Managing Basin-Scale Fluid Budgets to Reduce Injection-Induced Seismicity from the Recent U.S. Shale Oil Revolution

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ABSTRACT

With the U.S. unconventional oil revolution, adverse impacts from subsurface disposal of coproduced water, such as induced seismicity, have markedly increased, particularly in Oklahoma. Here, we adopt a new, more holistic analysis by linking produced water (PW) volumes, disposal, and seismicity in all major U.S. unconventional oil plays (Bakken, Eagle Ford, and Permian plays, and Oklahoma) and provide guidance for long-term management. Results show that monthly PW injection volumes doubled across the plays since 2009. We show that the shift in PW disposal to nonproducing geologic zones related to low-permeability unconventional reservoirs is a fundamental driver of induced seismicity. We statistically associate seismicity in Oklahoma to (1) PW injection rates, (2) cumulative PW volumes, and (3) proximity to basement with updated data through 2017. The major difference between intensive seismicity in Oklahoma versus low seismicity levels in the Bakken, Eagle Ford, and Permian basin plays is attributed to proximity to basement with deep injection near basement in Oklahoma relative to shallower injection distant from basement in other plays. Directives to mitigate Oklahoma seismicity are consistent with our findings: reducing (1) PW injection rates and (2) regional injection volumes by 40% relative to the 2014 total in wells near the basement resulted in a 70% reduction in the number of $M \geq 3$ earthquakes in 2017 relative to the 2015 peak seismicity. Understanding linkages between PW management and seismicity allows us to develop a portfolio of strategies to reduce future adverse impacts of PW management, including reuse of PW for hydraulic fracturing in the oil and gas sector.

Electronic Supplement: To be added later.

INTRODUCTION

The United States is the global leader in oil production since 2013, exceeding production in Saudi Arabia (U.S. Energy Information Administration [EIA], 2018a). The marked increase in U.S. oil production is attributed to technology advances, primarily hydraulic fracturing (HF) and horizontal drilling of wells up to 2–3 miles long (~3–5 km). These advances allow oil to be extracted from low-permeability source rocks (e.g., shales, tight sands, or carbonates) or through dewatering of oil reservoirs, as in Oklahoma (Murray, 2013; Scanlon *et al.*, 2016, 2017). Oil production from shales and tight rocks accounted for about half of the U.S. production in 2017, greatly enhancing U.S. energy security (U.S. EIA, 2018a). Shales and tight rocks are generally referred to as unconventional or continuous (areally extensive) reservoirs that require HF and horizontal wells to extract oil (Schenk and Pollastro, 2002). These unconventional reservoirs contrast with traditional higher permeability conventional reservoirs that can be developed with vertical wells and without large-water-volume HF.

Oil wells also produce large volumes of water, averaging ~10 barrels (bbl) of water per barrel of oil in the United States in 2012 (Veil, 2015). Water coproduced with oil has been referred to as produced water (PW), wastewater, or salt water. We have been generating large volumes of PW with oil production in the United States for decades (U.S. EIA, 2018b, c), but widespread induced seismicity (earthquakes caused by human activity) in some regions has been relatively recent, raising the question about what has changed. Are we generating more PW with oil production or are we managing PW differently? At the scale of the United States, we did not produce more water with oil and gas in 2012 relative to 2007 (< 1% change in PW relative to 30% increase in oil production; Clark and Veil, 2009; Veil, 2015). However, we are managing PW differently. PW from moderate-to-high-permeability conventional reservoirs is mostly injected back into the reservoir for pressure maintenance or for enhanced oil recovery injection (EORI) using water flooding, whereas PW from unconventional reservoirs cannot be reinjected into the producing reservoir because of the low permeability of the shales and tight rocks.

