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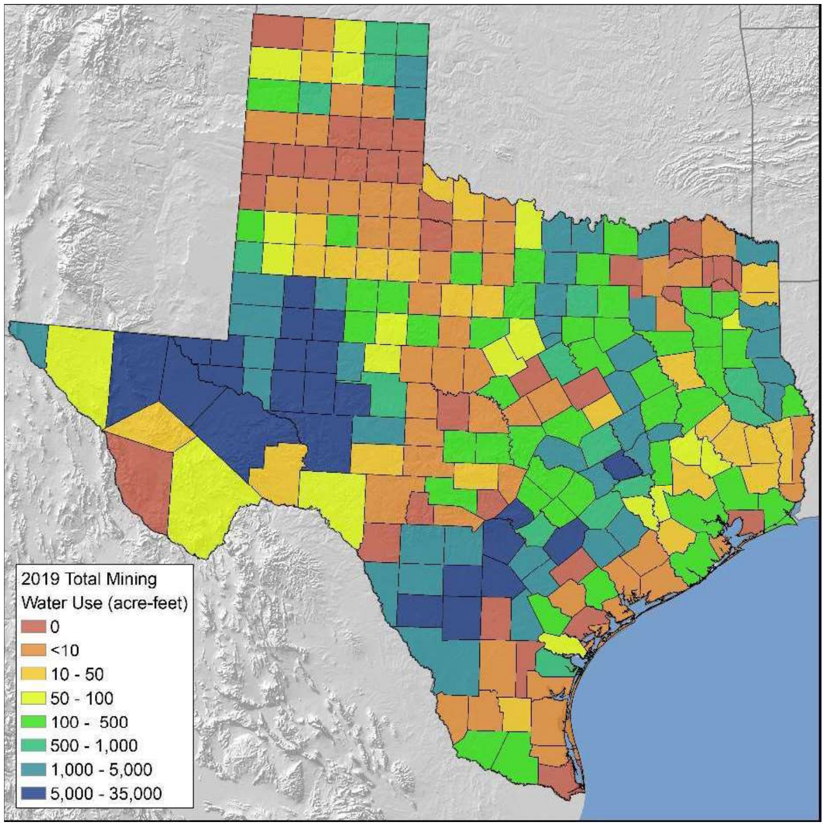
# Water Use by the Mining Industry in Texas

Final Report August 2022

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# Acronym List

EIA: US Energy Information Administration

EOR: Enhanced Oil Recovery

GAM: Groundwater Availability Model

HF: hydraulic fracturing

IHS: Information Handling Services (IHS)

maf: million acre-feet

O&G: oil and gas

PW: produced water

RRC: Railroad Commission of Texas

SDR: Submitted Driller Reports

SWAP: Source Water Availability Program

SWD: Salt Water Disposal

TCEQ: Texas Commission on Environmental Quality

TDLR: Texas Department of Licensing and Regulation

TDS: Total Dissolved Solids

TRR: Technically Recoverable Resources

TWDB: Texas Water Development Board

# Executive Summary

The mining industry in Texas is critical to the state's and the nation's economy, and the availability of adequate water is essential to many mining sectors. Accurate water use estimates and long-range projections associated with this industry are essential for Texas' regional water planning process and the development of the state water plan. The main purposes of this research were to:

1) provide a comprehensive and quantitative assessment of mining water use across Texas, and
2) improve the development process and accuracy of water use estimates and water demand projections.

The methodology involved the following:

1) quantification of current and historical water use for hydraulic fracturing (HF) and produced water (PW) volumes;
2) identification of the sources of water for HF;
3) development of projections of future water demand for oil and gas (2020-2080);
4) identification of locations of operations and quantification of current and projected future water use for coal and lignite mining;
5) identification of locations of operations and quantification of current and projected future water use for aggregates; and
6) comparison of our results with those reported by the U.S. Geological Survey.

Total water use for all purposes in Texas in 2019 was approximately 14.1 million acre-feet (maf) per year (TWDB, 2021-1). The results of this study indicate that water use by the mining industry is about 395,000 acre-ft/yr, representing 2.8% of total water use (Figure ES-1). Mining water use is estimated to gradually increase through about 2060, primarily as a result of increased demand for aggregate industry products and decline afterwards as major oil and gas play development matures (Figure ES-2).

*Oil and Gas Industry Water Use*

Oil and gas (O&G) reservoirs can be broadly categorized based on geological materials and fluid flow characteristics. Conventional reservoirs generally consist of coarse-grained materials (gravels and sands) having relatively high permeability compared to unconventional reservoirs that generally consist of fine-grained materials (tight sands and shales) having relatively low permeability. Producing formations in a given region, either singly or collectively, are often referred to as a "play" and more broadly, plays are typically associated with a geological "basin" representing a larger, more regional depositional environment.

Oil and gas wells can be categorized similar to reservoir types. Conventional O&G wells are oriented vertically or near-vertically with some classified as "directional". Conventional O&G wells are completed predominantly in conventional reservoirs, are completed with limited or no HF, use relatively small water volumes (less than about 0.4 million gallons per well) primarily for drilling fluids, and generally produce from relatively short vertical intervals (less than about 100 ft thick).

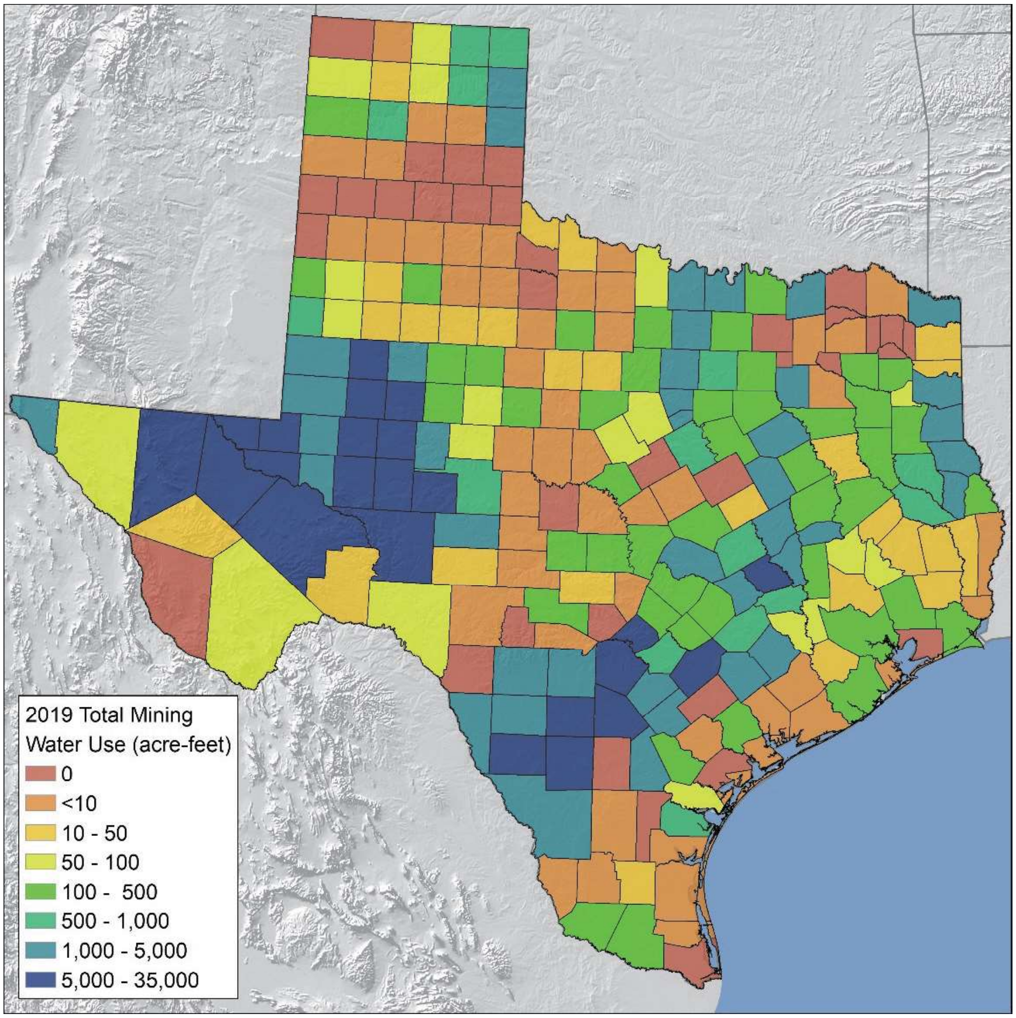

Figure ES-1. Distribution of total mining water use in Texas for 2019

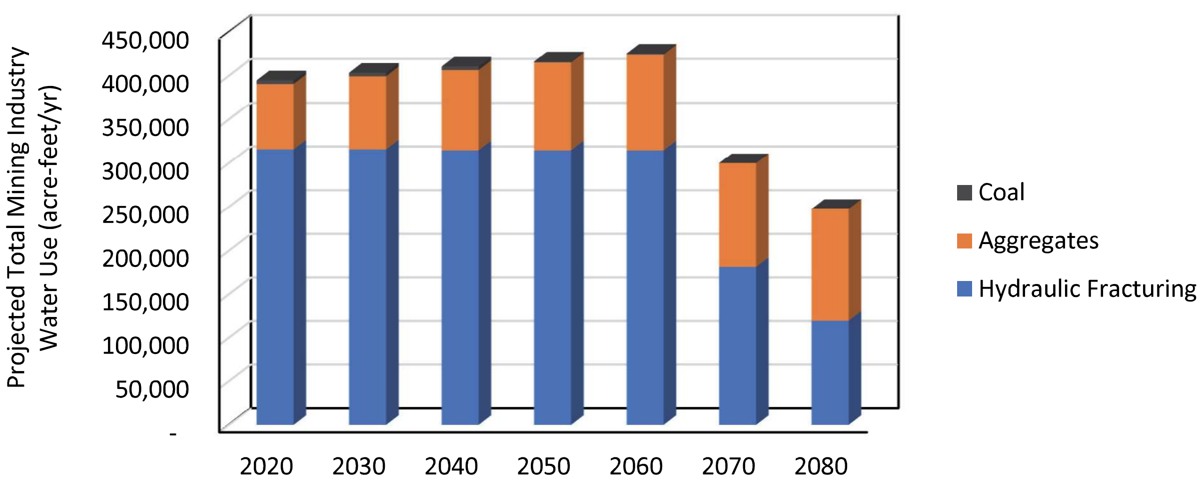

Figure ES-2. Projected annual mining water use in Texas by the industry sector.

Unconventional O&G wells are predominantly completed in unconventional reservoirs and use large HF water volumes. For the purposes of this report, this includes wells that used more than about 0.4 million gallons of water for completion. The primary use of water for unconventional wells is for HF with relatively small volumes for drilling fluids. In practice, the majority of recently completed unconventional wells have HF volumes of about 8-40 million gallons per well and produce from unconventional reservoirs over relatively long horizontal or “lateral” lengths (5,000-10,000 ft). Unconventional wells predominantly have horizontal sections, though some have vertical or directional orientations.

Water use by the O&G industry increased substantially with the advent of production from unconventional reservoirs beginning in about the mid to late 2000s as horizontal drilling and large-volume HF techniques were developed and refined [Nicot et al., 2012; Scanlon et al., 2017]. Hydraulic fracturing consists of injecting a fluid into the geological materials surrounding an O&G well borehole under pressures sufficient to induce fractures in the material. To maintain the fracture openings, the injected fluid includes suspended particles or “proppant”, usually sand, that remains in the fractures to “prop” them open and maintain flow paths.

Volumes of water used for HF and water co-produced with oil and gas, termed produced water (PW), were quantified for 2019 because of the reporting lag for produced water volumes (about 1 year). A total of 11,300 unconventional O&G wells were completed in 2019 using 320,000 acre-ft of HF water. Most of the HF water use (69%) occurred in the Permian Basin (Permian and Permian-Far West regions), followed by the Eagle Ford (27%) and the Haynesville (3%) plays, with the remainder (1%) in all other regions combined. Estimated produced water volume totaled 1,134,000 acre-ft across the state, slightly less than and in very good agreement with the total Class II injection volume of 1,160,000 acre-ft. Class II injection consists of enhanced oil recovery (EOR) and saltwater disposal (SWD)

Statewide, HF water use increased by a factor of approximately eight times between 2010 and 2019. HF water use increased steadily by a factor of approximately four times from 39,000 acre-ft to 165,000 acre-ft between 2010 and 2014 primarily reflecting increasing drilling activity in both the Permian Basin and the Eagle Ford Play. Volumes then decreased steadily to 117,000 acre-ft by 2016 reflecting a decline in new drilling in the Eagle Ford Play. Afterwards, volumes increased by a factor of approximately two times to 315,000 acre-ft by 2018 reflecting greatly increased drilling activity in the Permian Basin. Total HF water use increased slightly in 2019 to 320,000 acre-ft. A total of 1,592,000 acre-ft was used for HF between 2010 and 2019 in Texas. Most occurred in the Permian Basin (53%) and the Eagle Ford (34%), with much less in the Barnett (6%) and the Haynesville (3%).

Produced water volumes exhibited a similar overall pattern. Volumes steadily increased by 25% from 703,000 acre-ft to 877,000 acre-ft between 2010 and 2014 followed by a 7% decline to 815,000 acre-ft by 2016 and a rapid increase of 39% by 2019 to 1,134,000 acre-ft. Total PW was 8,660,000 acre-ft between 2010 and 2019 in Texas. Most occurred in the Permian Basin (60%) and the Barnett Play (10%), with relatively less in the Haynesville (6%) and Eagle Ford (5%) plays, and the remainder (18%) from all other regions combined.

The water sources for O&G industry uses vary among the major plays. In the Barnett Play, a total of 1,448 groundwater wells were completed in the region between 2002 and 2020, mostly in the Trinity aquifer (96% of groundwater wells for oil and gas industry). The water source was predominantly freshwater in the Barnett (less than 1,000 mg/L Total Dissolved Solids, TDS). In the Eagle Ford Play, a total of 3,707 groundwater wells were completed between 2002 and 2020 in the Carrizo-Wilcox, Gulf Coast, Queen City, and Yegua-Jackson aquifers. Groundwater from the Gulf Coast aquifer is mostly fresh (< 18% probability of exceeding 1,000 mg/L TDS), with salinity increasing in the Carrizo Wilcox (32% probability), the Queen City (52% probability), and the Yegua-Jackson (67% probability) aquifers. In the Haynesville Play, a total of 7,919 groundwater wells were completed between 2002 and 2020, mostly in the Carrizo-Wilcox aquifer. Water quality is generally fresh. In the Permian Basin, a total of 15,440 groundwater wells were completed between 2002 and 2020. These wells were completed in 12 aquifers, primarily in the Ogallala (37%), Dockum (32%), and Edwards-Trinity Plateau (12%) aquifers. The area-weighted probability of groundwater exceeding the 1,000 mg/L TDS threshold in the Permian Basin is highly variable within and between the various aquifers, including 54% in the Edwards-Trinity Plateau, 60% in the Ogallala, and 90% in the Dockum aquifers.

Projected O&G industry water use for HF varied among the plays. Unconventional development began earliest in the Barnett play in the late 1990s and peaked in 2008 with 2,700 O&G wells drilled. Between 2016 – 2020 only 242 O&G wells were completed (48 wells/yr), mostly in a four-county area (Denton, Johnson, Tarrant, and Wise counties). Projected water use for HF in the Barnett play is based on drilling an estimated 45 wells/yr that is assumed to continue to 2030, totaling 11,400 acre-ft of HF water use.

Projected HF water use in the other plays is based on Technically Recoverable Resources (TRR) for the different plays. In the Eagle Ford play, unconventional development began much later than in the Barnett play (in 2008) and a total of about 20,500 O&G wells were drilled through 2019 in the Eagle Ford Formation. TRR is estimated to be 112,000 wells with 91,600 wells remaining to be drilled from 2020 onward. Assuming 4,800 wells/yr (2017 – 2019 rates) it will require approximately 51 yr to complete all drilling (2020 – 2071). Median HF water use was 1,960 gal/ft in 2018 – 2021. Therefore, projected HF water use is 56,800 acre-ft/yr, totaling 2.9 million acre-feet (maf) over the remaining life of the play (2020 – 2071).

In the Haynesville Play, unconventional development began in 2008 with 30% of development in Texas and 70% in Louisiana. A total of 1,223 O&G wells were drilled in the Texas portion of the play through 2019 with a mean of about 100 wells/yr in the Haynesville Shale. The TRR includes 17,600 wells with 16,400 wells remaining to be drilled from 2020 onwards. Based on a drilling rate of 120 wells/yr (average for 2018 – 2020), it will require 136 years to drill all remaining wells. Median HF water use is 3,764 gal/ft, which is about two times greater than that in all of the other plays in Texas. Projected HF water use is 7,500 acre-ft/yr for 2020 – 2150, totaling 1 maf over the remaining life of the play.

The Permian has the largest unconventional reservoirs in the state and production began in about 2000. Initially many O&G wells were vertical, peaking in 2012 (5,100 wells) and decreasing to 500 wells in 2019. Horizontal well drilling increased from 2010 and accounted for 4,700 wells in 2018. A total of 55,400 wells were drilled in 2008 through 2019, 26,100 vertical wells and 20,300 horizontal wells. TRR analysis for this report focused on the main producing units, the Wolfcamp A and B units in the Delaware Basin and Midland Basin.

TRR in the Texas portion of the Delaware Basin is 137,400 wells with 130,400 wells remaining to be drilled. Based on a drilling rate of 1,700 wells/yr (2018 – 2019 rates), it will require about 77 yr to drill the remaining wells and would total 82,500 acre-ft/yr (2020 – 2096). TRR in the Midland Basin is slightly lower, 120,300 wells with 108,800 wells remaining to be drilled. Based on a drilling rate of 2,400 wells/yr (2018 – 2019 rates) it will require about 45 yr to drill the remaining wells. Projected HF water use is 128,000 acre-ft/yr totaling 5.8 maf over the 45 yr remaining life of the play.

*Coal Mining Water Use*

Total water use in by the coal mining industry in Texas was about 4,200 acre-ft in 2019. Coal mining in Texas consists almost completely of low-grade lignite coal, and the industry has experienced a steep decline in recent years. Total coal production in Texas was 19.7 million tons in 2020, about 37% of peak production in the 1990's (about 54 million tons/yr). As of January 2021, there were only four operating coal mines in Texas and one of those is scheduled to close in late 2023.

Water is pumped by the Texas coal mining industry primarily for two purposes, including dewatering and depressurizing and most, if not all of the water, is either pumped back into the ground at another location or is discharged to a convenient surface water body if available.

Water use for coal mining was quantified based on water use survey data and represents the least water use among all sectors examined in this study. Assuming the four remaining coal mine operations continue to operate as planned or until their associated power plant boiler life span is achieved, future water use by the Texas coal mining industry is predicted to be about 4,000 acre-ft/yr through 2040, declining to 1,000 acre-ft/year afterwards through 2060, and zero beyond.

*Aggregate Mining Industry Water Use*

Water use by the aggregate mining industry in Texas was about 74,800 acre-ft in 2019. The data for this study were based on survey responses of individual operators to the Texas Water Development Board (TWDB) and the Texas Commission on Environmental Quality (TCEQ). There were approximately 1,300 registered aggregate operations in the dataset, though not all are currently active and many have closed. Approximately 400 operators had reported or estimated water use in this study. Water use is mostly for sand and gravel mining (64%) followed by crushed stone production (36%). Most of the water used is groundwater (79%), followed by surface water (19%) and reuse water (2%). Most operations use no water in their processes while an unknown number of operators use rainwater that is collected on-site.

Most aggregate operations are located near the major population centers to support demand by the construction industry and also in the Permian Basin for the mining of sand used as a proppant for HF. Future water use by the aggregate industry is expected to grow in proportion to population growth, increasing at annual rates varying between 0.8% and 1.2% and increasing to about 128,000 acre-ft by 2080.

# Introduction

Recent water use by the mining industry in Texas was analyzed and is discussed in this report, covering the period from 2010 through 2019. This report also includes estimates of projected water use for 2020 through 2080 for long-term planning purposes. This report relied on data provided by the Texas Water Development Board (TWDB), the Texas Commission on Environmental Quality (TCEQ), the Railroad Commission of Texas (RRC), the United States Geological Survey (USGS), and FracFocus and additionally includes data provided indirectly from the RRC by Information Handling Services (IHS, https://ihsmarkit.com/) and B3 Insight (https://www.b3insight.com/). The various analyses in this report rely on archived data representing different time periods, beginning as early as 1992 and as recently as 2021. The data sets used for this report were provided by the different entities in late 2021 and early 2022.

Most of the source databases have on-going data collection and update activity and are therefore subject to future modification. However, the data used are considered to be generally stable and comprehensive for the requirements of this report. We do not expect that future changes, updates, or other modifications to the source databases will significantly impact the results of this report or future integration of data into the U.S. Geological Survey (USGS) databases. The only significant problem encountered during this study was a lack of oil and gas industry response to requests for data pertaining to water sources, including the amounts of produced water reuse and amounts and sources of water used for HF purposes (i.e. aquifer or surface water body sources).

The study will address Tier 1 USGS data goals by providing annual water use estimates by county, source of water, and water type. The study will also address Tier 2 data goals by verifying specific locations for mining operations in each sub-category. This information is critical to support state and local officials in their decisions regarding future water supplies, including stakeholders engaged in the regional water planning and groundwater management area joint planning processes. It will also support water modeling efforts, including the development of groundwater availability models. This project also addresses the U.S. Department of the Interior priority to avoid future water conflicts by providing current water use data and long- range water demand projections to local, regional, and state planning efforts, including the regional water planning and groundwater joint planning processes, which are the state's most consequential venues where stakeholders convene to address competing water supply concerns.

There are four main sections in this report. The first three sections discuss the three major mining sectors, including the oil and gas industry, coal mining, and aggregates mining, with methods, data sources, and results in each section.

The oil and gas industry water use analysis is based on information reported by the industry to the RRC of Texas and organized in a proprietary database maintained by IHS, a fee subscription service that collects and organizes data from the RRC, and FracFocus (https://fracfocus.org/). The FracFocus database only includes data on water use for HF and related water chemistry whereas the IHS database includes additional data on well characteristics (depth, length, etc.), produced water volumes from wells. Volumes of water that are injected back into the subsurface, either as saltwater disposal (SWD) or for EOR purposes, were obtained from B3 Insight, another fee subscription service that collects such data reported to the RRC by industry. The O&G sector currently represents about 80% of all mining water use in Texas.

Analyses of water use by the coal and aggregate mining sectors were based on information reported by industry operators to the TWDB and the TCEQ through annual survey reports. The aggregate industry sector currently accounts for about 19% and the coal mining sector for about 1% of mining water use in Texas.

The last section of this report summarizes current use for the combined analyses of all three sectors examined. Tabulated data, which are extensive in some instances, are included in separate appendices for each section.

## Existing water use data collection in Texas

Historical water use data serve as the basis for demand projections used in developing regional water plans, which are incorporated into the State Water Plan in Texas. The TWDB began collecting water use surveys in 1955. Since 1984, the TWDB has annually summarized survey data and estimated pumpage and since September 1, 2001, the Texas Water Code (Section 16.012(m)) and Texas Administrative Code (31 TAC §358.5) has required any entity that receives the survey to complete it and return the information to the TWDB due by March 1st every year. TWDB staff compile the information received from approximately 7,000 annual surveys from municipal and industrial entities and estimate water use for irrigation, livestock, mining, and rural domestic purposes to generate historical water use estimates which the TWDB uses for water resources planning. Community public water systems report their water intake volumes by water source (surface water, groundwater, reuse), sales, population served, and retail water volumes and connection by retail water use type (single and multi-family, commercial, institutional, industrial, agricultural and reuse) via the water use survey online application. Industrial facilities also report their intake by water source, sales, and other pertinent industry information.

For retail public water suppliers that have an active financial obligation with the TWDB or have more than 3,300 retail connections, a Water Loss Audit must also be submitted annually to the TWDB. Finally, if an entity has a financial obligation with the agency greater than $500,000, has more than 3,300 retail connections, or has a surface water right with the Texas Commission on Environmental Quality (TCEQ), a water conservation plan must be on file and a Conservation Annual Report must also be submitted each year that any of these conditions is true.

In 2013, the 83rd Texas Legislature appropriated funds to the TWDB to streamline online data collection for the agency's water planning and conservation programs. The Loss, Use, and Conservation (LUC) online reporting application eliminates redundant data entry for the Water Use Survey, the Water Loss Audit, the Conservation Annual Report, and the Utility Profile. The application also provides the opportunity for entities to upload their water conservation plans digitally. Use of this reporting application improves the data collection process and the quality and consistency of those data.

While the TWDB is the primary agency to report water use data to the USGS, they are not the only agency collecting water use data within Texas. The Texas Water Code requires all water rights holders to report their water use to the TCEQ. In areas without a Watermaster, water rights holders self-report their annual water use to the TCEQ, including the amounts of water used in each month by water use type. For Watermaster areas, diversion data is reported to the Watermaster on a real-time basis. In Texas, Groundwater Conservation Districts (GCDs) are the preferred entities for groundwater management. The GCDs collect water use data, but the type and level of detail varies greatly from district to district.

# 1. Oil and Gas Industry Water Use

## 1.1 Overview

Oil and gas (O&G) reservoirs can be broadly categorized based on geological materials and fluid flow characteristics. Conventional reservoirs generally consist of coarse-grained materials (gravels and sands) having relatively high permeability compared to unconventional reservoirs that generally consist of fine-grained materials (tight sands and shales) with relatively low permeability. Producing formations in a given region, either singly or collectively, are often referred to as a "play" and more broadly, plays are typically associated with a geologic "basin" representing a larger, more regional depositional environment.

Oil and gas wells can be categorized similarly. Conventional O&G wells are those that are oriented vertically or near-vertically, produce from conventional or unconventional reservoirs, are completed with limited or no HF or "stimulation" using smaller water volumes, and generally produce from relatively thin vertical intervals (less than about 100 ft thick). For the purposes of this report, a threshold water use for well completion of 0.4 million gallons of water is used to distinguish conventional O&G wells (≤0.4 million gallons of water) from unconventional wells (>0.4 million gallons of water). Wells classified as "directional" also fall into this category. Conventional O&G wells are predominantly completed in conventional reservoirs.

Unconventional O&G wells are predominantly completed in unconventional reservoirs using large HF water volumes (>0.4 million gallons per well). The primary use of water for unconventional wells is for HF with relatively small volumes for drilling fluids. In practice, the majority of recently completed unconventional wells have HF volumes of about 8-40 million gallons per well and produce from unconventional reservoirs over relatively long horizontal or "lateral" lengths (5,000-10,000 ft). Unconventional wells predominantly have horizontal sections, though some have vertical or directional orientations.

Water use by the oil and gas industry in Texas falls broadly into two categories:

1) Water used for drilling and HF operations during oil and gas well completions and
2) Recycling of produced water from oil and gas wells for EOR.

Hydraulic fracturing is the practice of injecting water mixed with proppant and various other ingredients (biocides, surfactants, gels, acids, scale inhibitors, etc.) using pressures sufficient to fracture the reservoir formation materials in the immediate vicinity of an oil or gas well borehole in order to increase permeability and production. Proppant generally consists of sand that is suspended in the injected fluid stream that remains in the fractures to prop them open and maintain the flow path network near the well.

Hydraulic fracturing has been used historically in the oil and gas industry since at least the 1950's, though originally on a limited scale over relatively short depth intervals in vertically-oriented wells. These conventional wells used relatively small amounts of water for drilling and completion, generally on the order of 0.4 million gallons or less. Beginning in the early 2000's, oil and gas operators in Texas began experimenting with horizontal drilling techniques in the Barnett Shale and in the Permian Basin (Nicot et al., 2012). Compared to vertical wells, horizontal wells allow for very long exposure lengths of the wellbore within a targeted producing formation. With the additional application of HF at points along the wellbore length, the surface area of the formation and therefore production is significantly increased in the vicinity of the wellbore. Analysis of HF water use data from this study in the Permian Basin between 2018 and 2021 for example was very large compared to conventionally completed wells, with a median value of 17 million gallons (50 acre-ft) and a $10^{th}$ to $90^{th}$ percentile range of 8 to 26 million gallons (25-80 acre-ft) per well.

