



Treated water from oil and gas extraction as an unconventional water resource for agriculture in the Anadarko Basin

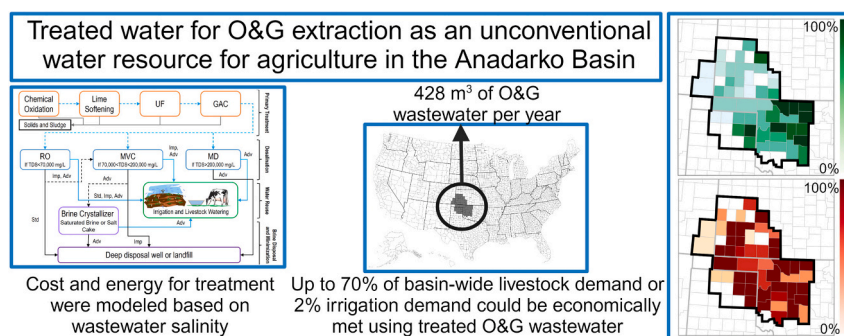
Alban Echchelh, Justin M. Hutchison, Stephen J. Randtke, Edward Peltier*

Department of Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrence, KS 66045, United States

HIGHLIGHTS

- The Anadarko Basin generates >400 million m³ of produced water per year.
- Produced water recovery could supply 70 % of regional livestock water.
- Only 2 % of irrigation water demand could be met by treated produced water.
- Up to 58 million m³ per year could be economically recovered with reverse osmosis.
- Recovery of higher-salinity water would require significant energy investment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Ouyang Wei

Keywords:
Produced water
Irrigation
Livestock watering
High Plains aquifer
High-salinity wastewater

ABSTRACT

The energy industry generates large volumes of produced water (PW) as a byproduct of oil and gas extraction. In the central United States, PW disposal occurs through deep well injection, which can increase seismic activity. The treatment of PW for use in agriculture is an alternative to current disposal practices that can also provide supplemental water in regions where limited freshwater sources can affect agricultural production. This paper assesses the potential for developing PW as a water source for agriculture in the Anadarko basin, a major oil and gas field spanning parts of Kansas, Oklahoma, Colorado, and Texas. From 2011 to 2019, assessment of state oil and gas databases indicated that PW generation in the Anadarko Basin averaged 428 million m³/yr. A techno-economic analysis of PW treatment was combined with geographical information on PW availability and composition to assess the costs and energy requirements to recover this PW as a non-conventional water resource for agriculture. The volume of freshwater economically extractable from PW was estimated to be between 58 million m³ per year using reverse osmosis (RO) treatment only and 82 million m³ per year using a combination of RO and mechanical vapor compression to treat higher salinity waters. These volumes could meet 1–2 % and 49–70 % of the irrigation and livestock water demands in the basin, respectively. PW recovery could also modestly contribute to mitigating the decline of the Ogallala aquifer by ~2 %. RO treatment costs and energy requirements, 0.3–1.5 \$/m³ and 1.01–2.65 kWh/m³, respectively, are similar to those for deep well injection. Treatment of higher salinity waters increases costs and energy requirements substantially and is likely not economically feasible in most cases. The approach presented here provides a valuable framework for assessing PW as a supplemental water source in regions facing similar challenges.

* Corresponding author at: 1530 West 15th Street, Lawrence, KS 66045, United States.

E-mail address: epeltier@ku.edu (E. Peltier).

<https://doi.org/10.1016/j.scitotenv.2023.168820>

Received 25 August 2023; Received in revised form 17 November 2023; Accepted 17 November 2023

Available online 29 November 2023

0048-9697/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Oil and gas (O&G) extraction generates large volumes of produced water (PW), a mixture of formation water, initially present in the petroleum reservoir, and water injected for oil and gas recovery and hydraulic fracturing (Engle et al., 2014). By volume, PW is the largest byproduct associated with O&G extraction (Veil, 2015). The United States produced an estimated 3.9 billion m³ of PW in 2017, which represents an increase of 18 % compared to 2007 volumes.

The High Plains region is a major contributor to PW generation, with three states (Texas, Oklahoma, and Kansas) contributing 41 %, 12 %, and 5 %, respectively, of the nationwide PW volume generated in 2017 (Veil, 2020). While 25–45 % of PW generated in these states is reused in O&G applications (Veil, 2020), the industry has limited capacity to increase this volume. Most of the remaining PW in the region (36 %, 42 %, and 75 %, in Texas, Oklahoma, and Kansas, respectively) is disposed of by injection into deep disposal wells. This process is both energy and carbon intensive and represents a significant share of the total operating cost of an O&G field (Stefanakis et al., 2018). Moreover, injecting PW into deep disposal wells contributes to increased environmental risks from induced seismicity (Pollyea et al., 2019; Walsh and Zoback, 2015) and groundwater contamination (Hagström et al., 2016). Finally, deep disposal wells have a limited absorption capacity, and increasingly stringent regulations limiting injected volumes and PW disposal permits to mitigate their negative environmental impacts are forcing O&G firms to seek alternatives to PW disposal (Ground Water Protection Council, 2019).

Outside of the O&G sector, PW has multiple potential uses, including agriculture, aquaculture, environmental restoration, mining, construction, fire control, snow control, and domestic water supply (Echchel et al., 2021). Of these options, PW reuse in agriculture is particularly relevant in the High Plains, where the economy and land use are dominated by the agri-food and O&G industries (McMahon et al., 2007; Scanlon et al., 2020). Texas, Oklahoma, and Kansas are leading states for grain and livestock production (National Agricultural Statistics Service, 2017). However, the future of agricultural production in this region is compromised by declining water levels and quality in the Ogallala aquifer, the area's major groundwater resource (Lauer et al., 2018).

Increasing PW recovery is key to improving the water footprint of oil production in water-scarce regions like the High Plains (Shahbaz et al., 2023). High volumes of PW from O&G development in this region provide a unique opportunity to transform a waste stream (PW) into a valuable resource. PW is generated throughout the region, with many O&G fields located in or near farm and pasture lands. This reduces the costs of PW transport and provides a consistent demand for treated water. In addition, using PW for agricultural irrigation and livestock watering reduces the negative environmental externalities of PW deep-well disposal (e.g., pressure-induced seismic activity, contamination of potable groundwater) and could reduce groundwater mining.

Despite the potential advantages, reusing PW in agriculture poses technical challenges related to the quantity and quality of PW and questions of environmental sustainability and financial viability. The volume of PW generated must be compared to agricultural water demands at the regional and local levels, but the best estimates of PW volumes exist mostly at a state-wide level (Veil, 2015; Veil, 2020). In a recent study, Scanlon et al. (2020) assessed the significance of PW volumes from major unconventional O&G basins across the United States, including some in Oklahoma and Texas. They found that the volume of PW generated in 2017 from unconventional O&G basins would represent only a fifth of the irrigation water demand but four times the volume of water used for livestock in these basins. However, this study did not consider PW generated by conventional O&G production and included only a portion of the Anadarko Basin – one of the largest O&G fields in the High Plains (Higley et al., 2011). Dolan et al. (2018) also assessed that PW reuse in Colorado could significantly affect irrigation demand in some areas.

The only current large-scale reuse of PW for irrigation has been in California, where low-salinity PW has been blended with surface water for over two decades (Kondash et al., 2020; Mahoney et al., 2021; Redmon et al., 2021). While the blended water was similar to local groundwater, irrigation increased the soil salt content. Further, the PW use increased boron soil content, which can be toxic to plants (see Supplementary Material, Table S1). However, PW in the Anadarko Basin is typically much more saline than the PW used in the California study. To mitigate the effects of salinity and sodicity buildup from PW use on soil quality (Kondash et al., 2020; Miller et al., 2020), as well as the potentially toxic effects of boron and other constituents on crop yield, PW will have to be treated to match irrigation water quality requirements (Al-Ghouti et al., 2019; Dolan et al., 2018; Geza et al., 2018; Ma et al., 2018; Myers, 2014; Plumlee et al., 2014). Unlike irrigation, livestock watering does not involve contact between water and soil; therefore, there is limited soil and groundwater contamination risk for this type of PW reuse. Moreover, livestock can tolerate relatively high salinity compared to most crops (see Supplementary Material, Tables S1 and S2).

Beyond salt management, PW treatment will be required to ensure the removal of individual constituents, both inorganic and organic, that can exceed threshold values recommended in the United Nations' Food and Agriculture Organization irrigation water quality guidelines (Alley et al., 2011; Beletse et al., 2008) and the Clean Water Act's Subpart E of 40 CFR Part 435 for livestock watering (Pichtel, 2016). Recent studies have assessed potential processes for treating PW to achieve beneficial reuse (Al-Ghouti et al., 2019; Cooper et al., 2022; Dahm and Chapman, 2014; El-badawy et al., 2022; Guerra et al., 2011; Samuel et al., 2022). In addition to the technical challenges involved in treating the water to acceptable quality standards, the cost and energy requirements of this treatment are critically important in determining the viability of the recovery process (Amakiri et al., 2022).

Previous assessments at other locations have found a wide range of potential costs for PW upgrading for agricultural use. Although Meng et al. (2016) estimated that it would cost \$0.19–0.36/m³ to upgrade PW of <25,000 mg/L total dissolved solids (TDS) to a potable level using desalination in California, crops do not need to be irrigated with potable-grade water (Shaw et al., 2011). Dolan et al. (2018) estimated an annualized cost range of \$2.32–3.21/m³ to reuse PW for irrigation in Colorado; a cost that falls between the price for private and commercial PW disposal. A regional-scale study conducted in Queensland, Australia, estimated the cost of treating coalbed methane (CBM)-PW for irrigation purposes at AU \$1.24/m³. This treatment cost assumed an investment of AU \$800 million for building a water treatment plant with a lifespan of 20 years (Monckton et al., 2017). However, CBM-PW is generally of higher quality than conventional O&G PW, which would be more expensive to treat. Other studies found that using a small-scale treatment unit (300 m³/day) to treat PW for the irrigation of halotolerant crops would cost \$0.46–1.09/m³ in Qatar (Echchel et al., 2020) and \$0.32–0.75/m³ in Oman (Echchel et al., 2021). Lastly, it was found that desalinating PW from the Marcellus Basin using electrodialysis to achieve irrigation and livestock water quality standards was more economical than reinjecting PW into deep disposal wells (Dickerson and Mirabolghasemi, 2021).

