Exploring the viability of produced water reuse for irrigation in the Permian Basin, Texas

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1. Introduction

Texans use a vast supply of water annually in the agriculture sector for irrigation. Experts estimate that around 8 million acre-feet of water was used for irrigation in 2018 and water use is projected to increase to 9.3 million-acre feet by 2030 (1). Most irrigation water demand is concentrated in the northwestern part of Texas, where water supply can be limited. The major source of water in the panhandle for irrigators is the Ogallala aquifer. Approximately 95% of water pumped from the Ogallala is used for irrigation (2). Unfortunately, the Ogallala has been declining for decades due to over pumping. In some areas, water level has declined by more than 150 feet (Figure 1). The strained water supply in this region has put a substantial stress on the farming industry, which contributes a significant amount of revenue to the Texas and U.S. economy. Having enough water supply for agriculture is paramount for our ever-growing state.

In addition to the existing low supply, the threat of drought looms over Texas, which has had a history of drought episodes and chronic water supply shortages. The drought of the 1950s, the worst in Texas history, devastated the state's agriculture and economy, forever changing the way Texans manage water. In northwest Texas, the number of irrigated acres increased from 300,000 in 1940 to 2,900,000 in 1953. Almost all areas in Texas had a deficient rainfall amount in forty or more months from 1952-1956 (3). Although the 1950s was the worst drought period in Texas history, the driest single year in Texas was in 2011, just ten years ago. From October 2010-September 2011, Texas received a total of 11 inches of rainfall. For comparison, the average amount of rainfall Texas receives annually is 27.95 inches (4). Due to this substantial decrease in rainfall, Texas farmers struggled to find enough water for irrigation. Reservoirs levels fell to unprecedented levels, wells ran dry, and streamflow decreased to record levels. Additionally, the lack of rainfall contributed to high temperatures, which further intensified the severity of the drought.

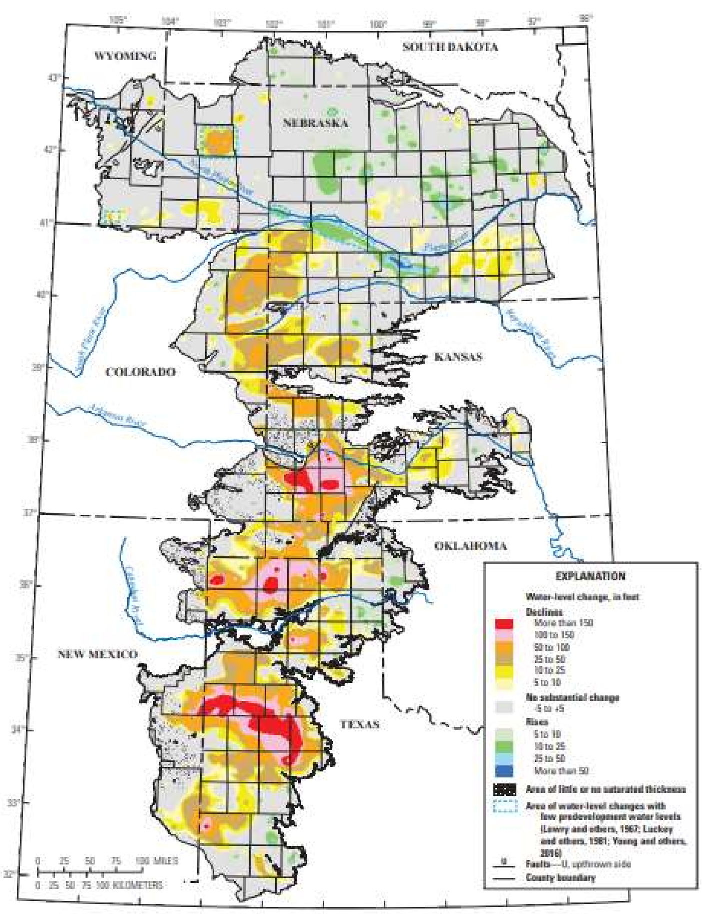

Figure 1- USGS map showing water level decline in the Ogallala Aquifer (24)

The lack of water during the 2011 drought caused a $7.6 billion loss to Texas agriculture. The cotton industry, which was the second largest impacted agriculture sector behind cattle, lost $2.2 billion. Cotton is the largest crop, regarding number of irrigated acres in Texas, and produces an average of $1.8 billion annually (5). According to the 2017 U.S. Agriculture Census, cotton accounted for around 30% of irrigated acres in Texas. Corn, wheat, hay, and sorghum follow close behind (Figure 4). Most of the irrigated acres are in the High Plains regions of Texas (Figure 2). Because of this, it is especially important to maintain a healthy supply of water in this region.

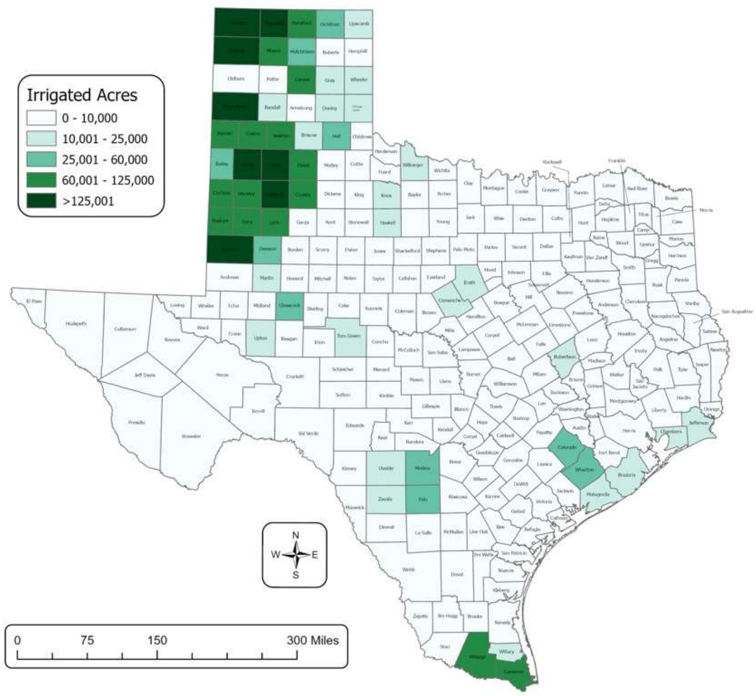

Figure 3 - Number of irrigated acres for all crops. Data from 2017 USDA Agriculture Census (6)

