2 Texas Commission on Environmental Quality (TCEQ)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2.2.4 Other petroleum-related permits

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.3 Other State Standards

3.3.1 Montana

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

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

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

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

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

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

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

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

3.3.2 New Mexico

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

3.3.3 Colorado

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

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

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

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

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

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

3.4 Guidelines

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

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

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

3.4.2 Groundwater Protection Council (GWPC)

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

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

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

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

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

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

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

3.4.3 National Research Council (NRC)

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

3.5 Ongoing and Future Research

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4 Economic Insights

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

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

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

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

4.1.1 Irrigated Agriculture

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

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

4.1.2 Municipalities

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

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

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

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

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

4.2 Targeted Research for Economic Viability of Treated Produced Water

4.2.1 Carbon Capture

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5 Desalination Technologies for Midland and Delaware Basin Produced Water

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

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

5.1 Characteristic of Delaware and Midland Basin Produced Water

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

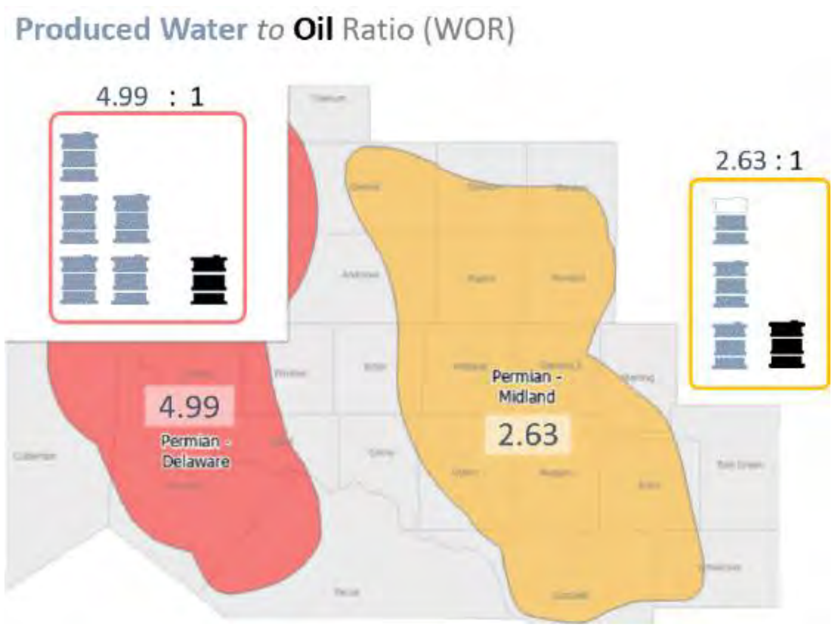

Figure 1: Produced Water-to-Oil ratios in the Permian's Delaware and Midland Basins.

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

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

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

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

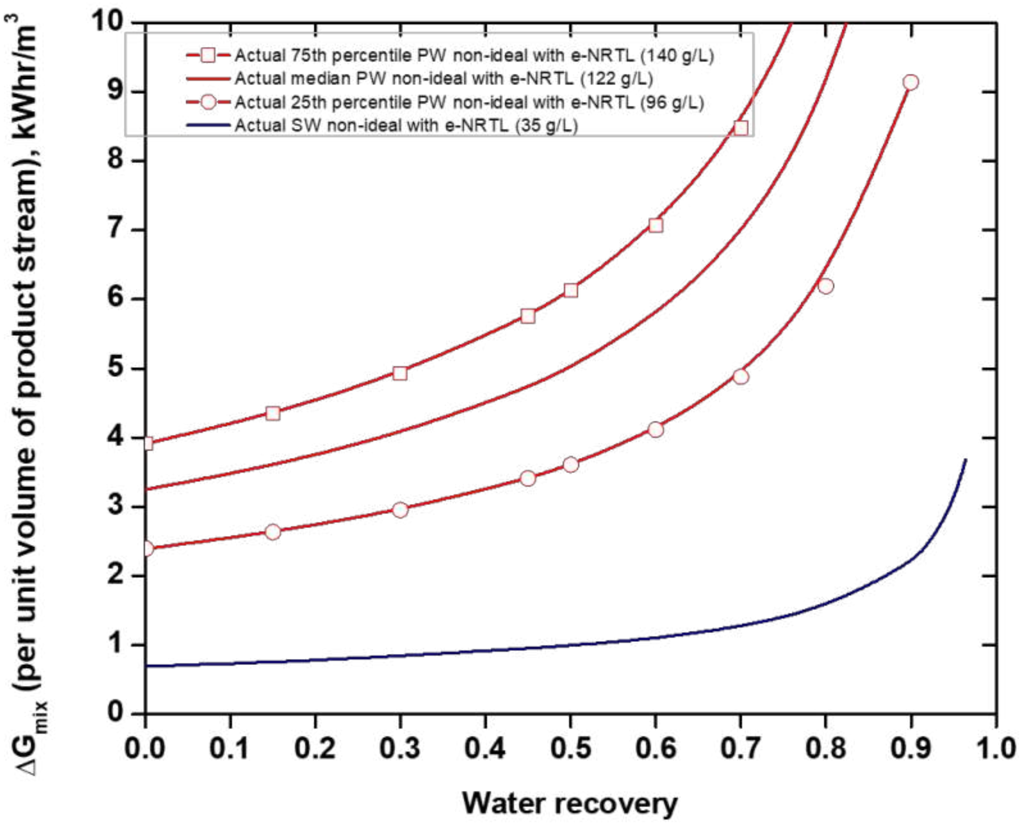

Figure 2: Minimum energy requirements to separate salts from seawater and 25th, 50th and 75th %ile Permian Basin waters

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

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

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

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

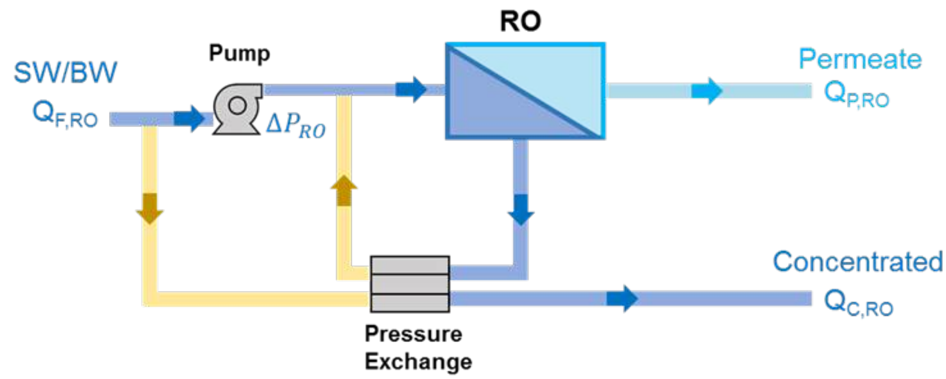

Figure 3: Simplified single stage RO system.

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

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

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

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

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

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

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

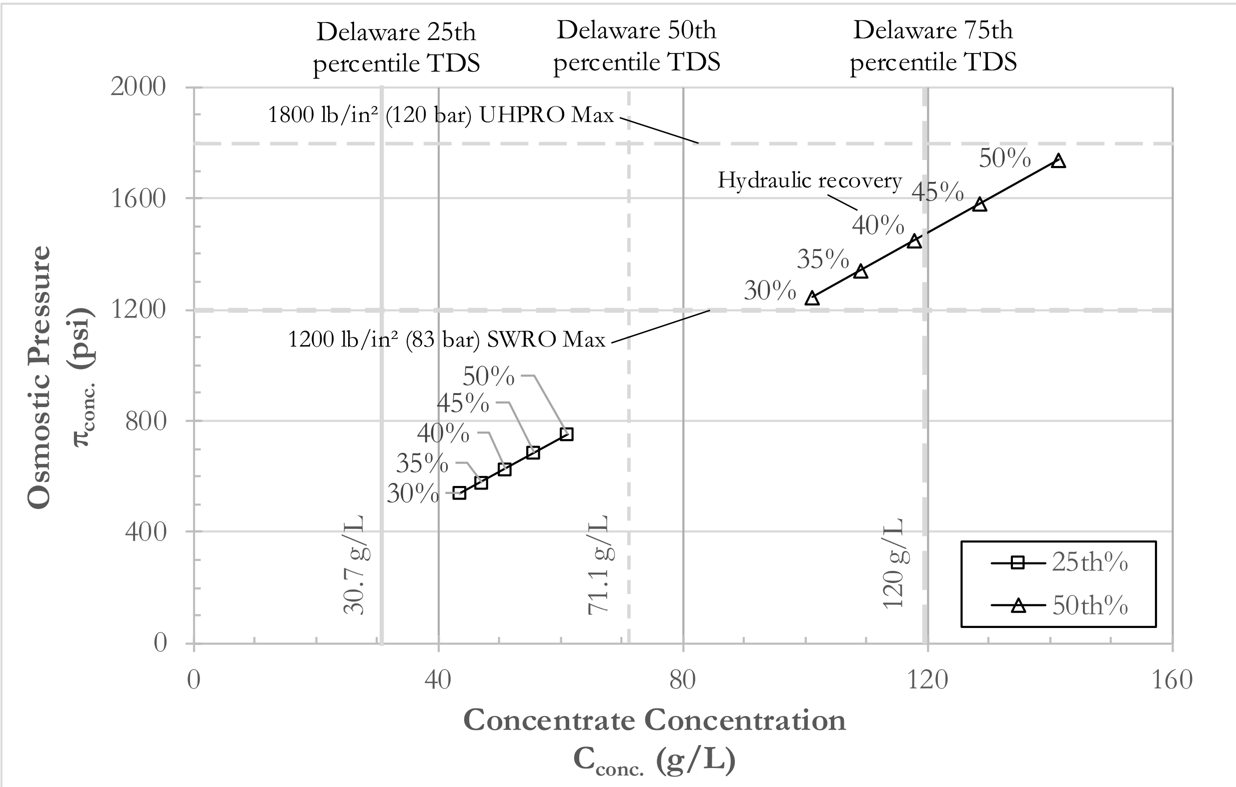

Figure 4: Estimated Delaware RO concentrate osmotic pressures as a function of percent recovery compared to RO limits.

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

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

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

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

5.3 Desalination of Delaware Basin Produced Water by MVR

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

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

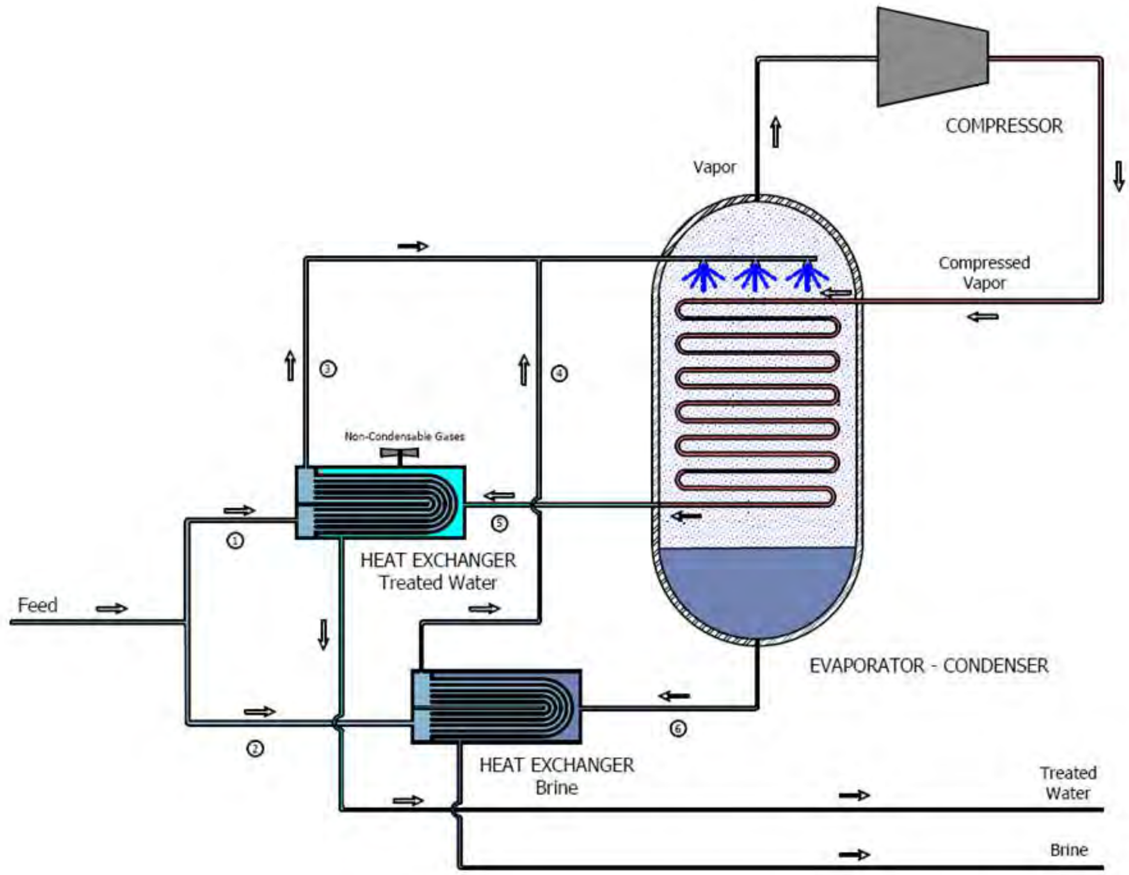

Figure 5: Simplified Flowsheet for MVR

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

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

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

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

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

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

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

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

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

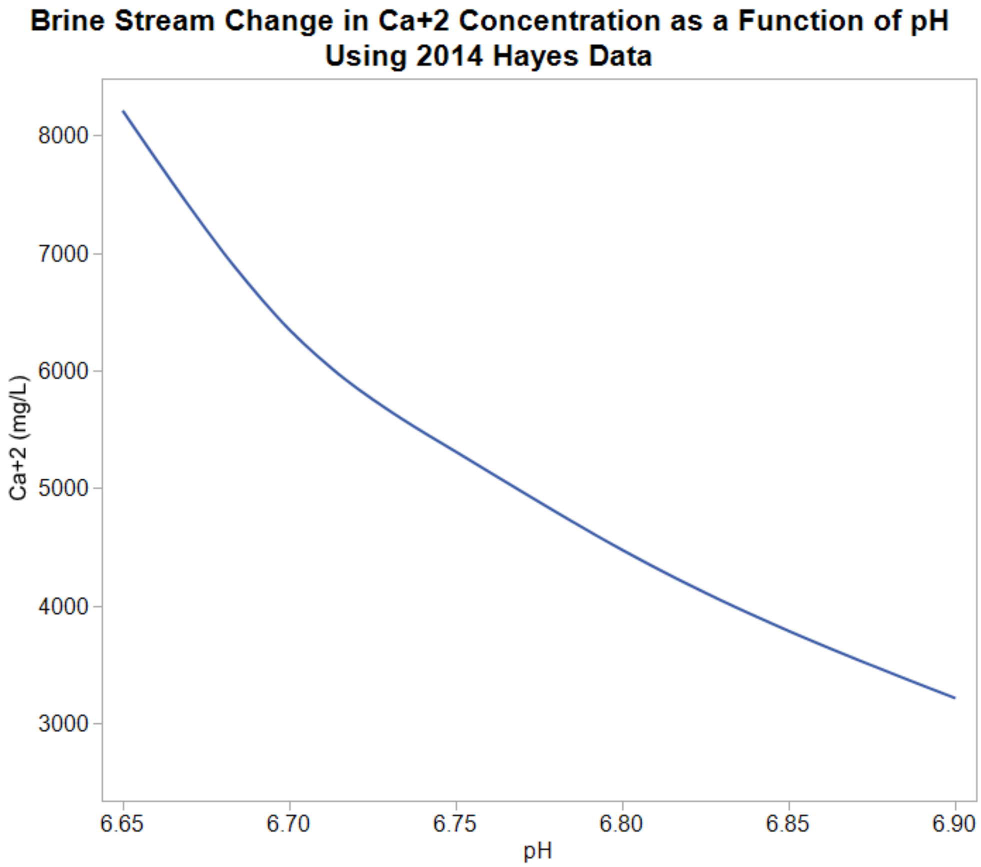

Figure 6: Calcium precipitation as a function of pH feed to the evaporator

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

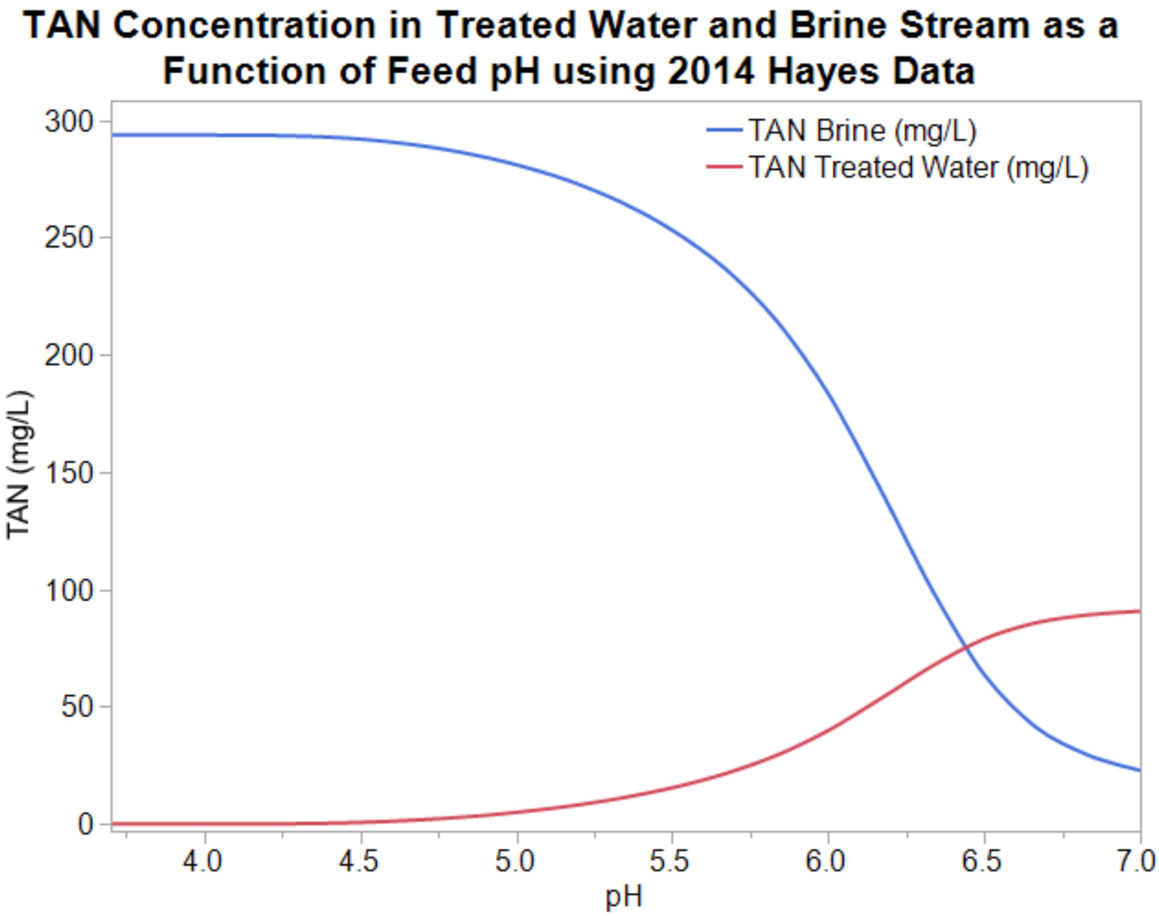

Figure 7: Total Ammonia Nitrogen as a function of feed pH

5.4 Conclusions for Delaware Basin

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

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

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

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

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

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

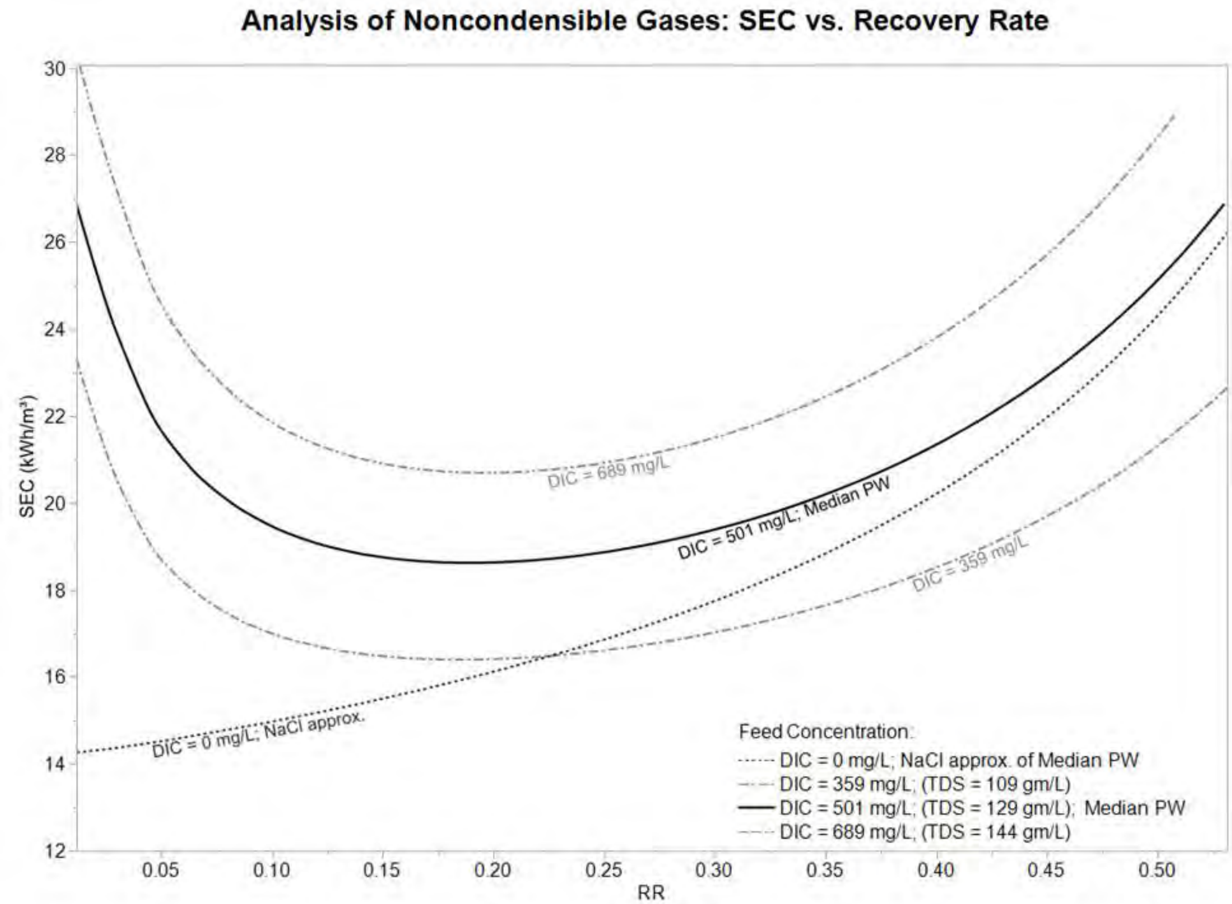

Figure 8: SEC versus recovery for DIC of 25%ile, median and 75%ile Midland Basin produced water. NaCl at TDS of median water also shown to reflect of SEC when there are no non-condensable gases in the overhead.

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

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

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

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

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

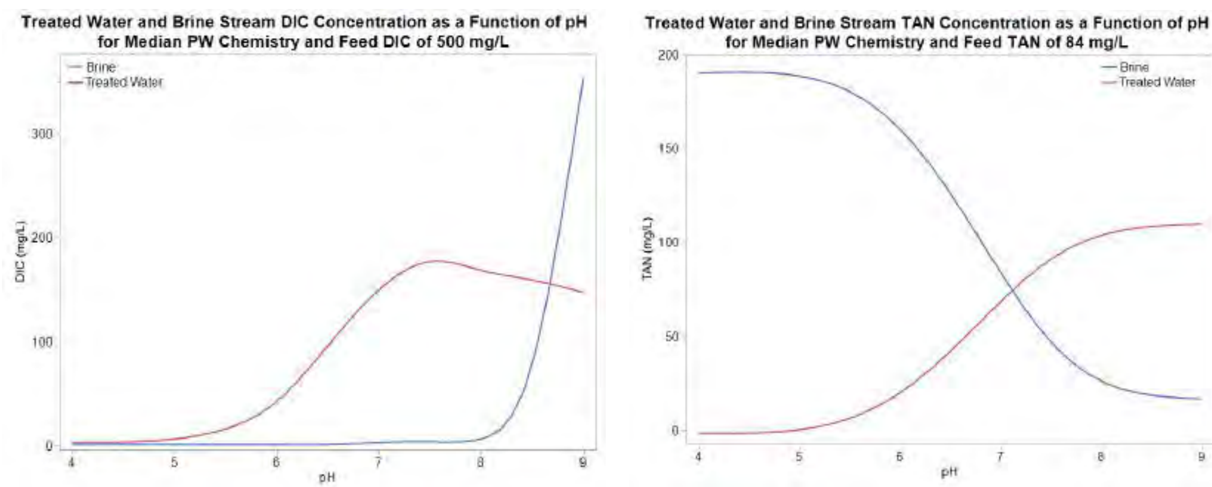

Figure 9: DIC (carbonates and CO2) and TAN distribution as a function of feed pH for Midland Basin median produced water

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

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

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

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

5.5 Conclusions for Midland Basin

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

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

6 Upcoming Research Project: Guayule Latex Production Using Produced Water

6.1 Introduction

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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116 Foster, M. A., & Coffelt, T. A. (2005). Guayule agronomics: Establishment, irrigated production, and weed control. Industrial Crops and Products, 22(1), 27–40. https://doi.org/10.1016/j.indcrop.2004.06.006

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

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

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

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

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

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

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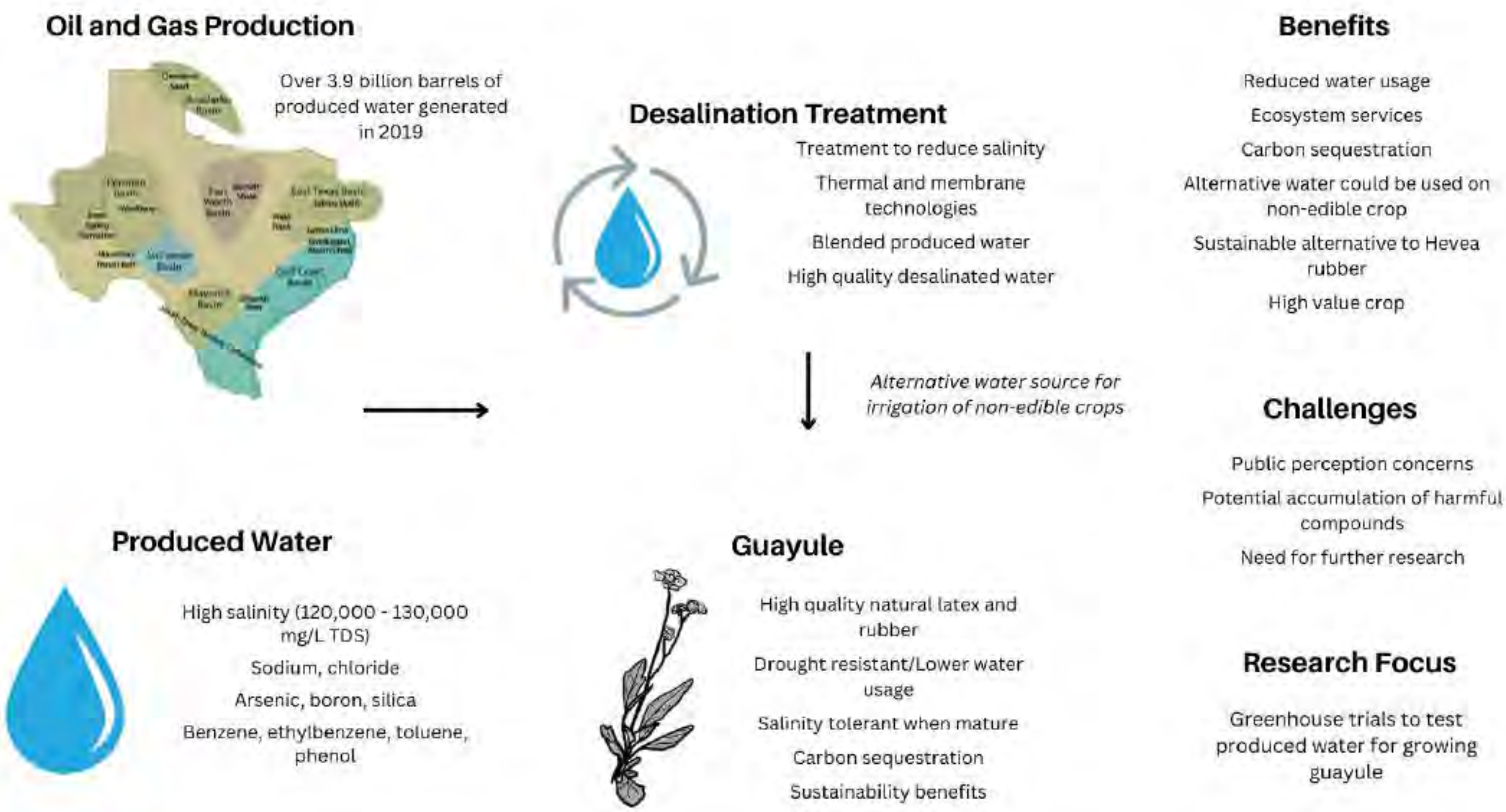

Figure 10: Project visual summary and justification for using produced water for guayule production in the Southern High Plains.

6.2 Work plan

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

6.2.1 Experimental setup

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

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

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

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

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

7 Upcoming Research Project: Critical Mineral Assessment & Recovery

7.1 Introduction

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

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

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

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

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

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

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

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

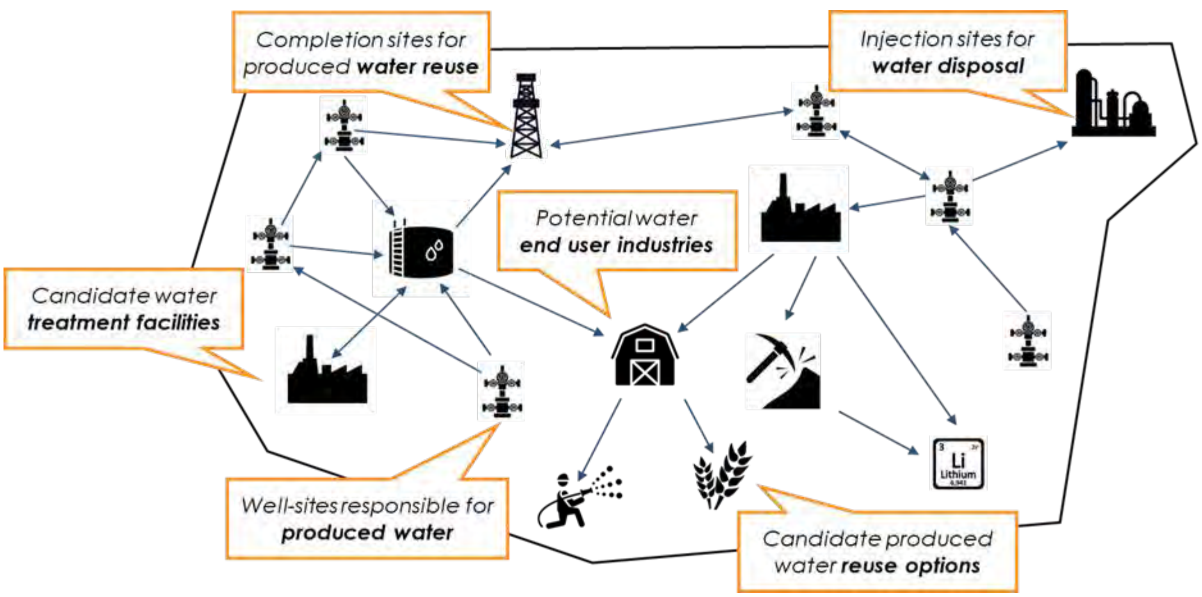

Figure 11: Illustration of the targeted scope of Project PARETO.

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

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

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

8.1 Introduction to the PARETO Suite

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

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

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

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

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

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

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

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

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

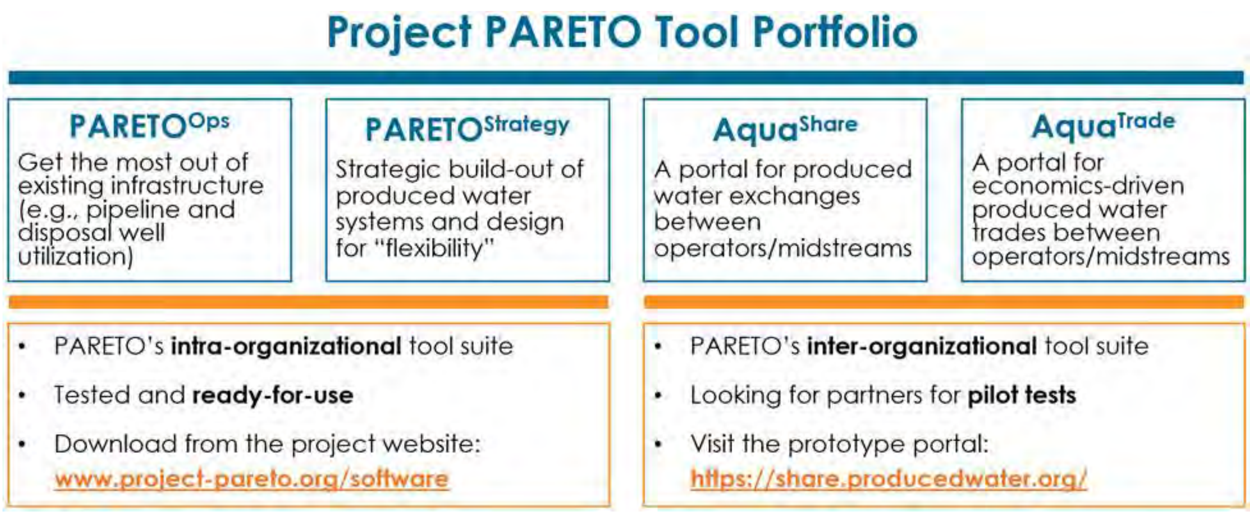

Figure 12: Overview of the Project PARETO tool portfolio.

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

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

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

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

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

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

8.2 PARETOStrategy – Industrial Case Study Demonstration

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

Figure 13: PARETOStrategy optimization workflow.

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

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

8.3 Industrial Case Study

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

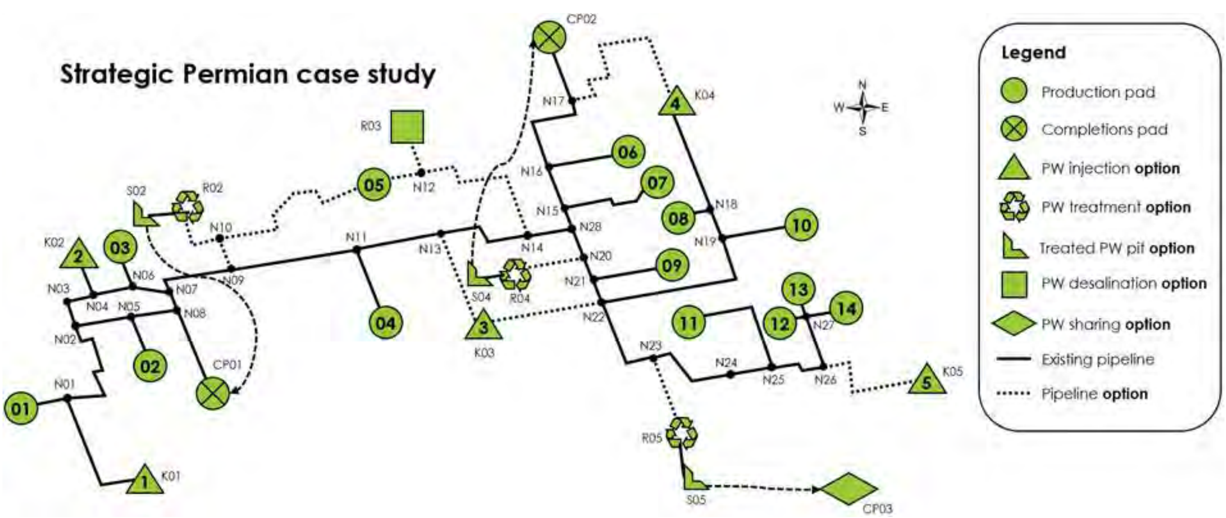

Figure 14: Strategic Permian case study schematic.

The case study is characterized by the following details:

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

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

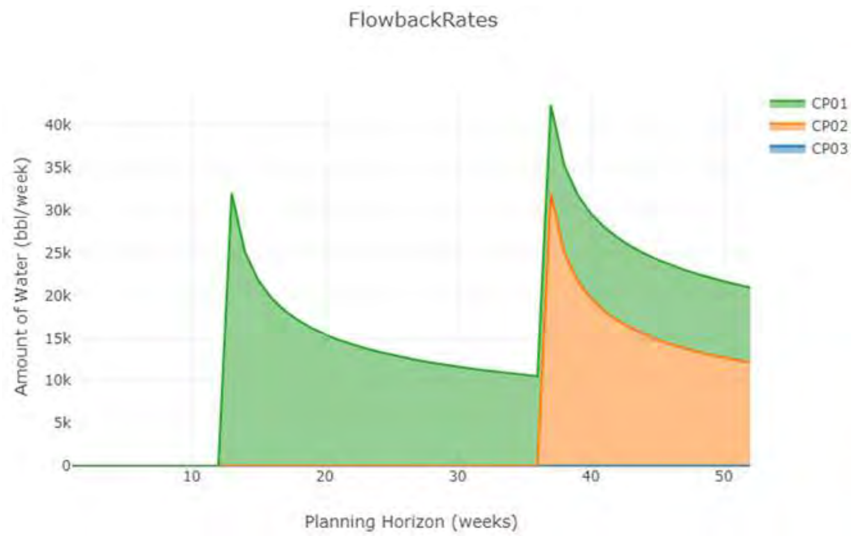

Figure 15: Flowback forecast over time. It is important to note that PARETO is designed so that it MUST "find a home" for every barrel of flowback that is coming into the respective PW system. If it cannot do so, the tool will return an "infeasible status".

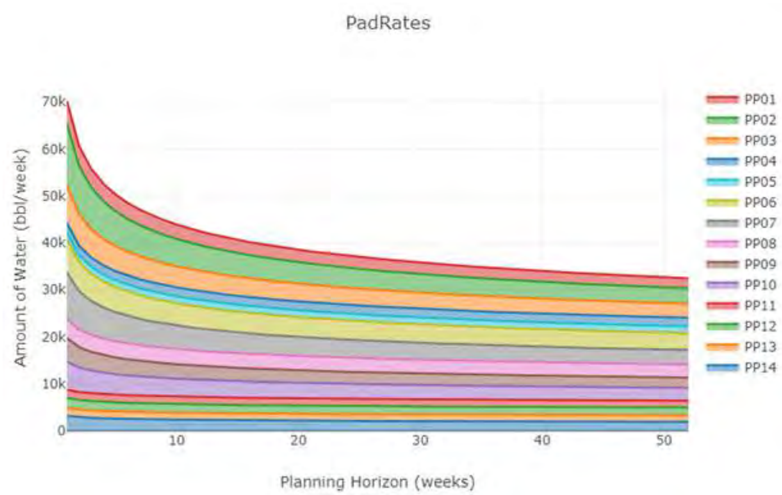

Figure 16: Production forecast over time. It is important to note that PARETO is designed so that it MUST "find a home" for every barrel of production that is coming into the respective PW system. If it cannot do so, the tool will return an "infeasible status".

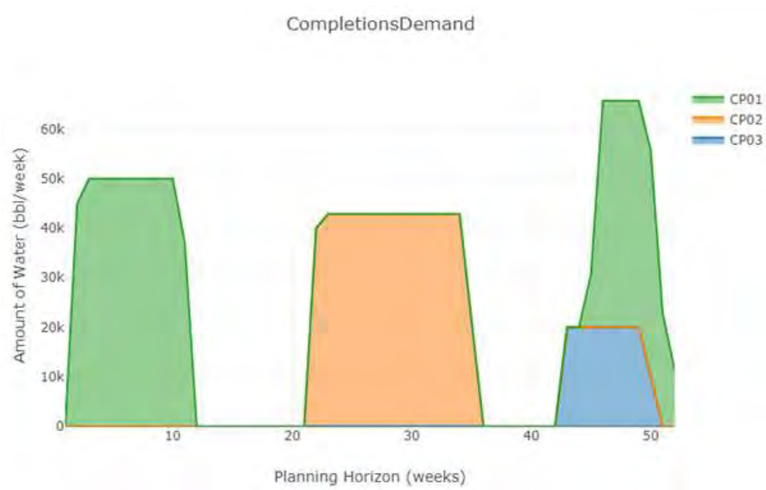

Figure 17: Completions demand over time. It is important to note that PARETO is designed so that it MUST meet every barrel of demand that has been specified at the respective completions pads. If it cannot do so, the tool will return an "infeasible status".

8.4 Industrial Case Study Results

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

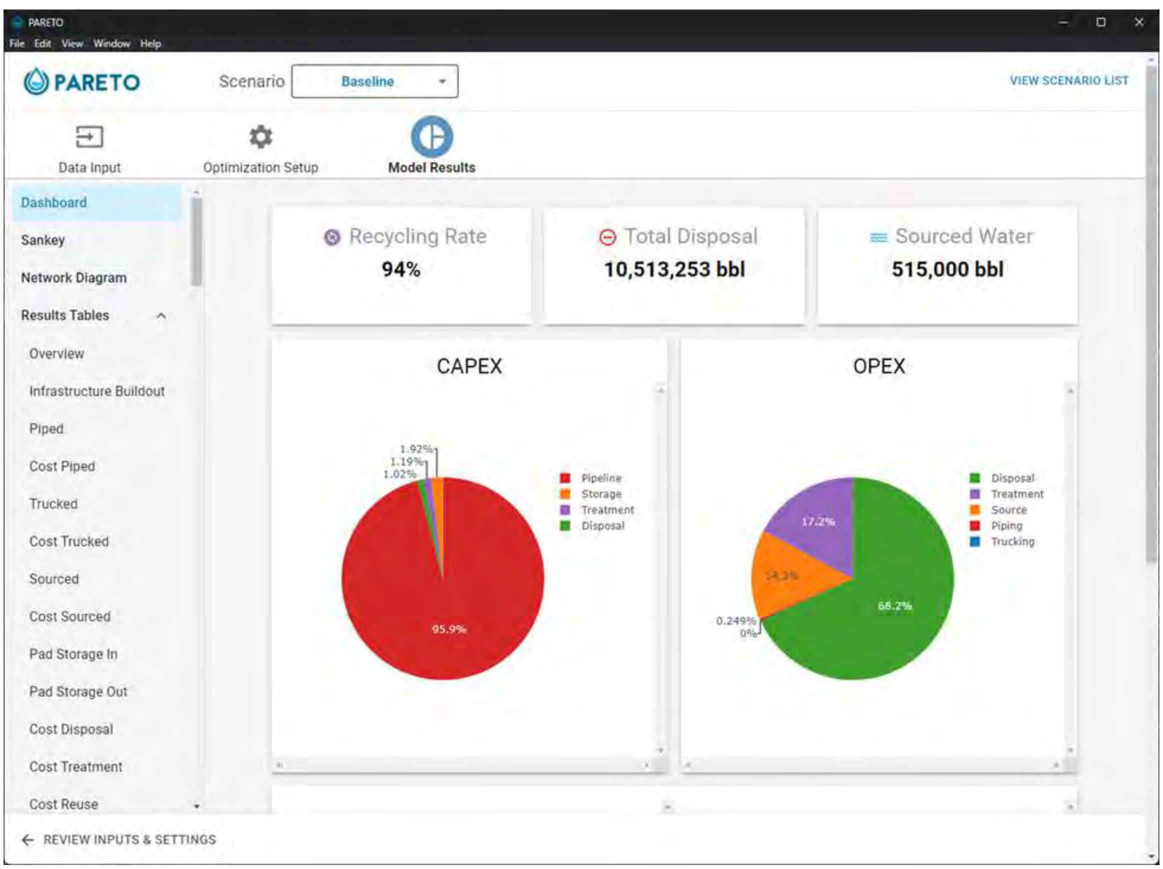

Figure 18: PARETO UI Model Results screen.

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

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

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

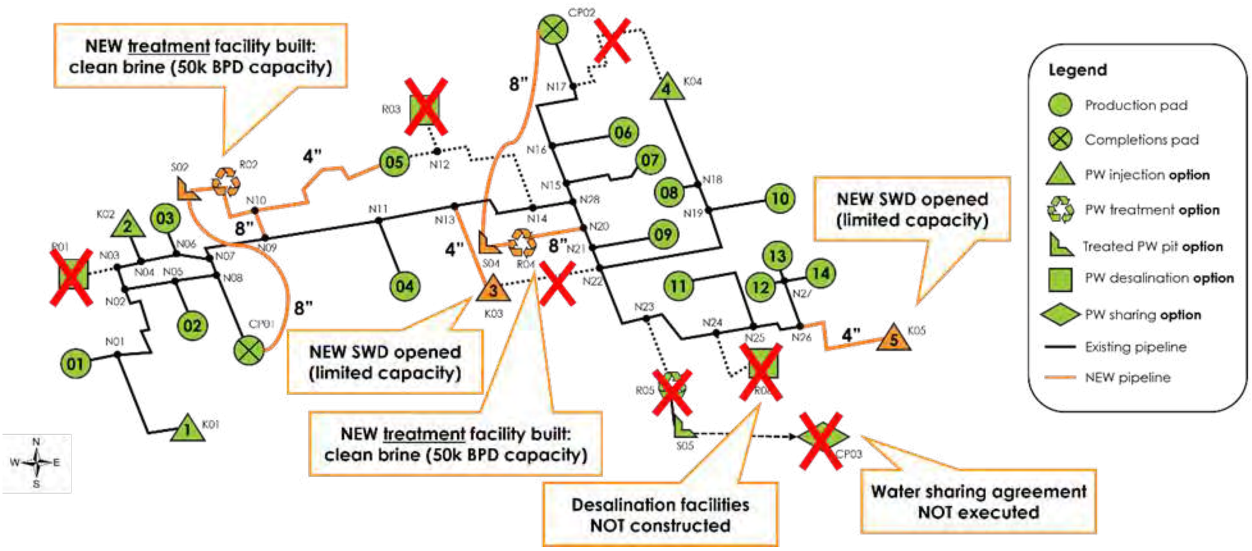

Figure 19: Strategic Permian case study – results.

8.5 Advanced Features

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

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

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

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

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

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

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

8.6 AquaShare and AquaTrade

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

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

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

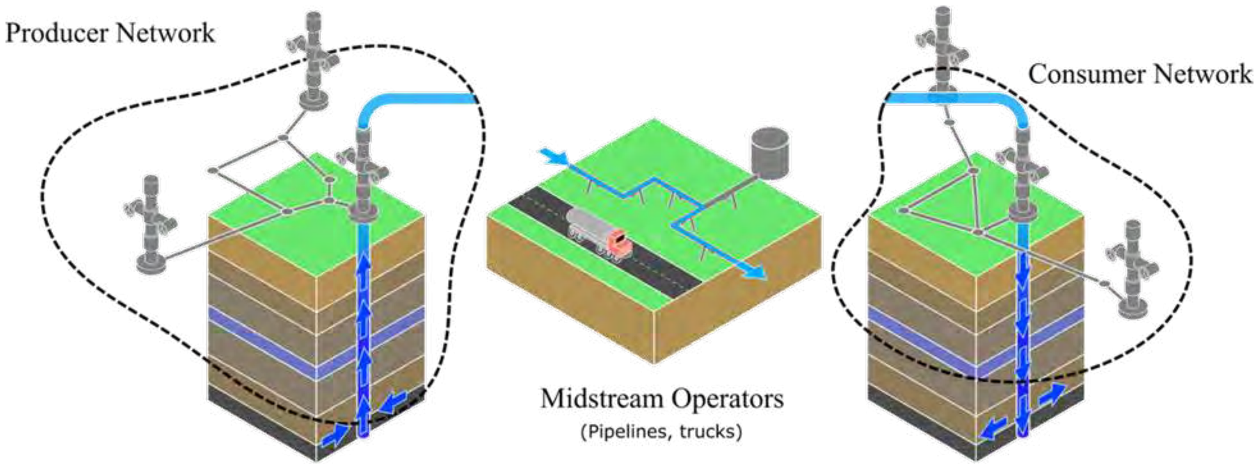

Figure 20: Schematic representation of two operator networks with a midstream operator providing transportation infrastructure. O&G operators have adopted practices of PW exchange for mutual benefit.

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

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

8.6.1 Aqua^{Share}

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

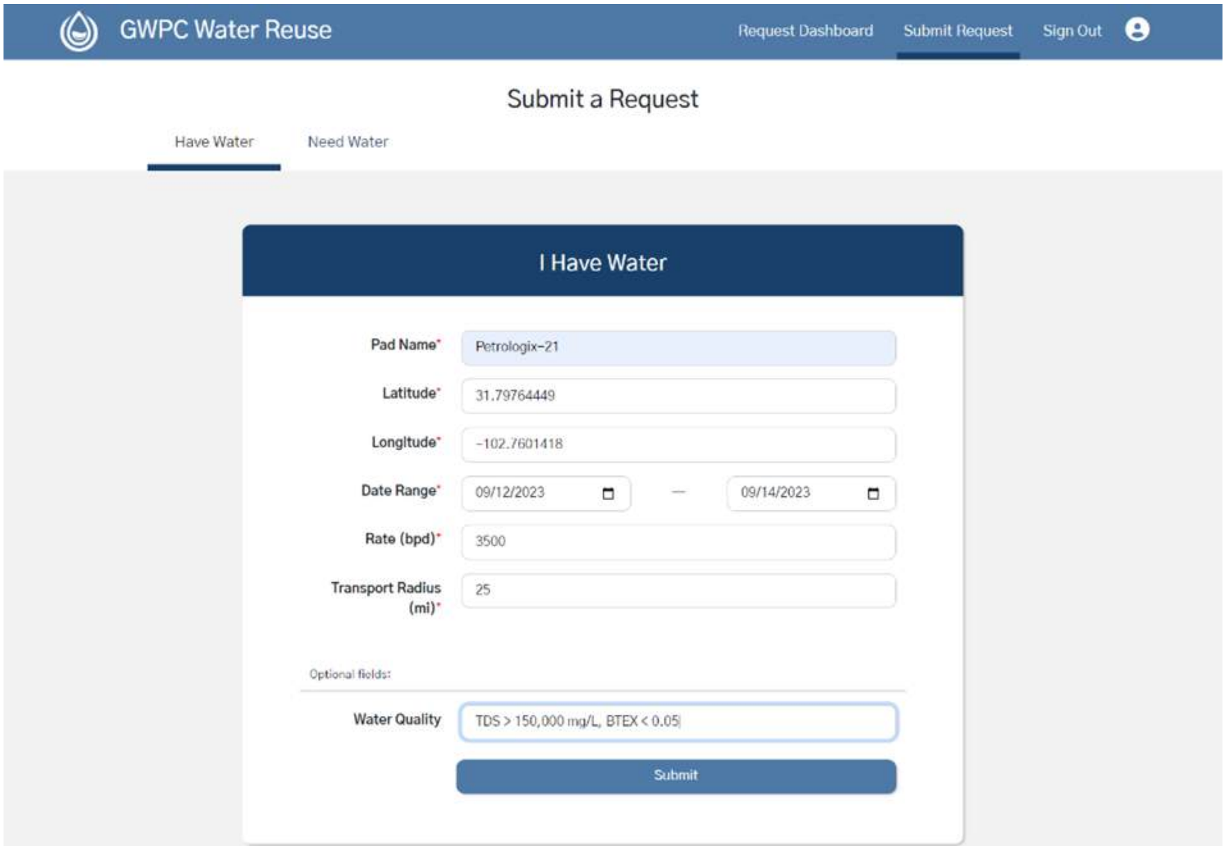

Figure 21: AquaShare request entry form. Part of a functional prototype.

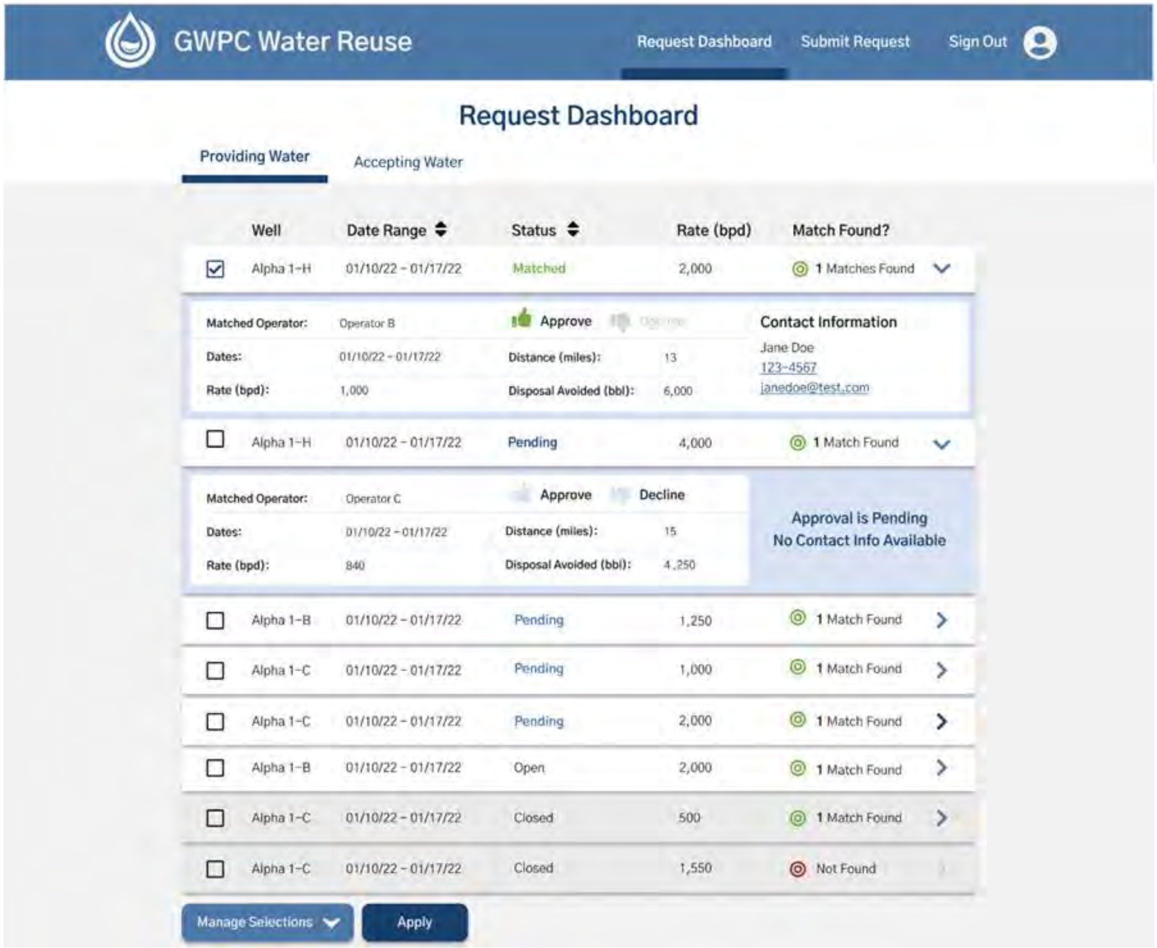

Figure 22: AquaShare match dashboard. Part of a functional prototype.

8.6.2 Aqua$^{\text{Trade}}$

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

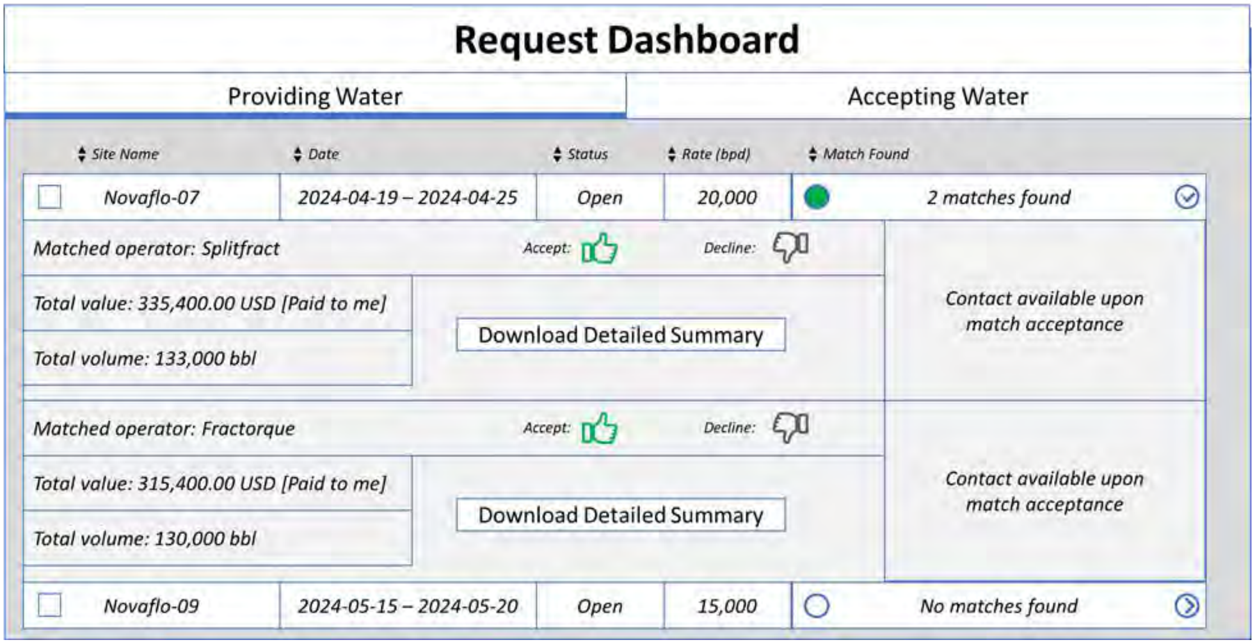

Figure 23: A mock-up of the proposed AquaTrade request dashboard.

8.7 Stakeholder Engagement and Community Outreach

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

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

8.8 Disclaimer

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

9 ADDENDUM
Volumetrics: Origin, Quantity, Forecast and Management

9.1 Area of study

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

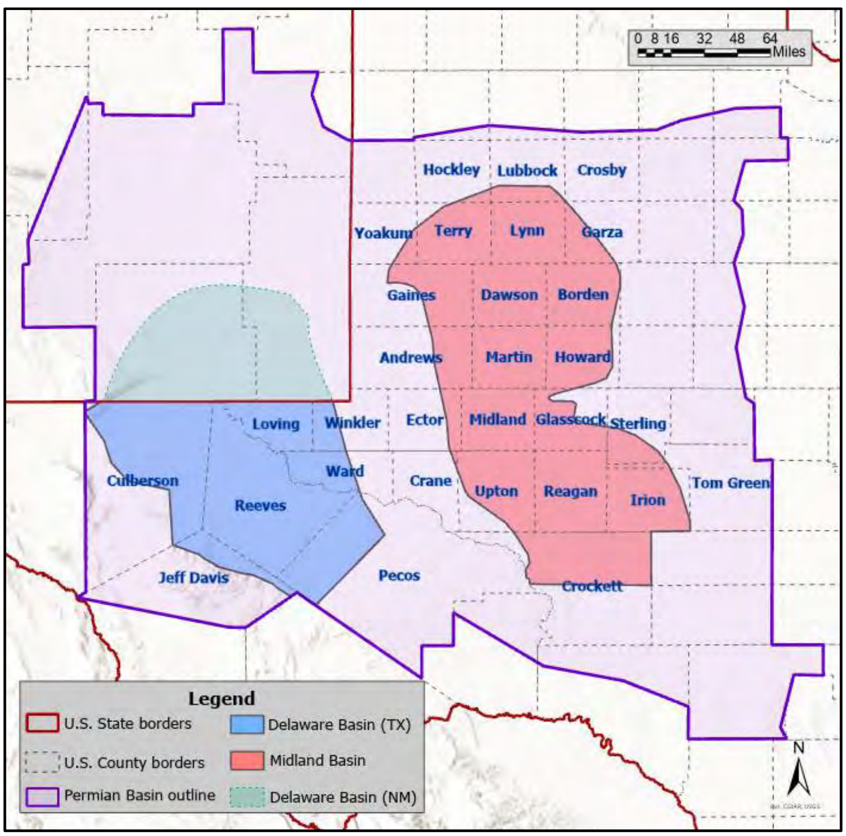

Figure 24. 2D map showing the Delaware Basin and Midland Basin, 2 sub-basins of the Permian Basin, along with the intersecting Texas counties.

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

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

9.2 Dataset for Produced Water

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

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

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

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

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

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

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

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

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

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

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

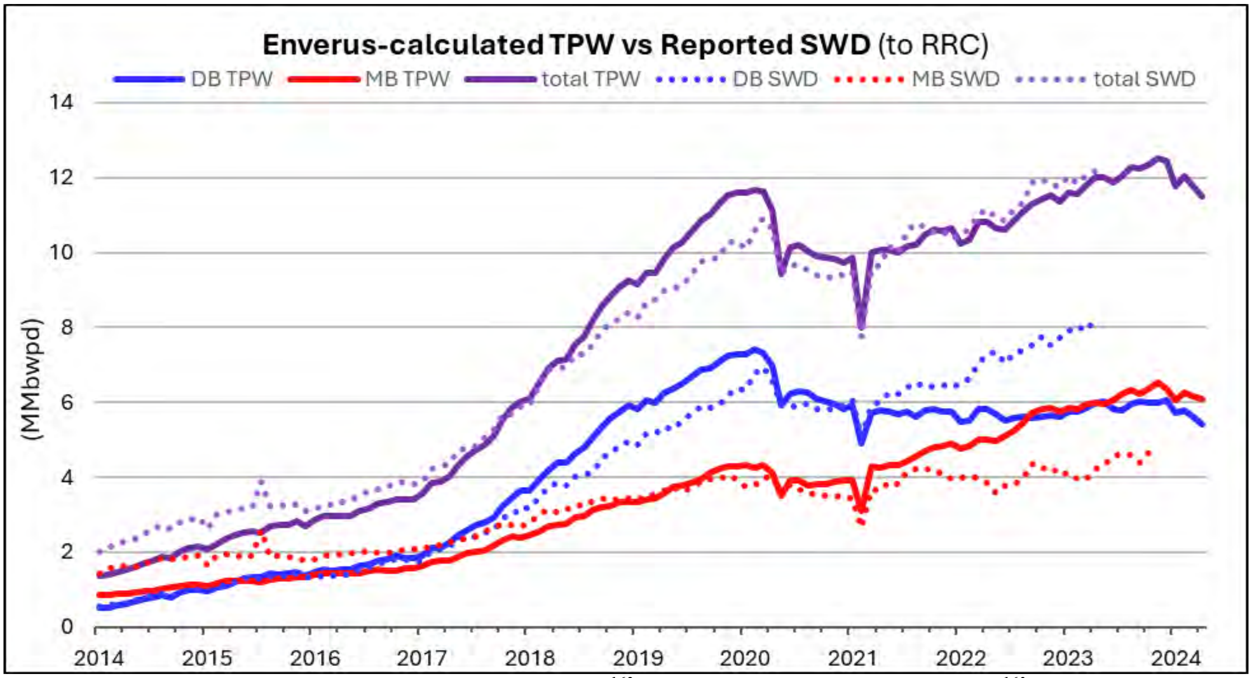

Figure 25. Enverus-calculated tight-oil produced water (TPW)[162] vs reported saltwater disposal (SWD)[163]

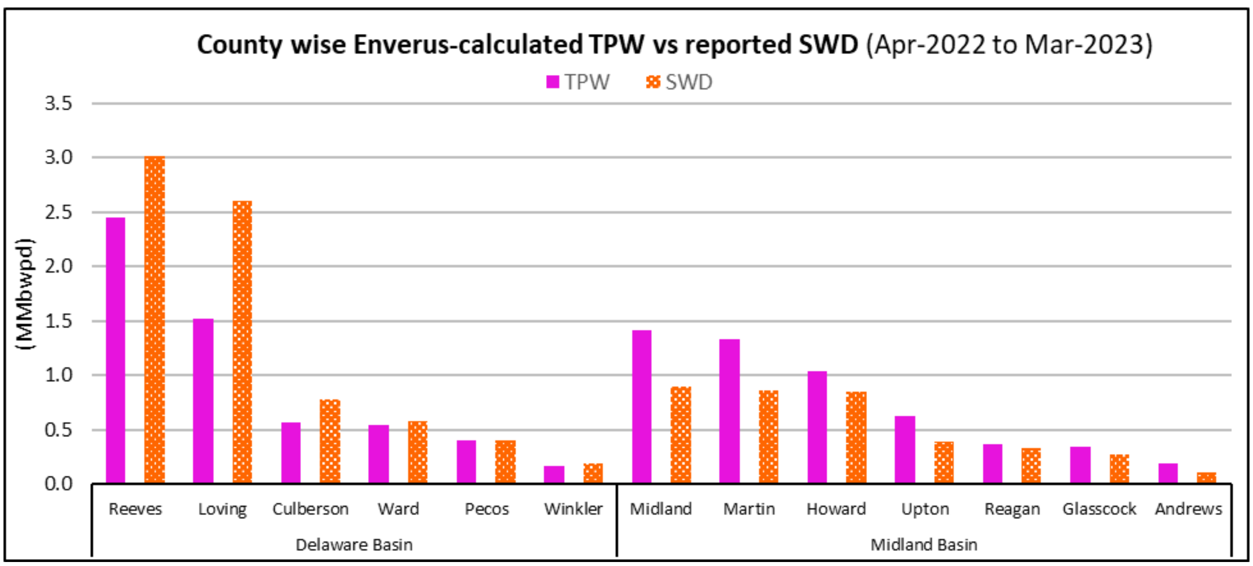

Figure 26. County wise Enverus-calculated tight-oil produced water (TPW)[164] vs reported saltwater disposal (SWD)[165], Apr-2022 to Mar-2023. The major TPW/SWD counties are displayed.