The aim of this study is to examine the potential of treated produced water to be used as a supplemental water source for agriculture in the Anadarko Basin. The high levels of PW generation and existing strains on groundwater supplies used for agriculture make this area a good test case for examining the potential of PW recovery. Annual volumes of PW generated from 2011 to 2019 were determined at the county level across the 60 counties within the basin and compared to existing information on agricultural water demand for irrigation and livestock watering to quantify the potential impact of PW recovery on local agricultural water demand. Estimates of the financial costs and energy requirements for treating this PW to irrigation and livestock water quality standards were developed using a treatment train consisting of general pre-treatment

steps followed by desalination. These results on water availability, composition, and treatment requirements were then used to provide a framework for assessing the viability and advantages of PW recovery for agricultural purposes across the Anadarko Basin.

2. Material and methods

2.1. Produced water volume and quality

The Anadarko basin includes parts of four states: Kansas (25 counties), Oklahoma (22 counties), Texas (11 counties), and Colorado (2 counties). Of these four states, only Colorado reports annual PW volumes by county. PW volumes for Colorado were obtained directly from the Colorado Oil & Gas Conservation Commission (COGCC, 2020). While Kansas and Texas did not provide quantitative data about PW by county, annual volumes of oil (V_{Oil}) and gas (V_{Gas}) produced are available in each state at the county level. O&G production values between 2011 and 2019 were obtained from the Kansas Geological Survey (KGS, 2020) and the Railroad Commission of Texas (RRC, 2020) and used to estimate the annual production of PW (V_{PW}) as follows. First, gas production was converted to oil equivalent – using a conversion factor of 181.59 barrels of oil equivalent per MMcf of gas (EIA, 2022a; Veil, 2020) – and added to the oil production to obtain the annual oil equivalent production by county (Eq. (1)). The average water-to-oil-equivalent ratios (WOER) of Kansas and Texas were estimated using state-wide oil (V_{Oil}), gas (V_{Gas}), and PW (V_{PW}) production data from 2017 as reported in Veil (2020) (Eq. (2)).

$$V_{PW} = V_{Oil} + (V_{Gas} \times 181.59) \times WOER \quad (1)$$

$$WOER = \frac{V_{PW\ 2017}}{V_{oil\ 2017} + (V_{gas\ 2017} \times 181.59)} \quad (2)$$

where V_{PW} is the estimated volume of PW generated by county in barrels per year, V_{Oil} is the annual volume of oil produced in each county in barrels per year, and V_{Gas} is the annual volume of gas produced in each county in barrels of oil equivalent per year.

Oil production data by county was not available from Oklahoma. Instead, the annual volumes of PW injected into deep disposal wells from 2011 to 2019 for each county were obtained from the Oklahoma Corporation Commission (OCC, 2020). Veil (2020) reported that deep-well injection accounted for 42 % of the total PW volume generated in Oklahoma in 2017. County-level PW production for Oklahoma was thus approximated by assuming that the injected PW volume was a constant percentage (42 %) of total PW generation in each county.

The volume of PW available for agriculture use was estimated by taking the estimated total PW generation and removing the volume of PW already reused in the O&G industry. The share of the total PW volume available for use was estimated at 59 %, 75 %, 55 %, and 54 % of PW generated for Colorado, Kansas, Oklahoma, and Texas, respectively (Veil, 2020). Because data were available only for the year 2017 for PW management practices, the PW volume generated during the same year was used to estimate the volume of PW available for agricultural use.

The quality of PW in each county of the Anadarko Basin was assessed using the USGS Produced Water Geochemical Database, which includes county information for each well (Blondes et al., 2018). All wells within one of the 60 counties of the Anadarko Basin were selected for this analysis. However, 12 of the 60 counties had no available water quality data. While PW can contain many potential constituents impacting water quality (e.g., dissolved hydrocarbons, organic chemicals, heavy metals), there is limited information for many of these compounds in the USGS database. Therefore, for this assessment, we focused only on constituents that were measured in at least 50 % of the 2762 PW samples collected in the Anadarko Basin. This included TDS, Na^+ , Cl^- , Mg^{2+} , Ca^{2+} , SO_4^{2-} , and pH. For each water quality parameter, the number of PW samples (n), minimum and maximum values, and the calculated

mean and median values were determined for each county. The sodium adsorption ratio (SAR) was calculated from Na^+ , Mg^{2+} , and Ca^{2+} concentrations. Water quality data and calculations are available in the associated Mendeley data set (Table M1).

2.2. Agricultural water demand and quality requirements

We obtained annual groundwater and surface water withdrawals for irrigation and livestock watering for each county in our study area for 2010 and 2015 from publicly available data on water use published by the U.S. Geological Survey (USGS, 2018). These values were averaged for each county to provide single values for irrigation use and livestock watering (county-by-county values are available in the associated Mendeley dataset, Table M2). Water quality requirements for irrigation and livestock watering (see Supplementary Material, Tables S1 and S2) were based on the most common crops grown and animals bred in the study counties according to the 2017 Census of Agriculture (National Agricultural Statistics Service, 2017). Threshold electrical conductivity (EC) values were estimated from TDS using the TDS-to-EC correlation factors reviewed by Rusydi (2018).

2.3. PW treatment assessment

Due to the lack of data regarding the contaminants other than TDS and major ions in Anadarko Basin PW, a generalized treatment train was chosen to address the removal of both organic and inorganic constituents to prepare the water for agricultural use (Fig. 1). In reality, not all PW sources may need all of these processes. Nitrogen and phosphorus removal was not addressed, as these constituents are typically present at low concentrations in PW compared to agricultural water quality requirements (Echchelth et al., 2018). The treatment trains presented here were designed to achieve the salinity requirements for irrigation reuse (see Supplementary Material, Table S1), which were more stringent than those for livestock reuse. The selected technologies have all been referenced and described in academic and technical reviews about PW treatment (Dahm and Chapman, 2014; Drewes et al., 2009; Guerra et al., 2011; Nasiri et al., 2017; Xu et al., 2016). Mature, field-proven, and robust technologies were prioritized to reduce uncertainty regarding their applicability to PWs of diverse quality. It was also assumed that coarse suspended solids and oil removal had already been carried out by

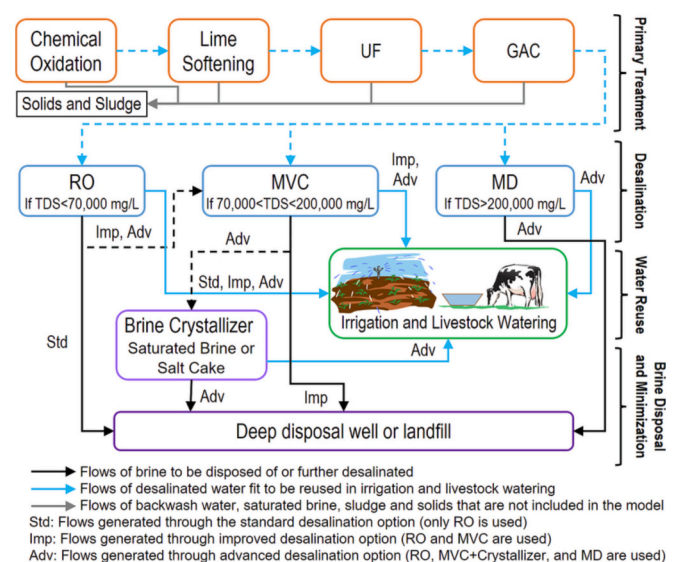


Fig. 1. Suggested treatment trains to treat PW from the Anadarko Basin to irrigation and livestock watering standards. GAC: Granular activated carbon, MD: Membrane Distillation, MVC: Mechanical Vapor Compression, RO: Reverse osmosis, UF: Ultrafiltration.

the operator using an oil-water separator.

The generalized treatment scheme (Fig. 1) used for this assessment can be broken into three stages: preliminary treatment, desalination, and brine/concentrate management and disposal. Preliminary treatment was designed to protect the desalination units by reducing PW corrosivity, scaling, clogging, and fouling potential (Tong et al., 2019). Chemical oxidation to oxidize iron, manganese, and non-volatile organics was followed by lime softening to remove scale-forming cations, metal oxides, and boron. Ultrafiltration (UF) was included to remove residual precipitated hardness salts remaining after softening and any remaining suspended solids. Finally, granular activated carbon was used to remove residual dissolved hydrocarbons and other dissolved organics, including hydraulic fracturing chemicals.

To tackle the wide range of TDS concentrations in the Anadarko Basin, three desalination technologies were considered, depending on the TDS content of PW. Reverse osmosis (RO) was used for desalination for PW with TDS content lower than 70,000 mg/L, mechanical vapor compression (MVC) for PW with TDS content between 70,000–200,000 mg/L, and membrane distillation (MD) for PW with TDS content higher than 200,000 mg/L (Fig. 1). The TDS threshold values for selecting the desalination technologies were determined based on previous PW desalination assessments (Ground Water Protection Council, 2019; Onishi et al., 2018). MD is still an emerging technique in PW desalination and was selected because the applicability of MVC to PW of TDS content beyond 200,000 mg/L remains uncertain (Onishi et al., 2018). In contrast, MD has virtually no upper TDS limit of applicability and has been successfully used to desalinate brines up to 300,000 mg/L of TDS (Subramani and Jacangelo, 2015). The combination of chemical oxidation, UF, and desalination processes was considered sufficient to reduce any pathogen load in the PW to acceptable levels (Cordier et al., 2020; Galeano et al., 2019).

Three different processes were modeled to determine the possible extent of PW recovery for agricultural use. In the standard treatment process, only water suitable for RO treatment (TDS < 70,000 mg/L) was treated, with the RO concentrate and higher TDS PW disposed of by deep-well injection. In the improved recovery process, water with TDS between 70,000 and 200,000 mg/L and RO concentrate was treated by MVC to increase overall recovery. Again, the highest TDS water, along with the MVC concentrate, was disposed of by deep-well injection. To achieve the highest possible level of water recovery, the advanced treatment scenario added MD treatment for PW with TDS > 200,000 mg/L. Brine crystallization was also used to increase water recovery from the MVC and MD concentrate streams before disposal.

Standard, improved, and advanced desalination scenarios were evaluated for each county using 2017 estimates of PW volumes available for agriculture. The volume of water in each TDS range (<70,000 mg/L, 70,000–200,000 mg/L, and >200,000 mg/L) was determined based on the TDS distribution from wells within that county. Twelve counties (Ford, Lane, Logan, Stanton, Wallace, and Wichita counties in KS; Greer and Kiowa counties in OK; and Carson, Gray, Hutchison, and Moore counties in Texas) where no water quality data were available in the USGS database were excluded from the calculations. Water recovery, operating costs, and energy consumption data for each scenario were determined from literature values for individual treatment process steps (see Supplementary Material, Table S3). Water loss in preliminary treatment, which was common to all scenarios, was considered to be minimal, and these processes were therefore set to 100 % water recovery. For each treatment scenario, both a minimum model and a maximum model were calculated. The minimum model used minimum values for water recovery, OPEX, and energy use, while the maximum model used the maximum values for all three parameters at each relevant stage. The energy use and OPEX estimates included the disposal of untreated PW and brine generated by PW desalination by deep-well injection. Solid waste management (i.e., sludge and salt disposal) was

not included due to a lack of available information. Water conveyance and storage were not considered in the energy use and OPEX estimates, as these parameters are similar across the different treatment trains.