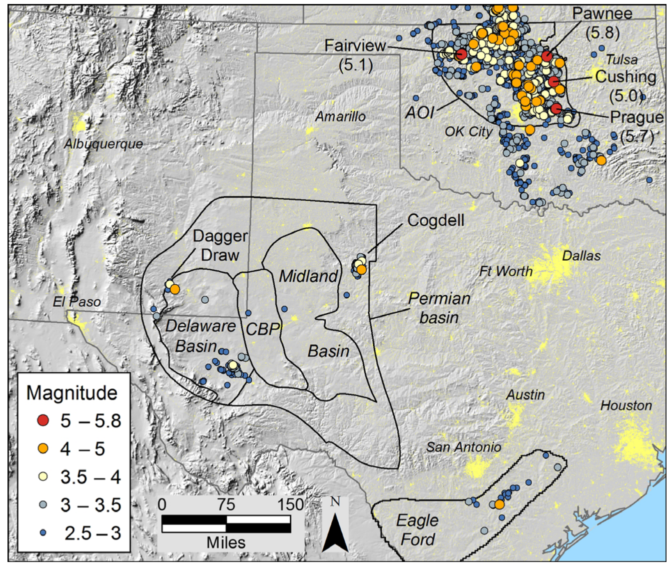
A National Research Council (NRC) report on induced seismicity emphasizes the impact of the net fluid balance (fluid injection minus extraction [or production]) in controlling subsurface pressure changes and induced seismicity NRC, 2013). Because injection and extraction are generally balanced in conventional reservoirs, net pore-fluid pressure changes should be minimal, reducing the risk of seismicity. However, seismicity related to water flooding has been recorded in some regions (e.g., the Cogdell field in the Permian basin; Frohlich *et al.*, 2016). In contrast, PW from unconventional reservoirs is generally injected into non-oil-producing geologic intervals, resulting in net fluid volume and related pressure increases. Some producing reservoirs in Oklahoma (e.g., Mississippi lime and Hunton lime) do not fit neatly into conventional or unconventional reservoir categories but have been referred to as "where unconventional meets conventional" because HF and horizontal drilling stimulation techniques are applied to these higher-permeability reservoirs (Drillinginfo, 2012). Because these Oklahoma reservoirs are being dewatered, PW is not reinjected back into the producing reservoir. Typical ratios of PW to oil in these dewatering reservoirs are up to ~120 bbl water/bbl oil initially (Oklahoma Corporation Commission [OCC], 2017).

PW management in unconventional or dewatering reservoirs is similar to other energy technologies that inject or extract large fluid volumes over long times (e.g., carbon capture and storage, some geothermal systems) and have a much higher potential of modifying pressures and inducing seismicity (Rubinstein and Mahani, 2015). Increasing pore-fluid pressure (ρ) reduces effective stress on faults (normal stress [σ] − pore-fluid pressure [ρ]) making fault slip more likely (NRC, 2013). Critical factors to consider for induced seismicity include (Ground Water Protection Council [GWPC], 2017):

1. sufficient pore pressure buildup from injection,
2. presence of an optimally oriented fault for movement located in a critically stressed region (fault of concern), and
3. a pathway connecting the pressure increase with the fault.

The pressure buildup is attributed to PW injection that is not offset by production, resulting in an increasing pressure footprint (U.S. EIA, 2014). The time period of injection is also important (U.S. EIA, 2014). Although seismicity has been linked to water injection during HF stimulation (the Horn River, Canada; Lancashire, United Kingdom; Oklahoma), time periods for HF are short (days) and any impacts from HF are generally mitigated within a short period (Davies *et al.*, 2013; OCC, 2017).

Previous studies examined linkages between PW injection and induced seismicity. Understanding these linkages has important implications for PW management. Many studies have focused on Oklahoma where several large earthquakes occurred, including the M 5.7 earthquake near Prague in November 2011, the M 5.1 Fairview earthquake in February 2016, the M 5.8 Pawnee earthquake in September 2016, and the M 5.0 Cushing earthquake in November 2016 (Fig. 1; Kroll *et al.*, 2017). A previous study found that PW injection rate was the most critical control on induced seismicity based