Just south of this region, the oil and gas industry booms (Figure 3). Known as the Permian Basin, this region is the top producing area for oil in Texas. According to the Energy Information Administration (EIA), the Permian Basin produces almost 5 million barrels of oil a day (7). Water used in the oil and gas industry, albeit a lot of water, is less than 1% of the annual total water demand in Texas. Interestingly, one of the biggest waste streams in this industry is water. It is estimated that for every barrel of oil, 7 barrels of water are generated. This can vary, depending on region, where some oil to water ratios are as high as 10:1 (8). There are even some wells that produce a 100:1 ratio (9). It is estimated that the Texas oil and gas industry produced almost 10 billion barrels of water in 2017 (10). With 42 gallons in one barrel, that is estimated at 420 billion gallons of water or 1.3 million acre-feet. In the Permian Basin the volume of wastewater increased 17-fold from 2011-2017 (Figure 5). The total projected volume, based on technically recoverable resources, is 13 trillion gallons in the

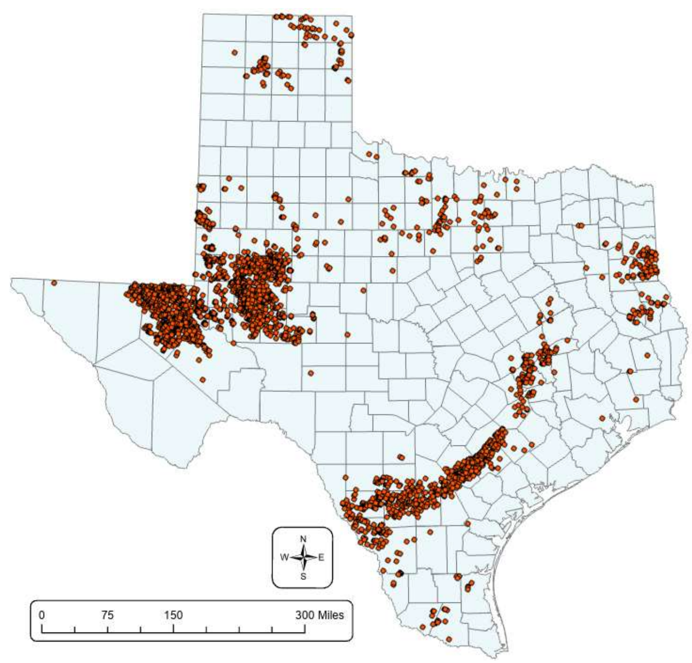

Figure 2 - Map of producing wells from FracFocus in 2019 (FracFocus.org)

Permian Basin over the lifetime of the formation (11). Current management practices are to inject the water into the ground for enhanced recovery on conventional wells or into disposal wells.

Reuse as a strategy for managing water supply has been around for a long time, especially in the manufacturing and municipal sectors. However, reusing generated wastewater from the oil and gas industry, known as produced water, and defined by EPA as "water (brine) brought up from the hydrocarbon-bearing strata during the extraction of oil and gas" has only been gaining strides recently (9). As fresh water supply becomes increasingly difficult to source due to population growth and climate change, and disposing of produced water has shown negative environmental effects, produced water could be key to augmenting irrigation water supply, especially in arid or semi-arid regions like the high plains of Texas. As oil and gas production is projected to increase by the Energy Information Administration (EIA) (12), an increase in produced water will follow suit. There is an emerging opportunity to reuse this water for beneficial use, including irrigation. In fact, the Texas Produced Water Consortium was just established that will study the technologies and economics of beneficial reuse of produced water. This is an opportune time to investigate the feasibility and effectiveness of reusing produced water for irrigation.

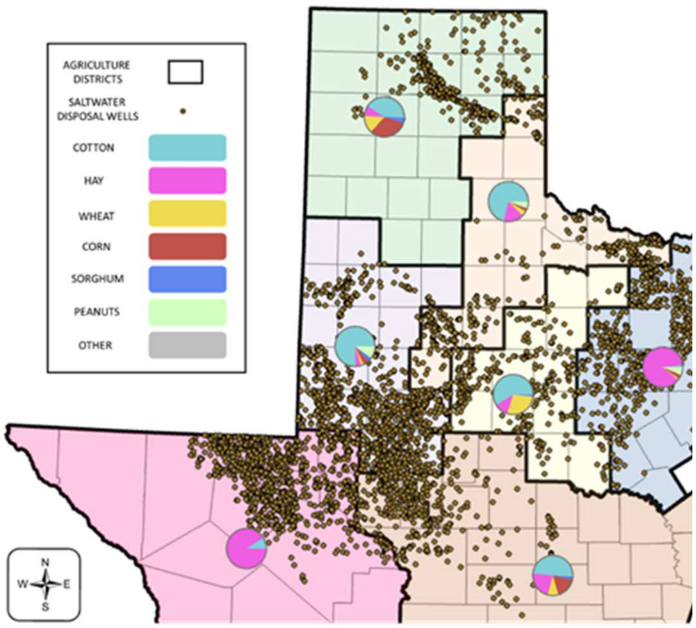

Figure 4 - Map showing crop percentages for agriculture districts near the Permian Basin. Data from USDA 2017 Agriculture Census (6) and Railroad Commission (43)

2. Background

The oil and gas industry uses water for both conventional and unconventional wells. For conventional wells, which extract oil using the natural pressure of the well, water is used mainly during drilling to lubricate and clean the drill. It can also be used for enhanced recovery, or water flooding, which is discussed later. For unconventional wells, usually called hydraulic fracturing wells, water is mixed with chemicals and sand and is injected into the ground at high pressures to cause fractures in the geologic formation. The new fractures in the formation allow the flow of oil or gas to the surface. Operators of unconventional wells must inject millions of gallons of fluid for this process and generally around 95% of the injected fluid into the formation is water (13). Most water use in the oil and gas sector is due to hydraulic fracturing wells.

Some of this injected water will return to the surface as "flowback water." Flowback water can be high in dissolved solids, salts, and chemicals previously used in the injected fluid. Generally, for hydraulically fractured wells, the volume of flowback water will be high in the initial stages of the well and will decrease over time (Figure 6). As flowback water decreases, the volume of produced water increases. Produced water is the water originally found in the geology formation and is mixed with oil and gas that is extracted. It generally consists of naturally occurring constituents from the geologic play, which can be radioactive materials, metals, and volatile gasses. In most research and studies, both flowback water and produced water are generally referred to as produced water. This paper will refer to all water that flows from an oil or gas well as produced water.