3. Results

3.1. PW generation in the Anadarko Basin

Over the period 2011–2019, the average annual PW volume generated in the Anadarko Basin was ~428 million m³ (Fig. 2a). Oklahoma contributed 61 % of the average annual PW volume generated during this period, while Kansas and Texas represented 21 % and 18 %, respectively. The volume of PW generated in Colorado has never been significant at the scale of the Anadarko Basin and represented only 0.06 % of the average annual PW volume of the basin over the period 2011–2019. PW production in the Anadarko Basin reached its highest level in 2014 at ~519 million m³ and decreased to ~369 million m³ in 2019 (Fig. 2a). Over the same period, oil price (Cushing, OK, WTI spot price) peaked at \$98 per barrel in 2013, that is, one year before peak PW generation. Oil prices decreased dramatically from 2014 to 2016, reaching a minimum price of \$43 per barrel in 2016, before slowly recovering to \$57 per barrel in 2019. While the decrease in PW volume started the same year as the oil price decline, PW volume did not increase in 2018–19 as prices recovered (EIA, 2022b). A general decline in PW production can be observed across the basin after 2014, but it was not uniform.

Oklahoma was responsible for the majority of the fluctuation in PW volume over the study period, with a difference of 140 million m³/year of PW between the minimum in 2011 and the maximum in 2014. Texas and Kansas PW volume fluctuations were modest, with variations of 52 million m³/year and 32 million m³/year between maximum and minimum years, respectively. At the county level, eighteen of the 60 counties saw increased PW generation ranging from 1 % to 479 % between 2014 and 2019, while 42 counties had decreasing PW production ranging from –1 % to –99 % over the same period. Twelve counties averaged >10 million m³ of PW generation per year during the study period (Fig. 2b). Seven of the highest ten counties for PW generation were in Oklahoma, with the counties of Alfalfa and Woods alone representing 16 % and 8 %, respectively, of the average annual PW production over this period (Fig. 2b). Geographically, these counties are primarily clustered in north-central Oklahoma (Alfalfa, Dewey, Garfield, Grant, Kingfisher, and Woods counties), north-east Texas (Wheeler and Hemphill counties), and south-western Kansas (Stevens and Grant counties) (Fig. 3a, b). Full data on PW volumes by county is available in the Mendeley dataset, Table M3.

At the basin scale, the production of PW reached its highest level in 2014 at 519 million m³. Production generally rose from 2011 to 2014, then declined rapidly in 2015 and 2016. By 2019, PW generation was estimated at 369 million m³, the lowest value during our study period (Fig. 2a).

After PW is separated from the recovered hydrocarbons, it is managed through reuse or disposal options depending on location, characteristics of the local O&G fields, and total PW volume. The O&G industry currently recovers a significant portion of PW for reuse in O&G operations (see Supplementary Material, Table S4). For this study, we have assumed that industry reuse would be the lowest-cost option due to minimal treatment requirements, so we considered PW recovered and reused by the O&G industry to be unavailable for agricultural uses. This assumption resulted in a peak volume of 301 million m³ of PW available for agricultural reuse in 2014, and an average of 254 million m³ per year over the period from 2011 to 2019 (see Supplementary Material, Table S5), approximately 60 % of the total PW generated. County by county data on PW availability are in the accompanying Mendeley data file, Table M4.

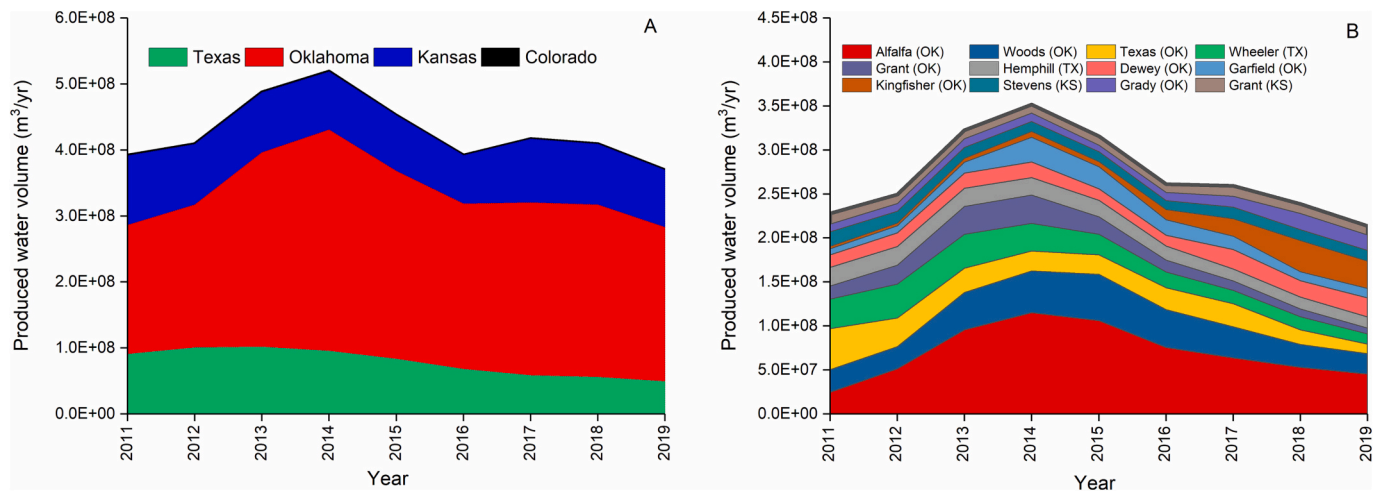


Fig. 2. Estimated volume of PW generated in the Anadarko Basin per year for the period 2011–2019 by state (a) and by county (b) for those counties that produced >10 million m^3 of PW per year on average over this period.

3.2. Agricultural water use in the Anadarko Basin

Irrigation water demand was highest in the central (i.e., southwest Kansas, western Oklahoma, and northwest portion of the Texas panhandle) and western (i.e., southeast Colorado) parts of the Anadarko Basin (see Supplementary Material, Fig. S1). Seventeen counties, including 11 in Kansas, individually withdrew >100 million m^3 per year for irrigation. At the other extreme, the eastern part of the Anadarko Basin (i.e., central Oklahoma) had the lowest irrigation water demand, with ten counties withdrawing annual water volumes as low as 2–5 million m^3 . At the basin scale, the volume of PW available for reuse was very modest compared to the 4.6 billion m^3 of water used for irrigation annually. Even at full recovery, the amount of PW generated would account for <5 % of irrigation withdrawals in 31 of the 60 counties (52 %) and <25 % in 46 counties (77 %) (Fig. 3c). The primary exception was in north-central Oklahoma, where high PW generation combines with low levels of irrigation agriculture.

Unlike irrigation water demand, livestock water use was more evenly distributed throughout the Anadarko Basin, with half of the counties withdrawing between 1 and 3 million m^3 per year for this purpose (see Supplementary Material, Fig. S2). Seven counties in the central parts of the basin withdrew 5–15 million m^3 of water per year for livestock watering, while 16 counties used only 400,000 to ~ 1 million m^3 per year for the same purpose. The volume of PW generated was on a similar scale to livestock use throughout most of the basin (Fig. 3d). At full recovery, the volume of PW available for use is sufficient to meet more than half of the livestock demand in 41 of the 60 counties in the basin (68 %), and greater than the total livestock demand in 34 counties (57 %).

3.3. Water quality and agricultural use requirements

The PW from the Anadarko Basin is characterized by its high salinity and high concentrations of alkali and alkaline earth metals compared to irrigation standards (Echchelth et al., 2018). The TDS of Anadarko Basin PW samples in the USGS Produced Water Geochemical Database (Blondes et al., 2018) ranged from 1005 to 404,739 mg/L, with a median TDS concentration (Q2) of 135,963 mg/L. PW with TDS $< 70,000$ mg/L, TDS 70,000–200,000 mg/L, and TDS $> 200,000$ mg/L represented 36 %, 35 %, and 29 % of the total samples ($n = 2762$), respectively. (For the full distribution of salinities of these PW samples, see Supplementary Material Fig. S3.) These concentrations were well above the irrigation and livestock watering TDS requirements of 704–4080 mg/L and 3000–7000 mg/L, respectively. In addition, PW in the Anadarko Basin

was very sodic, with a median sodium adsorption ratio (SAR) of 127. This value is not even suitable for a halotolerant crop such as cotton (threshold SAR value of 40). The high TDS and SAR values can be explained by the primacy of sodium chloride salts in these produced waters. The median pH of PW was within recommended values for irrigation and livestock watering, and other major ions were not a significant concern for irrigation, although median magnesium and sulfate concentrations exceeded livestock watering standards (see Supplementary Material, Table S2).

Anadarko Basin PW also contained concentrations of boron, copper, and iron over the irrigation and livestock watering threshold values in at least some wells. The median concentrations of barium and lithium were above the irrigation threshold values. Barium was below the livestock watering threshold values, however, while Li limits for livestock were not found. A complete specification and comparison of PW with agricultural water quality requirements could not be carried out due to the absence of sufficient data for a number of potentially occurring metals (beryllium, cadmium, chromium, cobalt, lead, mercury, molybdenum, nickel, selenium, and vanadium), arsenic, antimony and fluoride. PW is generally anoxic and is not expected to contain significant levels of nitrate. While nitrate contamination of groundwater is common in agricultural areas, the percolation of nitrate from fertilizers and animal waste typically occurs into shallow, fresh groundwater, not oil and gas reservoirs.