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

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

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

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

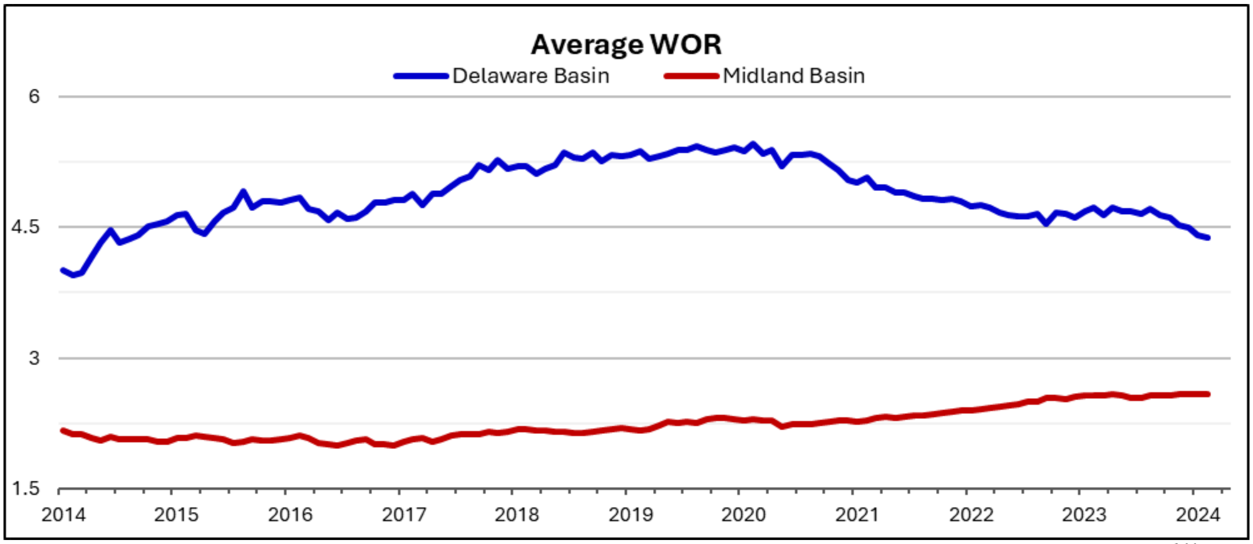

Figure 27. Average basin-wide monthly water-oil ratios (WOR) from tight-oil formations in West Texas, 2014-2024[166]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

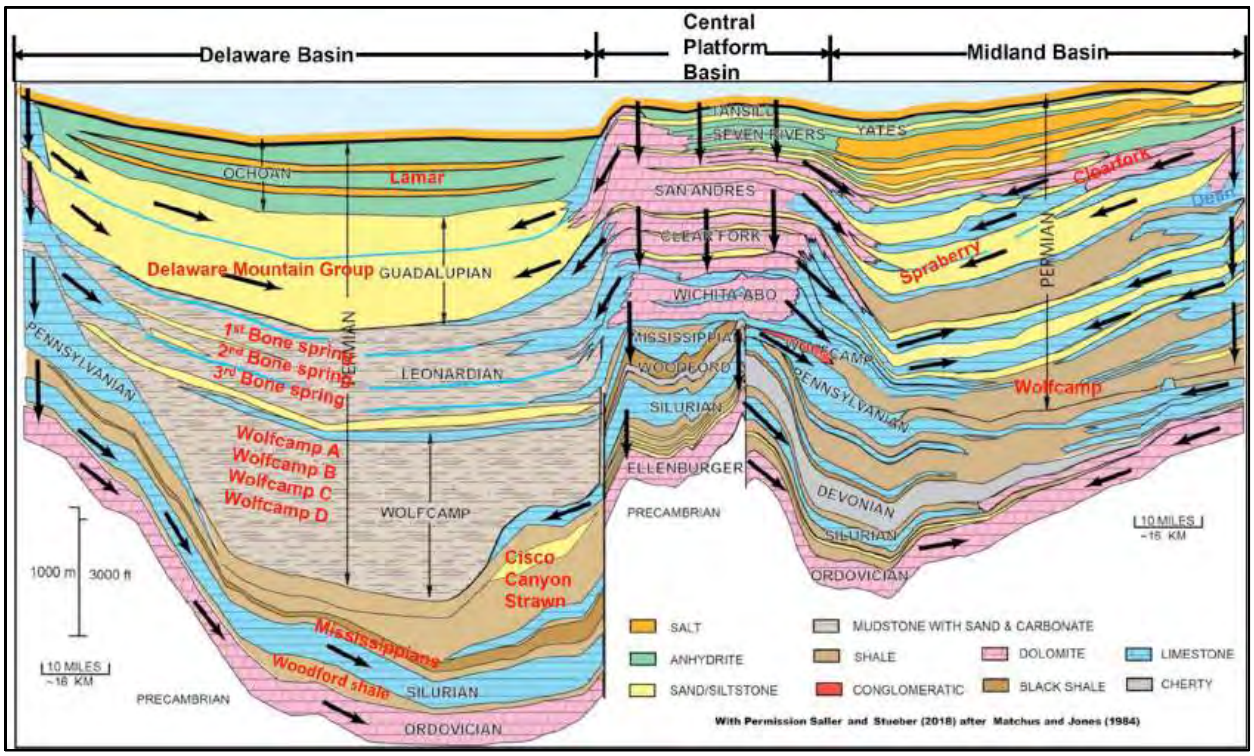

Figure 28. A cross-section of the Delaware Basin, Central Platform Basin, and Midland Basins: three sub-basins of the Permian Basin, displaying the geological intervals considered in our study[175]. We only considered the intervals within the Delaware and the Midland.

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

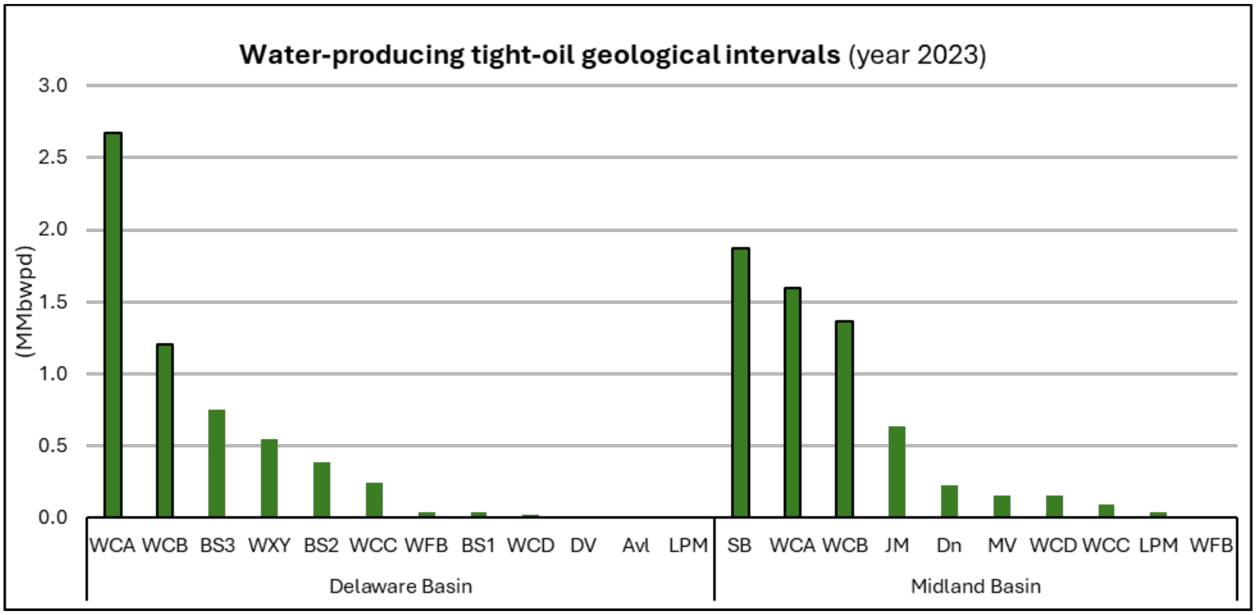

Figure 29. Water production from the water-producing tight-oil geological intervals considered by TxPWC in 2023[176].

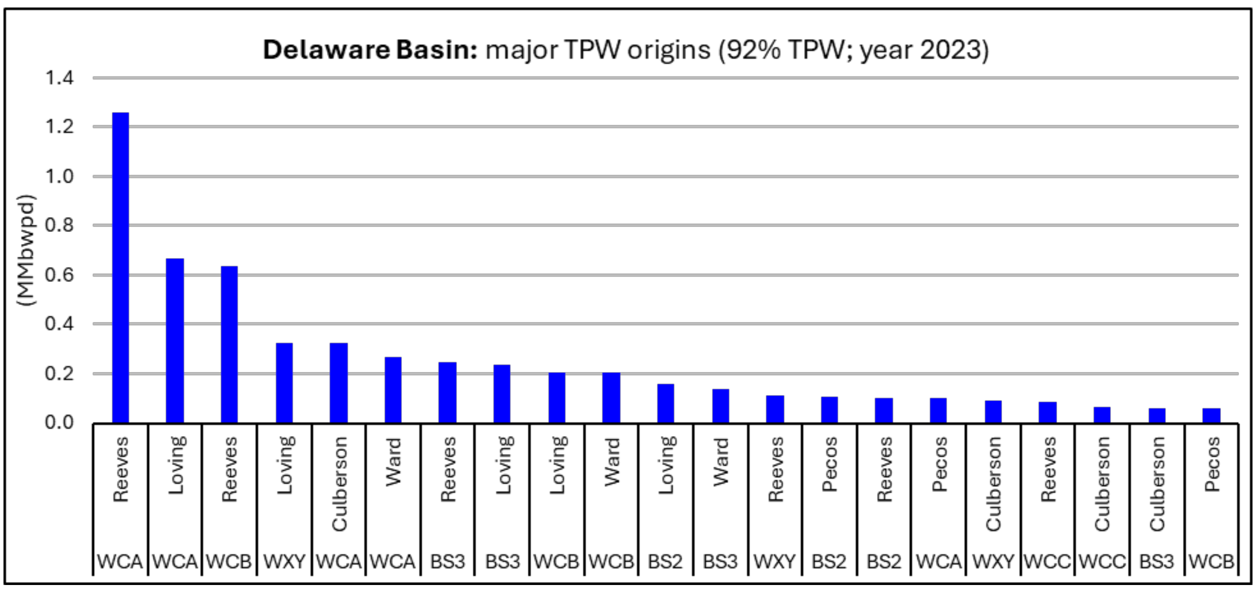

Figure 30. Water production from the major origins of tight-oil produced water (TPW) within the Delaware Basin in 2023. Geological interval and county are shown for each origin, with intervals abbreviated according to Table 7.

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

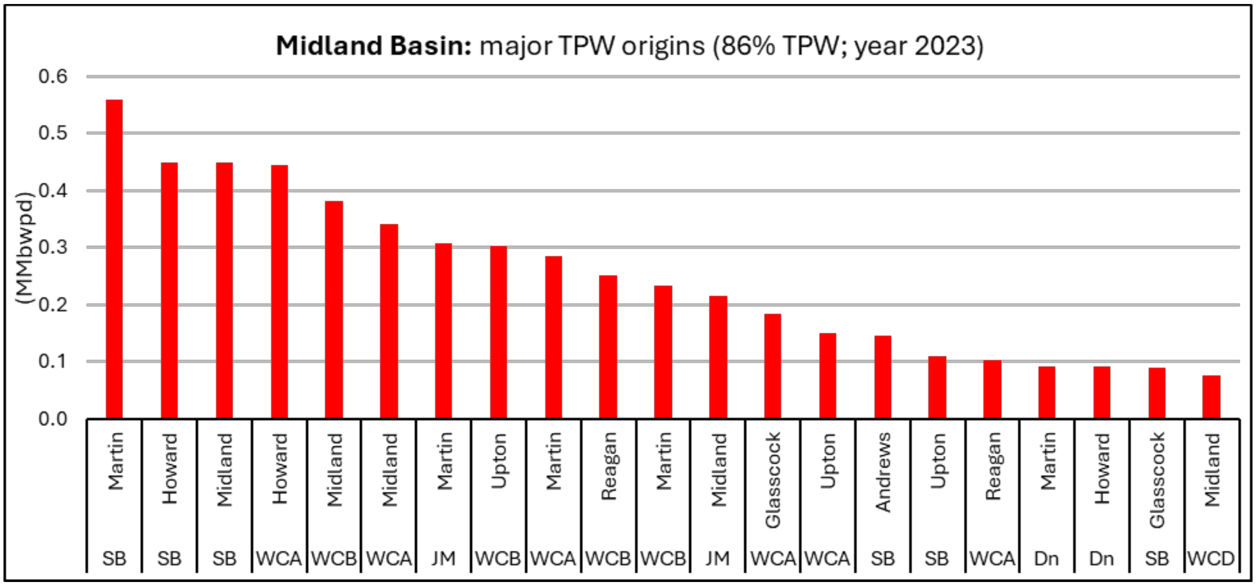

Figure 31. Water production from the major origins of tight-oil produced water (TPW) within the Midland Basin in 2023. Geological interval and county are shown for each origin, with intervals abbreviated according to Table 7.

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

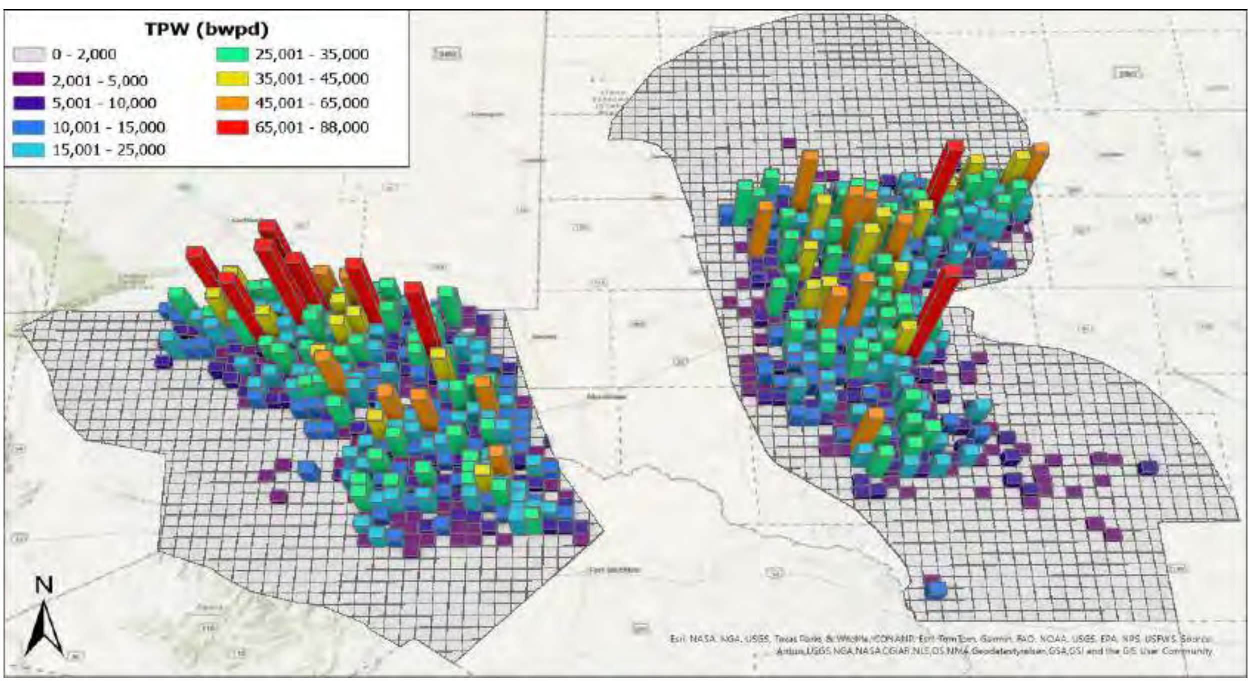

Figure 32. 3D map of tight-oil produced water (TPW) in 9-mi2 subdivisions of the Delaware and Midland basins for the year 2023.

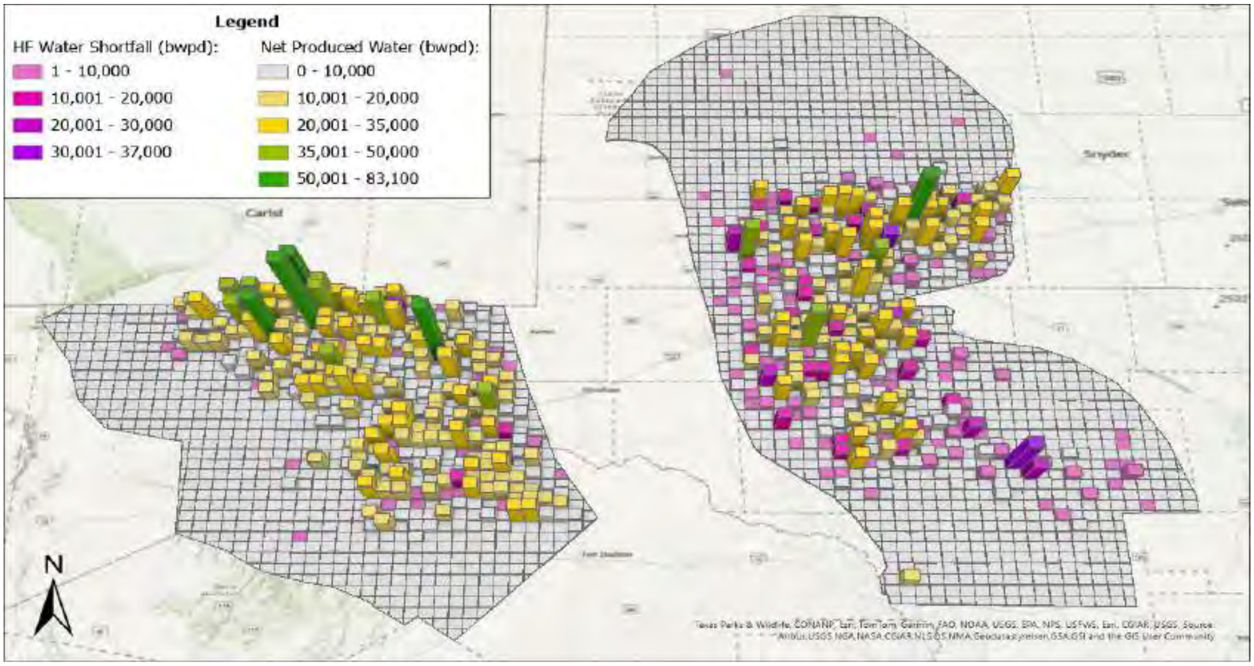

Figure 33. Net produced water (NPW) with Hydraulic Fracturing Reuse (2023). This map assumes that in each 9-mi2 subdivision, the largest possible volume of tight-oil produced water (TPW) is used for hydraulic fracturing (HF). It is determined accordingly whether a subdivision has an excess volume of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

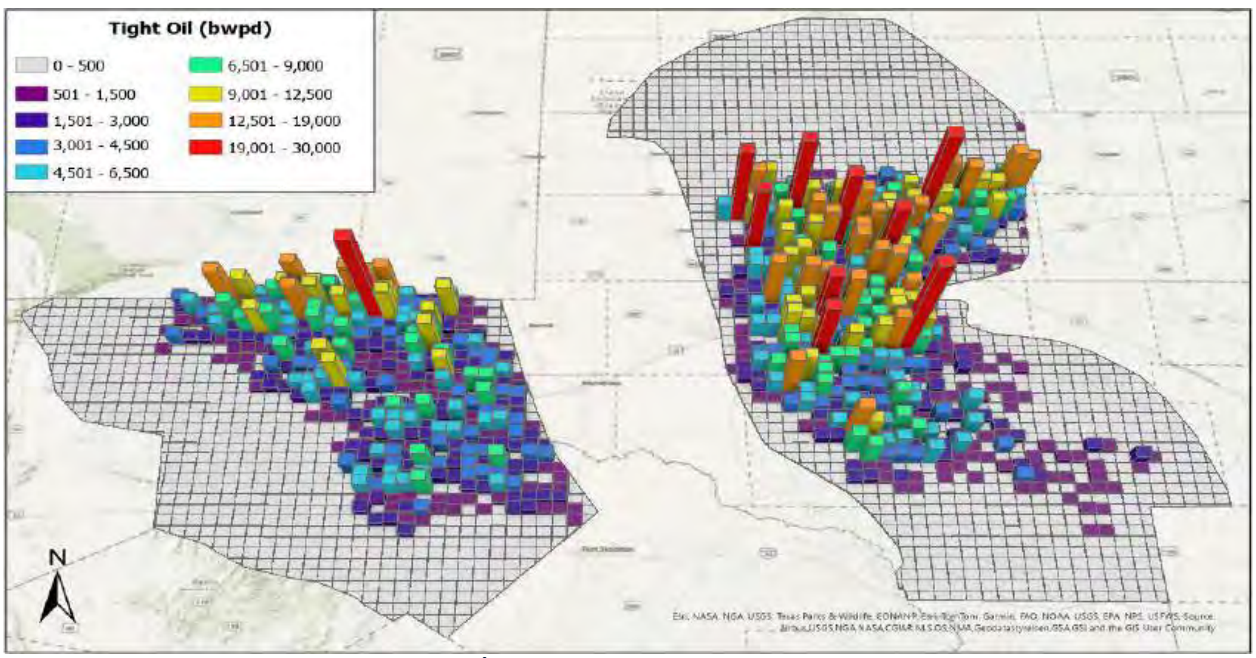

Figure 34. 3D map of tight oil production in 9-mi² subdivisions of the Delaware and Midland basins for the year 2023.

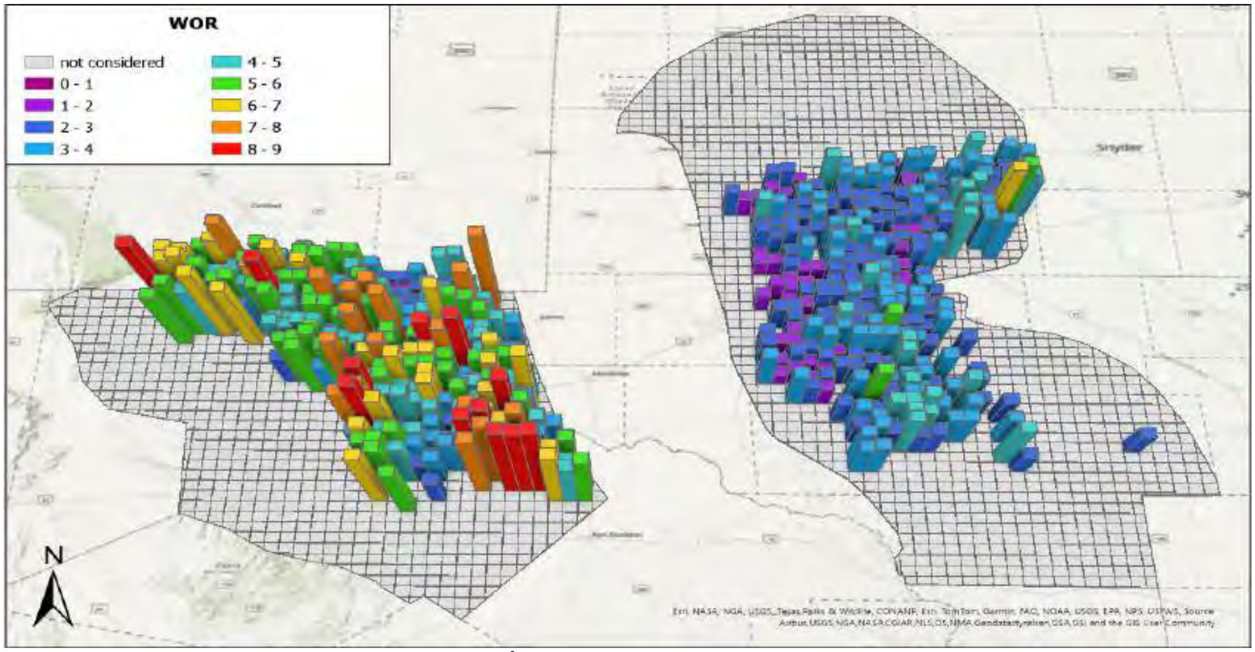

Figure 35. 3D map of water-oil ratio (WOR) in 9-mi² subdivisions for 2023: (WOR<=9) and (TPW>=5000 bwpd). Subdivisions with WOR>9 only represented 4.3% of the tight-oil produced water (TPW). Subdivisions producing less than 6,000 bwpd represented 7.2% of the TPW. The areas with high WOR produce minimal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

9.4 Effect of Lateral Distance on Hydraulic Fracturing and Production

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

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

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

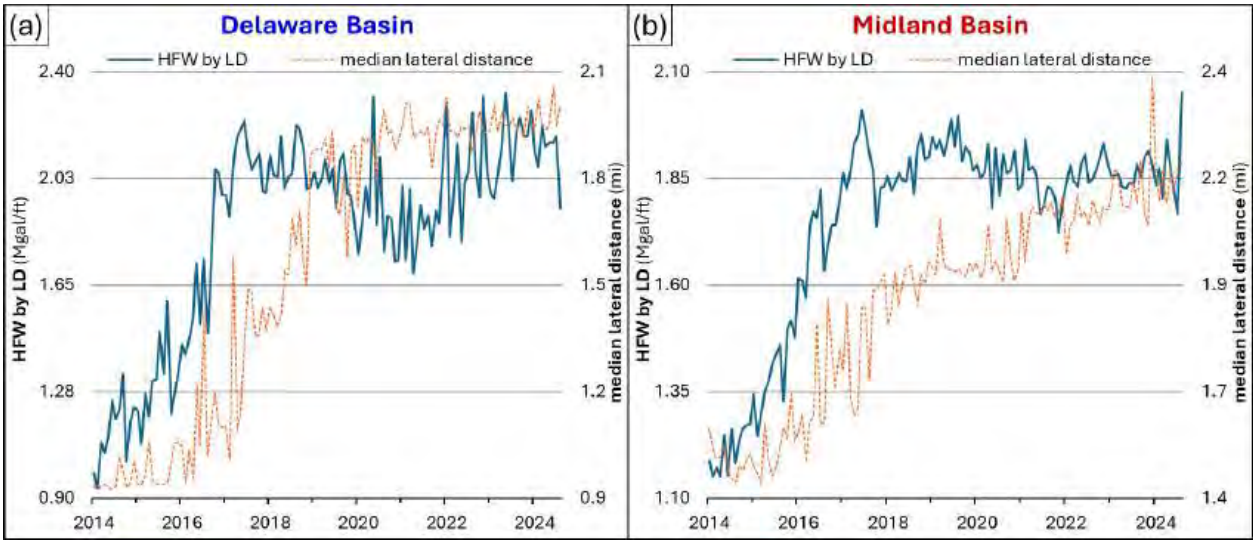

Figure 36. Monthly change in median lateral distance and in hydraulic fracturing water use by lateral distance (HFW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that were completed in said month.

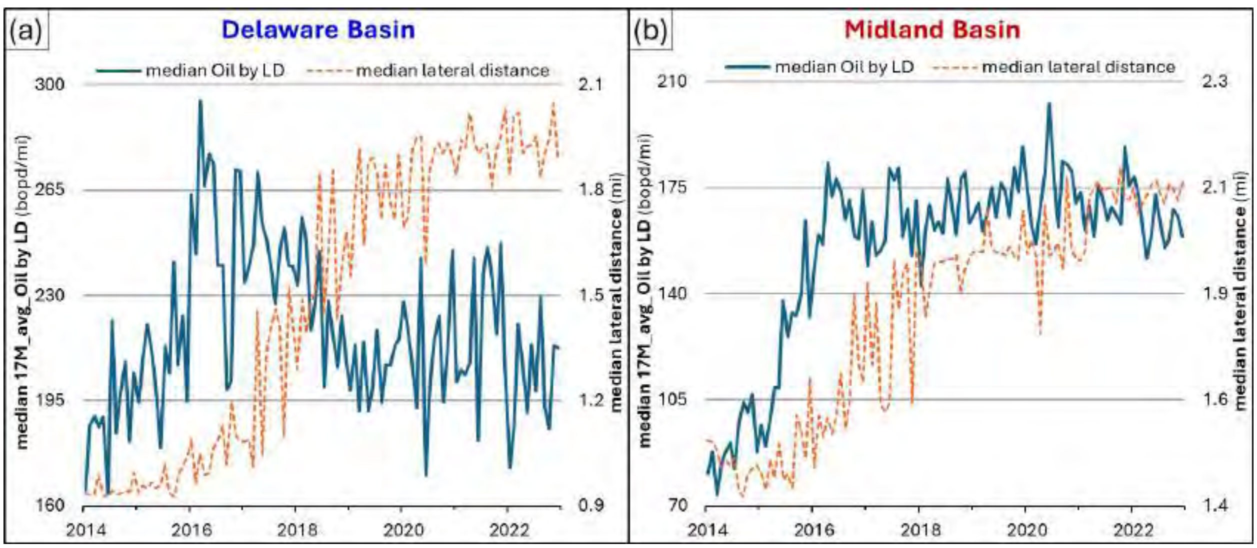

Figure 37. Monthly change in median lateral distance and in the Oil average of the first 17 producing months divided by lateral distance (median 17M_avg_PW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that started producing in said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

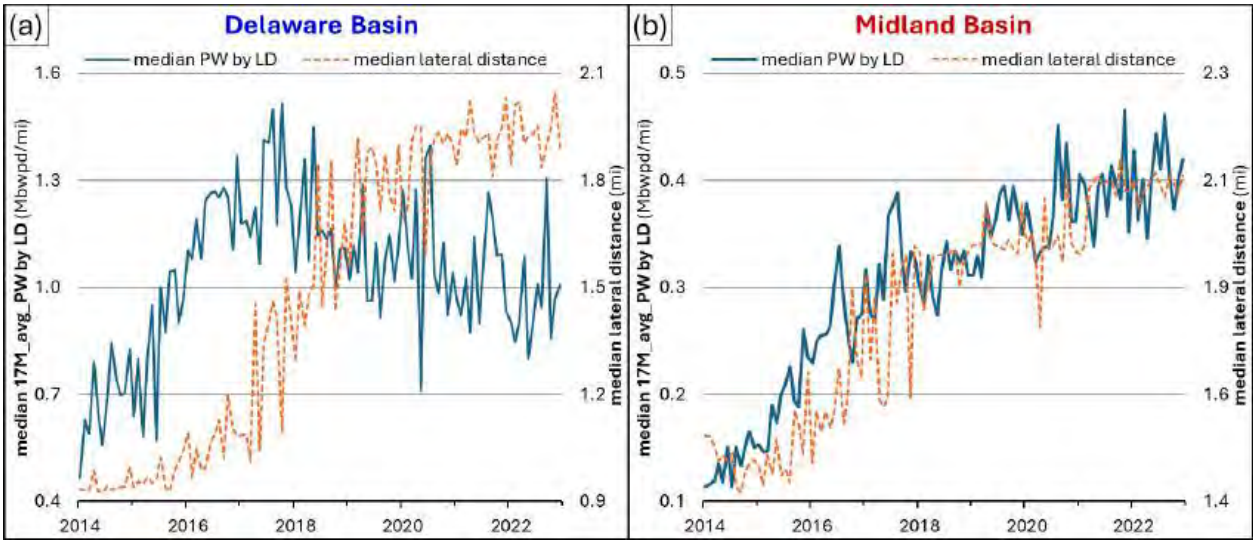

Figure 38. Monthly change in median lateral distance and in the PW average of the first 17 producing months divided by lateral distance (median 17M_avg_PW by LD): (a) the Delaware Basin; (b) the Midland Basin. The two values shown for a specific month represent the wells that started producing in said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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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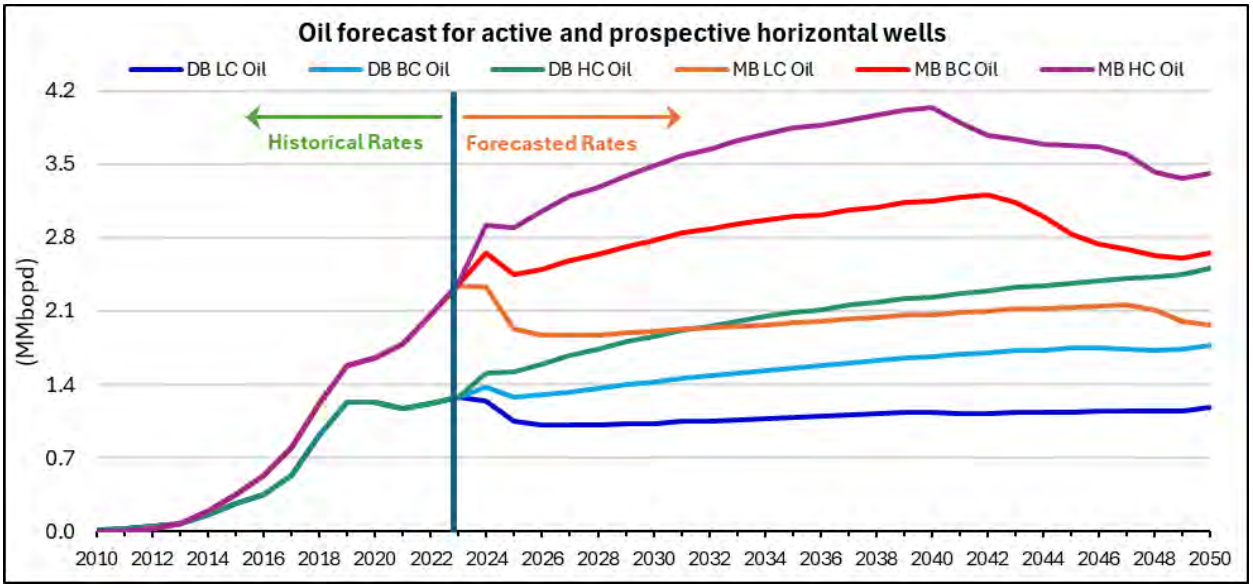

Figure 39. Forecast of Oil Production from active and future-producing horizontal wells, for both the Delaware Basin (DB) and Midland Basin (MB). Three cases are considered for each basin: low case (LC), base case (BC), and high case (HC).

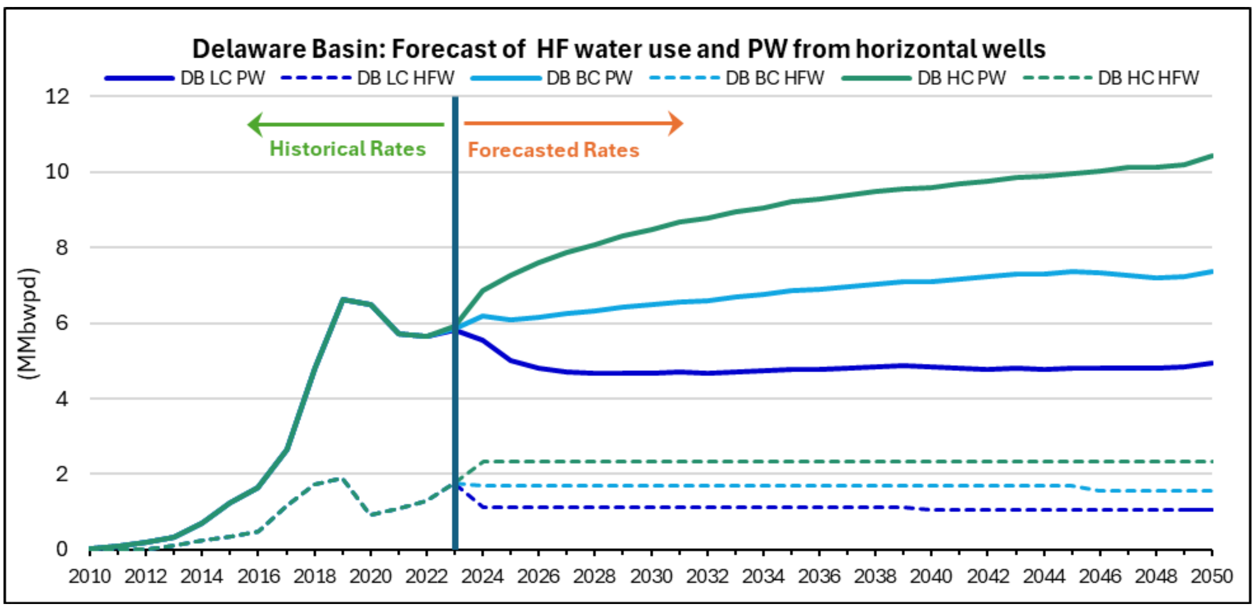

Figure 40. Forecast of produced water (PW) from active and future-producing horizontal wells, and hydraulic fracturing water use (HFW), for the Delaware Basin (DB). Three cases are considered for each basin: low case (LC), base case (BC), and high case (HC).

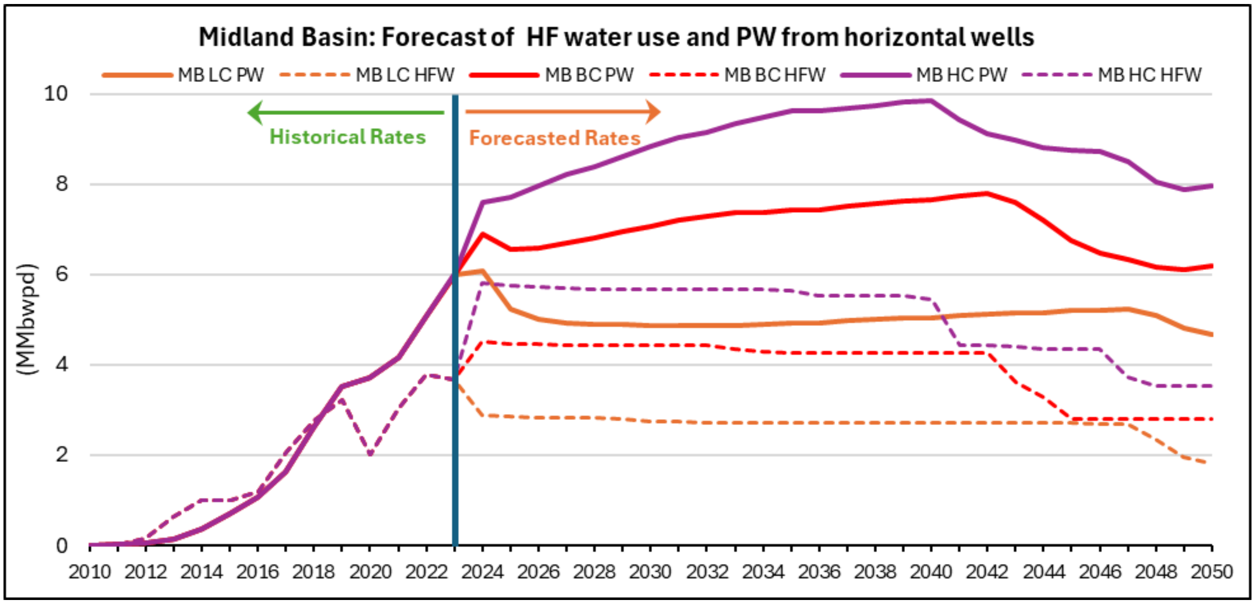

Figure 41. Forecast of produced water (PW) from active and future-producing horizontal wells, and hydraulic fracturing water use (HFW), for the Midland Basin (MB). Three cases are considered for each basin: low case (LC), base case (BC) and high case (HC).

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

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

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

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

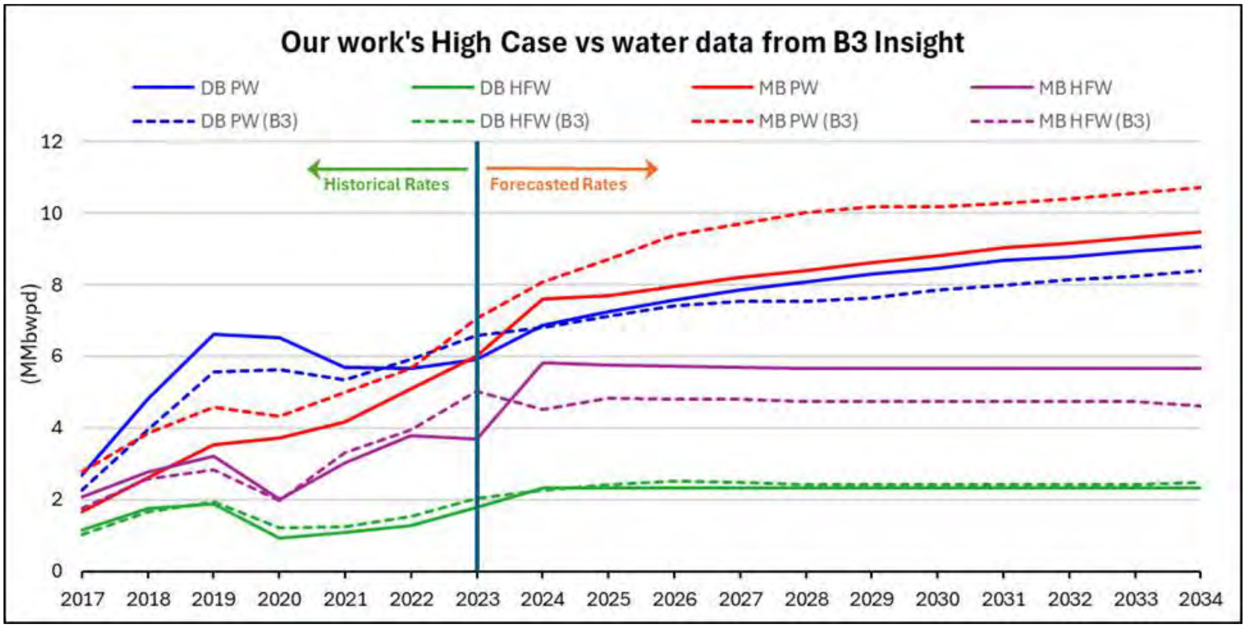

Figure 42. Comparison between our work's high case (HC) for the Delaware Basin (DB) and the Midland Basin (MB), and B3 Insight[188], concerning produced water (PW) and hydraulic fracturing water use (HFW). B3 Insight is referred to as B3 in this graph.

9.6 Suggested Water Management for Irrigation Shortages

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

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

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

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

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

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

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

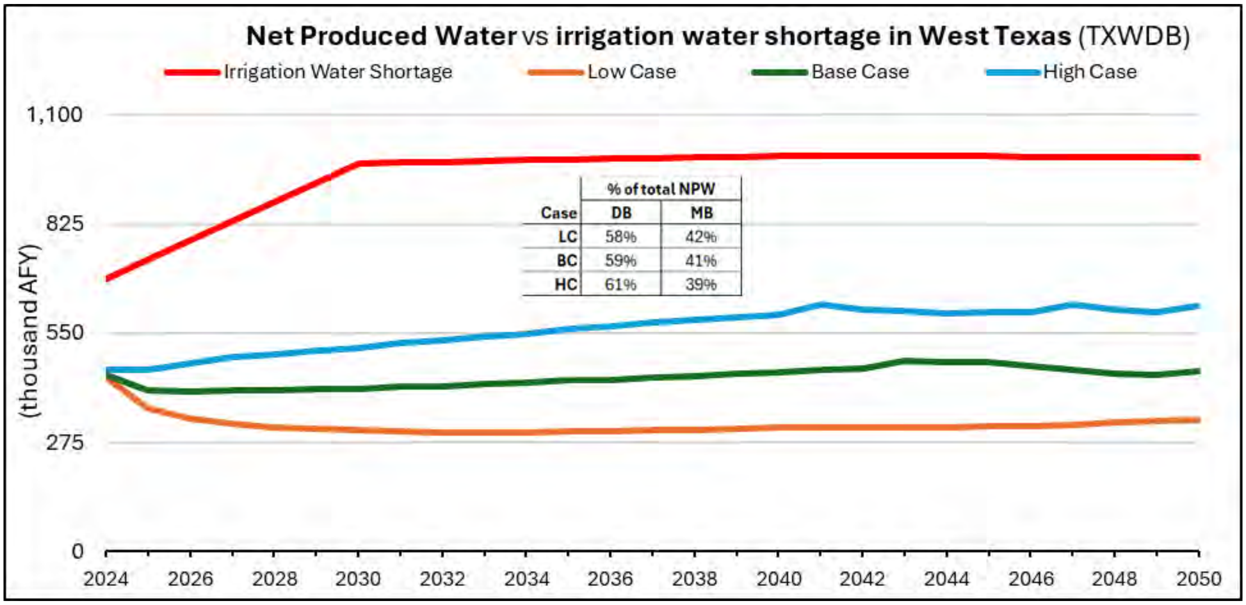

Figure 43. Net Produced Water (NPW) vs Irrigation Water Shortage through 2050. Three cases are considered for production: Low Case (LC), Base Case (BC) and High Case (HC). For each case, NPW is calculated by subtracting the PW recycled in HF from water production and the contribution of each of the Delaware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

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

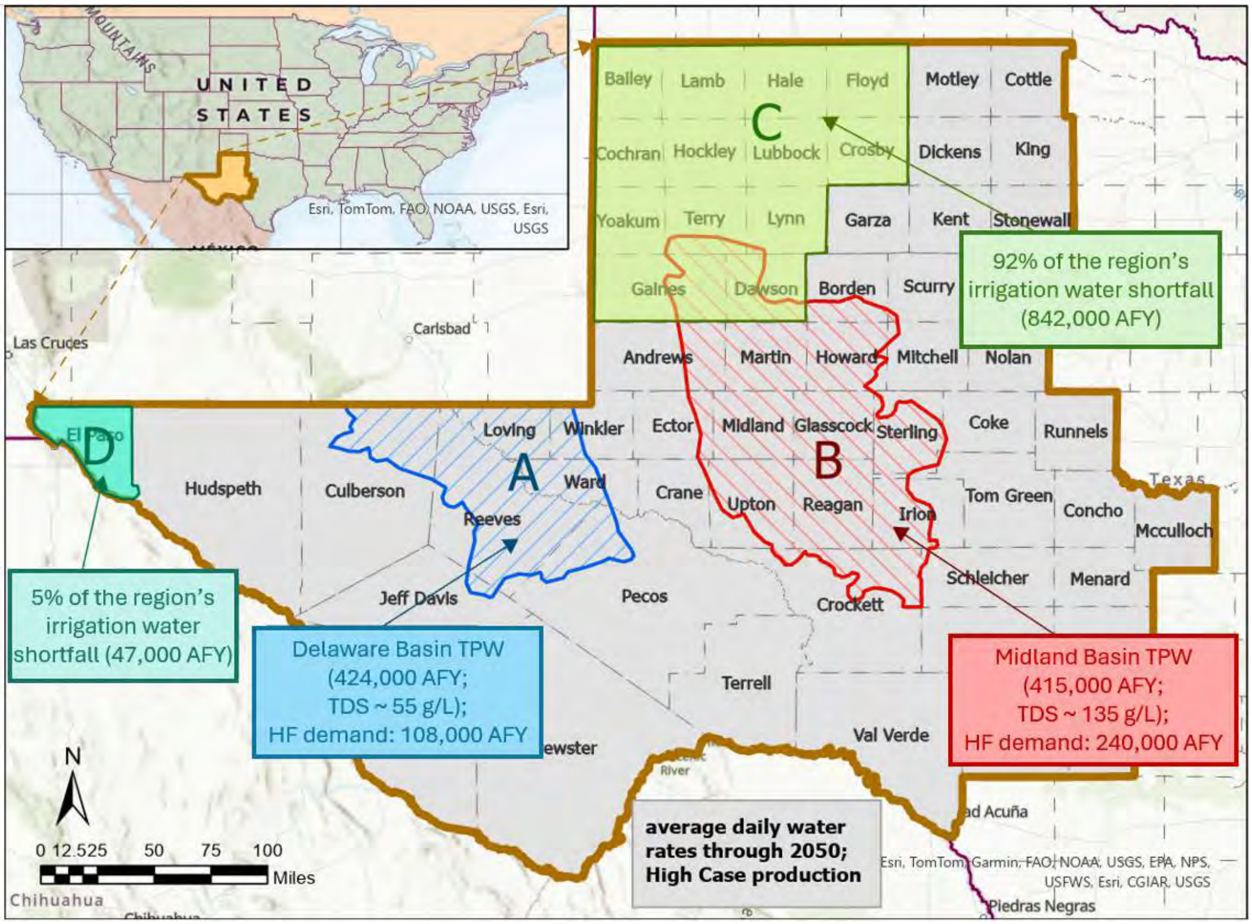

Figure 44. 2D map of the West Texas region showing the geographical extents of the Delaware Basin (area A), the Midland Basin (area B) and the areas with major irrigation water shortfall through 2050 (C and D). The High Case production is considered. The geographical extents are determined from geologic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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

9.7 Volumetrics Appendices

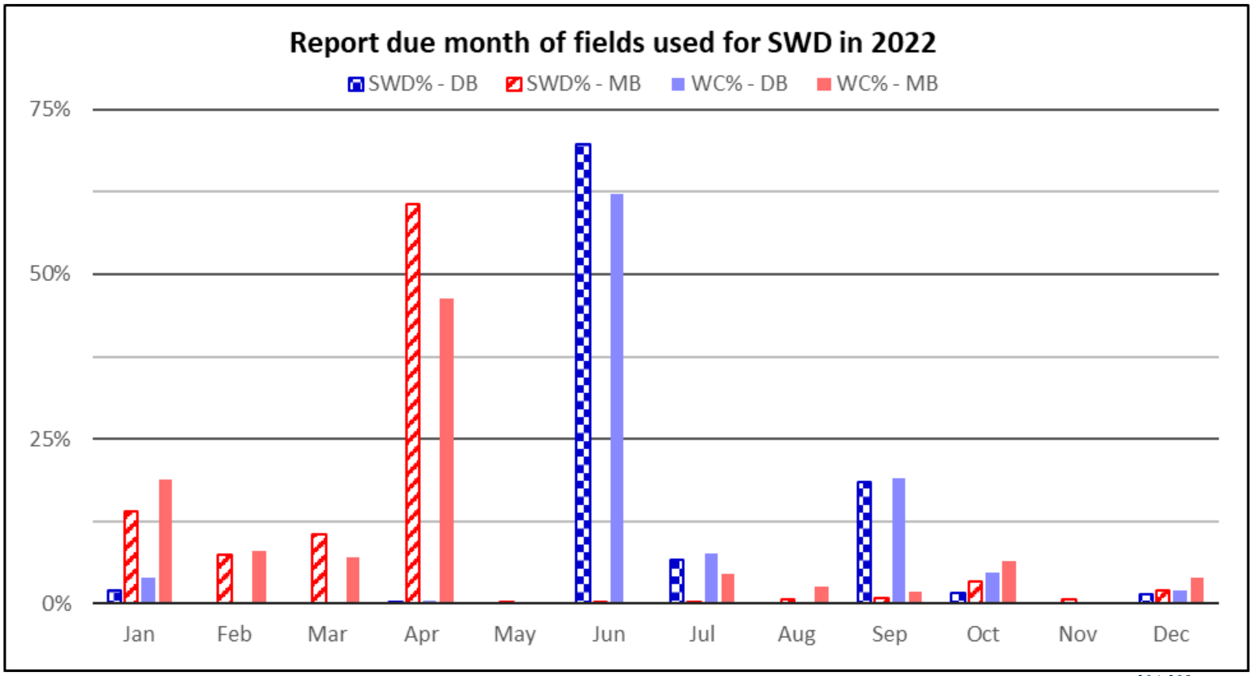

Figure 0.1. Due Months of field used for SWD throughout the Delaware Basin (DB) and Midland Basin (MB) in 2022[204 205]*. WC: Well Count.*

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

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

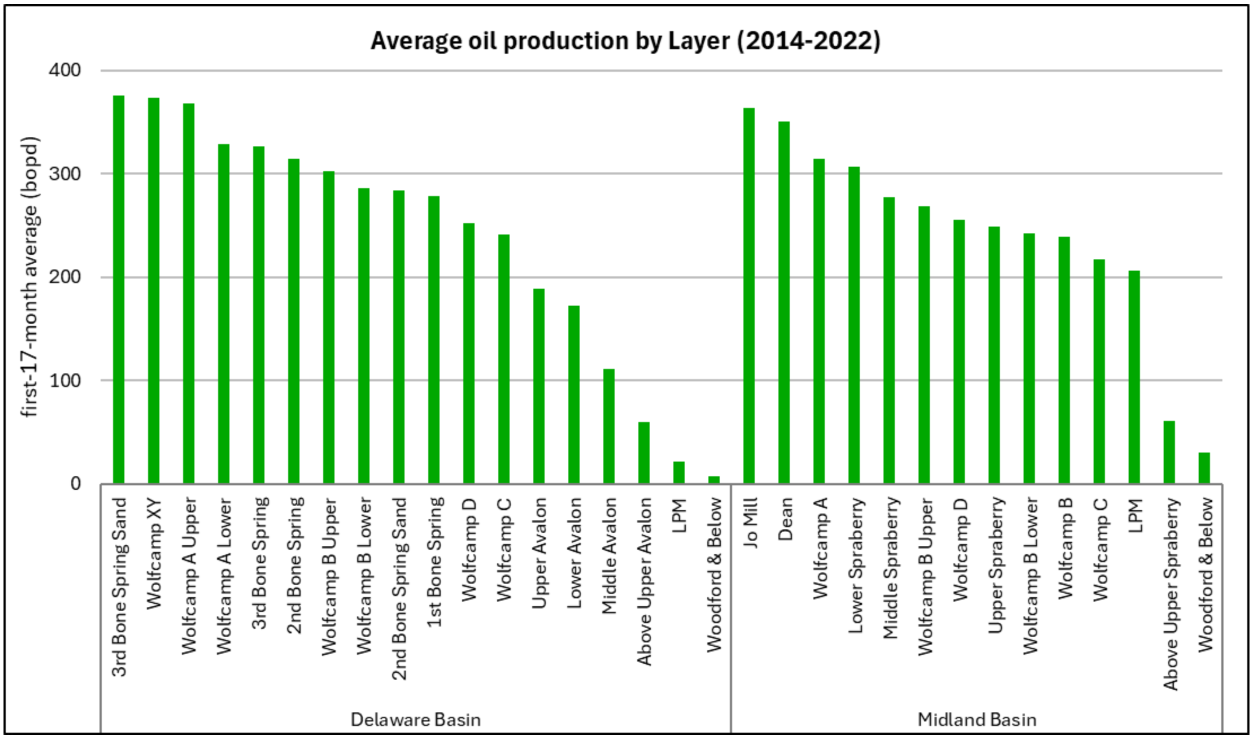

Figure 0.2. Average oil production by Layer (2014-2022): first-17-month average.

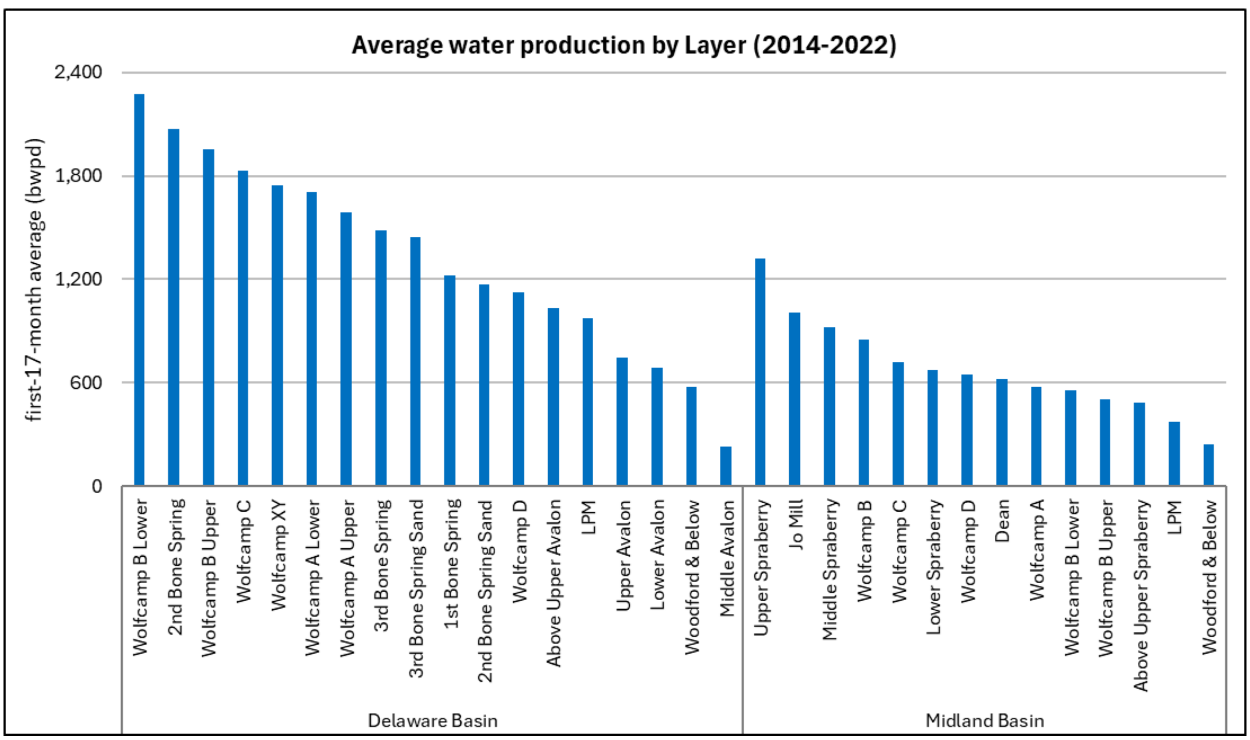

Figure 0.3. Average water production by Layer (2014-2022): first-17-month average.

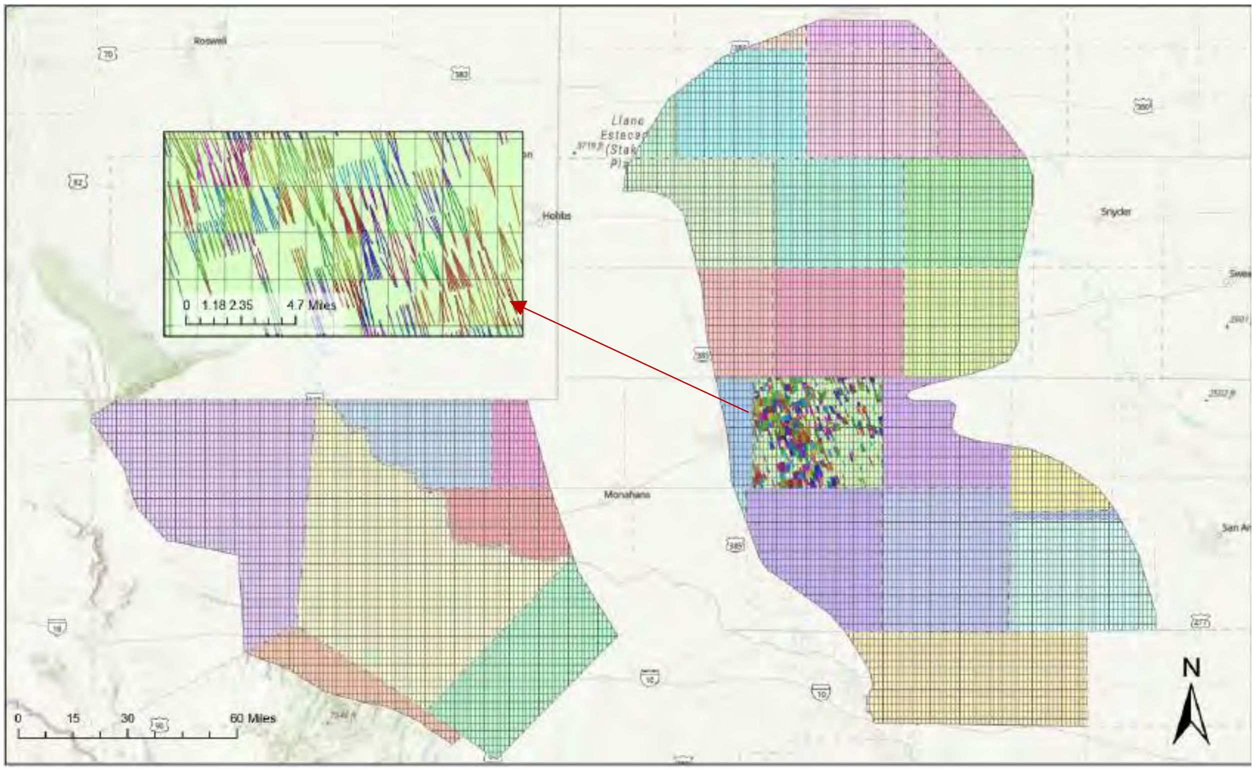

Figure 0.4. Basis for selecting the maximum lateral well density per Layer for a county: herein shown the selection for Midland County (138 ft/acre in the geographical extent of the Spraberry). Only displayed are the laterals of the wells producing from the Lower Spraberry and intersecting with Midland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

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

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

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

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

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

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

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

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

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

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

9.8 Nomenclature

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

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

Texas Permian Future Generations

Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

EXHIBIT 3

Texas Produced Water Consortium

Produced Water Treatment Pilot Testing: Water Quality Report

April 17, 2026

Table of Contents

List of Tables

List of Figures

List of Appendices (see separate spreadsheet file)

List of Abbreviations

CB	clean brine
DAF	dissolved air floatation
DPW	desalinated produced water
ED	electrodialysis
GAC	granular activated carbon
MCL	maximum contaminant limit
MD	membrane distillation
MDL	method detection limit
MF	microfiltration
NORM	naturally occurring radioactive material
NOEC	no observable effect concentration
ORP	oxidation-reduction potential
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PDPW	polished desalinated produced water
PW	produced water
REE	rare earth elements
RO	reverse osmosis
TDS	total dissolved solids
TOC	total organic carbon
TOX	total organic halides
TPH	total petroleum hydrocarbons
TPW	treated produced water
TxPWC	Texas Produced Water Consortium
UF	ultrafiltration
WET	whole effluent toxicity

Acknowledgements

The Texas Produced Water Consortium (TxPWC) was established at Texas Tech University in 2021 by Senate Bill 601 of the 87th Regular Session of the Texas Legislature to study the beneficial reuse of produced water. TxPWC is constituted by a wide and diverse spectrum of members representing all facets of water in industry, the environment, and society, and TxPWC would not exist without the support, feedback, and expertise of our members and advisory boards. As such, this report is a synthesis from a diverse group and does not necessarily represent the views of any individual or entity. TxPWC would also like to thank the leadership of the State of Texas for their continued dedication to future energy and water resource planning for our State.

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Executive Summary

With over 20 million barrels per day (*i.e.*,~1M acre-feet/year or ~1B gal/day) of produced water (PW) disposal in the Permian Basin, there is a great opportunity for beneficial reuse of treated produced water, and the Texas Produced Water Consortium (TxPWC) has collaborated with a diverse membership of stakeholders from the upstream industry, midstream industry, technology developers, landowners, agriculturalists, environmental defense, groundwater conservation districts, industrial water users, river authorities, municipal water suppliers, public health professionals, economists, academicians, and regulators to study technical aspects of the treatment of produced water for beneficial reuse such as stream discharge or land application (*e.g.*, crop irrigation or rangeland rehabilitation). The goal of this effort is to study water quality improvements through the three general stages of pilot tested treatment systems on real produced water (pretreatment, desalination [including distillation, pressure-driven membrane, and hybrid], and polishing/post-treatment) and the corresponding four general water types. This report highlights observations from the analyses of 60 samples from five pilot testing projects conducted in 2024-2025, including 17 raw produced water (PW), 13 clean brine (CB) or pre-treated PW (TPW), 12 desalinated produced water (DPW), and 18 polished DPW (PDPW). These samples were analyzed by Eurofins' laboratories (NELAP-certified). To our knowledge, this is the most extensive water quality analysis of PDPW to date. Overall, the pilot treatment systems were effective at removing >99% of salinity, organics, and radioactivity.

For these samples, 582 of the 765 analytes (*i.e.*, 76%) were not detected in concentrations above the method detection limits (MDLs), including chemical classes not expected to be present (*e.g.*, PCBs, PFAS, most herbicides and pesticides, *etc.*).

Generally, with average PW and TPW salinities of approximately 120,000 mg/L total dissolved solids (TDS), the thermal and membrane-based desalination pilot tests successfully removed bulk salinity to yield an average DPW salinity of 317 mg/L TDS, which is suitable for most beneficial reuse applications (*e.g.*, streamflow augmentation, rangeland rehabilitation, and crop irrigation). With respect to trace constituents, pilot testing of post-desalination polishing demonstrated effective removal of key indicators such as benzene, glutaraldehyde, gross alpha, methanol, naphthalene, and xylenes to below detection limits. At the time of this writing, TCEQ has not yet released draft permits for Surface Discharge or Land Application, so for the sake of performing an evaluation of water quality, PDPW quality was compared with drinking water limits. Of the 101 TCEQ drinking water limits, 76 were comparable with the PDPW water quality data, and >98% of these parameters complied with TCEQ drinking water limits.

With respect to whole effluent toxicity (WET) testing of water samples from the pilot testing projects, for two DPW samples, three of the 16 (*i.e.*, 19%) testing endpoints showed no toxicity, which confirms the importance of post-desalination polishing steps to remove trace constituents. For 16 PDPW samples, 85 of the 95 endpoints (*i.e.*, 89%) showed no toxicity for the undiluted sample, which is very promising. As industry continues to scale-up and automate treatment

systems, post-treatment/polishing unit processes are a critical step for robust removal of trace organics, trace metals, and toxicity (*e.g.*, ammonia removal for surface water discharge or boron removal for rangeland rehabilitation and crop irrigation).

