texaswaterjournal.org

An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

TEXAS WATER JOURNAL

Volume 6 Number 1
2015

TEXAS WATER JOURNAL

Volume 6, Number 1
2015
ISSN 2160-5319

texaswaterjournal.org

THE TEXAS WATER JOURNAL is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

For more information on TWJ as well as TWJ policies and submission guidelines, please visit *texaswaterjournal.org*.

The Texas Water Journal is published in cooperation with the Texas Water Resources Institute, part of Texas A&M AgriLife Research, the Texas A&M AgriLife Extension Service, and the College of Agriculture and Life Sciences at Texas A&M University.

Texas Water Resources Institute
make every drop count

Cover photo: Anzelduas Dam in Hidalgo County. Photo courtesy of the Texas Water Development Board.

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 45–63

Who regulates it? Water policy and hydraulic fracturing in Texas

Margaret A. Cook[1*], Karen L. Huber[2], Michael E. Webber[3]

Abstract: Hydraulic fracturing, the injection of a pressurized fluid mixture of mostly water, sand and a small amount of chemicals (frac fluids), increases extraction rates and recovery of oil or gas. The technique has become increasingly popular when used in combination with horizontal drilling, especially in Texas shale formations. Hydraulic fracturing often requires thousands of cubic meters of water per well. Access to water might be challenging due to water scarcity, allocation policies, price, location, and competition for water. In this policy analysis, we conducted a detailed bottom-up survey for each groundwater conservation district to catalog and assess the prevailing policies and practices related to water and hydraulic fracturing, focusing on the ways in which the State of Texas regulates the use of fresh and non-freshwater for hydraulic fracturing. We find that policies are inconsistent statewide with great variability from district to district in regulations and potential solutions to the challenge of freshwater use. From this analysis, we provide information on the practice of hydraulic fracturing and examine strategies for reducing freshwater use through recycling and use of non-freshwater. In this report, we present the current water policy framework and alternative solutions.

Keywords: Hydraulic fracturing, water policy, groundwater, produced water, brackish water

[1]Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712-1173
[2]Lyndon B. Johnson School of Public Affairs, The University of Texas at Austin, Austin, TX 78713-8925
[3]Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712-1591
*Corresponding author: margaretcook@utexas.edu

Citation: Cook MA, Huber KL, Webber ME. 2015. Who regulates it? Water policy and hydraulic fracturing in Texas. Texas Water Journal. 6(1):45-63. Available from: https://doi.org/10.21423/twj.v6i1.7021.

Terms used in paper

Short name or acronym	Descriptive name
NPDES	National Pollutant Discharge Elimination System
TDS	total dissolved solids

INTRODUCTION AND SCOPE

The interconnection between energy and water has become increasingly apparent as both resources are stretched to provide for growing populations. Hydraulic fracturing, the injection of a pressurized fluid mixture of mostly water and sand and a small amount of chemicals (frac fluids), increases extraction rates and recovery of oil or gas. This technique has become increasingly popular when used in combination with horizontal drilling, especially in Texas shale plays (Pacsi et al. 2014). Hydraulic fracturing encompasses less than 2% of overall state water supplies but sometimes results in much higher water use on the local scale (Nicot and Scanlon 2012; Vaughan et al. 2012). Moreover, 2 of the most active areas, the Permian Basin and Eagle Ford Shale, are located in water-scarce areas and have grown substantially since current water availability data was assessed and made public. As the use of hydraulic fracturing has increased, public concerns have been raised over the water quantity used in the hydraulic fracturing process, the source of that water, the proper management and disposal of wastewater, and seismic activity potentially resulting from wastewater disposal. This policy analysis provides information on hydraulic fracturing and examines ways in which the State of Texas regulates the use of fresh and non-freshwater for hydraulic fracturing. We present a case for increased use of alternative water resources, particularly recycling produced water. We outline recommended strategies for reducing freshwater use in favor of non-freshwater use.

BACKGROUND

Water availability in Texas

The 2010 U.S. census revealed that, over the last 10 years, Texas received the largest increase in population of any state (U.S. Census Bureau 2012). In the same period, Texas also suffered more weeks of exceptional drought—the worst drought classification given by the National Drought Mitigation Center—than any other state (National Drought Mitigation Center 2013). Between 2011 and 2014, water supplies in Texas dwindled. Surface water levels reached their 20-year low between February and October 2013 and again in 2014 as shown in Figure 1. Similarly, water levels in the Ogallala Aquifer in Texas have sharply decreased over the past 60 years (USGS 2014). The U.S. Geological Survey reports depletion of 45 to 122 meters across the Texas portion of the aquifer (USGS 2014). In the Winter Garden region of South Texas, in the Eagle Ford Shale area, groundwater levels have declined over 60 meters over an area of 6.5×10^3 square kilometers (Deeds et al. 2003). This increased water scarcity is the motivation for the research presented in this manuscript.

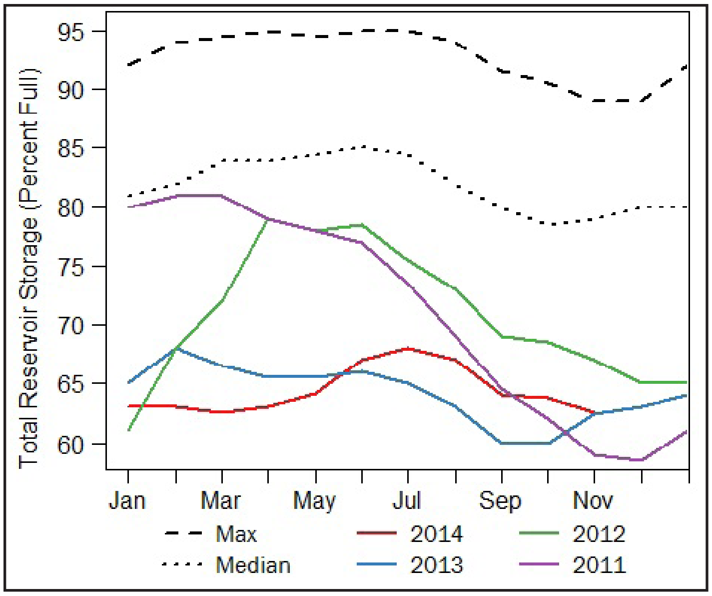

Figure 1. Surface water reservoir levels across the State of Texas remained below median levels between 2011 and 2014. Between February and October 2013, water levels remained at the lowest levels in 20 years. Water levels in 2014 then dipped lower between January and June. (Map created by the author based on data from Water Data for Texas.)

Water use for hydraulic fracturing in Texas

Hydraulic fracturing is often used alongside horizontal drilling, particularly in Texas shale plays. Shale deposits are thin, sometimes relatively impermeable, layers of rock that contain significant quantities of natural gas or petroleum liquids and often cover a large area underground. A horizontal well is developed by drilling a vertical well thousands of feet into the ground then turning the drill horizontally into the zone from which the operator would like to produce hydrocarbons, as shown in Figure 2.

The lateral portion will often extend many thousands of meters. The total length of the vertical and lateral portions of the horizontal well depends on the depth of the shale and the horizontal distance to the intended production zone. Within the aquifer, the wells are cased in concrete and steel to protect freshwater. Using a horizontal well rather than the traditional vertical well allows the well to be fractured at multiple points, or stages, along the horizontal line of the well instead of just along the vertical. By fracturing multiple points along the horizontal line, the operator is able to access a much wider area of shale. Thus, a horizontal well can be more productive in accessing the unconventional resource than a vertical well. Hydraulic fracturing in combination with horizontal drilling uses more water per well than conventional production does, though the ultimate ratio of water to energy extracted is similar to conventional production (Scanlon et al. 2014a).

Because the technologically advanced process of hydraulic fracturing allows access to oil and gas in shale rock previously considered too impervious for economic extraction, production has increased significantly. Many of these areas had some historical production, but production has increased in areas where little to no oil or gas activity occurred previously. These areas are now experiencing increased water demands from increased or new exploration. Some of these areas already experience high water demands from other water use sectors, such as irrigation for agriculture. Thus, the rise in the number of unconventional shale wells puts pressure on existing water resources, especially in the arid and drought-prone areas of Texas.

Texas has several shale plays, as shown in Figure 3. The Energy Information Administration estimates the Eagle Ford Shale holds about 4.3% of the nation's total natural gas reserves and about 7% of the nation's total oil reserves (US EIA 2011). As shown in Figure 4, Texas experienced increased levels of oil production and volatile gas production between 2007 and 2014. Some analysts expect continued long-term growth (US EIA, 2014a).

Hydraulic fracturing requires thousands of cubic meters of frac fluids per well. However, the specific amount of water and the specific frac fluid formula varies based on many factors, including the geology of the shale play. In the Barnett Shale, water use per well is on average 1.06×10^4 cubic meters. (2.8 $\times 10^6$ gallons) while in the Eagle Ford Shale, water use per

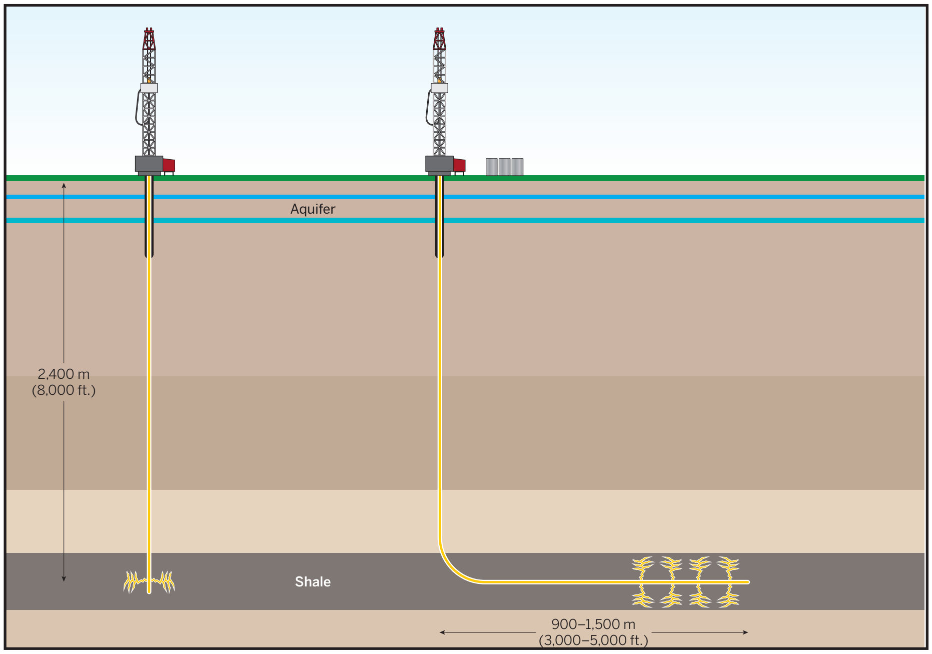

Figure 2. The figure shows examples of horizontal and vertical wells. A horizontal well is developed by drilling a vertical well thousands of meters into the ground then turning the drill horizontally into the zone from which the operator would like to produce hydrocarbons. The graphic is not to scale. (Graphic created by Jeff Phillips.)