▲ **Figure 1.** Seismic events with magnitude (M) ≥ 2.5 that occurred from January 2009 through December 2017 in the Oklahoma, southern Kansas, Permian basin, and Eagle Ford play study areas. There were 8532 events in the Oklahoma/South Kansas cluster, including four M ≥ 5.0 events (labeled). By comparison, there were 122 events in the Permian basin and 19 events in the Eagle Ford. However, 66 of the Permian basin events are associated with CO_2 injection in the Cogdell field (including an M 4.3 event) and 6 with enhanced oil-recovery injection (EORI) in the Dagger Draw field (including an M 4.1 event). The largest event in the Eagle Ford was an M 4.8 event. The number of earthquakes M ≥ 3.0 is provided in Ⓔ Table S1 (available in the electronic supplement to this article). Subregions outlined in the Permian basin include the Delaware basin, Midland basin, and the Central basin platform (CBP). Data source: U.S. Geological Survey (USGS) Advanced National Seismic System Comprehensive Catalog (see Data and Resources). The color version of this figure is available only in the electronic edition.

on linkages between seismicity and high-rate injection wells (≥ 300, 000 bbl/month) in the U.S. Midcontinent (Weingarten *et al.*, 2015). The study of seismicity in the U.S. Midcontinent indicated that cumulative PW injection volume or proximity of injection to the crystalline basement (consisting mostly of igneous or metamorphic rocks at the base of sedimentary units) was not statistically linked to seismicity. The implications of this study suggest that reducing injection rate could be used to minimize induced seismicity. A recent study related the occurrence of seismicity to proximity to basement, noting the absence of seismicity in the Bakken and Marcellus plays to shallow or little or no disposal respectively (Skoumal *et al.*, 2018). Another study underscored well depth related to proximity to basement in Oklahoma as the primary factor controlling seismicity (Hincks *et al.*, 2018). Large faults are expected to be more prevalent at greater depth, particularly in old brittle basement rocks that have been subjected to different stresses over long times. The study by Hincks *et al.* (2018)

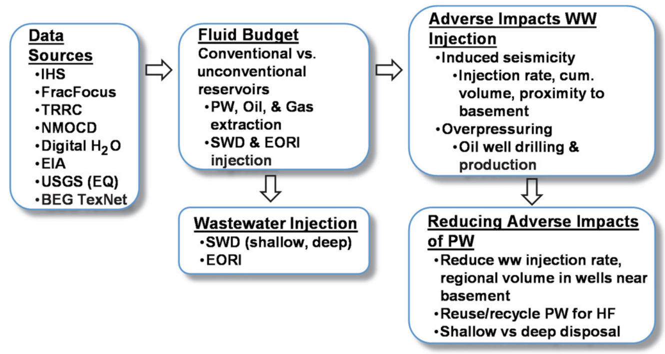
implies that disposing of PW in shallow zones away from the basement should minimize induced seismicity. In another study, monthly regional injection rates at depth near the basement (Arbuckle Group) were correlated to monthly earthquake counts in central and western Oklahoma (Langenbruch and Zoback, 2016). Additional factors considered important relative to seismicity include time-variable injection that was linked to large-magnitude earthquakes in Oklahoma, considering poroelastic effects (Barbour *et al.*, 2017; Goebel *et al.*,
7 2017). Chang *et al.* (2016) also linked injection-induced seismicity to basement faults, including poroelastic stressing. A much broader scale study relating induced seismicity to hydrocarbon production, used as a proxy for HF and PW volumes, in the United States and Canada emphasizes the importance of tectonic factors, for example, critically stressed, favorably oriented faults (van der Baan and Calixto, 2017). In contrast, another study assumes that seismogenic faults are pervasive in basement rocks in Oklahoma (Norbeck and Rubinstein, 2018). Understanding the controlling mechanisms for seismicity and the role of PW injection is critical for developing PW management strategies to mitigate or minimize seismicity.

Few studies address management strategies to reduce seismicity. Some studies focus on developing a detailed seismic
8 network to monitor induced seismicity (Norbeck *et al.*, 2018). A primer on technical and regulatory considerations related to risk management and mitigation strategies includes detailed recommendations on PW injection rates, volumes, and proximity to basement, among many other factors (GWPC, 2017). The EPA developed a decision model to manage and minimize injection-induced seismicity by considering critical factors, including pressure buildup, fault of concern, and interconnectivity and provides a number of recommendations (U.S. EIA, 2014).