Several large-scale pilot and full-scale produced water treatment systems are expected to come online in 2026. The opportunity for the beneficial reuse of polished desalinated produced water will be advanced through ongoing collaboration on water quality analyses, treatment technology development and optimization, basin-scale ecological, and field-scale land application studies.

1 Introduction

1.1 Produced water treatment processes and water types

Generally, as illustrated in **Figure 1**, the first water type, raw produced water (PW), can be treated to yield the second water type, *treated produced water* (TPW), also referred to as *clean brine* (CB), which can be reused in the oil and gas industry (*e.g.*, hydraulic fracturing). Similarly, produced water might also be pre-treated in preparation for desalination, so while the terms clean brine and *pre-treated produced water* have nuanced distinctions, for the purposes of this study, the second water type included both *clean brine* and *pre-treated PW*. Desalination processes are used to remove most of the salinity to yield the third water type, *desalinated PW* (DPW). Post-treatment or polishing treatments such as ammonia stripping, granular activated carbon (GAC) filtration, and adsorption processes can be used to yield the fourth water type, *polished DPW* (PDPW).

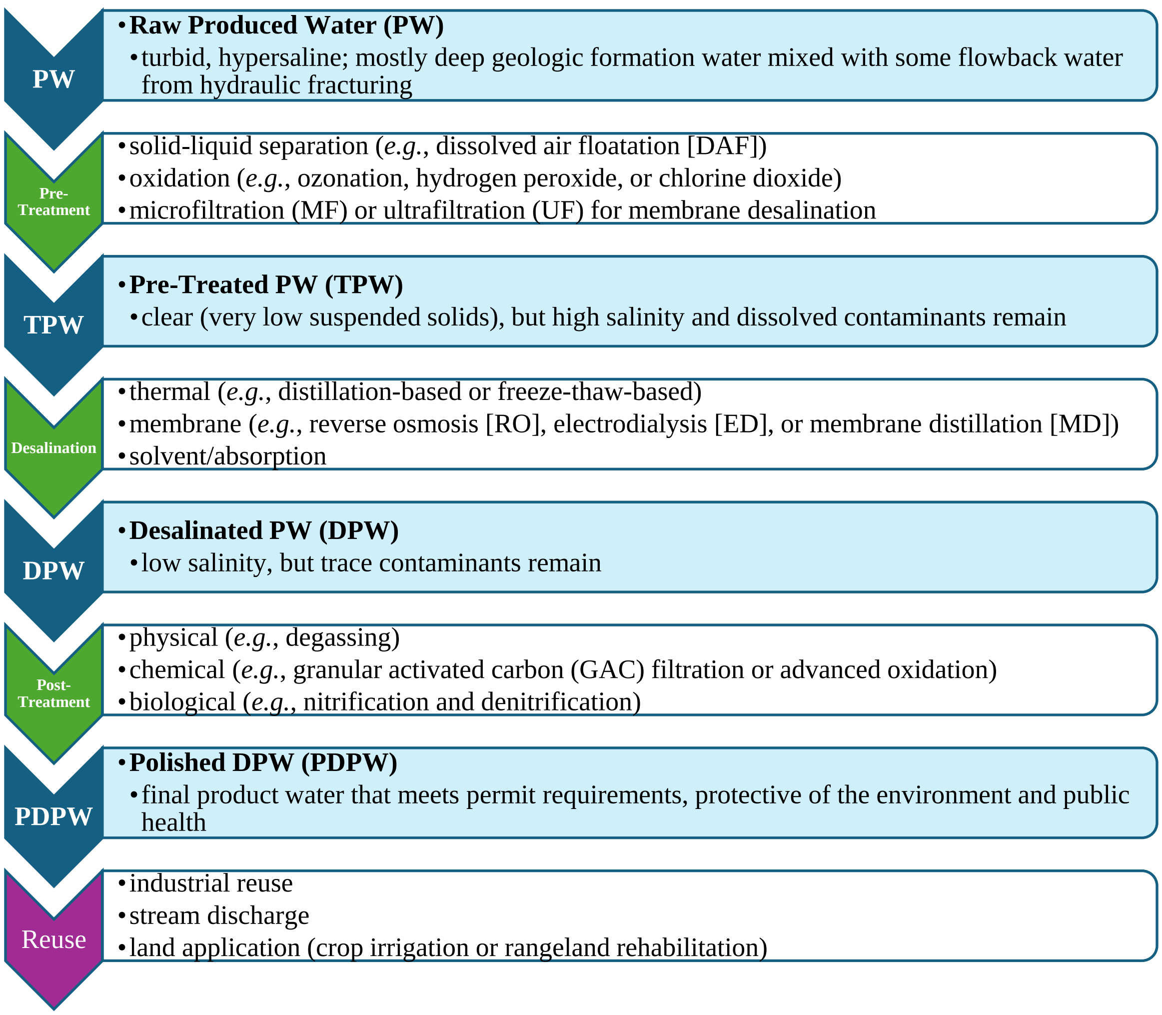

Figure 1. Four water types: raw produced water (PW), pre-treated PW (TPW), desalinated PW (DPW), and polished DPW (PDPW)

1.2 Pilot testing in the Permian Basin (2024-2025)

Five produced water treatment pilot testing projects that included pretreatment, desalination (including distillation, pressure-driven membrane, and hybrid), and polishing/post-treatment are summarized in **Table 1**, from which water quality data were collected. While some piloting systems were more advanced than others, all five were grouped together in this study to make observations across the breadth of treatment approaches, rather than differentiating (*e.g.*, thermal distillation versus pressure-driven membrane desalination). Some of the pilot treatment systems had extensive post-treatment polishing downstream of desalination, whereas some did not. Future research will compare performance between different types of treatment.

Table 1. Summary of Permian Basin pilot testing projects collaborating with TxPWC

Sub-Basin	Nominal Feed Flow Rate (bbl/day)	Number of Months of Testing
Delaware	100	18
Midland	300	6
Delaware	500	3
Delaware & Midland	20	18
Midland	800	2

2 Methodology

2.1 Collection of water samples and water quality data

From August 2024 to June 2025, in collaboration with the TxPWC, 45 water samples were collected from produced water treatment pilot testing in the Permian Basin for third-party water quality analyses by Eurofins, and TxPWC received the water quality results directly from Eurofins. Water quality data from Eurofins for an additional 15 samples were provided directly from a TxPWC member that had performed pilot testing in the Permian Basin. The number of each type of the 60 water samples are summarized in **Table 2**, and the 17,172 rows of water quality data are tabulated in **Appendix A.1** in a separate spreadsheet.

Table 2. Summary of water samples analyzed for water quality in pilot testing of treatment of produced water

Water Type	Number of Samples
Raw PW (PW)	17
Pre-Treated PW (TPW)	13
Desalinated PW (DPW)	12
Polished DPW (PDPW)	18
Total	60

The most abundant constituents in produced water from the Permian Basin are naturally occurring dissolved minerals, sodium and chloride, along with other dissolved minerals (*e.g.*, aluminum, bicarbonate, calcium, magnesium, potassium, sulfate, *etc*.). Produced water contains naturally occurring dissolved metals (*e.g.*, arsenic, barium, chromium, iron, lithium, manganese, strontium, *etc*.), naturally occurring radioactive material (NORM, *e.g.*, actinium-228, bismuth-214, lead-214, potassium-40, radium-226, radium-228, *etc.*), and naturally occurring reduced forms of nitrogen and sulfur (*e.g.*, ammonia and hydrogen sulfide). Obviously, produced water is expected to contain some naturally occurring organic compounds, especially petroleum hydrocarbons such as:

- aliphatics (containing straight or branched chains of carbon atoms)
  - alkanes (paraffins), containing only single bonds (*e.g.*, n-hexane, n-decane)
  - cycloalkanes (naphthenes), with carbon atoms arranged in ring structures (*e.g.*, cyclohexane)
- aromatics (containing one or more benzene rings)
  - single-ring aromatics (*e.g.*, benzene, toluene, ethylbenzene, xylene ("BTEX")
  - polycyclic aromatic hydrocarbons (PAHs), compounds with two or more bonded benzene rings (*e.g.*, naphthalene, anthracene)

Produced water may also contain chemicals (*e.g.*, formaldehyde, methanol, silicon dioxide [sand], *etc*.) used in well completion processes (*e.g.*, hydraulic fracturing).

To support thorough and robust research characterization of the potential contaminants in PW, some subcategories of contaminants were included in the analyses even though they would not be expected to be present in raw produced water or any derivative thereof. For example, herbicides, pesticides, polychlorinated biphenyls (PCBs), dioxin/furan, *etc.* are not expected to be present in produced water. In total, 765 distinct analytes were analyzed across the 60 samples, but not all samples were analyzed for all 765 analytes due to either matrix complexity (*e.g.*, high salinity, suspended solids, and oil/grease in raw produced water or high salinity of the clean brine) or some pilot plant operators wanted to analyze for additional parameters. A pivot table (**Appendix A.2**, see separate spreadsheet) was developed to summarize the results by water quality parameters (analytes) with number of detections, number of analyses, the range of method detection limits (MDLs), and the range of detected values.

2.2 Chemicals used in hydraulic fracturing

Generally, several types of chemicals listed in **Table 3** are used in hydraulic fracturing and subsequent conveyance, treatment, and disposal of produced water, and a detailed list from an analysis of FracFocus data from 203 wells in the Permian Basin from 2020-2024 is provided in **Appendix B** (see separate spreadsheet). Of the 130 Chemical Abstracts Service (CAS) Registry Numbers (RNs) listed in Appendix B, 54 were either analyzed directly or one or more of their constituents (*e.g.*, minerals with ions that dissociate when dissolved in water) were analyzed and are included in the 765 analytes in Appendix A. Example chemicals such as acetophenone, acrylamide, citric acid, ethanol, isopropanol, and methanol were not detected in the PDPW. Most of the constituents listed in Appendix B were also measured by aggregate analyses performed in this study, such as total suspended solids (TSS) for proppants, total dissolved solids (TDS) analyses for inorganic constituents, total organic carbon (TOC) for organic constituents, total petroleum hydrocarbon (TPH) for 6- to 35-carbon aliphatic and aromatic compounds, pH for acids and bases, and oxidation-reduction potential (ORP) for oxidizing and reducing agents.

Table 3. Purposes and examples of chemicals used in hydraulic fracturing and produced water management

Chemical Purpose	**Example Chemicals**
Antifreezing agent	ethylene glycol, methanol
Bacteria control, biocide	peracetic acid, glutaraldehyde, quaternary amines (benzalkonium), isothiazolinones
Clay stabilizer	quaternary ammonium salts, sodium chloride, potassium chloride
Coagulant	polyaluminum chloride
Corrosion inhibitor	amines, petroleum distillates
Crosslinker	borate salts and potassium hydroxide
Demulsifier (emulsion breaker)	ethyl-oxalated compounds, peroxydisulfate salts, nonylphenol ethoxylates, ammonium persulfate
Emulsifier	isopropyl alcohol
Enhanced oil recovery	terpenes from orange peel
Friction reducer	polyacrylamides, acrylamide copolymers, and AMPS copolymers
Gel breaker	strong oxidizers, ammonium persulfate, sodium bromate
Gelling agent	guar gum, sodium borate, cellulose-based polymers
Iron control	citric acid
Non-emulsifier	methanol, ethanol, petroleum distillates, naphtha, isopropanol
Oxidizer	hydrogen peroxide, sodium hypochlorite (bleach), chlorine dioxide
pH control	acids (acetic, hydrochloric, sulfuric) or bases (hydroxide, carbonate)
Proppant	silica sand, (specialty: glass beads)
Scale inhibitor	polyphosphonate (polyDADMAC) or polycarboxylic acid
Solvent	xylene
Surfactant	polyethylene glycol alkylphenyl ether, nonylphenol polyoxyethylene ether, ammonium sulfate

3 Results and Discussion

3.1 Undetected water quality analytes

For the 60 water samples analyzed in this study, 582 of the 765 analytes (*i.e.*, 76%) were not detected[1] in concentrations greater than method detection limits (MDLs) in any of the samples; these undetected analytes are listed in **Appendix C** (see separate spreadsheet) with minimum and maximum values of MDLs. Select subcategories of undetected analytes are summarized in **Table 4** by analytical method and analysis; the chemical classes (*e.g.*, PCBs, PFAS, herbicides and pesticides, rare earth elements [REEs], *etc.*) listed in Table 4 account for 300 of the 582 analytes not detected in any of the samples for which they were analyzed. These results indicate that further analysis of these chemical classes in PW, TPW, DPW, or PDPW is unlikely to contribute substantive new information, and future analyses are not justified.

Table 4. Select analytical methods from which there were no detected values in any samples for which they were analyzed

Analytical Method	Analysis	Samples	Number of Analytes
EPA 1668A	Chlorinated Biphenyl Congeners (PCBs) by HRGC/HRMS	3 (3 PW)	168
EPA 1633*	Per- and Polyfluoroalkyl Substances (PFAS) by LC/MS/MS	7 (2 PW; 1 PT; 1 DPW; 3 PDPW)	40
EPA 8141B*	Organophosphorous Compounds (Pesticides) by GC, Capillary Column Technique	6 (1 DPW; 5 PDPW)	26
EPA 8081B	Organochlorine Pesticides (GC)	26 (6 PW; 3 PT; 1 DPW; 16 PDPW)	24
EPA 6020B_REE	Rare Earth Metals (ICP/MS)	36 (17 PW; 3 PT; 16 PDPW)	19
EPA 8321B_Herb	Herbicides (LC/MS)	15 (1 PW; 1 PT; 2 DPW; 11 PDPW)	11
EPA 8082A	Polychlorinated Biphenyls (PCBs) by GC	26 (6 PW; 3 PT; 1 DPW; 16 PDPW)	7
EPA 504.1*	EDB, DBCP and 1,2,3-TCP (soil fumigants) by GC	10 (10 PDPW)	2
EPA 547	Glyphosate (DAI HPLC)	9 (9 PDPW)	1
EPA 6850	Perchlorate by LC/MS or LC/MS/MS	24 (11 PW; 1 PT; 1 DPW; 11 PDPW)	1
SM 4500SO3_B	Sulfite	19 (10 PW; 9 PDPW)	1
Total	-	-	*300*

Notes: * and variants; DIA – direct aqueous injection; GC – gas chromatography; HP – high performance; HR – high resolution; ICP – inductively coupled plasma; LC – liquid chromatography; MS – mass spectrometry

[1] The term "not detected" indicates that the analytical result of the analysis was less than the method detection limit (MDL) and does not guarantee that the constituent was not present.

3.2 Detected water quality analytes and general treatment efficacy

The 183 water quality analytes that had detected values are listed in **Appendix D** (see separate spreadsheet), along with minimum and maximum MDLs. Overall, across all five pilot treatment systems, the combination of three distinct treatment steps (pre-treatment, desalination, and polishing) was effective at removing >99% of salinity, organics, and radioactivity. A select set of analytes are listed in Error! Reference source not found. to highlight a range of key water quality indicators:

- aggregate parameters, including both inorganic and organic (*e.g.*, specific conductance [also called electrical conductivity], total dissolved solids [TDS], total organic carbon [TOC], total organic halides [TOX] total petroleum hydrocarbons [TPH], and ultraviolet absorption)
- metals (*e.g.*, arsenic, barium, chromium, and uranium)
- inorganic constituents (*e.g.*, ammonia and boron)
- volatile organic compounds (*e.g.*, acetone, benzene, and naphthalene)
- semi-volatile organic compounds (*e.g.*, benzyl alcohol and phenols)
- carbonyl compounds (*e.g.*, glutaraldehyde)
- non-halogenated organic compounds (*e.g.*, methanol)
- radioactivity (*e.g.*, gross alpha and gross beta)

Analytes such as benzene, glutaraldehyde, gross alpha, methanol, naphthalene, and xylenes are examples in **Error! Reference source not found.** of analytes not detected in the PDPW; of the 183 detected analytes listed in Appendix D, the 72 analytes NOT detected in the Polished DPW are listed in **Appendix E**. Finally, the 116 analytes detected in the polished DPW (PDPW) are listed in **Appendix F** with minimum and maximum MDLs, as well as minimum, average, and maximum detected values.

With respect to desalination performance, the average cumulative removal ratio from raw PW to Desalinated PW was 99.73%, 99.76%, and 99.86% for TDS, sodium, and chloride, respectively. Including the final post-treatment polishing steps downstream of desalination, most of the TOC and TPH analyses of polished DPW (PDPW) were below detection limits, representing average cumulative removal ratios of >99.3% and >99.4%, respectively. While the average detected concentration of ammonia in PDPW was 6.46 mg/L, the average concentration was less than 1 mg/L for pilot treatment systems with more robust ammonia polishing.

Table 5. Select detected constituents and averages of detected concentrations for the four PW water types

Analyte	Units	Raw PW (PW)		Pretreated PW (TPW)		Desalinated PW (DPW)		Polished DPW (PDPW)	
		detects/ analyses	avg. of det. conc.	detects/ analyses	avg. of det. conc.	detects/ analyses	avg. of det. conc.	detects/ analyses	avg. of det. conc.
Acetone	mg/L	3/11	0.652	9/11	0.264	11/11	0.169	0/10	<0.00307
Aluminum†	mg/L	0/11	ND	1/11	0.006	0/1	ND	8/11	0.107
Ammonia	mg/L	19/19	620	3/3	419	13/13	21.9	16/23	6.46
Arsenic†	mg/L	1/17	0.00246	0/3	<0.0345	0/1	<0.00138	8/17	0.00155
Barium†	mg/L	17/17	10.3	3/3	9.47	0/1	<0.00268	13/17	0.00925
Benzene	mg/L	17/17	6.32	3/13	0.2	7/12	0.00226	0/17	<0.00046
Benzyl alcohol	mg/L	1/6	0.00205	1/2	0.0277	NA	NA	5/6	0.00789
Boron†	mg/L	17/17	58.0	3/3	55.9	11/11	5.14	14/17	5.32
Chloride	mg/L	17/17	77,005	3/3	59,233	10/11	37.6	17/17	80.5
Chromium†	mg/L	3/17	0.342	0/3	<0.028	1/1	0.0284	7/17	0.00222
Ethylbenzene*	mg/L	17/17	0.229	1/13	0.0275	0/12	<0.00039	0/17	<0.00039
Formaldehyde*	mg/L	6/6	0.768	1/3	0.115	0/2	<0.00066	2/16	0.0352
Glutaraldehyde*	mg/L	1/1	0.557	1/1	0.0527	0/2	<0.03	0/11	<0.03
Gross alpha	pCi/L	13/16	1394	1/1	1370	1/1	1.63	0/15	<12.1
Gross beta	pCi/L	16/16	1014	1/1	598	1/1	1.75	8/15	1.73
Methanol*	mg/L	2/6	4.43	1/3	98.1	3/7	6.1	0/16	<2.27
Naphthalene	mg/L	7/18	0.0582	1/14	0.0043	0/14	<0.00135	0/28	<0.00135
Phenols, total	mg/L	NA	NA	NA	NA	1/1	0.0066	3/9	0.0112
Sodium†	mg/L	17/17	33,470	3/3	31,033	8/8	48.9	17/17	80.53
Specific Conductance‡	µS/cm	10/11	176,000	1/1	179,000	11/11	396	10/11	314
Toluene	mg/L	17/17	5.03	1/13	0.541	5/12	0.000755	4/17	0.00446
Total Dissolved Solids (TDS)	mg/L	17/17	131,117	3/3	124,333	11/11	317	15/15	352
Total Organic Carbon (TOC) †	mg/L	17/17	84.3	13/13	44.3	10/10	1.83	3/16	1.04
Total Organic Halogens (TOX)	mg/L	NA	NA	NA	NA	1/2	0.124	4/5	0.174
Total Petroleum Hydrocarbons (TPH) (C6-C35)	mg/L	10/11	158	0/1	<0.912	0/2	<0.876	3/11	1.13
Ultraviolet absorption	1/cm	9/9	0.206	9/9	0.165	1/1	0.066	10/10	0.0268
Uranium†	mg/L	0/16	<0.0105	0/3	<0.0105	0/1	<0.00042	1/16	0.00102
Xylenes, total*	mg/L	17/17	2.13	1/13	0.195	1/12	0.00234	0/17	<0.00124

* listed in Frac Focus; † unfiltered/total basis; ‡ electrical conductivity, µmho/cm = µS/cm = 0.001 mS/cm = 0.001 dS/m; "NA" not analyzed

3.3 Water quality comparison to regulatory water quality standards

At the time of this writing, TCEQ has not yet released draft permits for Surface Discharge or Land Application, which are two key beneficial reuse options for polished desalinated produced water (PDPW). While Surface Discharge and Land Application permits fall under the Clean Water Act framework, and while PDPW has not yet been proposed to be used for drinking water, some stakeholders have requested a comparison of the water quality of PDPW to drinking water limits because surface discharge to the Pecos River could influence the water quality of downstream drinking water intakes. Of the 101 chemical, radionuclide, and aesthetic drinking water quality parameters regulated by TCEQ[2], there are 86 primary limits and 16 secondary limits with two parameters (Cu and F) having both primary and secondary limits, tabulated in **Appendix G**. Of the 101 TCEQ drinking water limits, 76 were comparable with the TxPWC water quality data summarized in Sections 3.1 and 3.2, and the minimum value of Eurofins' minimum detection limits (MDLs) was less than the TCEQ maximum contaminant levels (MCLs) for all 76 parameters. Of the 76 parameters, 53 were not detected, and of the 23 parameters with detected values, 22 had average values that satisfied the TCEQ drinking water limits. Thus, >98% of the comparable analytes complied with TCEQ drinking water limits; the only few minor excursions were with respect to secondary limits: high total dissolved solids (TDS, 1 of 15 analyses), aluminum (8 of 11 analyses), and hydrogen sulfide (1 of 11 analyses), as well as low pH (1 of 16 analyses). There are known treatment methods for all of these parameters, and they could be controlled within safe limits. Certain pilot operations that were designed to be more robust showed no excursions.

3.4 Whole effluent toxicity (WET) testing

While other chemical constituents may be present in the water for which analyses were not performed, whole effluent toxicity (WET) testing can be helpful in reducing the uncertainty of the presence of hazardous chemicals. Thus, in addition to chemical analyses, acute and chronic toxicity analyses were also performed on 18 samples from the pilot treatment systems: two desalinated produced water (DPW) samples and 16 polished DPW (PDPW). WET tests were performed with organisms representing three trophic levels in aquatic ecosystems (*i.e.*, algae, microcrustaceans, and fish, representing primary producers, primary consumers, and secondary consumers, respectively). Two of the chronic tests had two toxicity endpoints for a total of 111 toxicity test results, tabulated in **Appendix H**. Undiluted sample water was tested along with serial dilutions with control water (*i.e.*, 100% [undiluted sample water], 50%, 25%, 12.5%, 6.25% [*i.e.*, 6.25% sample water with 93.75% control water]), and the no observable effect concentration (NOEC) is the highest concentration of sample water that yields no statistical

[2] Texas Administrative Code (TAC), Title 30, Part 1, Chapter 290, Subchapter F. Drinking Water Standards Governing Drinking Water Quality And Reporting Requirements For Public Water Systems, available at https://texas-sos.appianportalsgov.com/rules-and-meetings?chapter=290&interface=VIEW_TAC&part=1&subchapter=F&title=30#, accessed 2026 APR 11

difference in toxicity compared with the organism's response to the control water. Some PDPW samples were remineralized with calcium to avoid false toxicity due to nutrient deficiency.

Overall, for the two desalinated produced water (DPW) samples, three of the 16 (*i.e.*, 19%) endpoints listed in **Table 6** showed no toxicity, which confirms the necessity of post-desalination polishing steps to remove trace constituents. When post-treatment is added, the 16 polished desalinated produced water (PDPW) samples, 85 of the 95 endpoints showed no toxicity for the undiluted sample, and the weighted-average NOEC was 92.7%. These results are promising considering that most of these pilot treatment systems did not have fully-optimized polishing unit processes throughout the entirety of the piloting duration.

Table 6. Whole effluent toxicity (WET) test results

Test	**Endpoint**	**Desalinated PW (DPW)**		**Polished DPW (PDPW)**	
		Not Toxic/ Total	Avg NOEC	Not Toxic/ Total	Avg NOEC
Common Water Flea, Acute 48 or 96-hr (*Daphnia pulex*), EPA 2021	Survival	0/2	50%	2/2	100%
Fathead Minnow, Acute 48 or 96-hr (*Pimephales promelas*), EPA 2000	Survival	0/2	38%	16/16	100%
Fathead Minnow, Chronic (*Pimephales promelas*), EPA 1000	Growth	0/2	31%	10/14	80%
	Survival	1/2	56%	13/14	96%
Green Algae, Chronic 7-day (*Selenastrum capricornutum*), EPA 1003	Growth	0/2	27%	1/3	54%
Water Flea, Acute 48-hr (*Ceriodaphnia dubia*), EPA 2002	Survival	0/2	50%	15/18	88%
Water Flea, Chronic 7-day (*Ceriodaphnia dubia*), EPA 1002	Reproduction	0/2	38%	14/14	100%
	Survival	2/2	100%	14/14	100%

Note: "Not Toxic" refers to no observable effect at 100% concentration (*i.e.*, no dilution required); NOEC – no observable effect concentration (*e.g.*, 88% means 88% sample water with 12% control water to yield no statistical difference from 100% control water)

For these 18 DPW and PDPW samples, the *Ceriodaphnia* Chronic-survival was the least sensitive test (*e.g.*, no observed effects for undiluted DPW), while the Green Algae Chronic-growth was the most sensitive test (*e.g.*, average NOEC of 54% for PDPW). However, Green Algae tests generally exhibit higher interlaboratory variability compared to the Fathead Minnow and Water Flea tests and are not typically used in discharge permit standards. In acute toxicity tests, the organisms are not supplied with food, so they experience a different type of stress than chronic toxicity tests (typically 7 days with food). The acute toxicity tests in this dataset include tests performed at either 48-hr or 96-hr durations; some WET testing lab managers prefer the 48-hr test because the 96-hr test may be vulnerable to false-positive indications of toxicity due to the stress that the organisms experience from lack of food.

4 Conclusion

Water quality analyses were performed on 60 water samples from pilot testing produced water (PW) treatment in the Permian Basin in 2024-2025, and overall, the pilot treatment systems were effective at removing >99% of salinity, radioactivity, and organics. With average raw PW and pre-treated PW salinities over 120,000 mg/L total dissolved solids (TDS), the thermal and membrane-based desalination methods successfully removed bulk salinity to yield an average desalinated produced water (DPW) salinity of 317 mg/L TDS, which is a salinity suitable for most beneficial reuse applications (*e.g.*, streamflow augmentation, rangeland rehabilitation, and crop irrigation). With respect to trace constituents, desalination and post-treatment/polishing effectively removed key indicators such as benzene, glutaraldehyde, gross alpha, methanol, naphthalene, and xylenes to below analytical method detection limits (MDLs).

At the time of this writing, TCEQ has not yet released draft permits for Surface Discharge or Land Application, so PDPW quality was compared with drinking water limits: 75 of 76 comparable polished desalinated produced water (PDPW) water quality parameters (>98%) complied with TCEQ drinking water limits. With respect to whole effluent toxicity (WET) testing, 85 of 95 toxicity endpoints showed no toxicity in undiluted PDPW samples. These results are promising.

At the time of this writing, several larger pilot-scale and full-scale produced water treatment systems are under construction to be operational mid-2026 and will include robust post-treatment/polishing unit processes for ample removal of trace organics, trace metals, and toxicity (*e.g.*, ammonia removal for surface water discharge and boron removal for land application such as rangeland restoration and crop irrigation).

Ongoing and future work is investigating correlations among water chemistry and toxicity results, as well as best management practices on treatment plant operator training, online monitoring, and consistent laboratory water quality analyses. A related point of future work is the recovery of potentially valuable chemicals from the produced water or treatment residuals (*e.g.*, desalination concentrate).

Ultimately, the safe and beneficial reuse of polished desalinated produced water will be advanced through ongoing collaboration on water quality, water treatment optimization, basin-scale ecological and hydrologic studies, and field-scale land application studies.

Texas Permian Future Generations

Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

EXHIBIT 4
PART 1

Texas Aquifers Study

Groundwater Quantity, Quality, Flow, and Contributions to Surface Water

December 31, 2016

Geoscientists Seal

The contents of this report (including figures and tables) document the work of the following licensed Texas geoscientists:

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Executive Summary

Groundwater is a vital, yet hidden, natural resource that lies beneath Texas. More than 60 percent of water used in Texas comes from groundwater in 9 major and 21 minor aquifers. An aquifer is a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Major aquifers produce large amounts of fresh groundwater over large areas of the state, while minor aquifers produce smaller amounts of freshwater over large areas or larger amounts over smaller areas. There are also other aquifers in Texas that may represent significant local sources of groundwater. The major and minor aquifers, extending beneath 81 percent of the land area of Texas, include confined aquifers that are fully saturated, holding water under pressure, and unconfined aquifers that are partly saturated, where the water table surface is free to rise and decline.

This report presents information on the geology and hydrogeology of the confined and unconfined aquifers of Texas, including the quantity and quality of the groundwater that they contain, the volume of flows from the aquifers to the surface waters of the state, and the volume of flows between the aquifers. This report fulfills the requirements of House Bill 1232, which was passed by the 84th Texas Legislature and signed into law by Governor Greg Abbott on May 28, 2015. Key elements of the study are located in the report as shown below:

Study Requirement	Location in Report
Quantity and quality of groundwater in confined and unconfined aquifers	Chapter 2
Groundwater and surface water interactions	Chapter 3
Map identifying which aquifers are tributary and which are non-tributary	Figure 4-2
Map identifying the area and water quality of the confined and unconfined aquifers	Figure 1-1 Figure 1-2 Figure 2-3
Contribution of those aquifers to any surface flow of any water	Figure 3-1
Contribution of those aquifers to any other aquifer	Figure 5-2

Groundwater quantity

The total estimated quantity of fresh and brackish-to-saline groundwater in Texas aquifers is 16.8 billion acre-feet. Major aquifers contain an estimated 12.6 billion acre-feet of groundwater; minor aquifers contain an estimated 4.24 billion acre-feet of groundwater. Not all of this groundwater, however, is recoverable because of aquifer limits and the state of current technology. Between 25 and 75 percent of this volume may be recoverable, but this range does not account for possible economic, environmental, or legal consequences of such pumping.

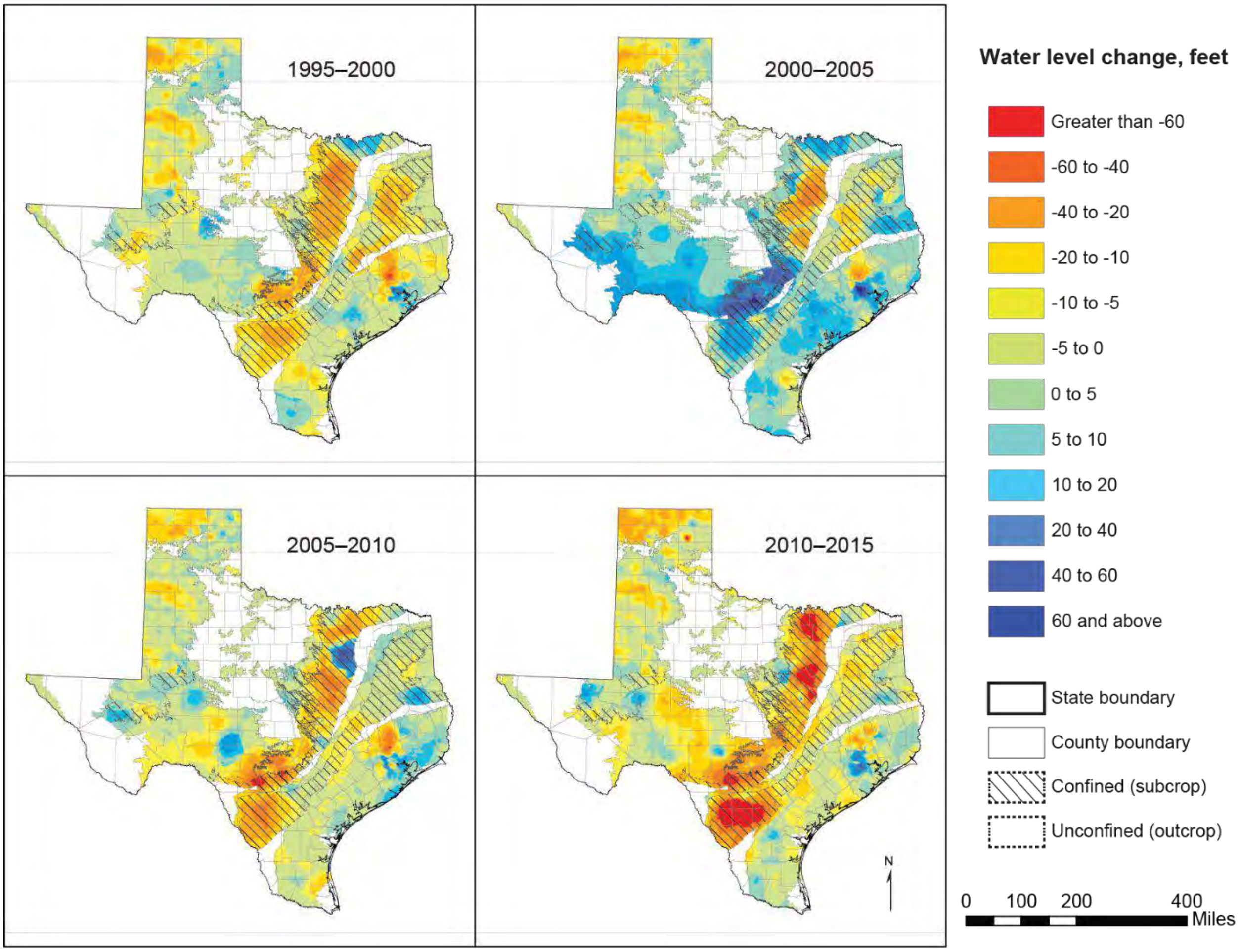
The Gulf Coast and Carrizo-Wilcox aquifers, in the coastal plains of Texas, cover about 30 percent of the state and account for two-thirds of the groundwater in storage. Although more groundwater is pumped from the Ogallala Aquifer than all other aquifers combined, the total recoverable groundwater storage remaining in this aquifer amounts to between 95.3 to 286 million acre-feet, or between 2 and 5 percent of the recoverable groundwater in storage in Texas.

Groundwater levels

Since 1895, over 1 million groundwater levels have been measured and are now accessible in the Texas Water Development Board (TWDB) groundwater database. Each year, the Texas Water Development Board, groundwater conservation districts, and the U.S. Geological Survey measure water levels in about 8,600 wells.

Groundwater levels in all major and minor aquifers have declined from predevelopment levels in response to development of groundwater resources for agricultural, municipal, and industrial uses. The annual volume of groundwater pumped in Texas increased rapidly in the 1950s and peaked at over 12 million acre-feet per year in the 1970s but has been between approximately 8 and 10 million acre-feet per year for the past 20 years.

Water levels in some areas have declined more than 100 feet between 1995 and 2015, generally in portions of confined aquifer systems with heavy pumping. The median water levels have declined statewide less than 2 feet per year during this period. Some groundwater declines have been reversed locally, such as in the Houston area, as pumping patterns change or recharge exceeds discharge.



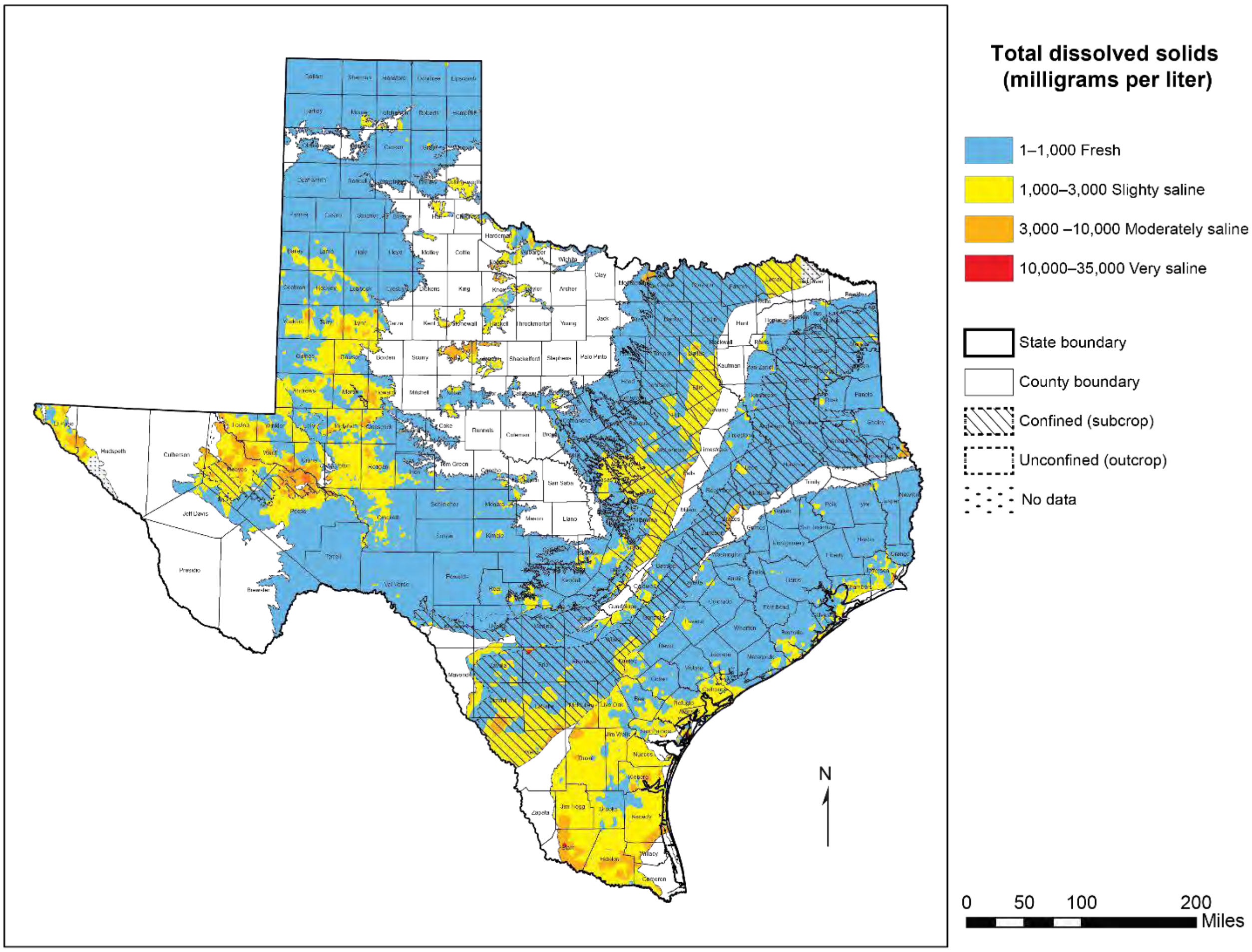
Water-level changes in the major aquifers of Texas (1995–2015).

Groundwater quality

Most groundwater in the major and minor aquifers is fresh, with total dissolved solids concentrations less than 1,000 milligrams per liter. In part this is because the official boundaries of many of the aquifers are determined based on water quality zonation; the water-bearing formation may continue beyond an aquifer boundary but contains more saline water.

Natural processes result in areas of higher total dissolved solids in some Texas aquifers, including the southern Ogallala, the Pecos Valley, the Seymour, and the southern Gulf Coast aquifers, and the down-dip confined areas of the Trinity and Carrizo-Wilcox aquifers. In some parts of the state, naturally-occurring levels of total dissolved solids, arsenic, and radionuclides, as well as high levels of nitrate from various sources, prevent the water from meeting drinking water standards.

The TWDB groundwater quality monitoring network has not detected significant changes in statewide groundwater quality over time.

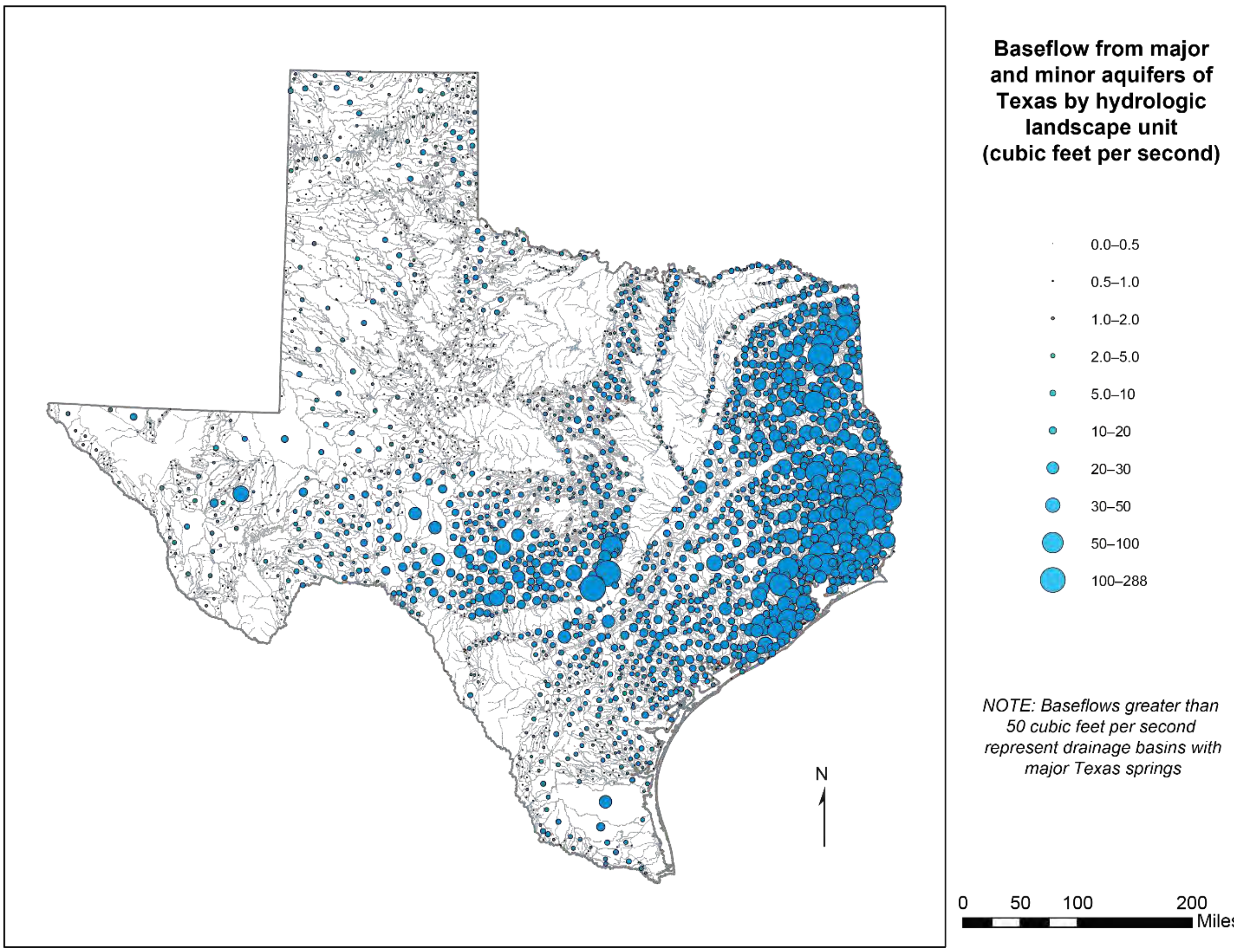


Concentration of total dissolved solids in major aquifers of Texas through 2015.

Groundwater and surface-water interactions

We estimated groundwater flow to surface water based on historical baseflow data from nearly 600 U.S. Geological Survey stream gaging stations in Texas. (Baseflow is the component of surface water flow that can be attributed to groundwater discharge to streams.) This estimate is derived from the use of "hydrologic landscape regions," which provide a framework for regionalizing streamflow assuming that watersheds with similar slopes, soils, geology, and climate respond in the same way to precipitation and groundwater and surface-water interactions. This approach yielded an estimated average net groundwater flow to surface water of 9.3 million acre-feet per year, or about 30 percent of all surface-water flows. This average historical flow may not accurately represent current or future conditions and does not address the inherent variability of groundwater processes.

Groundwater contributions to surface water are greatest in East Texas and around major springs in the Hill Country and west Texas. The Gulf Coast Aquifer discharges the most groundwater to surface water, with an estimated flow of 3.8 million acre-feet per year. The Edwards (Balcones Fault Zone) Aquifer discharges the greatest volume of baseflow per square mile of aquifer area. Springs and seeps in West Texas also contribute locally significant baseflow to streams. About half of Texas aquifers contribute less than 50,000 acre-feet per year to surface-water flows.

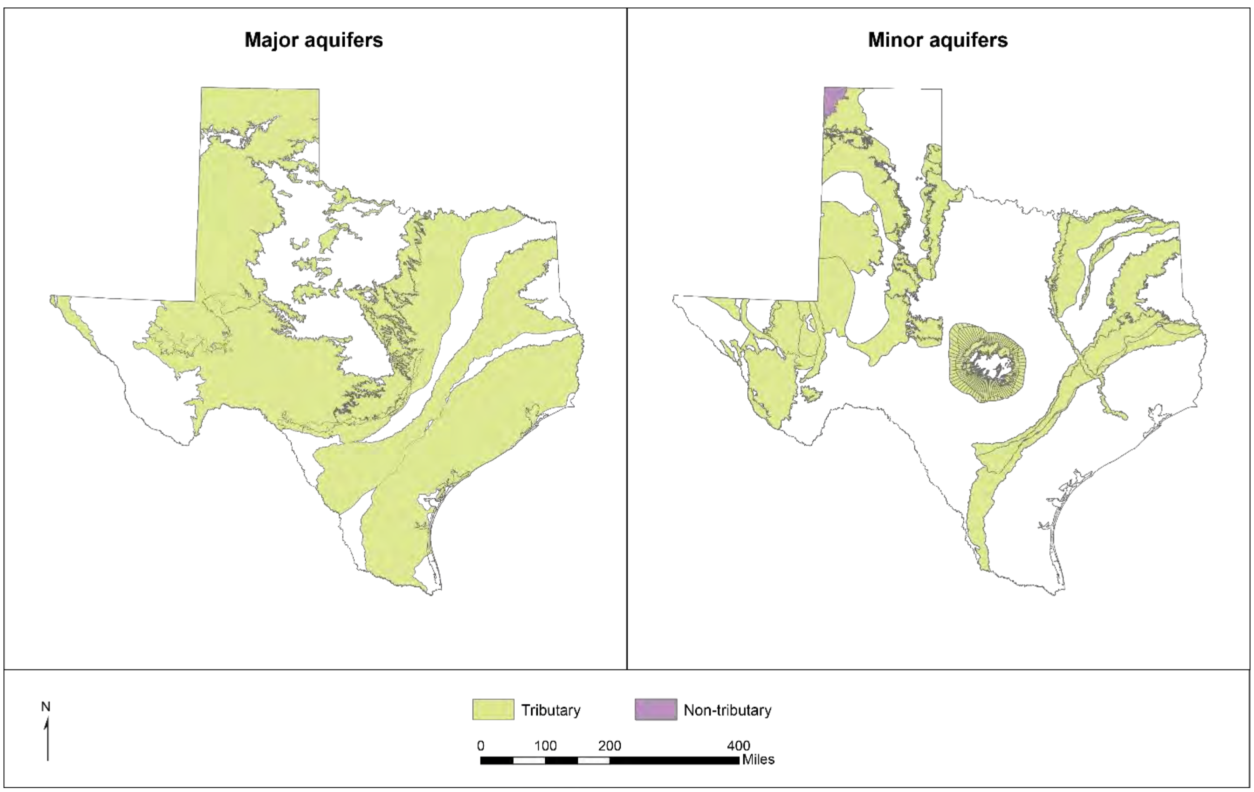


Baseflow from aquifers by hydrologic landscape unit (in cubic feet per second).

Tributary and non-tributary aquifers

The general definition that tributary groundwater is "groundwater that discharges into surface water" does not address how or where to distinguish between tributary and non-tributary aquifers. Our evaluation of streamflow data indicates that three major aquifers—the Edwards

(Balcones Fault Zone), Edwards-Trinity (Plateau), and Pecos Valley aquifers—contribute more than 50 percent of the baseflow of streams flowing across their outcrop zones on an average annual basis. This is supported by the number of current and historical springs that flow from these aquifers. Eighteen major and minor aquifers contribute between 20 and 50 percent of the flow to streams flowing over their outcrop zones. Eight minor aquifers contribute between 14 and 20 percent of the flow to streams flowing over their outcrop zones. These aquifers include the Blossom, Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), Igneous, Marathon, Nacatoch, and Woodbine aquifers. One minor aquifer, the Rita Blanca Aquifer, contributes zero percent to streamflow and is classified as non-tributary. Each of the state's aquifers has local areas that may differ from the regional, aggregate designation. For example, the confined areas of aquifers may exhibit characteristics that are non-tributary, whether or not they are tributary in their outcrop areas.

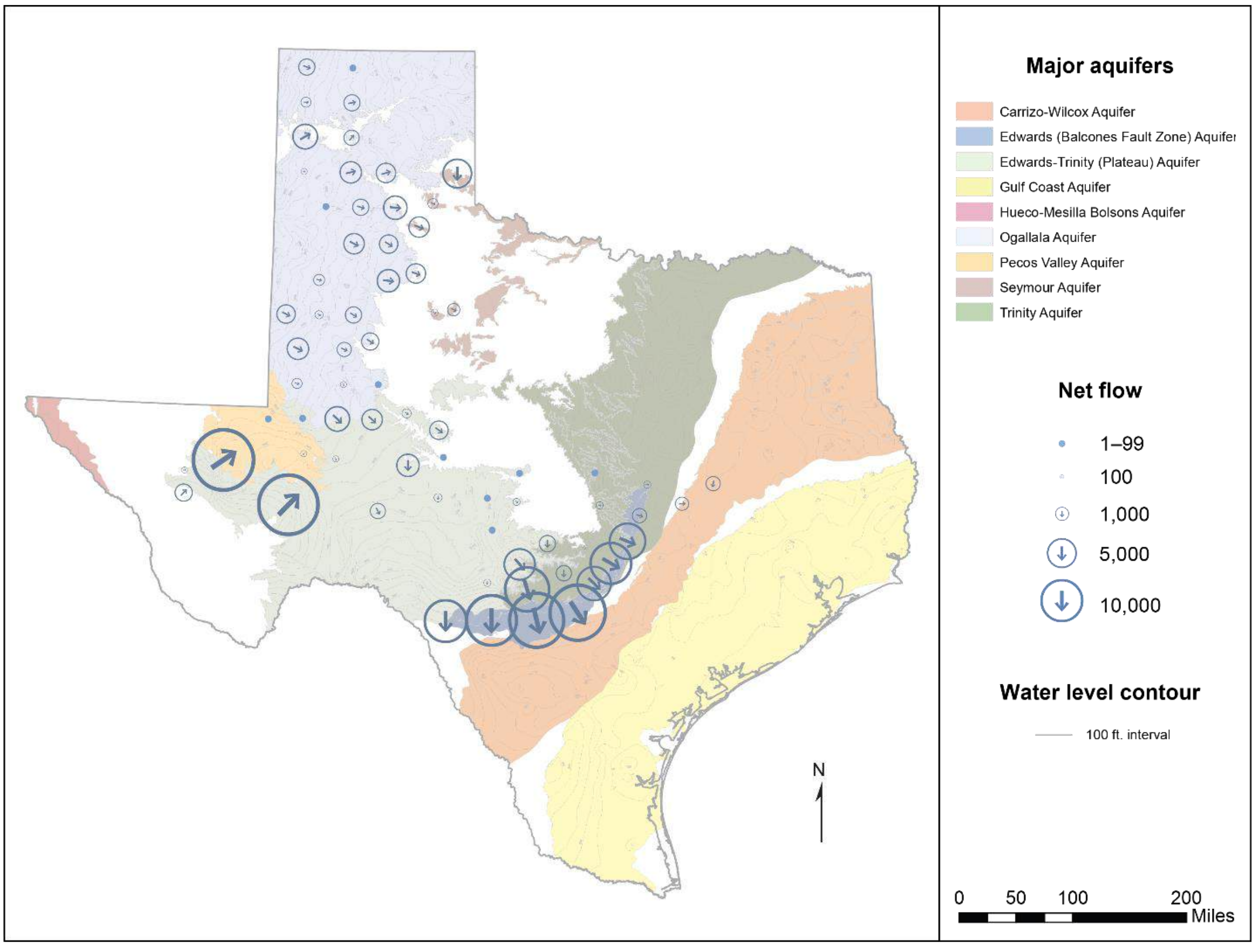


Map of the tributary and non-tributary aquifers of Texas.

Groundwater flows to other aquifers

Groundwater flow between aquifers has not been directly measured or monitored. Because of this lack of measurement, inter-aquifer groundwater flow has been estimated using groundwater availability models. These models, developed through the TWDB with stakeholder input, represent the best available compilation of hydrogeological data and processes with which to make such estimates. However, in most cases the models were not specifically designed or calibrated to estimate inter-aquifer flow. Aquifers bounded by low-permeability geological units have little or no interaction with neighboring aquifers. For these aquifers, the underlying confining layer is treated in the groundwater availability model as a no-flow boundary even though some flow could occur under certain pumping scenarios.

Groundwater modeling indicates that flows between aquifers occur primarily in the Hill Country and in the Pecos Valley. Smaller flows from the Ogallala into the Dockum occur in the High Plains. Groundwater flow between the major and minor aquifers in the eastern part of Texas is limited by the thick sequences of shale or clay that separate the aquifer systems and restrict vertical groundwater movement. Some aquifers in the central and western areas of the state are juxtaposed such that lateral groundwater flow probably occurs between them.



Relative magnitude of inter-aquifer flows where data or models are available.

Table of Contents

Table of Contents

1 Introduction

Groundwater is a vital, yet hidden, natural resource that lies beneath Texas. More than 60 percent of water use in Texas is groundwater from 9 major and 21 minor aquifers. An aquifer is a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Major aquifers produce large amounts of fresh groundwater over large areas of the state, while minor aquifers produce smaller amounts of freshwater over large areas or larger amounts over smaller areas. There are also other aquifers in Texas that may represent significant local sources of groundwater. The major and minor aquifers, extending beneath 81 percent of the land area of Texas, include confined aquifers that are fully saturated, holding water under pressure, and unconfined aquifers that are partly saturated, where the water table surface is free to rise and decline. Although groundwater is largely unseen, it plays a major role in Texas' hydrological cycle. The Texas landscape collects rainfall and generates runoff above ground that can recharge groundwater systems, while below the surface, groundwater moves through the aquifers, reacts with the aquifer materials, and discharges to other aquifers or to surface water.

This report presents information on the geology and hydrogeology of the confined and unconfined aquifers of Texas, including the quantity and quality of the groundwater that they contain, the volume of flows between the aquifers, and the volume of flows from the aquifers to the surface waters of the state. This report fulfills the requirements of House Bill 1232, which was passed by the 84th Texas Legislature and signed into law by Governor Greg Abbot on May 28, 2015.

This study incorporates information from previous TWDB reports on the aquifers of Texas, including George and others (2011), Ashworth and Hopkins (1995), and Ashworth and Flores (1991). Significant study on groundwater-surface-water interaction is documented in Parsons (1999) and Scanlon and others (2005). Detailed water quality studies of major and minor aquifers have also been performed by various organizations under contract for the TWDB Groundwater Availability Modeling Program, funded by the Texas Legislature to improve the scientific basis for regional groundwater availability models. These reports, and the large body of research supporting the groundwater availability modeling program, have provided most of the information on the geology, structure, and hydrogeology of Texas aquifers presented in this report.

TWDB staff has performed a new analysis of water level and water quality data collected by the TWDB, the U.S. Geological Survey, and groundwater conservation districts. In addition, the

TWDB groundwater availability modeling group developed a new analytical process to quantify groundwater and surface-water interactions and modeled flows between aquifers.

Aquifer summaries, with additional information and details not included in the specific study requirements, are provided for context and background in Chapter 6.

1.1 Legislative background

House Bill 1232 requires the TWDB to conduct a study of the unconfined and confined aquifers of the state and directs the TWDB to determine the following:

1. the quantity and quality of groundwater in those aquifers,
2. whether those aquifers are tributary or non-tributary,
3. the contribution of those aquifers to any surface flow of any water in this state, and
4. the contribution of those aquifers to any other aquifer in this state.

The TWDB is required to produce a map that identifies the area and water quality of the confined and unconfined aquifers, a map that identifies which aquifers are tributary and which are non-tributary, and a report on the contribution of those aquifers to any other aquifer. In addition, House Bill 1232 requires that, before conducting the study, the TWDB "shall determine the minimum rate at which an aquifer must contribute to another aquifer in this state or to the surface flow of any water in this state in order to be included in the study."

On October 26, 2015, the TWDB held a public meeting to receive and discuss technical input regarding the minimum rate at which an aquifer must contribute to another aquifer or to the surface flow of any water in the state to be included in the study. More than 50 stakeholders contributed written input via email or through an online survey. The comments and suggestions covered a range of technical considerations, including both qualitative and quantitative metrics, to determine the flow requirements for the study.

Upon considering the statute, legislative intent, and input from stakeholders, the TWDB Board members met on January 19, 2016, to approve the following technical definitions:

1. The minimum flow rate between aquifers is defined as the lowest annual net vertical flow from an aquifer to another aquifer, as estimated by the applicable groundwater availability model. There are no available direct measurements or data related to the flow of groundwater between aquifers, so an indirect approach based on groundwater availability models is used. If no groundwater availability model exists or if the applicable groundwater availability model is insufficient, other appropriate methods may be used to estimate flow.

2. The minimum flow rate for groundwater discharge to surface water is defined as a contribution of at least 0.1 percent of the mean annual surface-water flow over any specified geographic area of any major or minor aquifer.

   Understanding aquifer contributions to surface water, and vice versa, is a major research topic in the field of groundwater hydrology. As a practical matter, springflow and streamflow measurements are few (when viewed over the entire state) and vary widely over time. Furthermore, aquifer contributions to surface water may be discrete (springs) or diffused along the length of a stream. To address this issue, we evaluated baseflow data—the component of surface-water flow that can be attributed to groundwater discharge to streams. The U.S. Geological Survey has conducted extensive, statewide studies involving hundreds of stream gages that have been used to prepare baseflow indices (Wolock, 2003). A baseflow index is the ratio of baseflow to streamflow expressed as a percentage of the streamflow. These baseflow indices are not aquifer-specific, so we compared these datasets of baseflow index values to the surface outcrops of Texas aquifers. Based on an initial review of the U.S. Geological Survey's baseflow index data for Texas, we determined that a minimum rate of 0.1 percent of the mean annual surface-water flow over any unit area of any specific aquifer maximizes the number of gage sites available for a statewide evaluation. Regardless of the baseflow index, we included all major or minor aquifers that have available springflow data in the study.

As a result of these definitions, this study evaluates flows between all major and minor aquifers in Texas and flows from groundwater to surface water for the entire area of the state.

1.2 Major and minor aquifers of Texas

Texas has numerous aquifers capable of producing groundwater for households, municipalities, industry, farms, and ranches. For the purpose of this study, the evaluation of unconfined and confined aquifers has been limited to the TWDB-designated major and minor aquifers of the state. The TWDB recognizes 9 major aquifers—aquifers that produce large amounts of water over large areas (Figure 1-1)—and 21 minor aquifers—aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (Figure 1-2). These aquifers are critical sources of water for Texas, providing about 62 percent of the 13.7 million acre-feet of water used in the state in 2014, the latest year for which statistics are available. Groundwater represents about 85 percent of agricultural water, with irrigators withdrawing most of this water from the Ogallala Aquifer; 74 percent of all groundwater is used for irrigation, or 4.8 million acre-feet per year. About 36 percent of water used to meet municipal demands is from groundwater (TWDB, 2016).

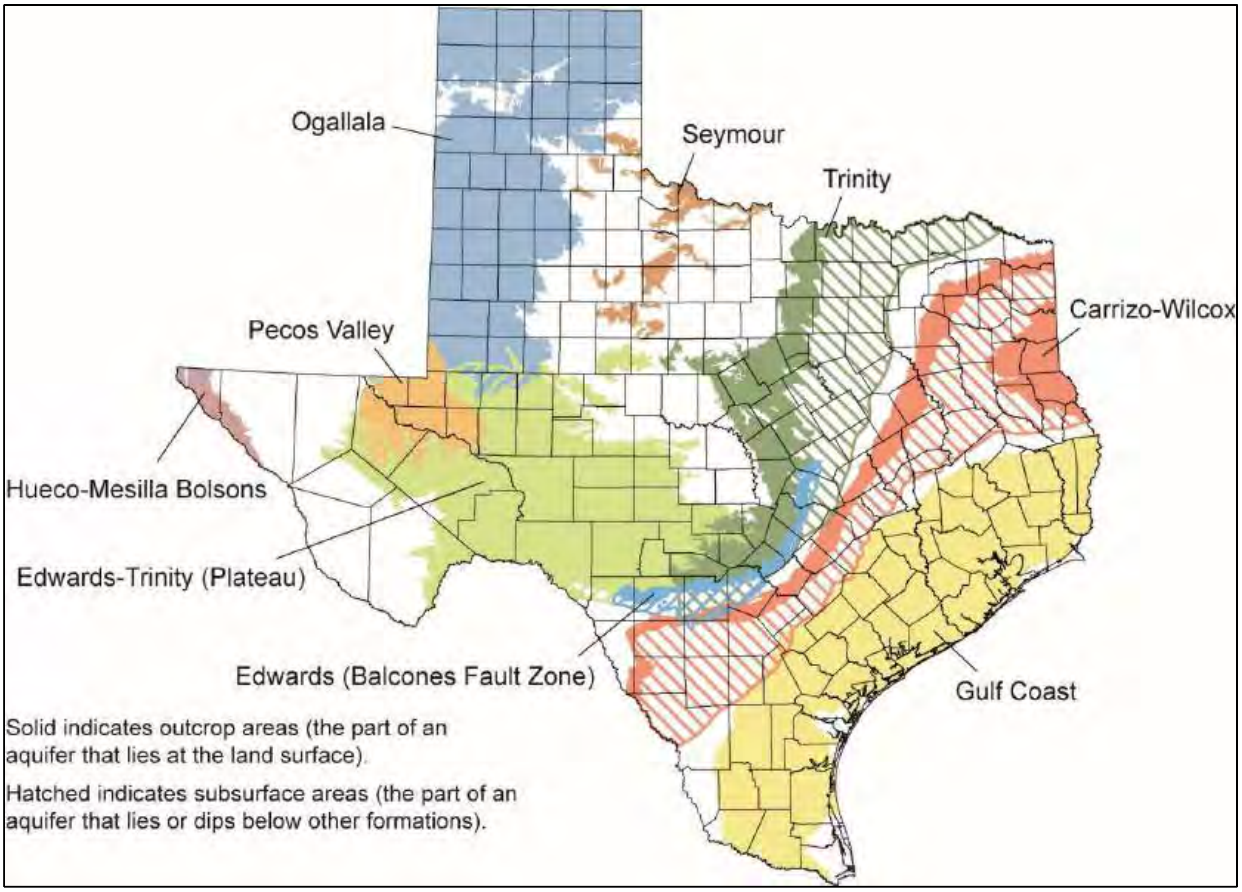


Figure 1-1. The major aquifers of Texas.

1.3 Confined and unconfined aquifers

Aquifers are geologic formations that contain sufficient saturated permeable material to yield significant quantities of water to wells and springs. A wide range of geologic formations can host aquifers, including sand, gravel, limestone, sandstone, or fractured igneous rocks. Permeability is a measure of how well a material can transmit water. Aquifer materials like gravel transmit water quickly and have high permeability. Aquifer materials like cemented sandstone transmit water more slowly and have lower permeability. Materials such as shales are typically classified as aquitards, or formations that restrict water movement, and have low permeability.

Some of the largest aquifers in Texas, including the Ogallala, Gulf Coast, and Carrizo-Wilcox aquifers, consist of sedimentary rocks with intergranular porosity and relatively high permeability. Limestone aquifers, such as the Edwards (Balcones Fault Zone) Aquifer, contain water in crevices and caverns caused mainly by the dissolution of limestone by groundwater. The Igneous Aquifer in West Texas is an example of an aquifer where groundwater flows through cracks, fractures, and joints developed in igneous and volcanic rocks.