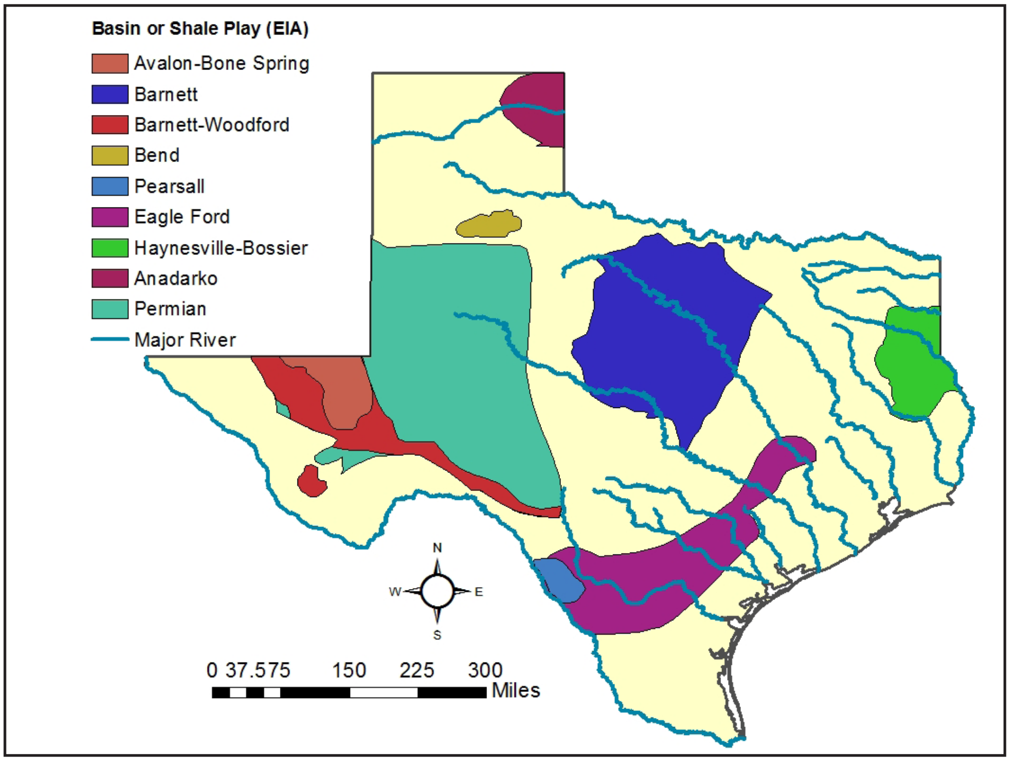

Figure 3. The map shows shale plays and major rivers in Texas. Surface water could be used in hydraulic fracturing operations when it is available physically and legally. (Map created by the author based on data from the Texas Water Development Board and EIA.)

well is on average 1.61×10^4 cubic meters (4.3×10^6 gallons) (Nicot and Scanlon 2012). In the Eagle Ford Shale, water use is equivalent to the water used for conventional oil production on a water-to-oil produced basis (Scanlon et al. 2014a). That water use amounts to less than 2% of state water use in Texas but could be significantly higher at the county or regional level (Nicot and Scanlon 2012; Vaughan et al. 2012). For example, oil and gas water use in Wise County was 40% of total water use in 2010 (Nicot and Scanlon 2012). In La Salle County, water use for oil and gas is expected to reach 89% of total water use by 2019, and in San Augustine County, oil and gas water use is expected to reach 136% of total water use by 2017 (Nicot and Scanlon 2012). In the United States, 48% of shale oil and gas wells are located in areas of high or extremely high

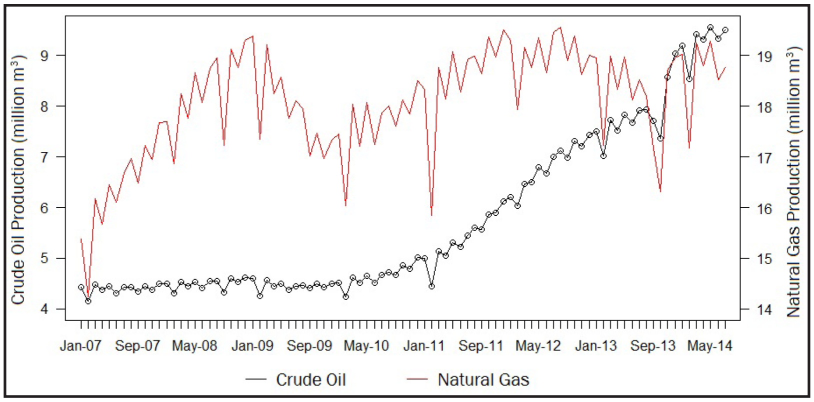

Figure 4. Between 2007 and 2013 natural gas production in Texas has fluctuated between 6 and 9 × 10^6 cubic meters, increasing from 2007 to 2009 and peaking in 2012 at close to 10 × 10^6 cubic meters. (Graph created by the authors based on data from RRC 2014a.)

water stress (Freyman 2014). In Texas, 28% of Eagle Ford wells are located in areas of high or extremely high water stress, while 87% of wells in the Permian Basin region are in areas of high or extreme water stress (Freyman 2014). Moreover, oil and gas production in these regions has also led to increased population growth, further taxing water availability and use (Freyman 2014).

In the area surrounding the Eagle Ford Shale formation, total water consumption is expected to increase from 7.15×10^6 cubic meters in 2010 to 5.5×10^7 cubic meters in 2020 due to oil and gas drilling (Nicot and Scanlon 2012). In a 2012 report, the Bureau of Economic Geology reported that groundwater provides approximately 100% of the water used for oil and gas in the Permian Basin, about 90% in the Eagle Ford, about 80% in the Anadarko Basin in the Texas Panhandle, and about 20% in the Barnett Shale (Nicot et al. 2012). In the Eagle Ford, operators mainly use groundwater from the Carrizo Aquifer, though some rely on surface water from the Rio Grande (Nicot and Scanlon 2012).

Past groundwater depletion from agricultural use already limits water availability in certain areas (Nicot and Scanlon 2012). These projections for high water use introduce a vulnerability and potential hindrance to increased hydraulic fracturing in Texas because the water might not be available due to prior allocation of surface water for other purposes, such as irrigation. This concern is most prevalent in areas where surface water resources are used for hydraulic fracturing. In areas where groundwater is used, water might not be available due to prior uses or water restrictions mentioned later in this paper. In certain areas of the state, water use for hydraulic fracturing has been banned or restricted. In August 2011, in the Barnett Shale region, the city of Grand Prairie banned the use of municipal water for hydraulic fracturing (Lee 2011). Similarly, in the Texas Panhandle the Board of Directors of the High Plains Underground Water Conservation District Number 1, which governs water use in the Ogallala Aquifer in its district, included limits on water use for hydraulic fracturing when it approved restrictions in July 2011 (Lee 2011). In 2014, citizens of the Denton voted to ban hydraulic fracturing from the city's limits. The ban was triggered partially by concerns over water (Dropkin and Henry 2014).

Significant volumes of flowback water—water that flows back to the surface from the well in the period immediately following hydraulic fracturing—and produced water,—water that originated in the production zone of the shale—return to the surface with the oil and gas after water is injected during the hydraulic fracturing process. These volumes vary by location. In the Permian Basin, the volume ratio of flowback and produced water to hydraulic fracturing water injected is 50-100% over the life of the well in the Midland Basin, the eastern portion of the Permian Basin, and 100% over the first year and about 200% over the life in the Delaware Basin, the western portion of the Permian Basin in Texas and New Mexico (Nicot et al. 2012). The volume ratio is much lower in the Eagle Ford—about 20% over the life of the well (Nicot et al. 2012). In the Barnett Shale area, the ratio is 10-20% in the first month and could reach 150% after 5 years (Nicot et al. 2012).

The significant volumes of flowback water and produced water are collected at the surface. Oil and gas are primarily disposed of in a different underground location via injection wells, removing it from the region's hydrologic cycle. According to the U.S. Environmental Protection Agency, "When states began to implement rules preventing disposal of brine to surface water bodies and soils, injection became the preferred way to dispose of this waste fluid" in the United States (US EPA 2014a). More discussion on injection and disposal is included later in this paper in the section "Disposal of production waste." Because much of the water used for unconventional oil and gas production is either sequestered in the shale formation during hydraulic fracturing or subsequently injected for disposal, most of the water used over the life of the well is considered consumed and is no longer part of the original hydrologic cycle. More discussion on how to reduce that consumption is included later in this paper in the section "Produced water reuse and recycling."

EXISTING POLICIES FOR WATER USE FOR HYDRAULIC FRACTURING IN TEXAS

An oil and gas operator has many choices in the selection of a water source, the essential ingredient in unconventional shale production. This section outlines the various policies associated with the water sources used in hydraulic fracturing operations.

Freshwater allocation policies in Texas

Freshwater is the most commonly used water source for hydraulic fracturing operations (Lyons and Tintera 2014). Surface water or groundwater is often located in close proximity to hydraulic fracturing operations, but Texas treats its surface water and groundwater differently from a regulatory perspective.

Price and location are major drivers in choosing the water source. Freshwater costs approximately \$0.35–\$1.50 for 1.6×10^{-1} cubic meters of water (a barrel of 42 gallons of water), according to estimates from various sources (Cook and Webber 2014; Galbraith 2013; Paul 2014). This price can be compared with the price of other source water that will also require minimal on-site treatment. If treatment is required, it is often helpful to compare total water costs, including the cost of source water, any required treatment for source water after purchase, transportation to and from the site, and storage, as well as disposal, reuse, or recycling for beneficial use. Total water costs vary by local market prices, by volume of water, and by distance and time in transit during transportation and often amount to several dollars per barrel of source water.