Together, horizontal drilling and HF ushered in a "fracking revolution" allowing the industry to exploit oil and gas formations that were previously not economical to produce, including shales and tight sands. These techniques can also result in increased production from conventional porous media formations and depleted conventional reservoirs. This study focuses on HF water use in the major shale and tight oil/gas plays in Texas including the Barnett, Eagle Ford, Haynesville, and Permian Basin plays.

The Barnett Shale in the Fort Worth Basin was extensively drilled during the period from 2005 through about 2014, peaking in 2008 (Browning et al., 2013). There was very limited drilling of new wells in the Barnet between 2015 and 2020. Through 2020, a total of about 15,100 wells had been completed in the play and production is almost completely natural gas.

Drilling in the Eagle Ford Play in the Upper Gulf Coast region began in earnest in 2010 and continues to date, though activity peaked in 2014 (Ikonnikova et al., 2017; Scanlon et al., 2014). The Eagle Ford Shale is the primary producing formation in the play, accounting for 97% of completed wells, with relatively fewer wells in the Austin Chalk (3%). Through 2020, a total of about 21,400 unconventional O&G wells had been completed in the play. Production is mixed, with crude oil in the up-dip regions grading down-dip to progressively more gas-rich production.

The Haynesville Shale Play is located in east Texas and northwest Louisiana, with the richest areas of the play located in Louisiana (Browning et al., 2015). Drilling activity began in 2008 and continued at a moderate rate to the present. Through 2020, a total of about 4,400 horizontal O&G wells had been completed in the play, with about 1,350 wells (30%) completed in Texas. Production is almost exclusively dry natural gas.

The Permian Basin is located in western Texas and southeastern New Mexico (Gaswirth et al., 2016, 2018; Ruppel, 2019; 2020). Drilling activity in the basin began in the early 1900's, though drilling of horizontal O&G wells with HF began in about 2005. From 2005 through 2020, a total of about 29,600 horizontal wells were completed in the Permian Basin, including about 22,600 wells (76.4%) in Texas. Most of the horizontal wells in Texas were completed in the Delaware Basin (about 8,000 wells, 35.4%) and Midland Basin (about 12,900 wells, 57.2%) with the remaining wells (about 1,700 wells, 7.4%) completed in other subregions of the Permian.

The Delaware Basin lies in both Texas and New Mexico while the Midland Basin is entirely in Texas. Several unconventional formations have been targeted using horizontal wells with HF, including the Bone Spring and Wolfcamp A and B formations in the Delaware Basin and the Spraberry, Dean, Clear Fork, and Wolfcamp A and B formations in the Midland Basin (Gaswirth et al., 2016, 2018; Ruppel, 2019, 2020). Horizontal wells in other subregions are completed in the same formations plus many others, including conventional reservoirs. Production from the Permian Basin is primarily crude oil with some co-produced natural gas.

Produced water represents water that is coproduced with oil and gas. PW could be considered both a resource and a waste product. For conventionally completed vertical oil and gas wells, most of the PW is injected back into the producing reservoirs to maintain pressures and also for secondary or tertiary recovery (Enhanced Oil Recovery, EOR) operations. The PW that is not needed for EOR operations, which represents a smaller overall volume, is disposed of in Saltwater Disposal (SWD) wells. SWD wells are used to inject produced water into either a producing or non-producing formation.

Produced water from wells completed in unconventional formations, such as shales and tight sands, cannot be reinjected back into the producing formation. This represents essentially all of the water produced by horizontal wells completed in shales and tight sands and such PW must be injected into an SWD well completed in a suitable formation stratigraphically above or below the producing formation. PW may also be used as a base fluid for the hydraulically fracturing of new wells.

## 1.2 Data Sources for Hydraulic Fracturing and Produced Water volumes

The primary data source for both HF water use and PW volumes for this study is the Information Handling Services (IHS) Enerdeq Database (https://my.ihs.com/Energy?errmsg=sessionInvalid), which holds comprehensive information related to the oil and gas production industry. IHS is a privately held company that provides subscription fee information services. The Bureau of Economic Geology has been provided free access to the database. IHS data for Texas oil and gas wells originate from Railroad Commission (RRC) of Texas records. HF water use values are reported directly by individual operators. PW volumes are not reported but are estimated by IHS using periodic well-specific production test results reported by the operators coupled with a proprietary method of estimating monthly produced water volumes between tests.

Since about 2012, oil and gas operators nationally have been legally required to report information regarding activity to FracFocus (https://fracfocus.org/) which is the national hydraulic fracturing chemical registry. FracFocus is managed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission and archives HF fluids data including water use, proppants, and additive chemicals. The IHS database incorporates much of the FracFocus water use information on a well-by-well basis.

The TWDB has not historically included injection of produced water from oil and gas wells as a water use. However, the United States Geological Survey (USGS) does characterize certain injection of oil and gas industry produced water volumes as a water use. Therefore, for comparison, we also tabulated data relating to the injection of fluids generated by the oil and gas industry. Such injection is regulated by the RRC and occurs using Class II injection wells as classified by the Underground Injection Control (UIC) program. Data relating to water injection wells in Texas are collected and archived by the RRC, which further classifies oil and gas injection wells into three general categories:

1) Injection into a non-producing zone
2) Injection into a producing zone
3) Injection for secondary or tertiary recovery

The first two categories combined constitute SWD while the third by itself represents EOR injection. SWD and EOR are both measured and monthly total volumes are reported annually by individual operators to the RRC. While IHS archives information on injection wells, we used a data subscription service company (B3 Insight, https://www.b3insight.com/) to provide injection data for this study because it is their primary product and they are more thorough and accurate in collecting and characterizing injection data.

## 1.3 Analytical Methods

### Hydraulic Fracturing and Produced Water Volumes

We aggregated annual HF water use and PW volumes for 2019 at both the county and play (multi-county) spatial resolutions. We also included SWD and EOR volumes for comparison with HF water volumes. The total combined SWD and EOR volumes should generally be similar to, but greater than, the total estimated PW volumes because some of the injected fluids do not originate as PW. We also tabulated historical annual total HF and PW volumes at both the county and play levels for the period 2010-2019.

At the play level, we compared the 2019 HF water use volumes in this study based on the (non-public) IHS database with those of an independent analysis by the TWDB based on the (public) FracFocus database. Finally, we also compared results for 2015 from this study with values published by both the TWDB (TWDB, 2022) and the USGS (USGS, 2018).

The USGS reports fresh water use data provided to them by TWDB that includes water use primarily by the oil and gas, coal mining, and aggregates industries. EOR is not considered as a water use *per se* as it does not originate from near-surface fresh or brackish water sources. EOR is a closed-loop system with virtually no net gain or loss of water. EOR is the recycling of PW that is separated from the production stream (consisting of oil, gas, and PW) and reinjected into the producing formation in near real-time for the purpose of maintaining reservoir pressures and for water flooding operations. Neither the TWDB nor the USGS consider EOR as a water use; however, the USGS mistakenly incorporated EOR in their 2015 estimates of mining industry water use. Injection volume data for 2015 were provided to them by the RRC that inadvertently included both the EOR and SWD components of Class II injection, which the USGS subsequently published as saline mining water use reflecting the quality of produced water. A revised report of the USGS data is forthcoming.

### Hydraulic Fracturing Water Sources

We analyzed the FracFocus database for indications of sources and quality of water used in unconventional oil and gas well completions, particularly seeking information regarding the use or recycling of PW or other water sources. We also worked with Texas Oil and Gas Association (TXOGA) to obtain estimates of produced water use for HF; however, operators do not record these data and were unable to provide estimates for this report of produced water use for HF. The FracFocus data tables were screened for entries pertaining to base or carrier fluid water volumes as defined by the "Purpose" attribute to exclude the water volumes of additive ingredients (i.e., acids, surfactants, etc.). The attributes "Trade Name" and "Ingredient Name", were next methodically searched for occurrences of relevant terms that might indicate the source and/or nature of the base/carrier water, including "water", "fresh", "produced", and "brine".

### Hydraulic Fracturing Water Quality

*General play groundwater quality*

This report finds that groundwater currently represents 89% of water use by the oil and gas industry in Texas, based on water sources available in the major plays, previous communications with operators (Nicot et al., 2011; 2012) including anecdotal information. We characterized overall groundwater quality using data in the TWDB groundwater database for the named major and minor aquifers of Texas focusing on the major unconventional play areas, including the Barnett, Eagle Ford, Haynesville, and Permian. We summarized water quality at the aquifer level aggregated across the counties in each play area as defined by the TWDB. We focused only on major water quality parameters, including cations (calcium, magnesium, sodium, and potassium), anions (carbonate, bicarbonate, chloride, and sulfate), other selected analytes (silica, fluoride, and nitrate), and total dissolved solids (TDS). We used the most recent charge-balance analysis for each well and excluded wells completed in multiple aquifers. We report the numbers of samples, mean concentrations, and selected percentile concentrations by play area by aquifer.

*Estimated water quality for oil and gas industry groundwater wells*

We estimated county-level percentages or splits of fresh and brackish HF water use based on groundwater well reports in the Texas Department of Licensing and Regulation (TDLR) Submitted Drillers Reports (SDR) database hosted by the TWDB. Fresh water in this study is defined as having a TDS concentration of ≤1,000 mg/L and brackish water as having TDS > 1,000 mg/L. We focused on county areas with HF activity and included SDR wells having a stated use of either "fracking supply", "rig supply", or "industrial".

The SDR database does not contain direct information on the producing aquifer for a given well. We assigned aquifers to each well based on their reported well locations and total depths using geologic formation elevation raster files in the TWDB Groundwater Availability Models (GAMs) and the TCEQ Source Water Availability Program (SWAP) database.

Water quality was estimated using kriged and rasterized aquifer water quality maps generated by Reedy et al. (2011). The maps were generated using indicator kriging methods and represent the spatially distributed probability of TDS exceeding 1,000 mg/L based on water quality samples in the TWDB groundwater database. The exceedance probability at any given location can range from 0% to 100% and values were assigned to each well based on the aquifer-specific water quality raster value at the well location.

The Permian and Rustler aquifers in the Permian Basin did not have TDS probability maps. These are saline aquifers and a probability of 100% brackish water was assigned to all wells completed in each of these aquifers. A probability of exceedance map was generated for this project for the Cross Timbers aquifer, which also was not included in the 2011 study (Reedy et al., 2011). A small number of wells was located in regions outside designated aquifer boundaries located primarily in down-dip regions on the Carrizo-Wilcox, Dockum, and Yegua-Jackson aquifers. Wells in these areas were assigned estimated exceedance probabilities based on local conditions.

The weighted average exceedance probability of all the wells completed in a given county/aquifer was used to represent the estimated percentage of brackish water use. Accordingly, this study inherently assumes that the well populations in each county/aquifer area are representative of the overall water quality pumped for that purpose, i.e., that each well contributes more-or-less equally to the net total water use from a given aquifer in a given county. In counties with well populations across multiple aquifers, an overall county exceedance probability was estimated as the average probability weighted by the numbers of wells in each aquifer.

## Hydraulic Fracturing Water Use Projections

Estimates of annual HF water use are based on Total Recoverable Resources (TRR) analyses of oil and gas reservoirs for three of the major plays in Texas, including the Eagle Ford, Haynesville, and Permian Basin (Gaswirth et al., 2016, 2018; Scanlon et al., 2020). Technically recoverable reserves include *proved reserves* and *unproved resources*. Proved reserves of crude oil and natural gas are the estimated volumes expected to be produced, with reasonable certainty, under existing economic and operating conditions. Unproved resources of crude oil and natural gas are additional volumes estimated to be technically recoverable without consideration of economics or operating conditions, based on the application of current technology. Projections based on TRRs assumes that all potential wells will be drilled using recent spacing and well length data (Scanlon et al., 2020). Production outlooks have been developed for some plays considering economic constraints (Ikonnikova et al., 2017). Recent large variations in oil and gas prices make it challenging to develop production outlooks for the plays. Therefore, we relied on TRRs to develop projections, which may overestimate future production. We focused on only two (Wolfcamp A and B) of potentially 10 producing horizons in the Permian Basin because these have been the main producing horizons to date. Therefore, overestimation of future production using TRRs may be compensated by not considering the other 8 producing horizons.

The fourth major play in Texas, the Barnett, has had little recent drilling activity, averaging only 48 wells play-wide per year after 2015, and is generally considered to be near maturity. HF water use projections in the Barnett are based on the extension of current trends.

This study focuses on unconventional horizontal wells, herein defined as 1) wells with at least 50% of their perforated (producing) intervals located in sections of the well that are horizontal (i.e., within 2.5 degrees of the horizontal plane) and 2) wells that consumed at least 400,000 gallons of water or at least 400,000 pounds of proppant during well stimulation and completion based on previous experience (Scanlon et al., 2020). As such, the term unconventional in this context refers to well completion practices and not strictly to reservoir characteristics, though most horizontal wells are completed in “unconventional” reservoirs (i.e., shales and other tight formations).

Estimates of projected future HF water use rely on:

1) The number of unconventional horizontal wells to be drilled (total well inventory),
2) The volume of water required for HF per well, and
3) The numbers of wells to be drilled each year.

Estimates of (1) are based on the TRR modeling (Scanlon et al., 2020). The modeling approach first divides the total play area into approximate square-mile blocks. Estimates of TRR are made for each block based on the local geologic, structural, and reservoir characteristics. The block-by-block TRR analysis dictates a horizontal well lateral spacing (well density) and a total well inventory for each block. For formations in the Permian Basin having thickness greater than approximately 300 ft, a vertical well spacing, or “stacking” component was also incorporated. Total well inventories are then calculated as the sum of the block-by-block inventories in each county.

Estimates of HF water volumes (2) required several steps. Total HF water use in a given area is based on the lengths of wells drilled and the HF water use intensity (gal/ft). In general, the numbers of wells drilled annually and their median lengths both vary through time. However, water use intensity has generally displayed a pattern of year-over-year increases during initial development phases that tend to reach a plateau or semi-steady-state value as HF techniques become more standardized and mature. Mean well lengths per county were calculated by dividing total well lengths by the total well inventory. Median HF water use intensities (gal/ft) in each county were calculated based on multi-year trends of recently completed wells in each county, variously between 2017 and 2021. The mean HF water use (gal/well) was estimated as the product of the total well lengths times the median HF water use intensity in each county.

Estimates of projected annual numbers of wells (3) across each play reflect recent play-specific trends and are approximate averages of multi-year periods generally between 2017 and 2021. The total remaining number of wells was calculated for each county as the total well inventory based on TRR minus the cumulative number of wells completed through 2019. Each county was then assigned a percentage value of the remaining well inventory for that county relative to the total remaining well inventory across the play. The projected annual number of wells to be drilled in each county in each year was then calculated as the product of the percentage value and the estimated total annual number of wells across the play. Therefore, wells are projected to be completed at a constant pace commensurate with the proportion of such wells for a given county.

The projected mean annual total HF water use by county was estimated as the product of the mean HF water use (gal/well) values times the number of wells to be drilled in each year.

## Oil and Gas Industry Water Use Projections

Hydraulic fracturing water use accounts for most but not all of the water used by the oil and gas industry. The HF water use projections were estimated only for the 58 counties located in the core areas of the unconventional shale and tight oil plays. Other water uses include drilling, work-overs, and completions of “conventional” wells. Many of the counties outside the major plays in Texas have some oil and gas activity that will continue into the future, albeit at relatively smaller volumes compared to the play core areas. Therefore, we include estimates for the 196 counties outside the play core areas as well as for continued “conventional” uses in the 58 core counties.

Estimates of “conventional” water use for the non-core counties in Texas are based on the 2010-2019 maximum annual HF water use and we assume those volumes will continue into the future. The maximum annual HF water use represents a conservative estimate for planning purposes. Conventional water use estimates that were determined in this manner that were less than 325,851 gallons (1 acre-ft) were not included in the final results. For counties located in play core areas, excluding the Barnett, we also used the 2010-2019 maximum conventional water use volumes as estimates of future conventional use in those counties and added them to the unconventional HF water use volumes estimated by the TRR approach described above. For the Barnett core counties, we used the 2016-2020 mean conventional water use values.

## 1.4 Results

Hydraulic Fracturing and Produced Water Volumes

Counties were aggregated to reflect the regional distribution of various oil and gas plays as defined by the TWDB (Figure 1-1). Some of the play areas are discontinuous while some include regions with little or no oil and gas activity.

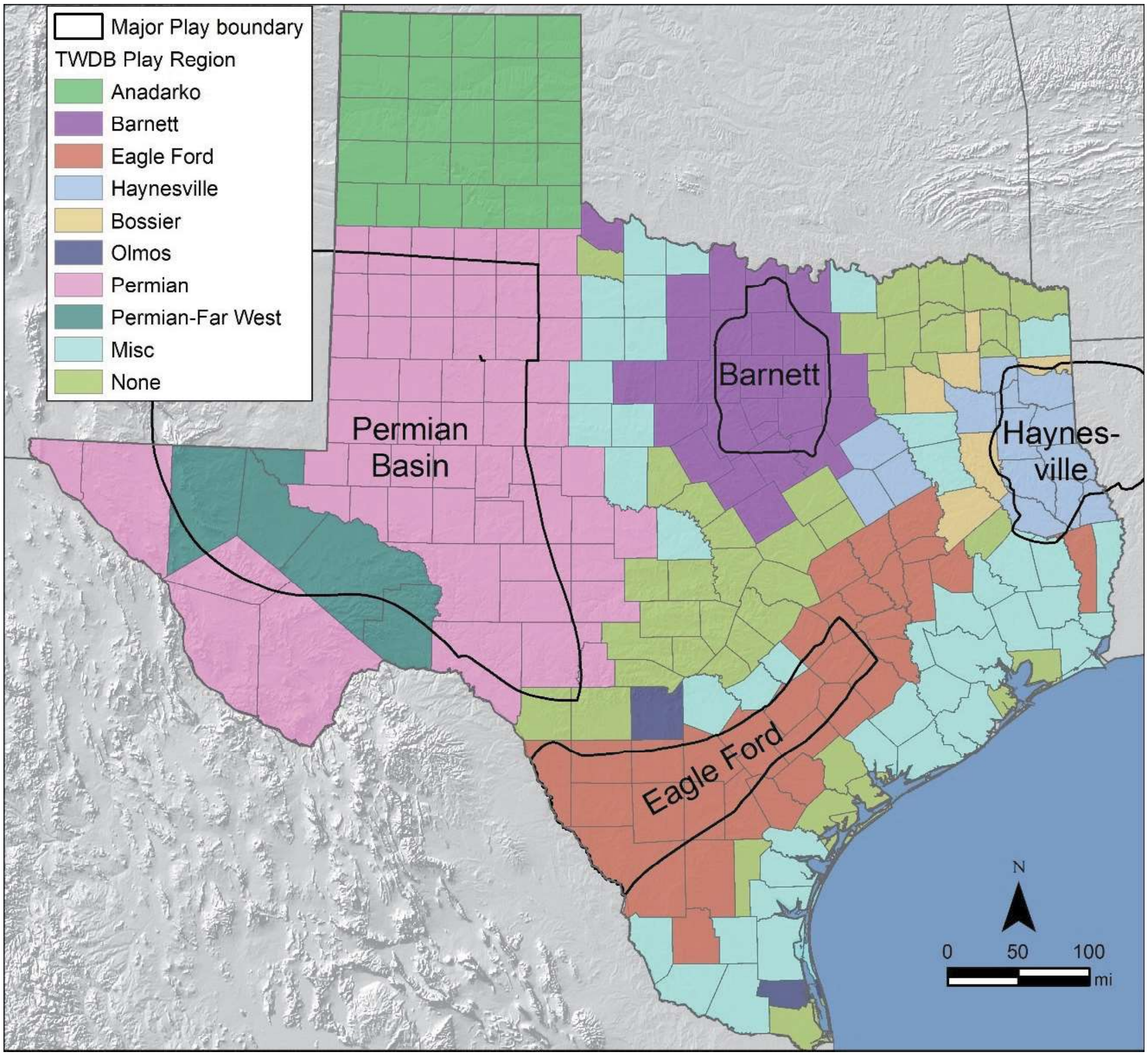


Figure 1-1. Texas counties and associated oil and gas play regions. The four major Texas plays are outlined and labeled. The generalized play regions defined by the TWDB are shown in different colors.

Total 2019 volumes for HF, PW, SWD, and EOR are shown by county in Table 1-1a and by play in Table 1-1b. About 11,300 unconventional oil and gas wells were completed in 2019 using 320,000 acre-ft of HF water. Most of the HF water use (69%) occurred in the Permian Basin (Permian and Permian-Far West regions), followed by the Eagle Ford (27%) and the Haynesville (3%), with the remainder (1%) in all other regions combined (Figure 1-2). HF water use in 2019 represents 2.3% of total water use in the state (14.1 maf) (TWDB, 2021-1). Estimated produced water volumes totaled 1,134,000 acre-ft across the state, slightly less than and in very good agreement with the total Class II injection volume (EOR + SWD) of 1,160,000 acre-ft, representing only a 2.4% difference. Volumes of PW are equivalent to 8% of total water use in the state in 2019. However, the comparison between PW and injection volumes varies at the county and play levels, likely reflecting movement of PW and injection water across county and play boundaries. Statewide, SWD accounts for 63% of all UIC Class II injection and EOR for 37%. Most of the statewide EOR (82%) occurs in the Permian Basin.

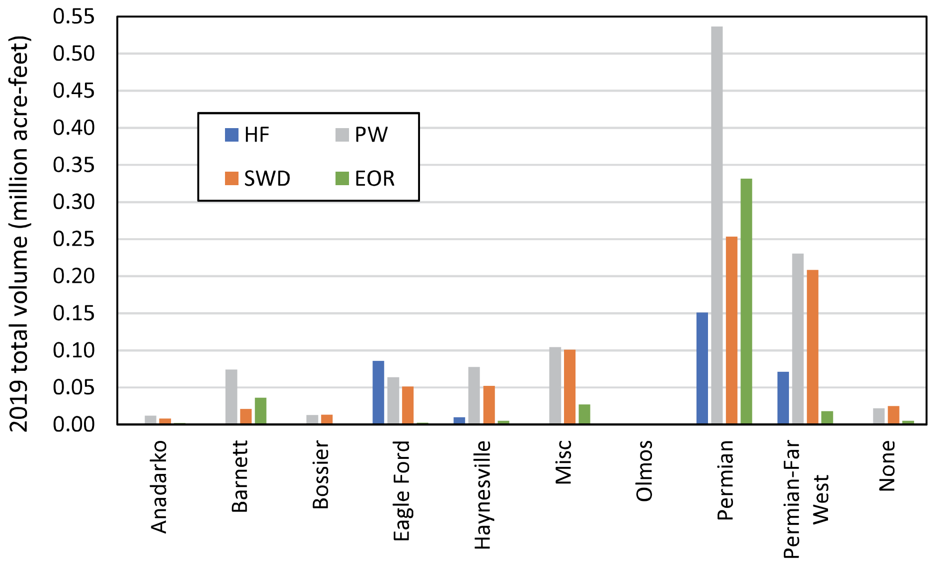


Figure 1-2. Total 2019 volumes of hydraulic fracturing use (HF), produced water (PW), saltwater disposal (SWD) and enhanced oil recovery (EOR) in the play regions of Texas (Figure 1-1).

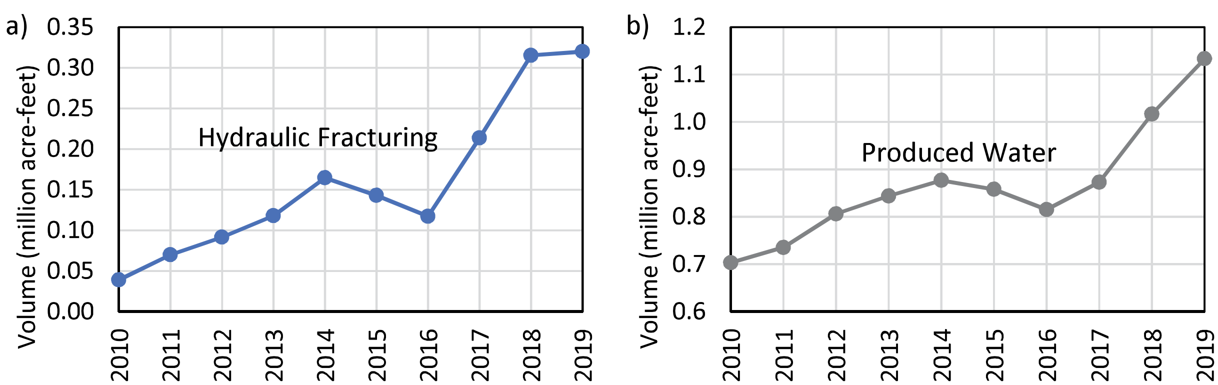


Figure 1-3. Time series of a) hydraulic fracturing water use and b) produced water volumes in Texas for 2010-2019.

Statewide, HF water use increased by a factor of about 8 times between 2010 and 2019 as listed by county (Table 1-2a) and by play (Table 1-2b) (Figure 1-3a). HF water use increased steadily by a factor of four from 39,000 acre-ft to 165,000 acre-ft between 2010 and 2014 primarily reflecting increasing drilling activity in both the Permian Basin and the Eagle Ford Play. Volumes then decreased steadily to 117,000 acre-ft by 2016 reflecting a decline in new drilling in the Eagle Ford Play. Afterwards, volumes increase by a factor of two to 315,000 acre-ft by 2018 reflecting greatly increased drilling activity in the Permian Basin. Total HF water use increased slightly in 2019 to 320,000 acre-ft. A total of 1,592,000 acre-ft was used for HF between 2010 and 2019 in Texas. Most occurred in the Permian Basin (53%) and the Eagle Ford (34%), with relatively less in the Barnett (6%) and the Haynesville (3%).

Produced water volumes exhibited a similar overall pattern as shown by county (Table 1-3a) and by play (Tables 1-3b) (Figure 1-3b). PW volumes steadily increased by 25% from 703,000 acre-ft to 877,000 acre-ft between 2010 and 2014 followed by a decline of 7% to 815,000 acre-ft by 2016 and a rapid increase of 39% by 2019 to 1,134,000 acre-ft. Total PW was 8,660,000 acre-ft between 2010 and 2019 in Texas. Most occurred in the Permian Basin (60%) and the Barnett (10%), with relatively less in the Haynesville (6%) and the Eagle Ford (5%), and the remainder (18%) from all other regions combined.

The results from this study are comparable with those previously published by both the USGS and the TWDB for 2015 at the county level (Table 1-4a) and the play and state level (Table 1-4b, Figure 1-4a). The USGS obtains their mining water use data in part from the TWDB and categorizes water use as fresh water use in the USGS report. The values for 2015 are therefore very similar as expected, with 147,000 acre-ft published by the USGS vs 141,000 acre-ft by the TWDB. A determination of total 2015 mining water use in Texas was not within the scope of the current study, which focuses on 2019. However, the 2015 value of total HF water use (143,000 acre-ft) from the current study is similar to the USGS and TWDB total mining estimates, indicating that both of those estimates, which additionally include estimates for the coal and aggregate mining sectors, may have been somewhat underestimated.

As noted earlier, the USGS erroneously included UIC Class II EOR injection for 2015 provided by the RRC to represent total saline mining water use in Texas for 2015. The USGS value of 1,125,000 acre-ft is virtually identical to the total 2015 Class II injection value from this study of 1,122,000 acre-ft, which includes both SWD and EOR (Table 1-4b, Figure 1-4b).