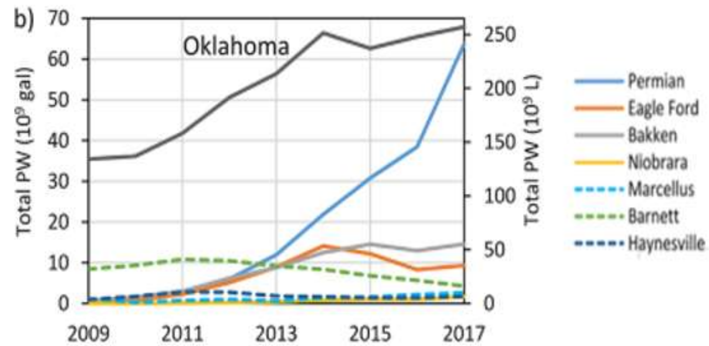

Figure 5 - Figure showing increase in produced water in various plays (11)

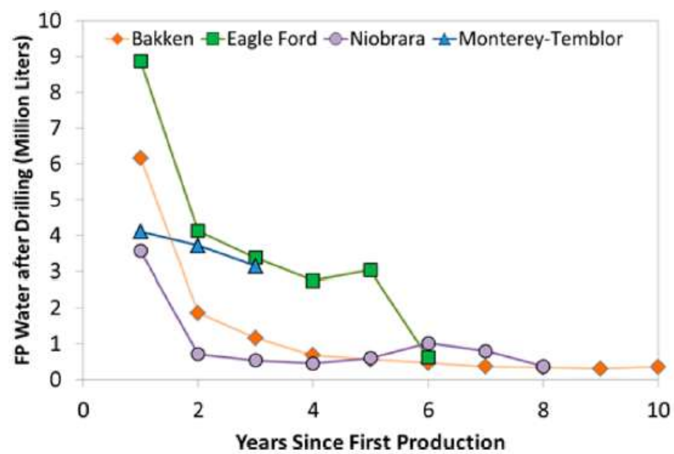

Figure 6 - Graphical representation of generated produced water volume throughout a lifetime of an unconventional oil well (14).

The quality and quantity of produced water varies tremendously throughout the state depending on elements such as location, geological formation, and the hydrocarbon being produced (Figure 7). Because oil and gas operators are not required to report the amount of produced water generated in Texas (10), we have to rely on estimates. To estimate produced water, some methodologies use volume of disposed water or even contact operators individually for volume data. To complicate these estimates, produced water quantity varies throughout the lifetime of a well (16). Additionally, wells extracting from oil plays are much more likely to have more produced water than wells extracting from gas plays (11). These nuances in produced water volumes make it difficult for researchers and government agencies to accurately estimate the volume of produced water.

Basin	**Average TDS (mg/L)**	**Max TDS (mg/L)**	**Min TDS (mg/L)**
Amarillo Arch	139,938	327,224	1,002
Anadarko	115,512	375,021	1,012
Anadarko - Southern Oklahoma	39,095	72,152	0
Bend Arch	131,170	244,396	3,756
East Texas	74,994	405,535	1,018
Fort Worth	172,734	300,155	21,926
Gulf Coast	49,244	398,024	0
Kerr	3,790	7,025	1,990

Llano Uplift	64,054	125,652	3,032
Ouachita Thrust	47,229	175,967	4,277
Palo Duro	151,027	338,520	5,865
Permian	113,725	395,348	1,048
Permian - Bend Arch	112,962	163,735	62,188
Southern Oklahoma	163,193	345,503	0
Strawn	50,464	76,863	24,065

Figure 7 - Table showing variety of TDS measurements in Texas taken from the USGS National Produced Waters Geochemical Database (15)

Produced water could potentially contain hundreds of chemicals, and unfortunately, the current status of produced water composition is lacking. A literature review of studies on produced water identified over 1,000 unique chemicals found in produced water (26). This can range from chemicals injected during the fracking process to chemicals naturally found in the geologic formation. In general, produced water can have organic constituents, such as hydrocarbons, inorganic constituents, usually measured by total dissolved solids (TDS), natural occurring radioactive material, such as radium-226 and radium-228, and various types of bacteria. Produced water in the Permian Basin is known to have a high variability of TDS. A review of the US Geological Survey National Produced Waters Geochemical Database shows a range of 1,048 mg/L to 395,348 mg/L TDS in sampled wells in the Permian Basin (Figure 7). For comparison, sea water usually has a TDS of 35,000 mg/L.

3. Disposal

With the average ratio of produced water to oil as 7:1 in Texas, oil and gas operators must have a management strategy for produced water. In Texas, there are currently a few options. What operators choose to do with produced water will generally depend on the location of the well, quality and quantity of produced water, access to disposal wells, and costs. Most produced water is either injected into a disposal well or injected for enhanced recovery. (10).

Subsurface Disposal

Subsurface disposal is the most common, and usually cheapest, way to dispose of produced water in Texas. In 2017, about 5.3 trillion barrels of produced water were injected into disposal wells (10). There are currently 7,405 active permits for subsurface disposal (Figure 8). In subsurface disposal, produced water is injected into a confined, non-hydrocarbon produced formation. To mitigate harmful effects of this process, injection wells are required to have certain safeguards in place, including concrete casings. Oftentimes these disposal wells are over a mile deep.

District	Disposal into nonproductive zone	Disposal into a productive zone	Secondary recovery (injection well)
1	189	174	538
2	193	113	137
3	434	181	150
4	173	108	73
5	53	53	60
6	218	220	165

6E	0	88	58
7B	224	389	1,546
7C	265	139	326
8	910	1,118	7,332
8A	167	617	9,754
9	429	533	2,147
10	132	285	139

Figure 8 - Number of active permits in Texas (49)

Although this may be one of the more common ways to dispose of produced water, some studies have shown negative effects of subsurface disposal. When water is injected over a mile deep into the ground, it is ultimately taken out of the water cycle (10). This only exaggerates the water supply issue, especially in areas that are already struggling. This disposal method has also been shown to increase seismic activities (20, 27). This type of disposal increases the pore pressure in the formation and initiates slips in nearby faults. This increase has spurred stricter regulations recently, like disposal capacity limits and flow rates, which have resulted in increased disposal costs for operators. Regulations regarding subsurface disposal is discussed further below.

Additionally, produced water can be injected into the ground for enhanced recovery. In 2017, about 4.5 trillion barrels of produced water were injected into the ground for this purpose (16). Currently, there are over 22,000 active permits in Texas regarding enhanced recovery (Figure 8). Enhanced recovery, or water flooding, is the process in which an operator injects water back into the producing formation using a nearby well. The injected water increases the pressure in the formation and forces the remaining oil to the surface of the producing well. Generally, half of injected produced water is used for enhanced recovery while the other half is disposed.