Surface water: prior appropriation

Access to water is exacerbated by water scarcity as well as water allocation policies. Texas surface water is allocated under the doctrine of prior appropriation, where a permit to withdraw water is based not on land ownership but on the point in time at which the permit, or "water right," was acquired from the Texas Commission on Environmental Quality or its predecessor agencies (Getches 2009). The system is often simplified as "first in time, first in right." Upon application, a permitting authority gives a water right holder a priority date and an allocation amount that resides with the water right as long as it remains valid. Thus, water shortages fall on those who last obtained a legal right to use the water. This is unlike under riparian water law, common in eastern states, where shortages are shared equally among landowners adjacent to the water source (Getches 2009). The Texas Commission on Environmental Quality can issue a priority call in times of drought, restricting users with permits after a certain priority date. In Texas, water users who seek to use less than 1.2×10^4 cubic meters (10 acre-feet or 3.25×10^6 gallons) can apply for a temporary permit for less than 1 year from the Texas Commission on Environmental Quality (TCEQ 2009). The commission may suspend all temporary permits in times of drought (TCEQ 2009). The commission, based on priority calls, can also restrict junior permit rights to withdraw in times of drought. Because appropriative rights exist separate from land ownership, they can be bought, sold, leased, or transferred, forming the basis for a surface water market.

In the Barnett Shale, about 80% of water used for oil and gas is surface water (Nicot et al. 2012). The Brazos River Authority has contracts to provide water to hydraulic fracturing operations while the Trinity River Authority does not supply water to oil and gas operations through such water contracts (Nicot et al. 2014). One of the major irrigation districts in the Lower Rio Grande, Hidalgo County Irrigation District No. 2, has added diversion points in the Middle Rio Grande, further upstream from its original diversion, where water can be easily delivered to energy entities that need water in the southern Eagle Ford Shale (Doherty and Smith 2012).

Groundwater: rule of capture and groundwater conservation districts

In contrast to its ownership and direct governance of surface water, the State of Texas does not incorporate permitting or judgments on reasonable use of water into its groundwater policy. Groundwater in Texas is owned by the landowner and follows the rule of capture. The rule of capture gives the right to withdraw groundwater to the landowner residing above that water and, absence trespassing, negligence, malice, or willful waste, landowners can withdraw as much water as they want without incurring liability, even if that withdrawal will inhibit access to water by neighboring landowners (Potter 2004). However, such rights are subject to groundwater conservation districts where present. Groundwater conservation districts are authorized by the Texas Legislature to protect and manage groundwater resources to maintain supplies in the area (Mittal and Gaffigan 2009). These districts have the ability to require permits and to place reasonable restrictions on water withdrawals or well location (Mittal and Gaffigan 2009). Some areas of the state are not within the boundaries of a groundwater conservation district, and therefore, water withdrawals are unregulated.

Because groundwater is a property right, it can be bought, sold, or traded. However, under the rule of capture, groundwater is an open-access good. Unless restricted by a groundwater conservation district or other authority, landowners may withdraw as much water as they need and are not prevented from over-exploiting it. No single user has an incentive to reduce exploitation due to knowledge that neighbors might exploit or sell water (Holland and Moore 2003).

On the other hand, regulations by groundwater conservation districts limit over-exploitation of groundwater while still allowing necessary water use and potential water marketing. Groundwater conservation districts have the authority to permit wells, require water withdrawal reporting and metering, and limit production. Figure 5 shows the groundwater conservation districts in which hydraulic fracturing operations are occurring as of December 2014 as recorded by the Texas Alliance of Groundwater Districts (TAGD 2014). There are hydraulic fracturing operations occurring outside of these areas where a groundwater conservation district is not present.

Figure 6 shows the groundwater conservation districts that require permits for wells used to supply water to hydraulic fracturing operations. As of December 2014, many districts that do not require permits are contemplating requiring them. Water restrictions for hydraulic fracturing are not uniform across the state, shale plays, or aquifers.

Part of the lack of uniformity and clarity is because wells for oil and gas drilling and exploration are exempt from groundwater conservation district permitting, but there is confu-

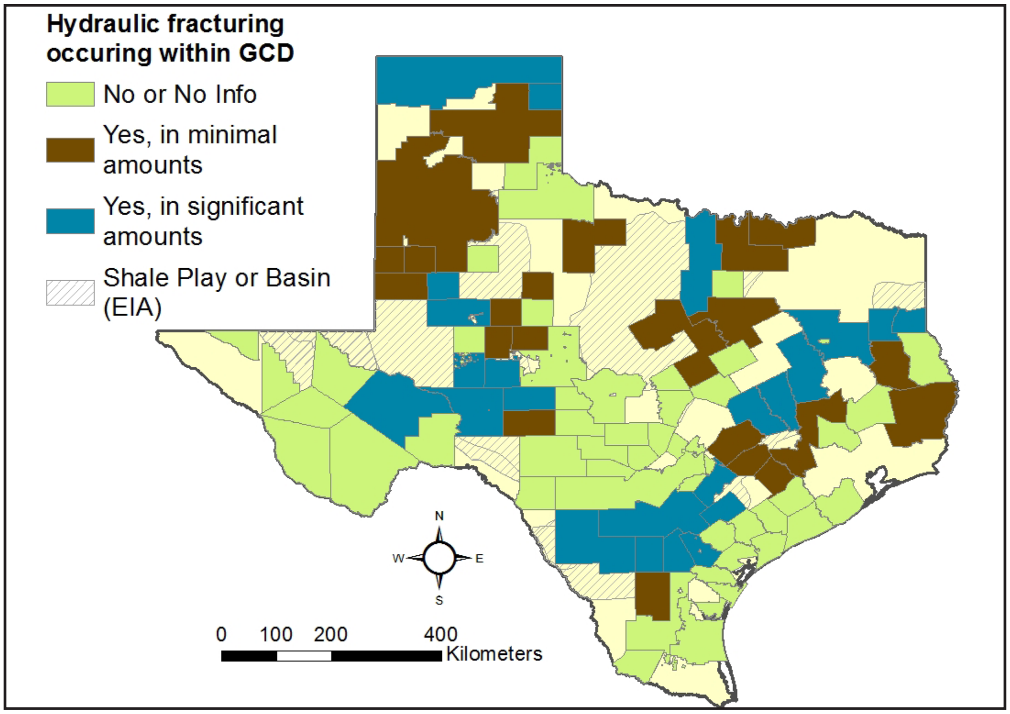

Figure 5. The map shows groundwater conservation districts in which hydraulic fracturing is occurring as of December 2014. There are parts of the state in which there is a groundwater conservation district but no hydraulic fracturing, conveyed by the "No or No Info" category. There are parts of the state in which hydraulic fracturing is occurring as of December 2014 but there is no groundwater conservation district regulating water withdrawals, conveyed with blank space. (Map created by the author based on data from TAGD 2014.)

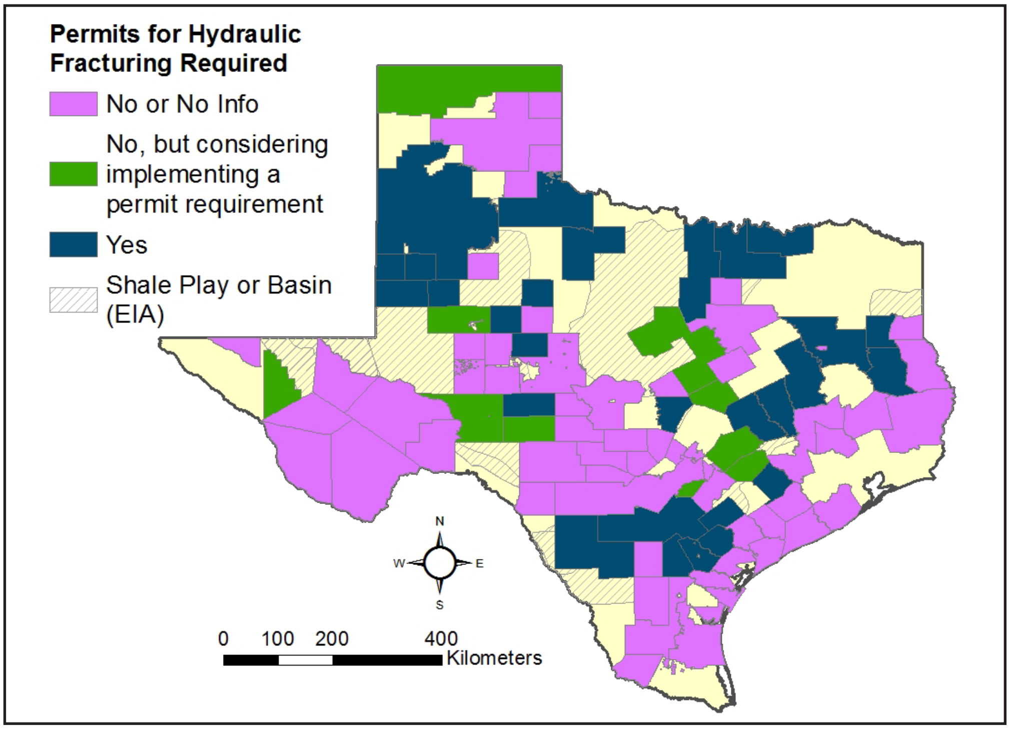

Figure 6. The map shows the groundwater conservation districts that require permits for wells to be used to provide water for use in hydraulic fracturing operations. Not all groundwater conservation districts with hydraulic fracturing operations present as of December 2014 (shown in Figure 5) require permits for wells that provide water for hydraulic fracturing. (Map created by the author based on data from TAGD 2014.)

sion among operators over whether water used for hydraulic fracturing applies to that exemption and whether groundwater conservation district can permit water wells used for hydraulic fracturing. Section 36.117 of the Texas Water Code outlines these exemptions. Under this section, a groundwater conservation district may not require a permit for "rig supply wells." If the well no longer serves as a rig supply well, the groundwater conservation district could require a permit. The Railroad Commission of Texas, the regulating authority for oil and gas operations, understands a "rig actively engaged in drilling or exploration operations for an oil or gas well" permitted by the railroad commission to include drilling rigs and hydraulic fracturing operations (Lyons and Tintera, 2014). However, there is still debate over whether water produced for hydraulic fracturing, a completion technique, qualifies as exploration or production (Scanlon et al. 2014b). In any case, exempt wells must still abide by other groundwater conservation district requirements like registration, well spacing, casing, and reporting.

Figure 7 shows the annual production limitations in groundwater conservation districts across the state. The limits shown might have other stipulations based on the type of water use or the amount of land owned. Many groundwater conservation districts have non-numeric production limitations on all wells, such as total aquifer limits, beneficial use, reasonable use, available water, or service area limitations. Some groundwater conservation districts limit production per well with use of formulas, permits, or studies. For non-exempt wells used to provide water to hydraulic fracturing, these production limitations could restrict the amount of water that can be used in a hydraulic fracturing operation or the rate at which water can be extracted from a well to provide water to an operation.