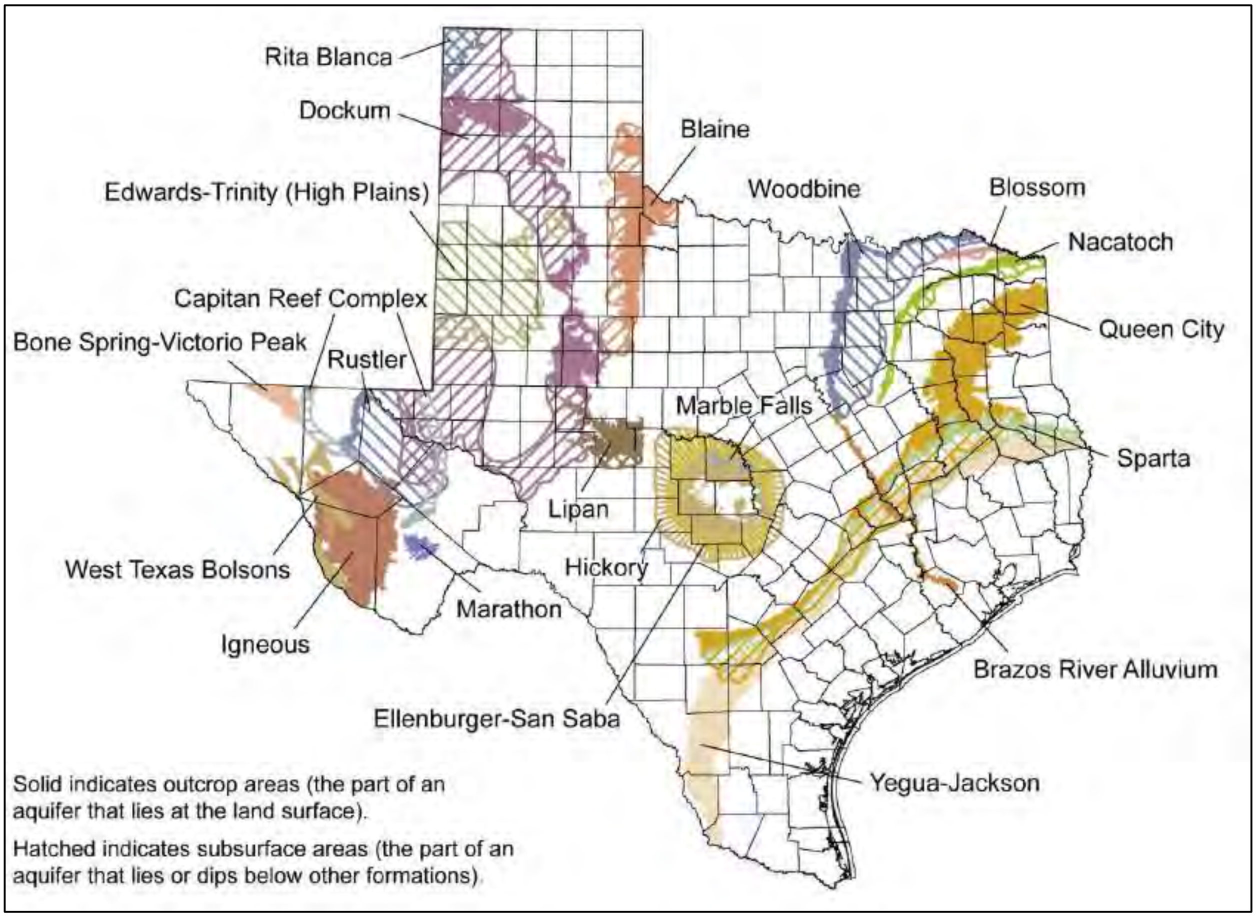


Figure 1-2. The minor aquifers of Texas.

The TWDB classifies Texas aquifers as confined (subsurface) or unconfined (outcrop). Confined and unconfined aquifers respond differently to pumping and other surface processes (Figure 1-3).

Unconfined aquifers are sometimes referred to as "water table aquifers" and occur in the outcrop area of the aquifer. An unconfined aquifer is one in which the water table is at or near atmospheric pressure and is the upper boundary of the aquifer. Because the aquifer is not under pressure, the water level in a well is the same as the water table outside the well (left side of Figure 1-3). Water levels in a well completed in an unconfined aquifer rise and fall in response to changes in recharge and discharge. When water levels decline, water physically drains from the aquifer. The specific yield of unconfined aquifers, or the volume of water produced per unit decline in water level, is typically close to the effective porosity and can range from 0.05 to 0.35 for sedimentary aquifers, depending on the aquifer material.

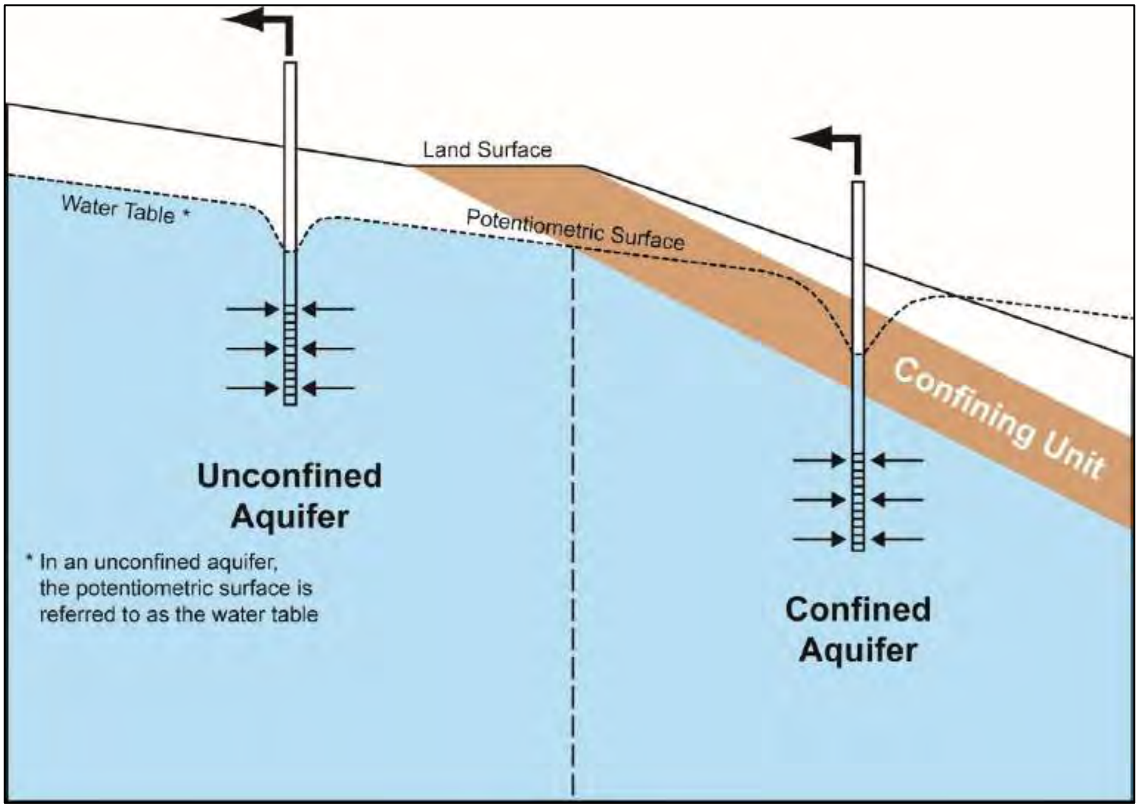


Figure 1-3. Schematic cross-section of an aquifer with unconfined and confined portions.

Confined aquifers are sometimes referred to as "artesian aquifers." These aquifers are overlain by confining units, such as clay and shale layers, that do not readily transmit groundwater (right side of Figure 1-3). These aquifers usually occur well below the land surface, are completely saturated with groundwater, and are under pressure. Because of this pressure, water in wells penetrating confined aquifers rises above the top of the aquifer. In some cases, water levels may rise above the land surface, resulting in a flowing well. The level to which water rises in a confined aquifer is the potentiometric surface of the confined aquifer. Pumping from wells reduces the water pressure in the aquifer and lowers the potentiometric surface in a "cone of depression" around the well, even though the aquifer remains fully saturated.

Groundwater storage in confined aquifers consists of two parts, the storativity and specific yield. The storativity represents the groundwater released from confined storage while the aquifer remains fully saturated. The specific yield represents groundwater released from the aquifer if the water level is drawn down below the top of the aquifer, at which point it becomes unconfined. The storativity is typically much smaller than the specific yield, ranging from 0.005 to 0.00005. Large decreases in the potentiometric surface over extensive areas typically are required to produce substantial quantities of water from confined aquifers; the total volume of the cone of depression in a typical confined aquifer is about 2,000 times larger than the total volume of the cone of depression in a typical unconfined aquifer (Alley and others, 1999).

The major and minor aquifers of Texas include both confined and unconfined systems. In many cases, a single aquifer system consists of both confined and unconfined portions. The Ogallala and Seymour aquifers are unconfined throughout; with a specific yield around 0.15, they can produce large volumes of water per unit area. The Gulf Coast Aquifer is also classified as unconfined in the outcrop area, where it is characterized by a shallow groundwater flow system. This aquifer has a complex structure of interlayered sand, silt, and clay strata that can result in a much lower specific yield, particularly in the deeper regional flow environment where confined conditions predominate. The Carrizo-Wilcox and Trinity aquifers are examples of systems that include both confined and unconfined portions. These aquifers are unconfined where they outcrop and are exposed at the ground surface but become confined in deeper zones where permeable strata extend below clay and shale formations.

1.4 Tributary and non-tributary aquifers

Although Texas water law does not define the meaning of tributary aquifer, the term has been applied in a number of court cases across the nation. In general, a tributary aquifer is an aquifer that has groundwater that discharges to surface water. Conversely, non-tributary aquifers do not discharge groundwater to surface water. Groundwater that is isolated from other aquifers and surface water is designated as non-tributary. Quatrochi (1996) uses these concepts in the context of the Clean Water Act definition of waters of the United States.

The concept of tributary aquifers is also used in the context of water management by the State of Colorado. Colorado considers that if groundwater production diminishes surface-water flows at an annual rate greater than one-tenth of 1 percent of the annual rate of groundwater withdrawal within 100 years, then the groundwater is considered tributary. Groundwater that is isolated from other aquifers and surface water is designated as non-tributary (Colorado Department of Natural Resources, 2016). Direct use of the Colorado definition for tributary groundwater is not necessarily appropriate for Texas because these terms are applied within a legal context entirely different from the water law in Texas. Additionally, the Colorado law is used to define administrative zones within an aquifer rather than to classify entire aquifers as tributary or non-tributary. As in Colorado, most aquifers in Texas include both unconfined outcrop zones, where the aquifer interacts with surface rivers and streams, and confined zones, where the aquifer is more or less separated from surface flows by less permeable formations.

Groundwater and surface-water interactions also vary over time, further complicating delineation of tributary zones. The normal seasonal cycles of recharge and discharge and longer term groundwater responses to drought and flooding affect groundwater and surface-water relationships. For example, groundwater production for municipal, industrial, and agricultural purposes has resulted in water-level declines in many Texas aquifers, such that springflows and groundwater contributions to surface water in general are greatly reduced from pre-development volumes.

Finally, the volume of groundwater discharge that is “enough to directly and significantly affect that body of water, stream, or river” depends on the total volume of flow in the surface-water body. In western parts of Texas perennial water sources are scarce, and even relatively small springs and seeps may be important resources for landowners and wildlife.

In Oklahoma, conflict between surface-water and groundwater rights led to litigation over management of the Arbuckle-Simpson Aquifer, although the term “tributary aquifer” was not specifically applied. Oklahoma’s Senate Bill 288, passed in 2003, imposed a moratorium on issuing groundwater permits for certain uses of the Arbuckle-Simpson Aquifer until the Oklahoma Water Resources Board approved maximum annual yield limits that do not reduce flow in springs and streams (Oklahoma Water Resources Board, 2003). The hydrological study to define the maximum annual yield limits took a decade to complete. In 2013 the Oklahoma Water Resources Board ruled that the maximum annual yield of the aquifer was 2.4 acre-inches per acre per year, which represents only about 10 percent of 2.0 acre-feet per acre per year of groundwater use previously allowed (Oklahoma Water Resources Board, 2013). The final maximum annual yield was contested as a “taking” by a group of affected landowners. The 2013 ruling was upheld on appeal in 2015 (State Impact Oklahoma, 2015).

In summary, there are a number of complicating factors when considering the question of tributary and non-tributary aquifers. This study is statewide in scope and evaluates the tributary groundwater conditions on a regional scale. Detailed analyses of groundwater and surface-water interactions will be required to address specific local questions of whether or not groundwater may be tributary in character.

2 Quantity and Quality of Groundwater in Confined and Unconfined Aquifers

The usability of groundwater resources depends on the quantity and quality of the water contained in each aquifer as well as the needs of users. The total recoverable storage in the saturated pore space of aquifers gives a snapshot of the quantity of groundwater in Texas, like the balance in a bank account, but doesn't address the effects or the economic viability of draining aquifers. Changes in groundwater quantity over time, reflected in water-level changes, give an indication of how we are managing the available resources. Water quality issues can also affect the production and use of groundwater. This section evaluates TWDB data on the quantity and quality of water in the confined and unconfined aquifers of Texas. A separate TWDB report to the legislature describes brackish groundwater resources outside the established areas of officially named aquifers.

2.1 Groundwater quantity

Key points:

- Confined and unconfined major and minor aquifers contain an estimated 16.8 billion acre-feet of fresh and brackish groundwater.
- Groundwater storage in confined aquifers consists of water stored under pressure in the saturated system (confined groundwater) plus water released as the aquifer physically drains under atmospheric pressure (unconfined groundwater). The amount of groundwater that can be produced before the aquifer starts to desaturate is very small compared to the total amount of water stored—probably much less than 1 percent of the total storage volume.
- The annual volume of groundwater pumped in Texas peaked in the 1970s and has been relatively stable for the past 20 years. Annual groundwater pumping is between approximately 8 and 10 million acre-feet per year.
- Large areas of some Texas aquifers have experienced drawdown of water levels over the past 20 years. The Hueco-Mesilla Bolsons, portions of the Ogallala, the northern Trinity, the northern Carrizo-Wilcox, and portions of the Gulf Coast aquifers have experienced consistent declines.
- Rising water levels in the Houston area are a result of reduced groundwater pumping to mitigate land subsidence.
- Emerging areas of drawdown are seen in the Ogallala Aquifer in the Pampa area (Roberts County) and in the Carrizo-Wilcox Aquifer south and west of San Antonio.

For this study, the quantity of groundwater in the state's unconfined and confined aquifers is expressed in terms of how much groundwater is physically present in the aquifers. This is in contrast to groundwater supply or availability, which represents the estimated amount of groundwater that can be withdrawn or is accessible as a result of policy decisions and management directives. For groundwater supply and availability estimates, please refer to the 2017 State Water Plan (TWDB, 2016), which includes estimates developed through joint planning efforts by groundwater conservation district representatives and regional water planning groups, and the study by Hermitte and others (2015), comparing groundwater availability estimates with the desired future conditions developed by groundwater management areas.

The quantity of groundwater in Texas aquifers can be estimated in a number of ways. For the purposes of this study, the TWDB defines quantity in terms of the 'total estimated recoverable storage'. We used this approach for two reasons:

1. the Texas Legislature in 2011 identified the concept of total estimated recoverable storage as a factor in statewide joint planning activities for groundwater management, and

2. the TWDB has calculated total estimated recoverable storage for almost all of the major and minor aquifers of the state and reported these estimates to groundwater conservation districts.

Total estimated recoverable storage

Total estimated recoverable storage values represent point-in-time, static estimates of the groundwater volume present in Texas aquifers and do not account for dynamic aspects of groundwater systems such as recharge and natural discharge. The total estimated recoverable storage values do not consider possible effects of groundwater withdrawals, including degradation of water quality, subsidence, dewatering of an aquifer, or other effects.

The total volume of recoverable groundwater in storage within the defined boundaries of the major and minor aquifers is estimated to be between 4.2 and 12.6 billion acre-feet (Table 2-1). Texas aquifers range from those that are entirely freshwater aquifers, to those with both fresh and brackish aquifers, and to some that are entirely brackish. Groundwater storage in brackish systems outside the delineated aquifer boundaries is the subject of a separate TWDB report to the Texas Legislature to be delivered by December 31, 2016.

Groundwater storage is dominated by the Gulf Coast and Carrizo-Wilcox aquifers, which together account for almost two-thirds of the groundwater in storage in Texas. Much of the groundwater in these aquifers may not be readily recoverable because of the excessive depth to the base of the aquifer in parts of the confined area or may not be economically viable at this time due to the occurrence of poor-quality groundwater at depth.

Although more groundwater is pumped from the Ogallala Aquifer than all other aquifers combined, the total recoverable storage remaining in this aquifer amounts to only 95.3 million to 286 million acre-feet, or just over 2 percent of the total groundwater in storage in Texas. Groundwater in the Ogallala Aquifer is being withdrawn at a rate roughly equivalent to 2 to 5 percent of the total recoverable storage per year.

Table 2-1. Total estimated recoverable groundwater storage in Texas aquifers[1].

Aquifer	25% of total storage (acre-feet)	75% of total storage (acre-feet)	Remarks
Major Aquifers			
Carrizo-Wilcox	1,310,000,000	3,920,000,000	Includes brackish water in deep confined portions of aquifer
Edwards (Balcones Fault Zone)	6,250,000	18,800,000	Storage estimates are very sensitive to the rapid recharge and discharge characteristics of aquifer
Edwards-Trinity (Plateau)	11,400,000	34,100,000	
Gulf Coast	1,300,000,000	3,890,000,000	Includes brackish water in deep confined portions of aquifer
Hueco-Mesilla Bolsons[2]	2,250,000	6,750,000	Freshwater portion of aquifer
Ogallala	95,300,000	286,000,000	Unconfined aquifer
Pecos Valley	81,000,000	243,000,000	Includes fresh and brackish groundwater
Seymour	1,280,000	3,850,000	Groundwater is seasonally depleted and recharged
Trinity	353,000,000	1,060,000,000	Includes brackish water in deep confined portions of aquifer
Minor Aquifers			
Blaine	43,000,000	129,000,000	Predominantly brackish groundwater.
Blossom	1,770,000	5,310,000	
Bone Spring-Victorio Peak	925,000	2,780,000	
Brazos River Alluvium	803,000	2,410,000	
Capitan Reef Complex	13,800,000	41,300,000	
Dockum	373,000,000	1,120,000,000	Predominantly brackish groundwater.
Edwards-Trinity (High Plains)	5,930,000	17,800,000	
Ellenburger-San Saba	21,800,000	65,250,000	
Hickory	16,600,000	49,700,000	
Igneous	16,000,000	48,100,000	
Lipan	1,050,000	3,150,000	
Marathon	375,000	1,130,000	
Marble Falls	66,300	199,000	
Nacatoch	1,020,000	3,070,000	
Queen City	135,000,000	404,000,000	Includes brackish water in deep confined portions of aquifer.
Rita Blanca	2,780,000	8,330,000	
Rustler	9,230,000	27,700,000	
Sparta	46,500,000	140,000,000	Includes brackish water in deep confined portions of aquifer.
West Texas Bolsons	12,900,000	38,600,000	
Woodbine	56,800,000	170,000,000	Includes brackish water in deep confined portions of aquifer.
Yegua-Jackson	300,000,000	900,000,000	Includes brackish water in deep confined portions of aquifer.

Notes:

1. Aquifer storage properties and geometries in approved groundwater availability models are used to calculate total estimated recoverable storage. Values for individual aquifers are rounded to three significant figures.
2. Value from Bredehoeft and others (2004); the TWDB has not established total estimated recoverable storage values for the Hueco-Mesilla Bolsons Aquifer.

2.2 Water-level changes

Key points:

- Groundwater levels in all major and minor aquifers have declined.
- Some groundwater declines have been reversed locally as pumping patterns change (Houston area) or recharge exceeds discharge (portions of the Ogallala Aquifer and the Edwards [Balcones Fault Zone] Aquifer).

Water-level changes over time reveal the responses of Texas aquifers to recharge and discharge conditions. Since 1895 over one million groundwater levels have been measured and recorded in Texas aquifers. Every year, an estimated 8,600 wells representing every county in Texas and every major and minor aquifer are monitored by the TWDB, cooperating groundwater conservation districts, and the U.S. Geological Survey. These data form much of the basis for evaluating the condition of Texas aquifers.

Figure 2-1 illustrates water-level changes derived from groundwater availability model estimates of changes in water levels between recently calibrated years (generally around the year 2000) and water levels in pre-development (pre-pumping) years. Water-level declines in the eastern part of the state tend to be declines in artesian pressure, whereas water-level declines in the western part of the state tend to be declines in the water table. Total water-level declines in the state's aquifers since 1900 range from less than 50 feet to more than 1,000 feet. The greatest water-level declines are in the Trinity Aquifer, focused in the Dallas–Fort Worth and Waco areas. One hundred years ago, wells in much of the Trinity Aquifer flowed at the surface, releasing so much artesian pressure that most ceased to flow by the mid-1910s. For example, a well screened in the lower Trinity Aquifer in Austin initially "threw water 40 feet high" (Brune, 1975). Other areas of large water-level declines are in the Carrizo-Wilcox Aquifer in the Winter Garden irrigation area north of Laredo; near Lufkin, Nacogdoches, and Tyler; and in the Gulf Coast Aquifer near Houston. Water levels in parts of the Ogallala Aquifer, an unconfined aquifer, have also declined more than 300 feet. All of these water-level declines have been caused by groundwater pumping, primarily since the 1950s. Figure 2-2 tracks the total groundwater pumping in Texas from 1937 to 2013, as estimated by the TWDB and the U.S. Geological Survey (USGS, 1950 to 2010).

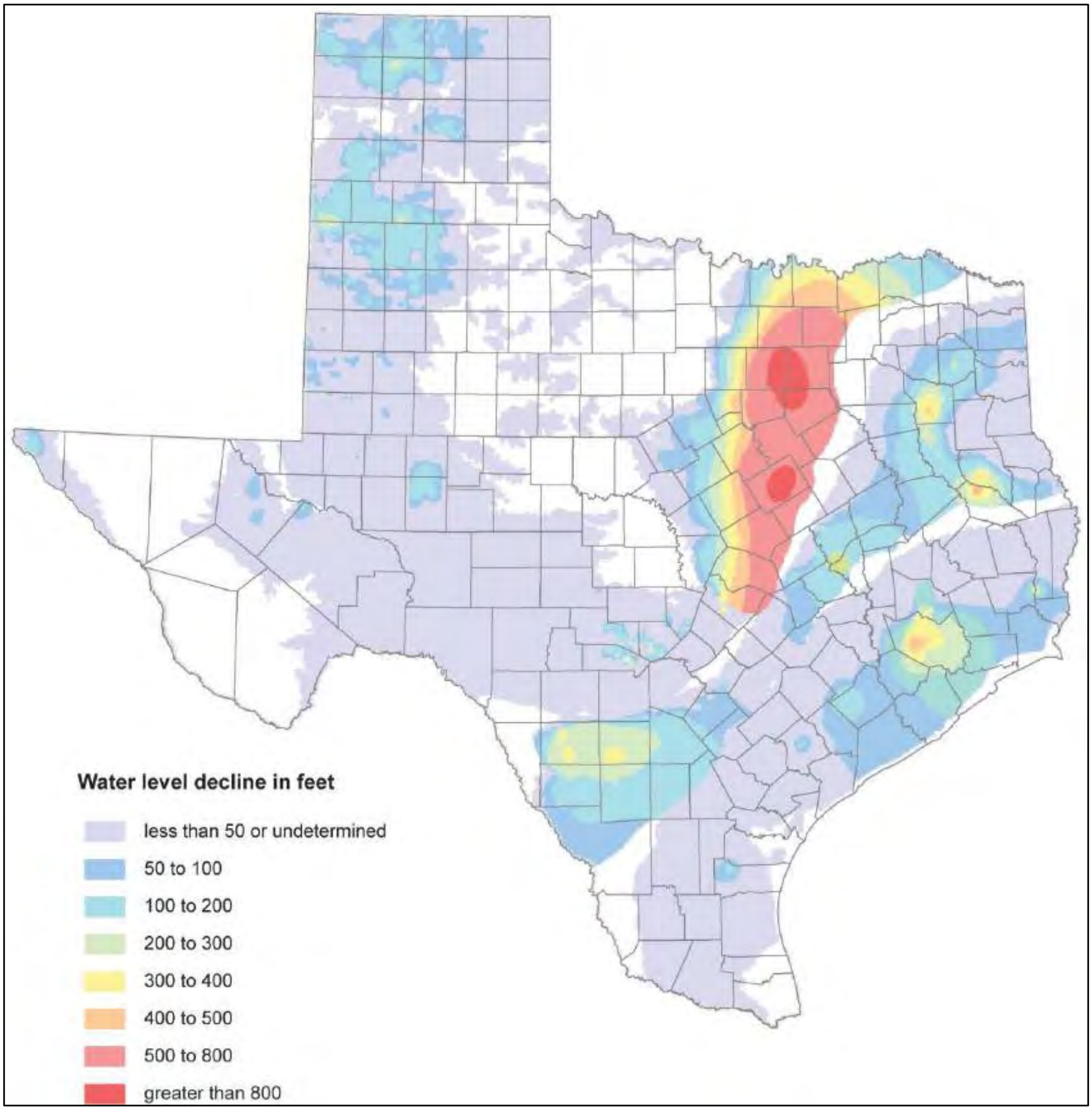


Figure 2-1. Estimated total water-level declines in the major aquifers of Texas.

For this study, we also considered a series of groundwater level measurements over the last 20 years—using data from between 3,786 and 4,606 wells—in five-year intervals beginning in 1995. We calculated the difference between the minimum depth to groundwater measured during the non-pumping season at the beginning and end of each period in each well and then used geostatistical interpolation (with default kriging parameters in ArcGIS 10.3) to generate a map of water-level changes across the areas of all major aquifers in Texas.

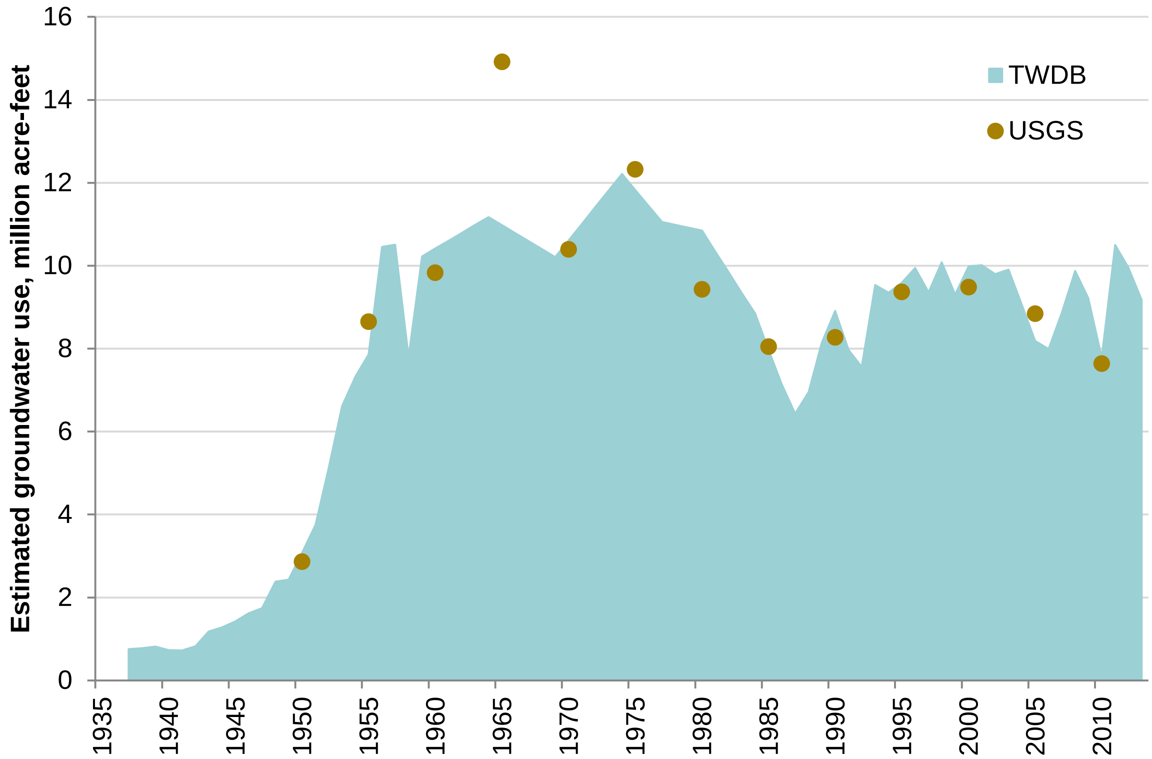


Figure 2-2. Estimated total annual groundwater use in Texas, in millions of acre-feet.

Figure 2-3 shows four maps of groundwater-level changes from 1995 to 2015. These maps show the dynamic nature of groundwater conditions, illustrating several areas where there have been significant groundwater-level increases or decreases. Consistent water-level declines occurred in several areas, including

- portions of the Ogallala Aquifer with active irrigation (Dallam and Hartley counties; Parmer, Castro, Lamb, and Hale counties; Gaines and Dawson counties);
- the Trinity Aquifer in the Dallas-Fort Worth and Waco areas;
- the Gulf Coast Aquifer north of Houston; and
- the southern Carrizo-Wilcox, where large-scale oil-field development has taken place since 2005.

Most wells show moderate drawdown over the 20-year period. The median drawdowns for all aquifers except the Edwards (Balcones Fault Zone) and Trinity aquifers are less than 10 feet over 5 years. Areas of greater drawdown are generally localized in the vicinity of municipal water supply well fields. The relatively large drawdowns in the Edwards (Balcones Fault Zone) and Trinity aquifers also reflect the unique hydrologic properties of these aquifers, specifically the low storage coefficients for the confined portions of these aquifers, which result in larger drawdown for a given volume of pumping, relative to unconfined systems.

Areas of increased water levels between 2000 and 2005 are likely the result of reduced demand and recharge from major storm events to the Edwards (Balcones Fault Zone) Aquifer and other aquifers in South and Central Texas. For example, in July 2002 a large area of Central Texas received 34 inches of rain in about a week.

In contrast, from 2010 to 2015 the state experienced significant drought. This led to widespread increases in groundwater use as surface-water supplies were diminished. Every aquifer experienced decreasing groundwater levels in this five-year period, with the exception of some areas in the Gulf Coast Aquifer, where pumping limits to mitigate subsidence have been in place for 40 years.

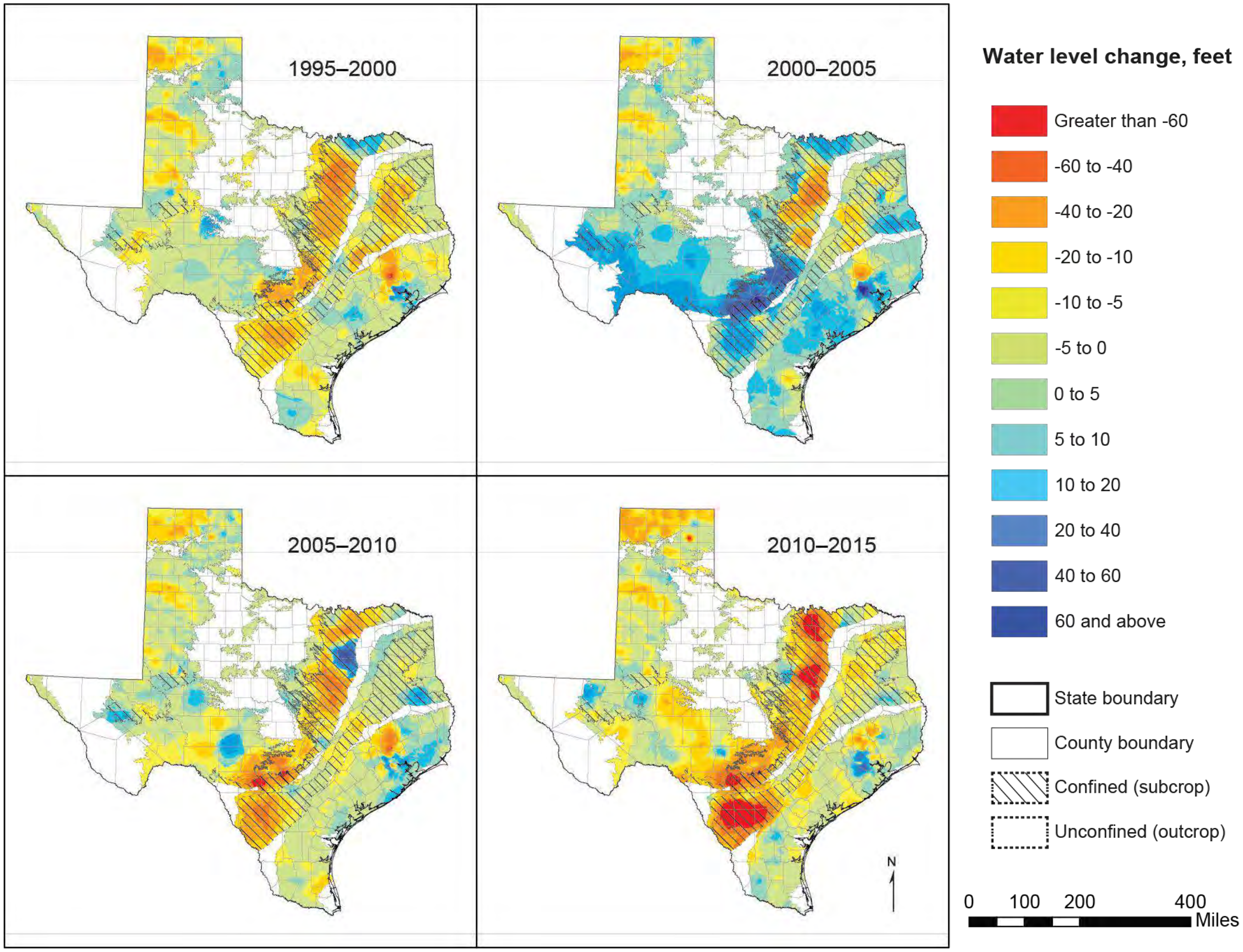


Figure 2-3. Water-level changes measured by the TWDB monitoring program in individual wells completed in major and minor aquifers in Texas, 1995 through 2015.

2.3 Groundwater quality

Key points:

- Most groundwater in major and minor aquifers is fresh. The total dissolved solids content of groundwater in these aquifers is mostly less than 1,000 milligrams per liter.
- The official boundaries of many of the aquifers are determined based on water quality zonation; the water-bearing formation may continue beyond an aquifer boundary but contains more saline water.
- Areas of the southern Ogallala, the Pecos Valley, the Seymour, and the southern Gulf Coast aquifers and the down-dip confined areas of the Trinity and Carrizo-Wilcox aquifers are brackish.
- Groundwater quality in minor aquifers is more variable. Areas of brackish groundwater are present in most of the minor aquifers.
- Groundwater quality reflects complex interactions between water and the geologic formation. Research on the geochemical effects of recharge and changing hydraulic gradients is part of the TWDB groundwater quality monitoring program.

Groundwater quality—expressed as salinity or total dissolved solids concentrations—has been studied extensively in the state's major and minor aquifers. The TWDB collects water samples from wells and springs in major and minor aquifers throughout the state as part of its ambient groundwater quality monitoring program. These samples are analyzed by an accredited lab to provide data to characterize the natural quality of groundwater in aquifers and any changes that may have occurred over time. Over a four-year sampling period, the TWDB collects or obtains—from samples collected by cooperators—analyses of up to 1,300 groundwater quality samples. No significant changes in water quality have been detected in groundwater from wells sampled by the TWDB and its cooperators, although evaluation is ongoing.

Groundwater quality is classified by the U.S. Geological Survey and the TWDB according to salinity (total dissolved solids) and the following criteria:

- Fresh–total dissolved solids concentrations less than 1,000 milligrams per liter
- Brackish–total dissolved solids concentrations between 1,000 and 10,000 milligrams per liter
- Saline–total dissolved solids concentrations greater than 10,000 milligrams per liter

The TWDB Brackish Aquifer Characterization System further subdivides brackish groundwater into slightly saline (total dissolved solids concentrations between 1,000 and 2,999 milligrams per liter) and moderately saline (total dissolved solids concentrations between 3,000 and 9,999 milligrams per liter) categories.

The total dissolved solids content of groundwater affects its usability for different purposes. Total dissolved solids are a measure of the salinity of water and represent the amount of minerals dissolved in water, generally reported as milligrams per liter of water. If water is too saline, then it may not be drinkable without treatment or it may not be suitable for irrigation. Water with total dissolved solids less than 1,000 milligrams per liter is considered fresh and is generally usable. Water with total dissolved solids of as much as 1,500 milligrams per liter may be used to irrigate crops, depending on the type of crop and the levels of other dissolved constituents in the water. Water with total dissolved solids as high as 3,000 milligrams per liter may still be used for livestock. Water with total dissolved solids between 1,000 and 10,000 milligrams per liter, also called brackish groundwater, is a potential source of water for desalination.

We mapped the total dissolved solids content of Texas groundwater using analytical results from the TWDB database for water samples from wells completed in all major aquifers. Several groundwater conservation districts and the U.S. Geological Survey provided additional data. Older data were not excluded from our evaluation as analytical methods for total dissolved solids have not changed significantly over time and are generally reliable. Where more than one value was listed for a particular well, only the latest value was used. We used a total of almost 40,000 data points to map the distribution of total dissolved solids across the state. Sample counts per aquifer ranged from over 9,000 data points in the Gulf Coast Aquifer to just over 600 data points in the Hueco-Mesilla Bolsons Aquifer. We used ArcGIS 10.3 to interpolate the data using ordinary kriging and plotted the results over the area covered by the major aquifers (Figure 2-4).

Much of the water in the state’s aquifers is fresh; however, brackish groundwater is more common than fresh groundwater in the southern Gulf Coast area and in large parts of west Texas. The confined portions of many aquifers become more saline down-dip (deeper in the aquifer) as a result of limited circulation and interaction with aquifer materials, in particular with evaporitic minerals that are present deeper in the geological section in many of the sedimentary basins of Texas. Our map of total dissolved solids is limited to officially-defined areas of the major aquifers and does not show the full down-dip extent of the water-bearing formations.

Although the vast majority of groundwater used for drinking in Texas meets state and federal requirements for safety, in some parts of the state naturally occurring levels of total dissolved solids, arsenic, and radionuclides, as well as human-caused nitrate contamination, prevent the water from meeting those standards. A TWDB study by Reedy and others (2011) documented the distribution of these naturally occurring contaminants in Texas groundwater. We discuss these water quality issues in the aquifer summaries presented in Chapter 6 of this report.

Localized areas of anthropogenic contamination are also present in Texas groundwater as a result of commercial, industrial, and agricultural activities. A 2011 TWDB study of groundwater in the vicinity of potential sources of contamination detected the herbicides atrazine and its metabolites, simazine, and prometon as well as the chlorinated compounds tetrachloroethylene, a dry-cleaning product, and chloroform, a common public water supply disinfection byproduct, in over 10 percent of the groundwater samples tested. Most of these detections were at concentrations below the laboratory's practical quantitation limits, and only two, tetrachloroethylene and atrazine, had greater than 1 percent of detections above the practical quantitation limits (O'Rourke and others, 2011). The Texas Commission on Environmental Quality also publishes an annual report on the quality of groundwater in Texas, listing all current groundwater contamination cases in the state and their enforcement status (TCEQ, 2015). Our study does not attempt to address specific instances of groundwater contamination at regulated facilities.

Finally, the TWDB has conducted extensive geochemical investigations of Texas groundwater to support the groundwater availability modeling program (Scanlon and others, 2011; Kreitler and others, 2013a; Kreitler and others 2013b; Young and others, 2014). The chemical and isotopic composition of groundwater serves as a powerful tool for understanding the natural recharge, flow, and reaction pathways in Texas aquifers.

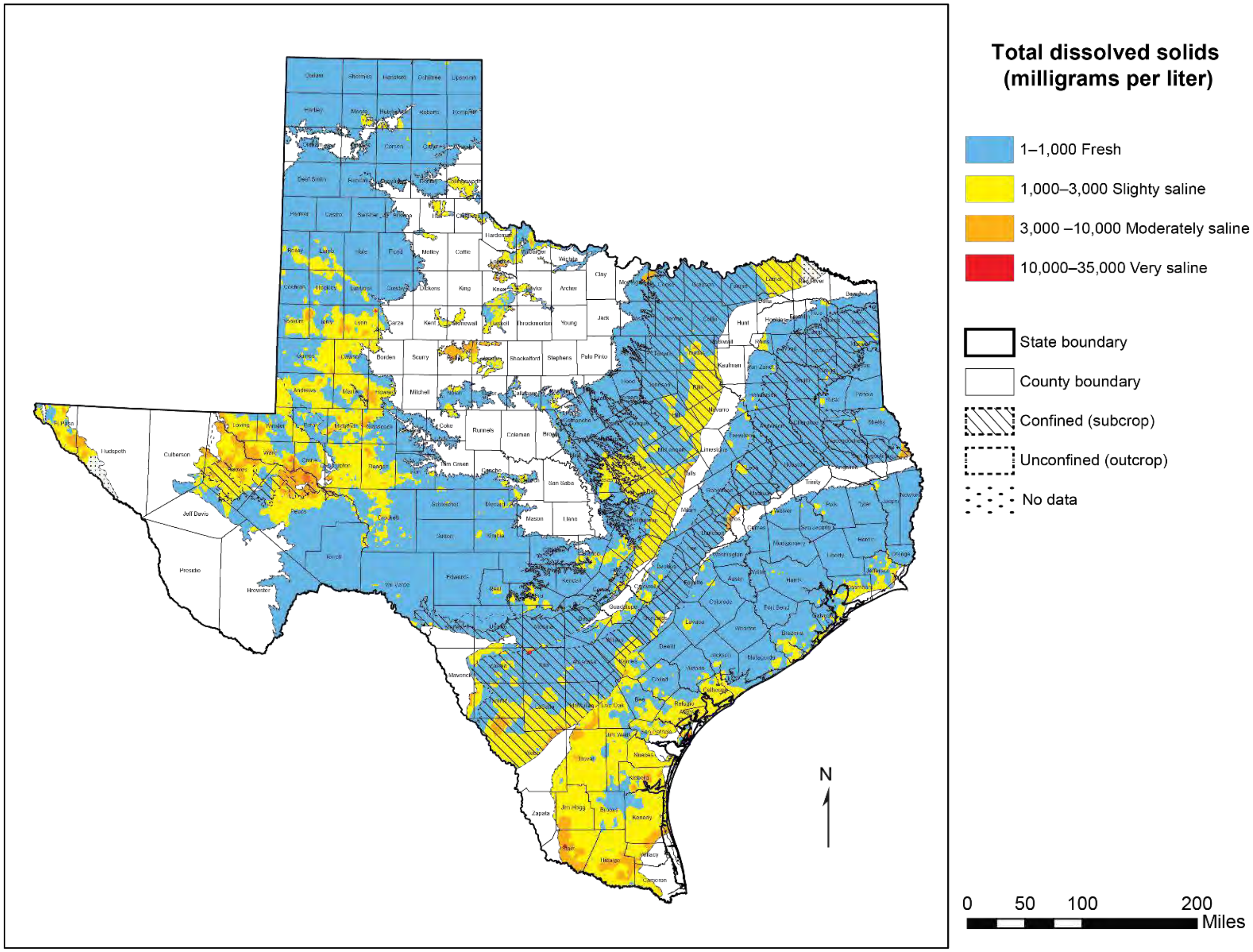


Figure 2-4. Concentration of total dissolved solids in wells sampled by TWDB and other cooperators through 2015.

3 Groundwater and Surface-water Interactions

Key points:

- All aquifers contribute some groundwater to the baseflow of streams and rivers in Texas.
- An estimated 9.3 million acre-feet of groundwater flows from major and minor aquifers to surface water in an average year. This represents about 30 percent of the average surface-water flow in Texas.
- Aquifer interactions with surface water vary regionally and within each aquifer. Between 14 and 72 percent of streamflow over aquifer outcrop areas is due to groundwater discharge from major and minor aquifers.
- The largest groundwater contributions to surface water occur in East Texas, the Hill Country, and around major springs in West Texas.
- The aquifer with the most groundwater discharge to surface water is the Gulf Coast Aquifer, with an estimated 3.8 million acre-feet per year.
- About half of Texas aquifers contribute less than 50,000 acre-feet per year to surface-water flows.

3.1 Background

Groundwater and surface-water interactions have been an area of interest for decades. Observations of groundwater and surface-water interaction originally focused on springflow; TWDB Report 189 (Brune, 1975) documents the major and historical springs of Texas. When the document was published, it was estimated that 3 million acre-feet per year flowed from Texas aquifers to surface water through large and small springs. Nearly half of the documented large springs were associated with two major aquifers: the Edwards (Balcones Fault Zone) Aquifer and the Edwards-Trinity (Plateau) Aquifer. The counties with the most springs classified as large were San Saba, Val Verde, and Kerr counties. Figure 3-1 shows the location of springs in the TWDB Groundwater Database along with the major aquifers in Texas, based on data from Heitmuller and Reece (2013). But groundwater and surface-water interactions involve much more than observable springs. The most difficult aspect of groundwater and surface-water interaction is quantifying the relationships along stretches of streams and rivers where diffuse groundwater flow contributes to or originates as aquifer recharge from surface water. In these cases, direct measurements and observations are problematic. Furthermore, seasonal changes in the magnitude and direction of groundwater and surface-water interactions confound efforts to quantify the interactions on a statewide level.

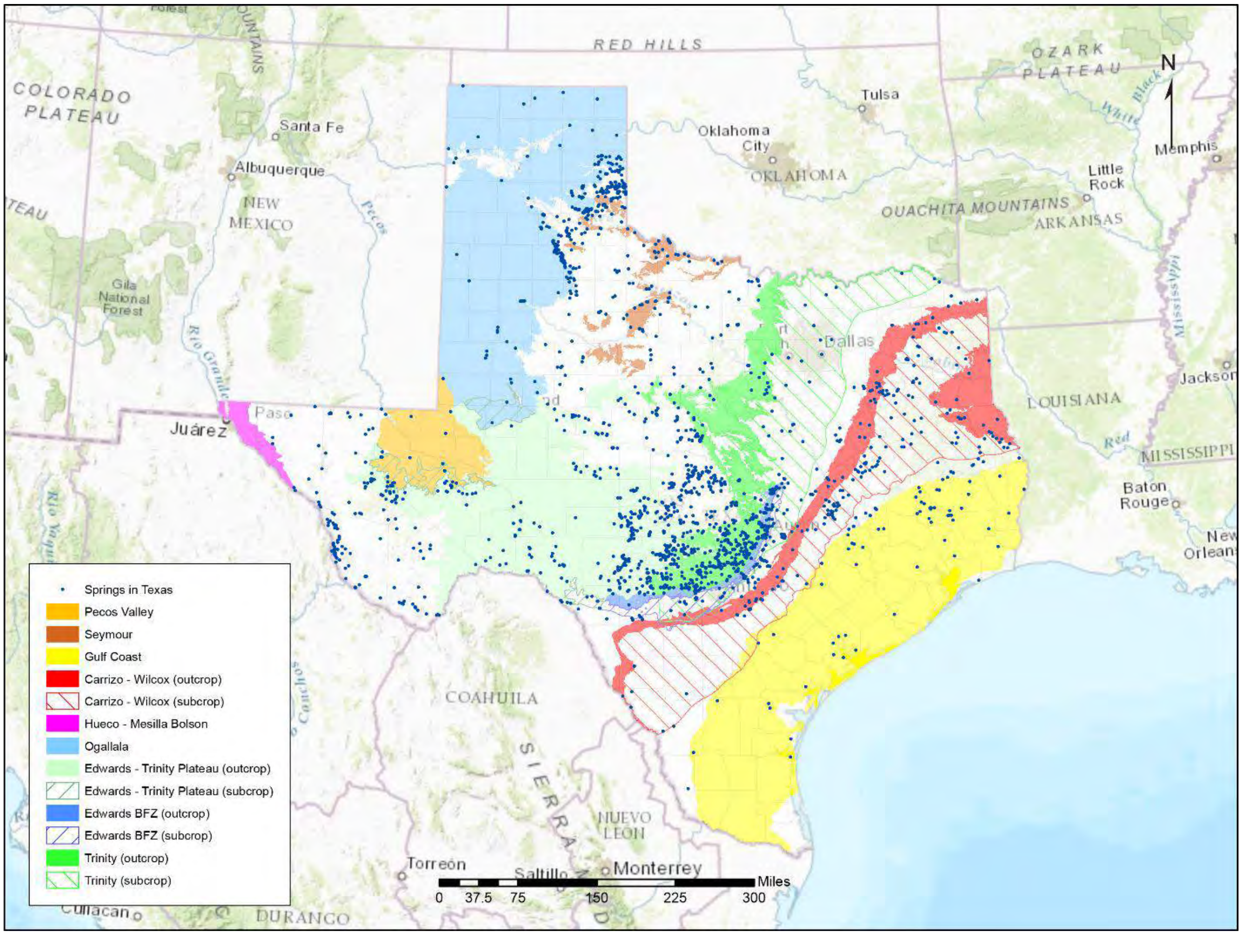


Figure 3-1. **Location of springs in Texas and the major aquifers of Texas (data from Heitmuller and Reece, 2013).**

A number of research projects on the topic have been conducted in recent decades, several of which have been funded by either the TCEQ or the TWDB. Parsons (1999) provides a descriptive statewide review of groundwater interaction in the major river basins; a qualitative summary is provided in Table 3-1. Scanlon and others (2005) compiled an extensive list of references on the general topic of groundwater and surface-water relationships, with particular focus on Texas. That study also examined techniques to quantify groundwater and surface-water interactions at the watershed scale in terms of both water flow and water quality. Detailed characterization of groundwater and surface-water interactions at the scale of entire river basins or aquifers remains incomplete.

Table 3-1. Summary of groundwater and surface-water interactions in the river basins of Texas.[1]

River Basin	Aquifers	Groundwater and surface-water interaction	Degree/direction of interaction
Brazos-Colorado Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Canadian River	Ogallala	Aquifer generally contributes to streams	Variable
Colorado River	Llano Uplift aquifers, Edwards-Trinity (Plateau), Trinity, Carrizo-Wilcox, Gulf Coast	Groundwater discharges to streams; surface water recharges groundwater	Large river basin has variable interaction due to geologic and climate variations
Colorado-Lavaca Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Cypress Creek	Carrizo-Wilcox, Queen City	Groundwater discharges to streams; surface water recharges groundwater	Variable (and generally diffuse) distribution of interactions
Guadalupe River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox, Gulf Coast	Aquifer generally contributes to streams	Variable
Lavaca River	Gulf Coast	Aquifer generally contributes to streams	Variable
Lavaca-Guadalupe Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Neches River	Carrizo-Wilcox, Queen City, Sparta, Gulf Coast	Aquifers generally contribute to streams	
Neches-Trinity Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	
Nueces River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox, Queen City, Sparta, Gulf Coast	Aquifers generally contribute to streams with some surface water recharge of aquifer in some locations	Variable
Nueces-Rio Grande River Basin	Gulf Coast	Aquifer generally contributes to streams	Variable

Table 3-1 (continued). Summary of groundwater and surface-water interactions in the river basins of Texas.[1]

River Basin	Aquifers	Groundwater and surface-water interaction	Degree/direction of interaction
Red River	Ogallala, Seymour	Aquifers generally contribute to streams	Seasonal variability
Sabine River	Carrizo-Wilcox, Nacatoch, Queen City, Gulf Coast	Groundwater discharges to streams; surface water recharges groundwater	
San Antonio River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox	Aquifers generally contribute to streams with some surface water recharge of aquifer in some locations	Variable
San Antonio-Nueces Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
San Jacinto River	Gulf Coast	Aquifer generally contributes to streams	Variable
San Jacinto-Brazos Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Sulphur River	Trinity, Woodbine, Carrizo-Wilcox	Streams contribute to Trinity and Woodbine aquifers; Carrizo-Wilcox Aquifer discharges to streams	Variable (and generally diffuse) distribution of interactions
Trinity River	Trinity, Woodbine, Nacatoch, Carrizo-Wilcox, Queen City, Sparta	Groundwater discharges to streams; surface water recharges groundwater	Large river basin has variable interaction due to geologic and climate variations
Trinity-San Jacinto Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	

1. Information in table summarized from Parsons (1999).

3.2 Study approach

House Bill 1232 directed the TWDB to determine the contributions of groundwater from major and minor aquifers to surface water in the state of Texas and to produce a map of these contributions. As noted above, there are numerous studies of groundwater and surface-water interactions but none provide a quantitative evaluation of groundwater contributions from all major and minor aquifers. We evaluated several possible technical approaches for this evaluation but chose to use a statewide baseflow analysis to determine the contributions of groundwater flows to surface water with consistent scale and conceptualization across the state. Although the TWDB groundwater availability models are capable of calculating groundwater flows to surface-water bodies, we decided not to use these models for this purpose since they are generally not appropriately scaled, conceptualized, or calibrated to model groundwater and surface-water interactions.

For this study, baseflow is defined as the component of sustained natural streamflow in the absence of direct runoff from precipitation and attributed specifically to natural groundwater discharge from the underlying outcrops of major and minor aquifers. Estimates of baseflow are conceptualized as the positive net flow of groundwater to surface water in excess of any surface-water losses to the underlying aquifer(s). The hydrologic process of groundwater discharge into surface water is assumed to occur naturally through stream beds and/or through seeps and springs contributing directly to a surface-water body or its tributaries within a surface-water drainage basin.

The U.S. Geological Survey has compiled a geospatial dataset of annual flow and basin characteristics for stream gages in the 48 contiguous states, including 599 locations in Texas (Wolock, 2003a). The annual flow data include the average annual streamflow and the average annual baseflow index (Wolock, 2003a). The basin characteristics used for this study include the watershed drainage area and the hydrologic landscape region associated with each of the stream gages. The baseflow index is the fraction of the average annual streamflow attributed to baseflow for periods of record representing unregulated streamflow at each site. The baseflow indices were computed by the U.S. Geological Survey using an automated deterministic, smoothed-minima hydrograph separation program.

The U.S. Geological Survey has also compiled a geospatial dataset of the hydrologic landscape regions of the United States (Wolock, 2003b and Wolock, 2004). Hydrologic landscape regions provide a framework for regionalizing streamflow characteristics based on the assumption that watersheds with similar slopes, soils, geology, and climate have the same response to precipitation and groundwater and surface-water interactions. The hydrologic landscape regions of Texas consist of watersheds ranging in size from 0.39 square miles to 3,267 square miles, with an average of 104 square miles, aggregated into 12 of the 20 possible hydrologic landscape regions developed by the U.S. Geological Survey.

We grouped the 599 Texas stream gage locations according to hydrologic landscape region and interpolated the average annual streamflow values and the average annual baseflow indices within each region on a 1-kilometer grid. We multiplied the average annual streamflow for each grid cell by the average annual baseflow to calculate a dataset describing the baseflow volume as a fraction of the average annual streamflow. We then used the ArcGIS zonal statistics tool to assign the average annual baseflow for each watershed polygon. Finally, the hydrologic landscape regions were intersected with the outcrop areas of the major and minor aquifers to create a map of the estimated baseflows from groundwater to surface waters of Texas for each hydrological landscape unit overlying an aquifer (Figure 3-2).

3.3 Summary

The estimated average annual baseflow from each aquifer is listed in Table 3-2 and illustrated graphically in Figure 3-3. In total, the net estimated average flow from the major and minor aquifers of Texas to surface water is about 9.3 million acre-feet per year. This means that on average, slightly less than one-third (about 30 percent) of surface-water flow in Texas is attributable to groundwater discharge from the major and minor aquifers. This represents an average; actual baseflow may vary significantly seasonally, year to year, or in different areas of the state.

The greatest volume of baseflow occurs in East Texas and the Edwards Plateau region, in the aquifer outcrop areas of the Carrizo Wilcox, Edwards (Balcones Fault Zone), Edwards-Trinity (Plateau), Gulf Coast, Queen City, and Sparta aquifers. Major springs in west Texas also locally contribute significant volumes of baseflow to surface water bodies in that region.

The volume of baseflow per unit area of aquifer outcrop follows the general distribution of climatic zones across the state (Figure 3-4). The Edwards (Balcones Fault Zone) Aquifer contributes the most baseflow per unit area of outcrop, followed by the East and Central Texas aquifers. West Texas aquifers produce smaller volumes of baseflow per unit area. The estimated percentage of average annual streamflow in each Texas river basin that is due to baseflow from groundwater is shown in Table 3-3. A larger percentage of streamflow due to baseflow is reflected in river basins that include outcrop areas of aquifers that contribute a significant amount of baseflow.

It should be noted that the baseflow indices represent average annual values estimated from period-of-record streamflow observations prior to any surface water impoundments. The period-of-record dataset may not represent current or future conditions and does not address the inherent seasonal variability of aquifer discharge and recharge processes.

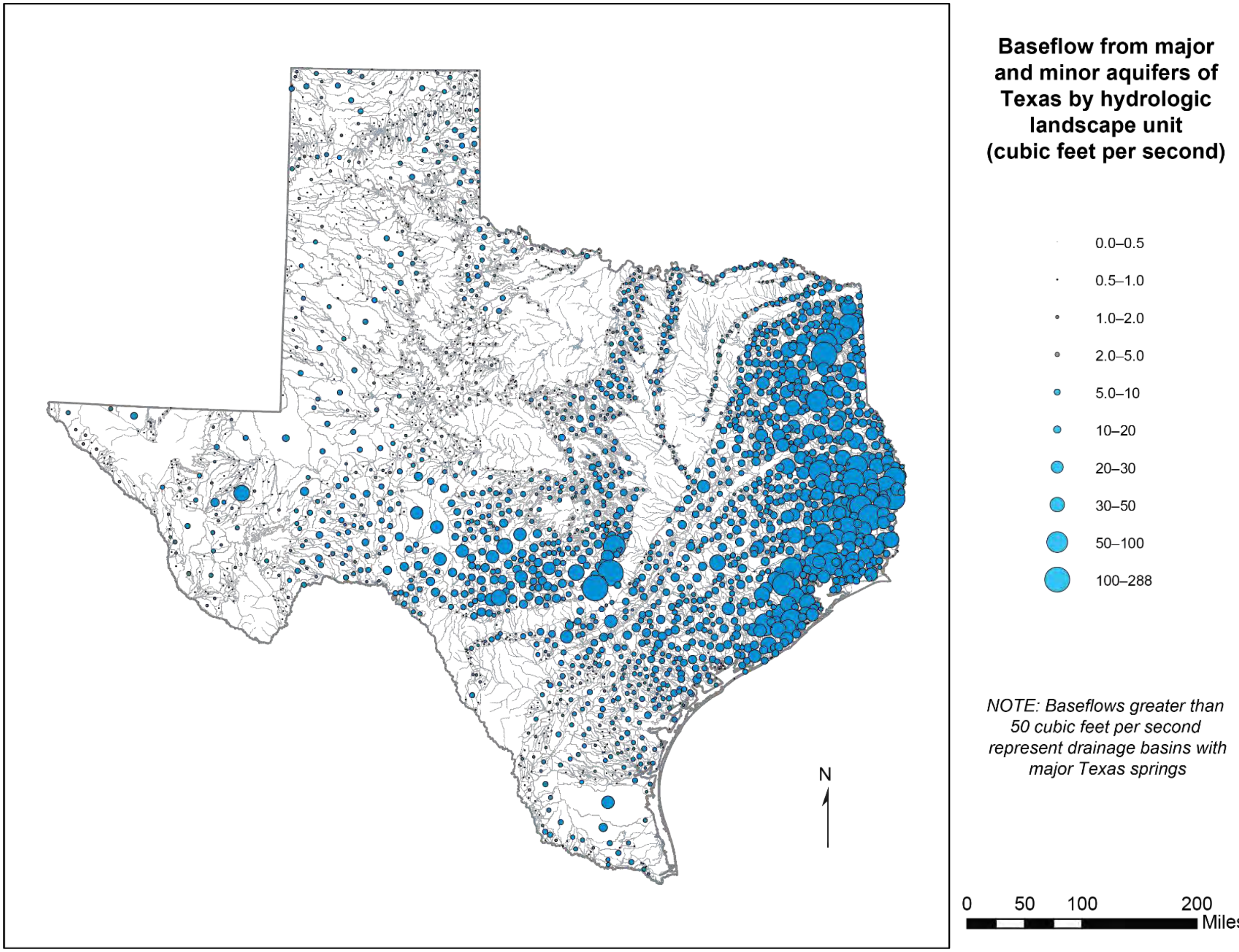


Figure 3-2. Baseflow from major and minor aquifers of Texas by hydrologic landscape unit (in cubic feet per second).

Table 3-2. Streamflow and baseflow estimates for the major and minor aquifers.

Aquifer	Average annual streamflow over aquifer outcrop (acre-feet per year) [1]	Average baseflow over aquifer outcrop (acre-feet per year)[1]	Percentage of streamflow due to groundwater discharge from aquifers
Blaine	132,000	29,900	23
Blossom	105,000	14,600	14
Bone Spring-Victorio Peak	15,300	6,710	44
Brazos River Alluvium	293,000	69,500	24
Capitan Reef Complex	3,450	667	19
Carrizo-Wilcox	4,380,000	1,100,000	25
Dockum	96,700	13,200	14
Edwards (Balcones Fault Zone)	678,000	487,000	72
Edwards-Trinity (High Plains)	592	100	17
Edwards-Trinity (Plateau)	1,480,000	818,000	55
Ellenburger-San Saba	87,700	29,000	33
Gulf Coast	13,900,000	3,810,000	27
Hickory	20,600	7,900	38
Hueco-Mesilla Bolsons	15,400	4,830	31
Igneous	114,000	18,300	16
Lipan	28,900	8,280	29
Marathon	10,500	2,060	20
Marble Falls	14,800	4,380	30
Nacatoch	486,000	67,700	14
Ogallala	473,000	121,000	26
Pecos Valley	67,700	47,300	70
Queen City	3,360,000	1,050,000	31
Rita Blanca[2]	-	-	-
Rustler	6,350	1,460	23
Seymour	136,000	28,500	21
Sparta	565,000	189,000	33
Trinity	1,630,000	552,000	34
West Texas Bolsons	13,500	4,000	30
Woodbine	518,000	73,700	14
Yegua-Jackson	2,370,000	714,000	30
Total (acre-feet per year)	**31,001,492**	**9,273,087**	**-**

[1] Estimated flows for each aquifer rounded to three significant figures. Differences between the totals presented in this table and Table 3-3 are a result of rounding.
[2] The Rita Blanca Aquifer does not have an outcrop area; therefore, there is no contribution of groundwater to surface-water flow.

Table 3-3. Streamflow and baseflow estimates for the Texas river basins.

River basin	Average annual streamflow (acre-feet per year) [1]	Average baseflow over aquifer outcrop (acre-feet per year)[1]	Percentage of streamflow due to groundwater discharge from aquifers
Brazos	2,660,000	613,000	23
Brazos-Colorado	835,000	222,000	27
Canadian	204,000	50,700	25
Colorado	1,650,000	645,000	39
Colorado-Lavaca	458,000	60,700	13
Cypress	1,500,000	489,000	33
Guadalupe	1,030,000	732,000	71
Lavaca	715,000	128,000	18
Lavaca-Guadalupe	445,000	61,100	14
Neches	4,810,000	1,810,000	38
Neches-Trinity	1,020,000	231,000	23
Nueces	1,040,000	367,000	35
Nueces-Rio Grande	518,000	80,500	16
Red	658,000	152,000	23
Rio Grande	819,000	407,000	50
Sabine	3,490,000	997,000	29
San Antonio	560,000	210,000	38
San Antonio-Nueces	398,000	64,900	16
San Jacinto	2,210,000	500,000	23
San Jacinto-Brazos	1,220,000	342,000	28
Sulphur	872,000	179,000	21
Trinity	3,290,000	877,000	27
Trinity-San Jacinto	153,000	34,000	22
Total (acre-feet per year)	**30,555,000**	**9,252,900**	-

[1] Estimated flows for each aquifer rounded to three significant figures. Differences between the totals presented in this table and Table 3-2 are a result of rounding.

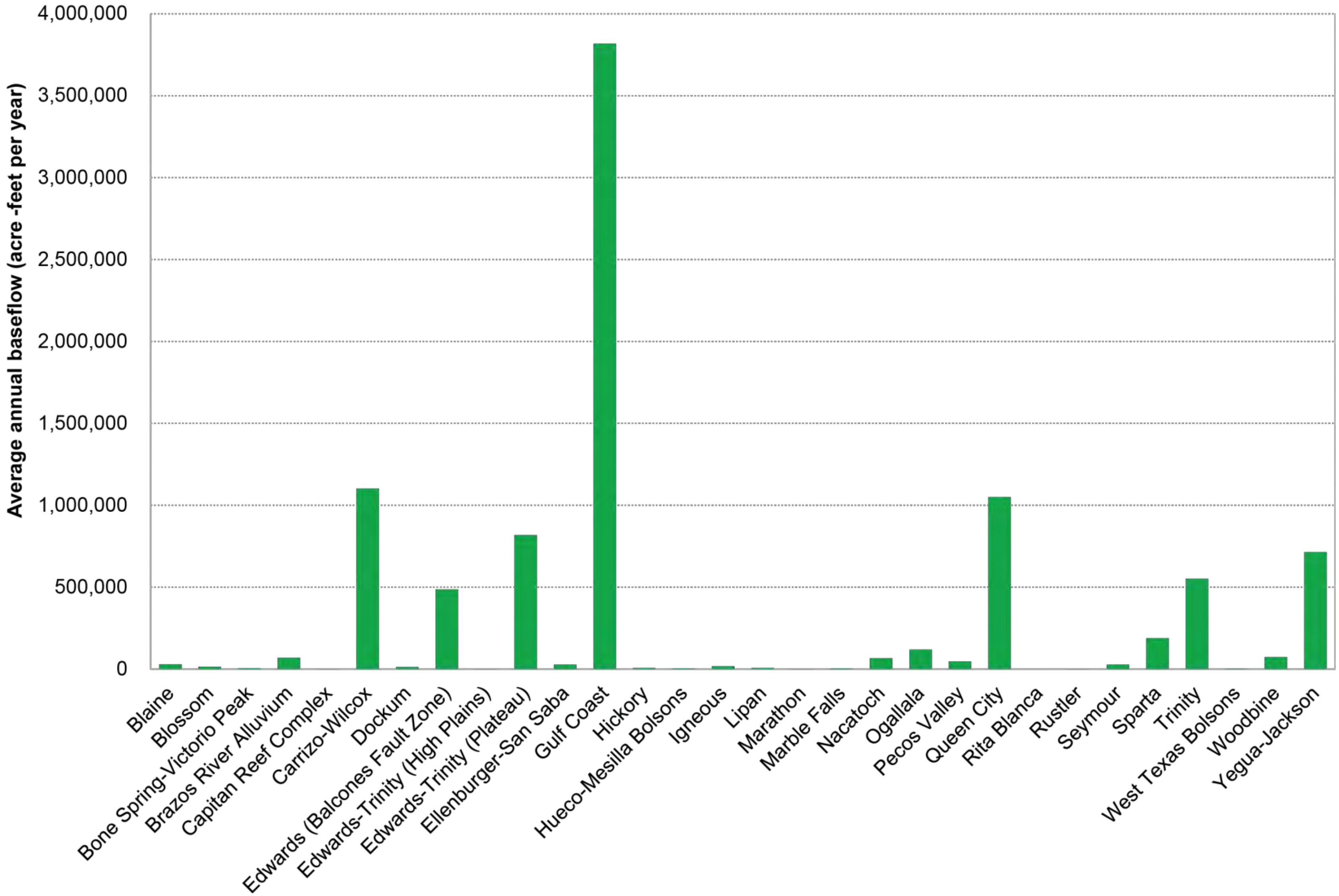


Figure 3-3. Estimated average annual baseflow contributions to surface water (acre-feet per year).