Surface water

Another way to dispose of produced water is through surface water, albeit this is very uncommon. Most operators do not discharge into surface water bodies because they are usually not operating in an area where there is enough surface water to discharge into (low dilution), high treatment cost, and because of the public perception associated to surface water discharge. Additionally, discharge into surface water is only allowed west of the 98th meridian. Regulations affecting surface water discharge are discussed further below.

Evaporation Ponds

Some operators use evaporation ponds to dispose of or reduce the volume of produced water. These ponds are lined with impermeable material and are large and shallow to allow for maximum evaporation. The effectiveness of evaporation ponds generally depends on the rate of evaporation in the area. If the evaporation rate is lower than the rate at which produced water is generated, then these ponds are usually not effective (16). Therefore, ponds are generally only effective for small volumes of produced water. However, the availability of these ponds can help lower volume for discharge, which can help when subsurface disposal capacity is limited. Evaporation ponds can lead to sludge material on the bottom of the pit that will need to be disposed. In addition, evaporation ponds can emit volatile air gasses, like methanol and sulfur dioxide (50), which can require air permits. Finally, evaporation ponds can attract waterfowl, therefore some type of netting over the pond is required (16).

Reuse (within oil and gas industry)

In Texas, reuse of produced water outside the oil and gas industry is currently not employed. However, some operators choose to reuse produced water within their operations. In fact, most produced water generated from conventional wells is reused in enhanced recovery. Reuse depends on produced water quality, volume variability, disposal cost, source water cost, and location of the well. Prior to 2011, reuse from fracking operations was very limited. Water used in fracking fluids had to be almost freshwater. The presence of any residual chemicals or bacteria could negatively impact downhole stimulation chemistry, and any unknown chemicals in produced water could trigger unwanted interactions during reuse (44). Because of advancing chemistry, some operators are able to reuse their treated produced water in their fracking operations (17, 48). Currently, more operators are choosing to reuse produced water in fracking operations.

Because the volume of produced water is variable throughout the lifetime of a well, storage capacity will need to be built in order to effectively reuse produced water—an additional cost that some operators choose not to take on. However, storage helps in times when there is a small volume of produced water. If produced water is not reused, truck or pipelines transport the produced water to a distant saltwater disposal well. This can be costly and increase risks of leaks and spills. Plus, some areas have capacity limits and flow rates for subsurface disposal.

Treatment of produced water is one of the biggest limitations to reuse. Because produced water can have high TDS and a variety of chemicals, the cost of treatment to end-use standards can be costly. Statistics about the volume of produced water reuse is currently not captured in Texas. However, in 2017 it is estimated that the volume of produced water used in enhance recovery was around 4.5 trillion barrels or 189 trillion gallons of water (10). This estimate does not include produced water that was reused in fracking operations.

4. Regulations

Regulations affecting produced water disposal fall under either the Underground Injection Control (UIC) program or the National Pollutant Discharge Elimination System (NPDES) program. Regulations affecting reuse of produced water are generally not well-developed. With interest growing in produced water reuse, regulations will need to be established or updated to meet the growing need of water.

Underground Injection Control

The use of produced water for enhanced recovery and the disposal of produced water via injection wells are regulated under the UIC program. In Texas this program is administered by the Railroad Commission (RRC). The RRC grants well permits for UIC Class-II-D wells and Class-II-R wells, which are wells associated with the oil and gas industry. The permitting process includes certain requirements to protect the environment and human health. Produced water disposed of in a Class II-D well is typically injected in formations below aquifers used for drinking water, however it can be disposed of in formations above drinking water aquifers. Considerations for Class II-D wells include well depth, location, impermeability of the formation, and distance from other developments. The permitting process involves a review of the area nearby to identify any possible pathways in which the disposed produced water could be released to another area. The operation of the injection well is also regulated under the permit, including the volume of produced water, pressure, and flow rate of injection (18). Additionally, the quality of the disposed water does not have to meet any regulatory standards.

Operators who reuse produced water for enhanced recovery or new drilling/fracturing fluids are not subject to any regulations. The operator will treat the produced water to meet their operational needs only and prolong the life of the well. Typically, iron reducers are added to prevent scaling. Additional treatment can be done to protect equipment from corrosion and prevent scaling or biofilm growth (44).

National Pollutant Discharge Elimination System

To dispose of produced water into a surface water body, operators must use a Texas Pollutant Discharge Elimination System (TPDES). This program was managed by the Environmental Protection Agency (EPA) until 2019, when the Texas Legislature passed House Bill 2771. This required the Texas Commission on Environmental Quality (TCEQ) to receive authorization from the EPA to handle this permitting process (19). Discharge into surface water bodies is only allowed west of the 98th meridian, must be "good enough quality to be used for wildlife or livestock watering", and be below 35 mg/L of oil and grease. Around 34 million barrels of water were discharged to surface water in Texas in 2017 (10).

5. Issues Driving Reuse

While the sheer volume of water used for irrigation in Texas is one reason behind the increasing trend of reuse, there are also additional reasons related to the negative effects of current management practices that are pushing this trend. These include the increase in seismic events in West Texas and the depletion of local aquifers.

Seismicity

As indicated earlier, subsurface disposal in some areas have been shown to increase seismic events, especially high-injection rate wells (27). It is generally thought that the increase in pore pressure from injected produced water can induce seismicity from nearby stressed faults. Although the correlation of earthquakes and wastewater injection is still under investigation, the rate of earthquakes has significantly increased since 2008 (20), especially in central U.S. Since shale gas development started in the Barnett Shale in 1998, nine earthquakes larger than 3 in magnitude have occurred. Within the previous 25 years before 1998, there had been no reported earthquakes larger than 3 in magnitude (21). Some argue that the increase in reported earthquakes is due to the increase in earthquake monitoring stations. In fact, in 2015 the Texas Legislature passed House Bill 2 that gave funding to the University of Texas to develop and manage an earthquake monitoring system, called TexNet Seismic Network. This program is currently monitoring and researching the correlation of injection disposal and earthquakes (23). Nevertheless, the increase in seismic events have pushed regulators to limit disposal capacity in some areas (see Figure 9).

Before approving new injection permits, the RRC reviews historical seismic activities in the area to determine if it is appropriate to approve a new permit. Additionally, the RRC can limit or even stop disposal injections if seismic activities have increased, which they have done recently. Since February

2020, six earthquakes with greater than 3.5 magnitude have occurred in West Texas. Because of this, the RRC released a notice in September 2021 to operators near Midland and Odessa that they will not be issuing any new permits for saltwater disposal wells and asked additional permittees to reduce daily injection rates (22). This area is shown in Inset A of Figure 9. The new capacity limits and potential future capacity limits have pushed operators to look elsewhere for produced water management.