Figure 8 shows the groundwater conservation districts that allow groundwater export out of the district. In these groundwater conservation districts, water can be extracted from the aquifer and transported to another location, potentially for use in hydraulic fracturing. For other groundwater conservation districts in Texas, export is not allowed. Water extracted in that groundwater conservation district must be used in that groundwater conservation district.

Landowner role in regulating water use

Under the rule of capture, landowners own the water under their land. This rule applies whether the landowners own the surface rights only, which includes groundwater, or the surface and mineral rights (the rights to the oil and gas under their land) but does not apply if the groundwater rights have been

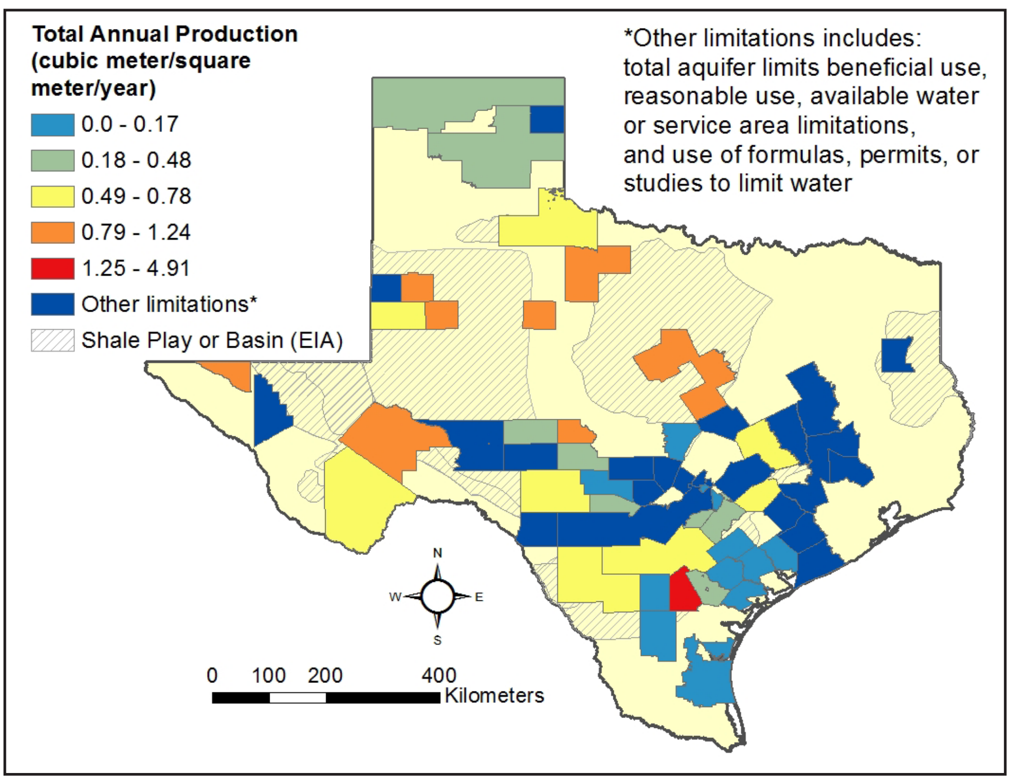

Figure 7. The map shows basic annual production limitations in volume of water per area of land per year (cubic meters/square meters/year) for non-exempt wells in Texas groundwater conservation districts. Some districts with annual production limitations have other stipulations associated with these limits. (Map created by the author based on data from TAGD 2014.)

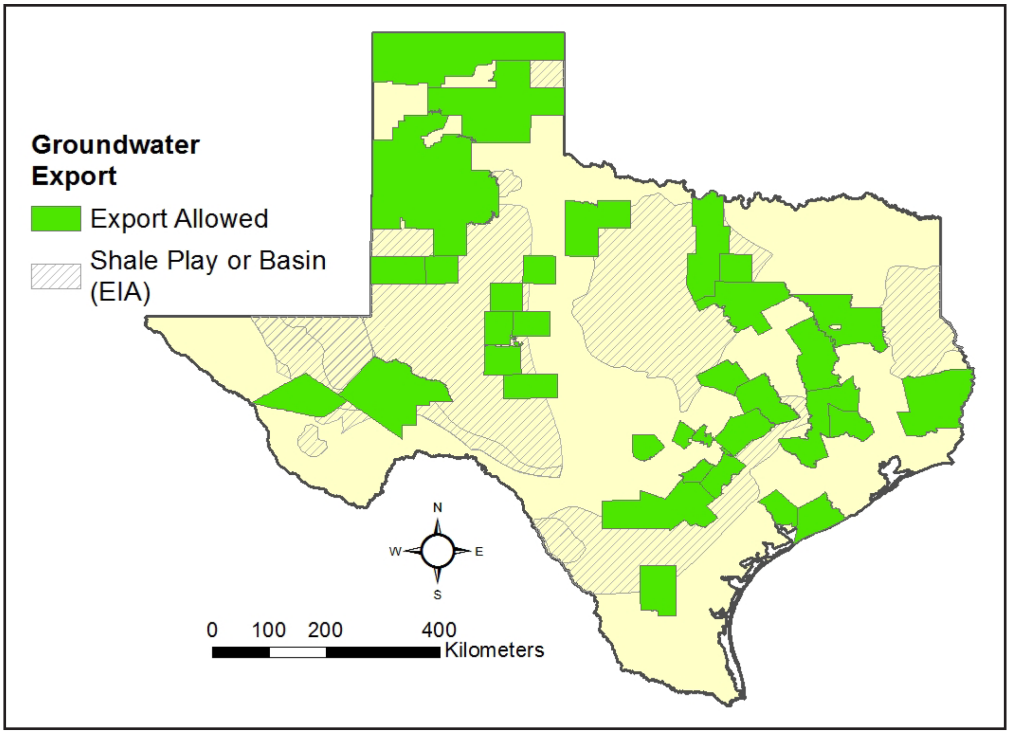

Figure 8. The map shows groundwater conservation districts that allow groundwater export outside of the groundwater conservation district. Groundwater from these groundwater conservation districts could be exported for use for hydraulic fracturing in other areas of the state. (Map created by the author based on data from TAGD 2014.)

severed from the surface estate (The City of Lubbock, Texas v. Coyote Lake Ranch, LLC 2014). If a landowner owns rights to the groundwater, s/he can sell the water to the operator to produce hydrocarbons.

When landowners own both the surface rights and mineral rights, they can play a key role in water allocation decisions. When negotiating a contract with operators for use of their mineral rights, landowners can also negotiate use of their water resources. In this contract, landowners can prohibit use of their water and restrict water use on their land to brackish water, effluent, or recycled water. Though some use of brackish water may be in question, if their land resides over brackish water resources, landowners can currently capitalize on selling that water for hydraulic fracturing. Conversely, landowners can prohibit use of alternative water resources on their land, requiring the use of only their freshwater resources. Landowners might not want recycled water brought onto their property because it might displace water they could sell to oil and gas operators (Lyons and Tintera 2014). To fully capitalize on their resources, some landowners require the oil and gas operator to drill a water well and purchase and use only that water for the hydraulic fracturing on that land (Galbraith 2013). Such contract negotiation, though legal, is a barrier to reducing freshwater use for hydraulic fracturing. In the current framework, both the landowner and the operator are economically motivated to exploit the groundwater resource.

Alternative water allocation policies in Texas

With freshwater supplies stretched across various water use sectors and long-term drought further constraining supplies, alternative water sources could be a good option for oil and gas operators seeking water for hydraulic fracturing operations. However, there could be additional costs associated with using an alternative source of water (Lyons and Tintera 2014). The price of water plays a role, but other factors associated with alternative water, such as quality, also determine cost and feasibility. Often, the alternative source of water is a degraded quality compared to freshwater. Due to improved technology and chemistry, more saline water and water of degraded quality can be used with the addition of additives. However, if the increase in chemical needs is not offset by the reduction in cost of water, the total cost at the well could increase. This study does not assess the changes in cost associated with degraded quality water, but they should be evaluated when determining water source for hydraulic fracturing operations.

There are other considerations to keep in mind when choosing whether to use an alternative source of water. A study conducted through the Atlantic Council determined conditions that support or challenge using alternative, non-freshwater sources (Jester et al. 2013; Lyons and Tintera 2014). According to that study, conditions that support using alternative water sources are

- limited availability of high-quality source water, such as fresh groundwater;
- high quality and availability of produced water, brackish water, municipal effluent, or other alternative water source;
- reduction in costs associated with use of alternative, non-freshwater, such as for logistics or transportation;
- high compatibility with frac fluid chemistry or easily treated to compatibility with frac fluid chemistry; and
- high compatibility with the production zone of the reservoir (Jester et al. 2013).

According to the same study, challenges to non-freshwater use are related to logistics, costs,and contamination risks associated with

- transportation and gathering of non-freshwater, including but not limited to:
  – truck accidents
  – pipeline leaks
  – spills in loading or unloading the fluid
- treatment of non-freshwater,
- storage of non-freshwater,
  – pond or storage tank leaks
  – birds landing in uncovered ponds
- blending of water from different sources,
- compatibility with frac fluid chemistry resulting in consistent and predictable frac fluid performance,
- impacts on reservoir and fracture conductivity, and
- impacts on short- and long-term field production (Jester et al. 2013).

There are multiple options for using alternative, non-fresh sources of water. This study characterizes the potential for use of brackish water, effluent, and produced water and the policies that influence whether these choices are viable options for use in hydraulic fracturing.

Brackish water

Freshwater is often defined as water with salinity less than 1,000 milligrams per liter total dissolved solids (TDS). Brackish water does not have an exact definition, but typically water that is 1,000–10,000 milligrams per liter TDS is considered brackish. Within that category is water that is slightly saline (1,000–3,000 milligrams per liter TDS), and water that is moderately saline (3,000–10,000 milligrams per liter TDS) (Godsey). Highly saline water contains over 10,000 milligrams per liter TDS (Godsey). Seawater contains greater than 35,000 milligrams per liter TDS (Godsey). Texas is estimated to have 3.3×10^{12} cubic meters (8.8×10^{8} gallons or 2.7×10^{9} acre-feet) of brackish water (Kalaswad et al. 2005). That water is more abundant in the Gulf Coast near the Eagle Ford Shale and in West Texas near the Permian Basin (Kalaswad et al. 2005). In the Permian Basin, 30% of water used for hydraulic fracturing is brackish (Nicot and Scanlon 2012). At least 2 companies, Fasken Oil & Ranch and Apache Corporation, use brackish water from the Santa Rosa Aquifer for their frac jobs (Buchele 2013). In other shale plays, brackish water is used less frequently (Nicot and Scanlon 2012).