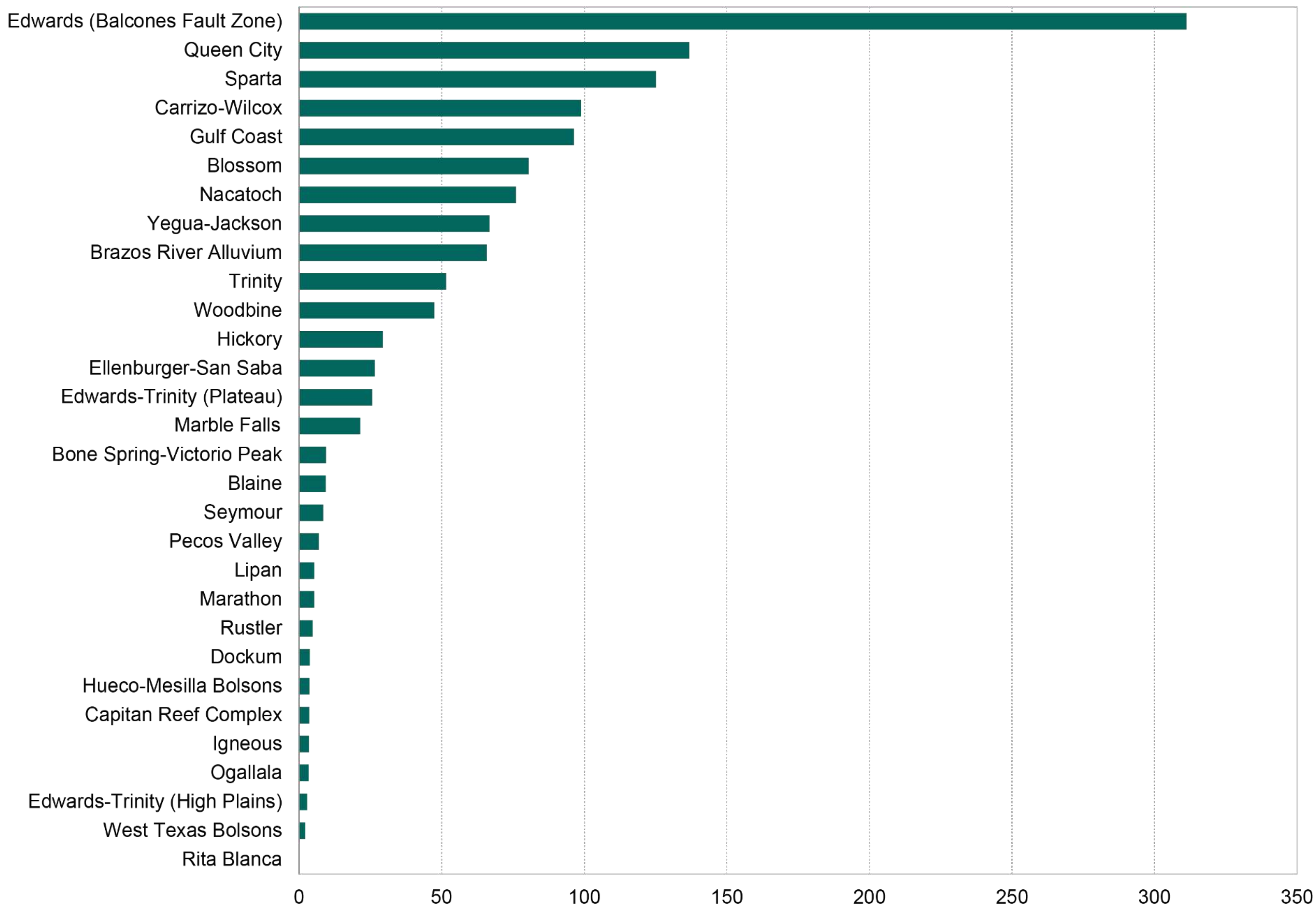


Figure 3-4. **Ratio of baseflow to aquifer outcrop area.**

4 Tributary and Non-Tributary Groundwater

Key points:

- We used baseflow data for the major and minor aquifers (Chapter 3) to categorize the tributary nature of Texas aquifers. Nearly all Texas aquifers discharge groundwater to streams and rivers that flow over their outcrop areas. We consider these aquifers to be tributary for the purposes of this study. However, each of the aquifers has local areas that may differ from the regional, aggregate designation.
- Better methods and data for quantifying groundwater and surface-water interactions are needed. The baseflow analysis used for this report relies on historical streamflow and spring discharge data that may not completely or accurately represent present or future conditions given the widespread drawdown of groundwater levels observed statewide.

The question of defining or designating tributary or non-tributary aquifers with specific, quantitative criteria has not been resolved on a nationwide basis, although certain states have adopted specific definitions that are tailored to their water management regulatory programs. For example, Colorado, a state that owns and regulates all water resources within its boundaries, has applied the concept of tributary aquifers to the adjudication or allocation of groundwater resources (Colorado Department of Natural Resources, 2016). The general definition that tributary groundwater is “groundwater that discharges into surface water” is silent in terms of the criteria to define the definitional boundaries between tributary and non-tributary aquifers. Colorado defines nontributary groundwater to be groundwater pumped at a well that will not deplete the flow of a stream at an annual rate greater than one-tenth of 1 percent of the annual rate of withdrawal. Such a specific, locally-scoped definition is problematic to use when evaluating the regional aquifer systems in Texas. Therefore, strictly speaking, groundwater in nearly every aquifer in Texas has some degree of movement into or out of surface water and could be considered as tributary.

We have evaluated the available surface-water and groundwater data to identify aquifers that could be considered tributary. These available data—generated by multiple federal, state, and academic organizations—are inherently uneven in terms of areal coverage, time and duration of measurements, and quality. Moreover, this situation is likely to remain the same for the foreseeable future. Further evaluation of data and inclusion of additional information as it becomes available may lead to an appropriate modification of our definition. As a basis for identifying tributary aquifers, we charted the estimated percentage of surface-water flow over the aquifer outcrop area that is attributable to groundwater discharge (Figure 4-1 and Table 4-1).

We chose to look at percentages, rather than absolute numbers, to normalize the effects of the different climate regions in the state. Based on the available data, all Texas aquifers (with the possible exception of the Rita Blanca Aquifer, which has no surface outcrop in the state) could be considered tributary aquifers since some groundwater from each aquifer does discharge to surface water. However, that approach obscures the fact that there are clear distinctions between Texas aquifers in the degree and significance of groundwater and surface-water interactions.

The statewide range of percentage of streamflow attributable to baseflow from aquifers shown in Figure 4-1 reveals a wide variation in the degree of regional groundwater-surface water interactions. While these percentages apply to regional aquifers—some of which cover thousands of square miles—it is more likely than not that within these aquifers there exists significant variation with respect to the degree of groundwater contributions to surface water.

This analysis applies specifically to the outcrop or unconfined areas of Texas aquifers. Confined portions of the aquifers are generally more isolated from interaction with surface water and can generally be considered "non-tributary," although springs, such as San Solomon Springs in West Texas, can originate from confined aquifers and may create local tributary aquifer zones. Groundwater discharge from three major aquifers—the Edwards (Balcones Fault Zone), Edwards-Trinity (Plateau), and Pecos Valley aquifers—contributes more than 50 percent of the baseflow of streams flowing across their outcrop zones on an average annual basis. This is supported by the number of current and historical springs that flow from these aquifers. Eighteen major and minor aquifers contribute between 20 and 50 percent of flow to streamflow over their outcrop zones. Eight minor aquifers contribute between 14 and 20 percent of the flow to streams flowing over their outcrop zones. These aquifers include the Blossom, Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), Igneous, Marathon, Nacatoch, and Woodbine aquifers. One minor aquifer, the Rita Blanca, contributes zero percent to streamflow in Texas and is classified as non-tributary. A map of the tributary and non-tributary aquifers of Texas is provided as Figure 4-2.

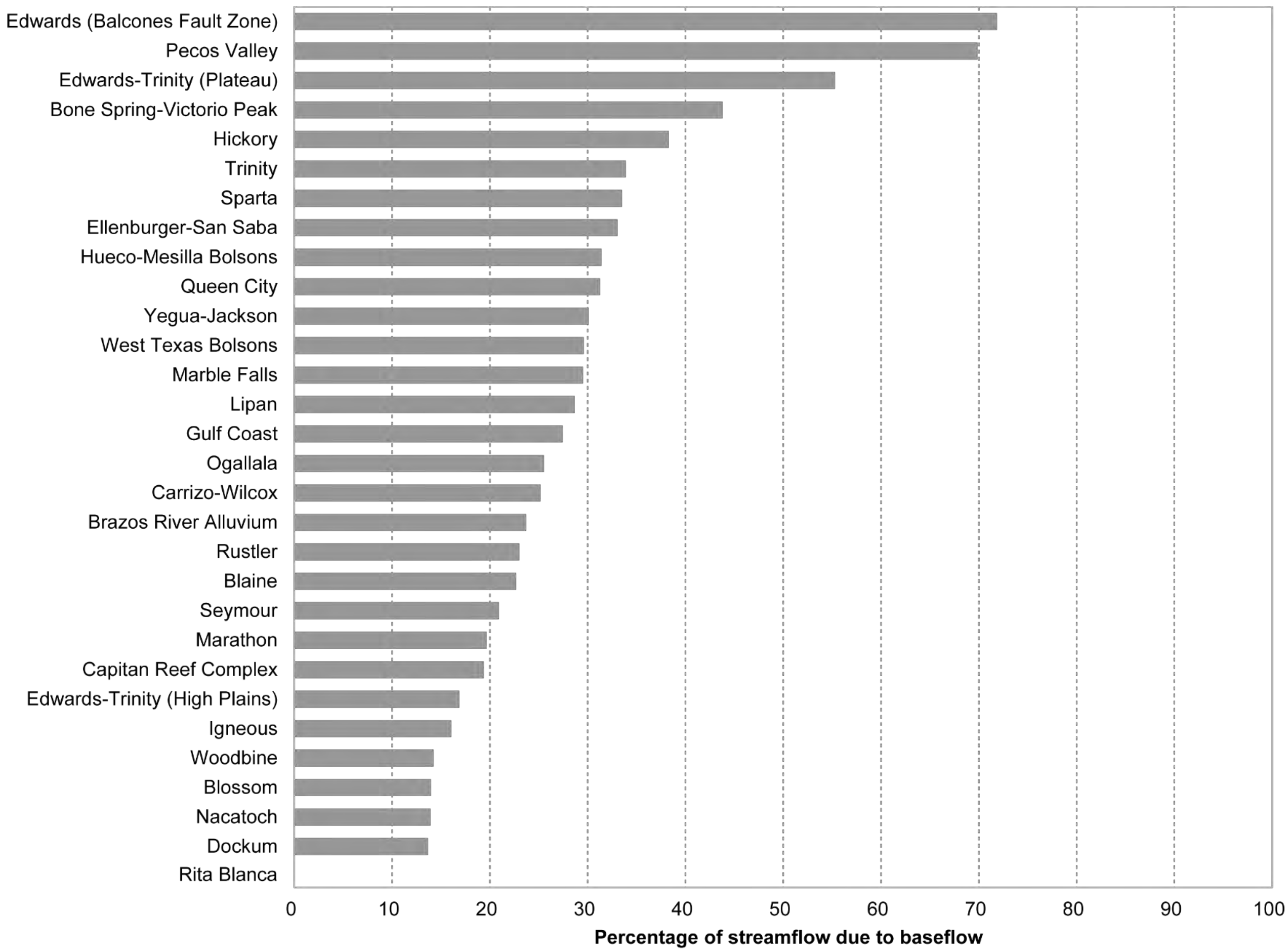


Figure 4-1. Percentage of streamflow due to baseflow from groundwater for major and minor aquifers in Texas.

Table 4-1. Percentage of streamflow in aquifer outcrop area from groundwater.

Aquifer	Percentage of streamflow in aquifer outcrop area from groundwater
Blaine	23
Blossom	14
Bone Spring-Victorio Peak	44
Brazos River Alluvium	24
Capitan Reef Complex	19
Carrizo-Wilcox	25
Dockum	14
Edwards (Balcones Fault Zone)	72
Edwards-Trinity (High Plains)	17
Edwards-Trinity (Plateau)	55
Ellenburger-San Saba	33
Gulf Coast	27
Hickory	38
Hueco-Mesilla Bolsons	31
Igneous	16
Lipan	29
Marathon	20
Marble Falls	30
Nacatoch	14
Ogallala	26
Pecos Valley	70
Queen City	31
Rita Blanca	0
Rustler	23
Seymour	21
Sparta	33
Trinity	34
West Texas Bolsons	30
Woodbine	14
Yegua-Jackson	30

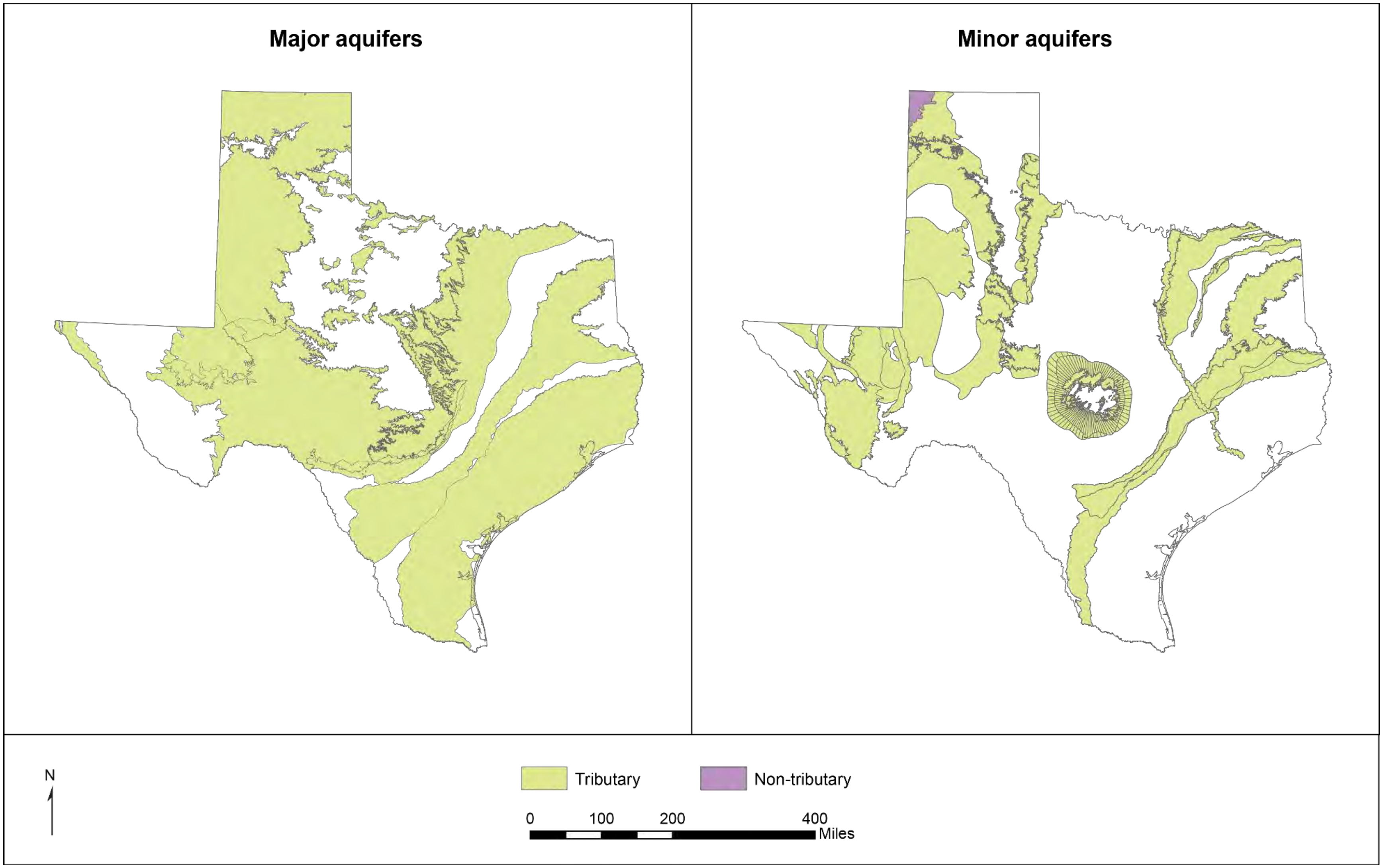


Figure 4-2. Tributary and non-tributary aquifers of Texas.

5 Groundwater Flows to Other Aquifers

Key points:

- There are no direct measurements of groundwater flow between aquifers. Estimates of inter-aquifer groundwater flow are best made by simulating flow conditions with groundwater availability models.
- Groundwater flow between the major and minor aquifers in the eastern part of Texas is limited by the thick sequences of shale or clay that separate the aquifer systems and generally restrict vertical groundwater movement between them. Conceptually, it is probable that over time groundwater in deep confined aquifers ultimately discharges regionally into overlying strata.
- Some aquifers in the central and western areas of the state are juxtaposed such that lateral groundwater flow probably occurs between them.
- Some groundwater availability models can be used to estimate flow between aquifers. However, many groundwater availability models have been designed with "no-flow" boundaries, precluding estimates of groundwater flow across those confining boundaries.
- Different model conceptualization would be needed to account for potential flows across those boundaries in response to pumping stresses.
- Groundwater flow between aquifers occurs primarily in the Hill Country, especially along the southern and eastern edge of the Edwards Plateau, and in the Pecos Valley.
- In the High Plains, some groundwater flow occurs from the Ogallala Aquifer to the Dockum Aquifer.
- The groundwater availability models used for the current estimates were not generally designed or calibrated with this application in mind, and different models produced widely varying results in areas of overlap.

5.1 Background

No direct measurements of inter-aquifer groundwater flow are available. Many aquifers—particularly in the eastern half of Texas—are bounded by thick sequences of shale or clay that isolate aquifers from each other and limit inter-aquifer groundwater flow. Therefore, inter-aquifer flow needs to be evaluated indirectly using groundwater flow models or by other analytical means. There are some situations in which groundwater level data in different aquifers can be compared to evaluate hydraulic gradients between aquifers and develop an indirect estimate of possible groundwater flow. In other cases, aquifers may contact other aquifers along lateral boundaries—such as along geologic fault zones—so that inter-aquifer flow may occur across those boundaries. Inter-aquifer groundwater flow can occur wherever a route for flow exists through direct physical contact of aquifers combined with a hydraulic gradient between the aquifers. To a lesser degree inter-aquifer groundwater flow may be possible over the long term between aquifers that are separated by low permeability shale or clay layers. For example, Huang and others (2012) note that in the Carrizo-Wilcox Aquifer groundwater moving through the deep confined portions probably discharges regionally to overlying strata. Typical groundwater flow patterns in the state's aquifers involve recharge to the aquifer at the surface in the outcrop zone and discharge to streams as baseflow or through pumping or evapotranspiration. Some groundwater also moves into deeper confined portions of aquifers or to other aquifers as inter-aquifer flow.

Prior to groundwater pumping in Texas, which altered hydraulic gradients in most aquifers, the recharge and discharge—including flows between aquifers—were balanced so there was little or no change in the amount of groundwater stored in aquifers. Groundwater pumping alters prevailing hydraulic gradients and, in some cases, reverses the direction of the gradient. This has been documented by Huang and others (2012) in areas of the Carrizo-Wilcox Aquifer where pumping has reversed the gradient from upward to downward relative to the overlying Queen City Aquifer. However, there is no documentation that groundwater flow directions have been correspondingly altered since long periods of time—decades or centuries—may be necessary to change flow directions when thick sequences of low permeability materials separate the aquifers.

5.2 Estimates of inter-aquifer groundwater flow

For the purposes of this study, we have considered steady-state (no pumping) groundwater conditions as presented in the various groundwater availability models. Groundwater availability models represent the best available compilation of hydrogeological data and processes with which to make such an estimate, but in most cases the models were not specifically designed or calibrated to estimate inter-aquifer flow. Groundwater availability models were developed for specific aquifers and use assumptions and conditions in their construction that may be different from groundwater availability models for other aquifers. Therefore, caution is necessary in reviewing and evaluating inter-aquifer groundwater flow estimates and particularly in comparing values for the same aquifer relationships estimated using different groundwater flow models.

We estimated inter-aquifer groundwater flow considering the following:

- flow in major and minor aquifers that are in direct contact with each other;
- flow within aquifers (for example, flow between the Chicot and Jasper aquifers within the Gulf Coast Aquifer System) was not considered;

- steady-state (pre-development) conditions were assumed; and
- groundwater availability models were used to develop groundwater flow estimates.

Vertical flow between aquifers

Aquifers bounded by low-permeability geological units have little or no interaction with neighboring aquifers. Figure 5-1 partially illustrates this for the Hill Country portion of the Trinity Aquifer, which has a low permeability confining layer that limits groundwater flow at its lower boundary. Therefore, the confining layer below the aquifer is coded in the groundwater availability model as a no-flow boundary even though some flow could occur under certain pumping scenarios. This approach is applicable to a number of Texas aquifers, is well-grounded in available data and science, and is based on a consensus of groundwater hydrologists and geologists across Texas who developed or peer-reviewed the conceptual models that were used to construct the numerical groundwater flow models.

Lateral flow between aquifers

Lateral groundwater flow can occur between aquifers where they overlap or are in contact with each other. The magnitude and direction of flow depends on the difference in hydraulic head between groundwater in the two aquifers as well as the hydraulic properties of the aquifer. In some cases, there is sufficient water level data in the contact area and these inter-aquifer flows are explicitly addressed in model development and calibration. In other cases, there are relatively little data for model calibration and/or inter-aquifer flows are small compared to flows within the aquifers and as a result the model values are poorly constrained. The Trinity Aquifer conceptual model also shows how lateral groundwater flow can occur between aquifers that are juxtaposed. Figure 5-1 also illustrates the conditions on the eastern boundary of the Trinity Aquifer, which is bounded by the Balcones Fault Zone and the Edwards (Balcones Fault Zone) Aquifer. In this case, groundwater flows eastward according to the prevailing hydraulic gradient into the Edwards (Balcones Fault Zone) Aquifer.

Table 5-1 summarizes estimates of inter-aquifer flows for the major and minor aquifers based on simulations of groundwater flow using groundwater availability models. In some cases, flows are listed for both directions between two aquifers; because of the large extent of some aquifers, flows may occur in one direction in one area of the aquifer and in the opposite direction in another area. In several cases, more than one model was used to assess inter-aquifer flows. Models may provide very different estimates that are attributable to a different conceptualization of the aquifer, variable boundary conditions, and different model codes. In these cases, the average value of the flow estimates is shown. The wide range of values—ranging from less than 10 to well over 50,000 acre-feet per year—reflect the area over which groundwater flux was estimated, and the variability of groundwater flows through complex aquifers.

Table 5-2 presents a detailed tabulation of simulated inter-aquifer groundwater flows on an aquifer and county basis. Several of the inter-aquifer flow values were estimated using different groundwater flow models in areas where several aquifers overlapped and had dedicated models with unique attributes and conceptual features. These situations resulted in different flow results for aquifers in the same region, illustrating the very approximate nature of developing inter-aquifer flow estimates using groundwater availability models.

The magnitude and location of inter-aquifer groundwater flow is unevenly distributed across Texas (Figure 5-2). The directions of the arrows approximate the lateral groundwater flow direction; however, in some cases actual flow may be primarily vertical. Ten counties have groundwater fluxes between multiple aquifers; for these counties only the largest flux is shown for clarity.

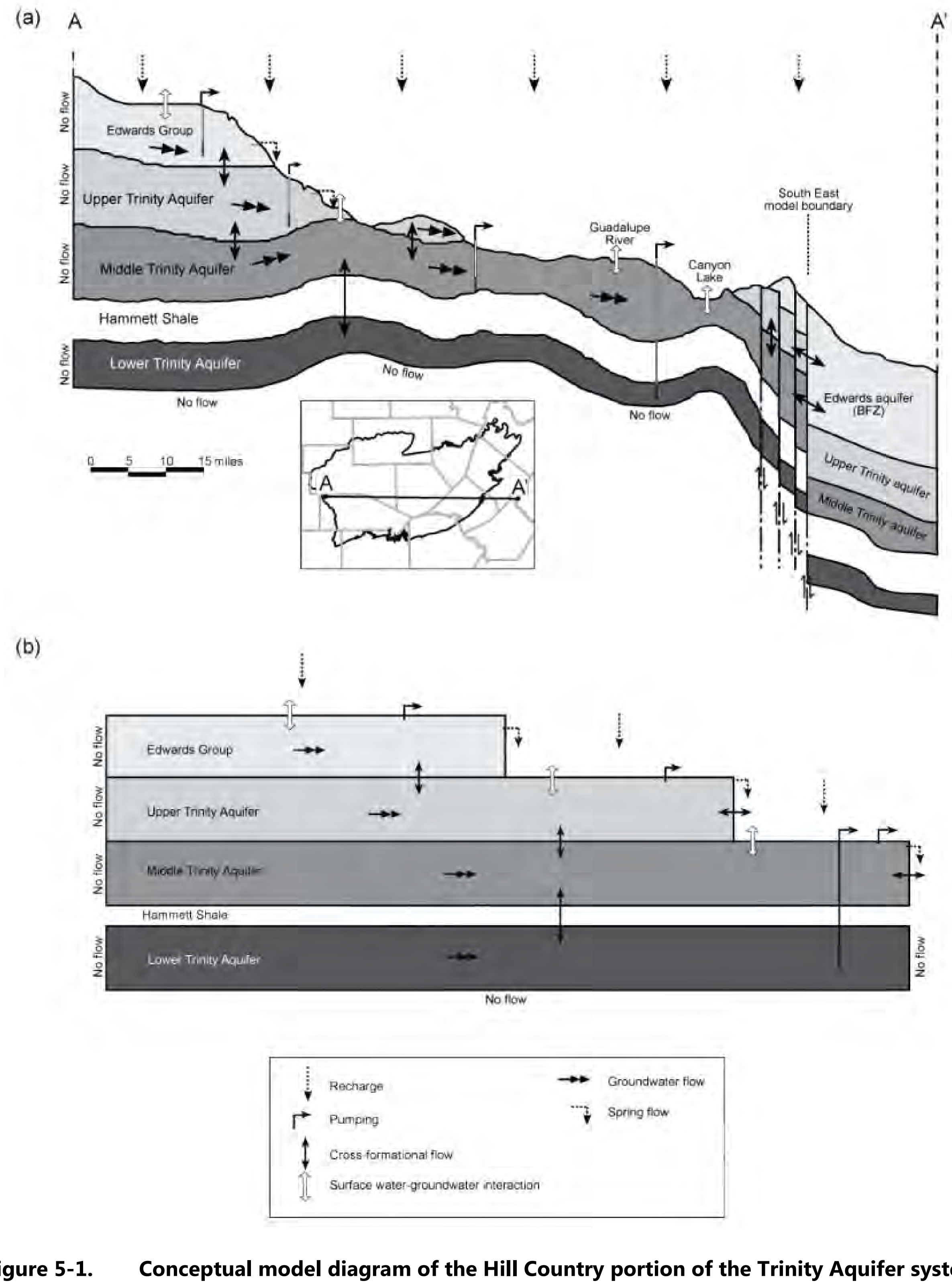


Figure 5-1. Conceptual model diagram of the Hill Country portion of the Trinity Aquifer system showing a (a) schematic cross-section and (b) conceptual model with flows between layers (Jones and others, 2009).

Table 5-1. Modeled estimates of inter-aquifer flows between the major and minor aquifers of Texas.

Flow from	Flow to	Total flow (acre-feet per year)	Remarks
Blaine Aquifer	Seymour Aquifer	34,072	TWDB staff model analysis
Seymour Aquifer	Blaine Aquifer	7,162	TWDB staff model analysis
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361	TWDB staff model analysis
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948	TWDB staff model analysis
Dockum Aquifer	Ogallala Aquifer	2,241	TWDB staff model analysis
Ogallala Aquifer	Dockum Aquifer	27,497	TWDB staff model analysis
Dockum Aquifer	Rita Blanca Aquifer	115	TWDB staff model analysis
Rita Blanca Aquifer	Dockum Aquifer	83	TWDB staff model analysis
Rustler Aquifer	Dockum Aquifer	1	TWDB staff model analysis
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381	TWDB staff model analysis – averaged value
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463	TWDB staff model analysis – includes San Antonio, Barton Springs, and Northern segments
Edwards-Trinity (Plateau) Aquifer & Other Formations	Lipan Aquifer	7,507	TWDB staff model analysis
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & otherformations	7,506	TWDB staff model analysis
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544	TWDB staff model analysis
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929	TWDB staff model analysis

Table 5-1 (continued). Modeled estimates of inter-aquifer flows between the major and minor aquifers of Texas.

Flow from	Flow to	Total flow (acre-feet per year)	Remarks
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341	TWDB staff model analysis
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966	TWDB staff model analysis
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647	TWDB staff model analysis
Ogallala Aquifer	Pecos Valley Aquifer	220	TWDB staff model analysis
Pecos Valley Aquifer	Ogallala Aquifer	0	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848	TWDB staff model analysis
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546	TWDB staff model analysis
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305	TWDB staff model analysis
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654	TWDB staff model analysis
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368	TWDB staff model analysis
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647	TWDB staff model analysis
Hickory Aquifer	Trinity Aquifer	64	TWDB staff model analysis
Ogallala Aquifer	Rita Blanca Aquifer	1,670	TWDB staff model analysis
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285	TWDB staff model analysis
Trinity Aquifer	Marble Falls Aquifer	144	TWDB staff model analysis

Note: Estimates are based on steady-state (no pumping) simulations of groundwater flow. Groundwater pumping in these aquifers would alter the dynamic equilibrium and result in different estimates of inter-aquifer flow rates.

Regional summaries

West and Central Texas

Aquifers in West and South Texas, particularly the Edwards Trinity (Plateau) and Pecos Valley aquifers, are flat-lying and directly contact each other without confining low permeability shale or clay. This geometry presents an opportunity for groundwater flow between aquifers. Other aquifers, such as the West Texas Bolsons or Igneous aquifers, are isolated or individual closed basins and offer little opportunity for inter-aquifer groundwater flow. Groundwater flows between aquifers are complex and poorly understood in some areas. For example, some major springs in Pecos County that discharge through the Edwards Trinity (Plateau) Aquifer may represent groundwater that originates in or traverses through other aquifers. Lateral movement of groundwater from the Edwards Trinity (Plateau) Aquifer and Trinity Aquifer to the Edwards (Balcones Fault Zone) Aquifer has been estimated in a number of studies (for example, Clark and Journey [2006] and Wong and others [2014]).

Regions of inter-aquifer flow include the following:

- Pecos and Reeves counties, where groundwater flows from the Edwards-Trinity (Plateau) Aquifer into the Pecos Valley Aquifer
- The Hill Country, where groundwater in the Edwards-Trinity (Plateau) Aquifer flows into the Edwards (Balcones Fault Zone), Trinity, and minor aquifers around the Llano Uplift
- Bell, Travis, and Williamson counties, where the Edwards (Balcones Fault Zone) Aquifer groundwater flows into the Trinity aquifer
- South central Texas where Trinity groundwater flows into the Edwards-Trinity (Plateau), Edwards (Balcones Fault Zone), and Llano Uplift aquifers

Panhandle and Northwest Texas

Aquifers in the Panhandle and northwest Texas, particularly the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers are flat lying and locally contact each other without intervening low permeability shale or clay. This geometry presents an opportunity for direct interaction between these aquifers.

Areas of inter-aquifer flow include the following:

- The High Plains, where Ogallala Aquifer groundwater flows into the Dockum, Edwards-Trinity (High Plains), and Pecos Valley aquifers
- The area of Collingsworth, Hall, Kent, and Stonewall counties, where Seymour Aquifer groundwater flows into the Blaine Aquifer

Gulf Coast, North, and East Texas

Major and minor aquifers in this region dip toward the Gulf of Mexico and are separated from each other by thick sequences of clay and shale. Direct groundwater flow between these aquifers is limited, although it is possible that at depth there may be inter-aquifer movement of groundwater under pressure, and along growth fault zones.

Areas of inter-aquifer flow include

- Milam and Robertson counties, where groundwater from the Carrizo-Wilcox Aquifer flows into the Brazos River Alluvium Aquifer.

5.3 Estimates of inter-aquifer groundwater flow required for groundwater management plans

For groundwater conservation districts, the TWDB estimates the "annual flow into and out of the district within each aquifer and between aquifers in the district, if a groundwater availability model is available" in compliance with Texas Water Code §36.1071(e). These estimates are provided to groundwater conservation districts for inclusion in their groundwater management plan. Because these estimates are prepared for specific districts, the groundwater flow values for these plans are limited to the area within the boundaries of each district. On the regional scale called for by this study, the summing of values for multiple districts for a major or minor aquifer would be incomplete because the administrative boundaries of districts do not coincide with aquifer boundaries.

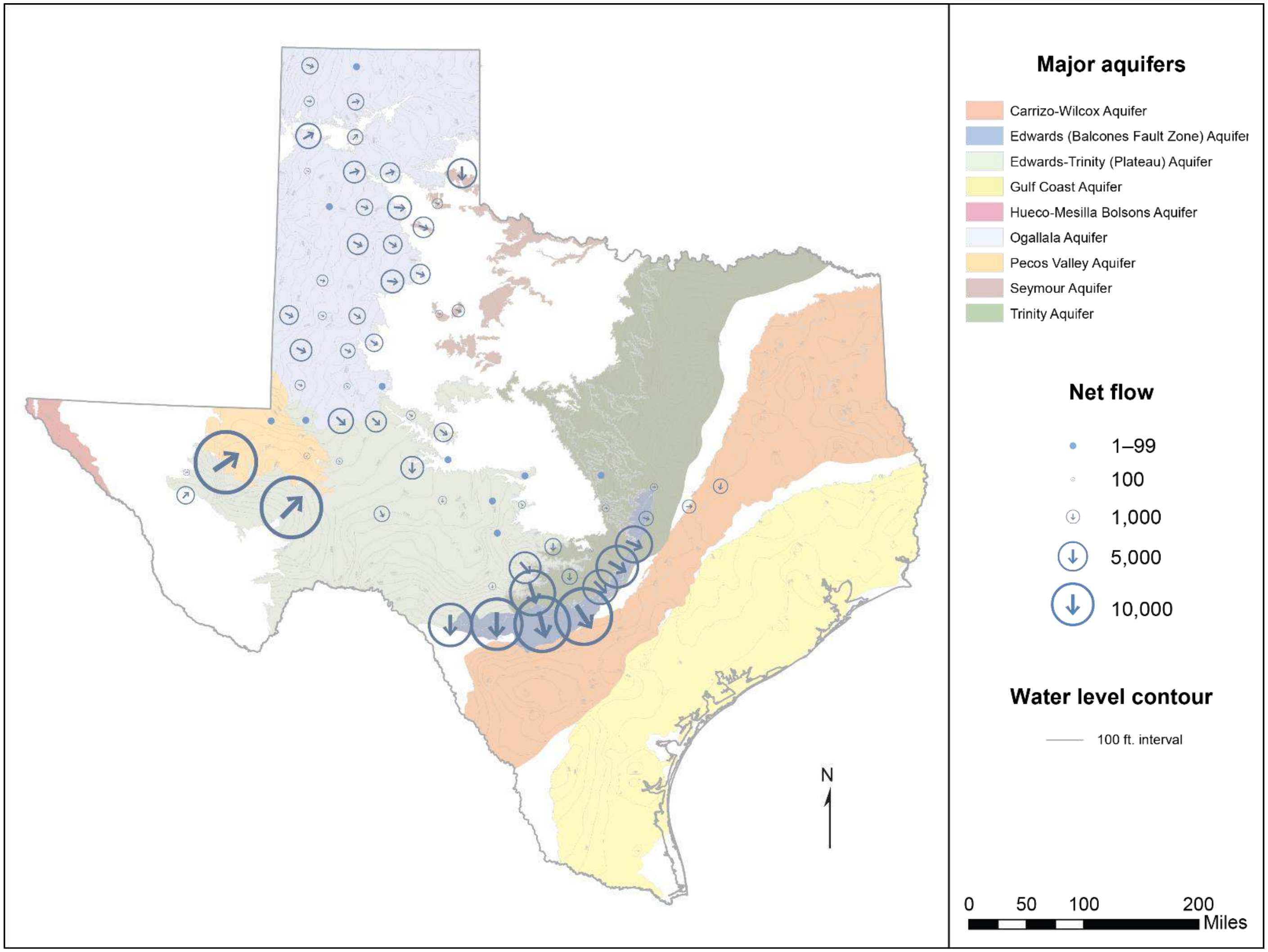


Figure 5-2. Estimated groundwater fluxes from major aquifers of Texas to other aquifers, by county. Arrow size is proportional to average annual flow, in acre feet, as determined by groundwater availability models; arrow direction approximates groundwater flow, based on water level contours.

Table 5-2. Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Andrews	Dockum	Ogallala	16	High Plains Aquifer System GAM v1.01	
Andrews	Dockum	Edwards-Trinity (Plateau)	11	High Plains Aquifer System GAM v1.01	
Andrews	Edwards-Trinity (Plateau)	Ogallala	1,085	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal
Andrews	Ogallala	Pecos Valley	182	High Plains Aquifer System GAM v1.01	
Andrews	Ogallala	Edwards-Trinity (Plateau)	212	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Andrews	Pecos Valley	Ogallala	0	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Armstrong	Ogallala	Dockum	2,174	High Plains Aquifer System GAM v1.01	
Baily	Ogallala	Edwards-Trinity (High Plains)	396	High Plains Aquifer System GAM v1.01	
Bandera	Edwards-Trinity (Plateau)	Trinity	12,911	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Bandera	Trinity	Edwards (Balcones Fault Zone)	2,621	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Bandera	Trinity	Edwards-Trinity (Plateau)	1,430	Draft Llano Uplift GAM	
Bell	Edwards (Balcones Fault Zone)	Trinity	352	Northern Trinity Woodbine GAM v2.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Bexar	Trinity	Edwards (Balcones Fault Zone)	5,831	Edwards (Balcones Fault Zone) San Antonio segment	Different models show different average flux
Bexar	Trinity	Edwards (Balcones Fault Zone)	30,810	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Blanco	Ellenburger-San Saba	Marble Falls	474	Draft Llano Uplift GAM	
Blanco	Hickory	Trinity	63	Draft Llano Uplift GAM	
Blanco	Hickory	Ellenburger-San Saba	4,124	Draft Llano Uplift GAM	
Blanco	Trinity	Edwards-Trinity (Plateau)	164	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Blanco	Trinity	Edwards-Trinity (Plateau)	38	Draft Llano Uplift GAM	Different models show different average flux
Blanco	Trinity	Marble Falls	99	Draft Llano Uplift GAM	
Blanco	Trinity	Ellenburger-San Saba	953	Draft Llano Uplift GAM	
Borden	Ogallala	Edwards-Trinity (High Plains)	1,918	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Briscoe	Ogallala	Dockum	3,395	High Plains Aquifer System GAM v1.01	
Burnet	Ellenburger-San Saba	Marble Falls	1,070	Draft Llano Uplift GAM	
Burnet	Hickory	Trinity	1	Draft Llano Uplift GAM	
Burnet	Hickory	Ellenburger-San Saba	7,659	Draft Llano Uplift GAM	
Burnet	Trinity	Marble Falls	8	Draft Llano Uplift GAM	
Burnet	Trinity	Ellenburger-San Saba	274	Draft Llano Uplift GAM	
Carson	Dockum	Ogallala	112	High Plains Aquifer System GAM v1.01	
Castro	Ogallala	Dockum	25	High Plains Aquifer System GAM v1.01	
Childress	Blaine	Seymour	2,9443	Seymour Aquifer GAM v_1.01	
Cochran	Edwards-Trinity (High Plains)	Ogallala	110	High Plains Aquifer System GAM v1.01	
Coke	Edwards-Trinity (Plateau)	Dockum	63	High Plains Aquifer System GAM v1.01	
Coke	Edwards Trinity Plateau & Other Formations	Lipan	1,961	Lipan GAM v_1.01	
Collingsworth	Seymour	Blaine	4,947	Seymour Aquifer GAM v_1.01	
Comal	Trinity	Edwards (Balcones Fault Zone)	4,395	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Comal	Trinity	Edwards (Balcones Fault Zone)	9,680	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Concho	Lipan	Edwards-Trinity (Plateau) & Other Formations	2,666	Lipan GAM v_1.01	
Crane	Edwards-Trinity (Plateau)	Dockum	108	High Plains Aquifer System GAM v1.01	
Crane	Pecos Valley	Edwards-Trinity (Plateau)	194	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Crockett	Dockum	Edwards-Trinity (Plateau)	511	High Plains Aquifer System GAM v1.01	
Crockett	Edwards-Trinity (Plateau)	Pecos Valley	1,385	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Crosby	Ogallala	Dockum	3,001	High Plains Aquifer System GAM v1.01	
Culberson	Pecos Valley	Edwards-Trinity (Plateau)	224	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Dallam	Dockum	Ogallala	501	High Plains Aquifer System GAM v1.01	
Dallam	Dockum	Rita Blanca	115	High Plains Aquifer System GAM v1.01	
Dallam	Ogallala	Rita Blanca	1,661	High Plains Aquifer System GAM v1.01	
Dawson	Ogallala	Edwards-Trinity (High Plains)	1,200	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Deaf Smith	Ogallala	Dockum	196	High Plains Aquifer System GAM v1.01	
Dickens	Ogallala	Dockum	2,300	High Plains Aquifer System GAM v1.01	
Ector	Edwards-Trinity (Plateau)	Ogallala	4,162	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Ector	Edwards-Trinity (Plateau)	Ogallala	6	High Plains Aquifer System GAM v1.01	Different models show different average flux
Ector	Edwards-Trinity (Plateau)	Dockum	769	High Plains Aquifer System GAM v1.01	
Ector	Ogallala	Dockum	16	High Plains Aquifer System GAM v1.01	
Ector	Pecos Valley	Edwards-Trinity (Plateau)	0	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Fisher	Blaine	Seymour	2,226	Seymour Aquifer GAM v_1.01	
Floyd	Edwards-Trinity (High Plains)	Ogallala	217	High Plains Aquifer System GAM v1.01	
Floyd	Edwards-Trinity (High Plains)	Dockum	1,009	High Plains Aquifer System GAM v1.01	
Floyd	Ogallala	Dockum	2,142	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Gaines	Dockum	Ogallala	1,111	High Plains Aquifer System GAM v1.01	
Gaines	Edwards-Trinity (High Plains)	Dockum	95	High Plains Aquifer System GAM v1.01	
Gaines	Ogallala	Edwards-Trinity (High Plains)	2,786	High Plains Aquifer System GAM v1.01	
Garza	Edwards-Trinity (High Plains)	Ogallala	1,881	High Plains Aquifer System GAM v1.01	
Gillespie	Edwards-Trinity (Plateau)	Trinity	4,339	Draft Llano Uplift GAM	Different models show flow reversal
Gillespie	Edwards-Trinity (Plateau)	Ellenburger-San Saba	523	Draft Llano Uplift GAM	
Gillespie	Edwards-Trinity (Plateau)	Hickory	11	Draft Llano Uplift GAM	
Gillespie	Hickory	Ellenburger-San Saba	3,419	Draft Llano Uplift GAM	
Gillespie	Trinity	Edwards-Trinity (Plateau)	1,054	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal
Gillespie	Trinity	Ellenburger-San Saba	57	Draft Llano Uplift GAM	
Glasscock	Edwards-Trinity (Plateau)	Ogallala	445	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Glasscock	Ogallala	Edwards-Trinity (Plateau)	5,457	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Hale	Dockum	Ogallala	254	High Plains Aquifer System GAM v1.01	
Hale	Ogallala	Edwards-Trinity (High Plains)	2,515	High Plains Aquifer System GAM v1.01	
Hall	Seymour	Blaine	644	Seymour Aquifer GAM v_1.01	
Hardeman	Blaine	Seymour	2,080	Seymour Aquifer GAM v_1.01	
Hartley	Ogallala	Rita Blanca	9	High Plains Aquifer System GAM v1.01	
Hartley	Ogallala	Dockum	644	High Plains Aquifer System GAM v1.01	
Hartley	Rita Blanca	Dockum	83	High Plains Aquifer System GAM v1.01	
Hays	Trinity	Edwards (Balcones Fault Zone)	3,192	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Hays	Trinity	Edwards (Balcones Fault Zone)	17,265	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Hockley	Ogallala	Edwards-Trinity (High Plains)	721	High Plains Aquifer System GAM v1.01	
Howard	Edwards-Trinity (Plateau)	Dockum	48	High Plains Aquifer System GAM v1.01	
Irion	Dockum	Edwards-Trinity (Plateau)	4	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Irion	Edwards Trinity Plateau & Other Formations	Lipan	2,966	Lipan GAM v_1.01	
Jeff Davis	Edwards-Trinity (Plateau)	Pecos Valley	1,757	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Jones	Blaine	Seymour	323	Seymour Aquifer GAM v_1.01	
Kendall	Edwards-Trinity (Plateau)	Trinity	3,564	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Kendall	Edwards-Trinity (Plateau)	Trinity	1,139	Draft Llano Uplift GAM	Different models show different average flux
Kendall	Hickory	Ellenburger-San Saba	1,625	Draft Llano Uplift GAM	
Kent	Seymour	Blaine	335	Seymour Aquifer GAM v_1.01	
Kerr	Edwards-Trinity (Plateau)	Trinity	5,847	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Kerr	Hickory	Ellenburger-San Saba	215	Draft Llano Uplift GAM	
Kerr	Trinity	Edwards-Trinity (Plateau)	15,094	Draft Llano Uplift GAM	
Kimble	Edwards-Trinity (Plateau)	Marble Falls	6	Draft Llano Uplift GAM	
Kimble	Edwards-Trinity (Plateau)	Ellenburger-San Saba	34	Draft Llano Uplift GAM	
Kimble	Ellenburger-San Saba	Marble Falls	824	Draft Llano Uplift GAM	
Kimble	Hickory	Ellenburger-San Saba	3	Draft Llano Uplift GAM	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	2,957	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	17,142	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	11,115	Kinney County Alternative GAM	Different models show different average flux
Lamb	Edwards-Trinity (High Plains)	Ogallala	188	High Plains Aquifer System GAM v1.01	
Lampasas	Ellenburger-San Saba	Hickory	19	Draft Llano Uplift GAM	
Lampasas	Marble Falls	Ellenburger-San Saba	98	Draft Llano Uplift GAM	
Lampasas	Trinity	Marble Falls	37	Draft Llano Uplift GAM	
Lampasas	Trinity	Ellenburger-San Saba	1	Draft Llano Uplift GAM	
Llano	Ellenburger-San Saba	Hickory	9,271	Draft Llano Uplift GAM	
Lubbock	Edwards-Trinity (High Plains)	Ogallala	2,044	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Lynn	Ogallala	Edwards-Trinity (High Plains)	1,708	High Plains Aquifer System GAM v1.01	
Martin	Dockum	Ogallala	9	High Plains Aquifer System GAM v1.01	
Martin	Dockum	Edwards-Trinity (Plateau)	1	High Plains Aquifer System GAM v1.01	
Martin	Edwards-Trinity (Plateau)	Ogallala	771	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Martin	Ogallala	Edwards-Trinity (Plateau)	204	High Plains Aquifer System GAM v1.01	
Mason	Edwards-Trinity (Plateau)	Ellenburger-San Saba	342	Draft Llano Uplift GAM	
Mason	Edwards-Trinity (Plateau)	Hickory	32	Draft Llano Uplift GAM	
Mason	Hickory	Ellenburger-San Saba	49	Draft Llano Uplift GAM	
McCulloch	Edwards-Trinity (Plateau)	Marble Falls	1	Draft Llano Uplift GAM	
McCulloch	Edwards-Trinity (Plateau)	Ellenburger-San Saba	9	Draft Llano Uplift GAM	
McCulloch	Hickory	Ellenburger-San Saba	114	Draft Llano Uplift GAM	
McCulloch	Marble Falls	Ellenburger-San Saba	1,836	Draft Llano Uplift GAM	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Medina	Trinity	Edwards (Balcones Fault Zone)	7,468	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Medina	Trinity	Edwards (Balcones Fault Zone)	28,617	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Menard	Edwards-Trinity (Plateau)	Ellenburger-San Saba	21	Draft Llano Uplift GAM	
Midland	Dockum	Edwards-Trinity (Plateau)	16	High Plains Aquifer System GAM v1.01	
Midland	Edwards-Trinity (Plateau)	Ogallala	3,838	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Midland	Ogallala	Edwards-Trinity (Plateau)	304	High Plains Aquifer System GAM v1.01	
Milam	Carrizo-Wilcox	Brazos River Alluvium	1,143	Carrizo-Wilcox GAM (central) v1.01	
Mills	Ellenburger-San Saba	Hickory	15	Draft Llano Uplift GAM	
Moore	Ogallala	Dockum	1,647	High Plains Aquifer System GAM v1.01	
Motley	Ogallala	Dockum	2,471	High Plains Aquifer System GAM v1.01	
Oldham	Ogallala	Dockum	3,720	High Plains Aquifer System GAM v1.01	
Other Areas	Seymour	Blaine	321	Seymour Aquifer GAM v_1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Parmer	Dockum	Ogallala	238	High Plains Aquifer System GAM v1.01	
Pecos	Edwards-Trinity (Plateau)	Pecos Valley	41,395	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Pecos	Edwards-Trinity (Plateau)	Pecos Valley	602	High Plains Aquifer System GAM v1.01	Different models show different average flux
Pecos	Edwards-Trinity (Plateau)	Dockum	925	High Plains Aquifer System GAM v1.01	
Pecos	Rustler	Dockum	1	Rustler GAM v1.01	
Potter	Ogallala	Dockum	1,345	High Plains Aquifer System GAM v1.01	
Randall	Ogallala	Dockum	2,757	High Plains Aquifer System GAM v1.01	
Reagan	Dockum	Edwards-Trinity (Plateau)	175	High Plains Aquifer System GAM v1.01	
Real	Trinity	Edwards-Trinity (Plateau)	272	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Reeves	Edwards-Trinity (Plateau)	Pecos Valley	44,182	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Reeves	Edwards-Trinity (Plateau)	Dockum	440	High Plains Aquifer System GAM v1.01	
Reeves	Pecos Valley	Edwards-Trinity (Plateau)	532	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Robertson	Carrizo-Wilcox	Brazos River Alluvium	1,218	Carrizo-Wilcox GAM (central) v1.01	
Runnels	Edwards Trinity Plateau & Other Formations	Lipan	2,185	Lipan GAM v_1.01	
San Saba	Hickory	Ellenburger-San Saba	4,446	Draft Llano Uplift GAM	
San Saba	Marble Falls	Ellenburger-San Saba	1,713	Draft Llano Uplift GAM	
Schleicher	Edwards Trinity Plateau & Other Formations	Lipan	395	Lipan GAM v_1.01	
Sherman	Ogallala	Dockum	62	High Plains Aquifer System GAM v1.01	
Sterling	Edwards-Trinity (Plateau)	Dockum	566	High Plains Aquifer System GAM v1.01	
Stonewall	Seymour	Blaine	915	Seymour Aquifer GAM v_1.01	
Swisher	Ogallala	Dockum	1,596	High Plains Aquifer System GAM v1.01	
Terry	Ogallala	Edwards-Trinity (High Plains)	449	High Plains Aquifer System GAM v1.01	
Tom Green	Edwards-Trinity (Plateau)	Dockum	9	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Tom Green	Lipan	Edwards-Trinity (Plateau) & Other Formations	2,967	Lipan GAM v_1.01	
Travis	Edwards (Balcones Fault Zone)	Trinity	12,403	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Travis	Edwards (Balcones Fault Zone)	Trinity	3,172	Northern Trinity Woodbine GAM v2.01	Different models show different average flux
Travis	Trinity	Edwards (Balcones Fault Zone)	1,072	Edwards (Balcones Fault Zone) San Antonio segment	
Upton	Dockum	Edwards-Trinity (Plateau)	358	High Plains Aquifer System GAM v1.01	
Upton	Pecos Valley	Edwards-Trinity (Plateau)	228	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Uvalde	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	9,604	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Uvalde	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	20,838	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Uvalde	Trinity	Edwards (Balcones Fault Zone)	1,616	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Uvalde	Trinity	Edwards-Trinity (Plateau)	3,649	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Uvalde	Trinity	Edwards (Balcones Fault Zone)	6,664	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Williamson	Edwards (Balcones Fault Zone)	Trinity	1,242	Northern Trinity Woodbine GAM v2.01	
Winkler	Edwards-Trinity (Plateau)	Dockum	20	High Plains Aquifer System GAM v1.01	
Winkler	Ogallala	Pecos Valley	38	High Plains Aquifer System GAM v1.01	
Winkler	Ogallala	Dockum	6	High Plains Aquifer System GAM v1.01	
Winkler	Pecos Valley	Edwards-Trinity (Plateau)	0	Edwards Trinity (Plateau) and Pecos Valley GAM v1.01	
Yoakum	Ogallala	Edwards-Trinity (High Plains)	2,119	High Plains Aquifer System GAM v1.01	
Other Areas	Lipan	Edwards-Trinity (Plateau) & Other Formations	1,873	Lipan GAM v_1.01	

6 Aquifer Summaries

Aquifers summaries are listed below alphabetically in major and minor categories. These summaries are derived from TWDB databases, reports, and maps, TWDB groundwater availability modeling studies, and scientific studies from outside institutions.

Each aquifer summary includes a snapshot of the geology and hydrogeology, flows to surface water and other aquifers, water quantity, and water quality.

Major Aquifers

Minor Aquifers

6.1 Carrizo-Wilcox Aquifer

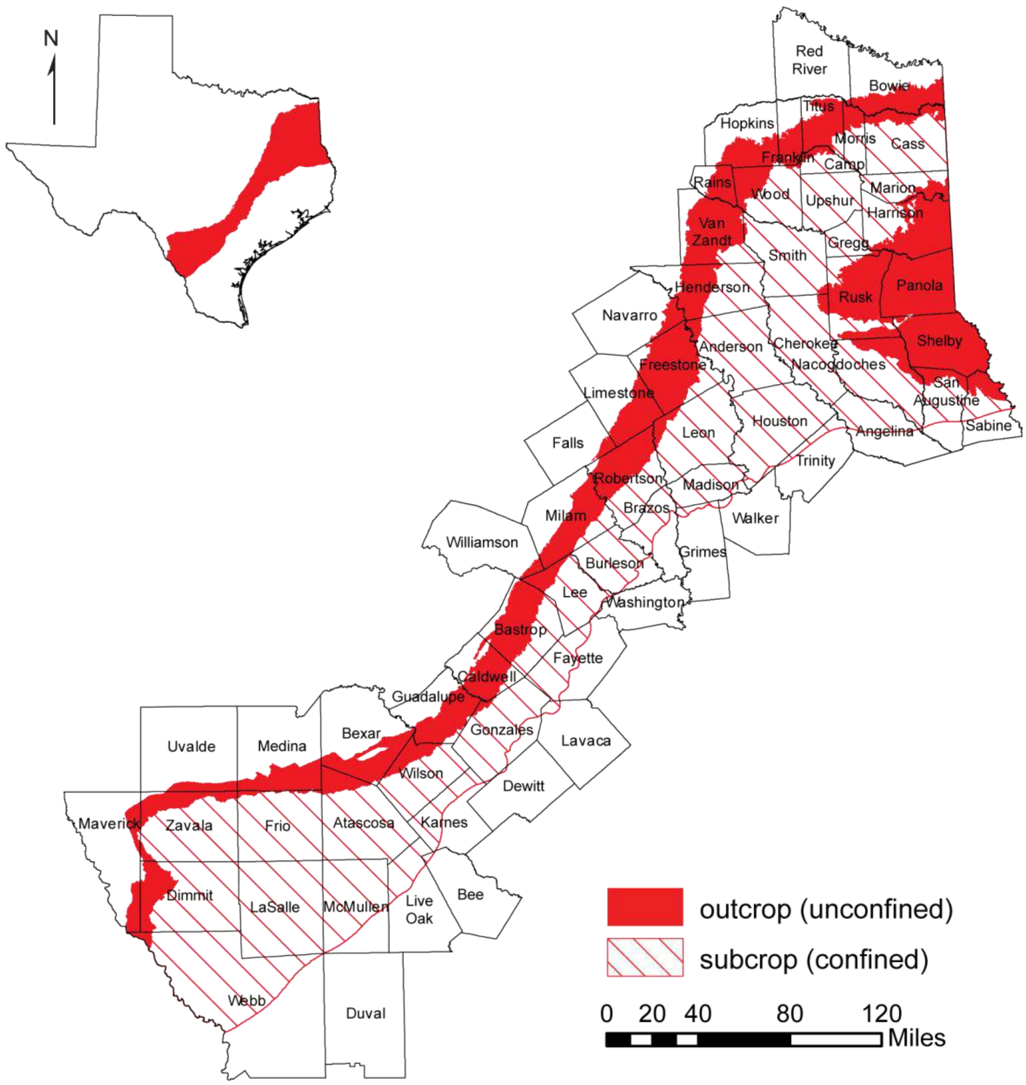


Figure 6-1. Extent of the Carrizo-Wilcox Aquifer, showing the unconfined (outcrop) and confined (subsurface) areas.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 11,227 square miles
- Area of subsurface: 25,491 square miles
- Proportion of aquifer with groundwater conservation districts: 65 percent
- Number of counties containing the aquifer: 66

Geology and hydrogeology

The Carrizo-Wilcox Aquifer is a major aquifer extending from the Louisiana border to the Mexico border in a wide band adjacent to and northwest of the Gulf Coast Aquifer (Figure 6-1). It consists of the Hooper, Simsboro, and Calvert Bluff formations of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group. The aquifer is primarily composed of sand locally interbedded with gravel, silt, clay, and lignite. Although the Carrizo-Wilcox Aquifer reaches 3,000 feet in thickness, the freshwater saturated thickness of the sands averages 670 feet.

The Carrizo-Wilcox Aquifer is unconfined in the outcrop area. The aquifer is confined in the down-dip region where it is overlain by the lower-permeability Reklaw Formation. Figure 6-2 summarizes the stratigraphic and hydrogeologic units of the aquifer. In general, the Simsboro and Carrizo formations contain thicker, more laterally continuous and more permeable sands and, therefore, are more important hydrostratigraphic units when determining groundwater availability. The Calvert Bluff and Hooper formations typically are made up of clay, silt, and sand mixtures, as well as lignite deposits. Because of their relatively low vertical permeability, the Hooper and Calvert Bluff formations act as leaky aquitards that confine fluid pressures in the Simsboro and Carrizo aquifers and restrict groundwater movement between the layers. Although the Hooper and Calvert Bluff formations contain sand units, they are generally finer and less continuous than the sands of the Simsboro and Carrizo formations (Hutchison and others, 2009).

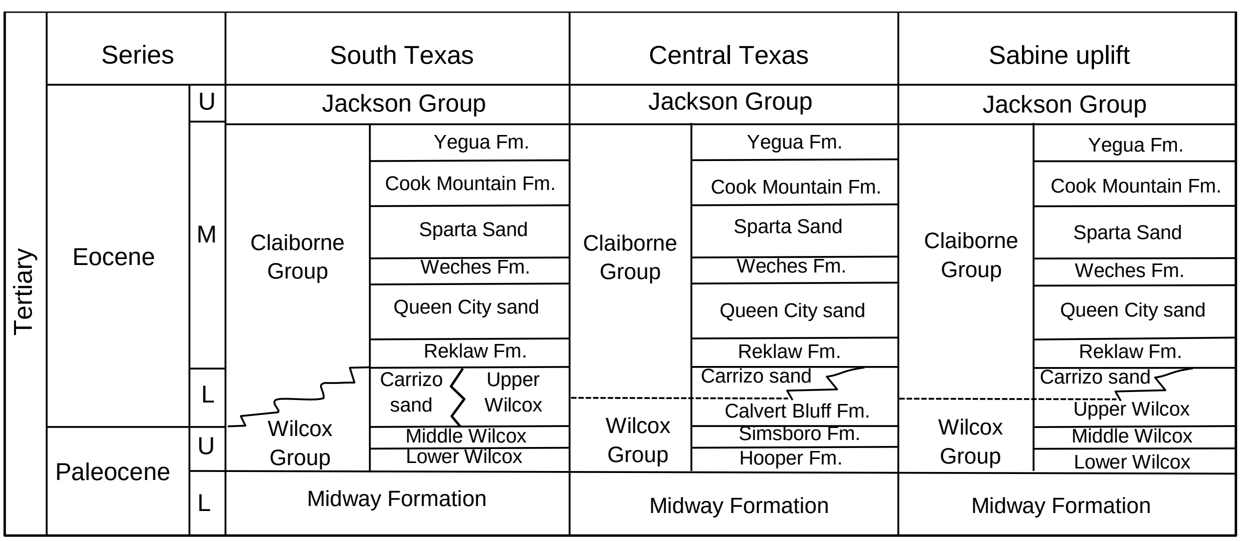


Figure 6-2. **Stratigraphy and hydrogeology in the Carrizo-Wilcox Aquifer (modified from Mace and others, 2000).** ***(Fm = Formation; U = Upper; M = Middle; L = Lower)***

The marine deposits of the Paleocene Midway Formation are the lower confining boundary of the Carrizo-Wilcox Aquifer. The Eocene Reklaw Formation represents a semi-confining unit between the Carrizo Sand and the shallower Queen City Aquifer. In the northeastern part of the aquifer the Reklaw clays become discontinuous, providing a more permeable connection between the Carrizo Sand and the overlying Queen City Formation. The Wilcox Fault Zone, a series of growth faults caused by sediment progradation onto marine clays and resulting basin-ward slippage and subsidence, defines the down-dip limit of the aquifer. Figure 6-3 shows structural cross-sections for the southern and northern portions of the aquifer.

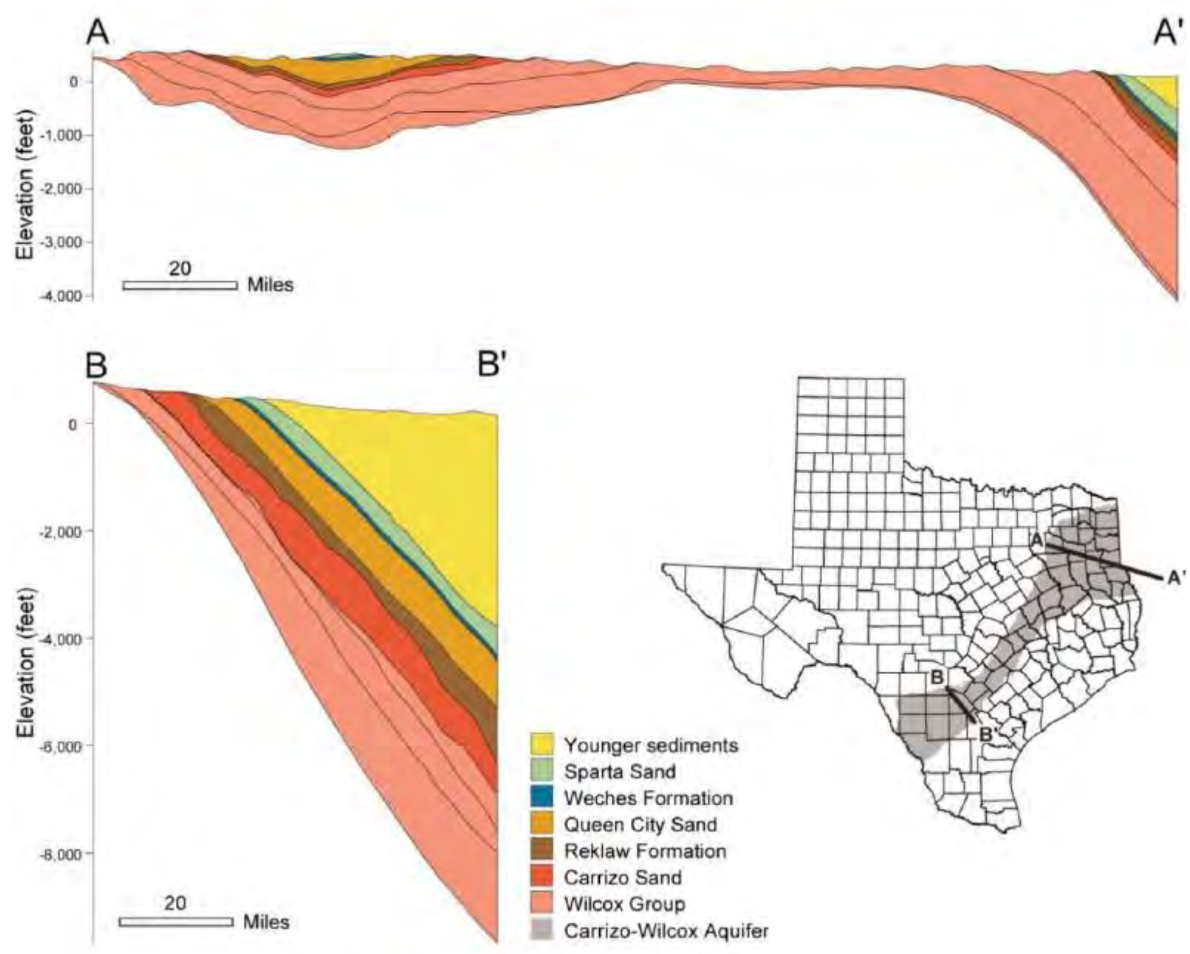


Figure 6-3. Structural cross-sections of the Carrizo-Wilcox Aquifer and overlying strata (modified from Kelley and others, 2004).