Application of the standard desalination scenario to each county with water quality data in the Anadarko Basin resulted in total freshwater production of 27–57 million m^3 per year, 11–23 % of the available PW in the region (Table 1). All water recoveries in Table 1 are low estimates, as they do not account for the 18 counties where no TDS data were available. The improved and advanced desalination scenarios would generate 82–143 million m^3 per year (33–58 % of available PW), and 213–232 million m^3 per year (86–93 %), respectively. In addition to recovering fresh water, PW treatment would result in an equivalent decrease in the total deep-well injection volume across the region. As a percentage of total PW, the impact of standard (RO only) treatment would be greatest in the northern and southern parts of the basin, as well as the two Colorado counties (Fig. 4). The smallest impacts of PW treatment were observed along the KS-OK border, where very high TDS concentrations resulted in low water recovery rates except under the advanced treatment scenario. (A breakdown of PW recovery by county is available in the accompanying Mendeley data file, Table M5.) The volume of freshwater generated from PW treatment in the Anadarko Basin represented <5 % of the irrigation water demand for all scenarios (Fig. 4). For livestock watering, the standard desalination scenario could

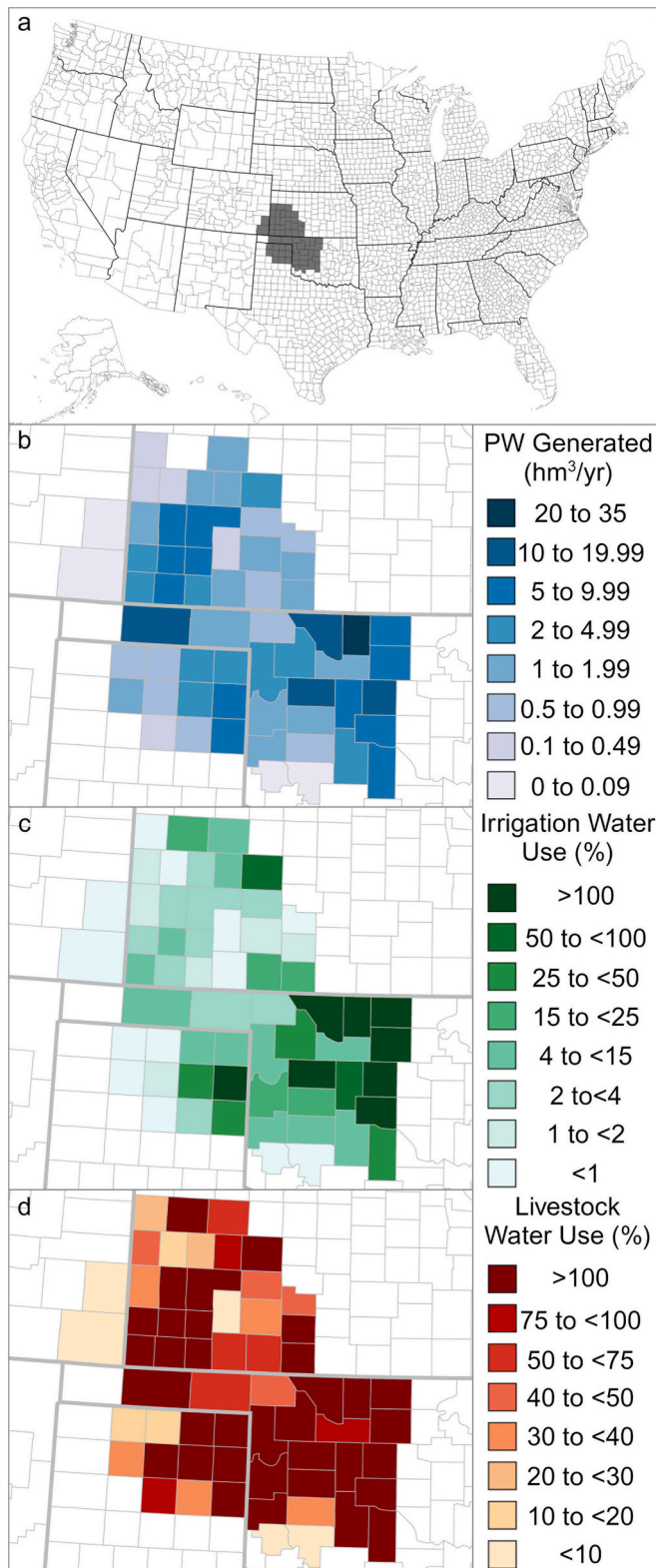


Fig. 3. Ability of PW to meet agricultural water demand in the Anadarko Basin, (a) Location of the Anadarko Basin within the United States, (b) PW volumes potentially available for agriculture reuse by county in 2017, (c) PW volumes as % of average irrigation water use, and (d) PW volumes as % of average livestock watering use.

Table 1

Summary of results by county for water recovery, energy requirements, and operating expenses for each treatment scenario.

Desalination scenario	PW recovery	Energy required (kWh/m ³)	Operating expenses (\$/m ³)
Disposal	0 %	3.6–5.5	0.6–16
Standard	11–23 %	0.06–5.6	0.02–3.8
Improved	33–58 %	0.38–31	0.13–13
Advanced	86–93 %	18–306	0.76–11

meet 20–42 % of demand, while the improved and advanced scenarios could meet or exceed most of the livestock water demand throughout the basin, except in the counties along the Kansas-Oklahoma border.

3.4. Energy requirements and operational costs for PW treatment

The estimated energy requirement for treating PW to agricultural water standards had an interquartile range of 1.01–2.65 kWh/m³ of treated PW for the standard desalination scenario, 5.71–14.4 kWh/m³ for the improved desalination scenario, and 26.3–90.0 kWh/m³ for the advanced desalination scenario (Fig. 5). As a comparison, the energy requirement for injecting PW lies between 3.6 and 5.5 kWh/m³ (Breuer and Al-Asmi, 2010; Schrevel et al., 2004). Typical energy requirements for PW treatment are, therefore, less than those for disposal for all standard desalination scenarios and the majority of improved desalination scenarios at low recovery, and for >75 % of standard desalination scenarios at high water recovery.

The estimated OPEX for treating PW to agricultural water standards had an interquartile range of 0.3–1.5 \$/m³ of treated PW for the standard desalination scenario, 2.0–5.8 \$/m³ for the improved desalination scenario, and 1.9–7.3 \$/m³ for the advanced desalination scenario. The cost of PW disposal depends strongly on whether the oil producer owns an injection well (0.6–0.9 \$/m³ (Pham, 2022)), or has to pay for commercial disposal (3–16 \$/m³ (McCurdy, 2011)). The operating costs for standard desalination scenarios with low water recovery were less than or equivalent to the costs of disposing of the same PW volume using producer-owned wells. Standard desalination scenarios with high water recovery, as well as some improved and advanced desalination scenarios with low water recovery, have higher operational costs than disposal in producer-owned wells, but lower costs than those for commercial disposal (Fig. 6).

In the standard desalination scenarios, both energy use and operational costs for treatment are offset to a notable extent by the reduced volume of PW disposal. At low water recovery, disposal of the remaining brine through deep-well injection accounts for 82 % of estimated energy use and 41 % of the operational costs. Expanding standard treatment to maximize water recovery substantially increases both total energy requirements (Fig. 5) and the share of energy required for treatment, to 85 %. RO treatment by itself accounts for 64 % of energy usage in these scenarios. For improved and advanced desalination treatments, energy requirements increase much more rapidly than expected operational costs. This is primarily due to the energy-intensive desalination processes required to treat high-salinity brines. Even with low water recovery and minimum energy use estimates, desalination processes (RO + MVC) account for 72 % of total energy use for improved desalination scenarios. This increases to >90 % for high water recovery and for all advanced desalination scenarios. Incorporating treatment of brines with TDS > 200,000 mg/L results in energy requirements that are a minimum of five times greater than those for deep well injection, and more than ten times those for standard desalination (Fig. 5). Expected operational costs also increase substantially for improved and advanced desalination, particularly for high water recovery scenarios (Fig. 6). Unlike energy costs, the estimated operational costs for low water recovery scenarios, even for advanced desalination, are below the expected range for commercial disposal costs. Costs rise substantially, however, for the

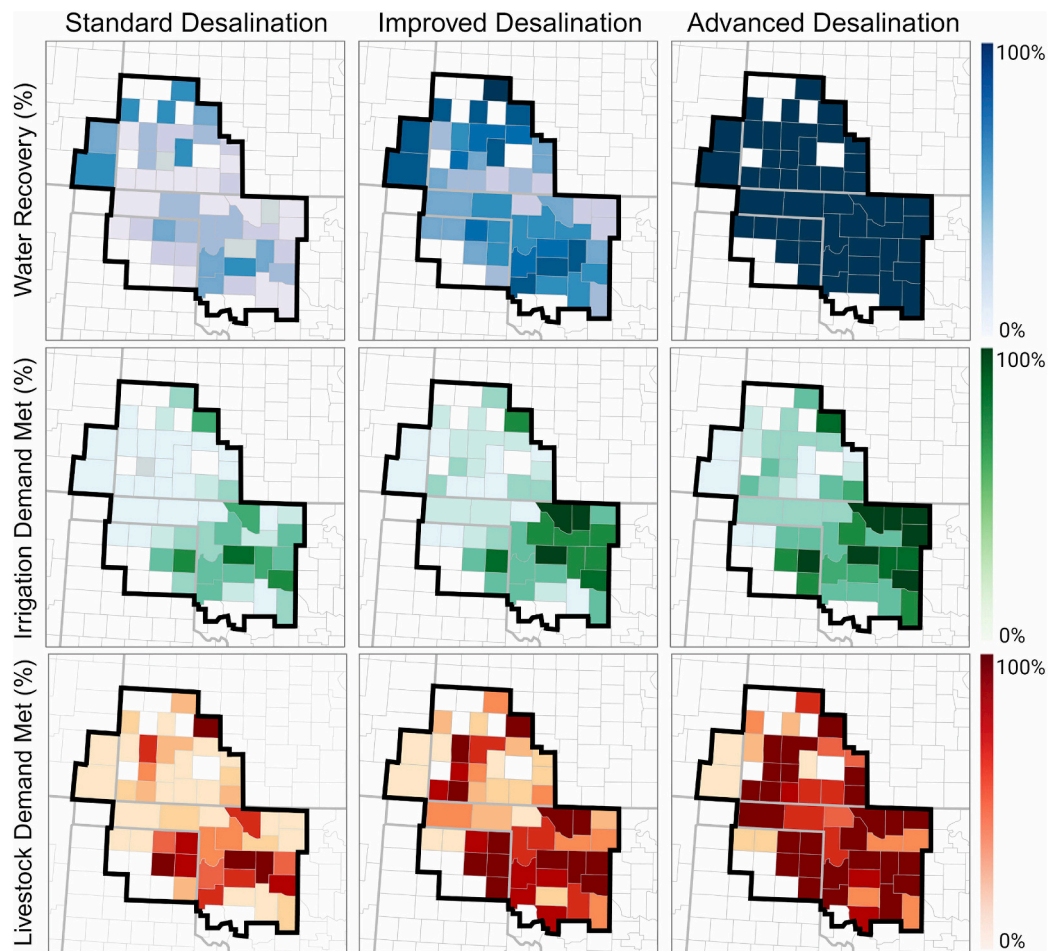


Fig. 4. Geographical distribution of the estimated water recovery (in %) and brine disposal reduction (in %) from produced water desalination, irrigation water demand met by desalinated produced water, and livestock water demand met by desalinated produced water, at maximum water recovery.

high water recovery (and high cost) scenarios, indicating that treatment costs under these conditions are substantially higher than those for direct disposal.