Improvements in efficiency of chemical additives to the frac fluid allow for use of more saline waters (Nicot and Scanlon 2012). However, friction reducers used in frac fluid might not work properly in water with high TDS (Nicot and Scanlon 2012). The dissolved solids might cause corrosion (Nicot and Scanlon 2012). In addition, handling costs for brackish water might be higher than those costs for freshwater (Lyons and Tintera, 2014). If brackish water resources are connected to freshwater resources as in the Carrizo-Wilcox Aquifer, there is a potential drawback in negatively impacting freshwater formations by drawing down brackish water (Lyons and Tintera 2014). If brackish water resources are below freshwater aquifers, drilling deeper into the earth to access the brackish water will increase the cost of accessing that water (Buchele 2013).

There is competition among operators as well as across water use sectors for brackish water resources. Agricultural operations in Gonzales County use water at 3,700 milligrams per liter TDS (Ritter and Fazio 2014). Municipalities looking to augment their water supplies by desalinating brackish water might be competing for the same supplies. The city of Gonzalez uses water of 2,800 milligrams per liter TDS for public supply, blending it with freshwater from the Guadalupe River (Ritter and Fazio 2014). As the salt content of brackish water increases, more energy is required to remove it if water is not available for dilution, and there is a higher cost to do so. Thus, cities will be looking to use slightly saline water to keep their energy and costs down. The Gonzales County Underground Water Conservation District has had reports of oil and gas companies using brackish water at 26,000 milligrams per liter TDS for hydraulic fracturing (Ritter and Fazio 2014).

There are policy hurdles to using brackish water that might increase the total cost. Water used for hydraulic fracturing is sometimes piped and stored in pits. However, if brackish water is used, it must be transported in no-leak transfer lines and held in containment suitable for salt water (Lyons and Tintera 2014; Nicot and Scanlon 2012). There is increased liability to producers that store and/or transfer large volumes of salt water (Lyons and Tintera 2014; Nicot and Scanlon 2012). A bird landing in the brackish water pit or a spillage of water creates environmental liabilities where use of freshwater would not (Lyons and Tintera 2014; Nicot and Scanlon 2012).

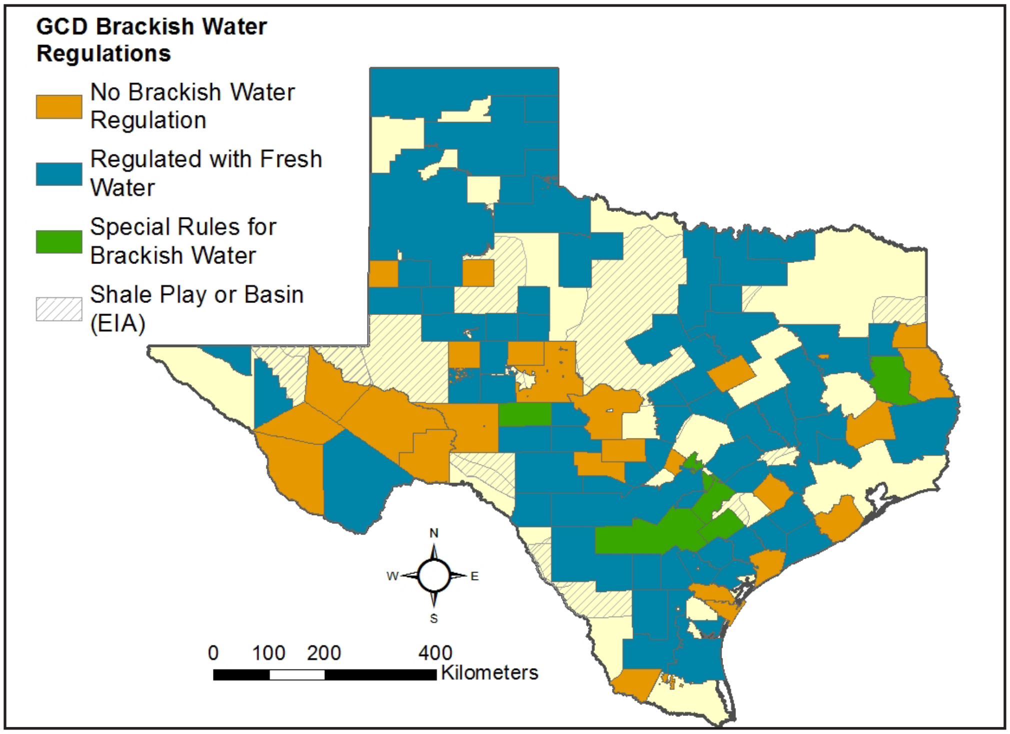

Figure 9. Brackish water is often regulated as if it is freshwater. Certain groundwater conservation districts have specific rules for brackish water, as shown in green in the figure. Some groundwater conservation districts do not regulate brackish water, and some areas of the state do not have a groundwater conservation district and are unregulated. In these areas, withdrawal of brackish water would follow the rule of capture. (Map created by the author based on data from TAGD 2014.)

Some groundwater conservation districts regulate brackish water use in the same way they regulate freshwater use. Some have specific policies for brackish water use. There are a few areas of the state where brackish water use is unregulated by a groundwater conservation district. Overall, the regulatory structure for brackish water is yet undeveloped but is at the forefront of issues for the 84th Texas Legislative Session. Figure 9 shows the difference in brackish water regulation in groundwater conservation districts across Texas. This difference in regulation could mean brackish water is easier to access in some areas than other areas.

Effluent reuse

Use of effluent is another option for an alternative water source that is becoming more common. Effluent could originate at a municipal wastewater facility, from an industrial process, or as irrigation tailwater. Each has its own considerations to maintain.

Municipal reclaimed water

There are 2 types of treated municipal wastewater (hereafter referred to as "municipal reclaimed water" or "municipal effluent"), Type I and Type II, which are defined according to whether people are likely to have contact with the municipal effluent during its use (TCEQ 2014). Type I water is that which public contact is likely (TCEQ 2014). This water requires more treatment and thus requires more energy and costs more to produce (TCEQ 2014). To reuse either type of municipal reclaimed water, the Texas Commission on Environmental Quality must give written approval to the provider of the water (TCEQ 2014). The water must then be sampled and analyzed before distribution (TCEQ 2014). To convey reclaimed water using waters of the state, the water provider must obtain a water-right authorization from the commission (TCEQ 2014). Reuse of untreated wastewater is prohibited.

Municipal reclaimed water is already commonly used by oil and gas operators in Texas. In the northern Eagle Ford Shale, Apache Corporation has a $\$5 \times 10^6$ 2-year agreement to use 1.1×10^4 cubic meters (3×10^6 gallons) per day of municipal effluent from Carter's Creek Wastewater Treatment Plant in College Station (Adger 2014). The water represents about half of the treated water produced in College Station (Apache Corporation 2014). Pioneer Natural Resources has a similar deal to purchase wastewater in Odessa. The $\$1 \times 10^8$ dollar agreement will provide Pioneer with about 5.7×10^6 cubic meters (1.5×10^9 gallons) of water per year for the next 10 years from the Bob Derrington Water Reclamation Plant (Paul 2014). Companies such as Alpha Reclaim Technologies LLC and PTP LP have emerged to function as intermediaries between wastewater treatment facilities and oil and gas operators. In 2013, Alpha Reclaim Technologies LLC collected water from more than 20 municipal wastewater facilities to sell for hydraulic fracturing operations (Hiller 2013). PTP LP contracted to purchase effluent water from Carrizo Springs, Eagle Pass, Pearsall, Pleasanton, and Shiner for the same purpose (Hiller 2013).

Municipal reclaimed water is often competitively priced with freshwater, and selling reclaimed water gives cities a new source of revenue (Eagle Ford Shale 2013). However, there is competition for use of municipal reclaimed water as Type I water can be used to water public parks, school yards, residential lawns, and athletic fields and can also be used for fire protection, food-crop irrigation, and application to pastures grazed by milking animals (TCEQ 2014). Type II water can be used for irrigation water that is not likely to contact edible portions of a crop, animal feed-crop irrigation that does not involve milking operations, supply to non-recreational water bodies, soil compaction, dust control, cooling tower makeup water, and certain applications at wastewater treatment facilities (TCEQ 2014). Moreover, water users including communities downstream of wastewater treatment plants rely on the discharged return flows for their water needs. In addition, water-stressed communities, such as Big Spring and Wichita Falls, have begun treating their wastewater many times over for municipal use, in a process known as "direct potable reuse" (Lawler 2014). In addition to increasing competition for municipal reclaimed water, use of this effluent in oil and gas operation does not decrease the amount of water consumed by the industry. The same amount of water injected in hydraulic fracturing that would normally be consumed if the water was fresh is still consumed when it originates as municipal reclaimed water.

Industrial reclaimed water use

To reuse industrial effluent water, the Texas Commission on Environmental Quality must give written approval before the water can be used off-site (TCEQ 2014). There are 2 levels used to assess treated industrial water, Level I and Level II (TCEQ 2014). The levels are classified according to "how they are generated and whether they will be used on-site or off-site" (TCEQ 2014). Both Level I and II water can be used off-site with written approval (TCEQ 2014). Level II water must be sampled to certify that it applies as reclaimed water before it can be used (TCEQ 2014).

Agricultural tailwater use

The runoff or "tailwater" from agricultural irrigation could also provide an option for non-freshwater. Because that water would normally soak into the earth or run into waters of the state, it is an unregulated effluent and does not require a permit for reuse. However, irrigation tailwater can have additional quality concerns during reuse in hydraulic fracturing. If there are bacteria in the tailwater, they would need to be removed prior to use in a hydraulic fracturing operation. The use of this water could jeopardize downstream flows or aquifer recharge depending on the location in which the agricultural tailwater would normally have gone.

Produced water reuse and recycling

While other user groups, including municipalities, compete for brackish water and effluent, there is little competition for reused (little to no treatment) or recycled (with treatment) produced, or flowback, water from oil and gas production. Also, in contrast to replacing freshwater use with another source such as brackish water or effluent, recycling produced water can offset multiple pieces in the chain of water use for oil and gas production. Recycling water replaces the need to dispose of most of the water as the treated water can then be reused. There is some disposal of waste from treatment, though. If that water is reused by the same company, recycling also replaces the need to find and purchase more water to hydraulically fracture a new well. If that new well is on the same well pad, recycling on-site could replace the need to transport (via truck or pipe) wastewater to disposal or water from a water source. Disposal and trucking are discussed further later in this paper in the sections "Trucking water and wastewater" and "Disposal of production waste."