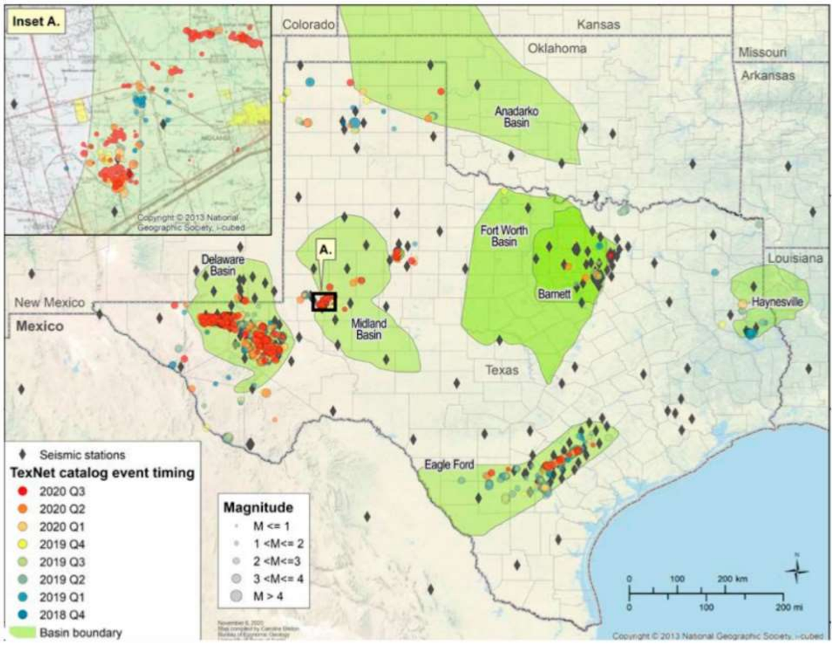

Figure 9 - Map from TexNet Seismic Monitoring Program showing high volume of earthquakes in the Gardendale area (Inset A) (23)

Groundwater Depletion

Another issue driving reuse is groundwater depletion, especially in the semi-arid regions of West Texas, including the Midland and Delaware Basins. The primary aquifers of this regions include the Ogallala, Edwards-Trinity, Dockum, and Pecos Valley (11). The Ogallala aquifer has seen significant depletion since the 1950s due mostly to irrigation demand and population growth. In some areas, it has dropped 300 feet over the past 60 years. The Pecos Valley aquifer has also been declining due to municipal and industry pumping (28). In some counties, like Loving and Irion, hydraulic fracturing demand is projected to be larger than the modeled available groundwater (11). This amplifies the regions water stress. Depletion of aquifers can lead to land subsidence, saltwater intrusion, and reduced surface flow.

As the water table declines, the extraction of water becomes costlier. In addition, the cost to dispose of produced water can increase as capacity limitations are implemented. This makes it all the more likely for operators to choose reuse instead of disposal.

6. Current Irrigation Reuse Projects/Studies

Using produced water outside the oil and gas industry is uncommon. Less than 1% of generated produced water in the U.S. is used outside the oil and gas industry (10). Efforts have included reusing produced water for dust suppression, de-icing, livestock watering, cooling manufacturing facilities, and irrigation. Whichever the end-use goal may be, the toxicity of the produced water is a major concern to the environment and human health. Therefore, it is especially important to study the effects and perform pilot studies to mitigate any negative harm.

California

In Kern County, California, farmers have been using produced water for irrigation for more than twenty years. Produced water is generated, pretreated by operators, and then sent to local water districts where it is blended with surface or groundwater at around a 1:1 ratio (29). Approximately 95,000 acres are irrigated with produced water in Kern County (30). Although this process has been going on for decades, there is currently heavy consideration and investigation as to whether using produced water for irrigation is appropriate. In fact, the California Regional Water Quality Control Board recently released a paper on the effects of produced water irrigation on food crops.

Their findings indicate that there is no elevated threat to human health in food crops using produced water for irrigation (31). Although, they indicate major data gaps within their study. This includes gaps in the amount of chemicals used in the oil and gas industry, gaps in the understanding of plant uptake for these chemicals, long term impacts on soil, transformation of chemicals (mixed with fertilizers, pest control, etc.), and toxicity levels of some chemicals. It is important to note that the produced water in Kern County is significantly lower in TDS than produced water in the Permian Basin. The produced water in Kern County is usually lower than 1,000 mg/L TDS, around 750 umhos/cm for electroconductivity and can meet local regulatory effluent limits without additional treatment. Additionally, irrigators do not use produced water from hydraulic fracking wells, as they are unsure about the toxicity of chemicals used in fracking fluids.

Wyoming

In September 2020, Wyoming approved its first permit for land application of produced water. The permit allows the discharge of 7,000 barrels of produced water that meet a list of requirements, including TDS less than 480 mg/L. The treatment process includes low-micron prefiltration, carbon filtration, and reverse osmosis. Analysis results are posted online and show that discharged water is meeting all application requirements. The company, Encore Green Environmental, plans to grow their business into New Mexico and Texas (32).

Texas

A project conducted by the Texas A&M AgriLife Research Center showed positive reviews on using produced water. In this study, they compared the effects of treated, blended produced water with 100% groundwater on cotton yields and soil health. Once the produced water was treated and blended with groundwater, most water quality parameters were similar to locally sourced groundwater. TDS, calcium, and magnesium measured from the treated, blended produced water was even lower than sourced groundwater. Plus, boron levels were very close to the sourced groundwater. Their study found that the treated, blended produced water did not negatively affect cotton yield and even resulted in lower conductivity in the soil (33). While this study is promising, future research will be needed to test other crops and evaluate long-term effects. Additionally, this study did not compare the cost of treatment, if done at a bigger scale, to the cost of disposal.

7. *Environmental Effects*

Although these reports have made promising remarks on the potential reuse of produced water for irrigation, other studies have shown the opposite. One found that diluted, untreated produced water had negative effects on soil health and crop yield. Their findings showed that salinity was the primary driver of the negative effects (37). Other studies have found that chemicals in produced water, such as boron, had influenced soil health and plant yield more than salinity (34). Boron, in addition to sodium and chloride, was found at significantly higher concentration in soil irrigated with blended produced water versus soil irrigated with locally sourced groundwater. The salt and boron in the diluted produced water met recommended levels but the long-term accumulation of these chemicals in the soil can affect the osmotic processes of plants. Accumulation of salt, especially in arid regions, can reduce infiltration rates of soil, making it more difficult for water to reach the subsoil. Additionally, high salinity can reduce the desorption rate of boron from the soil, exaggerating accumulation (34).