4. Discussion

4.1. Treated water as a resource

Despite the high volume of PW generated in the Anadarko Basin during the study period, the extent of water demand for irrigation agriculture means that PW can provide only a small supplemental water source for irrigators. Even if all currently unused PW could be recovered, it would still represent only 5 % of the annual irrigation water use in the basin. Available volumes would decrease even further if only the most economically viable fraction – lower salinity water that can be recovered using RO treatment – is considered. Because agricultural water use and PW volume and quality are not uniformly distributed across the Anadarko Basin, however, there are regions where the impact could be more significant. Five counties (Ness (KS), Blaine (OK), Canadian (OK), Dewey (OK), and Hemphill (TX)) had both a PW/irrigation water use ratio of 0.5 or greater and a high fraction (>40 %) of PW with salinity <70,000 mg/L. These areas thus provide the best options for further exploration of PW recovery for irrigation purposes.

By contrast, the amount of potentially recoverable PW across the basin is a much more substantial fraction of the water required for livestock use, even when accounting for only RO- treatable water (Table 1). In addition, the estimated livestock water demand met by treated PW was more evenly distributed than for irrigation, although the

counties with highest PW reuse for this application were more concentrated in the southern and central parts of the basins (see Supplementary Material, Fig. S2). Livestock watering thus seems to provide a more consistently productive avenue for potential reuse of produced water in this region, provided additional water quality questions can be addressed.

Increasing the use of PW for agricultural purposes could also help to decrease the rate of groundwater depletion in the Anadarko Basin region. Over the period 2013–2015, the depletion of water stored in the Ogallala aquifer, which underlies portions of Colorado, Kansas, Oklahoma, and Texas, was estimated at 12,700 million m³, or ~4200 million m³/yr (McGuire, 2017). Once treated to suitable standards, recovered PW could displace freshwater withdrawals, which are primarily used for irrigation, helping to slow this depletion. Alternatively, the treated PW could be used directly for aquifer recharge. The standard, improved, and advanced desalination scenarios were estimated to reduce the groundwater deficit by 0.6 %–1.3 %, 2.0–3.4 %, and 5.8 %–6.3 %, respectively. While a small fraction of total groundwater withdrawals, these volumes are comparable to those obtained through other existing recharge projects. For example, managed aquifer recharge projects using playas are estimated to recharge approximately 750 m³ per hectare per year (Gurdak and Roe, 2010). PW recovery and use could thus be the equivalent of adding almost 310,000 ha of managed aquifer recharge lands.

In Kansas, where aquifer levels have fallen most dramatically, groundwater management districts (GWMDs) have been formed to improve aquifer conservation, with some districts developing enforceable water use reduction programs to reduce this decline (Deines et al.,

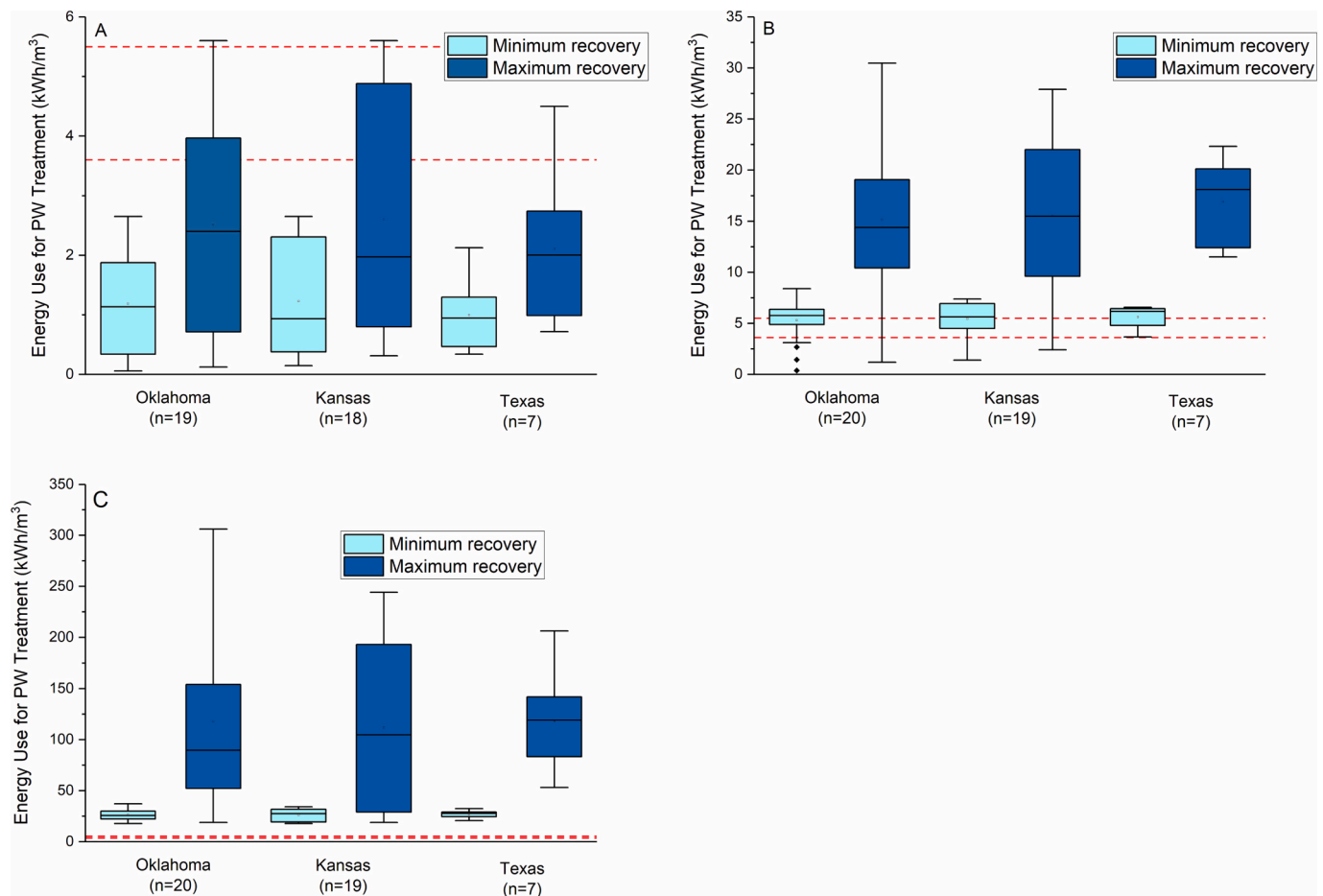


Fig. 5. Estimated energy requirement to treat PW up to agricultural standards by county for three scenarios: a) standard desalination, b) improved desalination, and c) advanced desalination. Dashed lines show the lower and upper limits of estimated energy use for disposal (3.6 and 5.5 kWh/m³, respectively).

2019; Whittemore et al., 2023). Five of the counties in this study (Greeley, Lane, Scott, Wallace, and Wichita) are included in one of these reduction programs. Analysis of local PW volumes and composition suggests that PW treatment using the standard recovery scenarios could contribute 0.3–6 % of agricultural water usage in these counties. At the high end, a 6 % replacement of freshwater withdrawals by treated PW could contribute significantly to typical Local Enhanced Management Area goals of 15–20 % reductions in groundwater use (KS Department of Agriculture, 2023). Groundwater Management District 3, which includes the majority of KS counties included in this study, has some of the highest PW generating counties in the Anadarko Basin, although high salinities in this area would reduce the fraction of PW that could be economically treated. Further research is recommended to better identify how patterns of PW generation and salinity (which impacts the extent of potential treatment and recovery) overlap with existing and proposed projects to manage the decrease in Ogallala aquifer levels in both Kansas and Oklahoma, including in other Kansas Groundwater Management Districts outside of the current study area.

4.2. Barriers and incentives to PW use in agriculture in the Anadarko Basin

Our assessment of PW generation and agricultural water use patterns across the Anadarko Basin shows the potential for PW recovery to meet a significant part of regional water needs. Additional considerations that could impact the potential for PW recovery for agricultural use in the Anadarko Basin include the cost of treatment, the uncertainty of PW quality, and the energy intensity required for high TDS PW. The analysis

presented here for PW treatment is only a partial assessment, as the cost estimates in Fig. 6 do not reflect the full costs of using treated PW in agriculture. Additional costs that would need to be considered in a full economic assessment include costs related to water conveyance (temporary lines, permanent pipes, trucking) and water storage (impoundments, above-ground storage, tanks). Storage infrastructure, in particular, may be needed to balance out temporal differences in PW generation, which occurs throughout the year, and agriculture demand, which is more seasonal. These costs would significantly increase the operating cost of PW recovery and management but are difficult to estimate accurately without focusing on more specific locations and water use scenarios. In addition, the capital expenditure (CAPEX) needed could not be estimated at this time, as further information is needed to determine the best actual configurations and process units for a full treatment train.