Recycling, like use of other water sources, is limited by cost, policy, and technology. While recycling and reusing water offsets freshwater use and disposal, it also carries risks. For example, spillage from human error in waste handling or leaks from pipes could create environmental issues. Thus, the railroad commission regulates the process through Statewide Rule 8, which was amended in 2013. The amendments to the rule eliminate the need for a permit to recycle water on-lease under the authority of the oil and gas operator, allows recycling on another operator's lease, and distinguishes between commercial and non- commercial recycling (Lyons and Tintera 2014). The railroad commission also authorizes reuse via permit-by-rule, allowing reuse of treated or recycled water in the wellbore of an oil or gas well (Lyons and Tintera 2014). Amendments to the Natural Resources Code in 2013 (via Texas House Bill 2767in 2013) establish ownership of oil and gas waste transferred for treatment and subsequent beneficial use (NRC). When the fluid waste is transferred to a person for treatment and beneficial use, that person owns the fluid and the treated water until either is transferred to another person (NRC). In the event of a transfer, the person to which the fluid or treated water is transferred would own the fluid or treated water (NRC).

Wastewater from hydraulic fracturing can be recycled and reused as long as that water is not returned to the waters of the state (surface water) (TAC § 3.8). If that water is used as makeup water for another hydraulic fracturing operation, no permit is required, as that reuse is regulated via permit-by-rule (TAC § 3.8). If the water is reused in any other manner, a permit is required from the state or federal agency that regulates that water use (TAC § 3.8). If that wastewater is treated to distilled water quality, no permit is required to reuse it in any other manner, but the water still cannot be discharged into waters of the state (TAC § 3.8).

Recycling is also complicated because the quality of water that returns to the surface after hydraulic fracturing varies between formations and wells depending on the constituents in the geology and in the frac fluids (Lyons 2014). Flowback and produced water might contain hydrocarbons, salts, toxic natural inorganic and organic compounds, chemical additives, naturally occurring radioactive materials, oil and grease associated with production, high TDS, suspended solids, iron, boron, or oil residue (Lyons 2014). The produced water quality determines the technology needed and the cost of treatment before the water can be reused. However, recycling and reusing produced water might still be a cost-effective option. With the combined use of brackish water and produced water, 1 operator is able to eliminate the need for freshwater in its hydraulic fracturing operations in Irion County in the Permian Basin (Buchele 2013).

Recycling is estimated to provide about 2.5 million cubic meters or 2,000 acre-feet of water use for hydraulic fracturing across Texas, which is about 3% of total water use for the process statewide. Recycling and reuse amounts vary by operator and basin or shale play (Ritter and Fazio 2012). In 2011, recycled or reused water provided 2% of water used for hydraulic fracturing in the Permian Basin, 20% in the Anadarko Basin, and 0% in the Eagle Ford Shale (Nicot et al. 2012). In 2012, in the Barnett Shale, recycling and reuse ranged from 5% to 10% and was about 0% of total water use in the Texas portion of the Haynesville Shale (Nicot and Scanlon 2012).

The amount of freshwater that can be offset by use of recycled and reused produced water depends on the volumes of produced water that returns to the surface. While almost 100% of water is recycled or reused in the Marcellus Shale in the Northeastern United States, the water accounts for only 10-30% of the water required for hydraulic fracturing in that shale play (Scanlon et al. 2014b). Moreover, small flowback and produced water volumes generally do not support reuse/recycling requirements as the small volume makes it difficult to collect enough water to support economic reuse or recycling. According to a report from the Bureau of Economic Geology, "there is limited potential for reuse or recycling of flowback or produced water because of small volumes" of water returned to the surface after hydraulic fracturing, less than 5% of water required to hydraulically fracture wells in the Eagle Ford Shale (Scanlon et al. 2014b).

Operational areas, policies that could affect the price of water

Total water costs, including water acquisition, storage, transfer, and waste disposal services associated with the initial hydraulic fracturing of a new well, can represent approximately 10% of the total cost of a new well (IHS 2014). Cost of transporting water is a major component of total water costs for a well (Eaton 2014). In the Eagle Ford and Permian Basins, at rates of $70–$110 per hour for trucks carrying 100–130 barrels of water, cost of transporting water by truck might be $0.50 to several dollars per barrel of oil produced (Eaton 2014). Disposal costs approximately $0.60 to several dollars per barrel. Increases in these costs caused by fees or taxes can increase total water costs for oil and gas operations.

Trucking water and wastewater

Trucking water or wastewater is often the most expensive piece in the chain of total water costs in extraction of oil and gas. The use of trucks also causes damage to roads. In 2012, the Texas Department of Transportation estimated the cost for rebuilding the infrastructure damaged by increased energy-related activities at approximately $4 billion per year on the state highway system, city streets, and county roads (TXDOT 2012). In the 83rd Texas legislative session in 2013, Rep. Drew Darby proposed increasing vehicle registration fees to pay for state highways (Texas House Bill 3664 2013). The increase in registration fees would be used in the following manner:

> "One-third dedicated to the payment of existing voter authorized transportation debt until such debt is retired; and the remaining amount may be used only for acquiring rights-of-way and planning, designing, and constructing non-tolled improvements to the state highway system."

The bill was not passed, but such a bill would increase the cost for all vehicles in the state to pay for roads. An increase in the cost of transportation increases the cost for trucking water and, thus, increases the total cost of water for an oil and gas operation.

Following the 83rd Texas legislative session, in September 2014, Rep. Tryon Lewis explained that a similar fee on gas use instead of vehicles would be a good mechanism to pay for road improvements as it invoked a "user pay" principle (Lewis 2014). These fees on vehicle registration or gas help pay for necessary road improvements. However, they also increase the cost of transportation. Where trucking is the main method for transporting water, increases in transportation cost could significantly increase the total cost of water and make recycling more affordable in comparison. When possible, use of piping instead of water trucking reduces total water costs as well as road damage. However, there are risks associated with piping, including potential for leaks. Pipes should be monitored, especially when carrying non-freshwaters.

Disposal of production waste

There are options for managing produced water that flows to the surface during hydraulic fracturing operations, including (Jester et al. 2013; Lyons and Tintera 2014)

- use of on-site evaporation pits (not in Texas).
- discharge with National Pollutant Discharge Elimination System (NPDES) permit (not allowed in Texas or for most cases of onshore facilities).
- disposal via injection.
  - disposal into on-site injection or disposal wells
  - disposal at a centralized off-site underground injection site like a Underground Injection Control Class II well
- recycling or reuse.
  - transportation to and then treatment at a treatment plant
  - on-site treatment by a mobile unit for oilfield reuse
  - on-site mixing of produced water and freshwater for reuse in hydraulic fracturing, and
- treatment for beneficial use.

Underground injection in Underground Injection Control Class II disposal wells is the preferred option by the U.S. Environmental Protection Agency because the waste stream is trapped underground (US EPA 2014a). Risk and cost is relatively low in Texas. Class II wells are specifically permitted for injecting "brines and other fluids associated with oil and gas production, and hydrocarbons for storage" (US EPA 2014a). For operators, the economics also tend to favor disposal since Texas has approximately 35,000 Class II injection and disposal wells and over 295,000 producing oil and gas wells (RRC 2014b). In Texas, the railroad commission regulates oil and gas waste and permits 3 types of underground disposal:

1. *Enhanced Recovery Wells:* The wastewater can be returned to the reservoir from which it originated for secondary or enhanced oil recovery (RRC 2014b). These wells are called "injection wells" or wells involved in "secondary recovery/injection wells" (RRC 2014b; US EPA 2014a).
2. *Hydrocarbon Storage Wells:* If the wastewater is returned to the production zone without secondary recovery, it is referred to as "disposal into a productive zone" (RRC 2014b; US EPA 2014a. These wells are often used for Strategic Petroleum Reserve or for gas storage, not for waste disposal.
3. *Disposal Wells:* Wastewater can also be disposed of by injection into rock formations that do not produce oil or gas but are isolated from usable quality groundwater and "sealed above and below by unbroken and impermeable strata." These injection wells are called "disposal wells" or wells involved in "disposal into a non-productive zone" (RRC 2014b; US EPA 2014a). There are approximately 7,500 disposal wells in Texas (RRC 2014b). Nationally, disposal wells represent about 20% of Class II wells (US EPA 2014a).

In recent years, questions have been raised surrounding induced seismicity caused by underground injection (Folger and Tiemann 2014). The railroad commission held a town hall in Azle in January 2014 to discuss this issue and amended the rules later that year. The rule amendments, effective November 17, 2014, require applicants for new disposal wells to search for earthquakes within a circular area of 100 square miles around the proposed site. The amendments also clarify the commission's authority to modify, suspend, or terminate a disposal well permit and allow railroad commission staff to require operators to disclose disposal volumes on a more frequent basis and to require an applicant to provide additional information about the well site (16 Texas Administrative Code § 3.46; 16 Texas Administrative Code § 3.9; Fox 2014).

The rule amendments serve a purpose in protecting human health, but they could lead to slow development of new disposal wells relative to the creation of new wastewater from oil and gas production. A limit in supply of injection sites relative to the demand could result in increased disposal well costs or increased truck waiting times like those in Pennsylvania and Canada, another increase in the total cost of water.

As of December 2014, Pennsylvania had 7 active deep injection wells for oil and gas waste and over 5.7×10^4 producing natural gas wells (NPR 2014; US EIA 2014b). Without adequate disposal methods in close proximity, operators in Pennsylvania truck their waste to Ohio. However, the cost of trucking has pushed operators to instead recycle and reuse their produced water in future operations.

In Texas, at least 2 bills filed in the 83rd legislative session in 2013 would have limited wastewater disposal in commercial injections wells. Texas House Bill 2992 by Rep. Tracy King would have prohibited disposal unless the wastewater could not be treated.

> "Flowback and produced water from an oil or gas well on which a hydraulic fracturing treatment has been performed using groundwater may not be dis- posed of in an oil and gas waste disposal well unless the fluid is incapable of being treated to a degree that would allow the fluid to be:

- used to perform a hydraulic fracturing treatment on another oil or gas well;
- used for another beneficial purpose; or
- discharged into or adjacent to water in the state."

The bill did not pass. Texas House Bill 379 by Rep. Lon Burnam would have imposed a fee on the volume of water disposed of in commercial injection wells, the proceeds of which would go to the Oil and Gas Regulation and Cleanup Fund.