Other studies found that the irrigation of produced water can affect the plant's ability to fight disease, reduce aboveground and belowground biomass, reduce photosynthetic efficiency, and reduce reproductive growth. In one study, researchers examined how the wheat plant (*Triticum aestivum*) would react to being inoculated with bacterial or fungal pathogens in addition to being irrigated with different produced water solutions. The study indicated that produced water did have negative effects on immune response. In addition, the constituents other than salinity were the key factors in suppressing immune response. The other constituents noted were boron and total organic carbon (36). In a similar study with *Triticum aestivum*, researchers irrigated the wheat plant with various dilutions of produced water, control water, and salt water. They found similar results in that salinity does not seem to be driving the reduction in plant health. The plants irrigated with salt water outperformed the produced water with the same amount of salinity (35).

All noted studies analyzed the effects of blended produced water rather than treated produced water – with salinity and boron being the main drivers of declining plant and soil health. These constituents should be heavily analyzed in Texas if irrigation using produced water is developed. Additionally, long-term effects and soil accumulation should be studied before implementation of large-scale projects.

8. Potential Issues with Reuse in Texas

Volume

There is plenty of produced water being generated in Texas, but the reuse potential of that water outside the oil and gas industry will depend on trends within the industry. Because treatment is a major factor in reuse, the lowest hanging fruit for reuse seems to be hydraulic fracturing. A review of sustainability reports from major oil companies in the Permian Basin indicate that reuse is a high priority. Pioneer Natural Resources has gone from using 3% recycled water in 2015 to 28% in 2020 (38). Produced water that is reused in hydraulic fracturing operations does not need to be treated as much as water used for irrigation. If operators begin to reuse produced water in hydraulic fracturing operations, there may not be enough produced water to make a significant difference in irrigation demands. According to Scanlon et al., 2020, produced water is projected to exceed hydraulic fracturing demand in the Permian Basin by 15 billion gallons of water, which can then be used for irrigation. Irrigation demand (estimated using 2015 USGS withdrawal data) is 221 billion gallons. The remaining produced water would fulfill only 6% of total irrigation demand (11). While not that much, this water could still help mitigate water shortage problems in this area. Additionally, hydraulic fracturing demand can fluctuate based on slower development, well completions, and economic price downturn. In these times, produced water can fulfill more agriculture demand.

Quality

When using produced water for irrigation, there are certain recommendations regarding the quality of water. When water is too saline, it can be toxic to plants. For example, water that is used to irrigate cotton should be around 5.1 millimhos per centimeter (mmhos/cm) in electric conductivity to get 100% yield. Anything higher than 12.0 mmhos/cm will produce less than 50% yield (39, 40). Wheat and corn have an even lower tolerance. If the soil gets too high in salts, plants will not be able to absorb water. The average electric conductivity in produced water sampled in the Permian Basin is 127 mmhos/cm (15). To meet irrigation recommendations for cotton, produced water will need to reduce electric conductivity by 90%-97%. See Figure 10 for other limits in association to cotton.

Constituent	**USGS Samples**	**Average**	**Max**	**Min**	**Irrigation Recommendation**	**% Reduction**
Conductivity, mmhos/cm	39	127	179	51	5.1	96%
Chloride (mg/L)	7,735	68,093	245,376	9	710	99%
Boron (mg/L)	372	27	396	0.4	3	88%
Sodium	371	43,884	133,343	600	710	98%
TDS mg/L	372	113,725	357,101	3,700	3,264	98%

Figure 10 - Data pulled from USGS National Produced Waters Geochemical Database (15)

Storage and Transportation

While the state's irrigation farming centers are close to the Permian Basin, water conveyance infrastructure will need to be built to transport the water to the treatment centers and then to the farms. This can be a major capital investment for companies who will need to be sure there will be enough produced water to supply the new infrastructure and that it makes sense economically. In addition, agriculture irrigation typically only occurs four or five months out of the year. This seasonality of demand creates challenges for a plant that is treating water throughout the year. Operators have to choose whether it makes sense to invest in infrastructure that is only used half of the year or find other uses for that infrastructure during low-use periods.

Ownership Liability

As reuse discussions increase, so does the issue of ownership and liability. In Texas, groundwater is governed by the Rule of Capture doctrine, which states that groundwater is owned by the landowner. Previously, it was unknown whether this doctrine applied to produced water. This ownership ambiguity stalled development from recyclers because they could not be sure who owned the water. Additionally, the question remained of who would be liable if there was a produced water spill.

In 2013, House Bill 2676 took effect that clarified ownership and liability. This bill stated that the ownership of produced water will transfer from the generator to the treatment operator. Additionally, the bill added tort liability for treatment operators. Once they transferred the treated produced water, they are immune from liability, excluding personal injury, death, or property damage from exposure to the treated water.

Although a milestone for development in reuse, this bill still left key gaps in ownership, especially when it came down to profit. There is still concern and confusion as to if the landowner should get any compensation if the produced water is sold rather than disposed. The bill gives authority to operators to transfer produced water but does not clarify who should benefit from that transfer. According to the Rule of Capture doctrine, the landowner still legally owns the water. The uncertainty could potentially hinder growth in reuse (41,42).

9. Treatment Options

Treatment, specifically the cost of treatment, is one of the major limiting factors in produced water reuse feasibility. After the initial treatment, including separating oil and grease using gravity- or centrifugal force-based separators, there are many technologies operators can choose for treatment. Because the chemical profile of produced water varies so much, treatment options can vary in effectiveness. Some of the more common produced water treatment processes include dissolved gas/air flotation, activated sludge, chemical and electrocoagulation, filtration, and desalination.

Dissolved gas/air flotation uses fine gas bubbles to float small, suspended particles to the surface. A foam layer forms at the surface that is removed by skimming. This sludge then needs to be disposed. Coagulants can be added before this process to allow for smaller particles to be removed. This process works well in removing natural organic matter, volatile organics, and oil and grease.

Activated sludge is the process of adding microbial sludge to produced water to biodegrade organic material and form biological floc. The floc is then removed in a settling tank. This process is one of the most common methods to treat wastewater; however the effectiveness of treatment depends on the correct choice of microbes to add in the sludge.