Looking solely at operating costs, this analysis shows that the costs of PW treatment for water with TDS < 70,000 mg/L (standard desalination) are comparable to, or less than, the costs of deep well injection (Fig. 6), especially when commercial disposal is required. Unfortunately, data on the relative prevalence of private vs. commercial disposal in this region is not readily available, but increased regulation of deep well injection volumes and rates could be expected to generally increase future disposal costs. The improved and advanced treatment scenarios increase the overall treatment costs substantially, especially for high recovery scenarios. These scenarios typically result in operating costs well above the minimum values for commercial disposal, suggesting that the cost of these processes would be a limiting factor except where local disposal options are not available. The large spread in

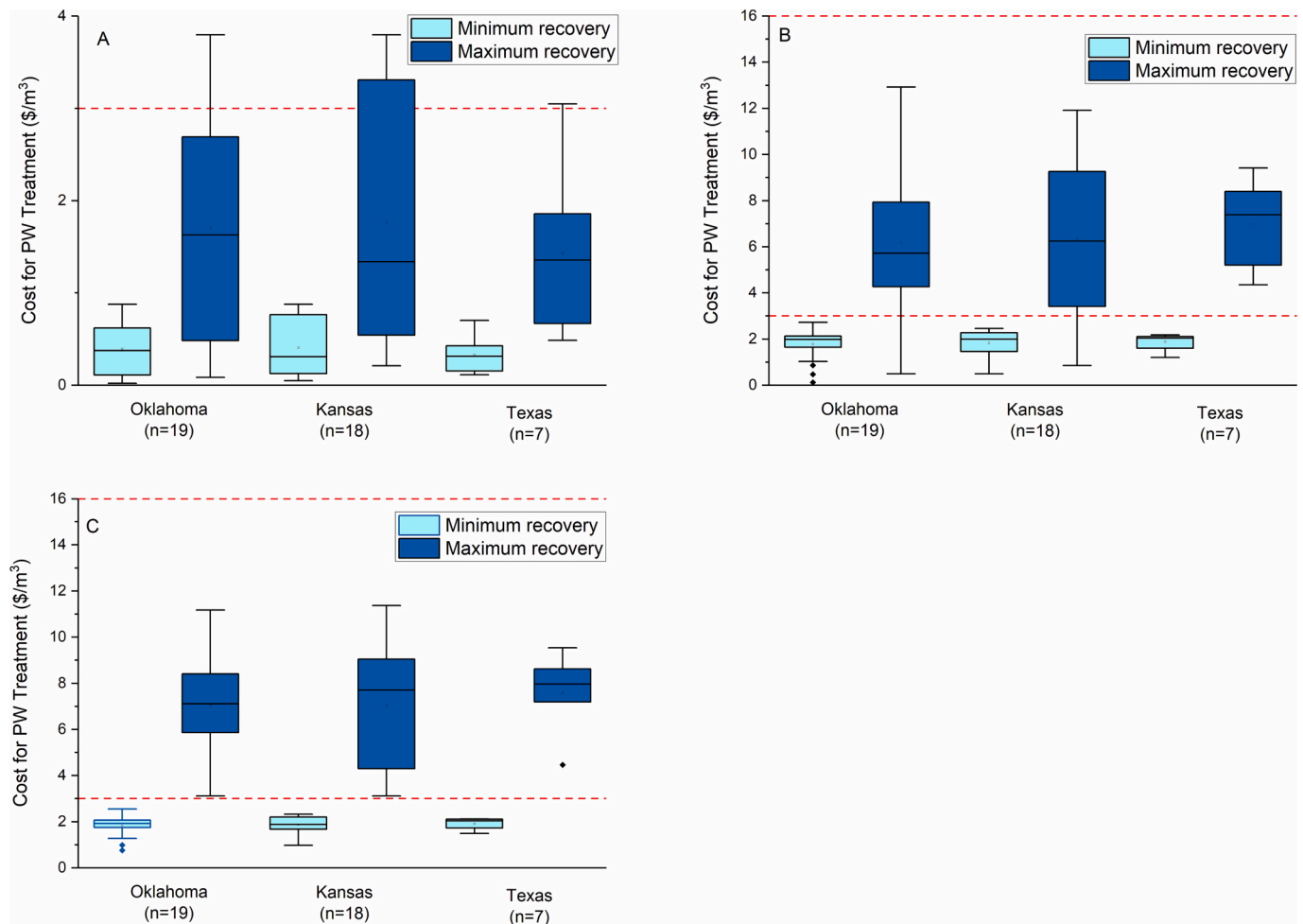


Fig. 6. Estimated operational cost to treat PW up to agricultural standards by county for three scenarios: a) standard desalination, b) improved desalination, and c) advanced desalination. Dashed lines show the cost of private disposal ($\$0.6/\text{m}^3$ (Pham, 2022)) and the lower and upper limits of cost for commercial disposal ($\$3$ and $\$16/\text{m}^3$, respectively (McCurdy, 2011)).

literature estimates for commercial disposal costs (McCurdy, 2011) is due largely to assumptions of longer transport distances to available disposal wells.

On the other hand, it can be hypothesized that the increasing water demand will increase fresh water prices, making PW reuse in agriculture more competitive than under current conditions. Estimates of water use patterns suggest that most of the Anadarko Basin will experience high to extremely high water stress by 2030 if there are no changes in current water consumption patterns. This assumption is in line with other predictions that see the increasing water stress causing a continuous increase in agricultural water demand by 2060 in the Anadarko Basin (Brown et al., 2013). Nonetheless, as the estimated operational cost of using RO to desalinate PW compares with the minimum operational cost of injected PW into deep disposal wells, the PW reuse option in farming deserves to be further studied as it could be an economic option in some areas of the Anadarko Basin. Moreover, other techniques, such as PW blending with freshwater and gypsum amendments to adjust water SAR, could reduce the need for PW desalination and, therefore, the cost of upgrading PW to agricultural standards (Echchel et al., 2018).

Second, uncertainties remain regarding the PW composition that could undermine the sustainability of using this water for agriculture. PW composition could vary from the estimates provided here both due to changes over the lifespan of a well (Ziemkiewicz and He, 2015) and as oil production shifts from one formation to another. This could affect the fraction of PW available for recovery through the different treatment scenarios. Even after treatment, the high SAR of most PW would require

specific attention to prevent soil structural degradation in the long term due to clay dispersion by excessive sodium added to the soil. Therefore, in addition to desalination, SAR adjustment through water remineralization, PW blending with non-sodic water, over-irrigation, or soil treatment with lime and gypsum could be necessary depending on PW quality, treatment performance, soil type, and climate aridity (Echchel et al., 2019). PW sodicity management would add to the energy requirements and cost of PW reuse in irrigation. This is an additional reason to favor livestock watering over irrigation as a PW end use.

In addition to salinity issues, the presence of production chemicals, particularly those related to fracking fluids, in PW could impact the suitability of this water for any agricultural use. Very limited data exist regarding the removal efficiency of production chemicals (added in hydraulic fracturing and remaining in flowback PW) by the PW treatment technologies selected in this study. This is critical as concerns have been raised following experiments that have shown that PW reuse in irrigation can result in production chemical uptake by crops (Shariq et al., 2021). Further data and experiments are needed to resolve this issue, as regulators are will certainly want to have evidence that production chemicals will not contaminate the crops, the animals and the environment before allowing PW use for livestock or food crops. In California, for example, PW reuse in irrigation has been allowed on food crops for decades. While salinity issues have been managed, concerns have been recently raised regarding human exposure to heavy metals and organic contaminants through the migration of these contaminants in crops (Redmon et al., 2021; Thebo et al., 2023). In those studies,

concentrations of inorganics were below irrigation standards, but a full assessment of potential organic contaminants has not yet been done.

Third, the energy intensity for PW treatment is a potential limitation to recovery of water with TDS >70,000 mg/L, independent of cost. The standard desalination scenario using membrane desalination (RO) had energy requirements that are comparable to, or less than, current energy requirements for deep well disposal of PW. While this assessment does not include the energy associated with PW transportation, the results suggest that energy intensity is not the major barrier to reusing lower salinity PW. However, thermal desalination technologies (MVC, MD, and brine crystallization) are substantially more energy intensive (Fig. 5). The energy requirements for the improved desalination scenarios are two to four times those for deep well injection. While this treatment scenario would increase the water recovery from PW and the water resources available to farmers, it would negatively impact the energy efficiency and carbon footprint of O&G production. This goes against the environmental engagements of the O&G industry, which has set greenhouse gas emissions reduction targets that will be partly achieved by cutting its own energy consumption (IEA, 2020). Moreover, the energy return on investment (EROI) of O&G production has tended to decline since the late 1950's (Guilford et al., 2011). Thus, even if PW treatment for agricultural use could be carried out with costs comparable to those for disposal with the improved treatment scenarios, it is not obvious that O&G firms would consider treatment of PW with TDS > 70,000 mg/L if it significantly increased the energy requirements and carbon footprint of O&G production. Advanced desalination scenarios, meanwhile, result in an average increase in energy intensity of five to twenty times that used by current disposal practices, making them impractical for water recovery. The most likely path forward for this treatment option would be if viable commercial products (such as rare earth metals) could be extracted from the brines.

5. Conclusion

The multifaceted assessment of PW resources presented here addressed the alignment of PW resources with local agricultural needs, water quality challenges and resource requirements for PW treatment to suitable quality for reuse, and the potential for PW to play a role in a more sustainable water management process in the High Plains. The results of this assessment show that PW generation in this region is substantial, averaging 428 million m³/yr. Using a combination of reverse osmosis and thermal desalination processes, up to 58 % of this water could be recovered for agricultural use. At the same time, these volumes are only a small fraction of the irrigation water demand across the same region. Based on this analysis, PW should be seen as a minor resource for irrigation agriculture across the Anadarko Basin, providing supplemental water in periods when demand is high and helping to reduce the rates of freshwater aquifer depletion.

For livestock ranchers, on the other hand, PW could be a substantial water resource that could provide anywhere from 20 to 100 % of water needs all year long. Further study should explore the potential for treated PW to contribute to irrigation and livestock watering on a more local level, as PW composition, volumes, and disposal costs can vary substantially over the study region. In fact, treating existing PW supplies could cover a large part, if not all, of the irrigation water needs for the counties located in the south-east of the Anadarko Basin. Meeting the full water demand of livestock is also feasible in most counties located in the southern and central parts of the basin.

The expected costs of PW treatment to agricultural reuse standards in each county vary from \$0.02 to \$13 per m³, depending on the level of treatment and extent of water recovery. Median costs were \$0.64 per m³ for standard desalination, \$2.44 per m³ for improved desalination, and \$2.84 per m³ for advanced desalination. Costs for the standard desalination scenario and improved desalination scenario with minimum freshwater recovery have an average OPEX similar to the costs of injecting PW into deep disposal wells. Energy requirements for these

scenarios are estimated at 0.06–5.6 kWh/m³, similar to the requirements for disposal by deep-well injection. Therefore, the volume of freshwater that is economically extractable from PW is estimated to be between 58 (using RO only with maximum recovery) and 82 million m³ per year (using RO with maximum recovery + MVC at minimum recovery). This freshwater volume could meet 1–2 % and 49–70 % of the irrigation and livestock water demands in the basin, respectively. Here again, an examination of disposal practices on a more local level is recommended for further study, as the difference between private and commercial disposal costs could have a major impact on the financial viability of PW recovery. The advanced desalination process using membrane distillation, while only slightly more costly, would require very high energy inputs (18–306 kWh/m³) and is not recommended.

In addition to contributing to meeting the agricultural water demand, PW can also modestly contribute to mitigating the decline of the Ogallala aquifer by ~2 % through the PW desalination scenarios that have an average OPEX lower than the cost of deep-well disposal. Assuming similar groundwater withdrawals and PW volumes and management practices in the future, PW reuse in agriculture could positively impact the Ogallala aquifer by reducing its decline, especially in Oklahoma. This is of particular importance for the environment, economy, and communities of the High Plains region, where unrelenting water stress and water scarcity are expected to further reduce the level of the groundwater reserves.