The mean hydraulic conductivity of the Carrizo-Wilcox Aquifer generally decreases to the northeast. Hydraulic conductivity ranges from about 0.01 to 4,000 feet per day and has a mean of about 6 feet per day. Transmissivity ranges from about 0.1 to 10,000 feet squared per day and has a geometric mean of about 300 feet squared per day. The Simsboro Formation and Carrizo

Sand portions of the Carrizo-Wilcox Aquifer have higher transmissivity and hydraulic conductivity than the Cypress Aquifer, Calvert Bluff Formation, and undivided Wilcox Group. The highest transmissivity and hydraulic conductivity for the Carrizo Formation is in the Winter Garden area. The highest transmissivity and hydraulic conductivity for the Wilcox Group is in the south central and northeast parts of the aquifer.

Flows to surface water and other aquifers

Groundwater discharges to local creeks and major streams crossing the unconfined area of the aquifer when the water level in the aquifer is higher than the stream. Conversely, stream water may recharge the aquifer during flood events when the stream is high or when pumping draws down the water level in the aquifer. Flows from the Carrizo-Wilcox Aquifer to surface-water bodies (Table 6-1), are estimated from stream baseflow and surface runoff measurements.

In general, the low-permeability geological units above and below the Carrizo-Wilcox Aquifer strongly limit inter-aquifer flow. The aquifer also has limited areas of overlap with other major or minor aquifers where freshwater flow could potentially occur. In these areas of potential communication, the direction and magnitude of any inter-aquifer flow depends on the hydraulic conductivity of the intervening formations and the potentiometric head differences between the aquifers.

In most of the groundwater availability models developed by the TWDB, the upper and lower boundaries of the Carrizo-Wilcox Aquifer are specified as no-flow surfaces, based on the conceptual model that any inter-aquifer flows that might occur are several orders of magnitude smaller than flows within the aquifer and are not significant on a regional scale.

Table 6-2 shows estimated flows from the Carrizo-Wilcox Aquifer to other major and minor aquifers, as calculated by approved TWDB models. The only inter-aquifer flow that is calculated by the models is the flow between the Carrizo-Wilcox and the Brazos River Alluvium aquifers. The Queen City Aquifer is present above the Carrizo-Wilcox Aquifer over much of its extent and, as noted above, has potential for inter-aquifer flow to the northeast where the Reklaw Formation clays become thin or discontinuous, but the model for the northern Carrizo-Wilcox Aquifer does not expressly calculate these potential flows.

Brackish and saline groundwater is present in the down-dip regions of the Carrizo-Wilcox Aquifer. The Carrizo and Wilcox sands become oil-producing reservoir rocks in the Gulf Coast region, where they are present at depths of several thousand feet beneath the Gulf Coast Aquifer. Growth faults along the Wilcox Fault Zone limit down-dip movement of freshwater into the brackish and saline zones beyond the established extent of the Carrizo-Wilcox Aquifer.

Table 6-1. Summary of groundwater flow from the Carrizo-Wilcox Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	47	2.7	0.6
Atascosa	143	12.9	4.5
Bastrop	462	24.1	4.2
Bexar	366	41.3	16.4
Bowie	359	78.1	18.1
Burleson	0	0	0
Caldwell	299	27.7	6.4
Camp	35	5.9	1.3
Cass	131	38.1	9.6
Cherokee	29	10.3	3.8
Dimmit	256	3.8	0.9
Falls	44	2.3	0.2
Franklin	147	24.4	5.5
Freestone	676	59.5	11.9
Frio	26	1.2	0.4
Gonzales	21	3.2	1.1
Gregg	8	2.4	0.7
Guadalupe	362	27.1	8.2
Harrison	526	124.1	29.4
Henderson	309	40.1	13
Hopkins	279	35.8	6.4
Lee	107	4.9	0.8
Leon	66	3.6	0.3
Limestone	338	18.4	1.6
Marion	82	24.4	7.2
Maverick	189	4	1
Medina	342	19.8	6.5
Milam	425	32.3	4
Morris	80	19.1	3.9
Nacogdoches	184	61.9	22
Navarro	101	6.5	1.1
Panola	816	144.3	27.9
Rains	166	18.8	2.7
Red River	6	0.9	0.1

Table 6-1 (continued). Summary of groundwater flow from the Carrizo-Wilcox Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Robertson	390	25.5	2.5
Rusk	646	198.1	65.2
Sabine	117	26	5.1
San Augustine	98	25.2	6.2
Shelby	817	148.7	24.8
Smith	15	4	1.3
Titus	296	60.2	12.1
Uvalde	118	3.9	0.8
Van Zandt	574	61	11.2
Webb	22	0.3	0.1
Williamson	39	2.1	0.3
Wilson	143	10.9	4
Wood	198	25	4.2
Zavala	255	7.6	1.7
Total	**11,155**	**1,522**	**361**

Table 6-2. Flow between the Carrizo-Wilcox and Brazos River Alluvium aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361

Water quantity

Total storage in the Carrizo-Wilcox Aquifer is estimated to be about 5.2 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.3 billion to 3.9 billion acre-feet (Table 6-3).

Figure 6-4 shows changes in water levels in the Carrizo-Wilcox Aquifer from 1995 to 2015. Most of the aquifer shows increased water levels as a result of recharge during the period from 2000 to 2005. Starting around 2005, the southernmost portion of the aquifer has experienced increasing drawdown, which may be correlated with the expansion of oil field activity in the Eagle Ford Shale and other formations in the area.

Table 6-3. Total estimated recoverable storage in the Carrizo-Wilcox Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
11	2,061,633,000	515,408,250	1,546,224,750
12	1,019,320,000	254,830,000	764,490,000
13	1,951,720,000	487,930,000	1,463,790,000
14	19,804,000	4,951,000	14,853,000
15	69,900,000	17,475,000	52,425,000
16	104,700,000	26,175,000	78,525,000
Total	**5,227,077,000**	**1,306,769,250**	**3,920,307,750**

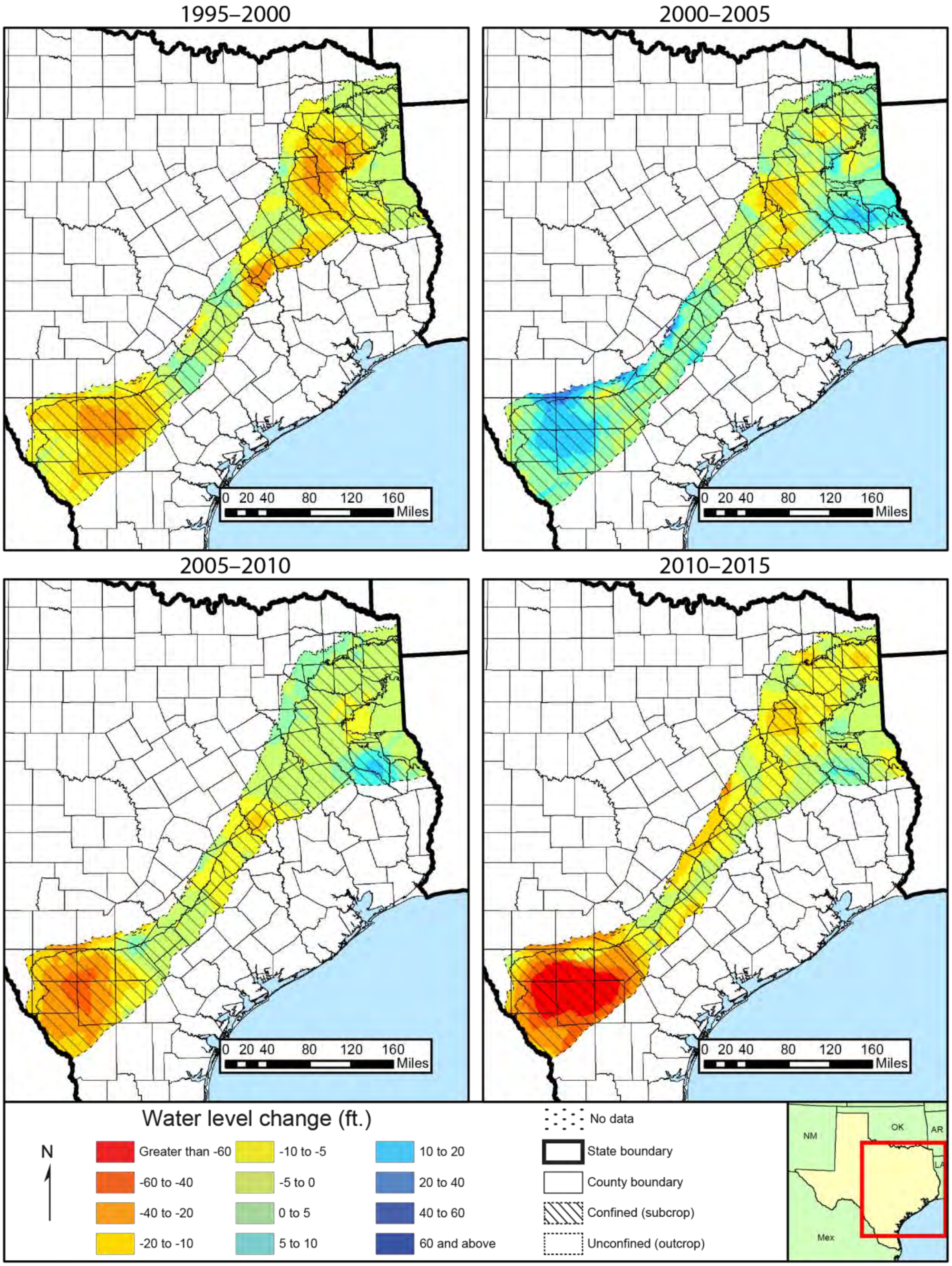


Figure 6-4. Water-level changes in the Carrizo-Wilcox Aquifer, 1995 to 2015.

Water quality

Water quality in the Carrizo-Wilcox Aquifer (Figure 6-5) shows isolated areas of slightly saline to moderately saline groundwater in the eastern and central portions of the aquifer and more widespread areas of slightly to moderately saline groundwater in the southwest. Groundwater in the unconfined area is hard and typically has total dissolved solids concentrations less than 1,000 milligrams per liter. Groundwater in the confined area of the aquifer is generally softer and has total dissolved solids concentrations less than 1,000 milligrams per liter except in the southern and western portions of the aquifer. Parts of the aquifer in the Winter Garden area and in parts of Brazos County are slightly to moderately saline, with total dissolved solids concentrations ranging from 1,000 to 7,000 milligrams per liter.

High iron and manganese content in excess of secondary drinking water standards is characteristic of the deeper subsurface portions of the aquifer. Radionuclides are found at concentrations exceeding drinking water standards in limited areas in the south and central outcrop regions (Reedy and others, 2011).

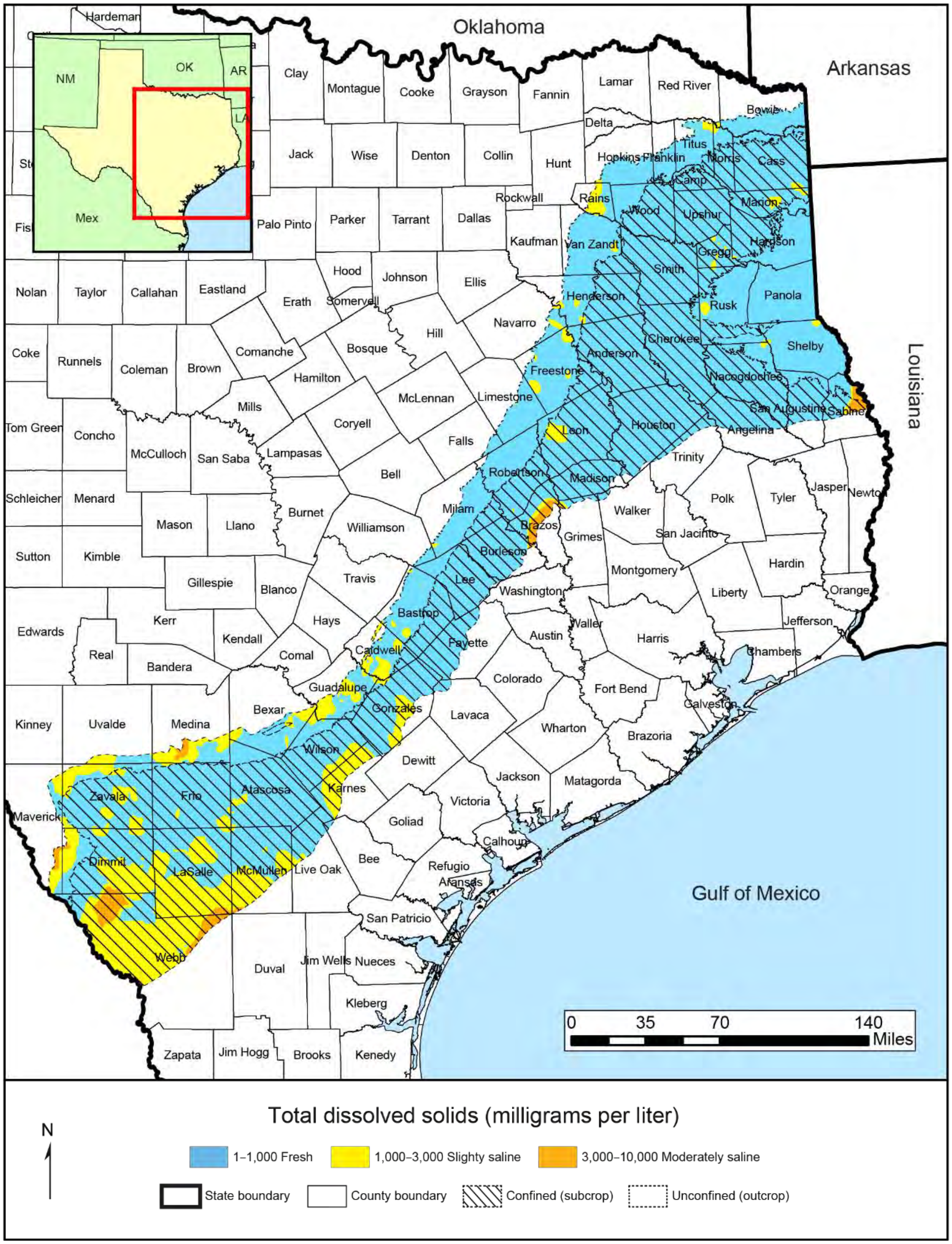


Figure 6-5. Total dissolved solids in the Carrizo-Wilcox Aquifer.

6.2 Edwards (Balcones Fault Zone) Aquifer

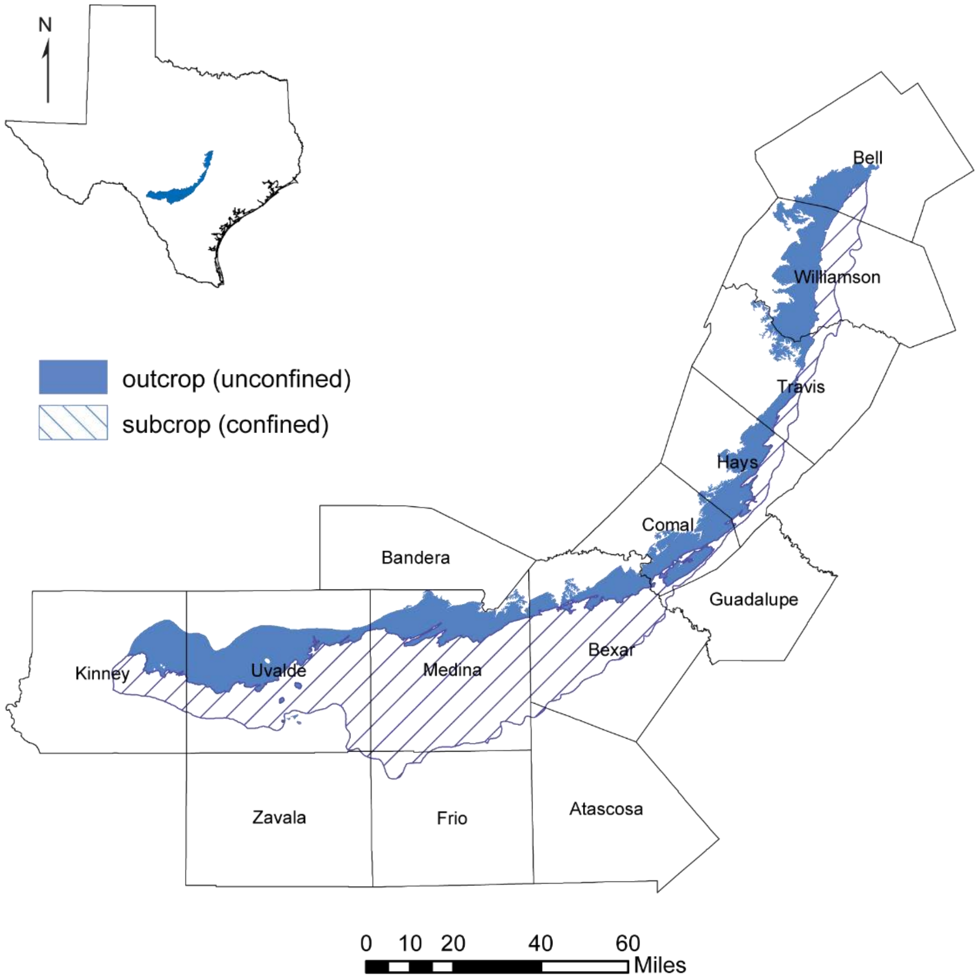


Figure 6-6. Extent of the Edwards (Balcones Fault Zone) Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,566 square miles
- Area in subsurface: 2,481 square miles
- Proportion of aquifer with groundwater conservation districts: 87 percent
- Number of counties containing the aquifer: 14

Geology and hydrogeology

The Edwards (Balcones Fault Zone) Aquifer is a major aquifer in the south central part of the state (Figure 6-6). It consists primarily of partially dissolved, or karstic, limestone that creates a highly permeable aquifer. Aquifer thickness ranges from 200 to 600 feet, and freshwater saturated thickness averages 560 feet in the southern part of the aquifer.

The Edwards (Balcones Fault Zone) Aquifer is part of an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The carbonates in the Edwards (Balcones Fault Zone) Aquifer are laterally and vertically heterogeneous. The stratigraphy and hydrogeology of the aquifer are outlined in Figure 6-7 and Figure 6-8. The Edwards (Balcones Fault Zone) Aquifer consists of highly permeable rocks, where water flows through faults, fractures, joints, and conduits.

The Edwards (Balcones Fault Zone) Aquifer is unconfined in the outcrop area. In the down-dip area the aquifer is confined by the overlying Del Rio Clay. The Glen Rose Limestone, which is the uppermost unit of the Trinity Aquifer, generally defines the lower boundary of the aquifer. The degree of hydraulic connection between the Trinity and Edwards (Balcones Fault Zone) aquifers is locally limited by the relatively low vertical hydraulic conductivities of the basal Edwards and upper Trinity units, but on a regional scale karstic features allow cross-formational flow to occur (Lindgren and others, 2004).

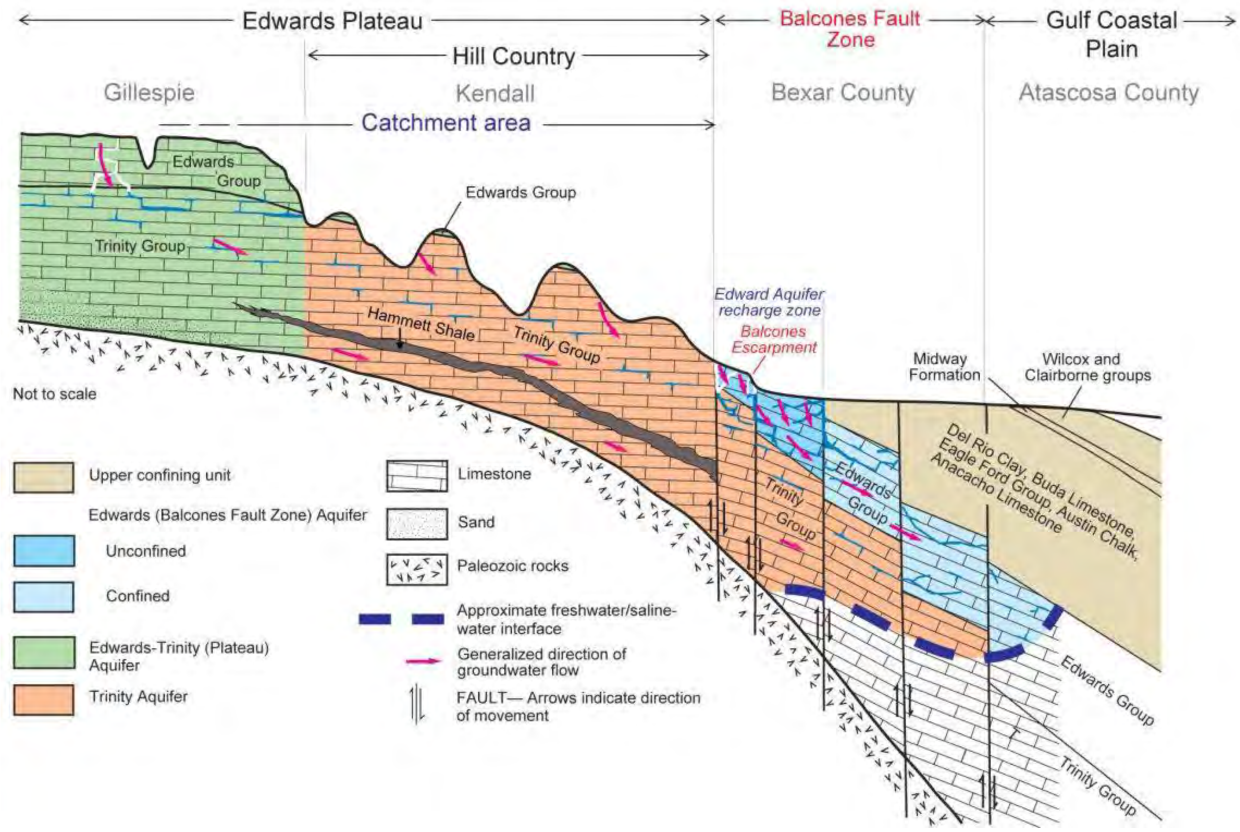


Figure 6-7. Diagrammatic cross-section showing hydrogeologic framework and generalized groundwater flow through the Edwards (Balcones Fault Zone) Aquifer, San Antonio region, Texas (modified from Barker and Ardis, 1996; Lindgren and others, 2004).

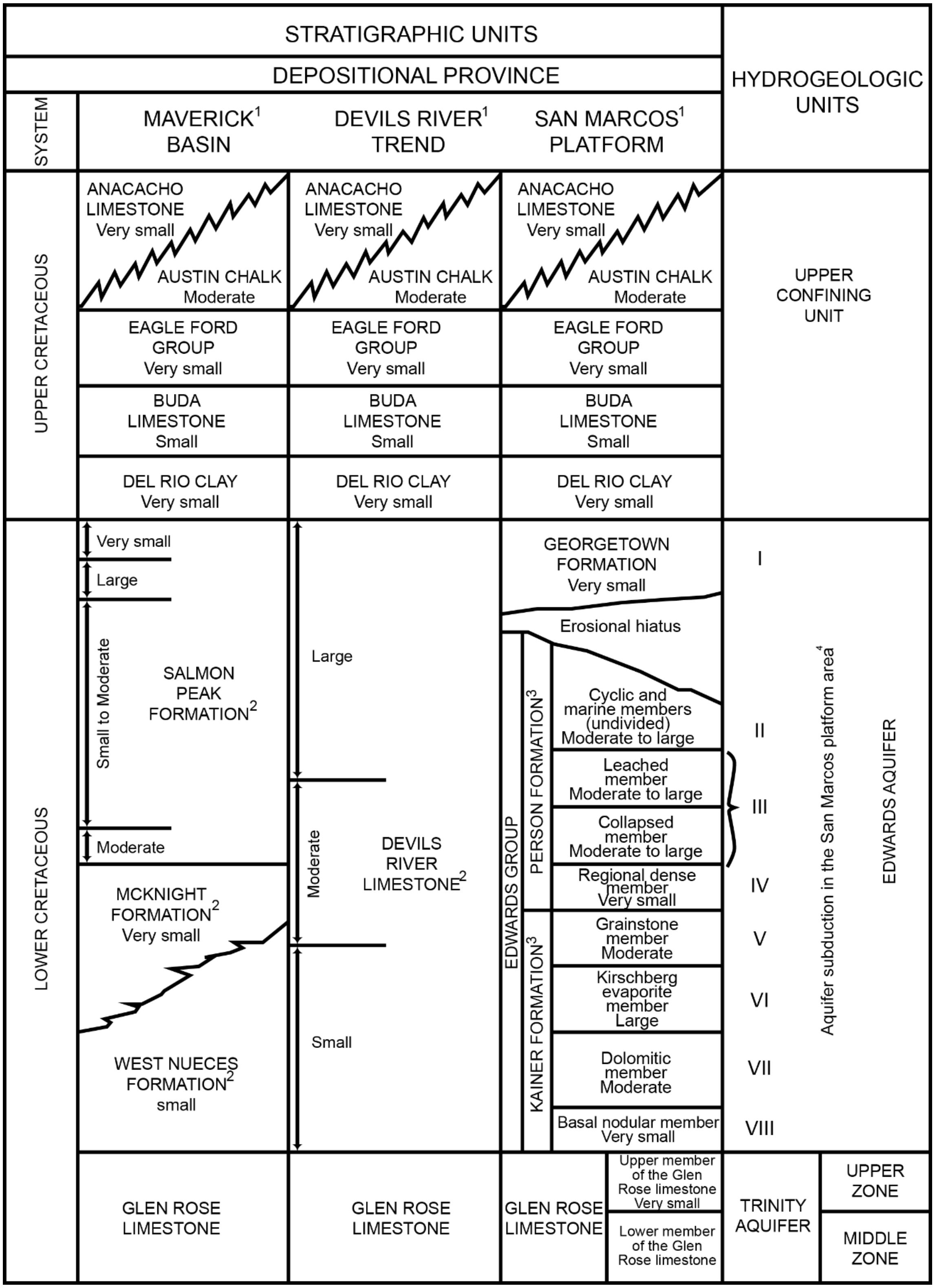


Figure 6-8. Hydrostratigraphy of the Edwards (Balcones Fault Zone) Aquifer (modified from Lindgren and others, 2004).

Flows to surface water and other aquifers

The Edwards (Balcones Fault Zone) Aquifer feeds several well-known springs, including Comal Springs in Comal County, which is the largest spring in the state, and San Marcos Springs in Hays County, which is the second largest. Hueco, San Pedro, San Antonio, and Leona springs also discharge from the aquifer. Table 6-4 shows flows from the Edwards (Balcones Fault Zone) Aquifer to surface-water bodies, as estimated from stream baseflow and surface runoff measurements.

Table 6-5 shows the amount of springflow that makes up baseflow. Because of the aquifer's highly permeable nature, water levels and springflows respond quickly to rainfall, drought, and pumping. Although water levels in wells throughout the aquifer decline rapidly in response to drought conditions, they also rebound quickly with adequate rainfall.

Table 6-6 shows flow between the Edwards (Balcones Fault Zone) Aquifer and the Trinity and Edwards-Trinity (Plateau) aquifers. Groundwater availability models indicate flow both from the Edwards (Balcones Fault Zone) Aquifer into the Trinity Aquifer in some locations and from the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer in others.

Table 6-4. Summary of groundwater flow from the Edwards (Balcones Fault Zone) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bandera	0	0	0
Bell	93	7.7	1.3
Bexar	118	7.6	2.4
Comal	168	315.4	316.7
Hays	149	180.3	150.7
Kinney	118	4.5	1.5
Medina	234	22.4	5.8
Travis	81	71.4	58.6
Uvalde	351	35.3	12.4
Williamson	254	27.9	4.2
Total	**1,566**	**673**	**554**

Table 6-5. Summary of springflow from the Edwards (Balcones Fault Zone) Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Comal	296.1	311	Comal Springs at New Braunfels, TX San Marcos Springs at San Marcos, TX
Hays	156	146	San Marcos Springs at San Marcos, TX
Travis	60.7	58	Barton Springs at Austin, TX

Note: Springflow values are included as part of the total baseflow presented in Table 6-4.

Table 6-6. Model estimates of inter-aquifer flows between the Edwards (Balcones Fault Zone) Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463

Water quantity

Total storage in the Edwards (Balcones Fault Zone) Aquifer is estimated to be more than 24 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 6.2 million to 18.7 million acre-feet (Table 6-7). Figure 6-9 shows changes in water levels in the Edwards (Balcones Fault Zone) Aquifer from 1995 to 2015.

The quantity of water that can be withdrawn from the aquifer within the Edwards Aquifer Authority jurisdiction is limited by law to be no more than 572,000 acre-feet per year to preserve the habitat for endangered species dependent on springflow from the aquifer. Counties within the Edwards Aquifer Authority’s jurisdiction include all of Uvalde, Medina, and Bexar counties, and parts of Atascosa, Comal, Guadalupe, Caldwell, and Hays counties.

Table 6-7. Total estimated recoverable storage in the Edwards (Balcones Fault Zone) Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
8	94,900	23,725	71,175
9	260,700	65,175	195,525
10	22,877,900	5,719,475	17,158,425
13	1,718,400	429,600	1,288,800
Total	**24,951,900**	**6,237,975**	**18,713,925**

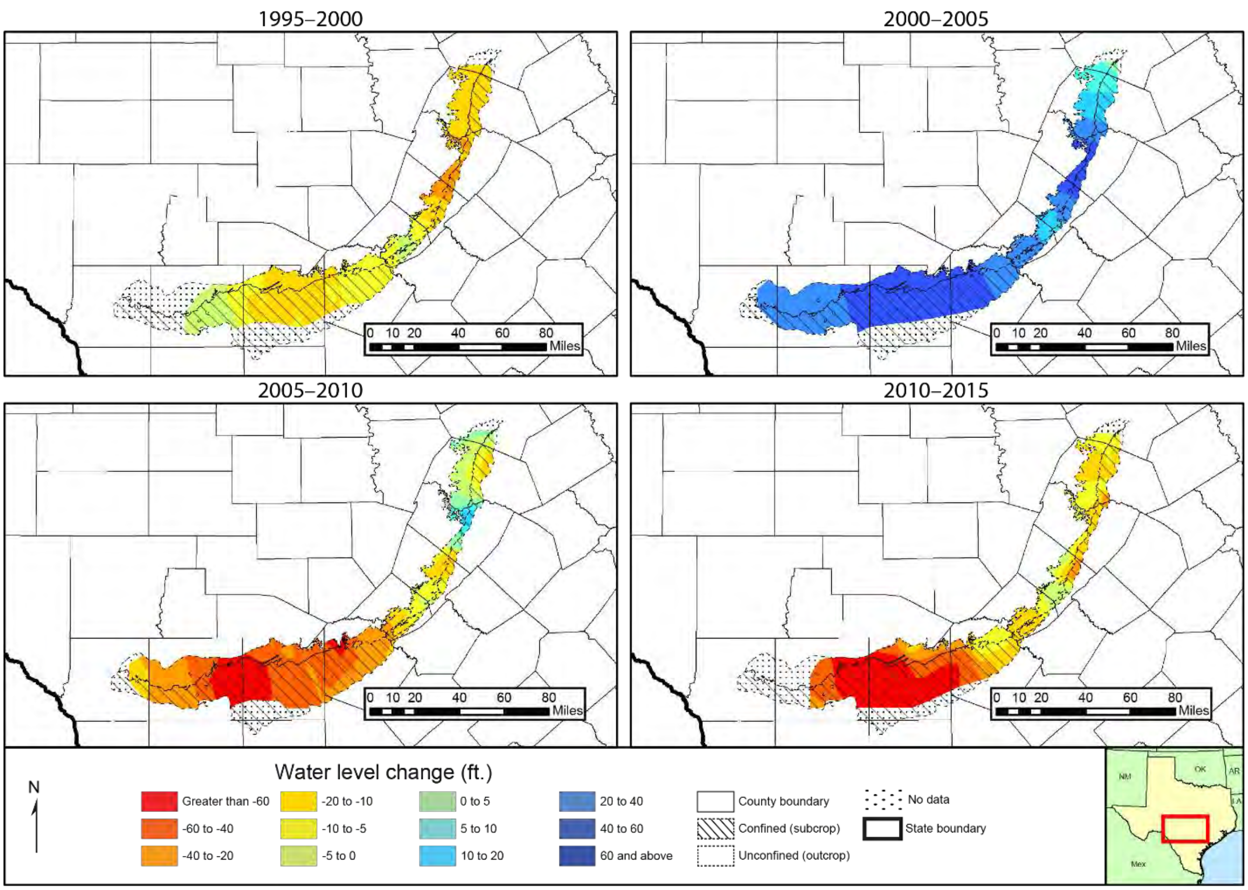


Figure 6-9. Water-level changes in the Edwards (Balcones Fault Zone) Aquifer, 1995 to 2015.

Water quality

Water quality in the aquifer is generally very good. The groundwater is hard but fresh and contains less than 500 milligrams per liter of total dissolved solids. Small regions of elevated fluoride are present in the northern Barton Springs segment and gross alpha radiation in the southern San Antonio segment of the aquifer (Reedy and others, 2011).

A map of the distribution of total dissolved solids in the Edwards (Balcones Fault Zone) Aquifer (Figure 6-10) shows freshwater in the unconfined area to the north and west of the Balcones Fault Zone and more saline water in the confined zone to the south and east, largely outside the official aquifer boundary. The rapid recharge and flow through karstic features results in a low residence time for water in the unconfined zone, limiting water-rock interactions that increase total dissolved solids. In the down-dip area the official boundary of the aquifer is largely determined by the extent of freshwater along the so-called “bad water line.” East and south of the “bad water line,” increased residence time and water interaction with evaporite members of the Edwards Formation result in increased groundwater salinity. The Edwards Formation continues laterally beyond the official aquifer boundary to the south and east, becoming highly saline with greater depth. The rapid recharge through the karstic outcrop increases the aquifer’s vulnerability to contamination, making nonpoint source pollution from runoff in urbanized areas a particular concern.

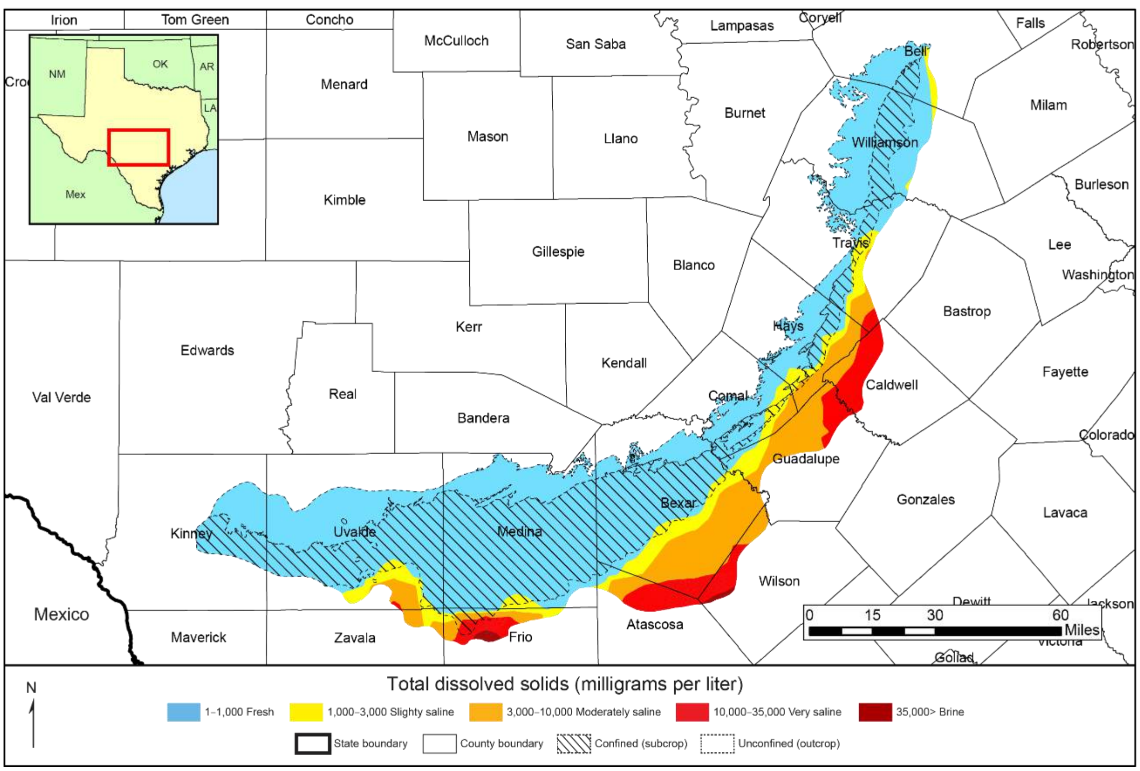


Figure 6-10. Total dissolved solids in the Edwards (Balcones Fault Zone) Aquifer.

6.3 Edwards-Trinity (Plateau) Aquifer

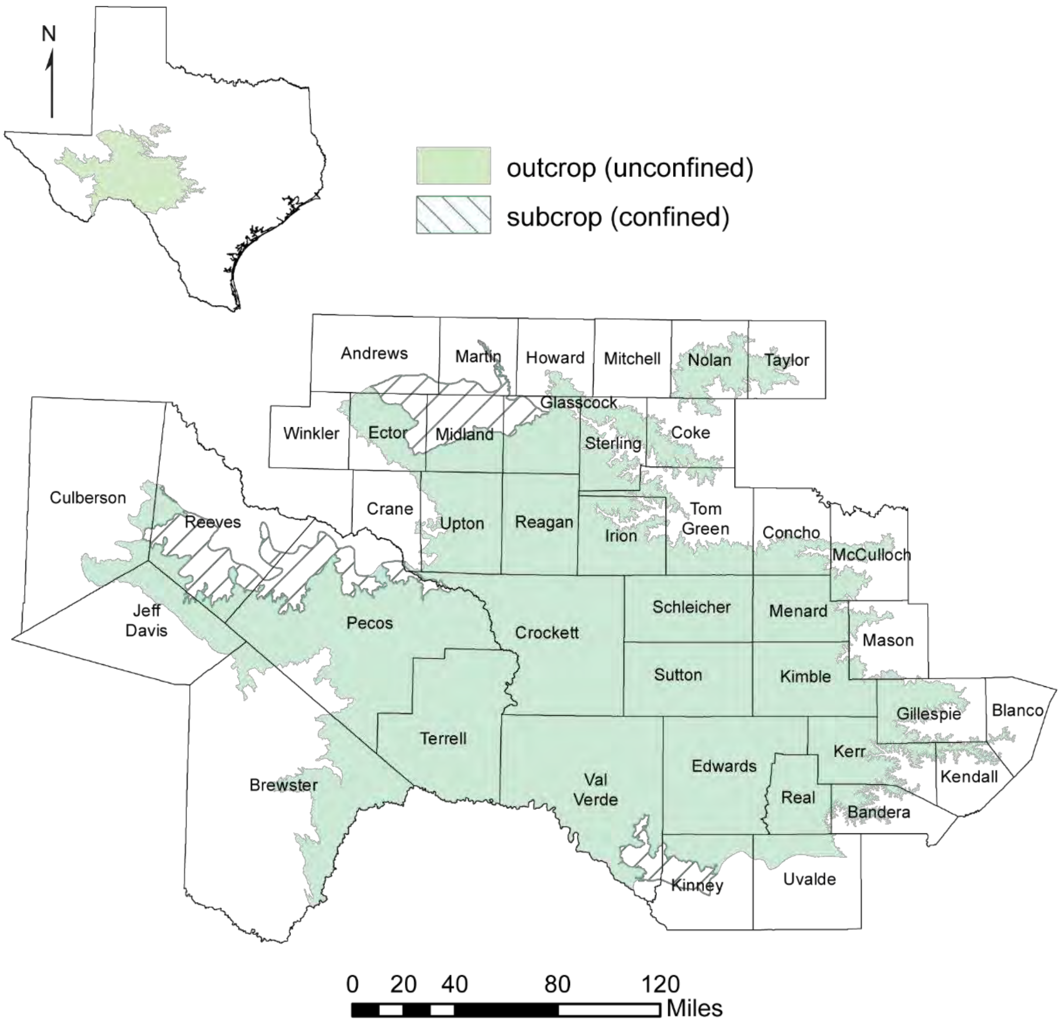


Figure 6-11. Extent of the Edwards-Trinity (Plateau) Aquifer, showing unconfined (outcrop) and confined (subsurface) areas.

Aquifer characteristics

- Aquifer type: mostly unconfined with small confined areas
- Area of outcrop: 32,373 square miles
- Area in subsurface: 3,051 square miles
- Proportion of aquifer with groundwater conservation districts: 82 percent
- Number of counties containing the aquifer: 41

Geology and hydrogeology

The Edwards-Trinity (Plateau) Aquifer is a major aquifer extending across much of the southwestern part of the state (Figure 6-11). The water-bearing units are composed predominantly of limestone and dolomite of the Edwards Group and sands of the Trinity Group. Freshwater saturated thickness averages 433 feet. The saturated thickness of the aquifer system generally increases from less than 100 feet in the north to greater than 800 feet down-dip to the south. Saturated thickness is influenced by ridges and troughs in the underlying Paleozoic depositional surface and variation in the surface topography (Barker and Ardis, 1996).

The aquifer is composed of Early Cretaceous-age sediments of the Trinity, Fredericksburg, and Lower Washita groups (Figure 6-12 and Figure 6-13). The Trinity Group sediments form the underlying Trinity portion of the aquifer while the Fredericksburg and Lower Washita Group sediments form the overlying Edwards portion of the aquifer. The Edwards-Trinity (Plateau) Aquifer sediments rest unconformably on top of an uneven erosional surface of folded and faulted Paleozoic to Triassic-age sediments (Anaya, 2004).

The aquifer is mostly under water table or unconfined conditions, although the Trinity unit of the aquifer may be semi-confined locally where relatively impermeable sediments of the overlying basal member of the Edwards Group exists (Ashworth and Hopkins, 1995). The base of the aquifer slopes generally to the south and southeast. Most of the rocks that underlie the Edwards-Trinity (Plateau) Aquifer are much less permeable than the aquifer and function as a barrier to groundwater flow. Locally, the underlying rocks are permeable and are hydraulically connected to the Edwards-Trinity (Plateau) Aquifer, thus extending the thickness of the flow system.

Except for areas of significant karst-induced permeability, the average hydraulic conductivity of the Edwards-Trinity (Plateau) Aquifer sediments is about 10 feet per day (Barker and Ardis, 1996). Wells commonly yield from 50 to 200 gallons per minute. Well yields can vary greatly depending on the amount of development of secondary permeability in the limestone; yields from jointed and cavernous limestone can be as much as 3,000 gallons per minute.

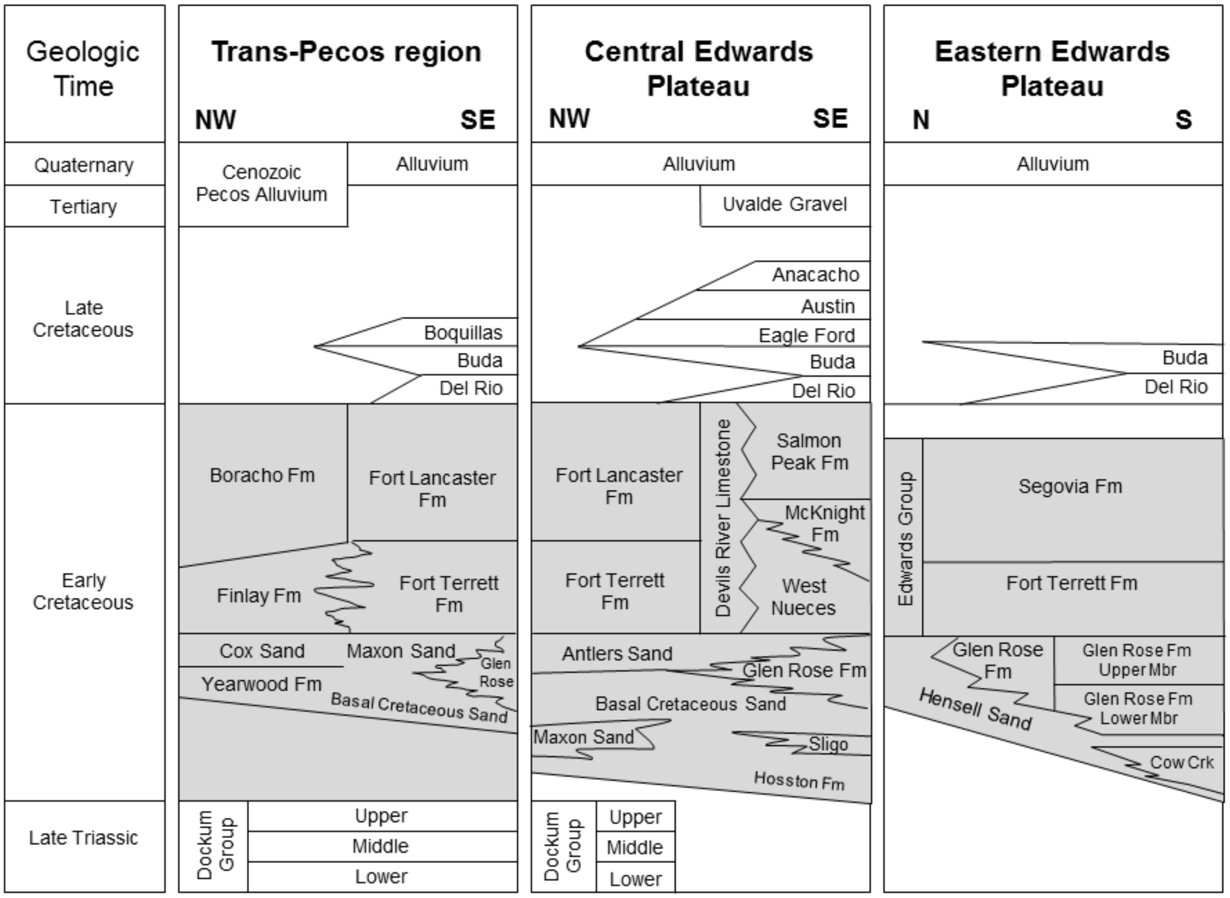


Figure 6-12. Stratigraphic chart of the Edwards Plateau region.

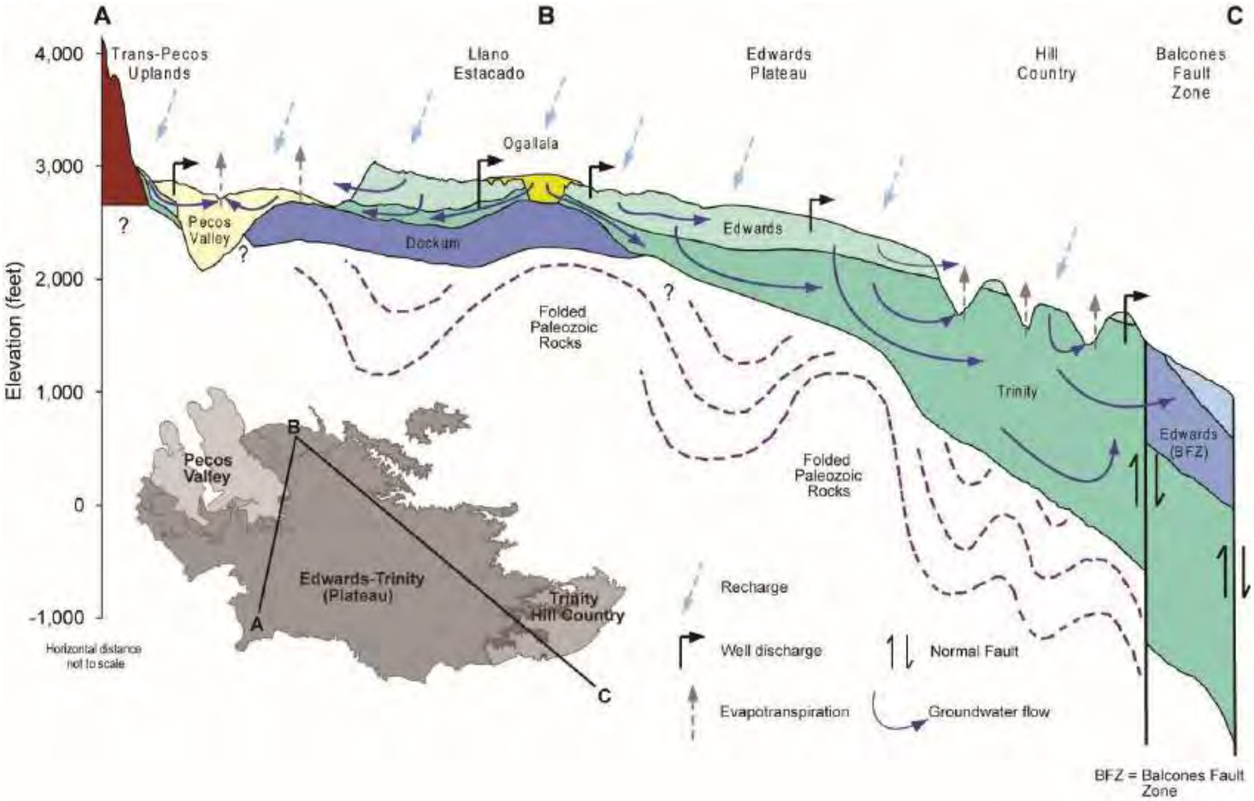


Figure 6-13. Conceptual model of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the Hill Country part of the Trinity Aquifer (modified from Anaya and Jones, 2004, 2009).

Flows to surface waters and other aquifers

Natural discharge from the Edwards-Trinity (Plateau) Aquifer to surface water occurs mostly from springs along the margins of the aquifer where the water table intersects the ground surface. Springs also discharge groundwater along the eastern flanks of the Trans-Pecos Mountains; the lower Pecos River canyons in Del Rio are the largest of these springs. As water levels have declined in the western portion of the aquifer due to increased irrigation pumping, springflows in those areas have also declined. In addition, many small springs that once flowed throughout the plateau have ceased flowing as a consequence of native grasslands being replaced by woody vegetation that consumes large amounts of potential recharge and allows more rainfall to run off before it is able to recharge the aquifer (Anaya, 2004).

Phreatophytic plants along major stream valleys, such as salt cedar on the Pecos River, discharge groundwater naturally as evapotranspiration. Most of the intermittent streams high on the plateau lose their flow to the underlying aquifer. The lower reaches of major streams along the northern, eastern, and southern margins of the plateau usually become gaining stream reaches when their stream channel elevation falls below the base of the Edwards unit. Table 6-8 summarizes groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface-water bodies. Table 6-9 shows the amount of springflow that contributes to baseflow.

The Edwards-Trinity (Plateau) Aquifer is hydraulically connected to four major aquifers: 1) Pecos Valley, 2) Ogallala, 3) Trinity, and 4) Edwards (Balcones Fault Zone). The aquifer is also hydraulically connected to several minor aquifers: 1) Dockum, 2) Capitan Reef Complex, 3) Rustler, 4) Hickory, 5) Ellenburger-San Saba, 6) Lipan, and, to a very small degree, 7) Marble Falls. Table 6-10 shows flow between the Edwards-Trinity (Plateau) and other aquifers.

Table 6-8. Summary of groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	10	0	0
Bandera	209	33.5	12.1
Blanco	19	2	0.6
Brewster	1,513	19.9	12.5
Coke	288	1.2	0.5
Concho	370	2.6	1
Crane	34	0.1	0.1
Crockett	2,792	68.6	38.3
Culberson	323	2.3	0.8
Ector	504	2	1.4
Edwards	2,124	159.6	62.7
Gillespie	567	48.6	23.3
Glasscock	685	3.5	2.3
Howard	82	0.3	0.1
Irion	900	18	9.2
Jeff Davis	240	0.9	0.5
Kendall	90	10.3	3.6
Kerr	833	118.3	56.5
Kimble	1,236	80.9	35
Kinney	350	15.1	5
Martin	7	0	0
Mason	158	7.2	3

Table 6-8 (continued). Summary of groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
McCulloch	277	4.9	1.5
Menard	891	29.6	12.2
Midland	406	2.1	0.9
Mitchell	1	0	0
Nolan	498	3	0.9
Pecos	3,408	52.7	54.2
Reagan	1,175	11.3	7.1
Real	687	91.2	32.8
Reeves	319	0.7	0.9
Schleicher	1,308	45.1	19.8
Sterling	623	2.6	1.5
Sutton	1,457	63.8	27.4
Taylor	189	1.6	0.3
Terrell	2,345	51	36.9
Tom Green	621	11.1	4.8
Upton	1,119	7.6	5.5
Uvalde	313	37.8	13.5
Val Verde	2,923	119.3	62.3
Winkler	21	0.1	0.1
Total	**31,915**	**1,130**	**551**

Table 6-9. Summary of springflow from the Edwards-Trinity (Plateau) Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Pecos	22.4	28	Comanche Springs at Ft Stockton, TX

Note: These values are included in the total baseflow values presented in Table 6-8.

Table 6-10. Model estimates of inter-aquifer flows between the Edwards-Trinity (Plateau) Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848
Edwards-Trinity (Plateau) Aquifer & other formations	Lipan Aquifer	7,507
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & Other Formations	7,506
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546

Water quantity

Total storage in the aquifer is estimated to be more than 45 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 11.3 million to 34.1 million acre-feet (Table 6-11). Water levels have remained rather stable because recharge has generally kept pace with the relatively low volume of water pumped from the aquifer. There are several areas in the northern and western plateau where water levels have declined as a result of increased pumping, including the agricultural district along the Reagan-Glasscock county boundary, and areas of concentrated oil production in Midland County. Figure 6-14 shows changes in water levels in the Edwards-Trinity (Plateau) Aquifer from 1995 to 2015.

Table 6-11. Total estimated recoverable storage in the Edwards-Trinity (Plateau) Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	142,000	35,500	106,500
3	390,300	97,575	292,725
4	3,780,000	945,000	2,835,000
7	38,821,000	9,705,250	29,115,750
9	2,358,000	589,500	1,768,500
Total	**45,491,300**	**11,372,825**	**34,118,475**

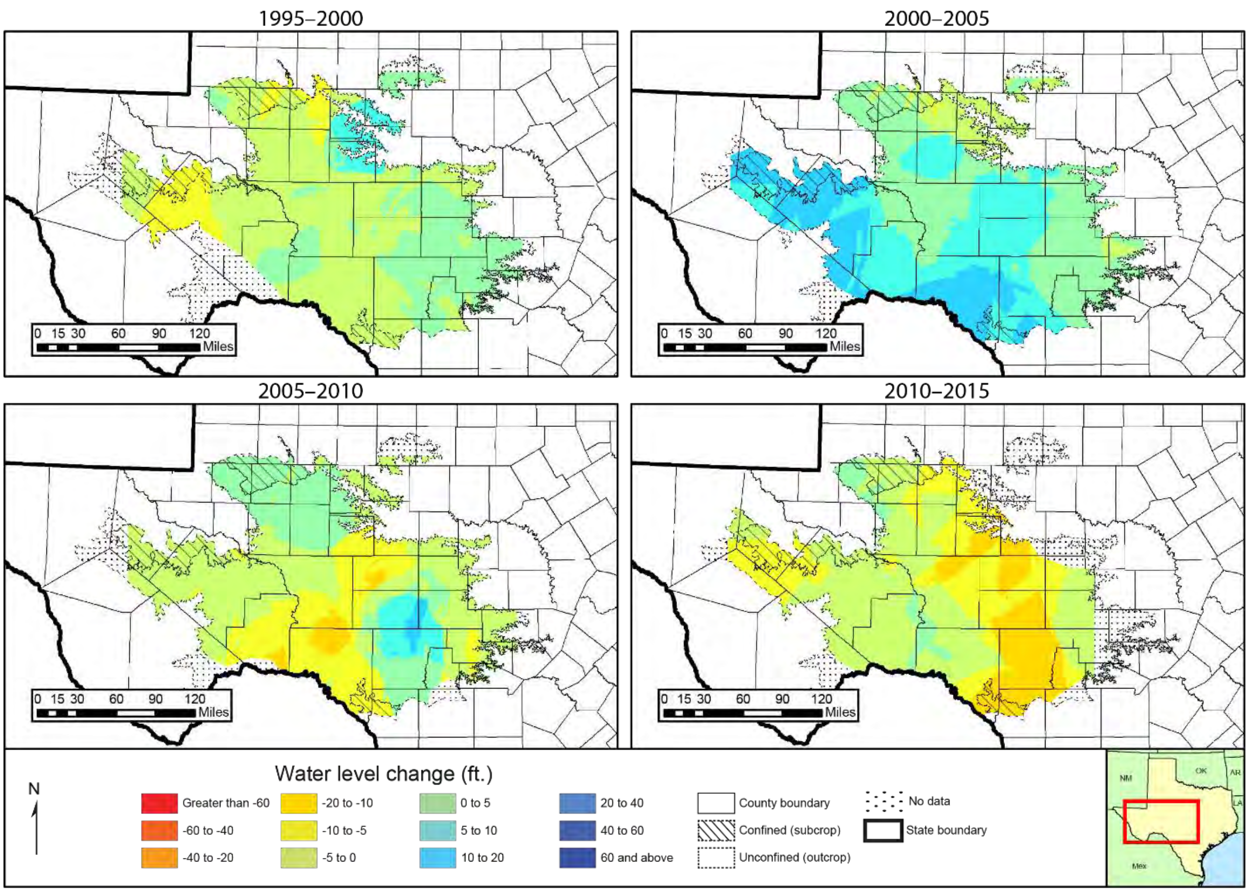


Figure 6-14. Water-level changes in the Edwards-Trinity (Plateau) Aquifer, 1995 to 2015.

Water quality

The water in the Edwards-Trinity (Plateau) Aquifer is generally a hard, calcium bicarbonate type and typically has total dissolved solids concentrations ranging from 400 to 1,000 milligrams per liter (Figure 6-15). Water quality in the unconfined portion of the aquifer is generally fresh, with only small, localized areas of slightly saline groundwater. Water typically increases in salinity to the west within the Trinity Group and in the confined portion of the aquifer where the groundwater is generally slightly to moderately saline.

Radionuclides are present in excess of drinking water standards in about 20 percent of the samples from the northwestern portion of the aquifer. Nitrate is present in excess of primary drinking water standards in a smaller number of samples. Groundwater exceeds secondary drinking water standards for total dissolved solids and sulfate in nearly 30 percent of samples, with less frequent exceedances for chloride, fluoride, iron, and manganese (Reedy and others, 2011).

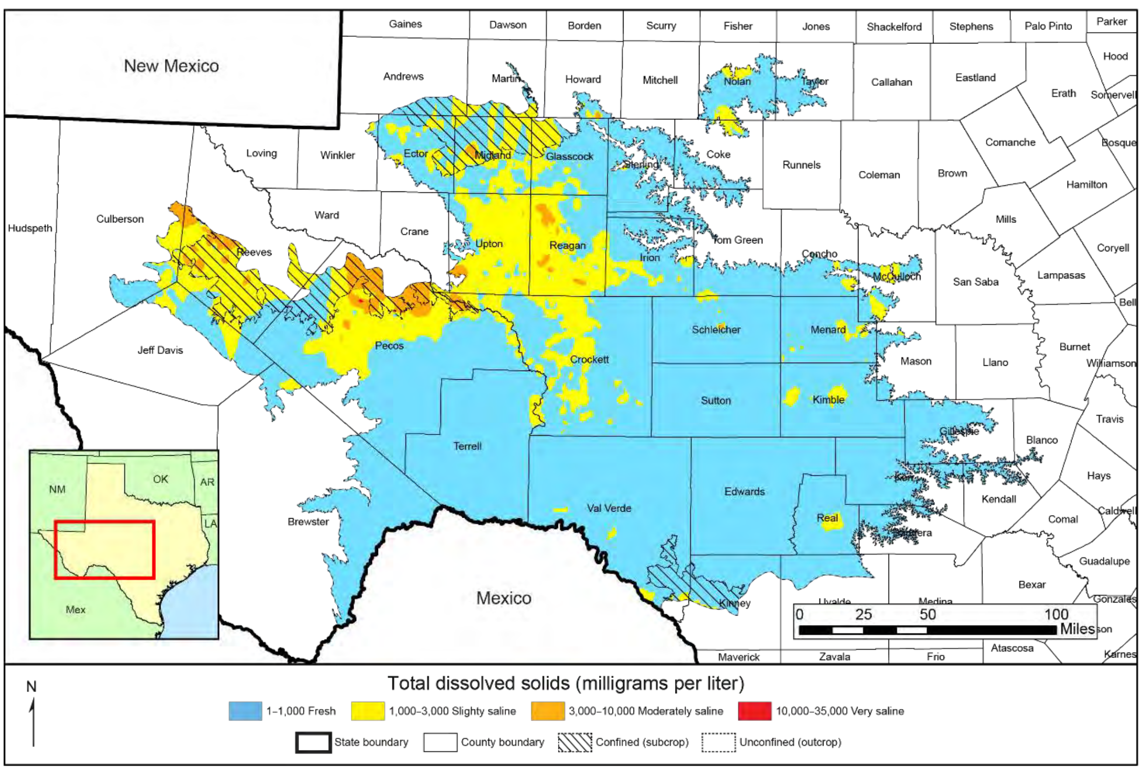


Figure 6-15. Total dissolved solids in the Edwards-Trinity (Plateau) Aquifer.

6.4 Gulf Coast Aquifer

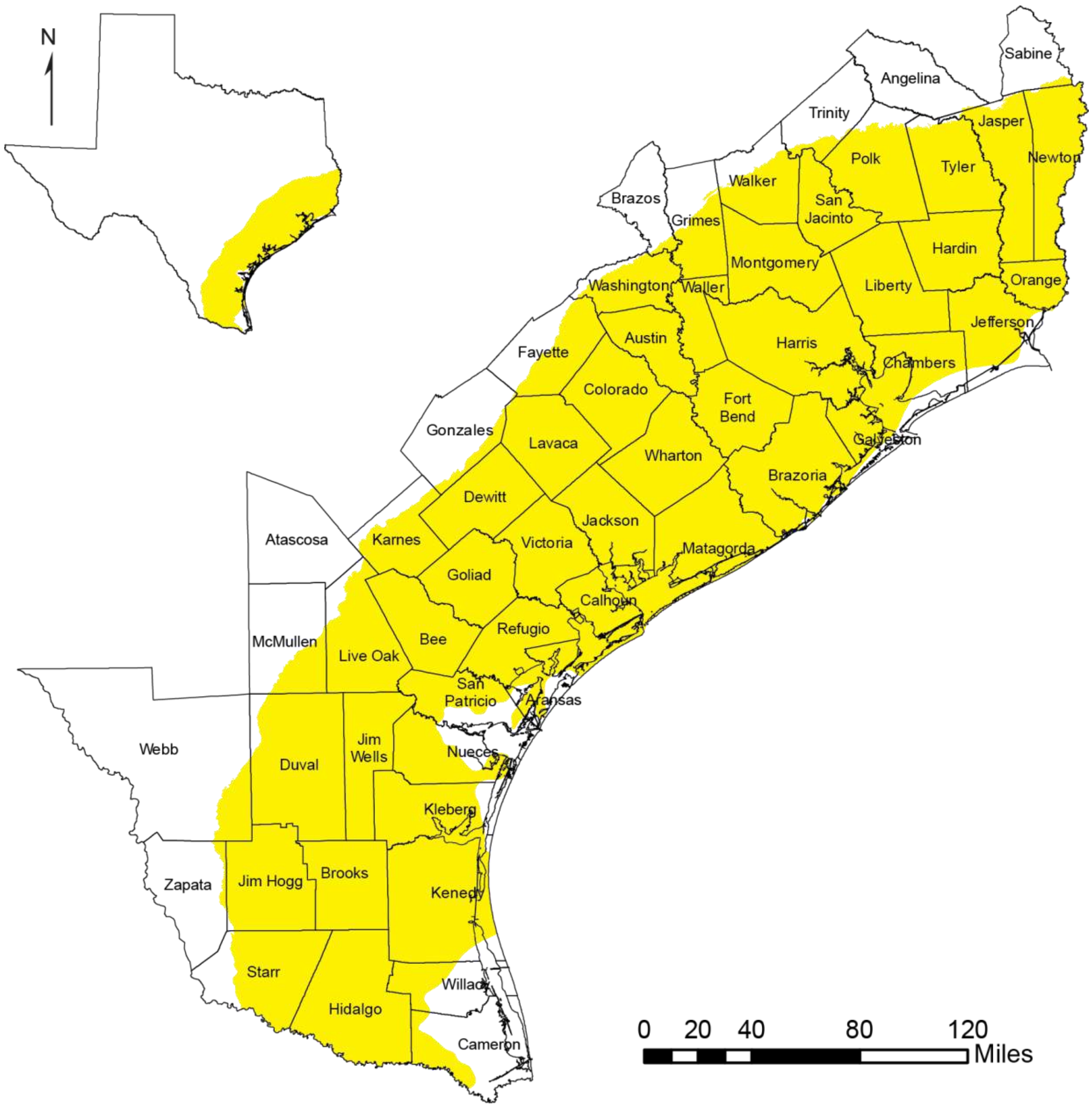


Figure 6-16. Extent of the Gulf Coast Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of aquifer: 41,970 square miles
- Proportion of aquifer with groundwater conservation districts: 81 percent
- Number of counties containing the aquifer: 56

Geology and hydrogeology

The Gulf Coast Aquifer is a major aquifer parallel to the Gulf of Mexico coastline from the Louisiana border to the Mexico border (Figure 6-16). It consists of several aquifers, including the Jasper, Evangeline, and Chicot aquifers, which are composed of discontinuous sand, silt, clay, and gravel beds of Miocene to Holocene age (Figure 6-17). The Oligocene Catahoula tuff forms a leaky confining layer at the base of the aquifer, and the Burkeville confining unit separates the Jasper Aquifer from the Evangeline Aquifer. All of the sedimentary units thicken toward the Gulf of Mexico. Growth faults, associated with loading on unconsolidated sediments, occur in several bands paralleling the coastline. Shallow salt domes locally intrude into the Gulf Coast Aquifer in the Houston embayment, with tops ranging from 0 to 2,000 feet deep (Hamlin, 2006).