> "An oil-field cleanup regulatory fee is imposed on oil and gas waste disposed of by injection in a commercial injection well permitted by the railroad commission under this chapter in the amount of 1 cent for each barrel of 42 standard gallons," or 1.6×10^{-1} cubic meters of water."

The bill did not pass. A fee on disposal could significantly increase the cost of disposal, thereby increasing the total cost of water and making recycling more affordable in comparison.

POLICY ALTERNATIVES

There are many policy options available to help reduce freshwater use for hydraulic fracturing. Some are listed below:

- *Improve public outreach*: By engaging the public in discussions about water use for hydraulic fracturing, the public could become aware of technological innovations in the industry and water policy decisions and help encourage more efficient use of water.
- *Reporting*
  - *Water source reporting*: Operators should report whether their water is freshwater, brackish water, municipal reclaimed water, recycled or reused produced water, or another source. This reporting could be collected with current water volume and chemical content reporting sent to the railroad commission. Operators could also report their water source in the existing reporting on FracFocus.com.
  - *Water recycling reporting*: By reporting water recycling, in particular, either voluntarily or by requirement, companies could gain recognition from the public and potentially encourage other companies to recycle more water. Operators could report their water source in reporting sent to the railroad commission or to FracFocus.com.
- *Mandates*
  - *Reduce underground injection and disposal*: Such a policy would artificially increase the price of underground injection and disposal by reducing the amount of disposal available for use and cause oil and gas operators to search elsewhere for disposal methods like recycling. An example of a policy that limits disposal and mandates recycling is included previously in this paper in the section "Disposal of production waste."
  - *Reduce water or wastewater trucking*: Such a policy would artificially increase trucking costs through limiting the availability of it. In areas where pipelines are unavailable—perhaps because landowners refuse to allow pipelines on their property—limitations on trucking increase the total cost of water.
  - *Increase reuse/recycling*: Such a policy could increase the amount of recycling without decreasing the cost of treatment or reuse. Although, with more volumes recycled and more use of technology, economies of scale could result in reducing the total cost of recycling. An example of a policy that limits disposal and mandates recycling is included previously in this paper in the section "Disposal of production waste."
- *Fees:* Unlike mandates, fees serve as an economic tool to change behavior, in this case, in underground injection and disposal and in trucking water or wastewater. The fees collected could be used in many ways, including funding a program for reporting water recycling.
  - *Underground injection and disposal*: Such a policy would increase the cost of disposal, making recycling more competitive in comparison. An example of a disposal fee policy is included in the section "Disposal of production waste" where the funds collected would have been used for oil field cleanup.
  - *Trucking water or wastewater*: Such a policy would increase the trucking costs, thereby increasing the total cost of water. An example of a fee on trucking is included in the section "Trucking water and wastewater" where the funds collected would have been used to improve road conditions.
- *Incentives for recycling*: Incentives could encourage innovation and could be applied when an operator recycles water, when a service company recycles water, toward economically efficient recycling research at universities, for pilot-scale programs, or for construction of larger scale recycling facilities to be used by multiple companies. Incentives for reducing freshwater use would need to come from the Texas Legislature, as the Legislature sets the state budget. Incentives could include a tax credit for developing new freshwater sources to replace those depleted by production use or for using a non-freshwater source such as brackish water, reused or recycled produced water, or wastewater effluent. Potential disincentives that could also reduce total freshwater consumption are fees set on produced water disposal or on freshwater use. A water use fee on freshwater use would be difficult to impose without water monitoring. In 2006, oil and gas accounted for 99.6% of state subsidies, a total of $\$1.4 \times 10^9$ (Combs 2014). Examples of

existing incentives for oil and gas include (Lyons and Tintera 2014)
– special tax credits
– deductions
– exemptions
– allowances
– property tax incentives
– franchise tax exemptions
– property tax exemption for energy producers

- *Regulated water market*: A regulated water market can help bring transparency to water prices for fresh and non-fresh resources, make alternative water sources more competitive in the market, and give incentive to reduce wasteful use of water. A regulated market could allow reallocation of water resources to beneficial uses while maximizing the utility of both the original owner of the water and the end users. Landowners could be made aware of the potential to profit off of brackish, agricultural reuse water, or conserved resources (after installing more efficient irrigation technologies), potentially reducing the tendency to over-exploit freshwater aquifers (Cook and Webber 2014).
- *Transparent groundwater restrictions*: Groundwater conservation districts in the same aquifer have differing policies for freshwater and brackish water, production limits, exporting, and other issues that could create confusion among oil and gas operators. To reduce that confusion, these regulations could be made more transparent. Further, water does not follow the political boundaries of groundwater conservation districts. Wells drilled outside of a district, though unregulated by the district, could still affect the water supply within that district. The regulations could also be amended to promote cohesion between groundwater conservation districts in the same aquifer, allowing regulations to follow aquifer boundaries rather than political ones. In addition, much of the groundwater in the state is not regulated by a groundwater conservation district. The Legislature should develop a plan to limit groundwater exploitation outside of the boundaries of current groundwater conservation districts.
- *Beneficial use of recycled water*: The NPDES permit allocation for treated produced water could be reviewed to allow beneficial use of treated water for purposes other than reuse in another hydraulic fracturing operation while still ensuring environmental protection (Lyons and Tintera 2014).

CONCLUSIONS

With freshwater supplies already stretched across water use sectors, use of alternative water supplies for hydraulic fracturing such as brackish water, effluent, and recycled produced water should be made a higher priority. Moreover, while other user groups, including municipalities, compete for brackish water and effluent, there is little competition for reused or recycled produced water. Technological innovation unlocked shale resources and great economic returns, changing the global energy balance. That same adaptation of technological innovation can address the complex issues associated with production in water scarce regions. The policy framework in Texas could also be augmented to encourage more alternative water use, especially recycled and reused produced water.

ACKNOWLEDGMENTS

The authors would like to acknowledge John Tintera for his intellectual contributions to this work. The authors would also like to acknowledge the Texas Water Policy class taught by Karen Huber and the Lyndon B. Johnson School of Public Affairs. This work was funded by the National Science Foundation Integrative Graduate Education and Research Traineeship, the Cynthia and George Mitchell Foundation, and the U.S. Department of Energy.

REFERENCES

16 Texas Administrative Code § 3.46.

16 Texas Administrative Code § 3.9.

Adger P. 2014 June 13. College Station City Council votes unanimously for Apache Corp. treated water deal. KBTX [Internet]. Available from: http://www.kbtx.com/home/headlines/College-Station-city-council-votes-unanimously-for--262980441.html

Apache Corporation. 2014. Personal communication.

Buchele M. 2013 March 28. Fracking boom spurs a rush to harness brackish water. NPR State Impact [Internet]. Available from: http://stateimpact.npr.org/texas/2013/03/28/drilling-boom-spurs-a-rush-to-harness-brackish-water/

Combs S. 2014. The energy report 2008 [Internet]. Austin (Texas): Texas Comptroller of Public Accounts. Available from: http://www.window.state.tx.us/specialrpt/energy/

Cook M, Webber M. 2014. The influence of hydraulic fracturing on the water market in Texas. Shale Energy Engineering. 530-542 p.

Deeds N, Kelley V, Fryar D, Jones T, Whellan AJ, Dean KE. 2003. Groundwater availability model for the Southern Carrizo-Wilcox Aquifer. Report prepared for the Texas Water Development Board.

Doherty T, Smith R. 2012. Water transfers in the West 2012: projects, trends, and leading practices in voluntary water trading. Denver (Colorado): The Western Governors' Association. 133 p.

Dropkin A, Henry T. 2014. How the Denton fracking ban could work. NPR State Impact [Internet]. Available from: http://stateimpact.npr.org/texas/tag/denton/

Eagle Ford Shale. 2013. Alpha reclaim technology opening Eagle Ford water facility [IntPernet]. Available from: http://eaglefordshale.com/press-releases/alpha-reclaim-technology-opening-eagle-ford-water-facility/attachment/alpha-reclaim-tech-facility-karnes-city-tx/.

Eaton C. 2014 April 17. Texas heading for major water shortage with limited oil field recycling. Fuel Fix [Internet]. Available from: http://fuelfix.com/blog/2014/02/17/texas-heading-for-major-water-shortage-amid-limited-oil-field-recycling/

Folger P, Tiemann M. 2014. Human-induced earthquakes from deep-well injection: a brief overview [Internet]. Available from: http://www.fas.org/sgp/crs/misc/R43836.pdf

Fox G. 2014. Texas Oil & Gas Association applauds Railroad Commission's adoption of disposal well rule amendments related to induced seismicity [Internet]. Available from: http://txoga.org/assets/doc/TXOGA_News_Release_on_Final_Railroad_Commission_Rules_on_Seismicity.pdf

Freyman M. 2014. Hydraulic fracturing & water stress: water demand by the numbers [Internet]. Boston (Massachusetts): Ceres. Available from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers/view

Galbraith K. 2013 March 8. In Texas, water use for fracking stirs concerns. The Texas Tribune [Internet]. Available from: http://www.texastribune.org/2013/03/08/texas-water-use-fracking-stirs-concerns/

Getches D. 2009. 4th edition. Water law in a nutshell. St. Paul (Minnesota): West Publishing Co. 492 p.