The objective of this study was to:

1. determine controls on linkages between PW management and induced seismicity, and
2. assess approaches to improve PW management to minimize future seismicity.

This study differs from previous studies in that (1) it considers all of the major tight-oil plays in the United States, not just Oklahoma; (2) it links PW injection to specific geologic zones, calculating net fluid balances of such zones; (3) it reevaluates the approach of assessing injection rates, cumulative injection volumes, and proximity to basement, previously applied to the U.S. Midcontinent (Weingarten *et al.*, 2015), by including an additional 3.5 yrs of data; and (4) it evaluates strategies for managing PW to minimize future seismicity, particularly through PW reuse and/or recycling. Although the U.S. Geological Survey currently develops hazard forecasts for induced seismicity (Petersen *et al.*, 2017) that do not consider PW injection data, results of this study relating PW management to induced seismicity should be valuable in future hazard forecasts that incorporate PW data. The insights from PW injection related to oil and gas production in this study may be considered an analog for



▲ **Figure 2.** Flow chart showing data sources, fluid balance (production vs. injection), adverse impacts, and approaches to reducing these impacts. TRRC, Texas Railroad Commission; NMOCD, New Mexico Oil Conservation District; OCC, Oklahoma Corporation Commission; EIA, Energy Information Administration; USGS (EQ), U.S. Geological Survey earthquake data; BEG TexNet, Bureau of Economic Geology Texas Network; PW, produced water; SWD, saltwater disposal wells; cum. vol., cumulative injection volume; HF, hydraulic fracturing. The color version of this figure is available only in the electronic edition.

CO_2 sequestration, injection of other industrial wastewaters, or fluid injection for geothermal energy projects.

MATERIALS AND METHODS

A flow chart describing the methodology is shown in Figure 2. Additional details related to methods applied in this study are provided in the Ⓔ Materials and Methods section, available in the electronic supplement to this article. Fluid (oil, gas, and water) production for the Bakken, Eagle Ford, and Permian basin plays and in Oklahoma was quantified based on data primarily from the IHS database (2009–2016). Monthly data 9
on PW volumes or PW injection into saltwater disposal (SWD) wells and into EORI wells were also obtained from IHS. Analysis of the net fluid balance consisted of quantifying oil, gas, and water extraction (production) and water injection (SWD or EORI) relative to oil-producing and non-oil-producing geologic intervals in the major tight-oil plays. The previous assessment of linkages between PW injection and earthquakes in Oklahoma (Weingarten *et al.*, 2015) was updated with an additional 3.5 yrs of data, evaluating injection rates, cumulative injection volumes, and proximity to basement. Earthquakes within 15 km of an active SWD well were assumed to be associated with that SWD well. A new basement depth map was compiled for the region with much more detailed information (Crain and Chang, 2018). Similar analysis was applied to the other major U.S. tight-oil plays (Bakken, Eagle Ford, and Permian basin). A first-order spatiotemporal filter was applied to identify earthquakes potentially associated with injection wells. Confidence limits on these associated earthquakes were determined using a bootstrap resampling method. Results from other plays were compared with those from Oklahoma to determine linkages between PW management and lower seismicity in other plays.

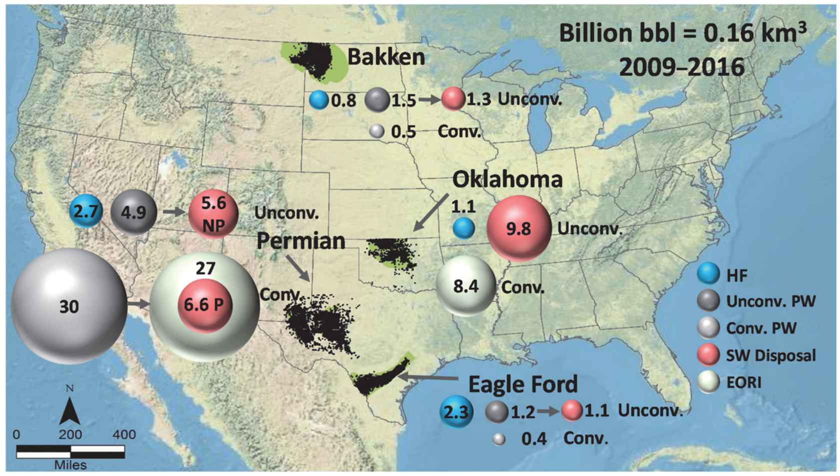
We examined current approaches to mitigating seismicity in Oklahoma and preventing potential seismicity in the other tight-oil plays. Various approaches to PW management were considered, including reducing regional-scale and local-scale injection rates and volumes, shallow versus deep injection, and reuse and/or recycling of PW for HF.