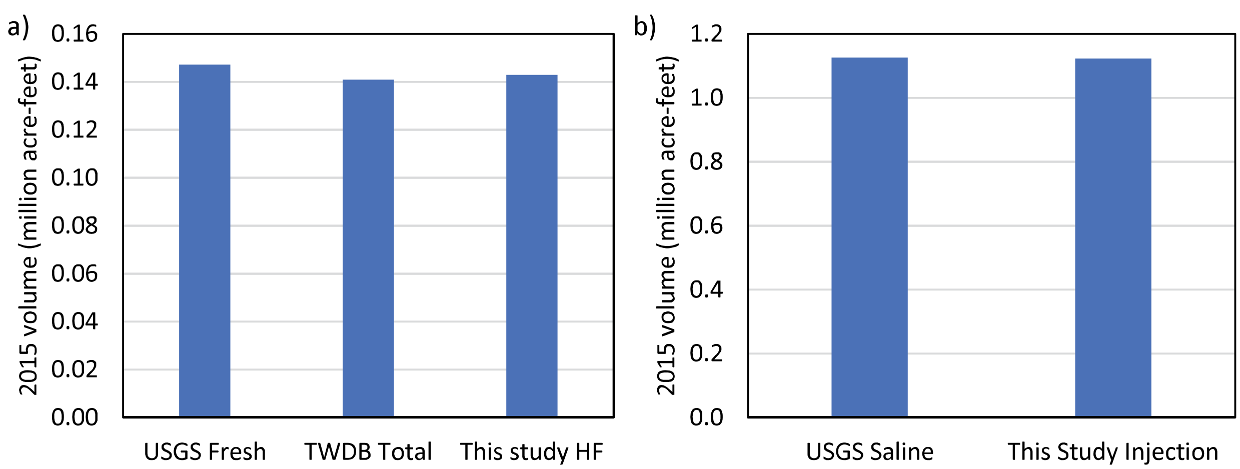


Figure 1-4. Comparisons between a) USGS fresh mining water use, TWDB total mining water use, and total HF water use from this study and b) USGS saline mining water use and total UIC Class II injection from this study, all 2015 total values for Texas.

## Hydraulic Fracturing Water Sources

The FracFocus database contained information for 7,601 wells completed in 124 Texas counties during 2019 (data downloaded Jan 4, 2022). Each well record usually contains multiple entries that characterize the ingredients used during the completion process. The attributes "Trade Name", "Purpose", and "Ingredient Name" were examined, and records were eliminated if they could not be identified as constituting some portion of the base or carrier fluid used in the completion. Many wells did not have an entry representing such fluid.

The analysis of FracFocus data did not produce significant useful information regarding the source and quality of HF water use in Texas. There were 6,445 wells that had some information pertaining to water type. On a mass-percentage basis, water typically accounts for ≥80% of the total mass of HF fluid used. Data for about 300 of the wells accounted for less than this amount and were discarded. Only 21 wells (0.3%) indicated the use of "produced water" and 19 wells (0.3%) indicated "recycled water". The largest number of remaining wells (4,603 wells, 71.4%) simply identified the base/carrier fluid as "water" with no qualifier. The second largest group of wells (1,432 wells, 22.2%) indicated "fresh water". The next group (323 wells, 5.0%) indicated "slickwater", which is not strictly the base/carrier fluid as it contains additives such as surfactants. Of the remaining wells, 47 wells (0.7%) indicated "Misc" or "Fluid".

The primary source of HF water is groundwater (Table 1-1c and Table 1-1d). Statewide, HF water use was about 89% groundwater (284,000 acre-ft), 10% reuse of produced water (33,000 acre-ft, entirely in the Permian Basin), and 1% surface water (3,000 acre-ft, entirely in the Haynesville Play). In the Barnett, there is very little current or projected drilling activity and future water use in that play is anticipated to be totally groundwater, with no surface water or reuse of produced water. Surface water in the Eagle Ford Play is very limited and future water use in that play is anticipated to be totally groundwater. Additionally, produced water volumes are small in the Eagle Ford and insufficient to provide the supply rates required to fulfill HF water demand. The Haynesville Play is located in east Texas where there is abundant surface water and shallow groundwater. Based on survey responses from a previous report (Nicot et al., 2011), surface water sources are estimated to meet 30% of HF water demand with the remaining 70% being groundwater with no produced water reuse. Generation of PW is low in the Haynesville Play because it is a gas play. The Permian Basin has virtually no surface water. Based on anecdotal information of somewhat increased PW reuse for HF relative to industry responses from a previous report (Nicot et al., 2011), PW reuse in the Permian Basin is estimated to represent 15% and groundwater to represent 85% of demand. In other regions, incidental water used is estimated to be 100% groundwater.

## Hydraulic Fracturing Water Quality

*General play groundwater quality*

Median water quality values for all play/aquifer combinations based the latest charge-balanced sample results for a given well during the period 1992-2018 from the TWDB groundwater database are given in Table 1-5. Overall, median water quality is least saline for aquifers in the Haynesville (TDS 120 – 600 mg/L), followed by the Eagle Ford (TDS 430 – 900 mg/L) and Barnett (550 – 950 mg/L) (Figure 1-5). Overall water quality is most saline in the Permian Basin (TDS 290 – 2,600 mg/L). Across all areas, median TDS exceeds 1,000 mg/L in only three aquifers, all located in the Permian Basin, including the Capitan Reef (1,440 mg/L), Pecos Valley (2,050 mg/L), and Rustler (2,600 mg/L). Comprehensive results by aquifer are given for the Barnett Play (Table 1-6), Eagle Ford Play (Table 1-7), the Haynesville Play (Table 1-8), and Permian Basin (Table 1-9).

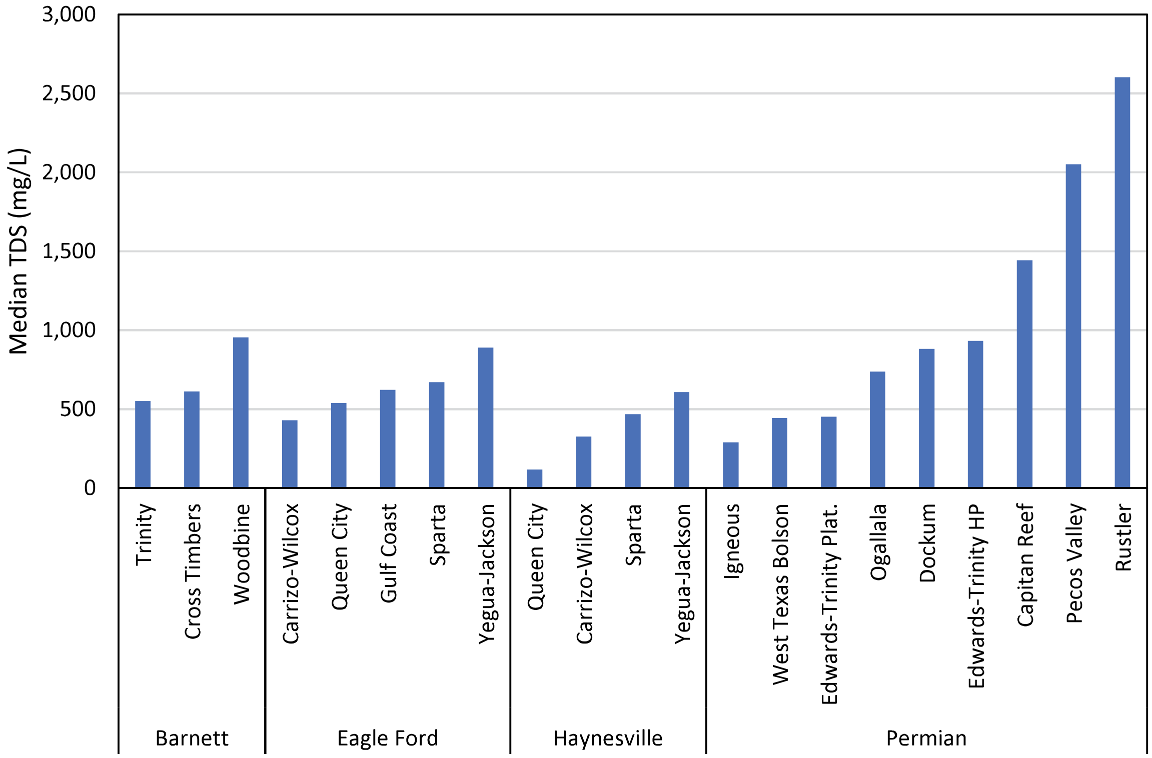


Figure 1-5. Median total dissolved solids (TDS) concentrations by aquifer in the major play regions of Texas using water quality samples from the TWDB groundwater database for the period 1992-2018

*Estimated water quality for oil and gas industry groundwater wells*

We estimated groundwater quality for the four major plays in Texas, including the Barnett, Eagle Ford, Haynesville, and separately for the Delaware and Midland basins in the Permian Basin, focusing only on counties with reported HF activity and on groundwater wells with stated uses of either “fracking supply”, “rig supply”, or “industrial”. Use of the term “fracking supply” was not available as a database attribute prior to about 2010. The results are reported by play.

*Barnett Play*

A total of 1,448 wells in the SDR database were completed in the Barnett Play region between 2002 and 2020 (Figure 1-6, Figure 1-7). Groundwater aquifer sources in the Barnett Play include the Trinity, Cross Timbers, and Woodbine aquifers. The Trinity is the major aquifer in the region and accounts for 96% of oil and gas industry groundwater well completions, with the remaining wells mostly in the Cross Timbers aquifer and a handful of wells in the Woodbine aquifer (Table 1-10a). Most of the wells (1,121; 78%) are classified as rig supply wells, with fewer classified as industrial (293, 20.4%) and fracking supply wells (20, 1.4%).

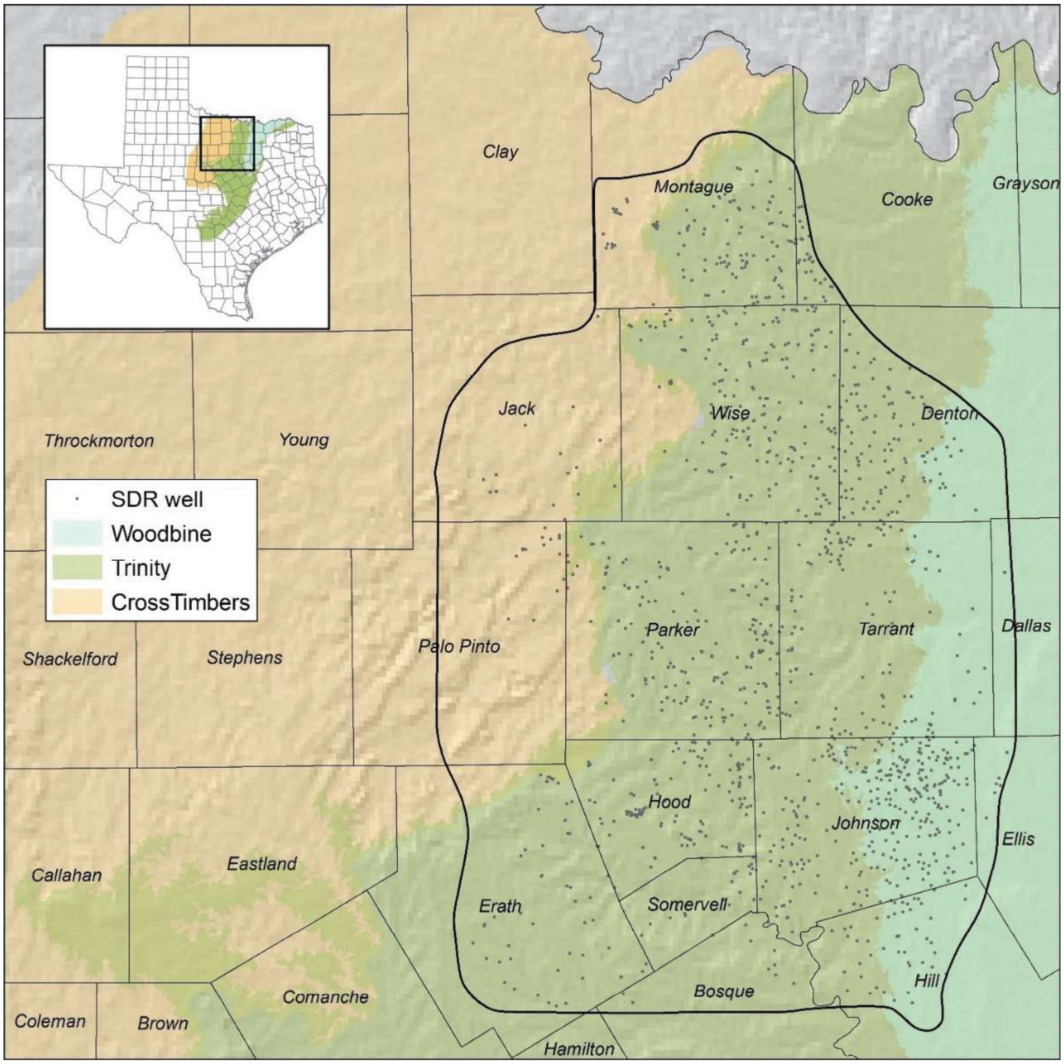


Figure 1-6. Barnett Play locations of oil and gas industry water supply wells completed between 2002 and 2020 from the SDR database. Aquifers are shown as shaded areas and younger aquifers locally overly older aquifers. The heavy solid line represents the approximate limits of drilling activity in the play.

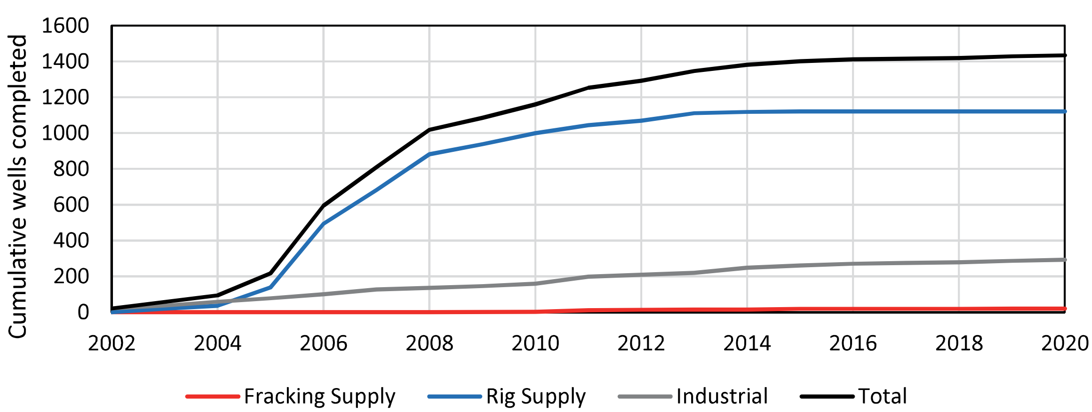


Figure 1-7. Barnett Play cumulative numbers of oil and gas industry water supply wells.

The area-weighted probability of groundwater exceeding the 1,000 mg/L TDS threshold is very low in the Trinity (7%), zero in the Cross Timbers, and moderate in the Woodbine (39%) (Figure 1-8, Table 1-11a). Overall, the groundwater splits average 93% fresh and 7% brackish in the Barnett Play and brackish probabilities range from 0 to 21% in different counties.

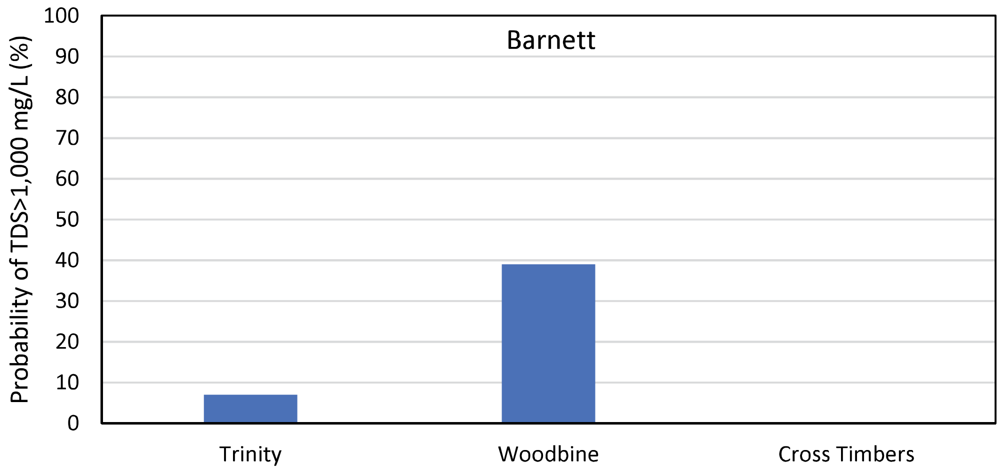


Figure 1-8. Barnett Play area-weighted probability of groundwater TDS greater than 1,000 mg/L by aquifer for oil and gas industry groundwater wells.

*Eagle Ford Play*

A total of 3,707 wells in the SDR database were completed in the Eagle Ford Play region between 2002 and 2020 (Figure 1-9, Figure 1-10). Groundwater aquifer sources for oil and gas industry wells in the Eagle Ford Play include the Carrizo-Wilcox, Gulf Coast, Queen City, and Yegua-Jackson aquifers. The Gulf Coast and the Carrizo-Wilcox aquifers are the major aquifers in the region, with the Gulf Coast aquifer accounting for 35% of wells and the Carrizo-Wilcox accounting for 32% (Table 1-10b). The remaining wells are mostly completed in the Yegua-Jackson aquifer (26%) and the least number of wells in the Queen City aquifer (7%). Most of the wells (2,287, 62%) are classified as rig supply wells, with fewer classified as industrial (847, 23%) and fracking supply wells (572, 15%).

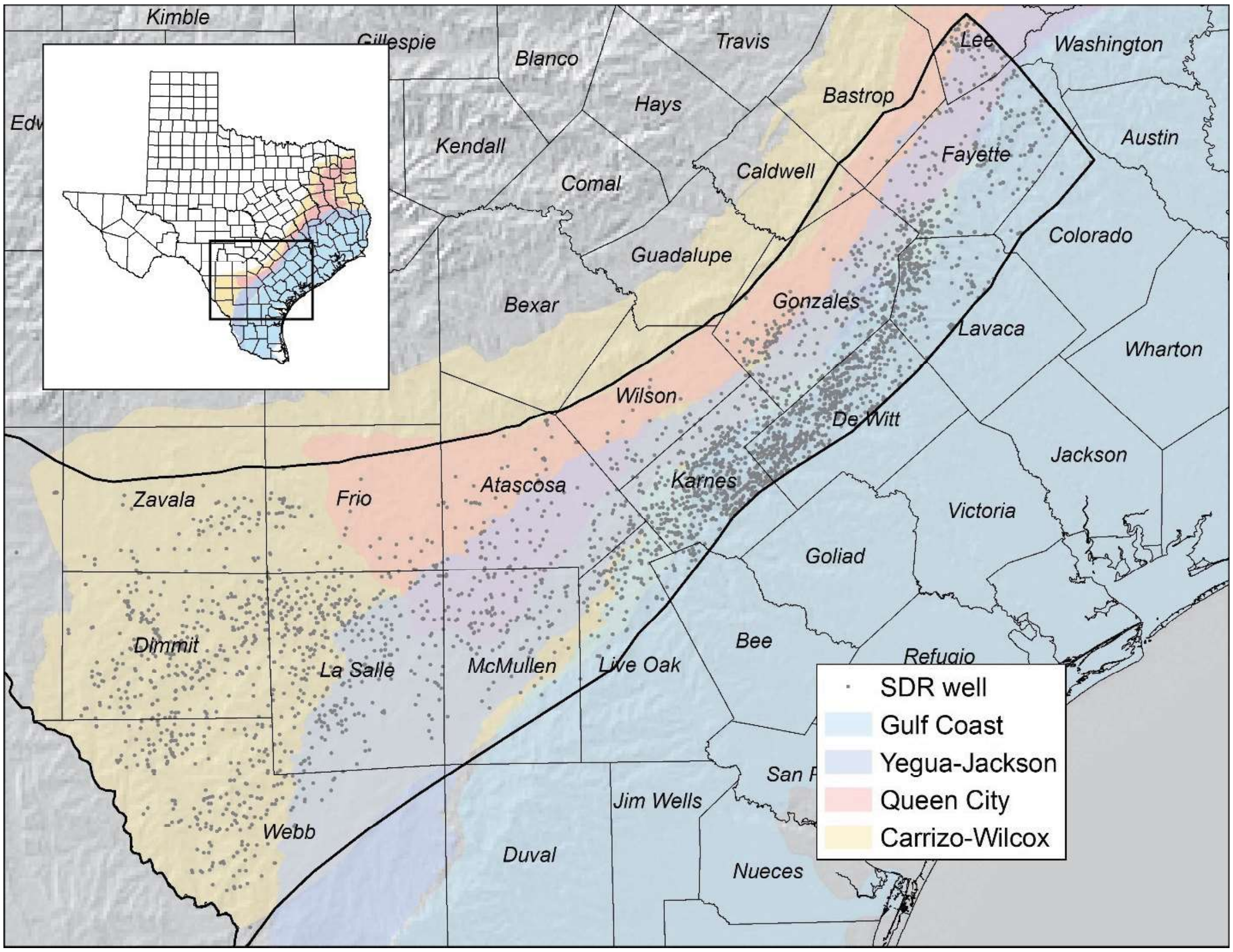


Figure 1-9. Eagle Ford Play locations of oil and gas industry water supply wells completed between 2002 and 2020 from the SDR database. Aquifers are shown as shaded areas and younger aquifers locally overly older aquifers. The heavy solid line represents the approximate limits of drilling activity in the play.

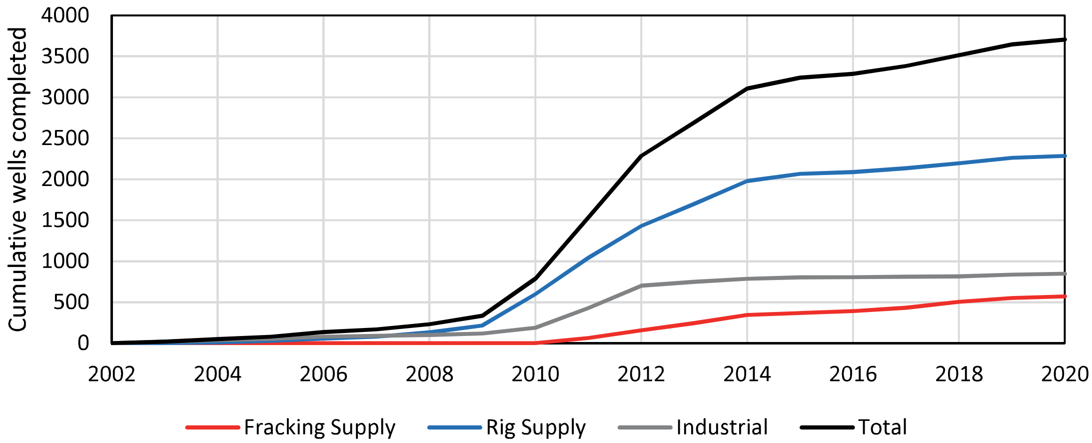


Figure 1-10. Eagle Ford Play cumulative numbers of oil and gas industry water supply wells.

The area-weighted probability of groundwater exceeding the 1,000 mg/L TDS threshold in the play is low in the Gulf Coast (18%), moderately low in the Carrizo-Wilcox (32%), and moderate to elevated in the Queen City (52%) and the Yegua-Jackson (67%) (Figure 1-11, Table 1-11b). Overall, the groundwater splits average 62% fresh and 38% brackish in the Eagle Ford Play and brackish probabilities range from 3 to 70% in different counties.

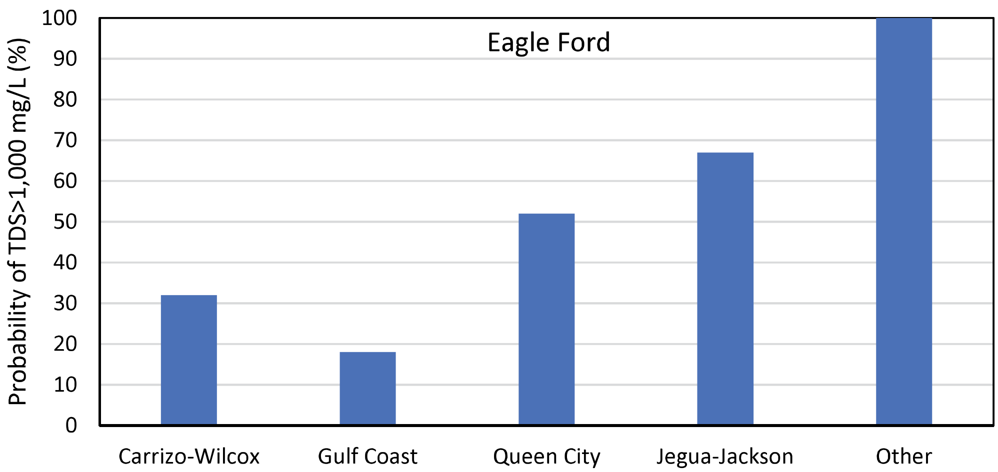


Figure 1-11. Eagle Ford Play area-weighted probability of groundwater TDS greater than 1,000 mg/L by aquifer for oil and gas industry groundwater wells. Note that only 1 well was completed in an unnamed (Other) aquifer.

*Haynesville Play*

A total of 7,919 wells in the SDR database were completed in the Haynesville Play region between 2002 and 2020 (Figure 1-12, Figure 1-13). Groundwater aquifer sources for oil and gas industry wells in the Haynesville Play include the Carrizo-Wilcox, Queen City, and Yegua-Jackson aquifers. The Carrizo-Wilcox aquifer is the major aquifer in the region accounting for 96% of wells (Table 1-10c). The remaining wells are mostly completed in the Queen City (3%) and a relatively small number are in the Yegua-Jackson aquifer (1%).

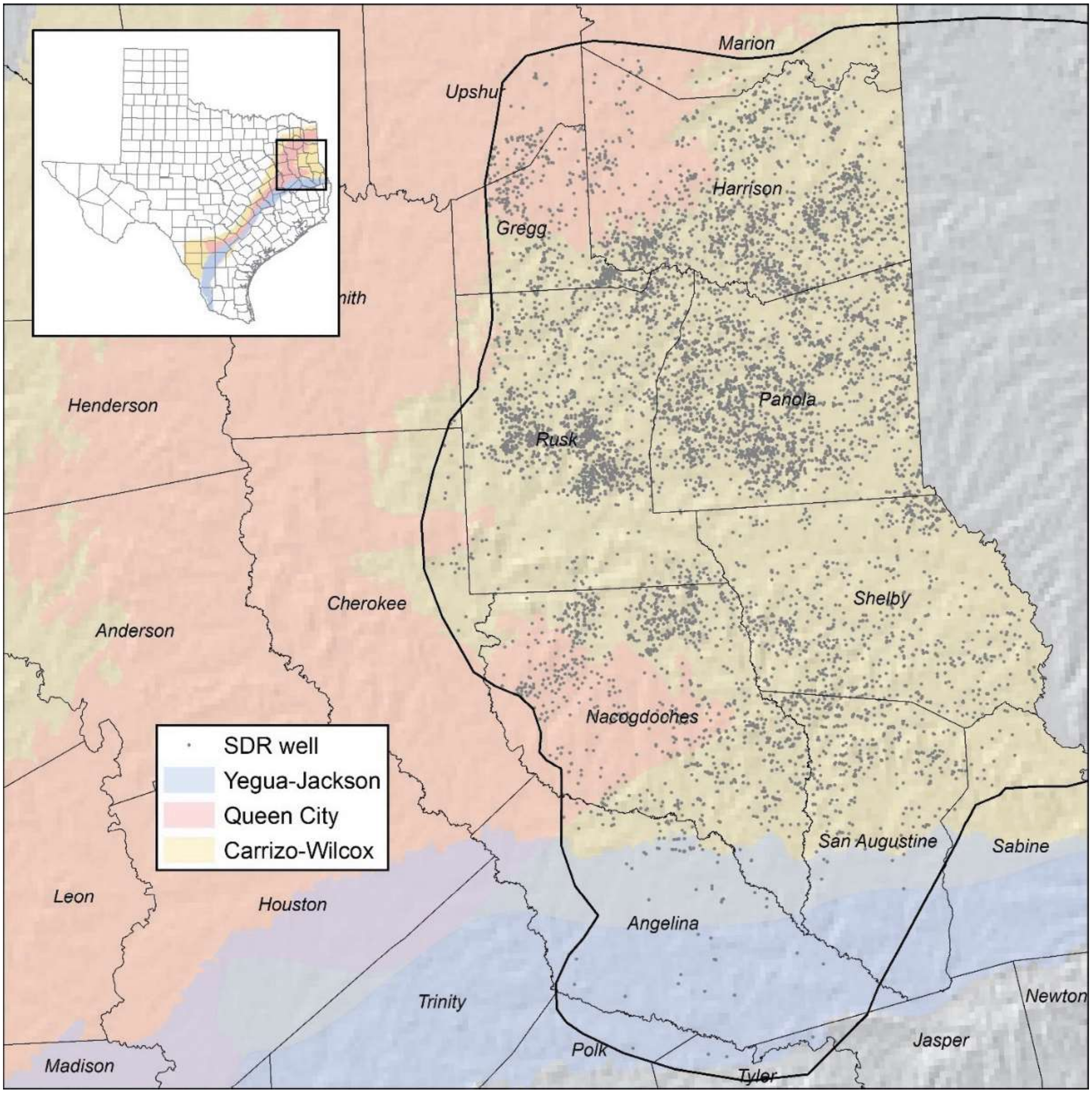


Figure 1-12. Haynesville Play locations of oil and gas industry water supply wells completed between 2002 and 2020 from the SDR database. Aquifers are shown as shaded areas and younger aquifers locally overly older aquifers. The heavy solid line represents the approximate limits of drilling activity in the play.