Another very common process in treating water is coagulation. This process may either use chemicals, such as alum or ferric chloride, or anodes to destabilize suspended or dissolved particles that are then aggregated in the subsequent process of flocculation. The aggregated flocs are then removed by gravity separation or media filtration.

Media filters can include sand, coal and other natural material. Filtration is generally effective at removing solids but not TDS. TDS can be removed through desalination, using thermal technologies or membrane filters. Thermal treatments include multistage flash distillation and vapor compression distillation. In general, thermal processes involve heating the water and reducing the air pressure, which in turn causes the water to transition into steam. The water will go through several similar stages before it is collected by condensation. Thermal technologies are mostly used in regions where energy is cheap as the amount of thermal and electrical energy usage account for most of the treatment cost. However, thermal technologies can treat very high TDS water - up to 300,000 mg/L (47). Another form of desalination is membrane filtration which includes techniques like reverse osmosis (RO), nanofiltration (NF), and electrodialysis (EDR). RO and NF use hydraulic pressure to diffuse produced water through a semi-permeable membrane. Both processes are very effective at removing contaminates in the water however can only treat water up to 45,000 mg/L TDS so extensive pre-treatment is required. EDR uses electrical potential gradients that attract ions and effectively remove them from treated water. Comparably, EDR requires extensive pre-treatment and can generally only treat water up to 35,000 mg/L TDS (44-46).

10. Location in Texas

Analysis was done to find the best areas in the Permian Basin to implement reuse for irrigation. The 2019 National Land Cover Database (NLCD), active saltwater disposal well locations, and 2019 injection volumes from the RRC were compared to find the most suitable regions. One limitation in this analysis is the location of treatment centers. In addition to its transportation to irrigated land, the produced water must first travel to a treatment plant. The major assumption in this analysis is that transportation for treatment of produced water will not be in a distant location. For this analysis, it is assumed that treatment for produced water will be semi-mobile in the beginning stages of reuse and can travel to saltwater disposal wells for treatment.

Latitude and longitude of wells can be found on the RRC website (49). These were then linked to active well attribute information using the wells (American Petroleum Institute) API number. The API number is a unique, permanent number for each wellbore. After associating attribute information to each well, wells with an active UIC permit number for disposal of salt water or flowback water into a nonproductive or productive zone were identified. The number of wells with this active permit are 7,129. Using the location of these wells, areas of dense statistically significant spatial clusters were identified (Figure 12). Additionally, spatial clusters of cultivated land were identified using the 2019 NLCD (Figure 11).

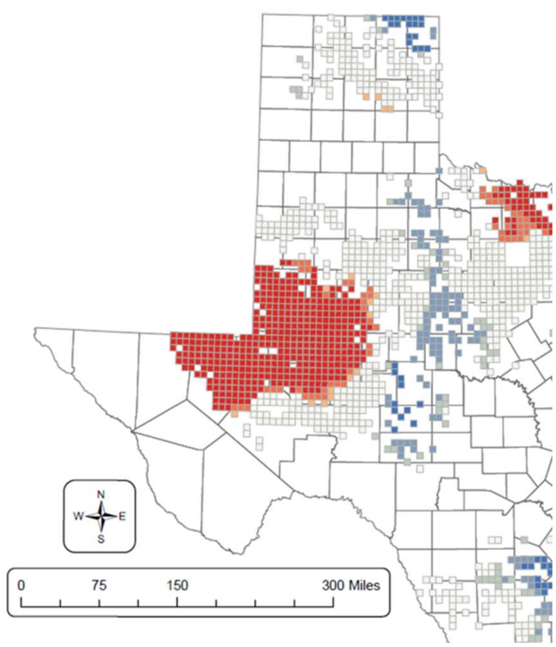

Figure 12 - Hotspots of active disposal wells

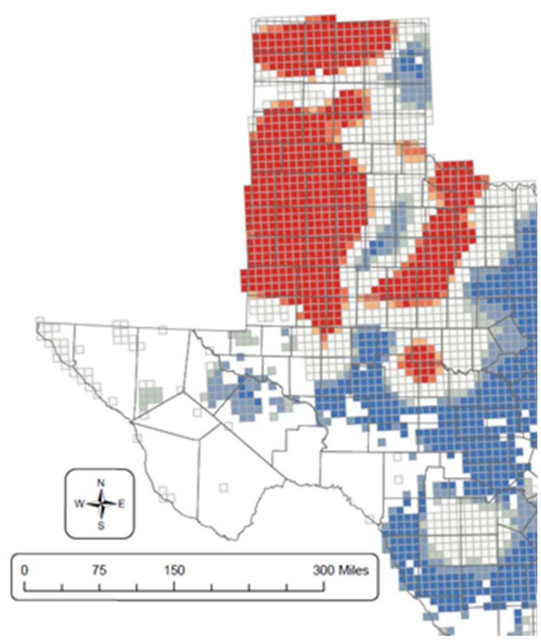

Figure 11 - Hotspots of cultivated land

Both spatial cluster datasets were overlayed on each other to find the best available area in the Permian Basin for reuse with regard to spatial distance of cultivated lands and disposal wells. These areas were in Gaines, Martin, Howard, Midland, Dawson, Borden, Terry, and Glasscock counties (Figure 13). Additionally, the RRC provides injection volumes by county and fluid. Monthly injection volumes of saltwater and flowback water were collected from the RRC for these counties (Figure 14). By aggregating the annual total injection volume for these counties and comparing it to 2015 irrigation withdrawals, produced water volumes in Martin, Midland, Borden, and Glascock counties could reasonably meet irrigation demand.