RESULTS

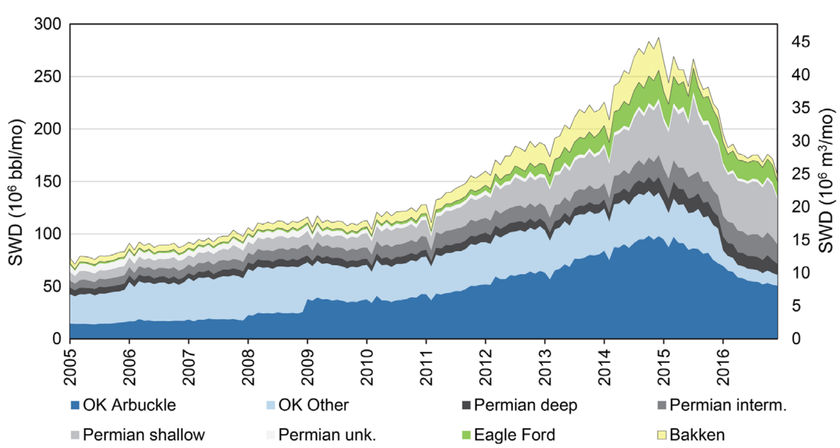
Net Fluid Balance of Major Tight Oil Plays

Water is a major component of the net fluid balance in the Permian, Bakken, and Eagle Ford plays and in Oklahoma (Fig. 3 and Ⓔ Fig. S1). Traditionally, PW is managed primarily via reinjection back into the producing horizon, often aimed at maintaining pressure or for enhanced oil recovery (EOR). The recent U.S. unconventional oil revolution, however, not only increased PW volumes but also created a marked shift in the net fluid balance of the major plays. The recent increase in PW has been managed primarily by PW disposal into nonproducing horizons, mostly using SWD wells (Fig. 4), because unconventional production primarily focuses on low-permeability reservoirs or dewatering reservoirs, not suitable for PW reinjection. This shift, increased disposal into nonproducing horizons, coupled with increased PW volumes, has likely yielded larger net positive reservoir pressure changes at the regional scale. Here, we quantify PW volumes in the Permian, Bakken, and Eagle Ford plays and in Oklahoma, with an emphasis on the breakdown of PW injection into oil-producing or nonproducing geologic intervals and disposal type (EORI or SWD).

Although PW volumes from conventional reservoirs are high, this PW is mostly recycled for EOR. PW volumes are the highest from the Permian basin conventional reservoirs, totaling 30 billion bbl (Bbbl, 4.8 km^3, 2009–2016), with an average of 14 barrels of water produced for every barrel of oil (Fig. 3 and Ⓔ Fig. S1). For context, this cumulative water volume (30 Bbbl, 1260 billion gallons, Bgal) is ~4.5 times the daily freshwater use in the United States in 2015 (281 Bgal; Dieter *et al.*, 2018). Conventional reservoirs are found mostly along the margins of the Permian basin and in the Central basin platform between the two mostly unconventional reservoirs in the Delaware and Midland basins (Ⓔ Fig. S2a). Most PW from Permian conventional plays is injected back into the producing reservoir for EOR (27 Bbbl; Fig. 3). There is no direct



▲ **Figure 3.** Total volumes of HF water use, of PW from unconventional and conventional wells, and PW management through SWD wells and EORI in the Bakken play, Eagle Ford play, Permian basin, and the State of Oklahoma for the period 2009–2016. Bubble areas represent fluid volumes and are proportionally consistent across all regions. PW management through EORI and SWD cannot be linked directly to PW generation. Data on PW are not available for Oklahoma. PW volumes are provided in Ⓔ Tables S2–S5. Additional information on SWD volumes is provided in Ⓔ Table S6. The color version of this figure is available only in the electronic edition.