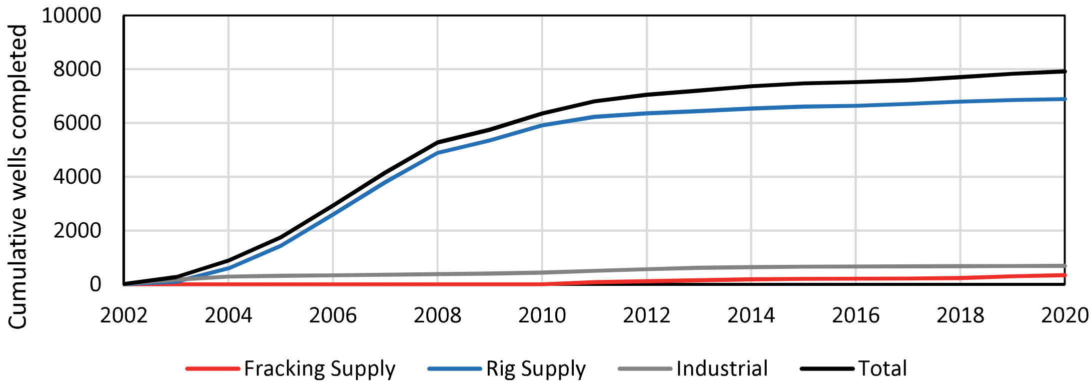


Figure 1-13. Haynesville Play cumulative numbers of oil and gas industry water supply wells.

The area-weighted probability of groundwater exceeding the 1,000 mg/L TDS threshold in the play is very low in the Carrizo-Wilcox (7%) and the Queen City (0%), and low in the Yegua-Jackson (18%) (Figure 1-14, Table 1-11c). Overall, the groundwater splits average 93% fresh and 7% brackish in the Haynesville and brackish probabilities range from 0 to 28% in different counties.

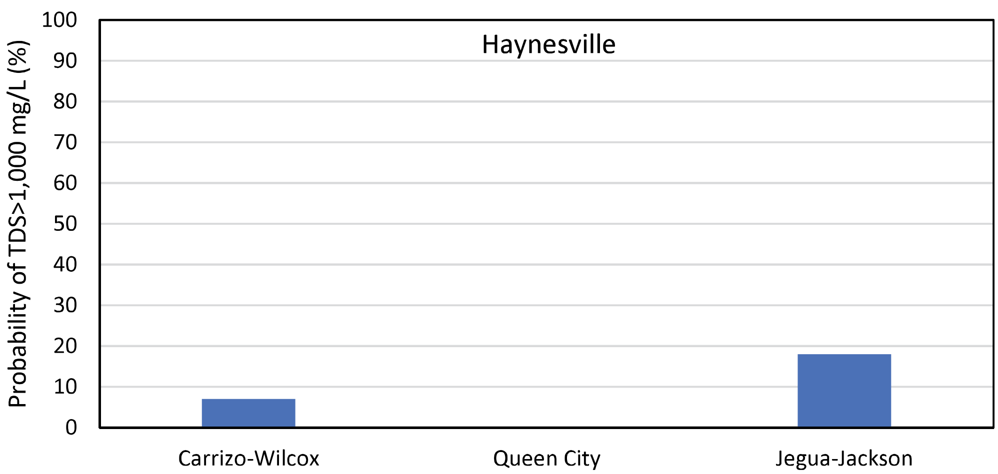


Figure 1-14. Haynesville Play area-weighted probability of groundwater TDS greater than 1,000 mg/L by aquifer for oil and gas industry groundwater wells.

*Permian Basin*

A total of 15,440 wells in the SDR database were completed in the Permian Basin between 2002 and 2020. Groundwater aquifer sources for oil and gas industry wells in the Permian Basin include twelve aquifers. Due to the number and complex distribution of the aquifers in the region, the major aquifers are shown in Figure 1-15 and the minor aquifers in Figure 1-16.

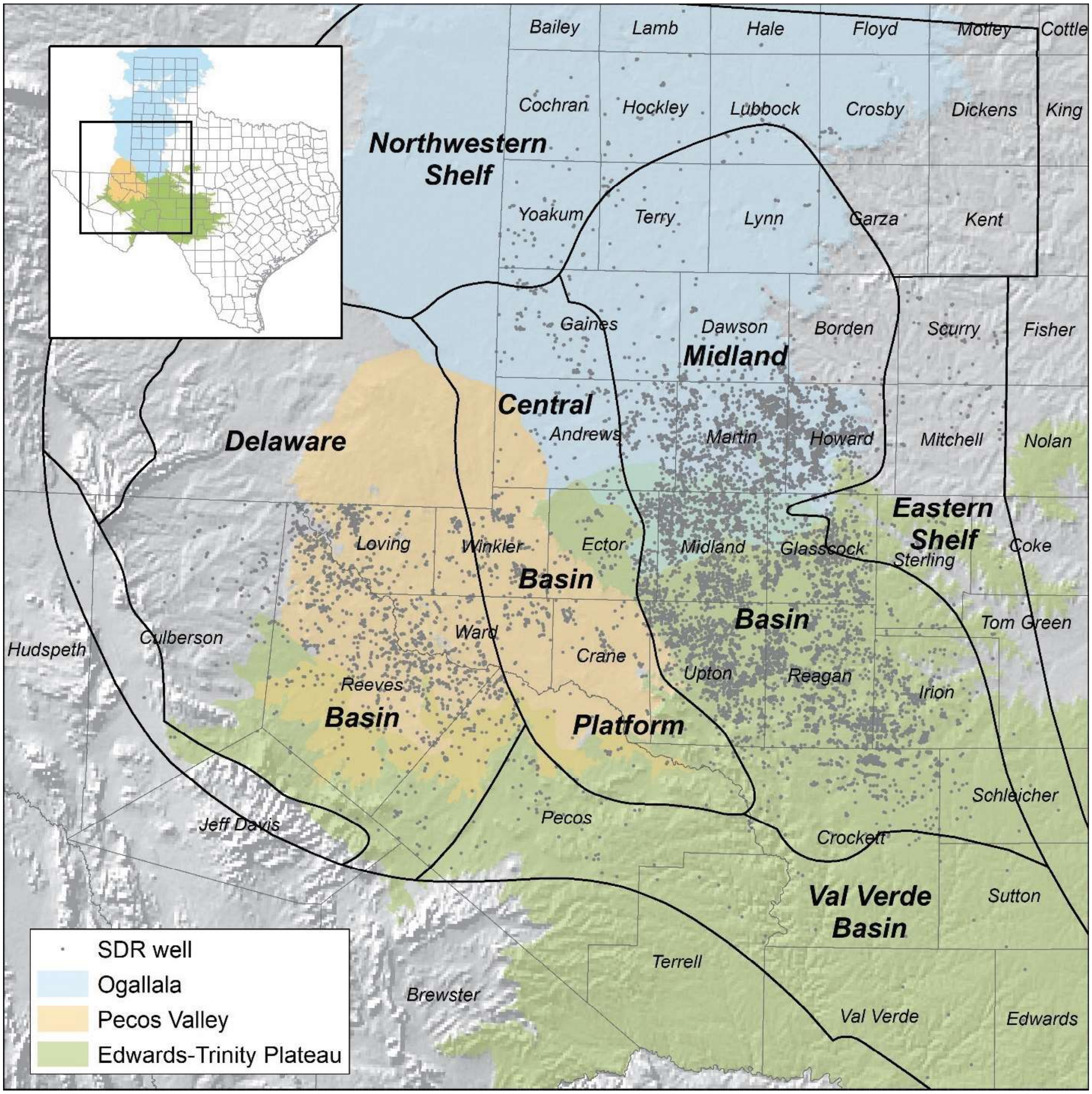


Figure 1-15. Permian Basin locations of oil and gas industry water supply wells completed between 2002 and 2020 from the SDR database. Major aquifers are shown as shaded areas and younger aquifers locally overly older aquifers. Boundaries for Permian Basin subregions are also shown.

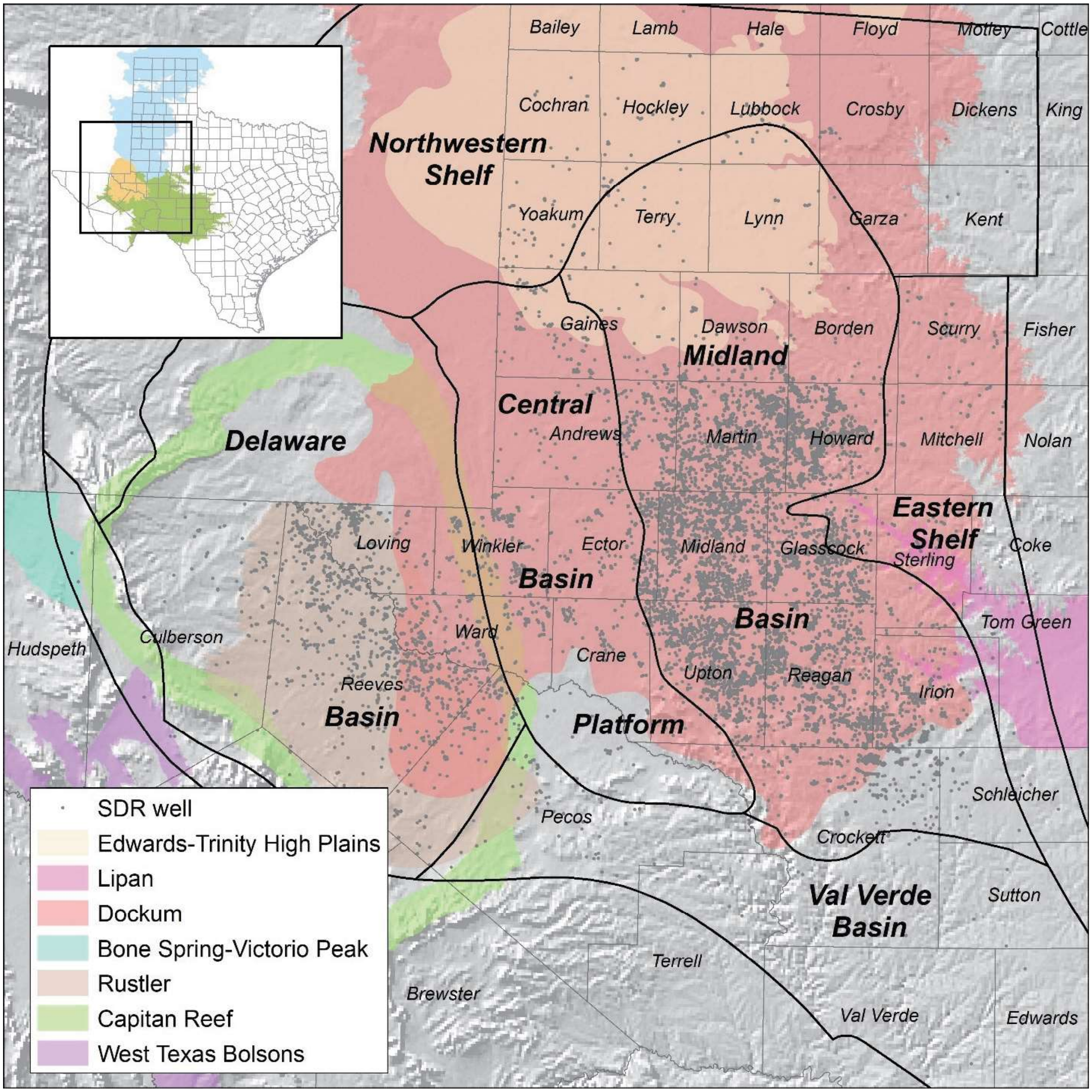


Figure 1-16. Permian Basin locations of oil and gas industry water supply wells completed between 2002 and 2020 from the SDR database. Minor aquifers are shown as shaded areas and younger aquifers locally overly older aquifers. Boundaries for Permian Basin subregions are also shown.

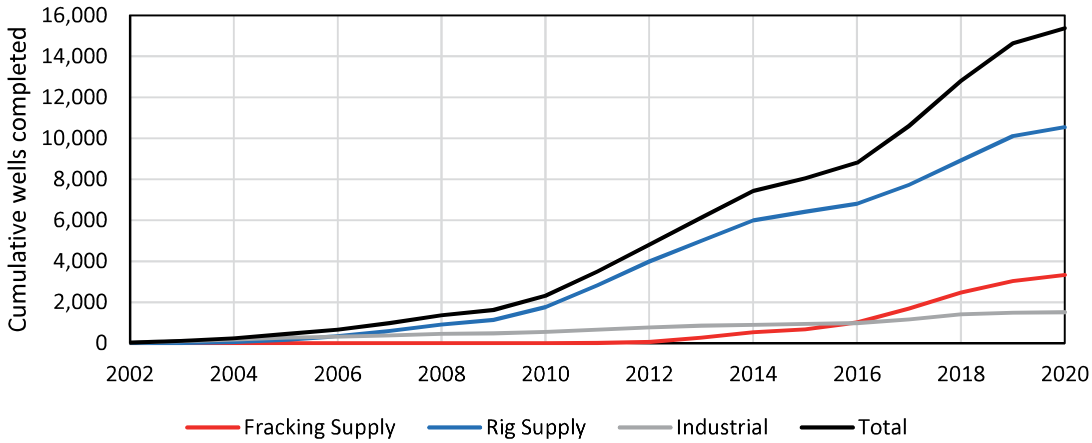


Figure 1-17. Permian Basin cumulative numbers of oil and gas industry water supply wells.

The time-series of well development is shown in Figure 1-17. Most (81%) of all wells are completed in either the Ogallala (37%), Dockum (32%), or Edwards-Trinity Plateau (12%) aquifers (Table 1-10d). The Permian aquifer, which is not mapped and consists of water-bearing strata below all of the other aquifers, accounts for 9% of wells and the Pecos Valley aquifer accounts for 6%. The remaining seven aquifers combined (Rustler, Edwards-Trinity High Plains, Lipan, West Texas Bolsons, Capitan, Bone Spring-Victorio Peak, and other undesignated local aquifers) account for the remaining 3% of wells.

The area-weighted probability of groundwater exceeding the 1,000 mg/L TDS threshold in the Permian Basin is highly variable within and between the various aquifers (Figure 1-18, Table 1-11d). Probabilities are low in the Lipan aquifer (25%), elevated in the Edward-Trinity High Plains (45%), West Texas Bolsons (52%), Edwards-Trinity Plateau (54%), and Ogallala (60%) aquifers, high in the Pecos Valley aquifer (79%), extremely high in the Dockum (90%) and Capitan (97%) aquifers, and virtually certain in the Bone Spring-Victorio Peak, Permian, Rustler, and Other aquifers (100%). Overall the groundwater splits average 25% fresh and 75% brackish in the Permian Basin and brackish probabilities range from 0 to 100% in different counties.

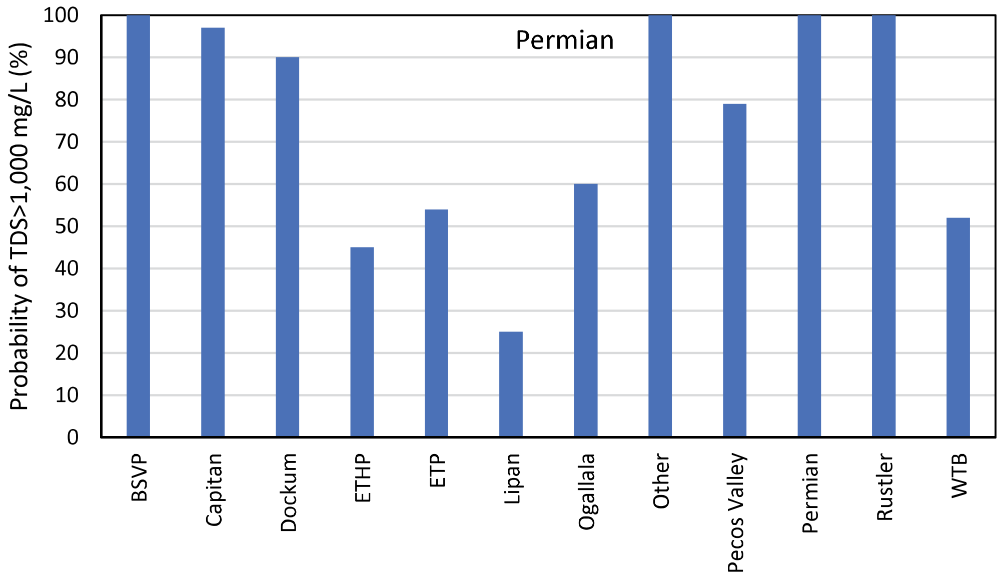


Figure 1-18. Permian Basin area-weighted probability of groundwater TDS greater than 1,000 mg/L by aquifer for oil and gas industry groundwater wells in the Submitted Drillers Reports (SDR) database. BSVP: Bone Spring-Victorio Peak, ETHP: Edwards-Trinity High Plains, ETP: Edwards-Trinity Plateau, WTB: West Texas Bolsons.

## Hydraulic Fracturing Water Use Projections

*Projection model conditions and parameters*

Projections of HF water use were based on estimates of TRRs for each of the plays, as described earlier. These estimates assume that all potential HF wells will be drilled considering recent data on HF well densities and lateral lengths. TRR estimates may overestimate future water use in the Eagle Ford and Haynesville plays because all wells will not likely be developed. In the Permian Basin, TRR estimates were based on only two out of 10 producing intervals; therefore, the TRR based estimates should not overestimate future HF water use in the Permian. Oil and gas commodity prices were not considered in future projections because these prices have been highly variable within the past few years and are difficult to constrain in the future. Projection outlooks may be considered in the future if commodity prices stabilize.

*Barnett Shale Play*

Hydrocarbon production from the Barnett is primarily natural gas. Unconventional development of the Barnett play began in the late 1990s, peaked in 2008 with about 2,700 unconventional horizontal wells completed in that year, and declined steadily to 205 new wells completed in 2015 (Figure 1-19, Table 1-12a). Between 2016 and 2020, a total of only 242 wells were completed in the play, averaging 48 wells/yr.

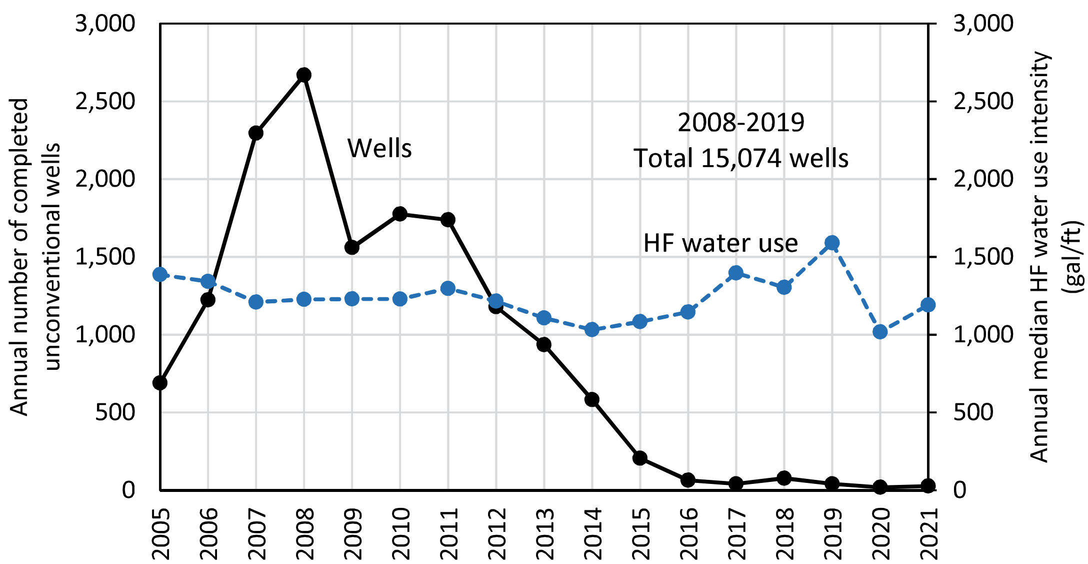


Figure 1-19. Barnett Play annual total unconventional O&G well completions and HF water use intensity for 2005-2021.

During the course of Barnett development, O&G wells were drilled in 23 counties in Texas between 2005 and 2019 (Figure 1-20), though just ten of those counties had more than 1% of all wells drilled in the play. A total of 15,074 wells were drilled during that period (Table 1-12b). The “core” region of the Barnett Play is located in just seven counties, including Denton, Hood, Johnson, Montague, Parker, Tarrant, and Wise counties, where 92% of all wells were drilled between 2005 and 2020. However, between 2016 and 2020, 92% of wells drilled were located in only four of those counties including Denton, Johnson, Tarrant, and Wise counties.

It is unclear if the 2020 global COVID-19 pandemic had a significant impact on drilling in the Barnett Play due to the very small numbers of wells completed annually during 2016-2019. However, the number of wells completed in 2020 (19 wells) is about half that of previous low-drilling years of 2017 (41 wells) and 2019 (41 wells). Median HF water use intensity also decreased somewhat.

TRR modeling was not performed for the Barnett, as it is largely considered to be a mature play with minimal potential for future development under current economic conditions. As such, the approach we used to estimate future HF water use was based on the assumption that large-scale development as in the past will not recur in the future. It also assumes that future drilling will occur at a pace commensurate with recent activity and will be confined to the four-county area described above.

Future drilling in the Barnett is estimated to be 45 wells/year confined to Denton, Johnson, Tarrant, and Wise counties located in the core area of the play. This number approximates the average number of wells drilled each year across these counties between 2016 and 2020 (Table 1-12c). County-level mean HF water use during 2016-2020 was 17.4–27.5 acre-ft/well, resulting in a projected annual HF water use of 1,035 acre-ft/yr across the four counties. Declining trends in new wells drilled since 2015 indicate that drilling may not continue beyond about 2030. Here we assume the 45 wells/yr drilling rate will continue through 2030 and then cease. Under these conditions, the total projected remaining HF water is 11,400 acre-ft.

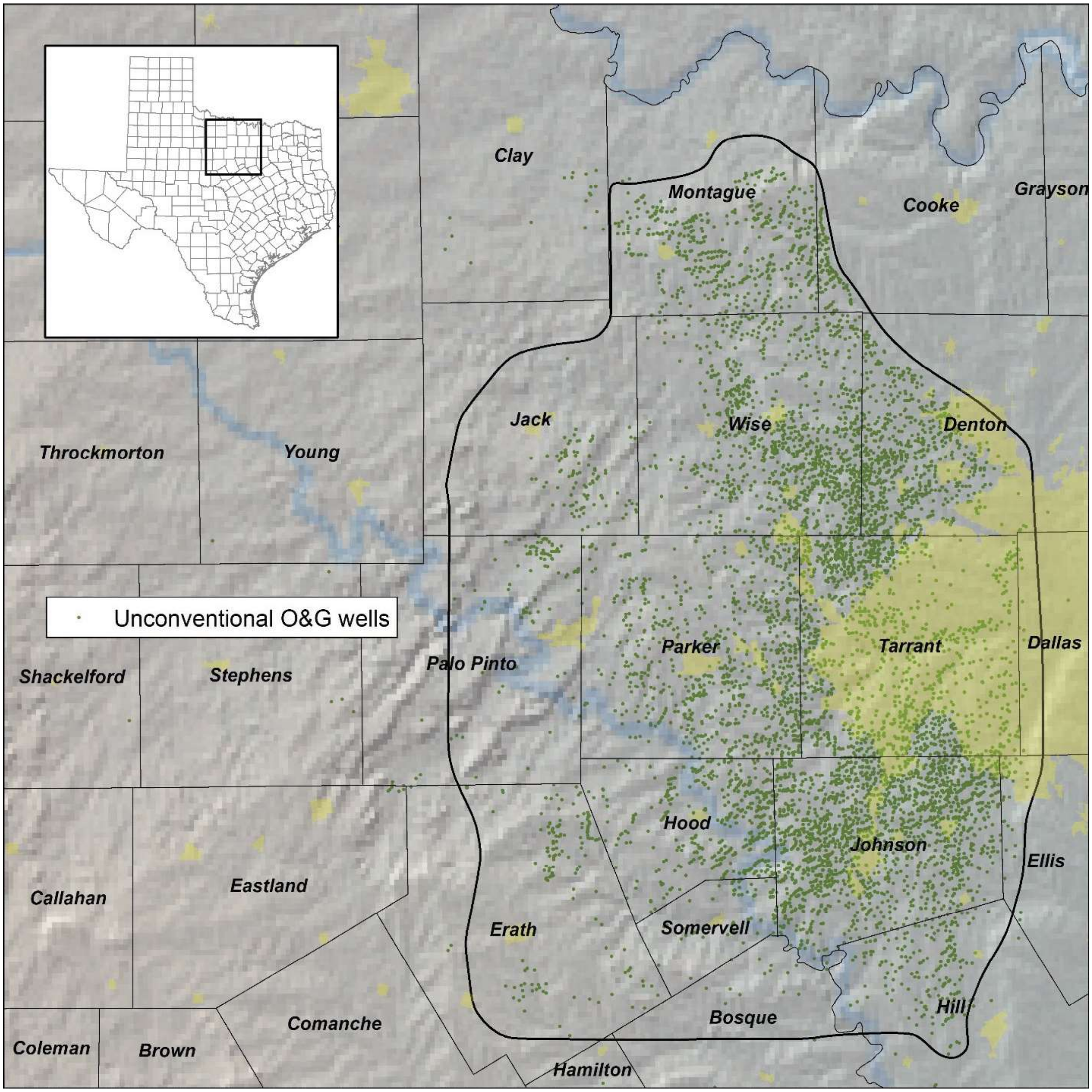


Figure 1-20. Barnett Play locations of unconventional oil and gas wells completed during 2005-2020.