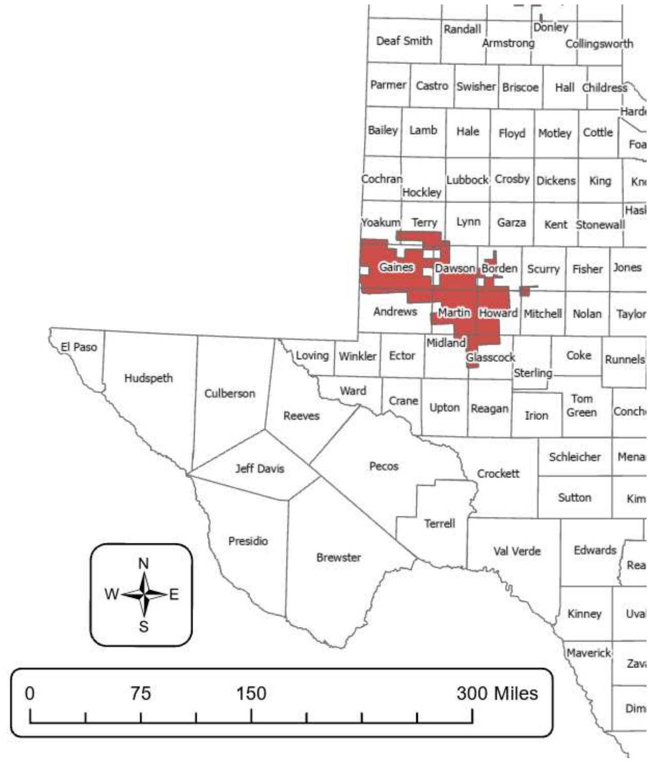

Figure 13 - Overlay of hotspot areas

County	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Gaines	1.319	1.161	1.289	1.217	1.257	1.182	1.201	1.246	1.184	1.238	1.788	1.972
Martin	0.774	0.707	0.820	0.923	0.979	0.970	1.027	1.084	1.077	1.211	1.102	1.092
Howard	1.339	1.263	1.338	1.329	1.403	1.296	1.427	1.369	1.397	1.498	1.616	1.583
Midland	1.033	1.014	1.140	1.022	1.041	0.890	0.981	1.037	1.030	1.000	1.058	1.047
Dawson	0.195	0.170	0.191	0.196	0.193	0.185	0.206	0.208	0.199	0.193	0.275	0.282
Borden	0.110	0.100	0.119	0.115	0.132	0.114	0.121	0.151	0.103	0.110	0.130	0.140
Terry	0.235	0.213	0.238	0.223	0.189	0.199	0.202	0.218	0.157	0.166	0.181	0.183
Glasscock	0.700	0.655	0.718	0.692	0.724	0.680	0.680	0.755	0.776	0.751	0.756	0.753

Figure 14 - Injection volumes of salt water and flowback fracking water by county from the RRC in billion gallons in 2019

11. Recommended Steps

The first step to implement produced water reuse for irrigation is to produce a centralized database for produced water characteristics and volume. Producing a reliable dataset of commonly found chemicals in produced water, with associated toxicity levels, should be a priority. A database that has a realm of constituents in produced water by formation will help to focus attention to develop analytical methods and toxicity levels for certain chemicals. Without established toxicity levels, endusers will not know if treated and/or diluted produced water is safe. Based on a literature review of identified chemicals in produced water, "(56%) of [identified] compounds had not been a subject of safety evaluation or mechanistic toxicology studies and 86% lacked data to be used to complete a risk assessment" (26). This is alarming and must be resolved in order to move forward with reuse. Additionally, there aren't approved testing standards for certain chemicals, and traditional analytical methods usually are not as accurate for such an intricate water matrix (26). High saline water also proves difficult to analyze with traditional methods (16). Accurate, precise, and standard testing methods are needed to produce reliable results in studies.

One possible solution is to require operators to test produced water for a variety of potential chemicals. This could be done for produced water that is disposed of in saltwater disposal wells. Although this does not test all produced water (supply that is reused in conventional wells), it will give a better understanding of the characteristics of produced water and a greater sample size. Testing produced water can also allow better understanding of any legacy pollutants that may be reintroduced into the water cycle if produced water were to be reused. This includes chemicals such as endosulfan, an organochlorine insecticide that was banned in the US in 2010 (26). In addition, removing "trade secrets" from the hydraulic fracturing sector would allow greater understanding of the potential chemicals in produced water.

In Texas, operators already are required to disclose chemical ingredients and volume used in hydraulic fracturing operations to a public registry called FracFocus, run by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission. This database is a good start but there are limitations, including poor data quality and trade names of chemicals. More importantly, this does not include chemicals found in produced water. Texans will need to completely understand, not only the chemicals in produced water, but how they interact and potentially transform in the environment.

The next step to implement produced water reuse is finding the right strategy for treatment. There are many studies being conducted to find the most effective treatment at reducing the many constituents in produced water. The main limiting factor in treatment will be cost to the operator. If the treatment is more expensive than disposal, the operator will more than likely choose disposal. However, with increasing limits on disposal capacity, decreasing freshwater supply, and advancing chemistry in fracking, operators may choose to treat their produced water to a certain standard to reuse in fracking completions. This will be a more feasible option if treatment costs are too high to meet irrigation standards. To be able to reuse produced water in fracking operations, reducing the salinity to agriculture standards is not necessary. However, for use in irrigation or agricultural activities, high salinity is a barrier that must be overcome (44). One strategy that may mitigate cost is to blend with local groundwater. Dilution by blending could help make produced water meet certain irrigation standards while reducing the cost. However, this strategy still relies on local water, which is the main driver behind produced water reuse. No matter how the produced water is treated, it must be less cost to farmers than the cost of pumping groundwater. This will be difficult as it is estimated that farmers can expect to pay 7.5 cents per barrel of water pumped (25).

Attention for reuse should be focused in the areas identified in Gaines, Martin, Howard, Midland, Dawson, Borden, Terry, and Glasscock County. Transportation can be a limiting factor for reuse. Trucking produced water far distances or building pipelines can be expensive. In addition, longer travel distances increase the risks of spills and leaks which can be detrimental to the environment. To help alleviate costs, infrastructure already in place should be used. In addition, government agencies should encourage a centralized network of pipelines used by a variety of operators to transport water to these locations.

12. Conclusion

Produced water reuse has the potential to be very effective in mitigating water supply shortages in West Texas. However, many steps need to be taken before implementation. The major limiting factor is cost. If the cost of treatment does not compete with the cost of disposal, reuse can never gain traction. The Permian Basin has exceptionally high TDS water. This can prove detrimental to crops and soil if not reduced at a significant level. TDS would have to be reduced by 98% for treated water to meet irrigation recommendations. While this treatment technology exists, it can be costly, due to the amount of chemicals and energy it takes to run the treatment process. The amount of various chemicals in produced water, some with unknown toxicity levels, is another limiting factor. It is important to understand the makeup of the water prior to treatment and reuse. The current status of produced water composition is lacking. Additional limitations include seasonal demand by irrigators and transportation, and storage capacity.

As Texans continuously try to find new innovative technologies and strategies to bring together water supply and demand, produced water reuse can be a solution. Although the volume that could potentially be used in irrigation is not large, it can make big differences at a local level. Mitigating water shortages due to climate change and population growth will persist as drivers for solutions. It is not only important to identify the necessary steps for reuse but to act thoughtfully and economically in implementation. While produced water has historically been seen as a waste product for decades, it could be soon seen as a valuable resource.

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