This analysis shows that there is potential for treating and recovering PW for agricultural use under some conditions in the Anadarko Basin. It is worth noting, however, that the median TDS of PW in the Anadarko Basin is among the highest compared to PW generated in other O&G basins in the United States (Scanlon et al., 2020). As desalination is the most energy-intensive and costly treatment step required for PW recovery, the Anadarko Basin might be one of the costliest and most energy-intensive areas for PW treatment for agricultural use. Therefore, it is worth replicating this research in other O&G basins where PW salinity is lower, as we can expect a larger proportion of PW to be economically treatable and usable in agriculture under those conditions. The approach presented here offers a valuable framework for policy-makers, researchers, and industry stakeholders to evaluate the feasibility and benefits of PW recovery for agriculture both in the Anadarko Basin itself and in other regions facing similar challenges.

CRedit authorship contribution statement

Alban Echchelh: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Justin M. Hutchison:** Formal analysis, Supervision, Writing – review & editing. **Stephen J. Randtke:** Conceptualization, Writing – review & editing. **Edward Peltier:** Conceptualization, Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data on produced water composition, produced water volumes and agricultural water use by county, and produced water treatment scenarios are available through Mendeley data (Echchelh et al., 2023) or upon request.

Acknowledgements

Funding for this work was provided by the National Science Foundation under Grants Nos OIA-1632892 and 1856084. Kylie-Grace Fair

contributed to the initial collection and analysis of produced water volume data as an undergraduate at the University of Kansas in 2020–2021.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2023.168820>.

References

- Al-Ghouthi, M.A., Al-Kaabi, M.A., Ashfaq, M.Y., Da'na, D.A., 2019. Produced water characteristics, treatment and reuse: a review. *J. Water Process Eng.* 28, 222–239. <https://doi.org/10.1016/j.jwpe.2019.02.001>.
- Alley, B., Beebe, A., Rodgers, J., Castle, J.W., 2011. Chemical and physical characterization of produced waters from conventional and unconventional fossil fuel resources. *Chemosphere* 85, 74–82. <https://doi.org/10.1016/j.chemosphere.2011.05.043>.
- Amakiri, K.T., Canon, A.R., Molinari, M., Angelis-Dimakis, A., 2022. Review of oilfield produced water treatment technologies. *Chemosphere* 298, 20. <https://doi.org/10.1016/j.chemosphere.2022.134064>.
- Beletse, Y.G., Annandale, J.G., Steyn, J.M., Hall, I., Aken, M.E., 2008. Can crops be irrigated with sodium bicarbonate rich CBM deep aquifer water? Theoretical and field evaluation. *Ecol. Eng.* 33, 26–36. <https://doi.org/10.1016/j.ecoleng.2007.12.011>.
- Blondes, M.S., Gans, K.D., Engle, M.A., Kharaka, Y.K., Reidy, M.E., Sarawathula, V., Thordsen, J.J., Rowan, E.L., Morrissey, E.A., 2018. U.S. Geological Survey National Produced Waters Geochemical Database v2.3. <https://doi.org/10.5066/F7J964W8>.
- Breuer, R., Al-Asmi, S.R., 2010. *Nimr Water Treatment Project - Up Scaling a Reed Bed Trail to Industrial*, SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production.
- Brown, T.C., Foti, R., Ramirez, J.A., 2013. Projected freshwater withdrawals in the United States under a changing climate. *Water Resour. Res.* 49, 1259–1276. <https://doi.org/10.1002/wrcr.20076>.
- COGCC, 2020. Production by County. Colorado Oil & Gas Conservation Commission. <http://cogcc.state.co.us/data4.html#production>. (Accessed 7 January 2022).
- Cooper, C.M., McCall, J., Stokes, S.C., McKay, C., Bentley, M.J., Rosenblum, J.S., Blewett, T.A., Huang, Z., Miara, A., Talmadge, M., Evans, A., Sitterley, K.A., Kurup, P., Stokes-Draut, J.R., Macknick, J., Borch, T., Cath, T.Y., Katz, L.E., 2022. Oil and gas produced water reuse: opportunities, treatment needs, and challenges. *ACS ES&T Eng.* 2, 347–366. <https://doi.org/10.1021/acsestengg.1c00248>.
- Cordier, C., Stavrakakis, C., Morga, B., Degremont, L., Voulgaris, A., Bacchi, A., Sauvade, P., Coelho, F., Moulin, P., 2020. Removal of pathogens by ultrafiltration from sea water. *Environ. Int.* 142, 105809. <https://doi.org/10.1016/j.envint.2020.105809>.
- Dahm, K., Chapman, M., 2014. *Produced Water Treatment Primer: Case Studies of Treatment Applications*, [U.S. Department of the Interior], Bureau of Reclamation, Technical Service Center, Denver, CO S&T Research Project #1617.
- Deines, J.M., Kendall, A.D., Butler, J.J., Hyndman, D.W., 2019. Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US High Plains Aquifer. *Environ. Res. Lett.* 14, 044014. <https://doi.org/10.1088/1748-9326/aaf39>.
- Dickerson, C., Mirabolphasemi, M., 2021. A Comparative Produced Water Management Decision Making Workflow: MSEEL Case Study, SPE Western Regional Meeting. Society of Petroleum Engineers SPE-200780-MS, Virtual.
- Dolan, F.C., Cath, T.Y., Hogue, T.S., 2018. Assessing the feasibility of using produced water for irrigation in Colorado. *Sci. Total Environ.* 640–641, 619–628. <https://doi.org/10.1016/j.scitotenv.2018.05.200>.
- Drewes, J., Cath, T., Debroux, J., Veil, J., 2009. An Integrated Framework for Treatment and Management of Produced Water - Technical Assessment of Produced Water Treatment Technologies, Colorado School of Mines, Golden, CO RPSEA Project 07122-12.
- Echchelth, A., Hess, T., Sakrabani, R., 2018. Reusing oil and gas produced water for irrigation of food crops in drylands. *Agric. Water Manag.* 206, 124–134. <https://doi.org/10.1016/j.agwat.2018.05.006>.
- Echchelth, A., Hess, T., Sukrabani, R., de Paz, J. M., Visconti, F., 2019. Assessing the environmental sustainability of irrigation with oil and gas produced water in drylands. *Agric. Water Manag.* 223, 105694. <https://doi.org/10.1016/j.agwat.2019.105694>.
- Echchelth, A., Hess, T., Sakrabani, R., 2020. Agro-environmental sustainability and financial cost of reusing gasfield-produced water for agricultural irrigation. *Agric. Water Manag.* 227, 105860. <https://doi.org/10.1016/j.agwat.2019.105860>.
- Echchelth, A., Hess, T., Sakrabani, R., Prigent, S., Stefanakis, A.I., 2021. Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments. *Agric. Water Manag.* 243, 106449. <https://doi.org/10.1016/j.agwat.2020.106449>.
- Echchelth, A., Hutchison, J., Randtke, S., Peltier, E., 2023. Dataset for assessing the potential of produced water as an unconventional water resource for agriculture in the Anadarko Basin. In: Mendeley Data, V1. <https://doi.org/10.17632/zgkct578f4.1>.
- EIA, 2022a. Energy Conversion Calculators. U.S. Energy Information Administration. <https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php>. (Accessed 7 July 2022).
- EIA, 2022b. Spot prices - Crude oil. U.S. Energy Information Administration. http://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm. (Accessed 14 October 2022).
- El-badawy, T., Othman, M.H.D., Matsuura, T., Bilad, M.R., Adam, M.R., Tai, Z.S., Ravi, J., Ismail, A.F., Rahman, M.A., Jaafar, J., Usman, J., Kurniawan, T.A., 2022. Progress in treatment of oilfield produced water using membrane distillation and potentials for beneficial re-use. *Sep. Purif. Technol.* 278, 26. <https://doi.org/10.1016/j.seppur.2021.119494>.
- Engle, M.A., Cozzarelli, I.M., Smith, B.D., 2014. USGS investigations of water produced during hydrocarbon reservoir development. In: U.S. Geological Survey Fact Sheet 2014-3104.
- Galeano, L.-A., Guerrero-Flórez, M., Sánchez, C.-A., Gil, A., Vicente, M.-Á., 2019. Disinfection by chemical oxidation methods. In: Gil, A., Galeano, L.A., Vicente, M.Á. (Eds.), *Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment*. Springer International Publishing, Cham, CH, pp. 257–295.
- Geza, M., Ma, G., Kim, H., Cath, T.Y., Xu, P., 2018. iDST: an integrated decision support tool for treatment and beneficial use of non-traditional water supplies – part I. Methodology. *J. Water Process Eng.* 25, 236–246. <https://doi.org/10.1016/j.jwpe.2018.08.006>.
- Ground Water Protection Council, 2019. *Produced Water Report: Regulations, Current Practices, and Research Needs*. Ground Water Protection Council, Oklahoma City, OK.
- Guerra, K., Dahm, K., Dundorf, S., 2011. *Oil and Gas Produced Water Management and Beneficial Use in the Western United States*, Bureau of Reclamation, Denver, CO S&T Report No. 157.
- Guilford, M.C., Hall, C.A.S., O'Connor, P., Cleveland, C.J., 2011. A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production. *Sustainability* 3, 1866–1887. <https://doi.org/10.3390/su3101866>.
- Gurdak, J.J., Roe, C.D., 2010. Review: recharge rates and chemistry beneath plays of the High Plains aquifer, USA. *Hydrogeology* 18, 1747–1772. <https://doi.org/10.1007/s10040-010-0672-3>.
- Hagström, E.L., Lyles, C., Pattanayek, M., DeShields, B., Berkman, M.P., 2016. Produced water—emerging challenges, risks, and opportunities. *Environ. Claims J.* 28, 122–139. <https://doi.org/10.1080/10406026.2016.1176471>.
- Higley, D.K., Gaswirth, S.B., Abbott, M.M., Charpentier, R.R., Cook, T.A., Ellis, G.S., Gianoutsos, N.J., Hatch, J.R., Klett, T.R., Nelson, P., Pawlewicz, M.J., Pearson, O.N., Pollastro, R.M., Schenk, C.J., 2011. Assessment of Undiscovered Oil and Gas Resources of the Anadarko Basin Province of Oklahoma, Kansas, Texas, and Colorado, 2010, U.S. Geological Survey Fact Sheet 2011–3003.
- IEA, 2020. *The Oil and Gas Industry in Energy Transitions*. The International Energy Agency, Paris.
- KGS, 2020. Production - Oil or Natural Gas Wells - County Production. Kansas Geological Survey. <https://www.kgs.ku.edu/PRS/petro/interactive.html>. (Accessed 7 January 2022).
- Kondash, A.J., Redmon, J.H., Lambertini, E., Feinstein, L., Weinthal, E., Cabrales, L., Vengosh, A., 2020. The impact of using low-saline oil field produced water for irrigation on water and soil quality in California. *Sci. Total Environ.* 733, 10. <https://doi.org/10.1016/j.scitotenv.2020.139392>.
- KS Department of Agriculture, 2023. Local Enhanced Management Area (LEMA). Kansas Department of Agriculture, Division of Water Resources. <http://kda-dwr-updates.org/local-enhanced-management-area-lema/>. (Accessed 8 July 2023).
- Lauer, S., Sanderson, M.R., Manning, D.T., Suter, J.F., Hrozencik, R.A., Guerrero, B., Golden, B., 2018. Values and groundwater management in the Ogallala Aquifer region. *J. Soil Water Conserv.* 73, 593–600. <https://doi.org/10.2489/jswc.73.5.593>.
- Ma, G., Geza, M., Cath, T.Y., Drewes, J.E., Xu, P., 2018. iDST: an integrated decision support tool for treatment and beneficial use of non-traditional water supplies – part II. Marcellus and Barnett shale case studies. *J. Water Process Eng.* 25, 258–268. <https://doi.org/10.1016/j.jwpe.2018.08.007>.
- Mahoney, J.G., Asami, R.T., Stringfellow, W.T., 2021. Food Safety Project White Paper: On the Reuse of Oil Field Produced Water for Irrigation of Food Crops in Central Kern County, California, Central Valley Regional Water Quality Control Board, Fresno, CA.
- McCurdy, R., 2011. *Underground Injection Wells for Produced Water Disposal*, Proceedings of the Technical Workshops for the Hydraulic Fracturing Study: Water Resources Management EPA 600-R-11-048, U.S. Environmental Protection Agency.
- McGuire, V.L., 2017. Water-level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2015 and 2013–15, Reston, VA 2017-5040.
- McMahon, P.B., Dennehy, K.F., Bruce, B.W., Gurdak, J.J., Qi, S., 2007. Water-quality Assessment of the High Plains Aquifer, 1999–2004. U.S. Geological Survey, p. 1749.
- Meng, M., Chen, M., Sanders, K., 2016. Evaluating the feasibility of using produced water from oil and natural gas production to address water scarcity in California's Central Valley. *Sustainability* 8, 1318. <https://doi.org/10.3390/su8121318>.
- Miller, H., Dias, K., Hare, H., Borton, M.A., Blotvogel, J., Danforth, C., Wrighton, K.C., Ippolito, J.A., Borch, T., 2020. Reusing oil and gas produced water for agricultural irrigation: effects on soil health and the soil microbiome. *Sci. Total Environ.* 722, 9. <https://doi.org/10.1016/j.scitotenv.2020.137888>.
- Monckton, D., Cavaye, J., Huth, N., Vink, S., 2017. Use of coal seam water for agriculture in Queensland, Australia. *Water Int.* 42, 599–617. <https://doi.org/10.1080/02508060.2017.1339259>.
- Myers, J.E., 2014. *Chevron San Ardo Facility Unit (SAFU) Beneficial Produced Water Reuse for Irrigation*, SPE International Conference on Health, Safety, and Environment. Society of Petroleum Engineers, Long Beach, CA.
- Nasiri, M., Jafari, I., Parniankhy, B., 2017. Oil and gas produced water management: a review of treatment technologies, challenges, and opportunities. *Chem. Eng. Commun.* 204, 990–1005. <https://doi.org/10.1080/00986445.2017.1330747>.