*Eagle Ford Play*

Unconventional development of the Eagle Ford play began in 2008. Hydrocarbon production in the Eagle Ford varies strongly as the formation dips toward the Gulf Coast. Wells completed in the shallower up-dip regions primarily produce oil while wells completed further down-dip produce progressively more natural gas. Natural gas liquids (NGLs) represent a major fraction of production in the intermediate zones and the NGL production is included in total oil production. Development to date has focused primarily on the oil and natural gas liquids producing regions as the natural gas alone is generally not economical to produce.

There were 20,542 unconventional horizontal wells completed through 2019 in the Eagle Ford Play (Figure 1-21, Table 1-13a). Of these, 97% were completed in the Eagle Ford formation and 3% in the Austin Chalk. HF water use for non-producing wells was included.

It appears that the 2020 global COVID-19 pandemic had an impact on drilling in the Eagle Ford. The number of wells completed in 2020 (845 wells) was about half that of the average during 2017-2019 (1,792 wells/yr). However, median HF water use intensity remained steady.

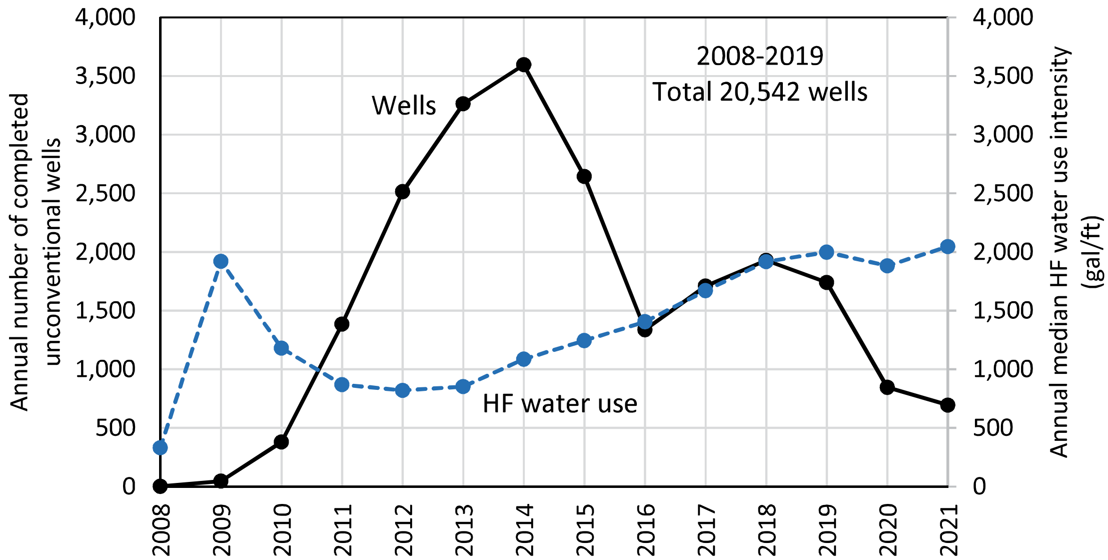


Figure 1-21. Eagle Ford Play annual total unconventional O&G well completions and median HF water use intensity for 2008-2021. Data for numbers of wells in 2021 are incomplete.

During the course of Eagle Ford development, 20,542 O&G wells were completed in 16 counties in Texas between 2005 and 2019 (Figure 1-22, Table 1-13b). The TRR modeling suggests a total inventory of about 112,000 wells in the Eagle Ford Play at maturity (Table 1-13c). There were about 20,500 unconventional horizontal wells completed through 2019, leaving about 91,500 future wells. Estimates of projected annual HF water use in the Eagle Ford Play were based on an assumed drilling rate of 1,800 wells per year, consistent with play-wide activity between 2017 and 2019. Drilling at that rate will require 51 years to complete the remaining well inventory and is estimated to end in the year 2071.

HF water use intensity was estimated for each county as the median of all wells completed between 2018 and 2021, a period when play-wide values remained generally stable and ranged from about 1,500 to 2,700 gal/ft in different counties with an overall play median value of 1,960 gal/ft (Table 1-13c). The intensities in counties with few or no wells completed by 2019 (Bee, Caldwell, Colorado, Guadalupe, and Maverick counties) were estimated as the average of (median) intensities for adjacent counties.

Estimated mean annual HF water use in the Eagle Ford Play ranges from 9 acre-ft/yr to 6,130 acre-ft/yr in different counties with an annual play total of about 56,800 acre-ft/yr from 2020 through 2071 (Table 1-13d). The projected 51-year remaining total HF is 2,888,000 acre-ft.

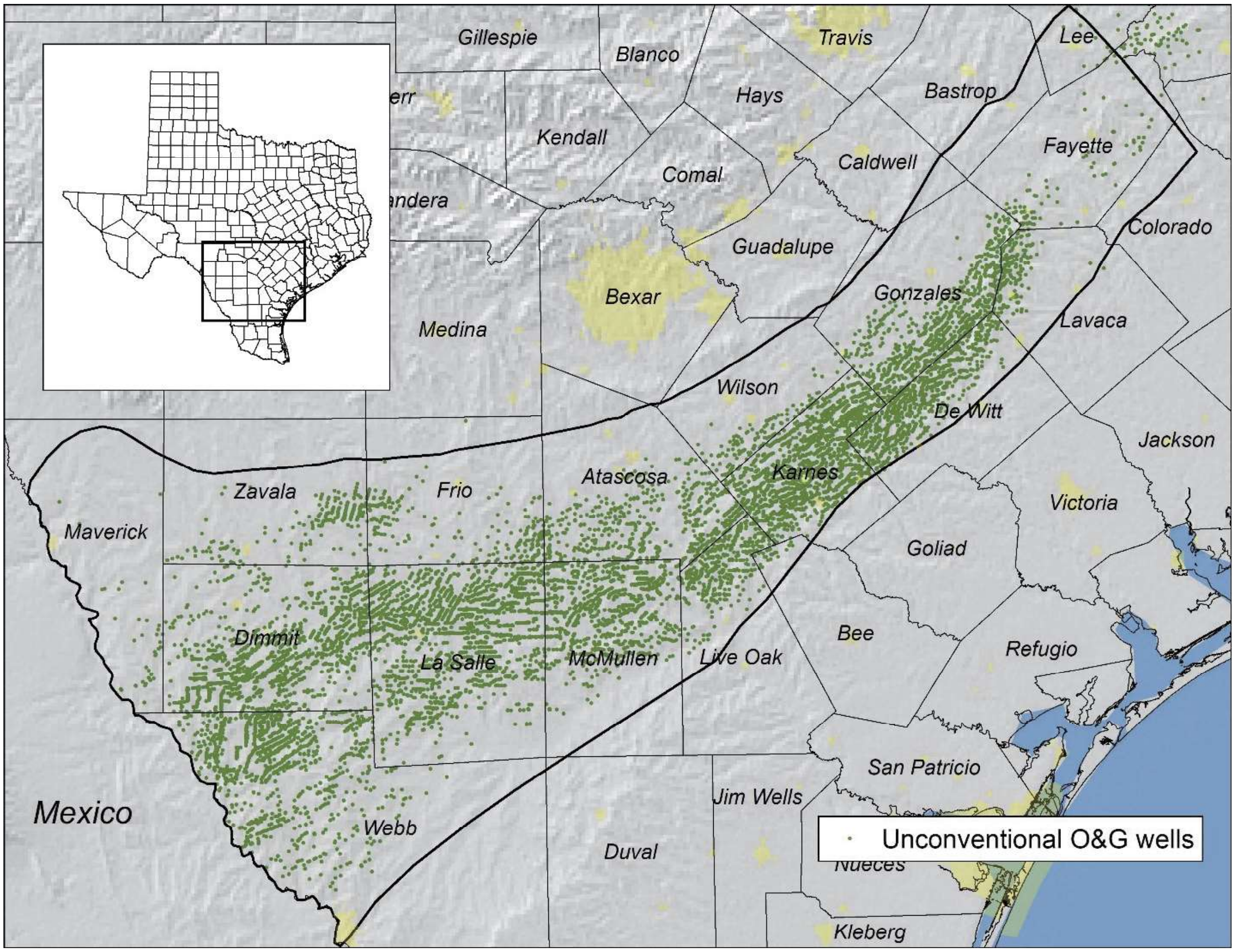

Figure 1-22. Eagle Ford Play locations of unconventional oil and gas wells completed during 2008-2020

*Haynesville Play*

Unconventional development of the Haynesville Play began in 2008. The Haynesville is located in both Texas and Louisiana and development to date has been focused primarily in Louisiana. Texas accounts for 30% of all wells completed between 2008 and 2019. The historical pace of drilling in the Haynesville in Texas was low compared to the other major plays with only 1,341 unconventional horizontal wells completed through 2020, averaging about 100 wells per year (Figure 1-23, Table 1-14a).

It appears that the 2020 global COVID-19 pandemic had no impact on drilling in the Haynesville. The number of wells completed in 2020 (118 wells) was similar to that of 2018 (115 wells) and 2019 (121 wells). Median HF median water use intensity has been increasing steadily throughout play development, though values remained steady in 2020-2021.

During the course of development, wells were completed in 9 counties in Texas (Figure 1-24, Table 1-14b). Most wells in Texas (96%) are located in five counties, including Harrison, Nacogdoches, Panola, San Augustine, and Shelby counties. Hydrocarbon production in the Haynesville is almost entirely natural gas. In Texas, the producing formation has historically been referred to interchangeably as the Haynesville Shale and the Bossier Shale depending on county location and based on differences in naming conventions between Texas and Louisiana. In 2009, the RRC consolidated all well completions and production under the Haynesville Shale name. This analysis focuses completely on the Texas areas of the play and refers to the producing formation as the Haynesville.

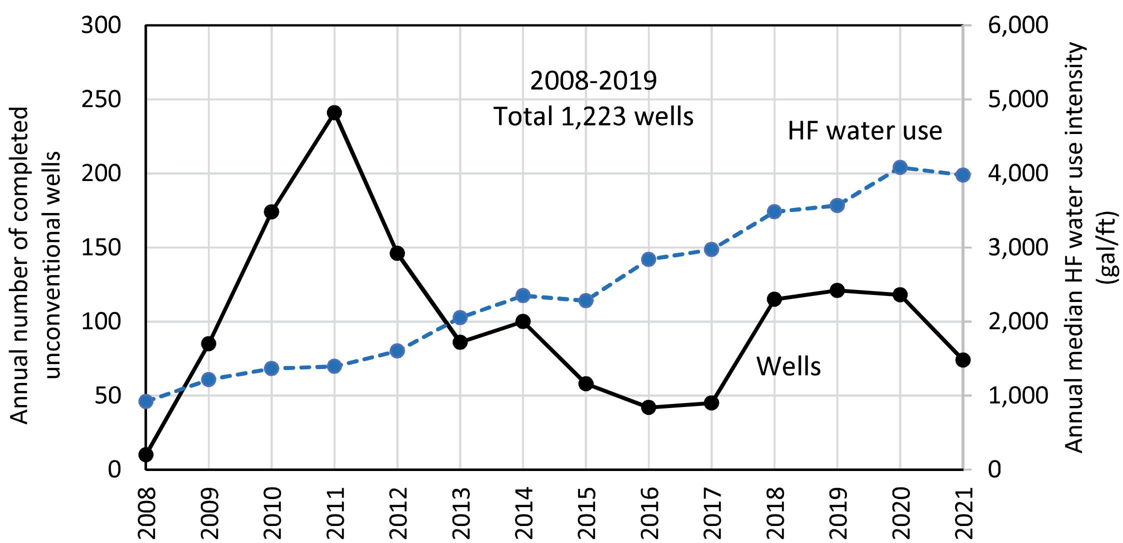


Figure 1-23. Haynesville Play annual total unconventional O&G well completions and median HF water use intensity for 2008-2021. Data for numbers of wells in 2021 are incomplete.

The TRR modeling suggests a total inventory of about 17,600 wells in the Texas Haynesville at maturity (Table 1-14c). There were 1,223 unconventional horizontal wells completed between 2008 and 2019, leaving about 16,400 future wells. Estimates of projected annual HF water use in the Haynesville Play were based on an assumed drilling rate of 120 wells per year consistent with activity between 2018 and 2020 (Table 1-14b). Drilling at that rate will require 136 years to complete the remaining inventory in the play and is estimated to end in the year 2156.

HF water use intensity was estimated for each county as the median of all wells completed between 2018 and 2021, a period when values remained generally stable. The intensities in counties with few or no wells completed by 2019 (Gregg, Marion, Rusk, and Sabine counties) were estimated as the average of (median) intensities for adjacent counties. Median HF water use intensity ranges from about 2,700 gal/ft to about 3,900 gal/ft in different counties with an overall play median value of about 3,800 gal/ft which is almost double that of other plays in Texas (Table 1-14c).

Estimated mean annual HF water use in the Texas Haynesville ranges from 8 acre-ft/yr to 1,998 acre-ft/yr in different counties with an annual play total of about 7,500 acre-ft/yr from 2020 through 2156 (Table 1-14d). The projected 136-year total HF is 1,023,000 acre-ft.

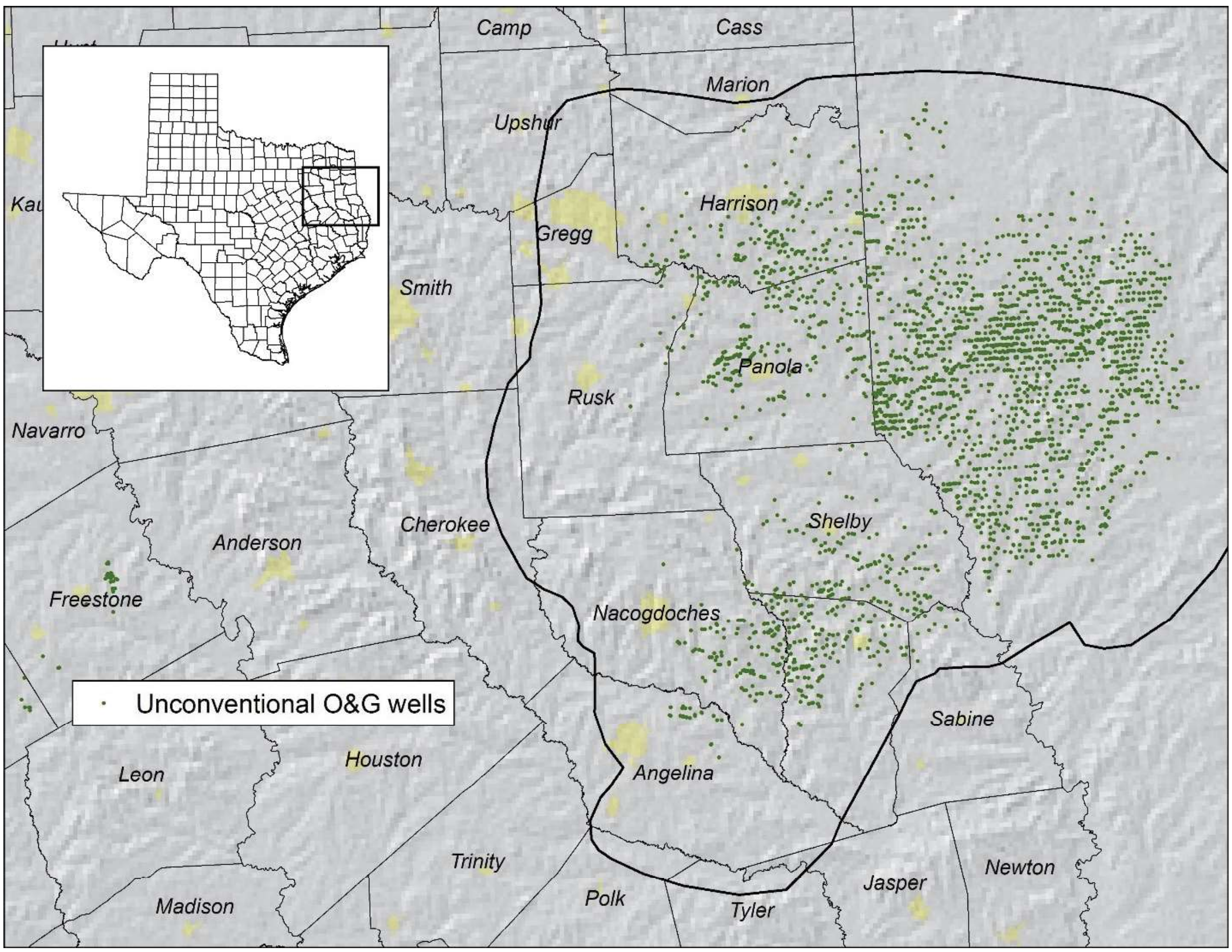


Figure 1-24. Haynesville Play locations of unconventional oil and gas wells completed during 2008-2020.

*Permian Basin*

Completions of unconventional wells in the Permian Play began in the early 2000s using HF with larger amounts of water and proppant than those used historically. Most of the early wells were vertical or directional wells with little or no true horizontal component. Vertical completions peaked in 2012 with 4,722 wells in Texas and decreased by 2016 to about 500 to 600 wells per year (Figure 1-25a). Horizontal well development increased after about 2010 and peaked in 2018 with 4,525 well completions in Texas. Between 2005 and 2019 a total of about 55,400 unconventional wells were completed in both Texas and New Mexico (Table 1-15a). Approximately 26,100 (90%) of all unconventional vertical wells and 20,300 (77%) of all unconventional horizontal wells were completed in Texas areas of the Permian Basin (Figure 1-26, Table 1-15b).

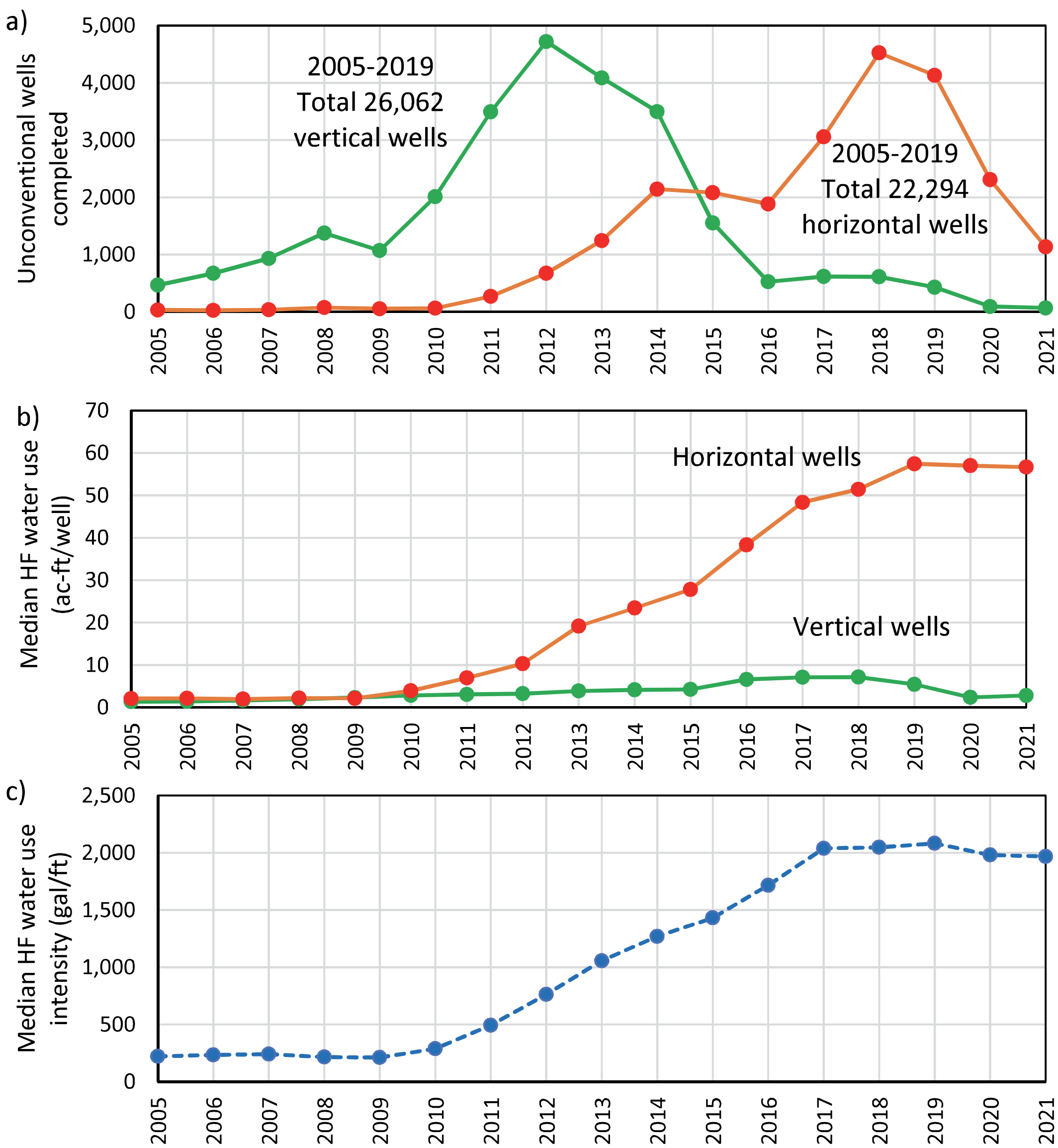


Figure 1-25. Permian Basin annual total unconventional O&G well a) completions and b) median HF water use in ac-ft/well and c) median HF water use in gal/ft for 2005-2021. Data for numbers of wells in 2021 are incomplete.

It appears that the 2020 global COVID-19 pandemic had a significant impact on drilling in the Permian Basin. The number of unconventional horizontal wells completed in 2020 (2,310 wells) was about half that of 2018 (4,525 wells) and 2019 (4,132 wells). However, median HF water use intensity remained steady

HF water use for vertical wells remained relatively small compared to horizontal wells, initially about 1-2 acre-ft/well and averaging about 6 acre-ft/well after 2015 (Figure 1-25b). Vertical wells are primarily located in the Midland Basin (Figure 1-26). HF water use for unconventional horizontal wells was initially similar to vertical wells but increased steadily to 57 acre-ft/well by 2019. Median HF water use intensity, an attribute only assigned to horizontal wells, remained steady at about 250 gal/ft through 2009 and then steadily increased to about 2,000 gal/ft by 2017 and remained steady at that value afterwards. Total HF water use in the Permian Basin between 2005 and 2019 was 975,000 acre-ft, with horizontal wells accounting for 833,000 acre-ft (85%) and vertical wells accounting for 142,000 acre-ft (15%) (Table 1-15b).

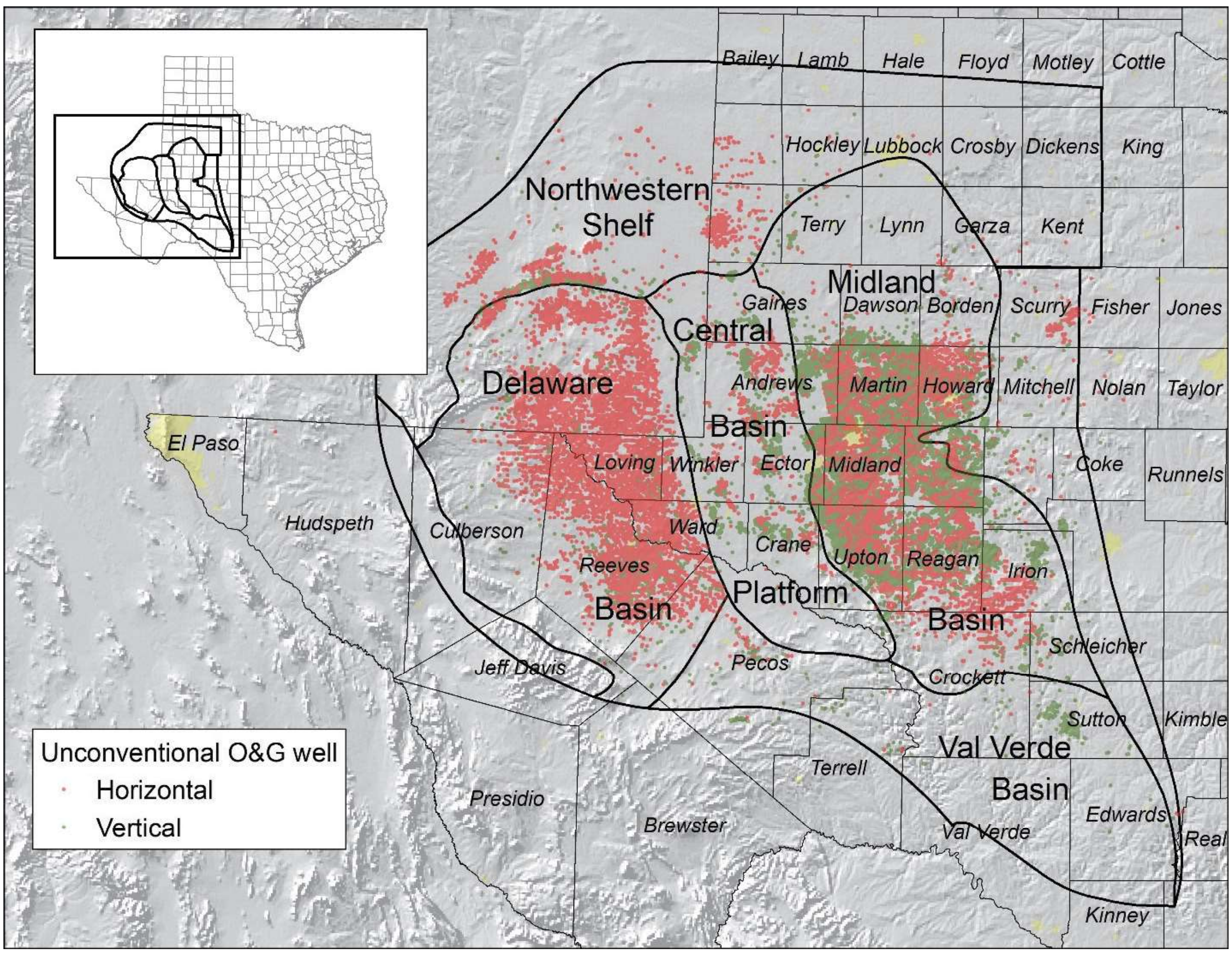

Figure 1-26. Permian Basin locations of unconventional oil and gas wells completed during 2005-2020.

Development of unconventional wells is primarily in the Delaware Basin (Bone Spring, Avalon, and Wolfcamp A and B formations) and the Midland Basin (Spraberry, Dean, and Wolfcamp A and B formations), with relatively few wells located in other regions. The Delaware Basin lies partly in New Mexico while the Midland Basin is entirely in Texas. Within the Permian basin in Texas, 96% of all unconventional vertical wells and 96% of all unconventional horizontal wells between 2005 and 2019 were completed in 17 counties, all of which are associated with the Delaware Basin or Midland Basin (Table 1-15c, Table 1-15d).

The TRR modeling was focused on the Wolfcamp A and Wolfcamp B formations in the Delaware Basin and the Midland Basin. Separate models were developed for each basin and all future wells were assumed to be horizontal. The projections of future HF water use in this study are restricted to these areas.

*Delaware Basin TRR*

The TRR model results for the Delaware Basin suggest a total inventory of about 137,400 wells in six Texas counties at maturity (Table 1-15e). There were about 7,000 unconventional horizontal wells completed between 2005 and 2019, leaving about 130,400 future wells. Estimates of projected annual HF water use in the Delaware Basin were based on an assumed drilling rate of 1,700 wells per year consistent with activity in 2018 and 2019 (Table 1-15e). Drilling at that rate will require 77 years to complete the remaining inventory in the play and is estimated to end in the year 2096.

HF water use intensity was estimated for each county (Table 1-15e) as the median of all wells completed between 2017 and 2021, a period when values remained stable (Table 1-15b). The global COVID-19 pandemic did not impact water use intensity values. Median HF water use intensity for that period ranges from about 1,800 gal/ft to about 2,700 gal/ft in different counties (Table 1-15e). Estimated mean annual HF water use ranges from about 3,200 acre-ft/yr to about 34,900 acre-ft/yr in different counties with an annual play total of 82,500 acre-ft/yr from 2020 through 2096. The projected 77-year total HF is 6,325,000 acre-ft (Table 1-15g).