Freshwater saturated thickness in the Gulf Coast Aquifer averages about 1,000 feet. The maximum total sand thickness ranges from 700 feet in the south to 1,300 feet in the north. The hydraulic conductivity of the aquifer also increases from 1 foot per day in the south to 7 feet per day in the northeast (Chowdhury and others, 2004). The transmissivity of the aquifer ranges from less than 1,000 feet squared per day in the southern portion to over 14,000 feet squared per day in the northeast.

Groundwater in the Gulf Coast Aquifer is typically unconfined or semi-confined. The groundwater availability model for the central Gulf Coast Aquifer determined calibrated specific storage values of 8×10^{-6} to 1×10^{-5} and specific yield values of 0.05 to 0.005. These specific yield values are low compared to typical specific yields of sedimentary materials in unconfined aquifers, which range from 0.14 to 0.38 (Freeze and Cherry, 1979). The lower specific yields in the Chicot, Evangeline, and Jasper aquifers reflect the numerous interbedded silt/clay lenses that locally confine groundwater in these aquifers (Chowdhury and others, 2004).

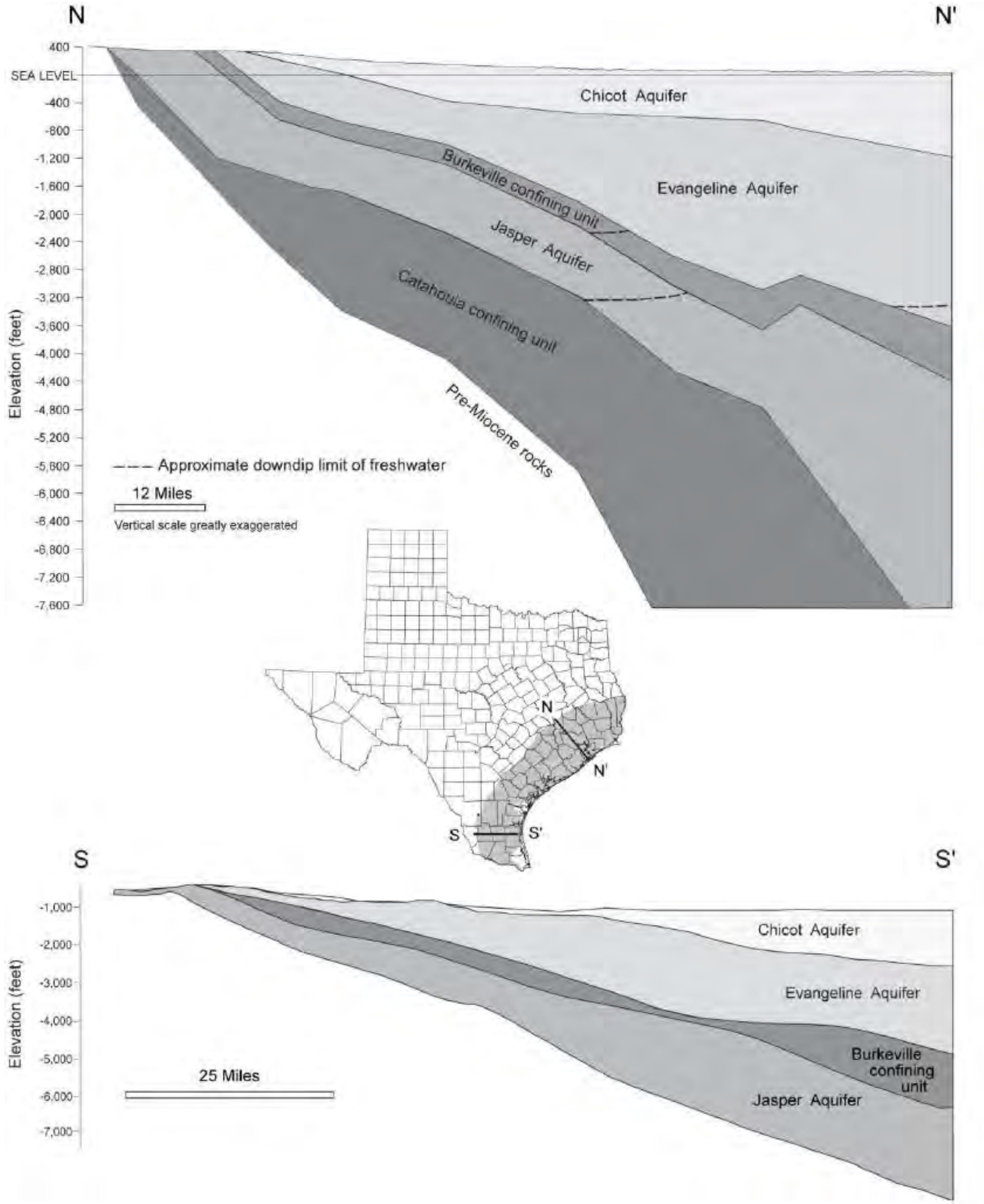


Figure 6-17. Cross-sections across the Gulf Coast Aquifer (modified from Baker, 1979, 1986; Chowdhury and Mace, 2003; Kasmarek and Robinson, 2004).

Flows to surface water and other aquifers

Of the total annual flow of approximately 620,000 acre-feet, about 84 percent discharges into the streams, and 16 percent discharges into the Gulf of Mexico (Chowdhury and others, 2004). Table 6-12 summarizes groundwater flow from the Gulf Coast Aquifer to surface water.

Cross-formational flow between the different aquifers and the confining units is generally upward. About 1,400 acre-feet per year flows from the Jasper Aquifer to the Burkeville confining unit, about 6,000 acre-feet per year flows from the Burkeville confining unit to the overlying Evangeline Aquifer, and about 20,000 acre-feet per year flows from the Evangeline to the overlying Chicot Aquifer. This suggests existence of a strong regional upward flow in the central Gulf Coast Aquifer system.

The down-dip boundary for the regional Gulf Coast Aquifer System should allow groundwater discharge across a large area of the ocean bottom. Two of three Gulf Coast Aquifer System groundwater availability models extend the regional flow system to about 10 miles past the coastline. These two models allow the exchange of flow between the ocean and the groundwater in the Chicot Aquifer. One of the Gulf Coast Aquifer System groundwater availability models has the down-dip boundary of the regional flow system terminate at the coast line. The groundwater flow paths inferred from the geochemical data suggest that near the coast the groundwater flow is predominantly horizontal or slightly downward. These inferred groundwater flow directions are in agreement with the general findings of Glover (1959). For the scenario of no pumping along the coastline, Glover (1959) shows that groundwater discharge should extend outward into the ocean. Glover's analysis shows that the distance groundwater flows into the ocean is a function of flow rate in the aquifer, the permeability of the aquifer, and the density differences between the ocean water and groundwater.

Groundwater from the Gulf Coast Aquifer System flows into the Brazos River Alluvium Aquifer, but the relative magnitude of the inflows are unknown. Further data is required to quantify this flow and flow from the Brazos River Alluvium Aquifer into the Gulf Coast Aquifer.

Table 6-12. Summary of groundwater flow from the Gulf Coast Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Angelina	4	1.5	0.6
Aransas	193	9.9	1
Atascosa	0	0	0
Austin	592	57.2	9.6
Bee	880	20.7	3.6
Brazoria	1,405	461.6	190.4
Brazos	4	0.4	0.1
Brooks	943	8.3	1.4
Calhoun	424	42	4.3
Cameron	258	4.8	0.7
Chambers	527	186.9	57.3
Colorado	974	63.9	13.7
DeWitt	910	85	25.7
Duval	1,714	13.3	2.6
Fayette	560	29.5	6.9
Fort Bend	689	111.5	28.2
Galveston	289	94.8	26.1
Goliad	860	43.9	10.6
Gonzales	136	9.8	2.1
Grimes	407	38.7	5.4
Hardin	897	334.5	119.9
Harris	1,747	377.8	86.1
Hidalgo	1,584	20.6	3.2
Jackson	851	78.6	10.7
Jasper	933	348.3	144.4
Jefferson	739	212.4	45.8
Jim Hogg	1,126	10	1.9
Jim Wells	869	9	1.8
Karnes	566	25.4	8.2
Kenedy	1,323	16.7	2.4
Kleberg	786	16.2	2
Lavaca	970	72	13.3
Liberty	1,175	440.6	182

Table 6-12 (continued). Summary of groundwater flow from the Gulf Coast Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Live Oak	966	19.9	3.8
Matagorda	1,122	202.5	56.1
McMullen	290	3.5	0.8
Montgomery	1,077	178.3	35.6
Newton	934	355.5	138.9
Nueces	622	15.8	1.9
Orange	346	89.5	16.7
Polk	974	251.8	71.1
Refugio	777	40.2	4.1
Sabine	27	13	6.1
San Jacinto	629	111.8	22.2
San Patricio	516	15.6	1.4
Starr	946	10.1	1.9
Trinity	91	14.4	2.6
Tyler	888	339.5	144
Victoria	889	78	11.1
Walker	552	75.3	9.6
Waller	420	48.2	10.5
Washington	493	42.1	7.1
Webb	292	2	0.4
Wharton	1,094	112	23.3
Willacy	271	3.6	0.6
Zapata	54	0.4	0.1
Total	**39,605**	**5,269**	**1,582**

Water quantity

Total groundwater storage in the Gulf Coast Aquifer is estimated to be 5.1 billion acre-feet. Recoverable groundwater storage is estimated to be between 25 and 75 percent of the total, about 1.2 billion to 3.8 billion acre-feet (Table 6-13). The large volume of groundwater pumped from the Gulf Coast Aquifer in the Houston area has caused land subsidence, but groundwater management strategies have been implemented to prevent further subsidence. In response, groundwater levels have rebounded in areas using these strategies, rising by more than 200 feet in some locations between 2000 and 2015. At the same time, groundwater extraction has shifted to areas north and west of Houston, where groundwater levels declined more than 100 feet between 2000 and 2015. Figure 6-18 shows water level changes in the Gulf Coast Aquifer from 1995 to 2015.

Table 6-13. Total estimated recoverable storage in the Gulf Coast Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
11	1,447,000	361,750	1,085,250
12	450,000	112,500	337,500
13	2,460,000	615,000	1,845,000
14	2,776,000,000	694,000,000	2,082,000,000
15	368,800,000	92,200,000	276,600,000
16	2,032,350,000	508,087,500	1,524,262,500
Total	**5,181,507,000**	**1,295,376,750**	**3,886,130,250**

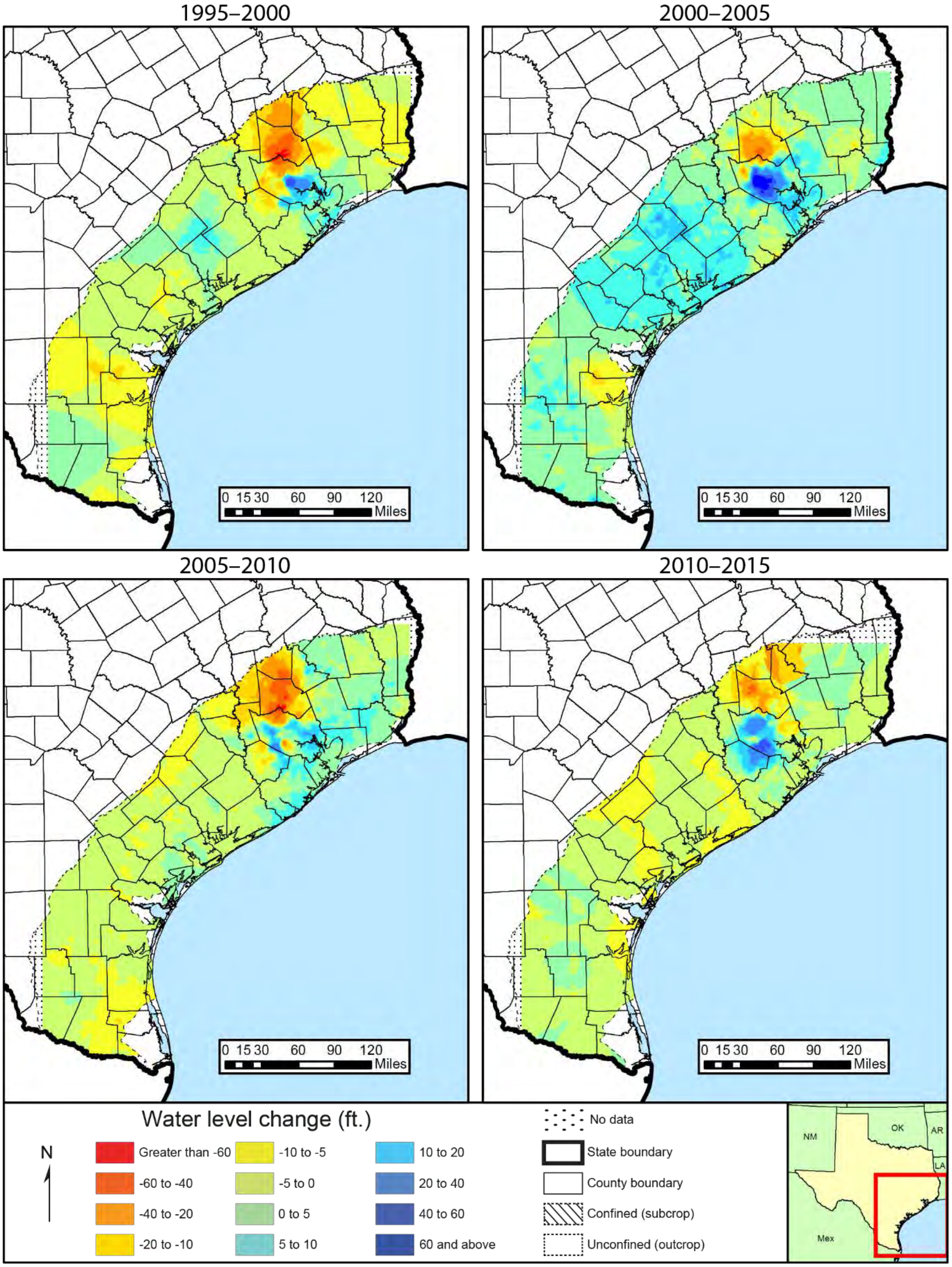


Figure 6-18. Water-level changes in the Gulf Coast Aquifer, from 1995 to 2015.

Water quality

Water quality varies with depth and locality. It is generally good in the central and northeastern parts of the aquifer, where total dissolved solids concentrations are less than 500 milligrams per liter but is more saline to the south, where total dissolved solids are typically 1,000 to more than 10,000 milligrams per liter and where the productivity of the aquifer decreases (Figure 6-19). Areas of increased salinity along the central and eastern Gulf Coast may be associated with saltwater intrusion in response to groundwater pumping or to brine migration in response to oil field operations and natural flows from salt domes intruding into the aquifer.

The extent of the aquifer along the Gulf Coast is generally defined by the down-dip limit of freshwater; the sedimentary units making up the aquifer continue below the Gulf of Mexico but become increasingly saline as a result of interaction with seawater, increasing groundwater residence time, and mixing with oil-field brines.

Arsenic and radionuclides are found in excess of primary drinking water standards in many wells in the Gulf Coast Aquifer, predominantly in the southern region. These contaminants are associated with the tuffaceous sands of the Catahoula Formation at the base of the aquifer and can be mobilized into the Gulf Coast Aquifer along leaky fault zones and around salt domes (Adams and Smith, 1980; Reedy and others, 2011). Chloride, iron, manganese, and total dissolved solids exceed secondary drinking water standards in up to 28 percent of wells sampled; iron and manganese exceedances are mostly in the northern portion of the aquifer, while chloride and total dissolved solids exceedances mostly occur in the southern part of the aquifer (Reedy and others, 2011).

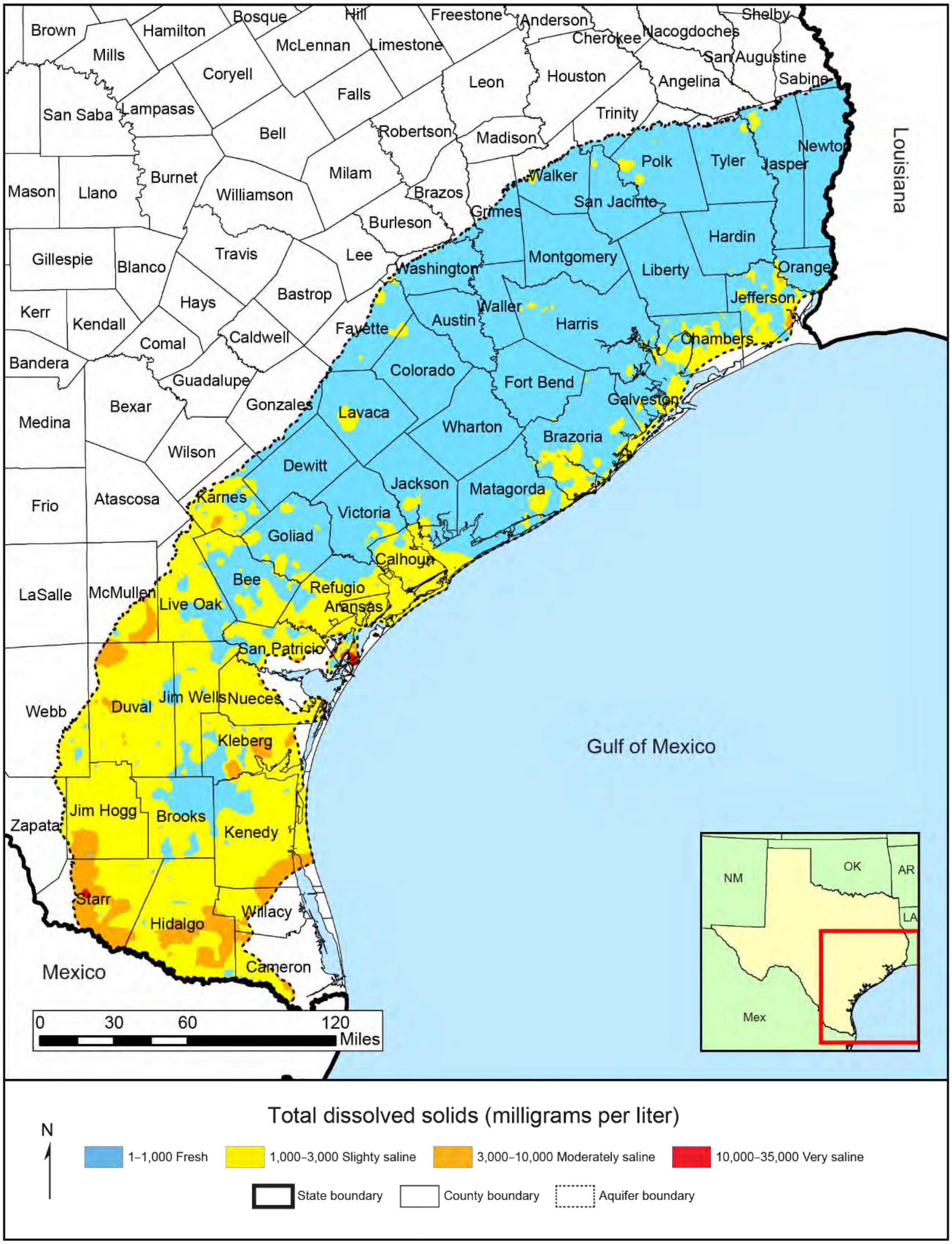


Figure 6-19. Total dissolved solids in the Gulf Coast Aquifer.

6.5 Hueco-Mesilla Bolsons Aquifer

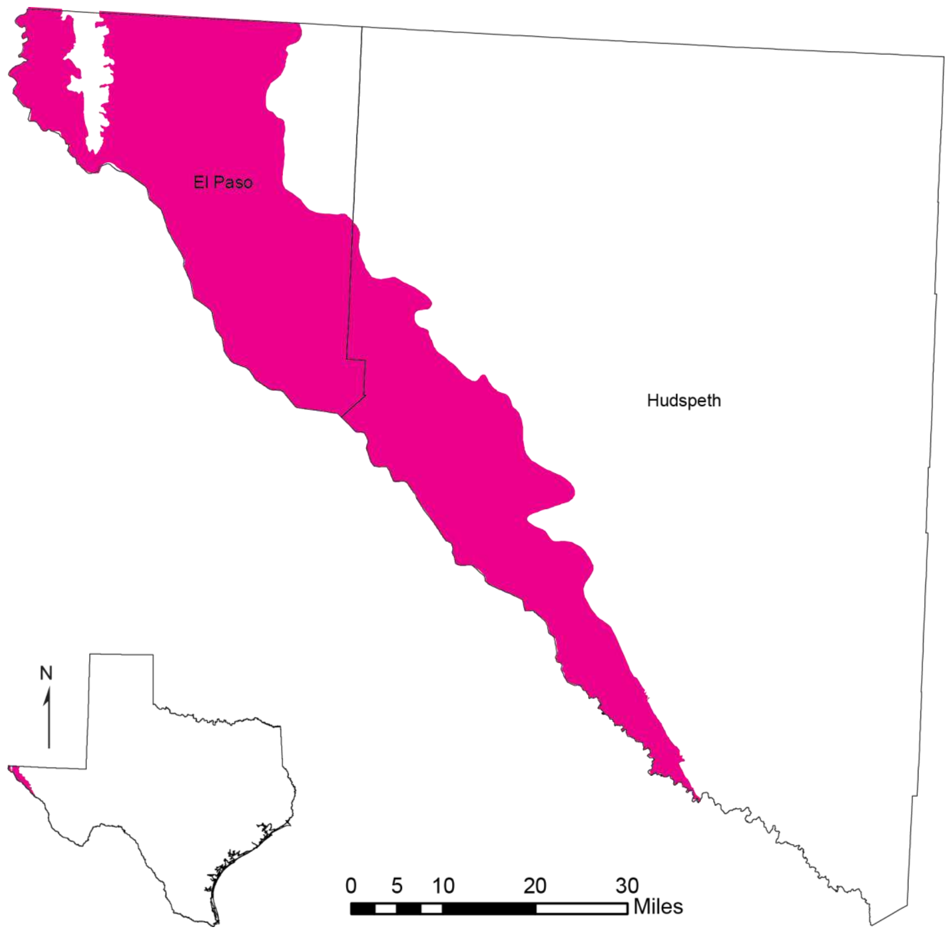


Figure 6-20. Extent of the Hueco-Mesilla Bolsons Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,376 square miles
- Proportion of aquifer with groundwater conservation districts: 0 percent
- Number of counties containing the aquifer: 2

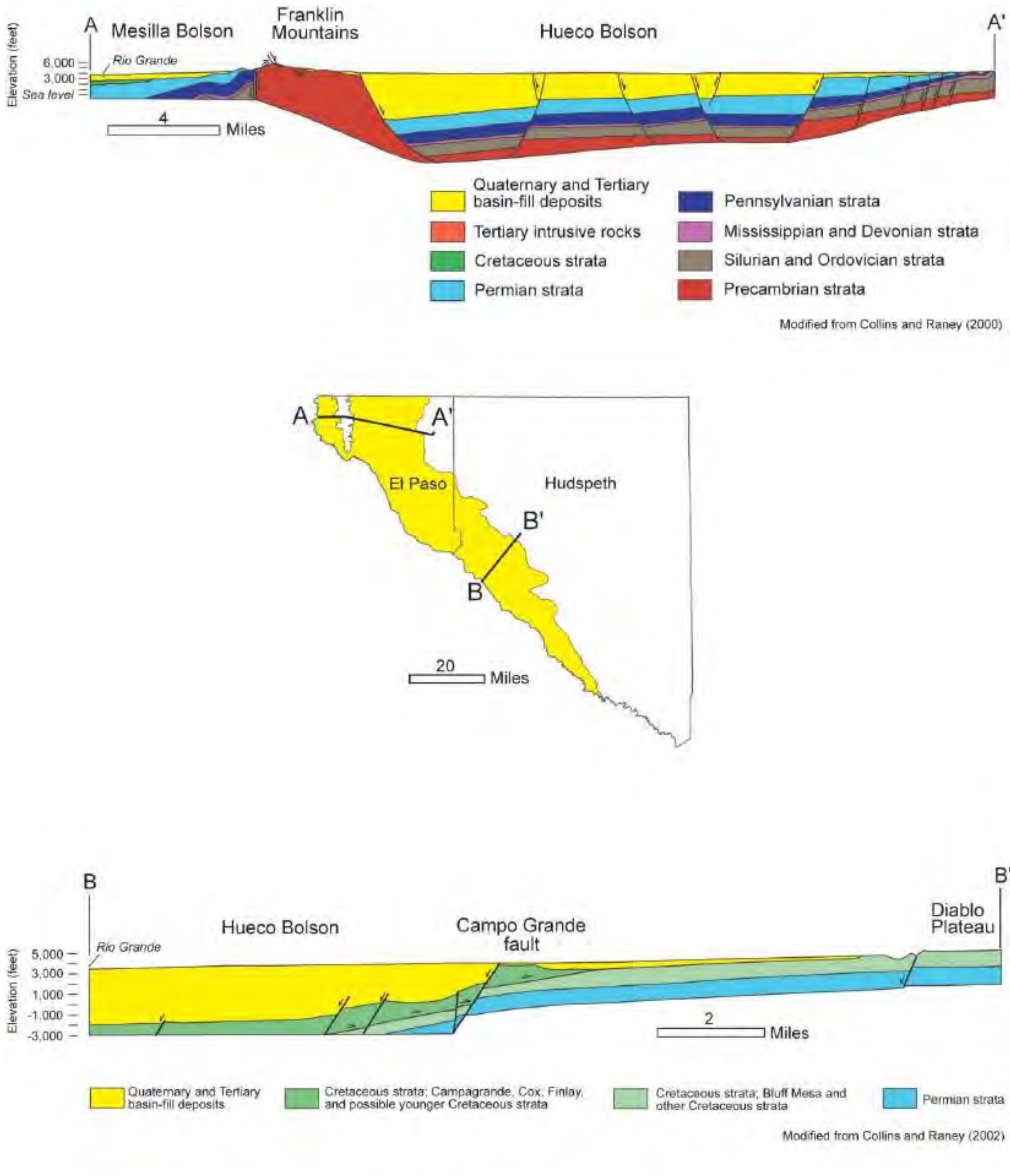
Geology and hydrogeology

The Hueco-Mesilla Bolsons Aquifer is a major aquifer located in El Paso and Hudspeth counties in far west Texas (Figure 6-20). The Hueco Bolson is considered the southern portion of the Tularosa-Hueco Basin. The northern portion of the aquifer, the Tularosa Basin, lies entirely in the state of New Mexico (Heywood and Yager, 2003). The Hueco and Mesilla Bolsons also extend under the Rio Grande into Mexico.

The Hueco Bolson is a fault-bounded structural depression associated with the Rio Grande Rift. Low-permeability igneous rocks of Precambrian age and sedimentary rocks of Paleozoic and Mesozoic age surround and underlie the Hueco Bolson (Figure 6-21) and are typically modeled as no-flow boundaries.

The aquifer is composed of unconsolidated to poorly consolidated basin-fill consisting of silt, sand, gravel, and clay in two basins, or bolsons: the Hueco Bolson, which has a maximum thickness of 9,000 feet, and the Mesilla Bolson, which has a maximum thickness of 2,000 feet. The average horizontal hydraulic conductivity ranges from 22 feet per day in alluvial fan sediments to 3.0 feet per day in lacustrine deposits (Heywood and Yager, 2003). The specific yield is estimated to be 0.18 (Heywood and Yager, 2003).

Prior to development, the Rio Grande was a gaining river in the El Paso area. Groundwater recharged in the northern parts of the aquifer and moved southward to discharge into the Rio Grande in the vicinity of downtown El Paso and Cuidad Juarez (Brehehoeft and others, 2004). That flow regime has been reversed by pumping. Today about half of the recharge to the aquifer comes from the Rio Grande, with the balance representing flow from the Tularosa Basin in New Mexico into the Hueco Bolson. Infiltration through permeable mountain-front alluvial fans represents a much smaller volume of recharge (Heywood and Yager, 2003).



Note: True fault geometries were not determined for both cross sections.

Figure 6-21. Cross-sections across the Hueco-Mesilla Bolsons Aquifer (modified from Collins and Raney, 2000, 2002).

Flows to surface water and other aquifers

There is no net discharge from the Hueco-Mesilla Bolsons Aquifer to surface water because of pumping in El Paso and Ciudad Juarez and associated water-level declines; at this time the Rio Grande is a losing stream and recharges the aquifer. Table 6-14 shows flow from the Hueco-Mesilla Bolsons Aquifer to surface water, as estimated from stream baseflow and surface runoff measurements.

Although the Hueco and Mesilla Bolsons share similar geology, very little water travels between them. Groundwater underflow from the Mesilla Basin to the Hueco Bolson may occur adjacent to the Rio Grande, but the underflow is estimated to be less than 80 acre-feet per year (Heywood and Yager, 2003). Groundwater levels in the Tularosa Basin (McLean, 1970) indicate a regional flow component to the south into the Hueco Bolson.

The area of the Hueco-Mesilla Bolsons Aquifer does not connect with any other major or minor aquifer in Texas, and there are no flows between the Hueco-Mesilla Bolsons Aquifer and any other major or minor aquifers in Texas.

Table 6-14. Summary of groundwater flow from the Hueco-Mesilla Bolsons Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
El Paso	786	3.2	2.8
Hudspeth	535	3.5	3.3
Total	**1,321**	**7**	**6**

Water quantity

El Paso Water Utilities has estimated the total volume of fresh groundwater in the Texas portion of the Hueco Bolson at 9 million acre-feet (Brehehoeft, Ford, Harden, Mace, and Rumbaugh, 2004). Water levels declined several hundred feet up to the late 1980s due primarily to municipal pumping in the Hueco Bolson. Since that time, however, observation wells indicate that water levels have stabilized. Figure 6-22 shows water-level changes in the Hueco-Mesilla Bolsons Aquifer from 1995 to 2015.

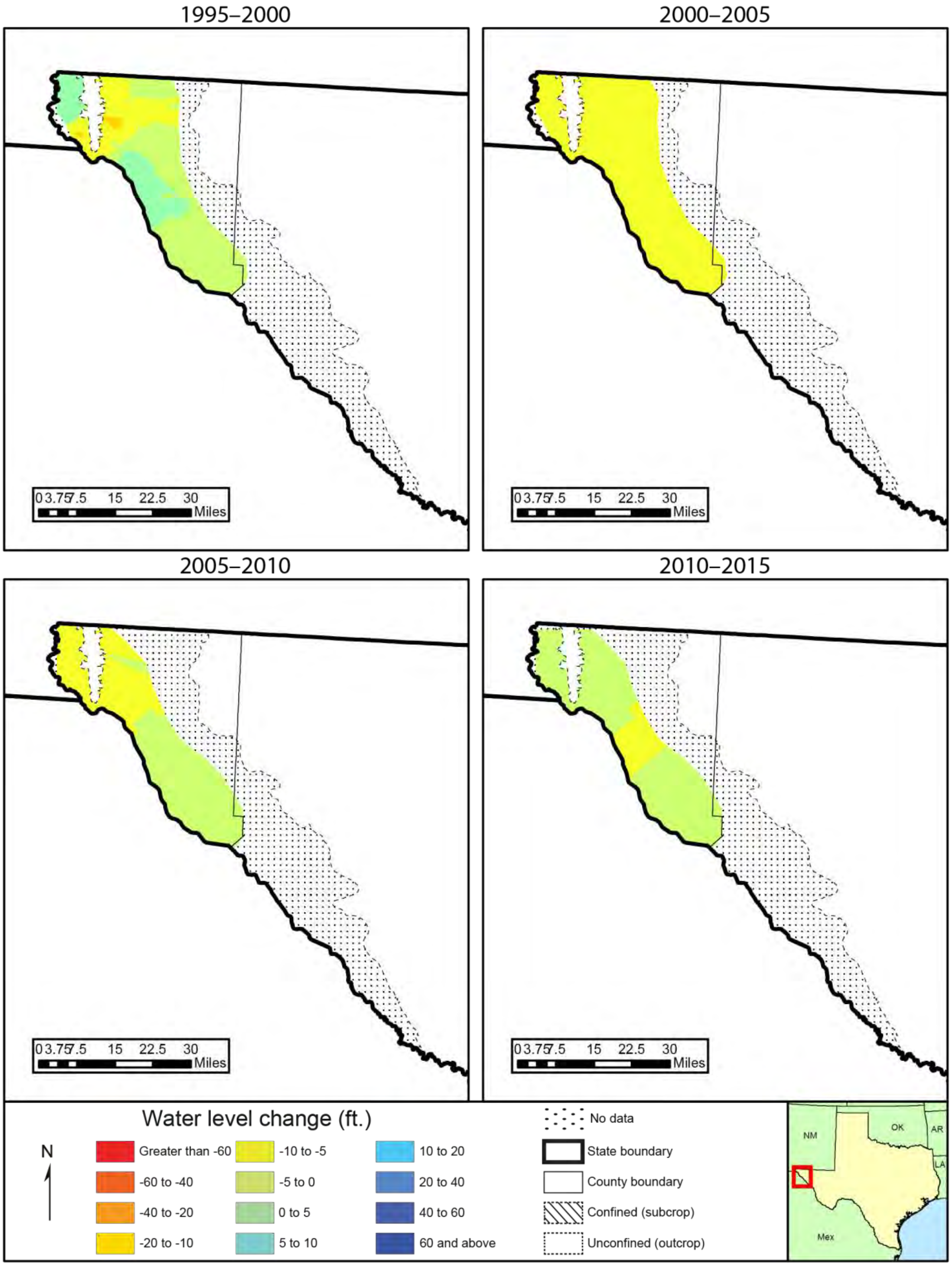


Figure 6-22. Water-level changes in the Hueco-Mesilla Bolsons Aquifer, 1995 to 2015.

Water quality

Fresh groundwater stored in the aquifer system beneath El Paso and Ciudad Juarez is bordered by regions of brackish to saline groundwater. As water levels in the freshwater portions of the aquifer declined, intrusion of the surrounding brackish water degraded water quality. Figure 6-23 shows the distribution of total dissolved solids in the Hueco-Mesilla Bolsons Aquifer.

The upper portion of the Hueco Bolson contains fresh to slightly saline water, with total dissolved solids concentrations ranging from 1,000 to 3,000 milligrams per liter. The Mesilla Bolson also contains fresh to saline water, with total dissolved solids concentrations ranging from less than 1,000 to 10,000 or more milligrams per liter of total dissolved solids. Its salinity typically increases to the south and in the shallower parts of the aquifer. In both aquifers, water-level declines have contributed to brackish water intrusion and increased salinity.

Arsenic is present in portions of the Hueco Bolson at concentrations exceeding drinking water criteria, primarily in the eastern and southern portions of the Hueco Bolson. A total of 17 out of 31 groundwater samples collected by the TWDB for dissolved arsenic between 2000 and 2015 contain concentrations exceeding the maximum contaminant level of 10 micrograms per liter, with a maximum concentration of 60.1 micrograms per liter. Secondary water quality standards for chloride, fluoride, iron, manganese, sulfate, and total dissolved solids are also exceeded in some samples (Reedy and others, 2011).

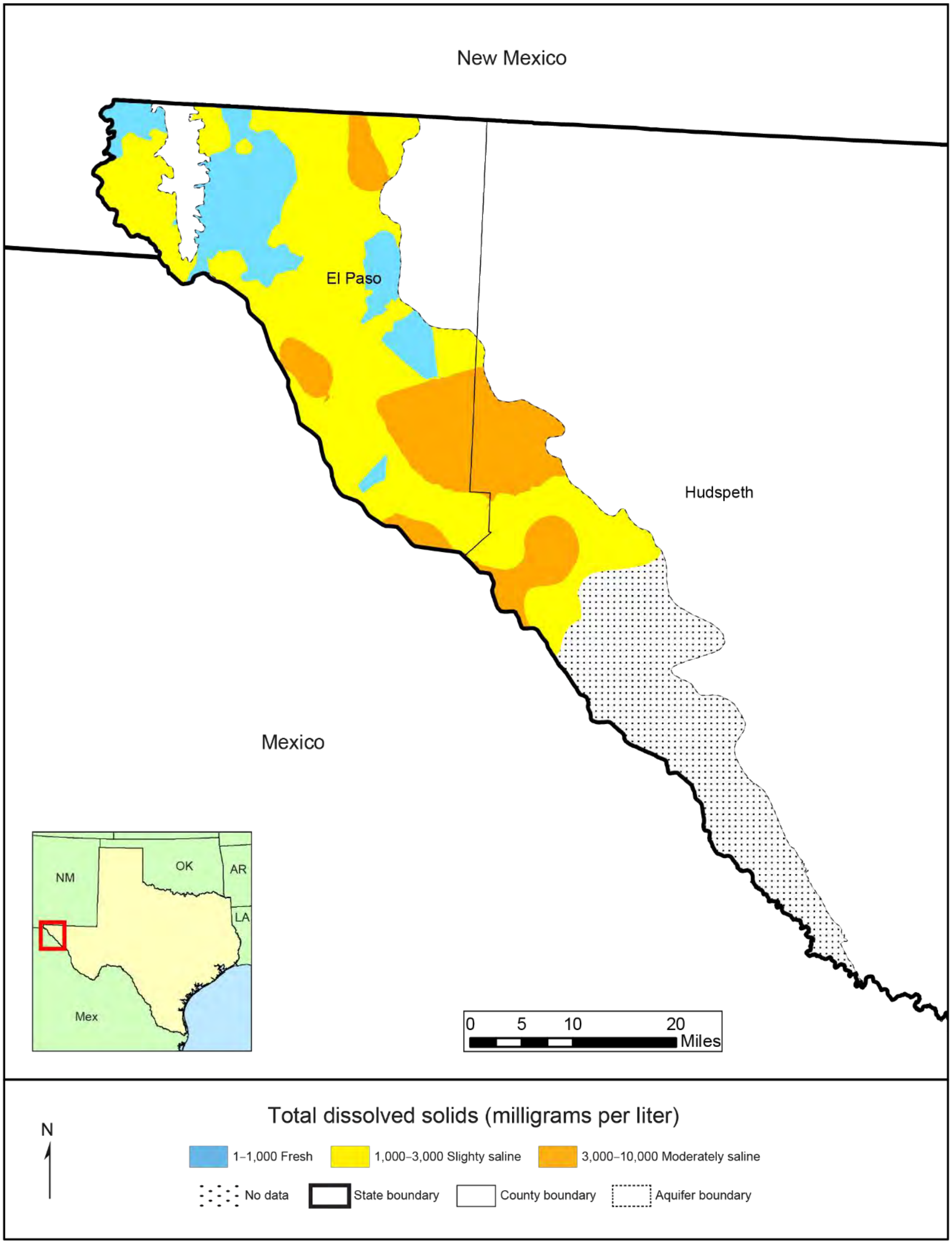


Figure 6-23. Total dissolved solids in the Hueco-Mesilla Bolsons Aquifer.

6.6 *Ogallala Aquifer*

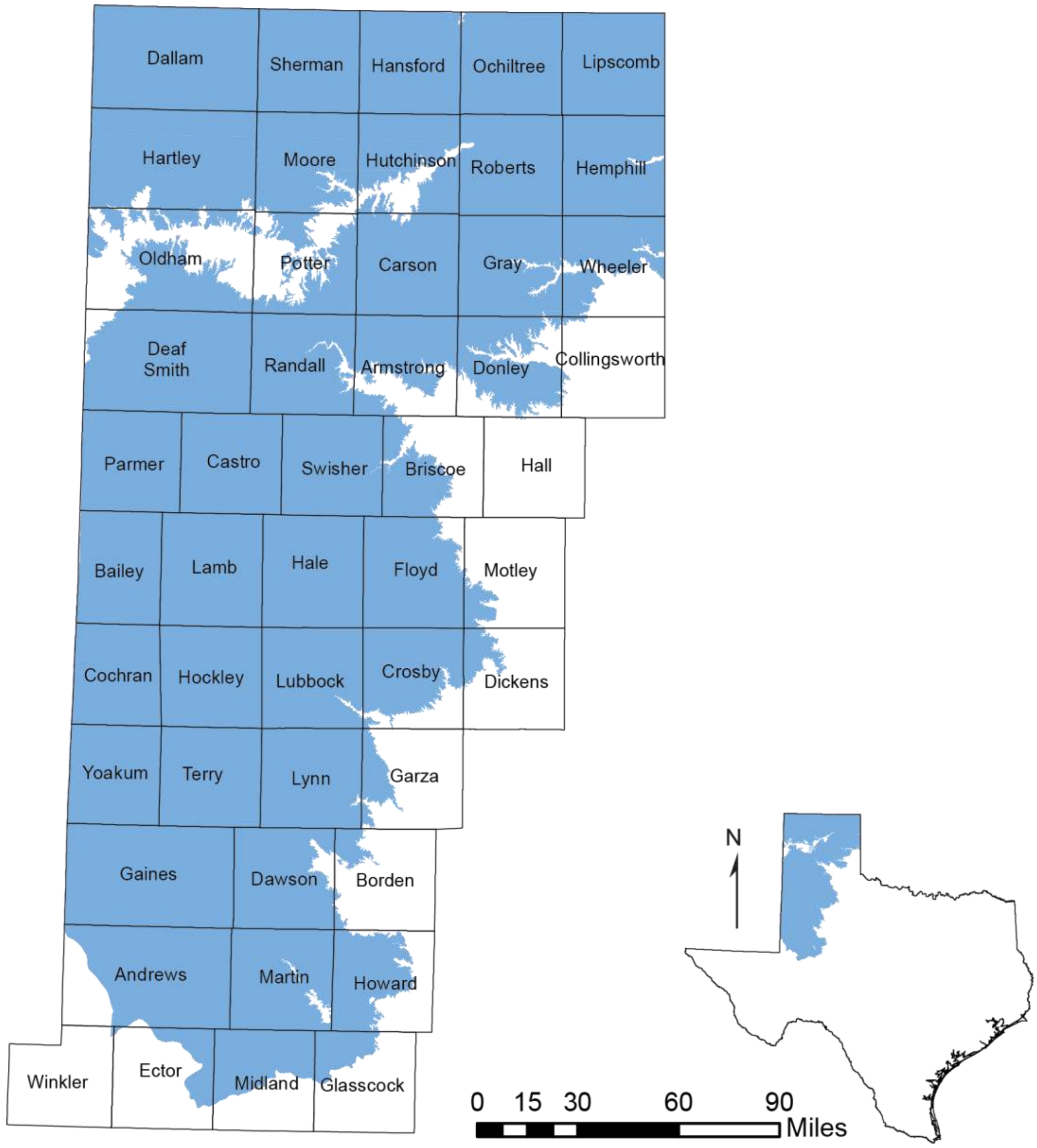


Figure 6-24. Extent of the Ogallala Aquifer in Texas.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 36,293 square miles
- Proportion of aquifer with groundwater conservation districts: 86 percent
- Number of counties containing the aquifer: 49

Geology and hydrogeology

The Ogallala Aquifer, an unconfined aquifer, is the largest aquifer in the United States and is a major aquifer of Texas, underlying much of the High Plains region (Figure 6-24). The aquifer consists of sand, gravel, clay, and silt and has a maximum thickness of 800 feet. Freshwater saturated thickness in the aquifer averages 95 feet but is significantly greater in several paleovalleys that were eroded into the Permian- to Cretaceous-aged surfaces before deposition of the Ogallala Formation.

The Ogallala Formation was deposited as alluvial outwash from the Rocky Mountains. The thickest and coarsest grained sediments are fluvial channel facies in alluvial fan lobes deposited in paleovalleys (Seni, 1980; Gustavson, 1996), where pebble- to boulder-size gravel lenses are common along the basal surface. Three major paleovalleys are located north of the Canadian River, and a smaller paleovalley stretches from near Clovis to southeast of Plainview. Most sediment in the preserved extent of the Ogallala Formation are sands and gravels that were deposited in braided stream channels (Seni, 1980). The Ogallala Formation becomes finer-grained with increased distance from the mountains. The Ogallala Formation is overlain by the Blackwater Draw Formation, which forms a layer of Quaternary eolian fine sand, silt, clay, and caliche that covers the Ogallala Formation except along breaks and draws.

The hydraulic conductivity of the Southern Ogallala Aquifer ranges from 0.01 to 2,600 feet per day with a mean of about 6.8 feet per day (Blandford, 2003). The geometric mean of hydraulic conductivity in the Northern Ogallala Aquifer is about 14.8 feet per day with a standard deviation of 5 to 44 feet per day (Dutton, 2001). The specific yield of the Ogallala Aquifer ranges from 15 to 22 percent, with an average of 16 percent (Blandford, 2003).

Studies indicate that recharge represents a small fraction of current water usage. Most recently, Deeds and Hamlin (2015) developed detailed maps of present-day recharge, dividing the Ogallala into two regions. Recharge in the southern region has been affected by agricultural development and ranges from 0.007 to over 3 inches per year, with the most recharge in areas where irrigated crops are raised on relatively permeable soils. In the northern region, relatively clayey soils limit agricultural influence on recharge, and the pre-development distribution of recharge remains in place, with rates ranging from 0.1 to 0.8 inches per year.

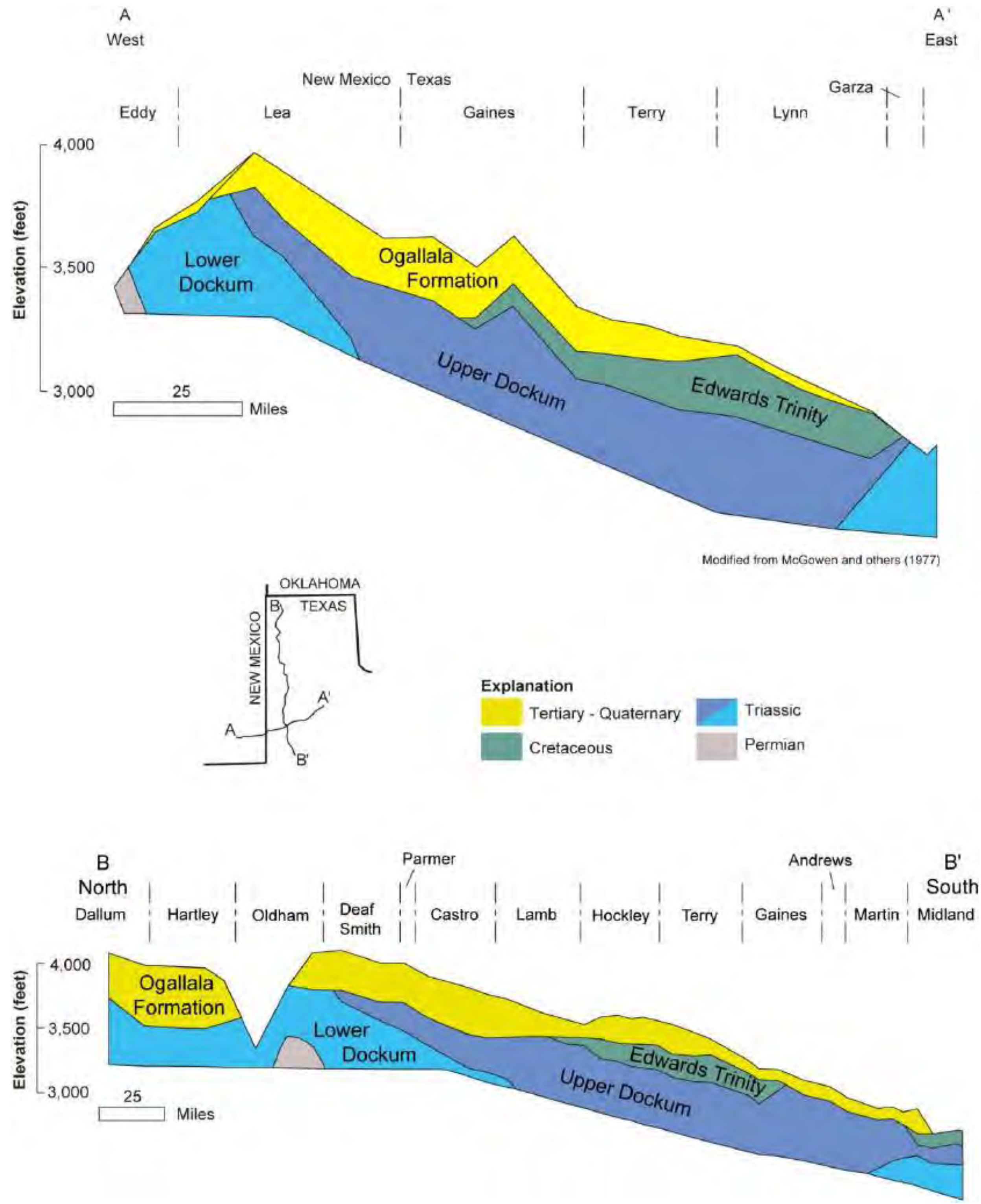


Figure 6-25. Geologic cross-sections showing the relationship of the Ogallala Formation to underlying strata (modified from McGowen and others, 1977).

Flows to surface water and other aquifers

Baseflow from springs or aquifer discharge has diminished due to the large volume of pumping for irrigation from the Ogallala Aquifer, resulting in low to no flow in streams that originally depended on aquifer discharge (Deeds and Hamlin, 2015). Table 6-15 summarizes groundwater flow from the Ogallala Aquifer to surface water.

The Ogallala Aquifer is in hydraulic communication with the underlying Cretaceous Edwards-Trinity (Plateau) Aquifer in the south, the Rita Blanca Aquifer in the northwest, and the Triassic Dockum Aquifer in the central region. Table 6-16 shows groundwater availability model estimates of total flow and average annual flow between the Ogallala Aquifer and other aquifers.

Table 6-15. Summary of groundwater flow from the Ogallala Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	1,215	4.3	3.1
Armstrong	620	1.6	1.1
Bailey	820	2.4	1.4
Borden	105	0.4	0.3
Briscoe	404	1.6	1.2
Carson	912	3.4	2.5
Castro	900	1.1	0.1
Cochran	775	2	1.4
Collingsworth	16	0.1	0
Crosby	696	5.3	5
Dallam	1,505	13.1	5.1
Dawson	846	2.9	1.8
Deaf Smith	1,439	3.1	0.8
Dickens	123	1	0.6
Donley	619	4.2	1.9
Ector	207	0.8	0.6
Floyd	924	7.7	6.6
Gaines	1,501	4.4	3.8
Garza	158	0.9	0.8
Glasscock	199	1	0.3

Table 6-15. Summary of groundwater flow from the Ogallala Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Gray	903	8.5	5.4
Hale	1,005	2.4	2.2
Hall	1	0	0
Hansford	917	3	1.7
Hartley	1,424	3.7	2.5
Hemphill	902	11	7
Hockley	910	1.1	1
Howard	548	1.8	0.7
Hutchinson	717	2.6	1.5
Lamb	1,018	2	1.5
Lipscomb	932	8.5	4.4
Lubbock	893	2.7	2.6
Lynn	889	3.8	4.4
Martin	884	3.6	1.7
Midland	496	2.2	1.2
Moore	842	2.7	0.9
Motley	100	1.2	0.9
Ochiltree	914	6.7	2.9
Oldham	733	3.9	1.6
Parmer	879	2	0.8
Potter	497	1.6	0.8
Randall	889	1.5	0.7
Roberts	917	6	4.5
Sherman	921	4.1	1.6
Swisher	900	1.7	0.9
Terry	890	1.9	1.3
Wheeler	581	13	8
Winkler	3	0	0
Yoakum	799	2.3	1.8
Total	**36,288**	**167**	**103**

Table 6-16. Model estimates of inter-aquifer flows between the Ogallala Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Ogallala Aquifer	Dockum Aquifer	27,497
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014
Ogallala Aquifer	Pecos Valley Aquifer	220
Ogallala Aquifer	Rita Blanca Aquifer	1,670
Dockum Aquifer	Ogallala Aquifer	2,241
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341

Water quantity

Total storage in the Ogallala Aquifer is estimated to be more than 380 million acre feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 95.1 million to 285.4 million acre-feet (Table 6-17). Throughout much of the Ogallala Aquifer, groundwater withdrawals exceed the amount of recharge, and water levels have declined over time. Although water-level declines in excess of 300 feet have occurred in several areas over the last 50 to 60 years, the rate of decline has slowed, and water levels have risen in a few areas. Figure 6-26 shows changes in water levels in the Ogallala Aquifer.

Table 6-17. Total estimated recoverable storage in the Ogallala Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
1	232,700,000	58,175,000	174,525,000
2	139,210,000	34,802,500	104,407,500
3	9,600	2,400	7,200
6	2,285,000	571,250	1,713,750
7	6,340,000	1,585,000	4,755,000
Total	**380,544,600**	**95,136,150**	**285,408,450**

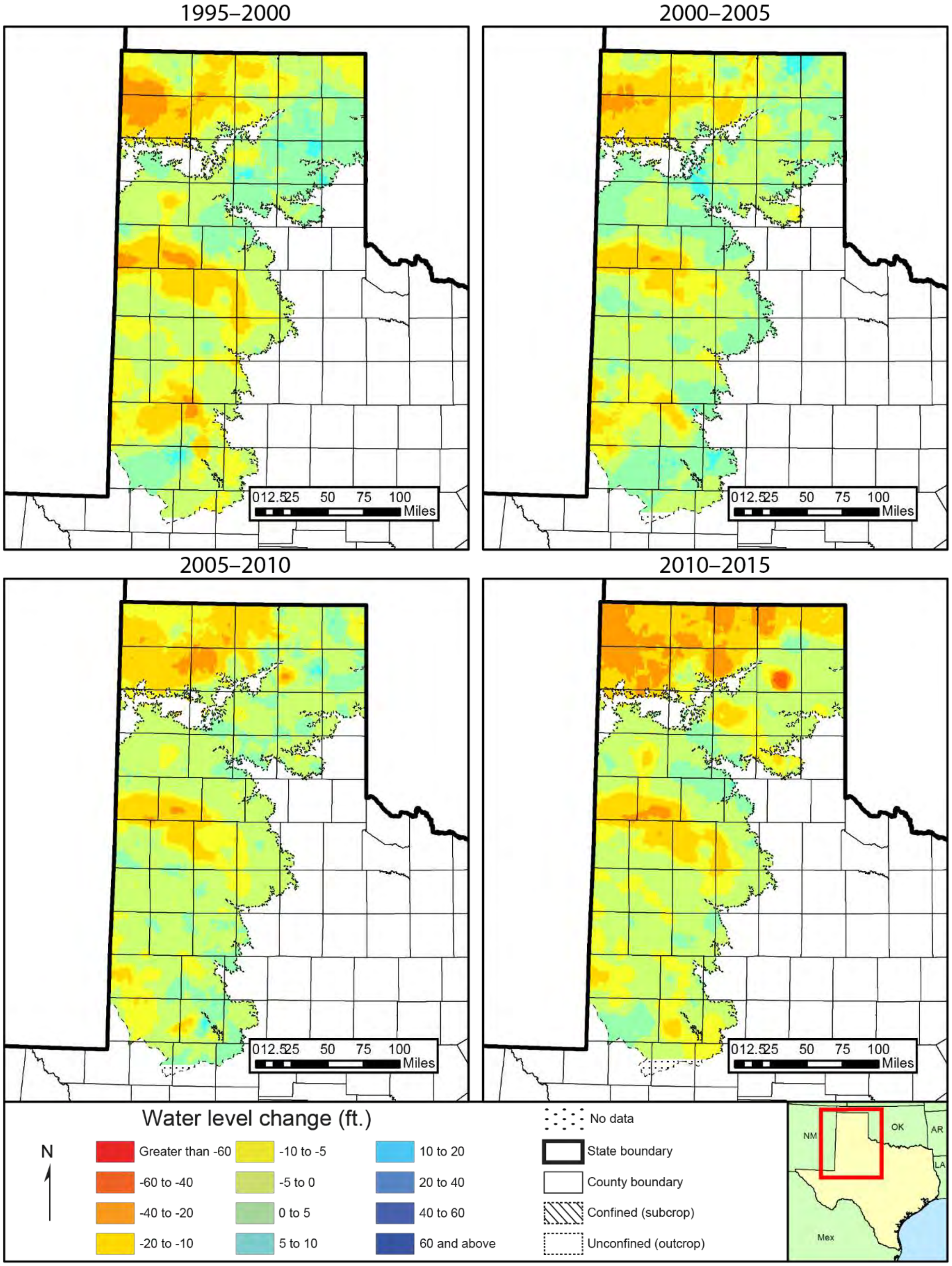


Figure 6-26. Water-level changes in the Ogallala Aquifer, 1995 to 2015.

Water quality

Water to the north of the Canadian River is generally fresh, with total dissolved solids concentrations typically less than 400 milligrams per liter. However, water quality diminishes to the south, where large areas contain total dissolved solids concentrations greater than 1,000 milligrams per liter (Figure 6-27). Increased salinity may be associated with evaporative concentration of groundwater in saline playa lakes in the southern portion of the aquifer, upflow of more saline groundwater from the underlying Dockum Aquifer, and other sources (Reedy and others, 2011).

Arsenic, fluoride, nitrate, radionuclides, and selenium levels have been known to be in excess of primary drinking water standards, primarily in the southern portion of the aquifer. Volcanic ash leaching in the aquifer is likely the source of arsenic, fluoride, selenium, and radionuclides. Sources of nitrate may come from agricultural activity in the area (Reedy and others, 2011).

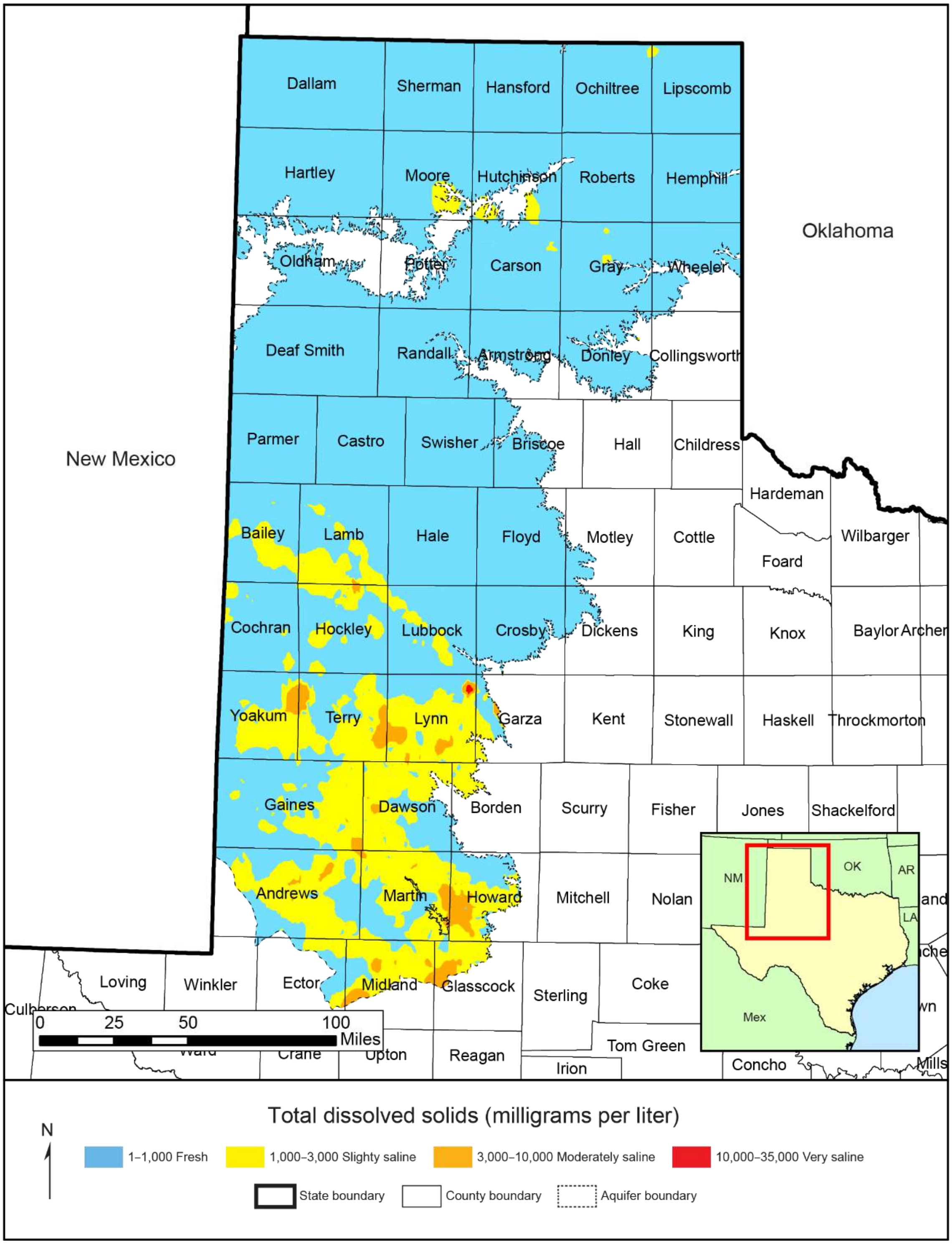


Figure 6-27. Total dissolved solids in the Ogallala Aquifer.

6.7 *Pecos Valley Aquifer*

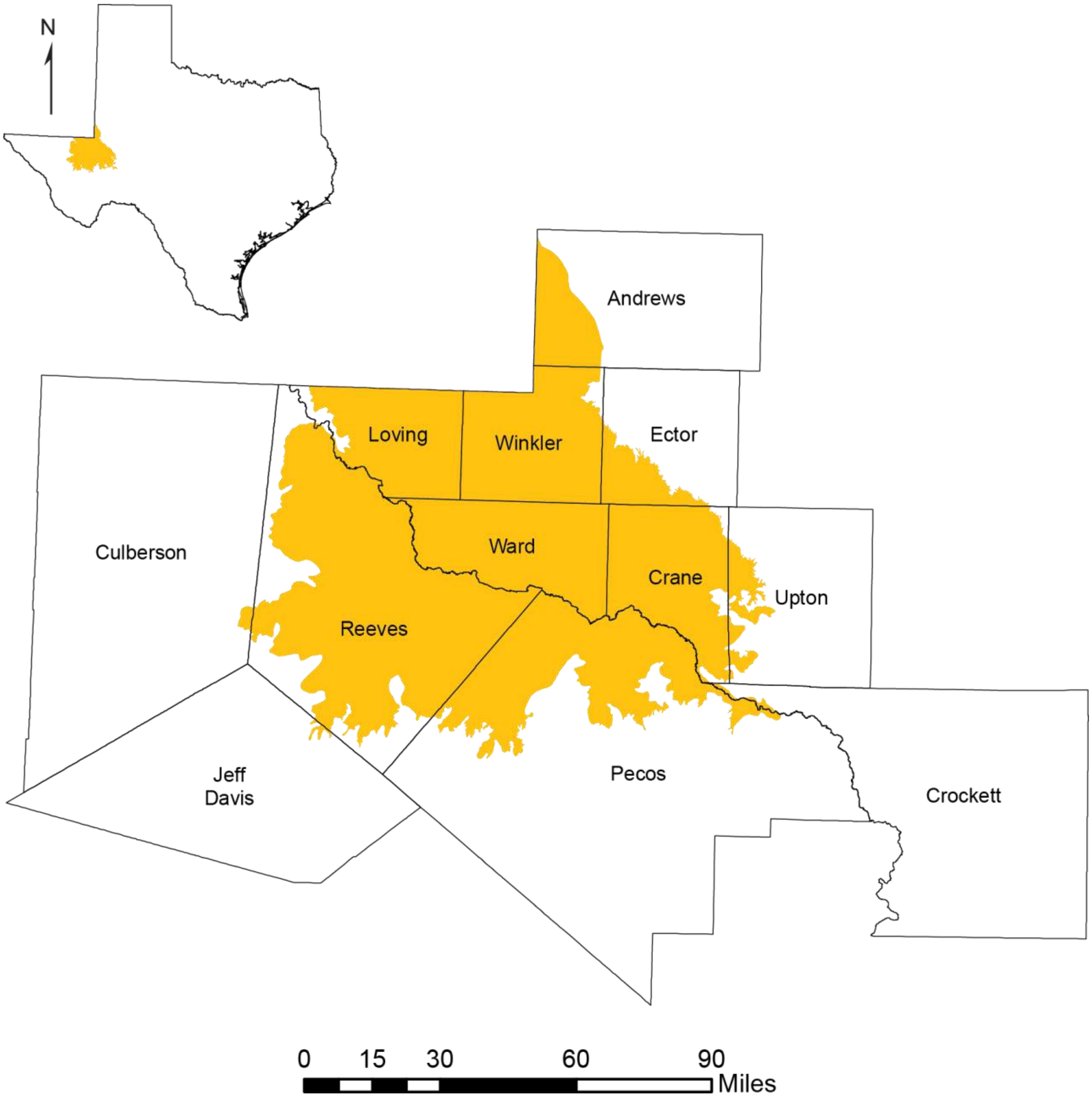


Figure 6-28. Extent of the Pecos Valley Aquifer.