- National Agricultural Statistics Service, 2017. Census of Agriculture, 2017 Census Ag Atlas Maps. U.S. Department of Agriculture. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Atlas_Maps/. (Accessed 5 January 2022).
- OCC, 2020. Salt Water Disposal Records by County. Oklahoma Corporation Commission. <https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/salt-water-disposal-records-by-county.html>. (Accessed 7 January 2022).
- Onishi, V.C., Fraga, E.S., Reyes-Labarta, J.A., Caballero, J.A., 2018. Desalination of shale gas wastewater: thermal and membrane applications for zero-liquid discharge. In: Gude, V.G. (Ed.), *Emerging Technologies for Sustainable Desalination Handbook*. Elsevier, Cambridge, MA, pp. 399–431.
- Pham, A., 2022. Geochemical and Economic Evaluation of Brine Exchange as a Means of Produced Water Management. MS Thesis. University of Kansas, Lawrence, KS.
- Pichtel, J., 2016. Oil and gas production wastewater: soil contamination and pollution prevention. *Appl. Environ. Soil Sci.* 2016, 1–24. <https://doi.org/10.1155/2016/2707989>.
- Plumlee, M.H., Debroux, J.-F., Taffler, D., Graydon, J.W., Mayer, X., Dahm, K.G., Hancock, N.T., Guerra, K.L., Xu, P., Drewes, J.E., Cath, T.Y., 2014. Coalbed methane produced water screening tool for treatment technology and beneficial use. *J. Unconv. Oil Gas Resour.* 5, 22–34. <https://doi.org/10.1016/j.juogr.2013.12.002>.
- Pollyea, R.M., Chapman, M.C., Jayne, R.S., Wu, H., 2019. High density oilfield wastewater disposal causes deeper, stronger, and more persistent earthquakes. *Nat. Commun.* 10, 3077. <https://doi.org/10.1038/s41467-019-11029-8>.
- Redmon, J.H., Kondash, A.J., Womack, D., Lillys, T., Feinstein, L., Cabrales, L., Weinthal, E., Vengosh, A., 2021. Is food irrigated with oilfield-produced water in the California Central Valley safe to eat? A probabilistic human health risk assessment evaluating trace metals exposure. *Risk Anal.* 41, 1463–1477. <https://doi.org/10.1111/risa.13641>.
- RRC, 2020. Oil and Gas Production Data Query. Railroad Commission of Texas. <http://webapps.rrc.texas.gov/PDQ/generalReportAction.do;jsessionid=QvI04ztmZZGgFx0qVX8P0LO7-Y7L51SWt2y3loQpcPh0kNXVmWI-1-380275275>. (Accessed 7 January 2022).
- Rusydi, A.F., 2018. Correlation between conductivity and total dissolved solid in various type of water: a review. *IOP Conf. Ser. Earth Environ. Sci.* 118, 012019 <https://doi.org/10.1088/1755-1315/118/1/012019>.
- Samuel, O., Othman, M.H.D., Kamaludin, R., Sinsamphanh, O., Abdullah, H., Puteh, M. H., Kurniawan, T.A., Li, T., Ismail, A.F., Rahman, M.A., Jaafar, J., El-badawy, T., Mamah, S.C., 2022. Oilfield-produced water treatment using conventional and membrane-based technologies for beneficial reuse: a critical review. *J. Environ. Manag.* 308, 23. <https://doi.org/10.1016/j.jenvman.2022.114556>.
- Scanlon, B.R., Reedy, R.C., Xu, P., Engle, M., Nicot, J.P., Yoxtheimer, D., Yang, Q., Ikonnikova, S., 2020. Can we beneficially reuse produced water from oil and gas extraction in the U.S.? *Sci. Total Environ.* 717, 137085 <https://doi.org/10.1016/j.scitotenv.2020.137085>.
- Schrevel, A., Hellegers, P., Soppe, R., 2004. Potential for Up-scaling Nimir Bed Facilities, Oman: Feasibility Study.
- Shahbaz, M., Rashid, N., Saleem, J., Mackey, H., McKay, G., Al-Ansari, T., 2023. A review of waste management approaches to maximise sustainable value of waste from the oil and gas industry and potential for the State of Qatar. *Fuel* 332, 25. <https://doi.org/10.1016/j.fuel.2022.126220>.
- Shariq, L., McLaughlin, M.C., Rehberg, R.A., Miller, H., Blotvogel, J., Borch, T., 2021. Irrigation of wheat with select hydraulic fracturing chemicals: evaluating plant uptake and growth impacts. *Environ. Pollut.* 273, 116402 <https://doi.org/10.1016/j.envpol.2020.116402>.
- Shaw, R., Gordon, I., Hinchley, D., Hill, C., Thorburn, P., Brebber, L., Doherty, J., Christiansen, I., Stallman, A., Carlin, G., Dowling, T., 2011. *Salinity Management Handbook*, 2nd ed. Department of Environment and Resource Management, State of Queensland, Brisbane.
- Stefanakis, A.L., Prigent, S., Breuer, R., 2018. Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis, A. (Ed.), *Constructed Wetlands for Industrial Wastewater Treatment*. John Wiley & Sons, Ltd, Hoboken, NJ, pp. 23–42.
- Subramani, A., Jacangelo, J.G., 2015. Emerging desalination technologies for water treatment: a critical review. *Water Res.* 75, 164–187. <https://doi.org/10.1016/j.watres.2015.02.032>.
- Thebo, A.L., Dery, J.L., Shimabuku, M., 2023. Potential of Oilfield Produced Water for Irrigation in California, The Water Research Foundation, Alexandria, VA Project No. 4993.
- Tong, T., Carlson, K.H., Robbins, C.A., Zhang, Z., Du, X., 2019. Membrane-based treatment of shale oil and gas wastewater: the current state of knowledge. *Front. Environ. Sci. Eng.* 13, 63. <https://doi.org/10.1007/s11783-019-1147-y>.
- USGS, 2018. USGS Water Use Data for the Nation. U.S. Geological Survey. <https://waterdata.usgs.gov/usa/nwis/wu>. (Accessed 7 January 2022).
- Veil, J., 2015. U.S. Produced Water Volumes and Management Practices in 2012. Groundwater Protection Council, Oklahoma City, OK.
- Veil, J., 2020. Produced Water Volumes and Management Practices in 2017. Groundwater Protection Council, Oklahoma City, OK.
- Walsh, F.R., Zoback, M.D., 2015. Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv.* 1 <https://doi.org/10.1126/sciadv.1500195>.
- Whittemore, D.O., Butler Jr., J.J., Bohling, G.C., Wilson, B.B., 2023. Are we saving water? Simple methods for assessing the effectiveness of groundwater conservation measures. *Agric. Water Manag.* 287, 108408 <https://doi.org/10.1016/j.agwat.2023.108408>.
- Xu, P., Ma, G., Stoll, Z., 2016. Assessment of Treatment Technologies for Produced Water to Improve Water Supply Sustainability in Southeastern New Mexico. New Mexico Water Resources Research Institute Las Cruces, NM.
- Ziemkiewicz, P.F., He, Y.T., 2015. Evolution of water chemistry during Marcellus Shale gas development: a case study in West Virginia. *Chemosphere* 134, 224–231. <https://doi.org/10.1016/j.chemosphere.2015.04.040>.