*Midland Basin TRR*

The TRR modeling in the Midland Basin suggests a total inventory of 120,300 wells in the Wolfcamp A and B at maturity (Table 1-15f). There were about 11,500 unconventional horizontal wells completed between 2005 and 2019, leaving about 108,800 future wells. Estimates of projected annual HF water use in the Midland Basin were based on an assumed drilling rate of 2,400 wells per year consistent with activity between 2018 and 2019. At that rate it will require 45 years to complete drilling in the Wolfcamp A and B formations in the Midland Basin, ending in the year 2064.

HF water use intensity was estimated for each county as the median of all wells completed between 2017 and 2021, a period when values remained very stable. The global COVID-19 pandemic did not impact water use intensity values. Median HF water use intensity for that period ranges from about 1,600 gal/ft to about 2,100 gal/ft in different counties (Table 1-15f). Estimated mean annual HF water use ranges from about 290 acre-ft/yr to about 19,600 acre-ft/yr in different counties with an annual play total of about 128,200 acre-ft/yr from 2020 through 2064. The projected 45-year total HF is 5,814,000 acre-ft (Table 1-15g).

*Comparison with TRR estimated by the USGS*

The USGS performed a similar TRR study for the Midland Basin based on data through 2015 (Gaswirth et al., 2016) and for the Delaware Basin based on data through 2016 (Gaswirth et al., 2018). The results for both studies are compared with this study in Table 1-16. The total number of wells across both basins projected by the USGS is about 60% of that from this study. Additionally, the Estimated Ultimate Recovery of individual wells is about 45% to 60% of that for wells in this study. Overall, the TRR oil volumes from this study are about 3 times those of the USGS studies. The USGS studies were based on fewer historical wells and also projected fewer and lower-producing future wells compared to this study. There are many differences between the previous USGS studies and the current study, including spatial resolution (very coarse resolution in USGS study versus square mile grid scale in this analysis) and length of available records to base future projections.

## Oil and Gas Industry Water Use Projections

This section focuses primarily on HF water use by the oil and gas industry for counties in the core regions of the major play areas (Table 1-17). Estimates of future water use by the oil and gas industry include both HF water use for unconventional wells and for other purposes including conventional well completions. Statewide, future oil and gas industry water use is projected to be about 315,000 acre-ft/yr for 2020 through about 2060 declining afterwards to about 119,000 acre-ft/yr by 2080. Data are tabulated by county (Table 1-18a) and by play (Figure 1-27, Table 1-18b). These estimates include about 26,400 acre-ft/yr of water use for on-going conventional purposes.

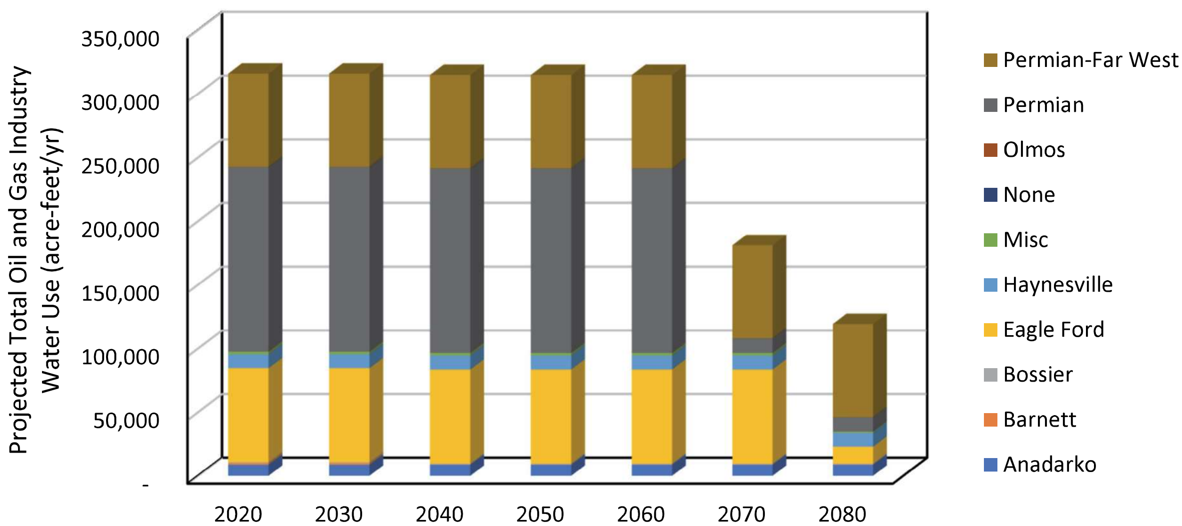


Figure 1-27. Projected statewide annual oil and gas industry water use by play region for 2020-2080. See Figure 1-1 for play areas.

# 2. Coal Mining Water Use

## 2.1 Overview

Coal mined in Texas consists almost entirely of lignite, the lowest quality grade of coal in terms of energy per unit mass (Kaiser et al., 1980). Texas lignite has historically been mined for use by the electric power generation industry and most mines are or were associated with a collocated "mine mouth" power plant. In recent years, many power plants began importing cleaner-burning subbituminous coal mined in Wyoming to supplement or altogether replace Texas lignite as a fuel source (EIA, 2022). As a result, coal mining in Texas declined significantly.

Coal mines in Texas are entirely surface or strip-mining operations where coal is mined by removing overlying material (overburden) to expose the coal seam. Economically, surface mining is limited to depths generally less than about 300 ft below the natural ground surface. Mines in Texas are generally located in or near outcrop areas of the Carrizo-Wilcox and the Jackson Group in an arc parallel to and inland of the Gulf Coast from the international border of Mexico to Louisiana (Figure 2-1). Most of the mines are associated with a mine-mouth power plant that uses the coal from the mine to generate electric power. About 35% of the coal burned for electric power generation in 2020 came from Texas (lignite) mines while the remaining 65% came from mines in the Wind River Basin of Wyoming (subbituminous).

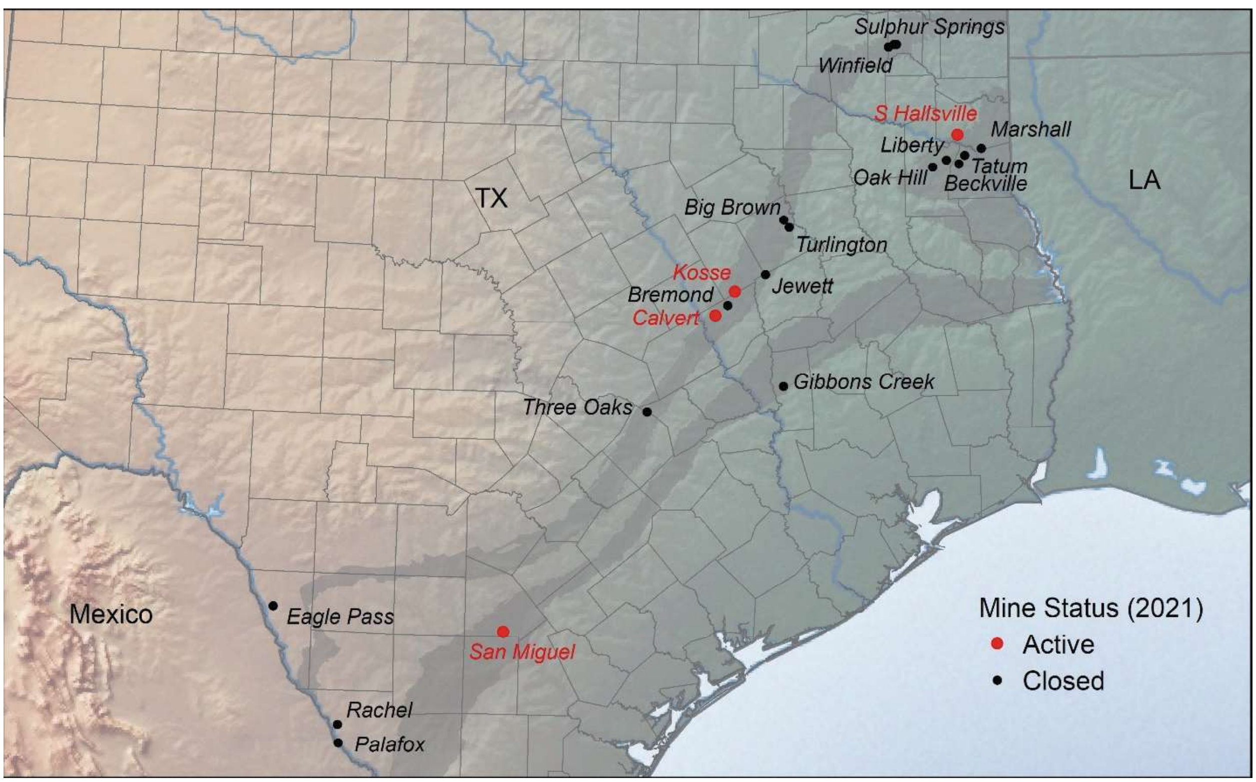


Figure 2-1. Locations of active (red) and closed (black) coal mines in Texas. Shaded areas indicate the outcrop areas of the Carrizo-Wilcox formation (inland) and the Jackson Group.

We tabulated Texas coal production by mine for 1983 through 2020 (Table 2-1a). During that period, coal mining in Texas peaked between 1987 and 1999 when total annual production averaged 53.5 million tons per year, ranging between 50.5 – 58.8 million tons (Figure 2-2, Table 2-1b). Production declined to 35.1 million tons by 2009 and then rebounded somewhat between 2010 – 2014 averaging 43.5 million tons per year. Total coal production in Texas declined to 19.7 million tons in 2020. Between 1983 and 2016, the number of operating mines varied annually from 11 to 16 and declined to seven mines in 2020 (Figure 2-2). As of January 2021, a further three mines had closed and there were only four operating coal mines in Texas, including the South Hallsville, Kosse, Calvert, and San Miguel mines (Figure 2-1). The South Hallsville mine is scheduled to cease operations in late 2023 while the three other mines have not publicly announced their plans.

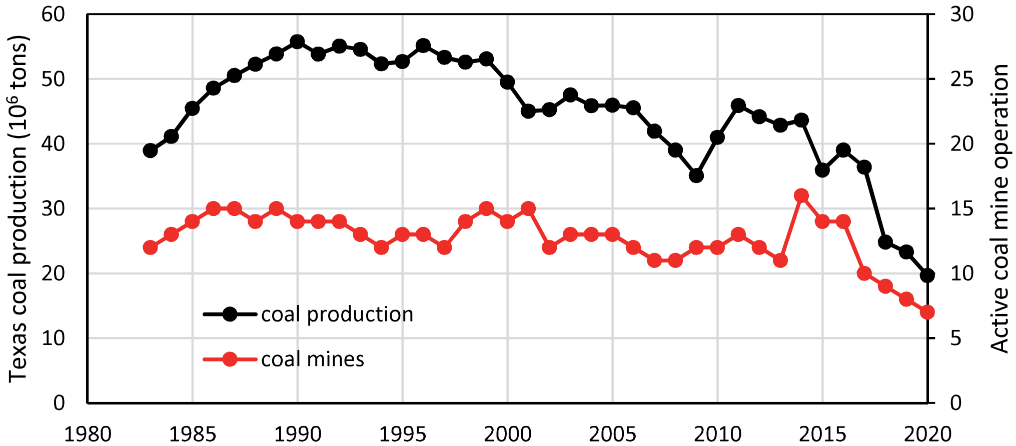


Figure 2-2. Texas annual coal production during 1983-2000 (EIA, 2022)

Water is pumped by the Texas coal mining industry primarily for two purposes, including dewatering and depressurizing. Dewatering is required to remove water that collects in the excavated area, including rainwater or groundwater if an aquifer is intersected. Depressurizing is required if the excavated area is located near the top of a confined (pressurized) or artesian aquifer and unmitigated pressures in the aquifer would lead to heaving of the mine floor. In both cases, most if not all of the pumped water is either pumped back into the ground at another location or is discharged to a convenient surface water body if available. Other uses include temporary irrigation for revegetation of reclaimed areas and relatively small amounts of the pumped water might be consumed for minor uses, such as dust control and equipment washing.

## 2.2 Data Sources and Analytical Methods for Coal Mining Water Use

The primary data source for coal production information is the U.S. Energy Information Administration (EIA) (https://www.eia.gov/coal/data.php), which collects and archives production data for all energy resources and data relating to electric power generation. The EIA has tracked coal production since 1983 and provides annual coal tonnage delivery by mine to individual power plants across the country. Information regarding power plant facilities, equipment, and management are also available. Texas coal mine operators report annual water use data with the Water Use Survey managed by the TWDB, which includes volumes of groundwater, surface water, and reuse. We used the TWDB data for 2010 through 2020 to characterize projected water use by the remaining operating coal mines.

## 2.3 Results

The four currently operating coal mines in Texas include the South Hallsville, San Miguel, Calvert, and Kosse mines. Each of these mines supplies 100% of their coal to an associated power plant, which includes the Pirkey, San Miguel, Major Oak, and Oak Grove power plants, respectively (Table 2-2a). The South Hallsville mine and Pirkey power plant are scheduled to close in late 2023. The remaining three mines currently have no announced plans to curtail or cease operations. Traditional steam coal power plants employ boilers that are designed to operate with specific fuel sources. Coal-fired boilers have a practical life span generally on the order of 50 years, ranging from 40 to 65 years. Assuming the four remaining coal mine operations continue to operate as planned or until their boiler life span is achieved and also that their respective annual water use remains similar to recent volumes, future water use by the Texas coal mining industry is predicted to be about 4,000 acre-ft/yr through 2040, declining to 1,000 acre-ft/year afterwards through 2060, and zero afterwards.

*South Hallsville Mine*

Lignite production from the South Hallsville mine in Harrison County has decreased precipitously, from about 4.2 million tons in 2016 to about 1.6 million tons in 2020 (Table 2-2b). Between 2015 and 2020, water use averaged about 150 acre-ft/yr, and was 56% surface water and 44% groundwater (Table 2-3a). Total future water use (2020-2023) is estimated to be no more than 600 acre-ft by the time the mine closes (Table 2-3b).

*San Miguel Mine*

The San Miguel Mine in Atascosa County reported no water use. The San Miguel produced an average of about 3 million tons of Jackson Group lignite per year between 2010 and 2020 (Table 2-2b). The Jackson Group is comprised of the Whitsett, Manning, Wellborn, and Caddell formations. Water-bearing units in the Jackson Group in conjunction with the Yegua Formation of the upper Claiborne Group form the Yegua-Jackson aquifer system in Texas. For depressurization purposes, the San Miguel Mine produces about 2,000 acre-ft/yr of saline groundwater from the Jackson Group that is reinjected into the subsurface (Nicot and Scanlon, 2011). The single lignite-fueled boiler at the San Miguel power plant began operating in 1982. Based on an assumed life span of 50 years, the lignite boiler is projected to retire in about 2032.

*Calvert Mine*

Lignite production from the Calvert mine in Robertson County has remained mostly steady at about 2 million tons per year between 2010 and 2020 (Table 2-2b). Reported water use varied widely between an initial 7,441 acre-ft in 2010, followed by virtually no water use from 2011 through 2014, and finally very steady pumping averaging about 3,000 acre-ft/yr between 2015 and 2020, all of which is groundwater (Table 2-3a). Future pumping is estimated to remain at 3,000 acre-ft/yr. The two lignite-fueled boilers at the Major Oak plant began operating in 1990 and 1991. Based on an assumed life span of 50 years, the boilers are projected to retire in about 2040 (Table 2-3b).

*Kosse Mine*

Lignite production from the Kosse mine is the greatest among all of the active mines. Production began in 2010 with about 6.3 million tons increasing to an average of about 9.5 million tons/yr between 2014 and 2020 (Table 2-2b). Reported water use has generally been less than about 500 acre-ft/yr (Table 2-3a). While lignite production remained relatively stable, pumping recently increased from 300 acre-ft in 2016 that was about 15% groundwater and 85% surface water) to 850 acre-ft in 2020 that was about 50% groundwater and 50% surface water. Future water pumping may reflect this increased trend somewhat but is conservatively estimated to be no more than 1,000 acre-ft/yr. The two lignite-fired boilers at the

Oak Grove power plant began operating in 2010 and 2011. Based on an assumed life span of 50 years, the boilers are projected to retire in about 2060 (Table 2-3b).

*Coal Mining Water Use Projections*

Estimates of future water use by the coal mining industry are relatively small. Statewide, future coal mining water use is projected to be about 4,150 acre-ft/yr for 2020, declining slightly to 4,000 acre-ft/yr in 2030 through 2040, and declining further to 1,000 acre-ft in 2050 and 2060. There is not expected to be any coal mining water use after 2060. Data are tabulated by county (Table 2-3b) and by mine (Table 2-3b, Figure 2-1).

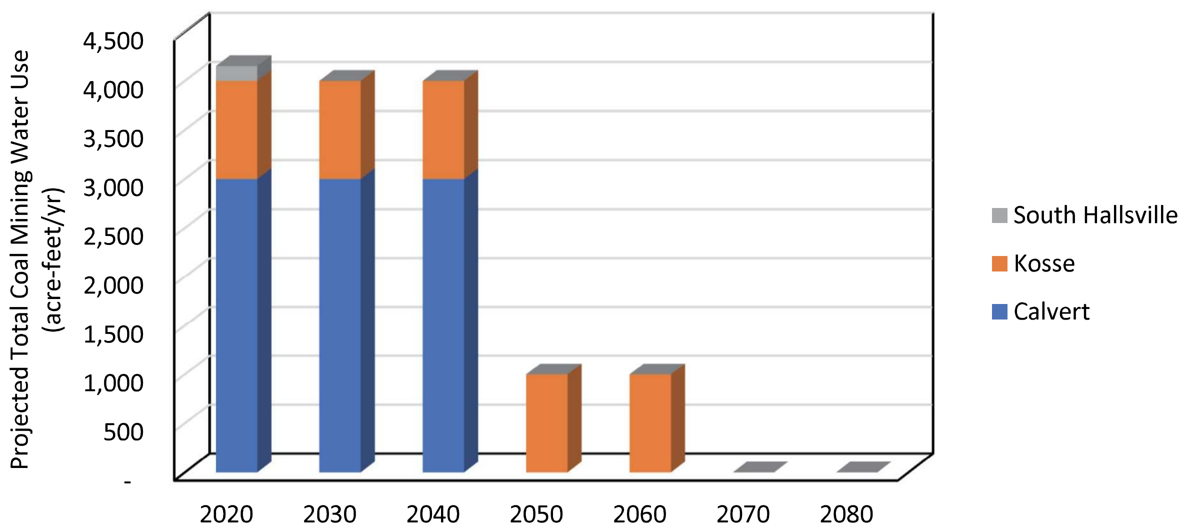


Figure 2-1. Projected statewide annual coal mining industry water use by mine for 2020-2080. See Figure 2-1 for mine locations.

# 3. Aggregate Mining Industry Water Use

## 3.1 Overview

The aggregate industry encompasses sand, gravel, and crushed stone mining primarily for construction purposes. For this study, we refer to aggregate mining operations in Texas as those that fall within the North American Industry Classification System (NAICS) code range from 212311 to 213115 (Table 3-1). Sand and gravel that is mined by concrete manufacturers is classified as an industrial activity and is not a part of this study. However, operations that might sell sand and gravel to a concrete manufacturer or other industrial user are considered part of the aggregate mining industry in this study.

Water is used by the aggregate industry primarily for grading sands and gravels, i.e., usually for washing gravel and sand to remove silt and clay to generate a product with the desired particle sorting. Historically, water use data for the aggregate mining industry has been lacking. Many operators do not respond to requests for surveys by state agencies such as the TWDB and TCEQ. Also, many operators use rainwater that collects on-site, and whatever the source, water is frequently reused multiple times in a closed-loop process.

## 3.2 Data Sources and Analytical Methods for Aggregate Mining Water Use

The primary sources of water use information by the Texas aggregate mining industry are tabulated Water Use Survey results provided by both the TWDB and TCEQ by verbal request that were compiled from survey responses by individual operators (TWDB, 2021-1). The TWDB also requested aggregate water use from Groundwater Conservation Districts (GCDs) and provided the results from six responding districts.

The TWDB provided survey results for 944 operators in the NAICS aggregate mining industry categories in Texas that were sent water use surveys. The TWDB dataset contained annual total water use reported variably for 2010 through 2020. A similar dataset provided by the TCEQ listed 1,002 operators and annual total water use values reported variably for years 2016 through 2019. The TCEQ dataset also distinguished 273 inactive sites and provided notations regarding the nature of any water use at some sites. We combined the information to generate a single database comprehensive of both the TWDB and TCEQ datasets. In cases where there was conflicting information between the two datasets regarding reported water use volumes, the larger volumes were used.

We used Google imagery to examine non-reporting sites for evidence of recent activity and the absence or presence of on-site equipment. In making decisions whether to assign an estimated water use value to a given non-reporting site, the extent of the disturbed area and the nature of similar operations in the same county or surrounding counties were taken into consideration. Where water use was generally reported for similar operations in a county, the approximate water user per disturbed acre was applied to non-reporting sites that appeared to be active.

Projected county level total annual water use by the aggregate industry was estimated based on county population projections for 2020 to 2070 as published by TWDB in the 2022 State Water Plan (TWDB, 2021-2). Populations for 2080 were calculated by extending trends defined by 2060 and 2070 populations. Projected water use by county is assumed to track population changes in direct proportion.

## 3.3 Results

Total aggregate mining water use in Texas was 74,822 acre-ft in 2019 (Figure 3-1, Table 3-1). There was a total of 1,295 aggregate operations located in 201 counties that were listed in the combined TWDB and TCEQ dataset (Figure 3-2, Table 3-2). In the overall combined dataset, 84% of operations (1,090 sites) reported either positive water use (381 sites, 29%) or zero water use (709 sites, 55%), representing 71,599 acre-ft (96%) of aggregate industry water use. Water use was estimated for the remaining 16% of operations (205 sites) with positive water use (23 sites, 2%) or zero water use (182 sites, 14%), representing 3,223 acre-ft (4%) of the total aggregate industry water use.

Of the 84% of operations that did respond, 1,082 operations (99%) either provided water use information during 2019-2020 (positive or zero) or indicated they were closed. The remaining eight responding operations (1%) provided water use information during the period 2016-2018. If water use data were reported for both 2019 and 2020 for a given operation, the larger of the values was used to represent 2019 water use.

Overall, 724 operations (57%) appeared in both datasets. In the TWDB dataset, there were 406 operations (32%) that did not respond to the survey. In the TCEQ dataset, there were 240 operators that did not respond with positive water use but reported either zero water use or that they were no longer operating. A total of 52 operations, all of which reported water use values, had only county locations and did not have coordinate locations. A further 78 operations, all of which reported either zero water use values or that they were closed, did not have either coordinate or county locations.

In many cases, non-reporting sites showed no evidence of recent activity, with no facilities or equipment located on-site. Using Google Imagery, many sites were overgrown with vegetation and/or had excavated areas that were completely flooded. Many such sites were also quite small with disturbed areas much less than about 10 acres. Sites with combinations of these characteristics were generally assigned zero water use, though values were estimated for a few sites based on reported water use per disturbed acre for nearby operations. Mistakenly assigning zero water use to sites with these characteristics should not have a significant impact on total water use values. The statewide median water use for sites reporting positive water use is 8 acre-ft. Assigning that value to all of the sites that were assigned zero water use would result in about 1,500 additional acre-ft statewide, or a 1.9% increase.

For systems that did not report water use by source (groundwater, surface water, or reuse) and that were not within a mile or so of surface water bodies, all water use was assumed to be groundwater because groundwater is generally more available, less expensive, and easier to obtain than surface water. The county level data are summarized in Table 3-3.

Industrial sand mining in the Permian Basin region represented 12,055 acre-ft of aggregate water use in 2019, or about 16% of the state-wide total. There are 20 such sites listed in Winkler County (11 sites), Crane County (6 sites), and Ward County (3 sites). By comparison, HF water use in the Permian and Permian-Far West plays was about 222,000 acre-ft in 2019 (Table 1-2b), about 18 times greater.

Most of the aggregate industry water use was groundwater (79%), followed by surface water (19%), and reuse (2%). Most of the water use was by sand and gravel operations (64.1%), followed by the crushed stone operations (35.3%), with the remaining use by dimension stone (0.3%), and other (0.2%) operations (Table 3-1). Total aggregate water use from this study for 2019 is very similar to that estimated by Nicot et al (2011) for their 2010 water use estimate (75,300 acre-ft) and about 10% less than their estimated (then future) 2020 water use (82,500 acre-ft).

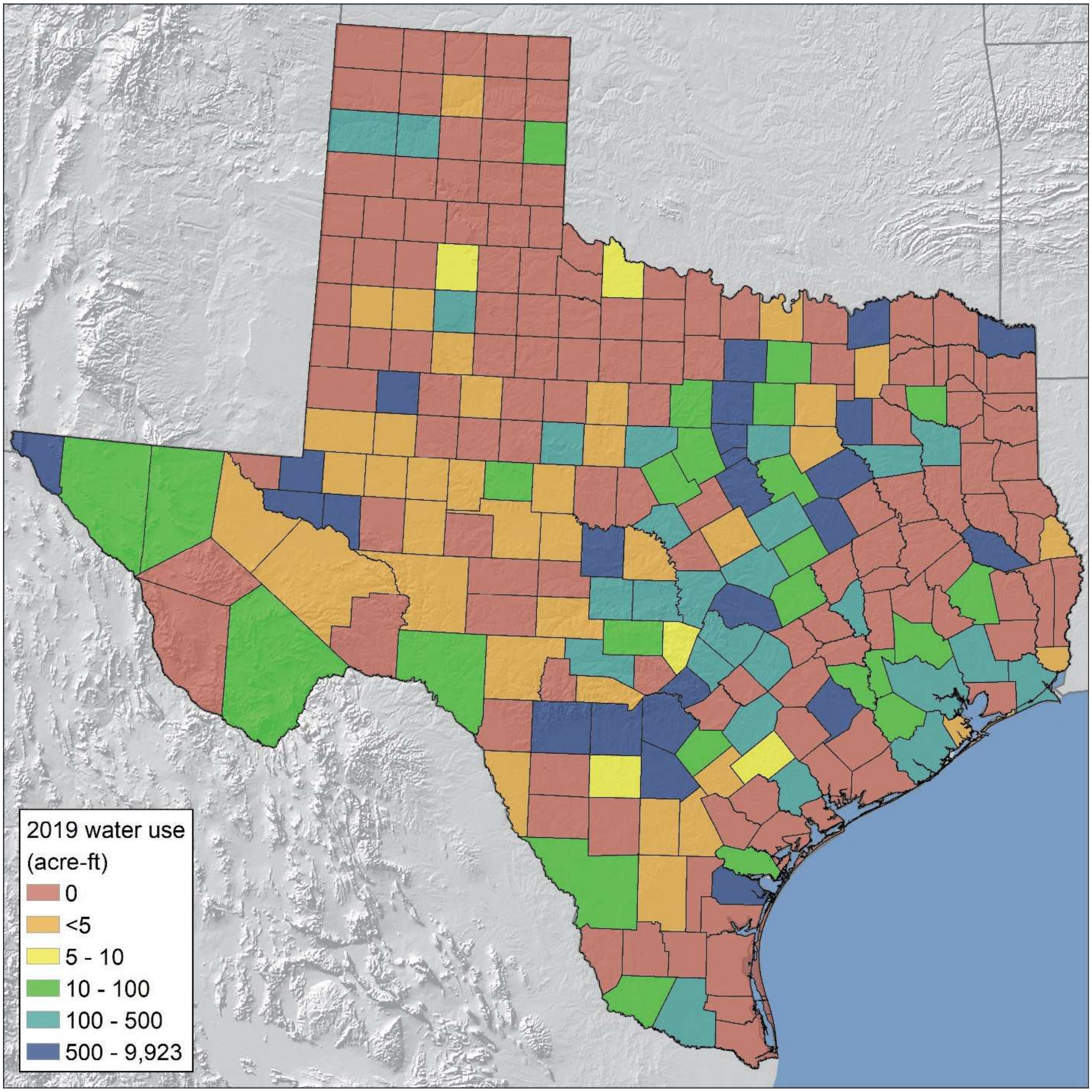


Figure 3-1. Distribution by county of 2019 aggregate industry water use. Total water use was 74,822 acre-ft.