Aquifer characteristics

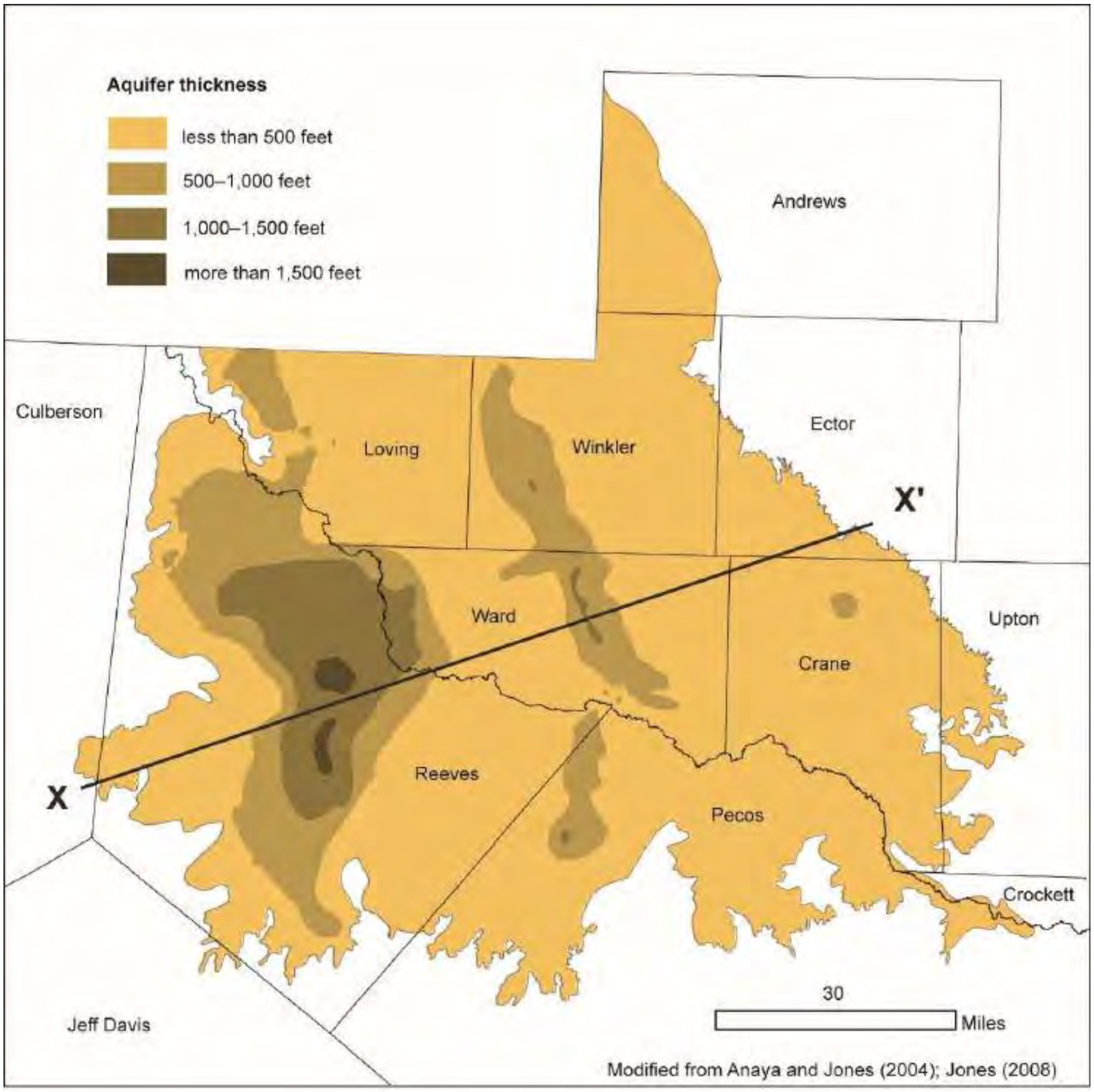
- Aquifer type: unconfined
- Area of aquifer: 6,829 square miles
- Proportion of aquifer with groundwater conservation districts: 47 percent
- Number of counties containing the aquifer: 12

Geology and hydrogeology

The Pecos Valley Aquifer is a major aquifer in west Texas. It consists of alluvial, lacustrine, and eolian deposits of Tertiary and Quaternary age deposited in the Pecos River Valley (Figure 6-28). Some of the valley fill deposits correlate with the Ogallala Formation (Hawley and others, 1976). These sediments fill several structural basins, the largest of which are the Pecos Trough in the west and Monument Draw Trough in the east (Figure 6-29). Thickness of the alluvial fill reaches 1,500 feet, and freshwater saturated thickness averages about 250 feet.

Groundwater in the Pecos Valley Aquifer is unconfined. The top of the aquifer is exposed at the ground surface over the entire extent of the aquifer. Recharge to the Pecos Valley Aquifer is estimated at about 89,800 acre-feet per year (Anaya and Jones, 2009). Recharge is generally higher south and west of the Pecos River. Return flows from Pecos River water applied for irrigation are estimated to be over 50 percent of the recharge to the Pecos Valley Aquifer (Ashworth, 1990). Induced recharge from the Pecos River also occurs in Pecos and Reeves counties, where irrigation pumping has drawn down the water table (Barker and Ardis, 1996).

The Pecos Valley Aquifer has a hydraulic conductivity ranging from 4 to 20 feet per day (Figure 6-30), a specific yield of 0.2, and specific storage of 0.0002, based on calibrated model results (Anaya and Jones, 2009).



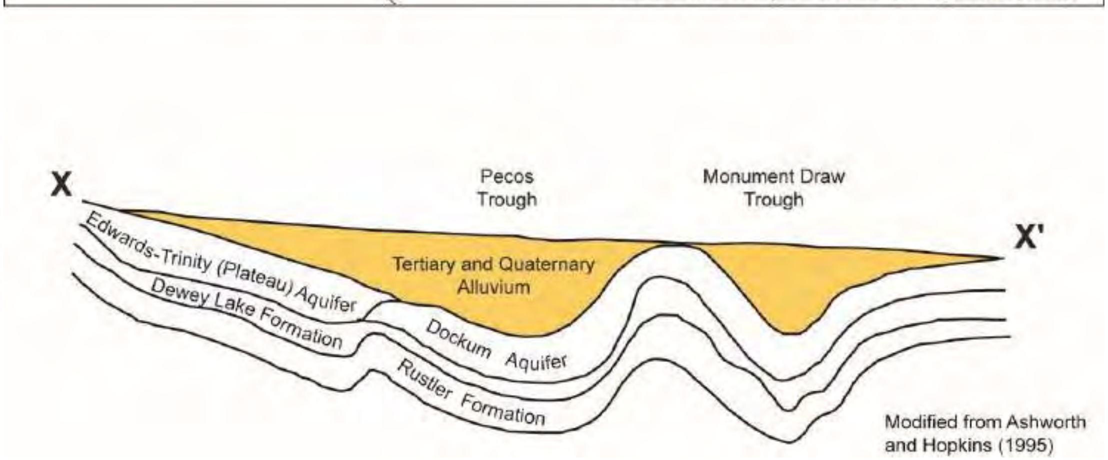


Figure 6-29. Generalized cross-sections across the Pecos Valley Aquifer (modified from Ashworth and Hopkins, 1995; Anaya and Jones, 2004; Jones, 2008).

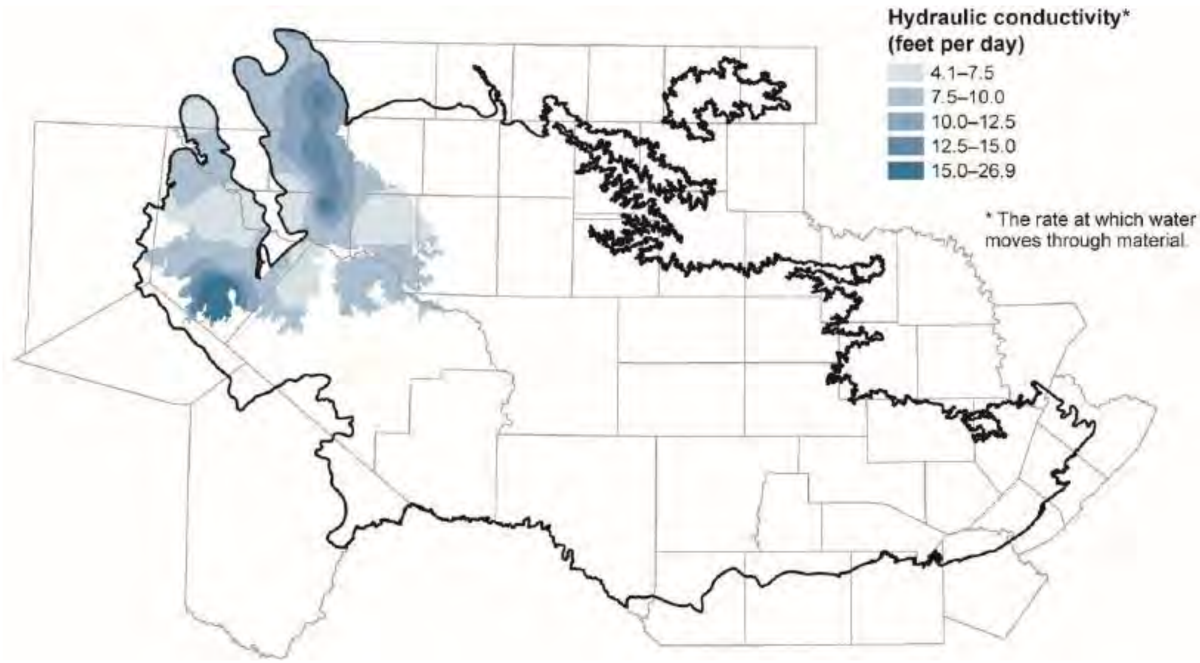


Figure 6-30. Interpolated hydraulic conductivity for the Pecos Valley Aquifer (from Anaya and Jones, 2009).

Flows to surface water and other aquifers

The Pecos Valley Aquifer discharges through evapotranspiration along the Pecos River where the water table is near the surface, as baseflow to the Pecos River, and as pumping from irrigation wells. Except for local cones of depression caused by intense pumping, groundwater flow in the Pecos Valley Aquifer is generally toward the Pecos River (Anaya and Jones, 2009). Table 6-18 summarizes groundwater flow from the Pecos Valley Aquifer to surface water. Table 6-19 shows the amount of springflow that makes up baseflow.

The Pecos Valley Aquifer is hydraulically connected to the underlying minor aquifers—the Dockum, Capitan Reef Complex, and Rustler aquifers. Groundwater flow between the Pecos Valley Aquifer and the minor aquifers is assumed to be insignificant based on geochemical data (Anaya and Jones, 2009). Table 6-20 shows groundwater availability model estimates of total flow and average annual flow between the Pecos Valley Aquifer and other major aquifers.

Table 6-18. Summary of groundwater flow from the Pecos Valley Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	276	0.8	0.8
Crane	747	2.4	2.2
Crockett	12	0.1	0.1
Culberson	14	0	0
Ector	192	0.6	0.6
Jeff Davis	7	12.1	11.7
Loving	635	1.9	1.8
Pecos	1,056	3	3.4
Reeves	2,116	39.6	37.6
Upton	120	0.4	0.4
Ward	836	2.2	2.3
Winkler	816	2.2	2.4
Total	**6,827**	**65**	**63**

Table 6-19. Summary of springflow from the Pecos Valley Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Jeff Davis	12.4	12	Phantom Lake Spring near Toyahvale, TX
Reeves	34.1	32	San Soloman Springs at Toyahvale, TX

Note that these values have been added to the total baseflow presented in Table 6-18

Table 6-20. Model estimates of inter-aquifer flows between the Pecos Valley Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647
Pecos Valley Aquifer	Ogallala Aquifer	0
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966
Ogallala Aquifer	Pecos Valley Aquifer	220

Water quantity

Total storage in the Pecos Valley Aquifer is estimated to be more than 323 million acre-feet Recoverable storage is estimated to be between 80.9 million and 242.8 million acre-feet (Table 6-21). Localized water levels have rebounded in south central Reeves and northwest Pecos counties since the late 1970s as irrigation pumping has decreased. However, water levels continue to decline in central Ward County because of increased municipal and industrial pumping. Figure 6-31 shows water-level changes in the Pecos Valley Aquifer from 1995 to 2015.

Table 6-21. Total estimated recoverable storage in the Pecos Valley Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	2,000,000	500,000	1,500,000
3	309,000,000	77,250,000	231,750,000
4	1,490,000	372,500	1,117,500
7	11,370,000	2,842,500	8,527,500
Total	**323,860,000**	**80,965,000**	**242,895,000**

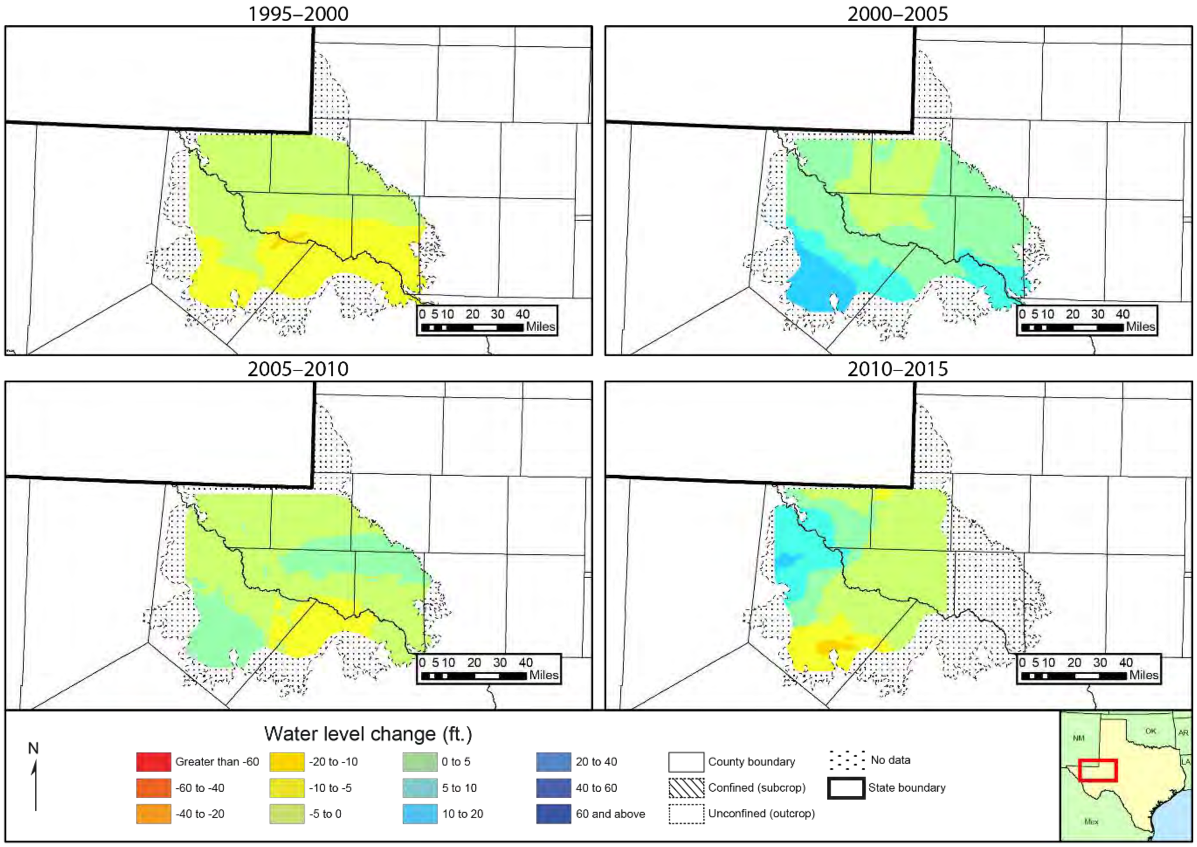


Figure 6-31. Water-level changes in the Pecos Valley Aquifer, 1995 to 2015.

Water quality

Water quality in the Pecos Valley Aquifer is highly variable, though it is typically hard and generally has lower total dissolved solids concentrations in the Monument Draw Trough than in the Pecos Trough. Total dissolved solids concentrations in groundwater from the Monument Draw Trough are usually less than 1,000 milligrams per liter (Figure 6-32). The aquifer is characterized by high levels of chloride and sulfate, frequently in excess of secondary drinking water standards. Although groundwater in the Monument Valley Trough is generally fresher, arsenic, fluoride, and radionuclides are more frequently detected in excess of drinking water standards there than in the Pecos Trough (Reedy and others, 2011). Arsenic and fluoride concentrations tend to decrease with increasing well depth.

Water quality is affected by recharge from the Pecos River, which has a high total dissolved solids content acquired by dissolution of evaporites in the river basin (Miyamoto and others, 2006). Water quality may be degraded by cross-formational flow from underlying saline aquifers induced by pumping in the Monument Draw Trough (Jones, 2004). East of the Pecos River, oil field brines and agricultural runoff have a significant effect on the groundwater quality of the Pecos Valley Aquifer (Ashworth, 1990).

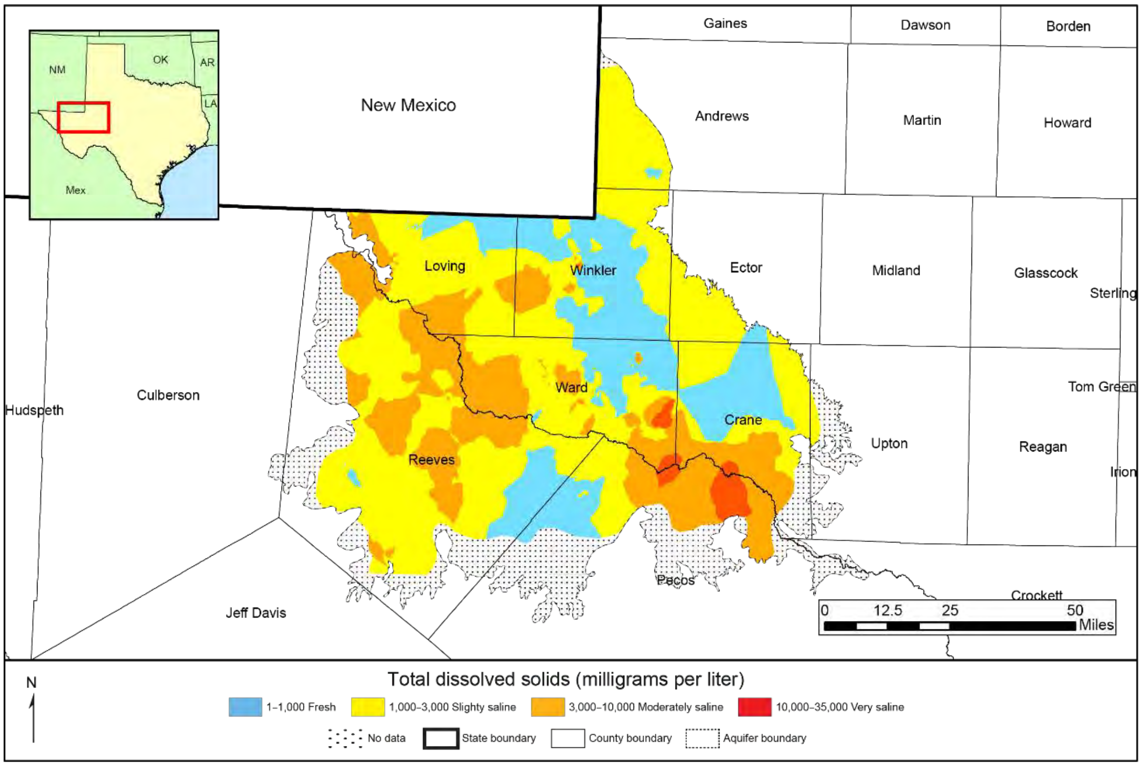


Figure 6-32. Total dissolved solids in the Pecos Valley Aquifer.

6.8 Seymour Aquifer

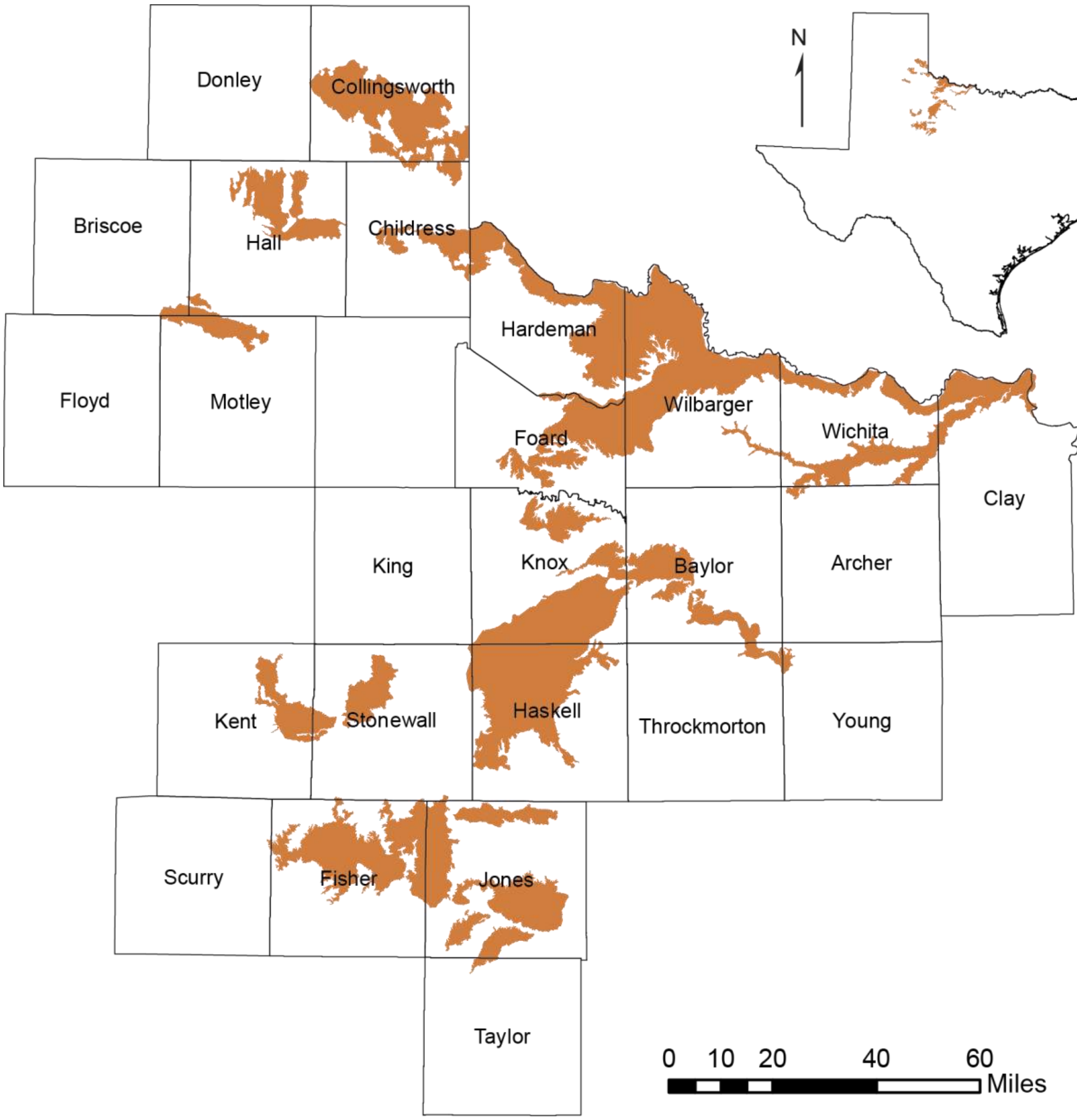


Figure 6-33. Extent of the Seymour Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 3,374 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 25

Geology and hydrogeology

The Seymour Aquifer is a major aquifer extending across north central Texas (Figure 6-33). The aquifer consists of Quaternary-age, alluvial sediments unconformably overlying westerly-dipping Permian-age rocks (Figure 6-34). The Seymour Aquifer is composed of discontinuous beds of poorly sorted gravel, conglomerate, sand, and silty clay eroded from the High Plains and deposited by eastward moving streams (R.W. Harden and Associates, 1978; Nordstrom, 1991; Duffin and Beynon, 1992). The sediments likely originally blanketed the entire region but were eroded by recent streams, leaving only the isolated areas, or “pods,” of sediment found today (Ogilbee and Osborne, 1962; Preston, 1978; Price, 1978). The sediments generally coarsen downward to the basal section of coarse sand and gravel. This basal section is the predominant water-producing zone.

Groundwater in the Seymour Aquifer is unconfined. Water is contained in pods of alluvium as much as 360 feet thick. The average recharge rate is 2 inches per year. It is reported that prior to significant land clearing and farming, the Seymour Aquifer was not a productive aquifer; the saturated thickness was inadequate to support pumping. Evapotranspiration losses decreased after the land was cleared, resulting in greater recharge and a gradual increase in the saturated thickness of the aquifer.

The geometric mean of the horizontal hydraulic conductivity for the aquifer is 68.5 feet per day. The specific yield of the Seymour Aquifer is estimated to range from 11 to 15 percent (Ewing and others, 2004).

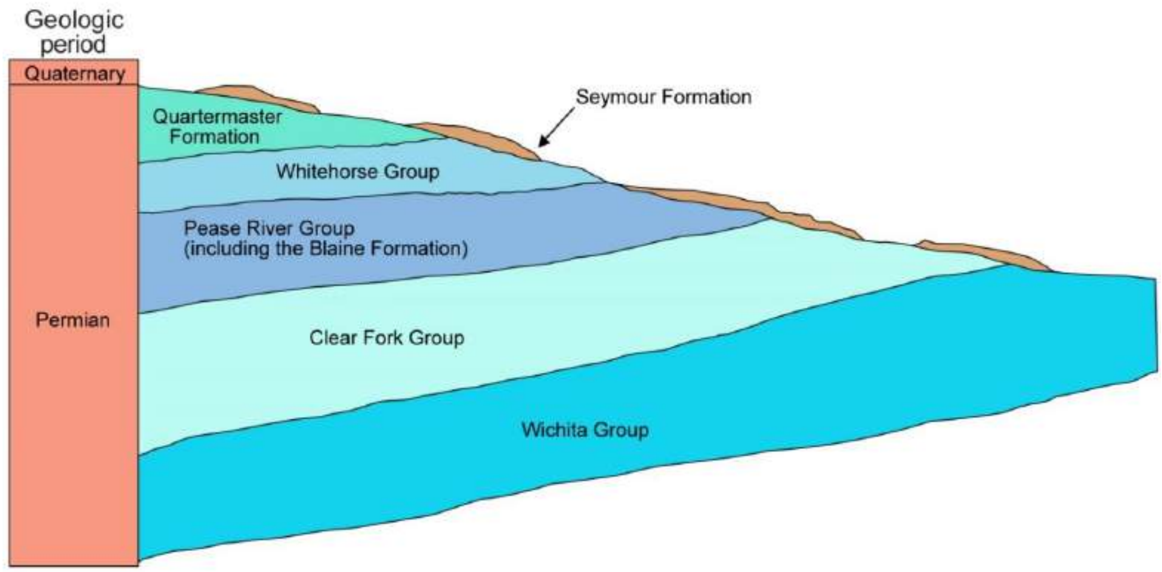


Figure 6-34. Generalized stratigraphy of the Seymour Aquifer and underlying Permian rocks (modified from Ewing and others, 2004).

Flows to surface water and other aquifers

Groundwater flow within the Seymour Aquifer is controlled by topography, structure, and permeability variation. Groundwater discharges to springs and seeps, local creeks, and major streams throughout the area, contributing to the baseflow of the streams. More than 600 springs and seeps are documented along the boundary of the Seymour Formation. Discharge directly to streams occurs in the younger Quaternary alluvium portions of the Seymour Aquifer where the aquifer is in direct contact with streams (Ewing and others, 2004). Table 6-22 summarizes groundwater flow from the Seymour Aquifer to surface water.

In addition, discharge from the Seymour Aquifer occurs by cross-formational flow into the underlying units. Cross-formational flow from the Seymour Aquifer is expected to be lowest in the eastern portion of the model domain where the Seymour Aquifer overlies the Wichita and Clear Fork groups of the Permian System. Some measurable discharge from the Seymour Aquifer to the Clear Fork Group may occur in Jones County (Price, 1978). In the north central region of the model domain, where the Seymour Aquifer overlies the Blaine Aquifer, appreciable, localized cross-formational flow to the Blaine Aquifer may occur (Ewing and others, 2004). Table 6-23 summarizes flow between the Seymour and Blaine aquifers.

Table 6-22. Summary of groundwater flow from the Seymour Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Archer	5	0.1	0
Baylor	136	1.1	0.1
Briscoe	10	0	0
Childress	82	0.4	0.1
Clay	106	3.7	1
Collingsworth	276	2.4	0.6
Donley	0	0	0
Fisher	283	2.1	0.4
Floyd	0	0	0
Foard	186	2.1	0.4
Hall	147	0.4	0.1
Hardeman	241	3.2	0.8
Haskell	370	3.7	0.9
Jones	326	3.3	0.7
Kent	80	0.3	0.1
King	0	0	0
Knox	307	4.3	1.2
Motley	54	0.4	0.1
Scurry	1	0	0
Stonewall	96	0.5	0.1
Taylor	5	0	0
Throckmorton	16	0.1	0
Wichita	189	4.4	0.9
Wilbarger	449	6.7	1.5
Young	7	0.1	0
Total	**3,372**	**39**	**9**

Table 6-23. Model estimates of inter-aquifer flows between the Seymour Aquifer and the Blaine Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Seymour Aquifer	Blaine Aquifer	7,162
Blaine Aquifer	Seymour Aquifer	34,072

Water quantity

Total storage in the Seymour Aquifer is estimated to be more than 5 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.2 million to 3.8 million acre-feet (Table 6-24). Figure 6-35 shows changes in water levels in the Seymour Aquifer from 1995 to 2015.

Table 6-24. Total estimated recoverable storage in the Seymour Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
1	760	190	570
2	57,000	14,250	42,750
6	5,070,100	1,267,525	3,802,575
7	610	153	458
Total	**5,128,470**	**1,282,118**	**3,846,353**

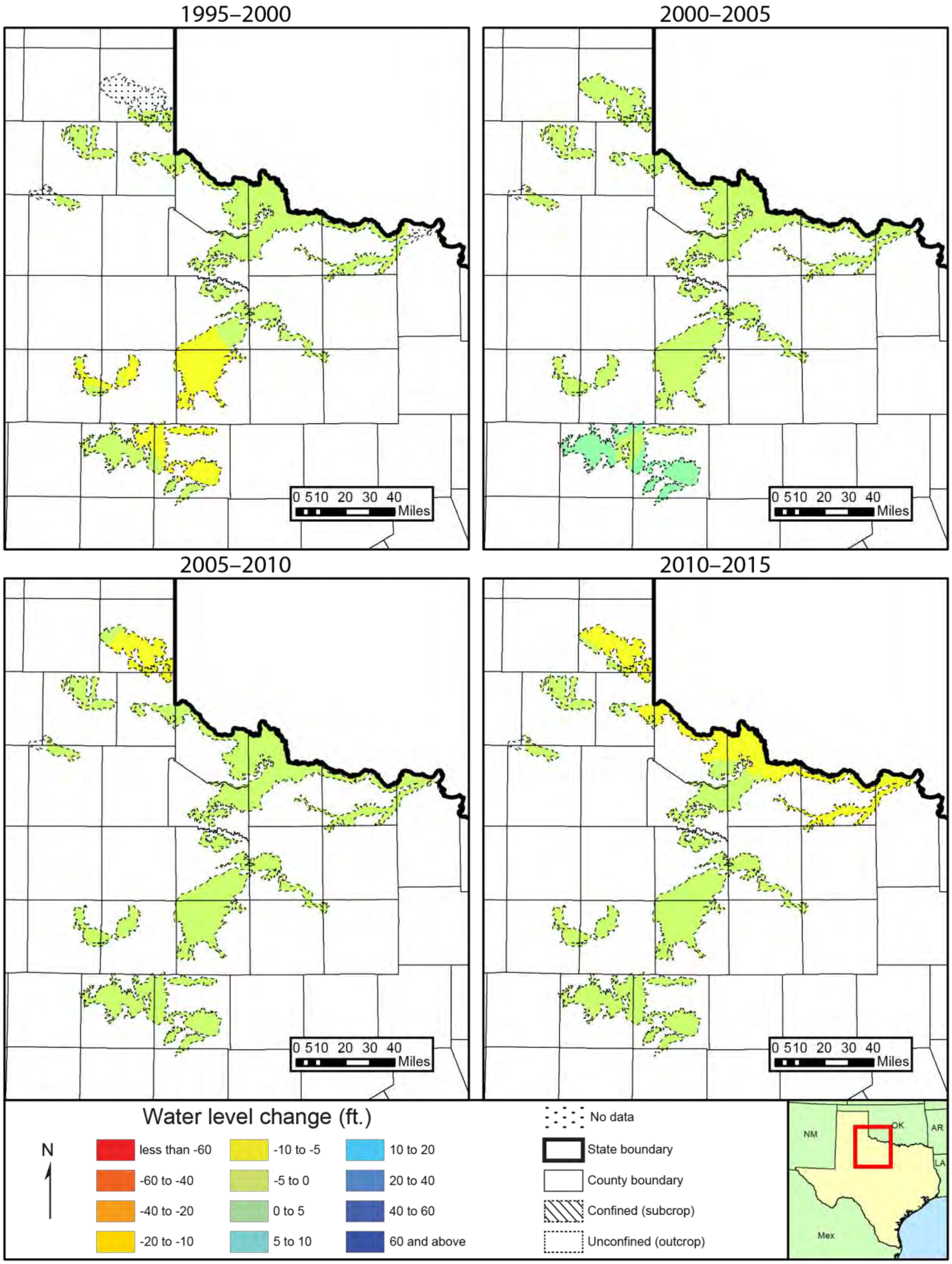


Figure 6-35. Water-level changes in the Seymour Aquifer, 1995 to 2015.

Water quality

Water quality ranges from fresh to slightly saline, with total dissolved solids concentrations ranging from about 100 to 3,000 milligrams per liter. However, moderately to very saline water exists in localized areas, with total dissolved solids concentrations ranging from 3,000 to more than 10,000 milligrams per liter (Figure 6-36).

Throughout its extent, the aquifer is affected by nitrate in excess of primary drinking water standards. High nitrate concentrations are attributed to oxidation of soil organic nitrogen during initial cultivation followed by leaching of fertilizers on cultivated land. Excessive chloride and sulfate also occur throughout the aquifer. The Haskell-Knox counties pod of the aquifer has the highest probability for exceeding any primary drinking water standard (Reedy and others, 2011).

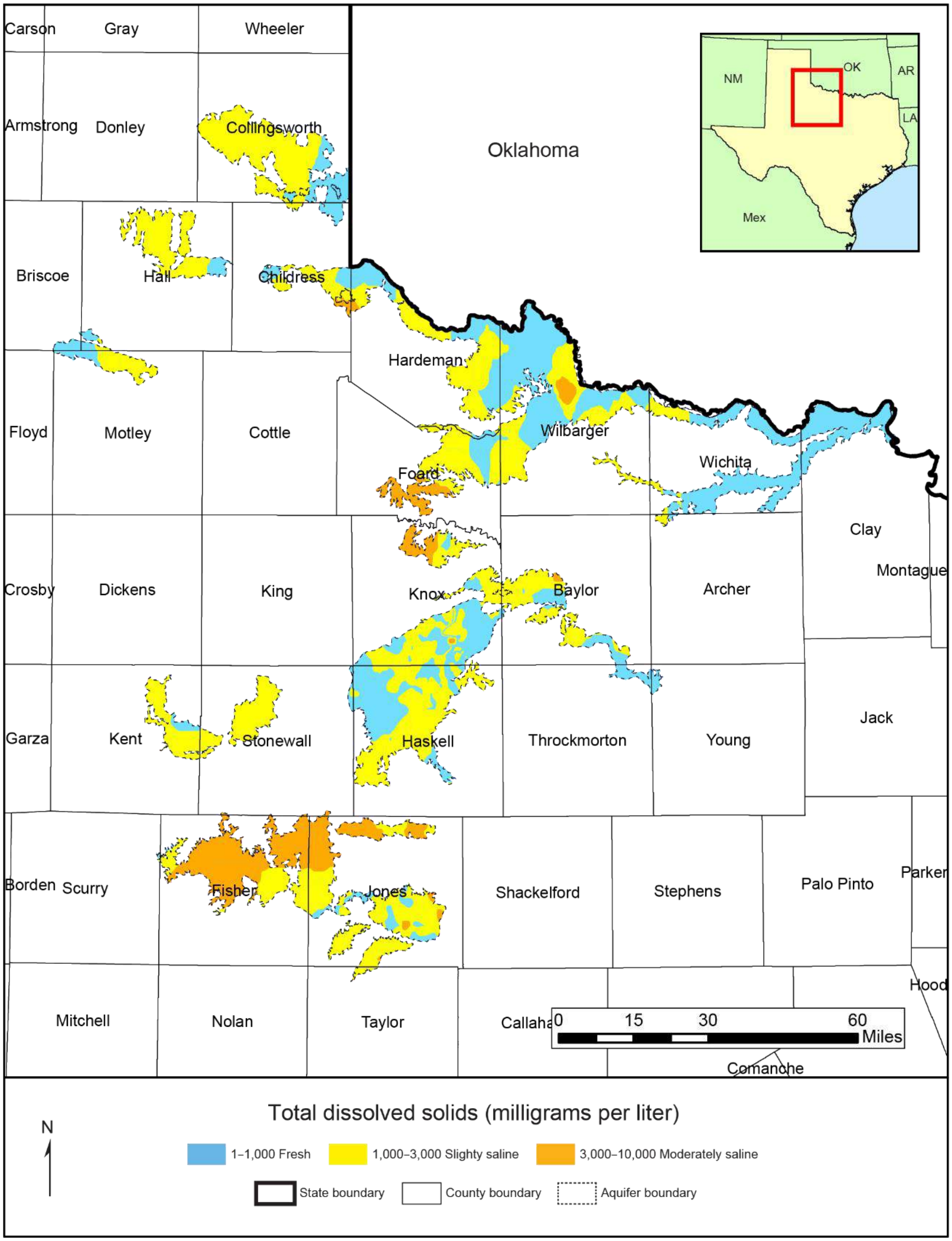


Figure 6-36. Total dissolved solids in the Seymour Aquifer.

6.9 Trinity Aquifer

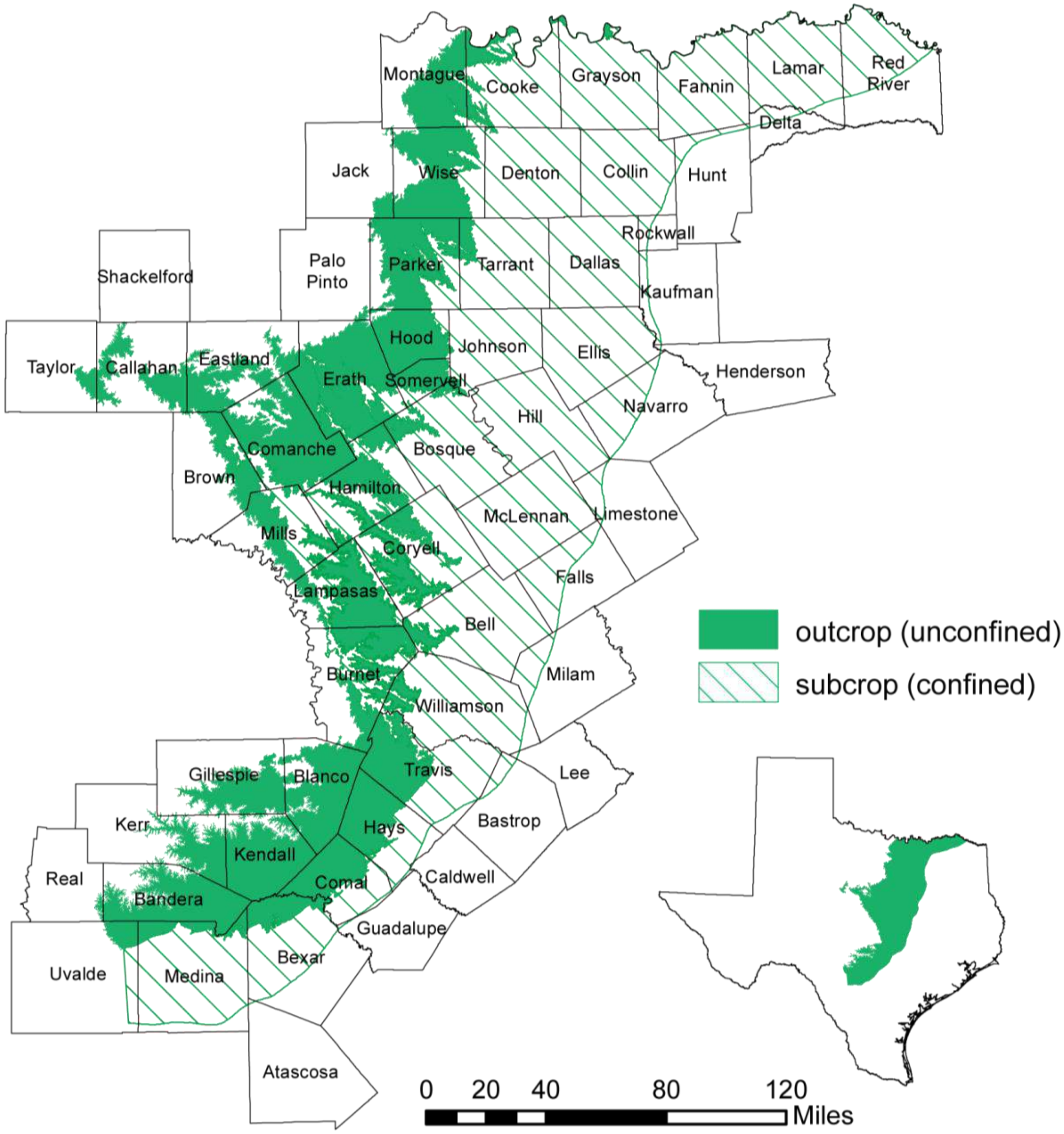


Figure 6-37. Extent of the Trinity Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 10,692 square miles
- Area in subsurface: 21,308 square miles
- Proportion of aquifer with groundwater conservation districts: 82 percent
- Number of counties containing the aquifer: 61

Geology and hydrogeology

The Trinity Aquifer is a major aquifer extending across much of the central and northeastern part of the state (Figure 6-37). It is composed of several water-bearing formations within the Trinity Group. Although referred to differently in different parts of the state, they include the Antlers, Glen Rose, Paluxy, Twin Mountains, and Travis Peak. These formations consist of limestones, sands, clays, gravels, and conglomerates. Their combined freshwater saturated thickness averages about 600 feet in North Texas and about 1,900 feet in Central Texas (Figure 6-38 and Figure 6-39).

Sand distribution and thickness largely controls the productivity of the aquifer. The depositional environment in the Cretaceous Period resulted in a layered system of aquifers and aquitards in the northern Trinity Group. These sandstones were deposited in two contrasting environments, resulting in fluvial and shoreline water-bearing sandstones (Kelly and others, 2014).

The hydraulic properties of the formations making up the northern Trinity Aquifer vary considerably. The median hydraulic conductivities in the calibrated groundwater model for the Woodbine, Paluxy, Hensell, and Hosston aquifers are 0.15, 0.47, 1.67, and 2.27 feet per day, respectively. Storativity ranges over several orders of magnitude between layers and geographically within each layer, with values from 1×10^{-6} to 3×10^{-3}. The specific yield of the unconfined portion of the aquifer was modeled as 0.1. In Central Texas, calibrated values of the specific yield were 0.0005 for the upper portion of the Trinity Aquifer and 0.0008 for the middle and lower portions of the Trinity Aquifer (Kelly and others, 2014).

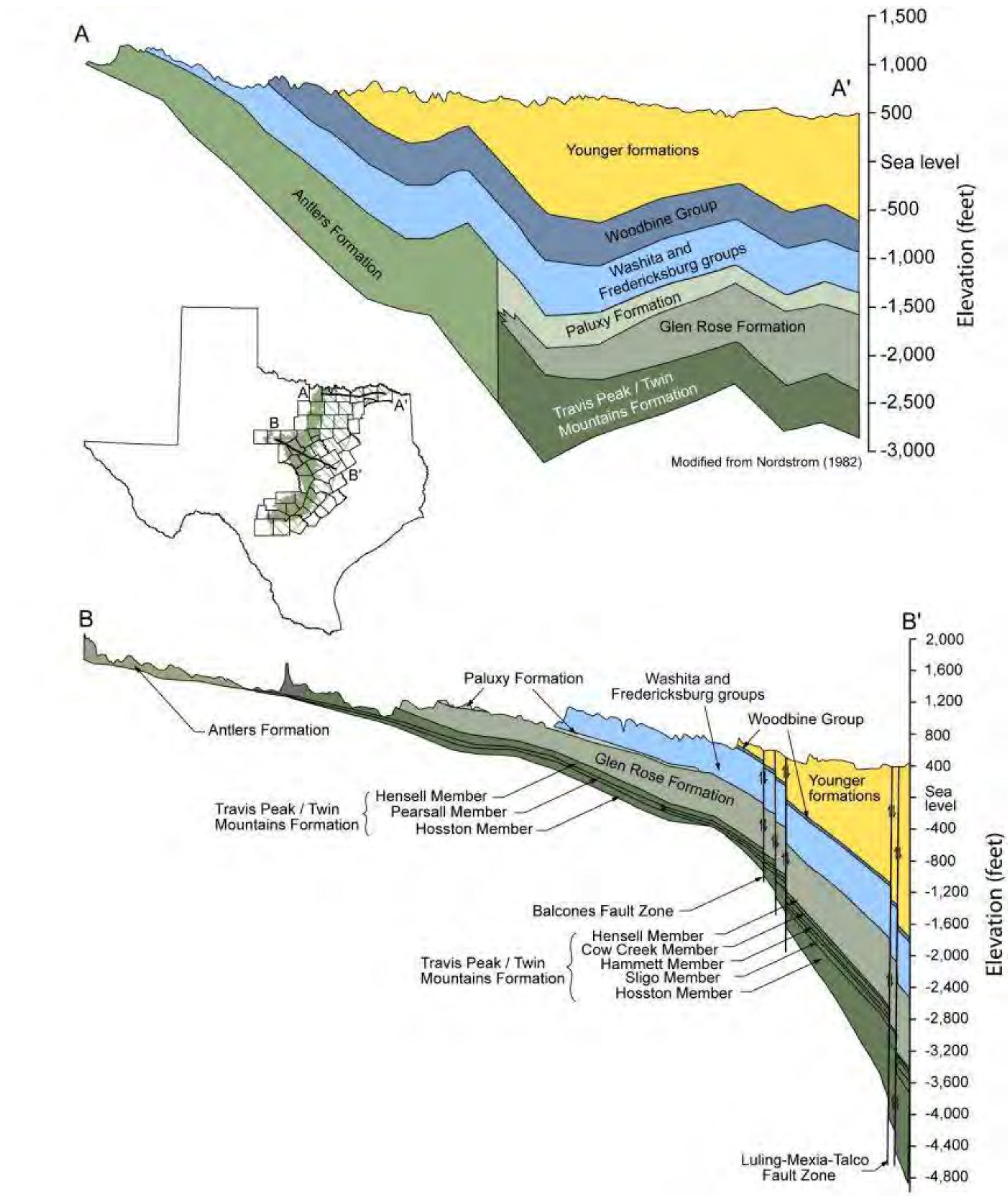


Figure 6-38. Structural cross-sections of the northern Trinity Aquifer, shown in shades of green (modified from Klemt and others; 1975; Nordstrom, 1982).

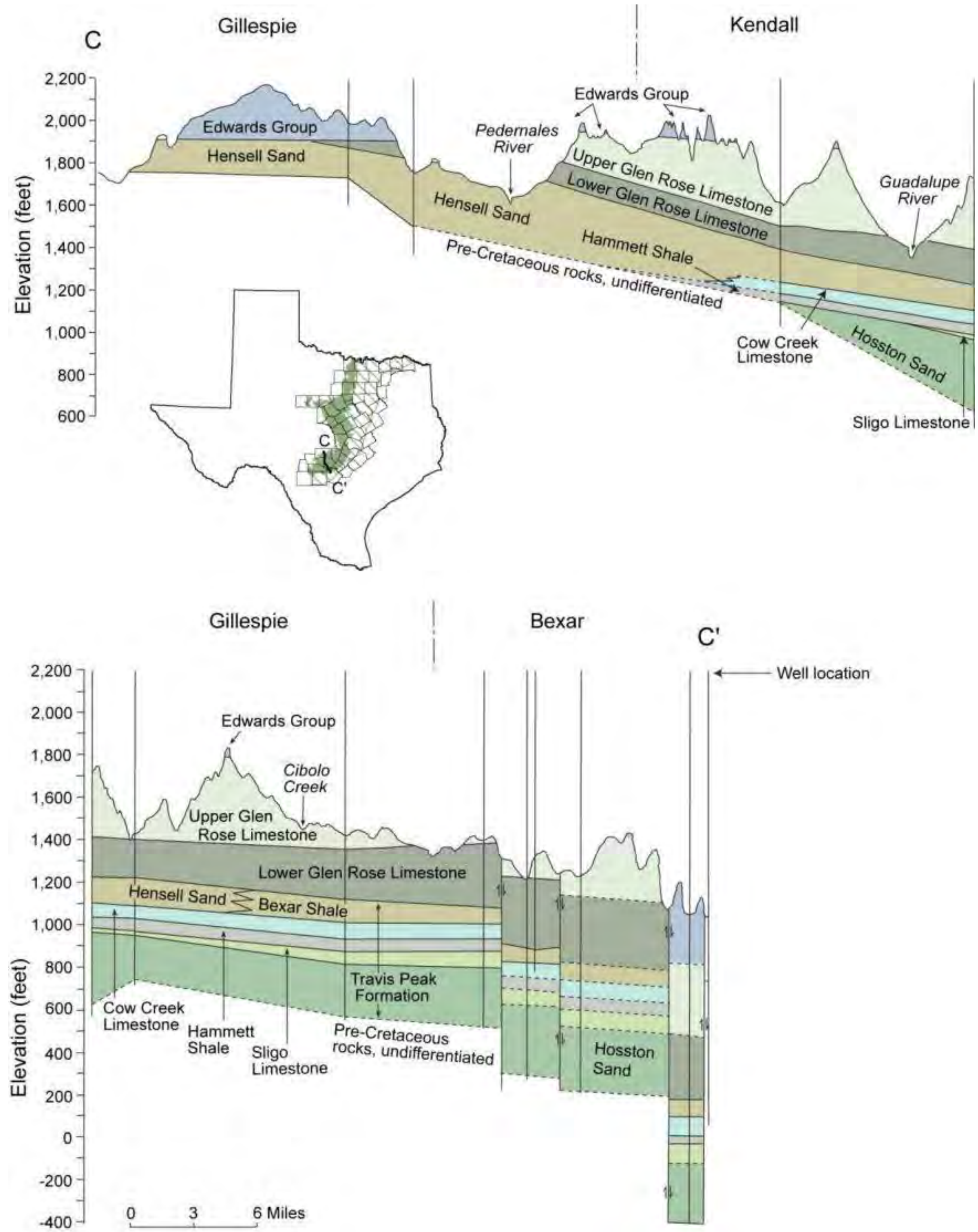


Figure 6-39. Structural cross-section of the Trinity Aquifer in the Hill Country, including rocks from the Upper Glen Rose Formation to the Hosston Sand (modified from Ashworth, 1983; Mace and others, 2000b).

Flows to surface water and other aquifers

The Trinity Aquifer discharges to a large number of springs, with most discharging less than 10 cubic feet per second. Table 6-25 summarizes groundwater flow from the Trinity Aquifer to surface water as baseflow. Table 6-26 shows groundwater availability model estimates of total flow and average annual flow between the Trinity Aquifer and other aquifers.

Table 6-25. Summary of groundwater flow from the Trinity Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bandera	589	81.7	26.1
Bell	67	5.9	1.4
Bexar	178	10.9	2.5
Blanco	571	57.6	14.9
Bosque	85	4	0.5
Brown	225	5.1	0.7
Burnet	434	38.8	5.9
Callahan	276	2.8	0.2
Comal	322	41.5	14.6
Comanche	760	23.9	3
Cooke	122	5.3	0.8
Coryell	303	16.4	2.8
Denton	3	0.2	0
Eastland	351	5.5	0.5
Erath	817	30.8	4.3
Gillespie	380	26.9	10.8
Grayson	15	0.9	0.2
Hamilton	325	13.8	1.9
Hays	353	57.3	13
Hood	384	18.2	3.1
Jack	53	1.3	0.1
Johnson	11	0.4	0.1
Kendall	573	73	23.5
Kerr	274	42.5	19.7
Lampasas	456	32.1	5.1
Llano	0	0	0
Medina	121	11.9	3

Table 6-25. Summary of groundwater flow from the Trinity Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Mills	261	10.4	1.6
Montague	416	15	1.7
Palo Pinto	14	0.2	0
Parker	565	23.2	3.3
Real	13	1.9	0.6
Shackelford	0	0	0
Somervell	142	9.5	1.6
Tarrant	58	2.6	0.3
Taylor	49	0.4	0
Travis	393	51.1	8.2
Uvalde	84	9.8	2.7
Williamson	70	8	1.2
Wise	594	21.7	2.6
Total	**10,707**	**763**	**183**

Table 6-26. Model estimates of inter-aquifer flows between the Trinity Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285
Trinity Aquifer	Marble Falls Aquifer	144
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848
Hickory Aquifer	Trinity Aquifer	64

Water quantity

Total storage in the Trinity Aquifer is estimated to be more than 1.4 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 357.2 million and 1.0 billion acre-feet (Table 6-27). Figure 6-40 shows water-level changes in the Trinity Aquifer from 1995 to 2015.

Table 6-27. Total estimated recoverable storage in the Trinity Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	23,710,000	5,927,500	17,782,500
6	471,000	117,750	353,250
7	523,000	130,750	392,250
8	1,359,530,000	339,882,500	1,019,647,500
9	5,280,000	1,320,000	3,960,000
10	23,057,000	5,764,250	17,292,750
11	500,000	125,000	375,000
12	11,100,000	2,775,000	8,325,000
13	4,695,000	1,173,750	3,521,250
Total	**1,428,866,000**	**357,216,500**	**1,071,649,500**

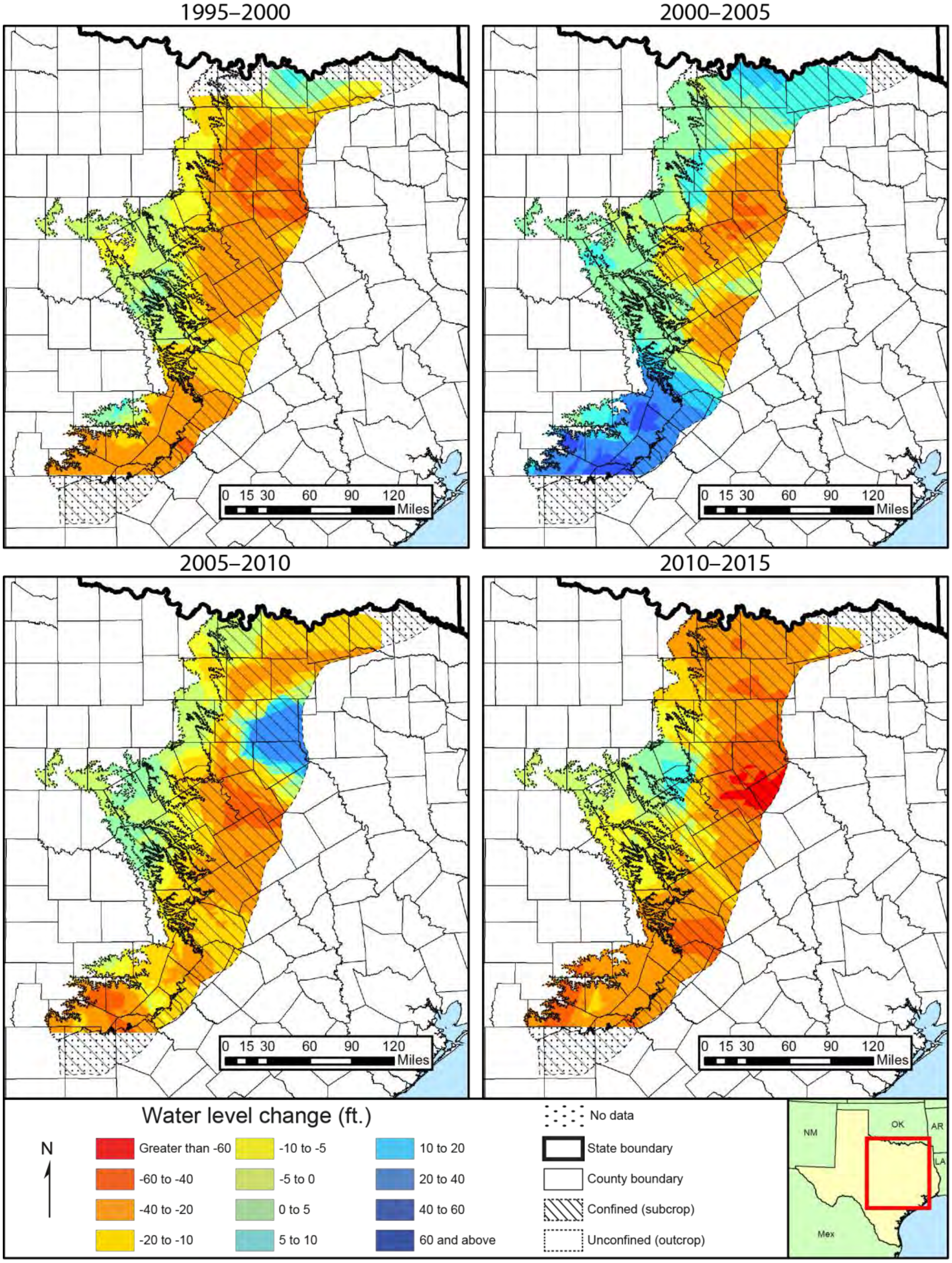


Figure 6-40. Water-level changes in the Trinity Aquifer, 1995 to 2015.

Water quality

In general, groundwater is fresh but very hard in the outcrop of the aquifer. Total dissolved solids concentrations increase from less than 1,000 milligrams per liter in the outcrop area to between 1,000 and 5,000 milligrams per liter, or slightly to moderately saline, down-dip as the depth to the aquifer increases (Figure 6-41). High sulfate and chloride concentrations in the Trinity Aquifer are attributed to dissolution of evaporite beds in the upper unit of the Glen Rose Formation and in the Middle Trinity Aquifer to gypsum and evaporite beds in the Cow Creek Member of the Travis Peak Formation.

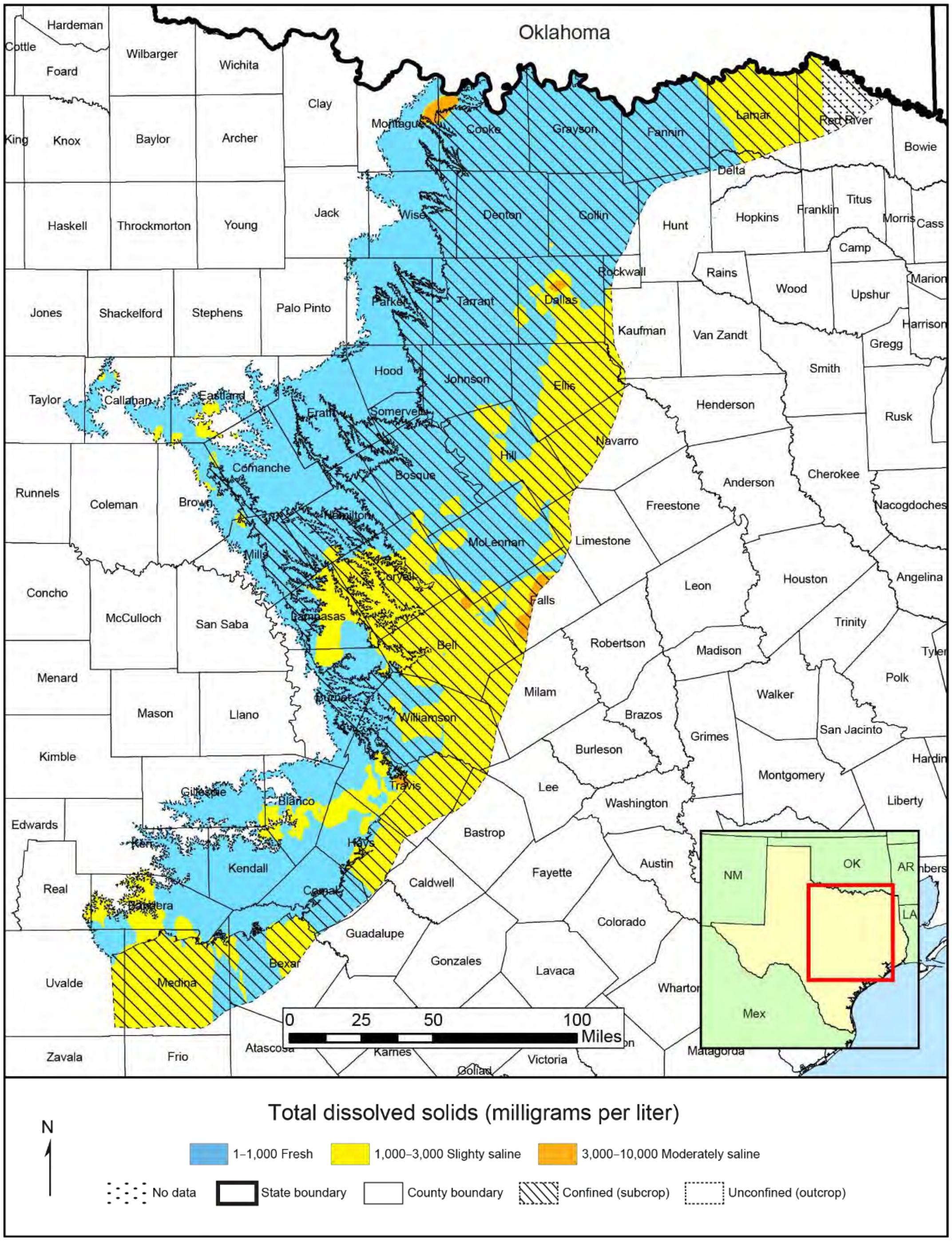


Figure 6-41. Total dissolved solids in the Trinity Aquifer, based on samples from 5,999 wells. Water quality in individual formations within the Trinity Aquifer may vary from the distribution shown here.

6.10 Blaine Aquifer

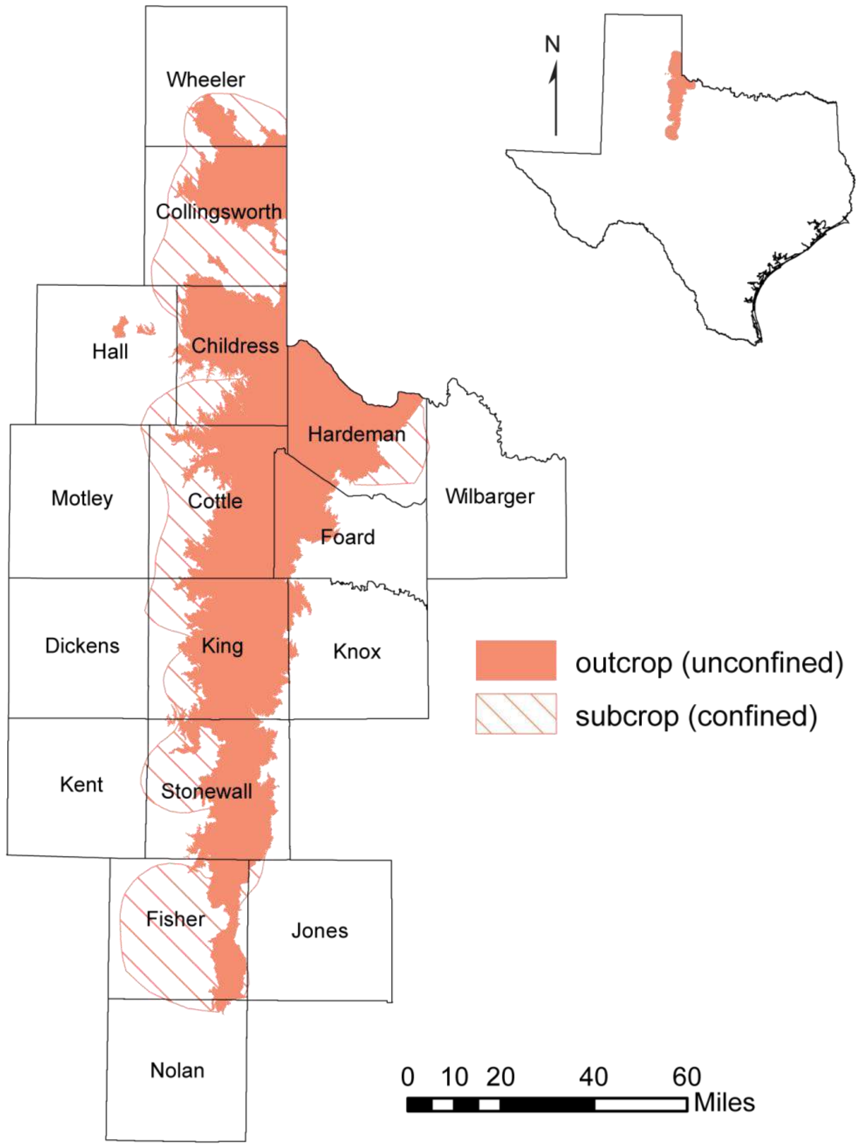


Figure 6-42. Extent of the Blaine Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 3,443 square miles
- Area of subsurface: 2,234 square miles
- Proportion of aquifer with groundwater conservation districts: 74 percent
- Number of counties containing the aquifer: 17