Godsey W. Fresh, brackish or saline water for hydraulic fracs: what are the options? [presentation, Internet]. Available from: http://www2.epa.gov/sites/production/files/documents/02_Godsey_-_Source_Options_508.pdf

Hiller J. 2013 March 9. Companies try selling effluent water in the Eagle Ford. The San Antonio Express-News [Internet]. Available from: http://www.mysanantonio.com/business/article/Companies-try-selling-effluent-water-in-the-Eagle-4342096.php

Holland S, Moore M. 2003.Cadillac Desert revisited: property rights, public policy and water-resource depletion. Journal of Environmental Economics and Management. 46:131-155,

IHS. 2014. Water management at forefront of exploration and production operators' considerations, says new IHS study. Available from: http://press.ihs.com/press-release/ep-water-use/water-management-forefront-exploration-and-production-operators-considera#sthash.NxpKoVxO.dpuf

Jester S, Bjornen K, Sharma R. 2013. Evaluation of produced water reuse for hydraulic fracturing in Eagle Ford [presentation, Internet]. Available from: http://www.slideshare.net/atlanticcouncil/produced-water-session-x-steve-jester

Kalaswad S, Christian B, Petrossian R. 2005. Brackish groundwater in Texas [Internet]. Available from: https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R363/B2.pdf

Lawler D. 2014 July 25. Direct potable reuse to provide cleaner drinking water. Houston Chronicle [Internet]. Available from: http://www.houstonchronicle.com/opinion/outlook/article/Direct-potable-reuse-to-provide-cleaner-drinking-5648285.php

Lee M. 2011 Oct. 6. Parched Texans impose water-use limits for fracking gas wells. FuelFix [Internet]. Available from: http://fuelfix.com/blog/2011/10/06/parched-texans-impose-water-use-limits-for-fracking-gas-wells/

Lewis T. 2014 Sept. 14. Guest view: why I am voting no to prop 1. Odessa American [Internet]. Available from: http://www.oaoa.com/editorial/columns/guest_columns/article5a5baae0-3b98-11e4-850a-001a4bcf6878.html

Lyons B. 2014. Produced water: asset or waste? [Internet]. Washington, D.C.: Atlantic Council. Available from: http://www.atlanticcouncil.org/publications/reports/produced-water-asset-or-waste

Lyons B, Tintera J. 2014. Sustainable water management in the Texas oil and gas industry [Internet]. Washington, D.C.: Atlantic Council. Available from: http://texasalliance.org/wp-content/uploads/2014/08/Texas-White-Paper-on-Sustainable-Water-Management-by-the-Oil-and-Gas-Industry-July-29-2014.pdf

Mittal A, Gaffigan M. 2009. Energy-water nexus: improvements to Federal water use data would increase understanding of trends in power plant water use [Internet]. Washington, D.C: U.S. Government Accountability Office. Report to the Chairman, Committee on Science and Technology, House of Representatives. GAO-10-23. Available from: http://www.gao.gov/assets/300/296960.pdf

National Drought Mitigation Center. 2013. Current U.S. drought monitor [Internet]. Available from: http://droughtmonitor.unl.edu/

Nicot JP, Reedy RC, Costley RA, Huang Y. 2012. Oil & gas water use in Texas: update to the 2011 mining water use report [Internet]. Austin (Texas): Texas Oil & Gas Association. Available from: http://www.beg.utexas.edu/water-energy/docs/Final_Report_O&GWaterUse-2012_8.pdf

Nicot JP, Scanlon BR. 2012. Water use for shale-gas production in Texas, U.S. Environmental Science & Technology. 46(6):3580-6.

Nicot JP, Scanlon BR, Reedy RC, Costley RA. 2014. Source and fate of hydraulic fracturing water in the Barnett Shale: a historical perspective. Environmental Science & Technology. 48(4):2464-71.

[NPR] National Public Radio. 2014. Deep injection wells: how drilling waste is disposed underground [Internet]. Available from: http://stateimpact.npr.org/pennsylvania/tag/deep-injection-well/

Pacsi P, Sanders KT, Webber ME, Allen DT. 2014. Spatial and temporal impacts on water consumption in Texas from shale gas development and use. ACS Sustainable Chemistry and Engineering. 2(8):2028-2035.

Paul C. 2014 July 22. City OK's Pioneer water deal. Odessa American [Internet]. Available from: http://www.oaoa.com/inthepipeline/article_a2a730fe-120c-11e4-8f17-0017a43b2370.html

Potter HG. 2004. History and evolution of the rule of capture. In: Mullican III WF, Schwartz S. editors. 100 years of rule of capture: from East to groundwater management. Symposium sponsored by the Texas Water Development Board, June 15, 2004. Austin, Texas. 1–9 p.

Ritter A, Fazio E. 2014. Interim report to the 84th Legislature [Internet]. Texas House Committee on Natural Resources. Texas House of Representatives. Available from: http://www.house.state.tx.us/_media/pdf/committees/reports/83interim/House-Committee-on-Natural-Resources-Interim-Report-2014.pdf

Ritter A, Fazio E. 2012. Interim report to the 83th Legislature [Internet]. Texas House Committee on Natural Resources. Texas House of Representatives. Available from: http://www.house.state.tx.us/_media/pdf/committees/reports/82interim/House-Committee-on-Natural-Resources-Interim-Report.pdf

[RRC] Railroad Commission of Texas. 2014a. Texas monthly oil & gas production [Internet]. Available from: http://www.rrc.state.tx.us/oil-gas/research-and-statistics/production-data/texas-monthly-oil-gas-production/

[RRC] Railroad Commission of Texas. 2014b. Saltwater disposal wells [Internet]. Available from: http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-saltwater-disposal-wells/

Scanlon BR, Reedy R C, Nicot JP. 2014a. Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. Environmental Science and Technology [Internet]. 12386-12393 p. Available from: http://pubs.acs.org/doi/abs/10.1021/es502506v

Scanlon BR, Reedy R C, Nicot JP. 2014b. Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays? Environmental Research Letters. 9(124011). Available from: http://iopscience.iop.org/1748-9326/9/12/124011/pdf/1748-9326_9_12_124011.pdf

[TAGD] Texas Association of Groundwater Districts. 2014. Groundwater conservation district index [Internet]. Available from: http://www.texasgroundwater.org/gcdi-map.html

[TCEQ] Texas Commission on Environmental Quality. 2009. Rights to surface water in Texas [Internet]. (GI-228), Available from: http://www.tceq.state.tx.us/files/gi-228.pdf_4467322.pdf

[TCEQ] Texas Commission on Environmental Quality. 2014. Requirements for reclaimed water [Internet]. Available from: https://www.tceq.texas.gov/assistance/water/reclaimed_water.html

[TAC] Texas Administrative Code § 3.8.

Texas House Bill 3664, 83d Leg., R.S. 2013.

[NRC] Texas Natural Resource Code § 122.

The City of Lubbock, Texas v. Coyote Lake Ranch, LLC. Texas. 2014.

[TXDOT] Texas Department of Transportation. 2012. Task force on Texas' energy sector roadway needs [Internet]. Available from: http://ftp.dot.state.tx.us/pub/txdot-info/energy/final_report.pdf

U.S. Census Bureau. 2012. The 2012 statistical abstract [Internet]. Available from: http://www.census.gov/compendia/statab/cats/population.html

[US EIA] United States Energy Information Administration. 2011. Review of emerging resources: U.S. shale gas and shale oil plays [Internet]. Available from: http://www.eia.gov/analysis/studies/usshalegas

[US EIA] United States Energy Information Administration. 2014a. Annual energy outlook 2014 Early release overview [Internet]. Available from: http://www.eia.gov/forecasts/aeo/er/pdf/0383er%282014%29.pdf

[US EIA] United States Energy Information Administration. 2014b. Natural gas: number of producing wells [Internet]. Available from: http://www.eia.gov/dnav/ng/ng_prod_wells_s1_a.htm.

US EPA] United States Environmental Protection Agency. 2014a. Class II wells - oil and gas related injection wells (Class II) [Internet]. Available from: http://water.epa.gov/type/groundwater/uic/class2/

[US EPA] United States Environmental Protection Agency. 2014b. Classes of wells [Internet]. Available from: http://water.epa.gov/type/groundwater/uic/wells.cfm

[USGS] United States Geological Survey. 2014. Groundwater depletion [Internet]. Available from: https://water.usgs.gov/edu/gwdepletion.html

Vaughan EG, Crutcher JM, Labatt III TW, McMahan LH, Bradford BR, Cluck M. 2012. Water for Texas: 2012 State Water Plan.

Water Data for Texas. 2014. [Internet].Available from: http://www.waterdatafortexas.org/reservoirs/statewide

APPENDIX A. GROUNDWATER CONSERVATION DISTRICT POLICIES

The map shows total annual water production in groundwater conservation districts using English units. One acre-foot is approximately 3.25 × 10^5 gallons.

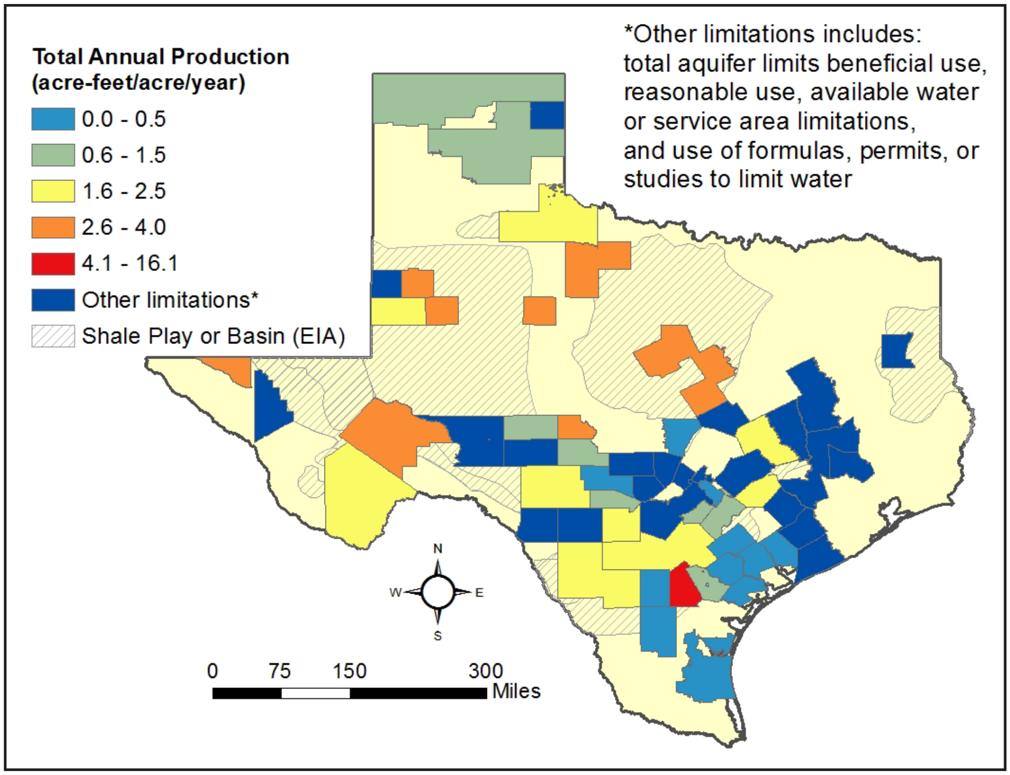

Figure 10. The map shows basic annual production limitations (acre-feet/acre/year) for non- exempt wells in Texas groundwater conservation districts. Some groundwater conservation districts with annual production limitations have other stipulations associated with these limits. Many groundwater conservation districts have non-numeric production limitations on all wells such as total aquifer limits, beneficial use, reasonable use, available water, or service area limitations. Some groundwater conservation districts limit production per well with use of formulas, permits, or studies. (Map created by the author based on data from TAGD 2014.)