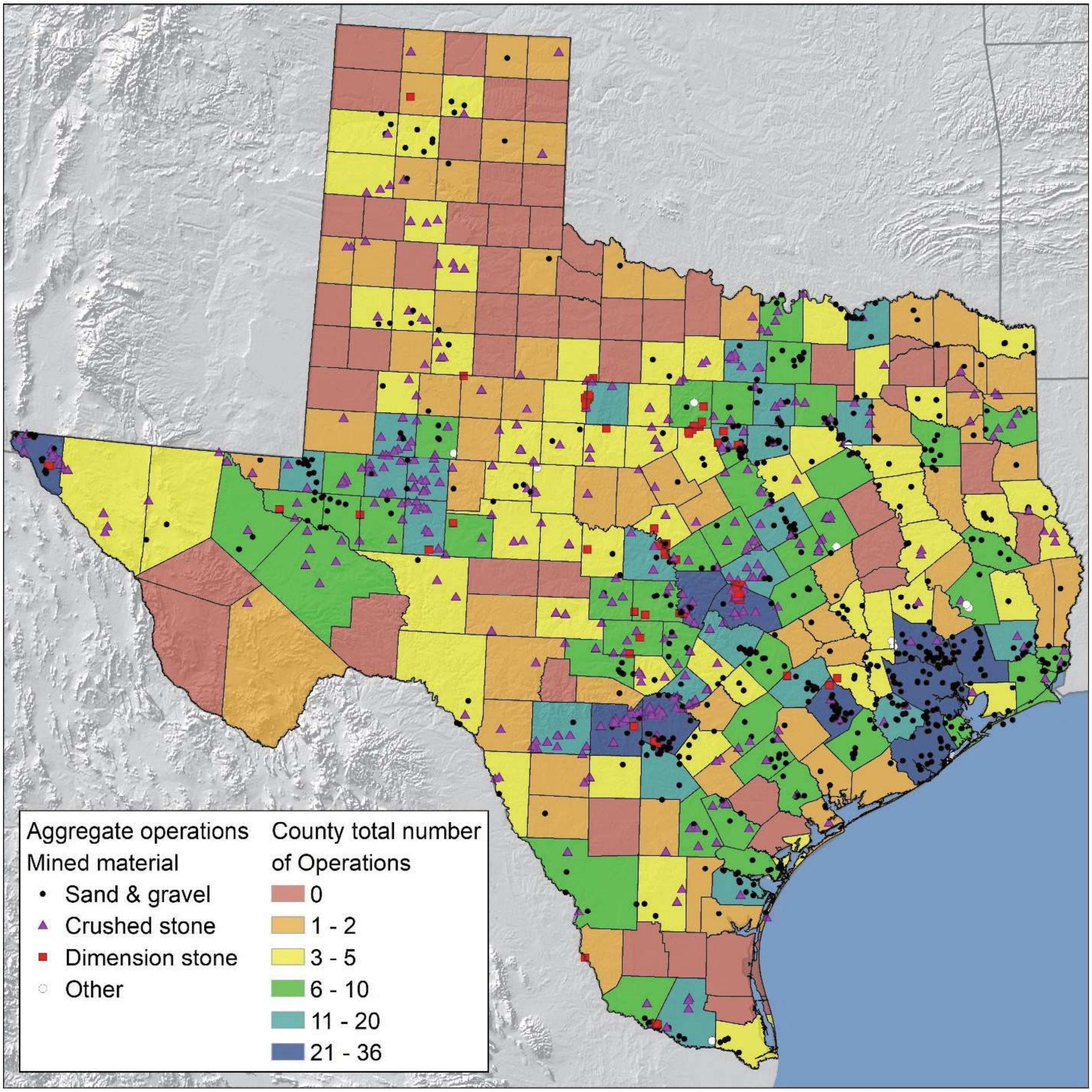


Figure 3-2. Locations and total numbers by county of 1,165 aggregate operations in Texas that were listed in the dataset for 2016-2020. Not shown are 130 operations that did not have coordinate locations. However, 52 of these sites did have county locations and are included in the map county symbology. See text for discussion.

County level total annual water use by the aggregate industry is expected to increase by 8-12% per decade during 2020-2080 for different counties (Figure 3-3, Table 3-4), corresponding to about 84,000 acre-ft/yr by 2030 and increasing to about 128,000 acre-ft/yr by 2080. Projected values are estimated based on projected county population projections as published by the TWDB in the 2022 Texas Water Plan. Water use is assumed to track population percentage changes directly.

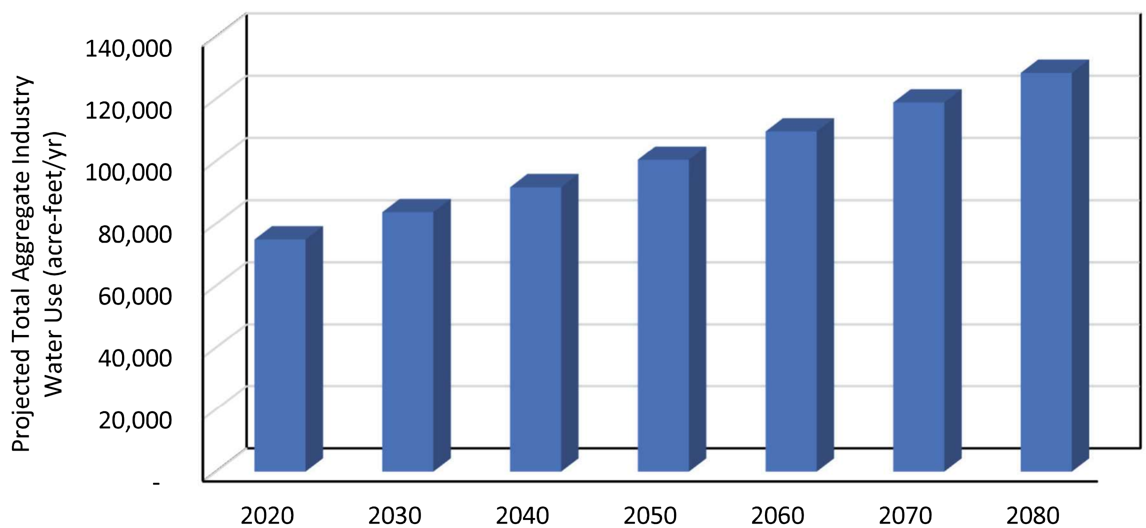


Figure 3-3. Projected statewide annual aggregates industry water use for 2020-2080.

# 4. Mining Industry Water Use Summary

Total mining water use in Texas was 395,000 acre-ft in 2019, representing 2.8% of water use in the state (14.1 maf) (TWDB, 2021-1) (Figure 4-1, Table 4-1a) and very close to the TWDB estimate of 408,622 acre-ft. Mining water use was analyzed for three sectors, including the oil and gas industry (Figure 4-2, Table 4-1b), coal mining (Figure 4-3, Table 4-1c), and aggregate mining sectors (Figure 4-4, Table 4-1d). Most mining water use (316,000 acre-ft., 80%) was associated with the oil and gas sector with the greatest use located in the Permian Basin in West Texas and in the Eagle Ford Play in Southcentral Texas. The aggregates industry accounted for the next greatest water use (74,800 acre-ft, 19%) generally located near population centers. The coal mining industry accounted for the least water use (4,200 acre-ft, 1%).

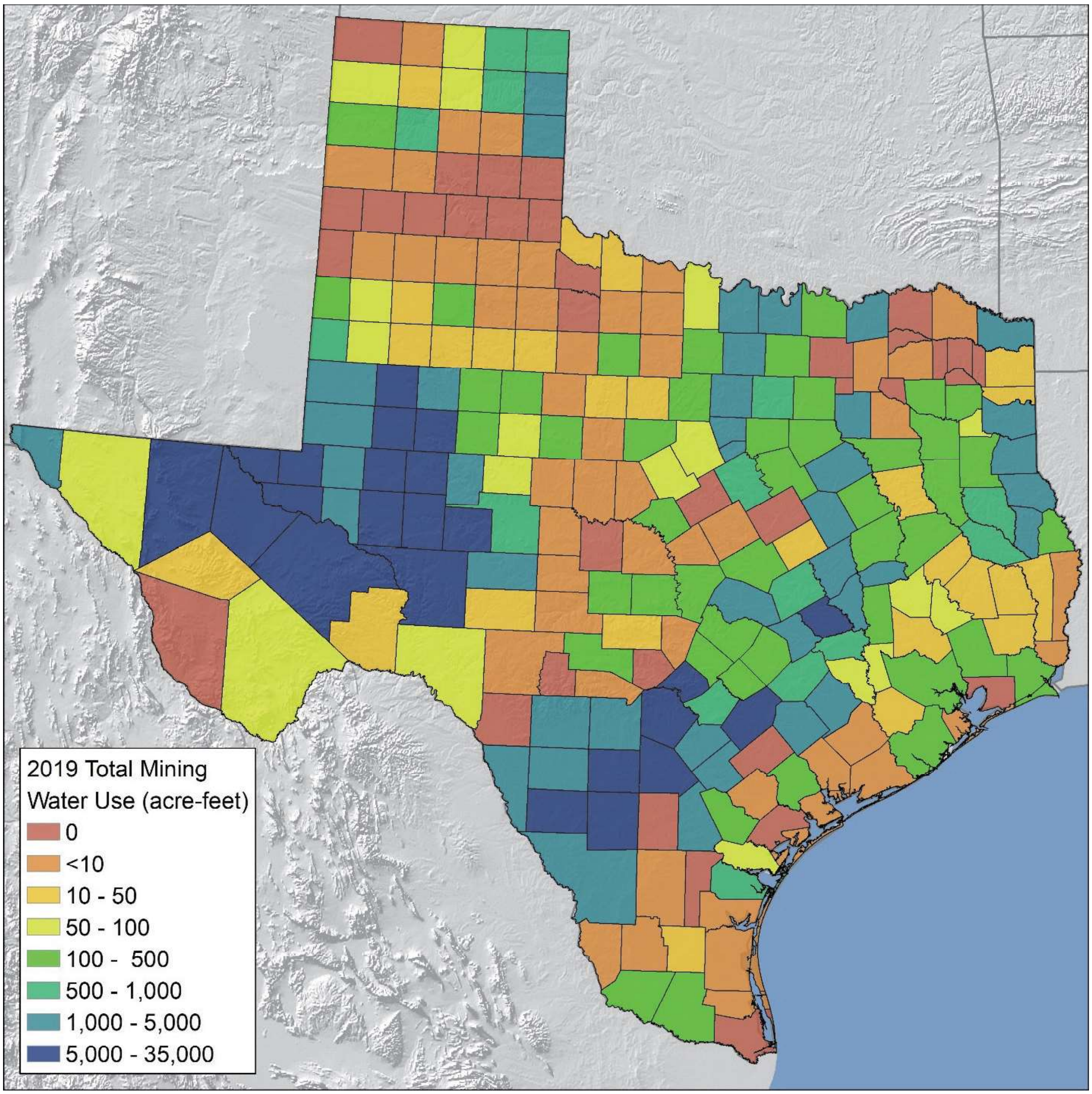


Figure 4-1. Total mining water use for Texas in 2019 of 395,000 acre-ft. Data are provided in Table 4-1a.

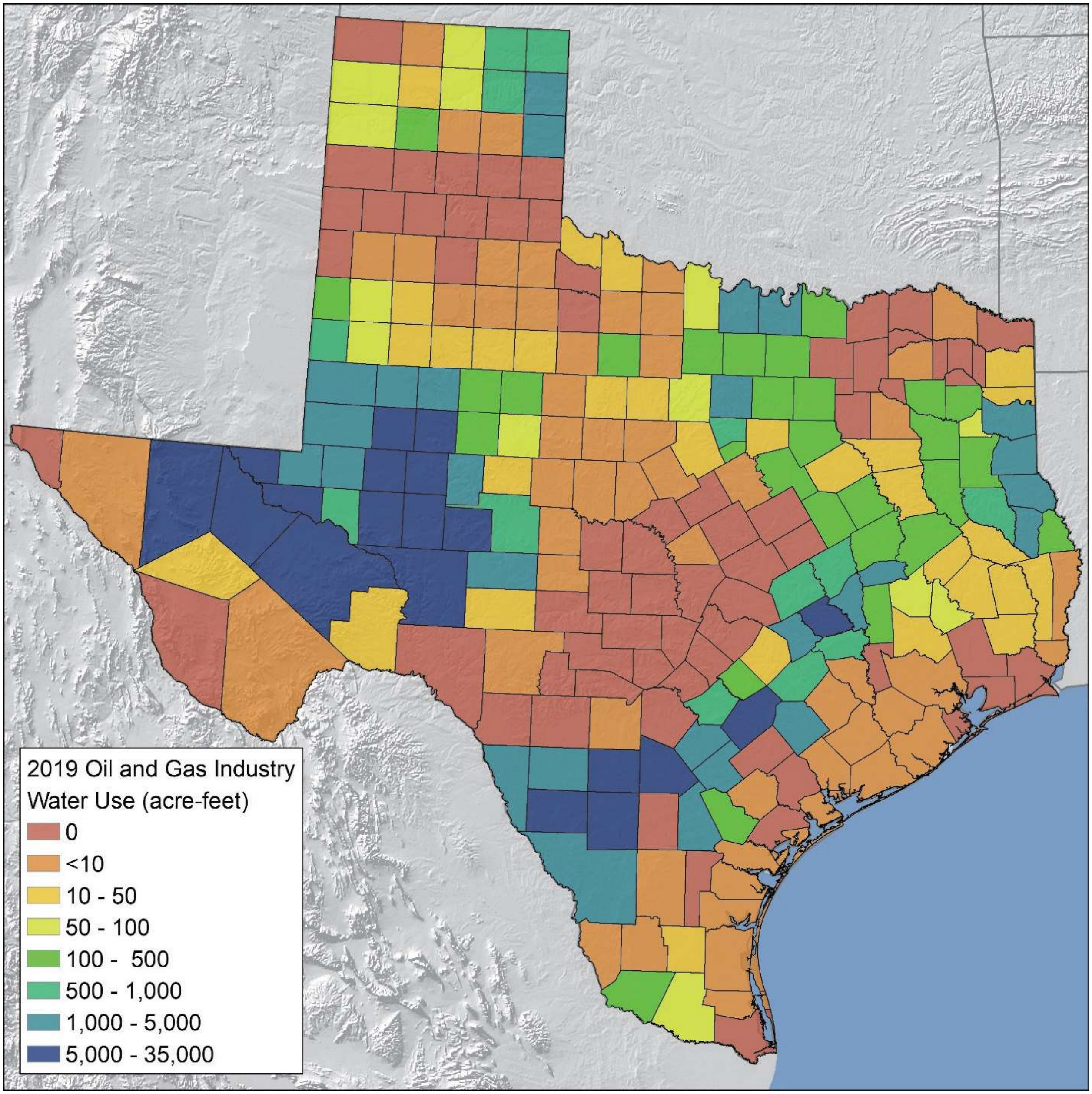


Figure 4-2. Oil and gas industry sector water use in Texas for 2019 of 316,000 acre-ft. Volume range category symbolization is the same as for Figure 4-1. Data are provided in Table 4-1b.

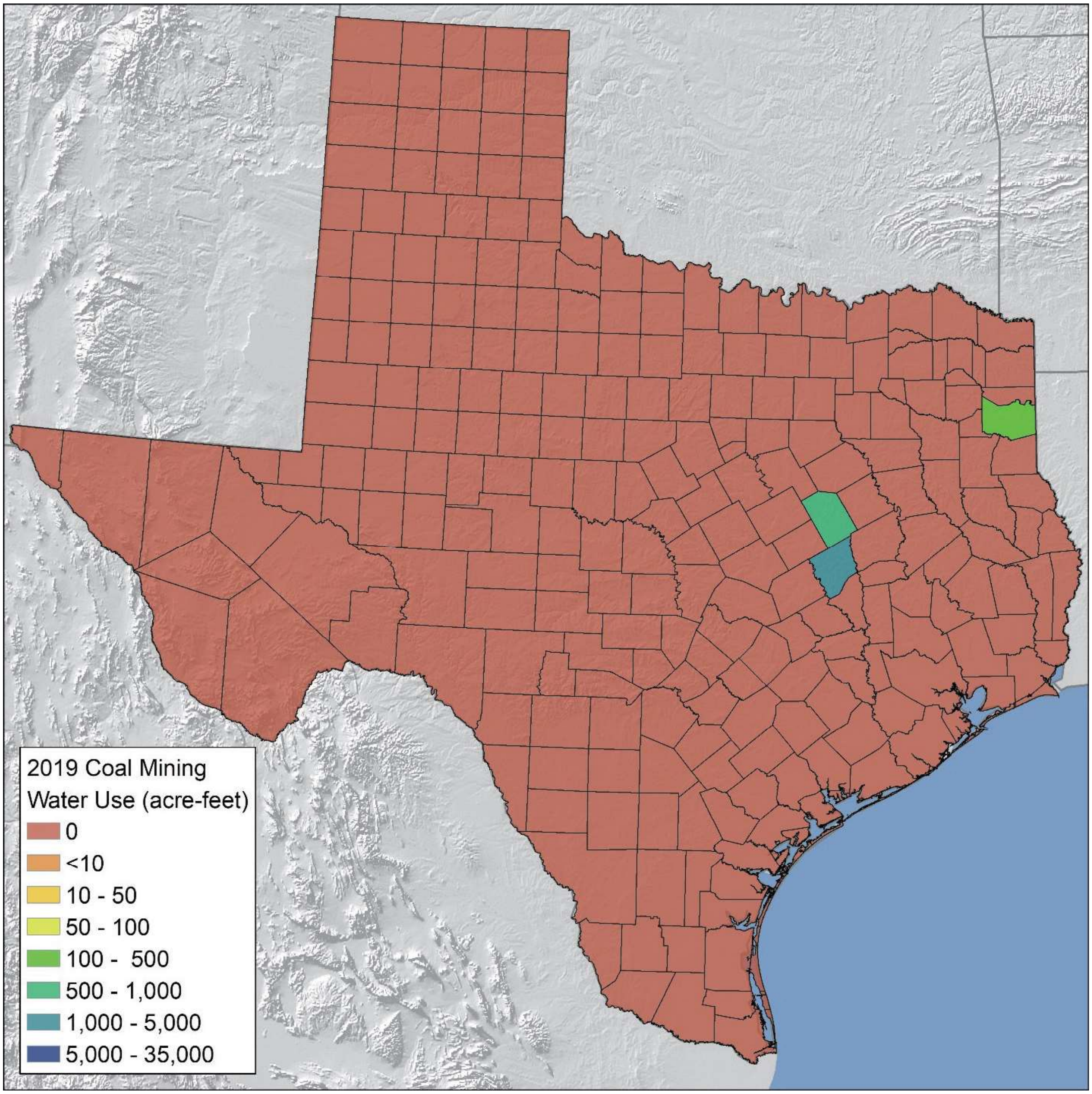


Figure 4-3. Coal mining sector water use in Texas for 2019 of 4,200 acre-ft. Volume range category symbolization is the same as for Figure 4-1. Data are provided in Table 4-1c.

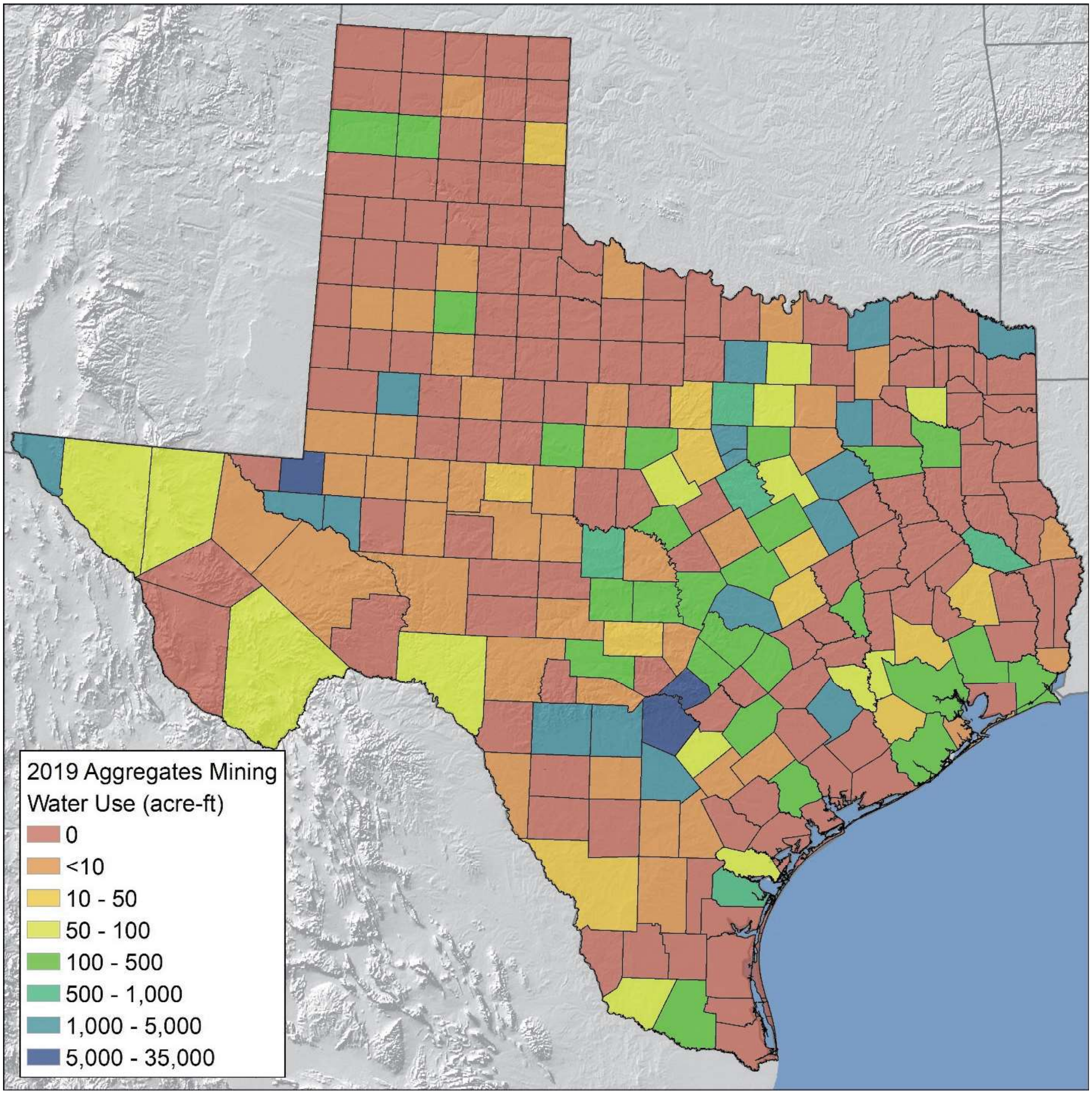


Figure 4-4. Aggregate mining sector water use in Texas for 2019 of 74,800 acre-ft. Volume range category symbolization is the same as for Figure 4-1. Data are provided in Table 4-1d.

## Projected Mining Water Use

Total mining water use in Texas is projected to increase from about 395,000 acre-ft in 2020 to about 425,000 acre-ft/yr by 2060 based on a steady demand of HF water, a gradual increase in aggregates industry demand as populations increase, and minor and diminishing coal mining water use (Figure 4- 5, Table 4-1a). Mining water use is projected to decrease sharply thereafter to about 248,000 acre-ft/yr by 2080 based on declines in HF water use demand as the major unconventional oil and gas plays mature.

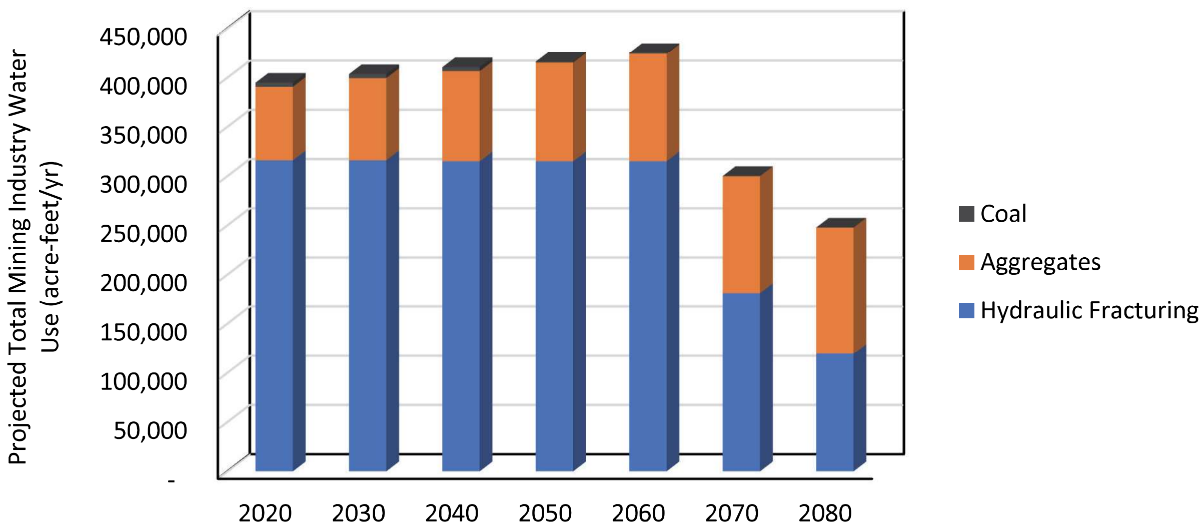


Figure 4- 5. Projected total annual water use by the mining industry in Texas.

Future groundwater pumping for HF water use demand may impact regional groundwater levels in two of the major plays including the Eagle Ford Play and the Permian Basin. In the Barnett, there is expected to be very little future development and thus HF water demand will be small. In the Haynesville Play, the primary groundwater source is the Carrizo-Wilcox, with lesser contributions from the Queen City-Sparta aquifers as well. Groundwater and surface water are abundant in this region and aquifer recharge rates are high, averaging about 3.5 in/yr (Reedy et al., 2009). Groundwater pumping for HF demand in the Haynesville is comparatively small and groundwater levels will likely not be impacted regionally.

In the Eagle Ford Play, the primary groundwater source for much of the play is the Carrizo-Wilcox aquifer, which provides abundant fresh water over most of the region. There have been occurrences of local water level declines up to several hundred feet in the Carrizo-Wilcox as a result of pumping for HF. However, those instances have thus-far been relatively localized and water levels tend to recover following cessation of pumping due to the confined nature of the aquifer. Overall, water levels will likely be moderately impacted in the Carrizo-Wilcox as a result of sustained pumping for HF (Scanlon et al., 2020). The Gulf Coast Aquifer outcrops in the Eagle Ford Play in a relatively limited region along part of the southeastern boundary of the play and conditions range from unconfined to confined. However, this region of the play is predominantly deep and dry gas production, which is not the primary target of present drilling activity.

Water resources in the Permian Basin are limited. Surface water is all but absent and groundwater resources are stressed due to low recharge rates and pumping for irrigated agriculture demand. Monitoring of the most utilized aquifers in the Permian Basin in areas that coincide with HF water demand, which include primarily the Edwards-Trinity Plateau and Pecos Valley Aquifers, have thus-far not indicated declining trends in water level in areas primarily associated with pumping for HF demand. However, the monitoring network is currently not sufficient to quantify regional water level changes. The greatest water level declines have been primarily associated with irrigated agriculture. In the northern Midland Basin the Ogallala Aquifer is a source of HF water where aquifer saturated thickness is relatively thin and pumping for HF competes with agricultural demands. However, the Wolfcamp A and B formations are also not as thick in the northern Midland Basin as compared to the central areas and there has been relatively less unconventional oil and gas development. Therefore, total HF water demand may be less intense in that area.

## Limitations of this Study and Future Work

This study provides a comprehensive assessment of current and projected mining water use in Texas. The results presented in this analysis greatly expand on previous mining water use in Texas published in 2011 when unconventional oil and gas production was in the early stages of development (Nicot et al., 2011). One of the main limitations of the current study is the lack of data on the extent of produced water reuse to support hydraulic fracturing. While anecdotal data suggest increased reuse of produced water for HF, particularly in the Permian basin, there are no formal reports on produced water reuse. Increasing seismicity in the Permian Basin linked to SWD and hydraulic fracturing along with increasing volumes of produced water may result in increased reuse of produced water for HF in the future. Anecdotal accounts also suggest that operators share PW among each other to support HF water demands and reduce subsurface disposal.

The Groundwater Protection Council is working with the oil and gas industry to encourage submission of data on the source of water used for HF, including produced water and brackish groundwater. The FracFocus database is being modified to make it easier for operators to report different water sources. More accurate reporting of water sources of HF in FracFocus would help constrain the splits of surface water and groundwater used for HF in the Haynesville Play. Reporting of the quality of the source water would also be helpful in constraining impacts of HF water use on freshwater resources. Future studies should consider these data in the water budgets for hydraulic fracturing water use.

Projections of HF water use would benefit from improved assessments of TRRs and outlooks constrained by economics and technical advances. Projections of HF water use in this study rely on TRRs for each of the plays, with the exception of the Barnett Play which has already matured. TRR projections for the Eagle Ford and Haynesville plays may overestimate actual future production because it is unlikely that all potential HF drill locations will be economical. Therefore, these estimates of HF water use in the future likely represent upper bounds on actual HF water use. The much longer record for unconventional oil and gas production relative to the 2011 report and likely for the next statewide assessment should provide much more data to constrain TRR estimates and also to allow energy outlooks that consider a range of commodity prices as experienced in recent years. The TRR estimates for the Permian Basin were constrained to the Wolfcamp A and B units; however, there are about eight additional unconventional reservoirs in the Basin that could produce oil and gas. With increasing development of these other units in the future, new TRR estimates should be feasible for some of these other units.

## Online Data Access

This final report and the historical and current water use estimates and projections by the Texas mining sector are publicly accessible via an online data dashboard on the TWDB's website:

https://www.twdb.texas.gov/waterplanning/data/projections/MiningStudy/index.asp


## Acknowledgments

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The authors are grateful for thoughtful project management and insights of Katie Dahlberg and Yun Cho of the Texas Water Development Board. We are also grateful for cooperation provided by C. J. Tredway of the Texas Oil and Gas Association. This study is based on excellent databases maintained by the Texas Water Development Board, the Texas Commission on Environmental Quality, The Railroad Commission of Texas, the U.S. Geological Survey, and the U.S. Energy Information Agency.

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# Responses to Draft Final Report Comments

## TWDB Comments

**Development of Water Use Estimates and Projections in the**

**Texas Mining and Oil and Gas Industries**

**2020 - 2022**

**TWDB Contract # 2100012474**

**USGS Award Number G20AC0039**

**Comments to Draft Final Report**

**REQUIRED CHANGES**

Per Contract Exhibit C, Item 2, include a copy of these Texas Water Development Board (TWDB) comments in the final report.

**General Draft Final Report Comments:**

1. Per Contract Exhibit C, Item 1-B e., please describe any updates made to databases or data delivery during period of award. If none, then please state this in the main body of the report.
   *Response: Added text to the Introduction section regarding updates to databases.*

2. Per Contract Exhibit C, Item 1-B f., please describe any problems, including in obtaining data, encountered during the project period.
   *Response: Added discussion to the Introduction section regarding problems encountered*

3. Per Contract Exhibit C, Item 1-B g., please provide notice of any changes in databases or web services that would impact future integration of data into the U.S. Geological Survey (USGS) databases.
   *Response: Added discussion to the Introduction section regarding problems encountered*

4. Per Contract Exhibit C, Item 1-B h., please add a List of Tables with table names and references to the appendices.
   *Response: List of Tables added to beginning of document with table names references and references to the appendices.*

5. Please include a reference section with appropriate citation references in the text.
   *Response: Reference section added with citations.*

6. Please be sure that all numbers greater than 999 have thousand separators. The current use of thousand separators in the report is inconsistent.
   *Response: Added separators.*

7. Please consistently use 'acre-feet' throughout the report, instead of 'ac-ft' or 'acre-ft' to avoid confusing the reader.
   *Response: Used acre-feet throughout.*

8. In the Executive Summary, please define conventional versus unconventional wells and/or plays to help the reader better understand the context throughout the report. Additionally, to help orient the readers, please define different terms, such as shale, plays, and basins, which are used throughout the report
   *Response: Added definitions for conventional and unconventional as they pertain to both oils and gas reservoir characteristics and to oil and gas wells. Added definitions for relevant terms.*

9. Please create print formats for all tables and do not have separate tables in the digital spreadsheet from the printed appendices (PDF).
   *Response: All tables are now in print form only, with the exception of Table 3-2 as per communications with Katie Dahlberg. Table 3-2 contains the combined TWDB and TCEQ aggregate operator survey results. An abbreviated form of Table 3-2 is included in print format and the expanded version is submitted in digital form.*

10. Each time a percent distribution is described, please ensure that the total of components equals 100%. For example, on Page 9, second to last full paragraph, the percent distribution of wells in the Eagle Ford Shale equal 101%.
    *Response: This is an issue of rounding, of course. We modified stated percentages to sum to 100%, including some cases were decimal values were added.*

11. Throughout the report, please avoid using less than or greater than (>, <) and "~" symbols in front of approximations. Consider spelling out "approximately", "greater than", and "less than." Likewise, please state "times" instead of "x" such as "3x" should be "three times." This will ensure accessibility requirements are met.
    *Response: Removed referenced symbols and converted their meanings to text..*

12. Per Contract Exhibit A, Task 2, the contract requires identifying source water for hydraulic fracturing by county and by play. Please provide water supply source including surface water, groundwater (fresh/brackish), reuse/recycled for hydraulic fracturing (HF) by county and play.
    *Response: Sources for HF water were added*

13. All table references should direct the reader to the correct table. Examples are on page 28 when Table 12 is referenced, and on page 35 during the discussion about the Permian Basin, Table 1-14c and Table 1-14b are refenced which both refer to the Haynesville Play.
    *Response: References to tables now include specific sub-parts (a, b, etc.) throughout the report.*

14. On page 11, please clarify why Enhanced Oil Recovery (EOR) should not be included in oil and gas drilling water use estimates, regardless of the TWDB or USGS inclusion in the past.
    *Response: Discussion justifying the exclusion of EOR added.*

15. Please discuss if there was a significant impact in the mining industry in the year 2020 due to the global pandemic. This is particularly relevant since the report methodology relied on using 2020 values, such as in the Barnett play projections (page 28) and the Delaware and Midland basin median water use intensities (page 36).
    *Response: Added discussions where appropriate in each play section characterizing potential impacts of the pandemic on oil and gas activity.*

16. Please add a qualitative discussion about the trend in the HF historical data illustrating the increased water use for HF that can be attributed to the lateral length well design component. This appears to be a significant factor that has affected increased water use since the first mining use estimates report was completed in 2011. Graphs comparing lateral lengths, water use intensity (gallons/foot), and/or total water use per frac (gallons/well) over time would add comprehensive value to this report. For example, this could be incorporated as a paragraph in the executive summary or results sections via a graph for each play using the numbers tabulated in Tables 1-13a, 1-14a, 1-15a and 1-16a.
*Response: Graphs and discussion were added to the respective play sections.*

17. Please include a discussion or evaluation of the potential impact of water pumping for HF might have on groundwater depletion per Task 2 in Contract Exhibit A.
*Response: Discussions were added for each major play in the Section 4 summary.*

18. Per Contract Exhibit A, Task 3, please add a qualitative discussion around the economic outlooks developed to provide time series projections constrained by economic limitations and commodity pricing.
*Response: Added discussion to clarify the projection parameters.*

19. In section 1.3, please describe efforts made to work with operators in the oil and gas industry to collect hydraulic fracturing data.
*Response: Added discussion.*

**Specific Draft Final Report Comments:**

20. Per Contract Exhibit C, Item 1-A a., please add the USGS Award Number to the Cover Page.
*Response: Done*

21. Per Contract Exhibit C, Items 1-A d., e., and f., please add the report author(s) title, address, phone number, and email address.
*Response: Done*

22. Per Contract Exhibit C, Item 1-A g., please add the contract start and end dates.
*Response: Done*

23. Per Contract Exhibit C, Item 1-B d., please include the following language:

*"The study will address Tier 1 USGS data goals by providing annual water use estimates by county, source of water, and water type. The study will also address Tier 2 data goals by verifying specific locations for mining operations in each sub-category. This information is critical to support state and local officials in their decisions regarding future water supplies, including stakeholders engaged in the regional water planning and groundwater management area joint planning processes. It will also support water modeling efforts, including the development of groundwater availability models. This project also addresses the U.S. Department of the Interior priority to avoid future water conflicts by providing current water use data and long- range water demand projections to local, regional, and state planning efforts, including the regional water planning and groundwater joint planning processes, which are the state's most consequential venues where stakeholders convene to address competing water supply concerns."*
*Response: Added text as 3rd paragraph in the Introduction.*

24. On page four, third paragraph, please cite the reference of the first sentence ("Current total water use for all purposes in Texas is ~16 million ac-ft/yr.") and specify the year of the water use estimates.
    *Response: The value was actually inaccurate and has been changed and referenced.*

25. In the Executive Summary, under the 'Oil and Gas Industry Water Use' section, please define "EOR" and "SWD" and then use acronyms throughout the report.
    *Response: Done.*

26. On page six, please spell out "maf" before using the acronym throughout the remainder of the report.
    *Response: Done.*

27. In the Executive Summary, on page six, second to last full paragraph, please clarify "In the Eagle Ford play, unconventional development began much later much later (2008)..."
    *Response: Done.*

28. On page seven, please define TWDB and TCEQ before using acronyms throughout the remainder of the report.
    *Response: Done.*

29. On page 11, second paragraph from the bottom, please cite the 2015 USGS data.
    *Response: Done.*

30. On page 11, last paragraph, please explain the "multiple attributes" used to identify records.
    *Response: Done.*

31. On page 12, first paragraph, please specify the source of this statement or explain how you came to this conclusion, "Water use by the oil and gas industry in Texas is almost entirely from groundwater sources."
    *Response: Done.*

32. On page 13, first full paragraph, please remove duplicate sentences.
    *Response: Done.*

33. On page 13, second to last paragraph, please specify the year range used for water use estimates "multi-year trends of recently completed wells."
    *Response: Done.*

34. On page 14, in the 'Oil and Gas Water Use Projections' section, please justify your assumption that maximum annual water use assumed to continue into the future for conventional water use for the non-core counties rather than the average and also explain why Barnett was excluded. Additionally, please address the contradiction that counties outside of major plays will have oil and gas use that "continues into the future, albeit at relatively smaller volumes," but the max HF water use volume between 2010-2019 was assumed for the projections.
    *Response: Done. The discussion was modified for clarity and to justify using the maximum vs medium values and the quoted text was removed.*

35. On page 16, last paragraph, fifth sentence, please correct "Total HW…"
    *Response: Done.*

36. On page 17, second paragraph, please identify what other mining water use was included in the USGS study which is outside the scope of the current study.
    *Response: Clarified statement.*

37. On pages 17 and 18, split paragraph, please review the well distribution. Well counts listed total 6,398 which is 47 fewer wells than the total count of wells with information pertaining to water type. This value is inconsistent with the stated value of 300 excluded wells.
    *Response: Done. Accounted for remaining wells*
38. On pages 19 to 28, please change references to Table 1-10, Table 1-11, and Table 1-12 referenced in the reports to the correct referenced tables including letter a, b, c, or
    *Response: Done.*
39. On page 28, second paragraph, first sentence, please explain "though just ten of those counties had more than 1% of all wells completed in the play" and what it means for a well to not be completed.
    *Response: Replaced "completed" with "drilled".*
40. On page 30, second paragraph, please clarify if non-producing wells were included for the Eagle Ford play projections.
    *Response: Clarified.*
41. On page 30, paragraph below Figure 1-21, please correct the approximate values so that total well inventory equals the sum of completed and future wells.
    *Response: Done.*
42. On page 32, first paragraph, please clarify if the Bossier and Haynesville Shales are separate formations.
    *Response: Added discussion about formation naming conventions.*
43. On page 36, comparison with Total Recoverable Resources (TRR) estimated by USGS, please explain the major factors causing the differences in TRR estimates so the readers understand the validity of the TRR estimates used in this study.
    *Response: Added discussion.*
44. In the 'Hydraulic Fracturing Water Use Projections' section, there is no reference to Table 1-17 (Projected Hydraulic Fracturing (HF) water use for counties in play core areas).
    *Response: Added reference to table.*
45. Page 37, please cite the basis of the third sentence, "In recent years, many power plants began importing cleaner-burning subbituminous coal mined in Wyoming to supplement or altogether replace Texas lignite as a fuel source."
    *Response: Added source reference.*
46. On page 40, section 3.2 is mistitled.
    *Response: Fixed.*
47. On page 40, first sentence in section 3.2, please specify the source of the TWDB and the TCEQ data (for example, TWDB's annual water use survey).
    *Response: Added reference.*
48. Page 41, paragraph one, please specify a reference year for the data presented.
    *Response: Added reference.*
49. On page 41, Figure 3-1 description, the author calls out 130 operations not shown on the map. It is unclear if these unlocated operations were used in the study or how they would be assigned to a county without a coordinate location or listed county. Please clarify.
    *Response: Added descriptive discussion in body text.*

50. On page 42, first paragraph, please use commas to separate each list item when describing the source water distribution in the second and third sentences of that paragraph.
    *Response: Done.*
51. On page 43, first paragraph, in the third to last sentence please specify the number of operations which were excluded and the number of sites which were estimated.
    *Response: Done. Reorganized discussion in this section.*
52. On page 43, first paragraph, the last sentence states all water was assumed to be groundwater for systems that did not report water by source. Please add an explanation for why this assumption was used.
    *Response: Discussion added.*

**Figures and Tables Comments:**

53. Please list all tables from the Appendices in the table list (a, b, c, etc.).
    *Response: Done.*
54. Please refer to specific tables in the paper (a, b, c, etc.).
    *Response: Done.*
55. The font within the tables is inconsistent. Please make the table rows use a consistent font and text size.
    *Response: Done.*
56. Please ensure all tables are being correctly referenced. For instance, on page 35, the second paragraph from the bottom, the discussion is focused on the Permian Basin and references (Table 1-14c) and (Table 1-14b), both of which are referring to the Haynesville Play.
    *Response: Done.*
57. Please add appropriate spacing between the Figure 1-1 description and the next paragraph.
    *Response: Done.*
58. On page 28, please correct the reference to Table 12 in the last paragraph.
    *Response: Done.*
59. Table 1-12b: The table caption reads "Barnett Play unconventional well completions by county for 2005-2021 and HF water use parameters for projected HF water Use" but the table does not include any water use. Please correct the caption accordingly.
    *Response: Done.*
60. Figures 1-23 and 1-24: please change the caption from Eagle Ford Play to Haynesville Play.
    *Response: Done.*
61. In Table 1-16, please add footnotes spelling out the abbreviations in the table Comparison of Permian Basin Technically Recoverable Resources (TRR) values between USGS and BEG analyses.
    *Response: Done.*
62. On pages 25 and 26, Figures 1-15 and 1-16, and on page 36, Figure 1-26, the subregion basin names are hard to interpret. Please adjust the label properties so that subregion labels are distinguishable from county labels.
    *Response: Changed subregion names to bold.*

63. Please add a reference to table 1-15g Permian Basin HF Water Use Projections 2030-2080 in section 1.4 Results.
    *Response: Reference added.*

64. On page 36, within the 'Oil and Gas Industry Water Projections' the table is mislabeled. Please change to table 1-18a (instead of "Table 18-1").
    *Response: Fixed.*

65. On page 37, within section 2.1 the reference to tables are mislabeled. It should be table 2-1a and table 2-1b.
    *Response: Fixed.*

66. Please indicate the difference between "No" and "NR" in the APO survey data table (Table 3-2).
    *Response: Added explanation to caption.*

67. In Figure 3-1, please specify a reference year for the data used in the figure.
    *Response: Added reference year range.*

68. In Figure 4-2 caption, please correct the reference to Figure 4-1 from "Figure 4-0-1."
    *Response: Fixed.*

69. Please include in the Appendices, Table 4-1 from the digital spreadsheet that includes projections by mining type.
    *Response: Expanded Table 4-1 to include the component types.*

## SUGGESTED CHANGES

**Specific Draft Final Report Comments:**

70. Please consider providing an acronym list at the beginning of the report.
    *Response: Added list.*

71. Please consider ensuring that consistent spacing and numbering formats are used throughout the report, such as on page four the first paragraph has two different numbering formats.
    *Response: Done.*

72. After an acronym is defined in the paper, please consider continuing with the acronym only. Several acronyms are defined multiple times.
    *Response: We find that providing a repetition of the acronym definition can be helpful at strategic locations in the text*

73. In the Executive Summary, please consider changing "Mining water use is projected to gradually increase" to instead read "Mining water use is estimated to gradually increase."
    *Response: Done.*

74. Please consider specifying well types if water supply wells or oil and gas wells throughout the report to avoid confusion in the report and table headers.
    *Response: Attempted to distinguish between well types where confusion might arise.*

75. Please consider including limitations of the projection methodology proposed, considering market conditions, produced water management, advanced technology, etc.
    *Response: Added limitations discussion in the closing paragraphs of the Summary, Part 4.*

76. Please consider including a discussion of the potential impacts of produced water on the mining projections, including current issues with SWD wells, price of produced water management, seismicity, or reuse effort by midstream companies.
*Response: Added discussion in the closing paragraphs of the Summary, Part 4.*

77. On page six, please consider fixing the typo "The TRR isn 17,600 wells…"
*Response: Fixed.*

78. Please consider reorganizing the sections 1.3 and 1.4 into water use estimates (including methodology) and projections (including methodology) rather than group them into "Results" section.
*Response: We are comfortable with the original order.*

79. On page 11, first two sentences in the first paragraph, please consider addressing the tenses "has not historically include injection" and "does characterizes."
*Response: Fixed.*

80. On page 14, the discussion appears to jump between conventional and non- conventional and core counties and non-core counties. Please consider moving the sentence, "The HF water use projections were estimated for 58 counties located in the core areas of the unconventional shale and tight oil play," so that it follows the sentence "Hydraulic fracturing water use accounts for most but not all of the water used by the oil and gas industry." Additionally, consider adding the words "only for the" before "58 counties" so that it reads, "The HF water use projections were estimated only for the 58 counties located in the core areas of the unconventional shale and tight oil plays."
*Response: Changes made.*

81. On page 14, in the second paragraph, please consider removing the word "also", replace "remaining" with "196", and add "58" before "core counties" so that it reads "Therefore, we include estimates for the 196 counties outside the play core areas as well as for continued "conventional" uses in the 58 core counties."
*Response: Changes made.*

82. On page 15, last paragraph, please consider correcting grammatical error in "are shown by county in Table 1-1a and by play and Table 1-1b." The second "and" should be "in."
*Response: Change made.*

83. On page 17, paragraph three appears to be missing words. Please consider restating what was noted earlier, that the USGS percent saline values erroneously includes both EOR and SWD. Additionally, since this data only serves to characterize produced water quality, it may be prudent to remove Figure 1-4b, which essentially compares the same data from different contributors.
*Response: Paragraph rephrased. We left the figure as its contents are clearly described in the text and caption.*

84. Please consider consistently distinguishing between Wolfcamp A and B formations, such as on page 34.
*Response: References to Wolfcamp have been changed throughout the report to state Wolfcamp A and B.*

85. On page 36, last paragraph, please consider changing the language of "and additionally" in the first sentence.
*Response: Change made.*

86. On page 39, South Hallsville Mine and Kasse Mine, the percentage of surface water or groundwater is listed only. Please consider listing the full source water distribution.
    *Response: Added both percentages.*

87. On page 39, section 2.3 discusses the San Miguel Mine in Atascosa County. The results of the analysis concluded that the mine reported zero water use and water use at this mine is "minor and not considered in this study." In table 2-3b, the mine is not included in the projections. Please consider if it would be appropriate to estimate the water use for this mine and include projections for coal mining water use in Atascosa County or clarify how it was determined that the water use is minor.
    *Response: Expanded discussion of depressurization and removed references to "minor use" as it was anecdotal and unquantified.*

88. On page 39, first paragraph, please consider removing "However" from the second full sentence.
    *Response: Change made.*

89. On page 39, San Miguel Mine, please consider removing "which" from the second sentence.
    *Response: Change made.*

90. On page 40, second paragraph, please consider correcting grammar error in the second to last paragraph. The sentence should read "operators do not respond."
    *Response: Change made.*

91. On page 41, first paragraph, please consider listing the percent of non-respondents for both the TWDB and the TCEQ or remove the percentage of the TWDB non- respondents.
    *Response: This section was reorganized for more clarity.*

92. On page 43, first paragraph, please consider describing the number of operations with water use from a year prior to 2019 as eight instead of "very few."
    *Response: Change made.*

93. On Page 43, last paragraph, please consider inserting an 'and' in-between "corresponding to ~84,000 ac-ft/yr by 2030" and "increasing to ~128,000 ac-ft/yr by 2080."
    *Response: Change made.*

94. On page 44, first paragraph, when summarizing the total mining water use estimated in 2019, please consider mentioning how close the BEG estimate was to the TWDB 2019 annual estimate of 408,622 acre-feet.
    *Response: Change made.*

95. Please consider adding a qualitative discussion in Section 3 regarding water use patterns by different operations, including relative water use volumes and how water use may or may not correlate to acres disturbed.
    *Response: Discussion was not added.*

96. Please consider estimating a HF component split within the aggregate mining sector of this report. This split would identify an approximate percent of HF water use within the sector that is attributed to sand plants built primarily for providing proppant sand for fracking. This HF split might continue to be effective for the life of the play. At a minimum, please acknowledge this split as a future improvement that needs quantification. The numbers are a small component of total water use for HF but are a significant portion of total industrial mining use. At a minimum, please add a qualitative discussion to address this portion of HF water use and how it may be addressed in the next update.

*Response: Discussion specifically quantifying sand mining for proppant in four Permian Basin counties was added and compared to HF water use.*

There are numerous entities that may be identified by plant name or company name such as Lonestar Prospects, Black Mountain Sand, Freedom Proppant, ETX Proppants, SP Silica, Hi-Crush Permian, WI Texas Frac, EOG Resources, etc. that are essentially a viable component of HF water use. Counties of note include Atascosa, Crane, Dimmit, Hood, Loving, Mason, McCulloch, Somervell, Ward, Wilson and Winkler.

97. Please consider adding a qualitative discussion that addresses potential future improvements. Specifically, add a discussion relevant to the water quality component of the study to delineate the 'brine line,' or the downdip extent of brackish groundwater resources. Discuss how exceedance probability rasters might feasibly be created using the USGS Produced Water database[1] to delineate probability of exceeding 35,000 mg/L. It is the opinion of BRACS that by the time the next mining use report is updated, the brackish-brine split will be relevant for the purposes of regional groundwater planning.

**Figures and Tables Comments:**

98. Please consider including executive summary figures in the figures list.
*Response: Figures added.*

99. Please consider including the data sources within tables, either in the table description or as footnotes.

100. Please consider adding well point locations to Figure 1-1.
*Response: Not implemented. Due to high density of wells at the map scale, adding the well point locations resulted in obscuring the underlying play colors.*

101. Please consider adding polygons to the legend of Figure 1-1.
*Response: Added.*

102. In Figure 1-1, the color ramp is pastel and difficult to differentiate and identify non- primary basins. Please consider revising the color scheme.
*Response: Modified color ramp for more saturated color appearance.*

103. Please consider adding charts displaying statewide water use projections by decade for each mining category, such as by oil and gas on page 36, coal on page 39, and aggregates on page 43.
*Response: Charts were added at the end of each section.*

104. In the figure description for Figure 1-5, please consider clarifying if the data is from a specific time period.
*Response: Added time period to caption.*

105. Please consider using the same number of decimal places consistently within tables, such as in Table 1-12a.
*Response: Change made. Decimals in referenced table were inadvertent.*

106. Tables 1-6, 1-7, 1-8 and 1-9: please consider correcting "mean concentraitons" to "mean concentrations" in table titles.
*Response: Fixed typos.*

107. Please consider clarifying 'water use' in the description of Tables 1-12a, 1-13a, 1-14a, and 1-15a, if appropriate.

*Response: Done.*

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[1] Blonds and others, 2019. U.S. Geological Survey National Produced Waters Geochemical Database v2.3 [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7J964W8

108. Please consider including a separate table with side-by-side water use for TRR (unconventional) and conventional HF water use for all counties.
*Response: Table 1-18a and 1-18b contain this information.*

109. Please consider specifying in Table 1-16 if WCA, AU, and EUR are included in the volumes listed in the table.
*Response: The referenced items refer to spatial resolutions of the different studies and not to volumes..*

110. In figures 1-19, 1-21, and 1-23, please consider fixing the typo on the Y-axis "unvonventional."
*Response: Fixed.*

111. Figure 1-25: Please consider adding two separate Figure captions for each a) and b). Additionally, please make the label on the y-axis in Figure b clearly visible.
*Response: Fixed.*

112. Please consider adding an explanation for any counties for which the projected oil and gas industry water use (Table 1-18a) does not reflect the HF water use time series (Table 1-2a) historical water use trend.
*Response: Added.*

113. In table 2-3a, please consider including 2015-2020 average water use in acre-feet per year, instead of summed water use 2010-2020, as the average is referenced in the report on page 37 and the sum is not. Please also consider changing the title of the column headers to reflect the water source (groundwater, surface water).
*Response: Added values to table.*

114. On page 47, Figure 4-4, the previous three figures use a common scale, but here there is a different scale. Please consider using a representative scale for each figure or a common scale for all three.
*Response: Legend fixed*

115. In the table Appendices, please consider only listing table descriptions once at the beginning of each table, even when a table spans multiple pages, such as Table 1-10d, or clarifying in the table description that different aquifers are listed.
*Response: Done*

USGS Comments

**Final Technical Report Review for grant application year: FY2020**
**State: Texas**
**Agency: Texas Water Development Board (TWDB)**
**Title: Water Use by the Mining Industry in Texas**

**Overall Comments:**
We appreciate all the time spent to improve mining water-use data for Texas by capturing the best available data for the oil and gas sector, coal mining, and aggregates mining. The comprehensive summary and quantitative assessment of mining water use will prove invaluable for the state of Texas and other agencies, including the U.S. Geological Survey. Furthermore, the projections of future water use across the different mining sectors (oil and gas, coal, and aggregates) will be beneficial for water resource management and predicting potential areas of water conflict ahead of time. ***As with previous work performed by the state of Texas with the Water Use Data and Research (WUDR) program, Texas continues to set the bar for its level of excellence within WUDR for other states to attain.***

**Continuing Items:**
*The following items should continue after project completion:*

- Continue to keep personnel from both the Water Use Data and Research (WUDR) program and the Oklahoma-Texas Water Science Center aware of any new data or developments that come from this project.

**Recommendations:**

- A couple instances where report lists the work thick as think. Simple search and replace will fix this error.
  *Response: Typographical errors fixed.*

Let me know if you have any questions. Otherwise, great work!

Thanks,
Erik

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