▲ **Figure 4.** Comparison of annual total SWD volumes in the Permian basin, Oklahoma, Eagle Ford play, and the Bakken play. SWD in the Permian is based on injection into nonproducing intervals and is subdivided relatively into deep (lower Paleozoic), intermediate (Pennsylvanian, Wolfcampian, and Leonardian), and shallow (Guadalupian) depth formations. SWD in Oklahoma is subdivided into Arbuckle Group wells and all other wells. Other wells in Oklahoma include Devonian to Middle Ordovician rocks (Wilcox and Simpson Groups, ~7% of SWD), Mississippian to Pennsylvanian age rocks (~11%), Permian rocks (~5%), and wells completed in multiple zones (~11%). SWD in the Eagle Ford is also subdivided into shallow units above the Eagle Ford Shale. SWD in the Bakken play is primarily (93%) in the Dakota formation above the Bakken/Three Forks producing units. Annual data are provided in Ⓔ Tables S7–S10. The color version of this figure is available only in the electronic edition.

linkage between PW volume reporting and SWD volume reporting. SWD wells in Texas are classified as disposing into producing (SWD-P) or nonproducing (SWD-NP) intervals based on the presence or absence, respectively, of any current or historical hydrocarbon production within a 2-mile radius of the SWD well. Some of the PW from the conventional reservoirs is assumed to be disposed into producing intervals (SWD-P: < 6.6 Bbbl). Imbalances in PW and SWD volumes are likely related to uncertainties in reporting, particularly in the PW volumes. Water production or extraction from conventional plays is generally balanced with water injection, and regional-scale pore-fluid pressure changes should be minimal. Water essentially moves in a large recycle loop in these conventional reservoirs (Ⓔ Fig. S3b). PW is not reported in Oklahoma; however, conventional reservoirs likely operate in a similar way to those in the Permian basin, and the large volume of EORI (8.4 Bbbl) should represent PW from conventional reservoirs (Fig. 3).

PW from unconventional reservoirs in the Permian, Bakken, and Eagle Ford plays, as well as from Oklahoma reservoirs that are being dewatered, is managed in a markedly different fashion from that in conventional reservoirs. PW is not injected back into the oil-producing intervals but instead is injected into non-oil-producing intervals using SWD wells, resulting in a net pressure increase. Cumulative PW injection into non-oil-producing intervals is the highest in Oklahoma (9.8 Bbbl), followed by the Permian basin (5.6 Bbbl) but is much lower in the Bakken (1.3 Bbbl) and Eagle Ford (1.1 Bbbl) plays (2009–2016; Fig. 3). Monthly total SWD volumes into non-oil-producing intervals more than doubled from a monthly mean of 1.1 Bbbl in 2009 to a monthly peak of 2.9 Bbbl in 2014 (Fig. 4).

How much water is produced relative to oil in the various reservoirs? The PW intensity relative to oil production (PW to oil ratio, PWOR) is the highest in Oklahoma, ranging from 21 bbl PW/bbl of oil (water cut [WC = PW/[PW + oil] = PW/[PW + 1]; e.g., 21/22 = 95%) for conventional wells to 25 for unconventional wells (2009–2016; Ⓔ Fig. S1). These PW intensities in Oklahoma assume that EORI and SWD serve as proxies for PW from conventional and unconventional reservoirs, respectively. In the Permian basin, the PWOR for conventional wells (PWOR: 14; WC, 93%) is much higher than that for unconventional wells (PWOR: ~2.6; WC, ~70%). PWORs are much lower in the Bakken (5 for conventional wells [WC, 83%] and 0.7 for unconventional wells [WC, ~40%]) and in the Eagle Ford (~4 for conventional wells [WC: ~80%] and 0.6 for unconventional wells [WC: ~40%]).

What Controls Linkages between Produced Water Management and Seismicity?

Oklahoma

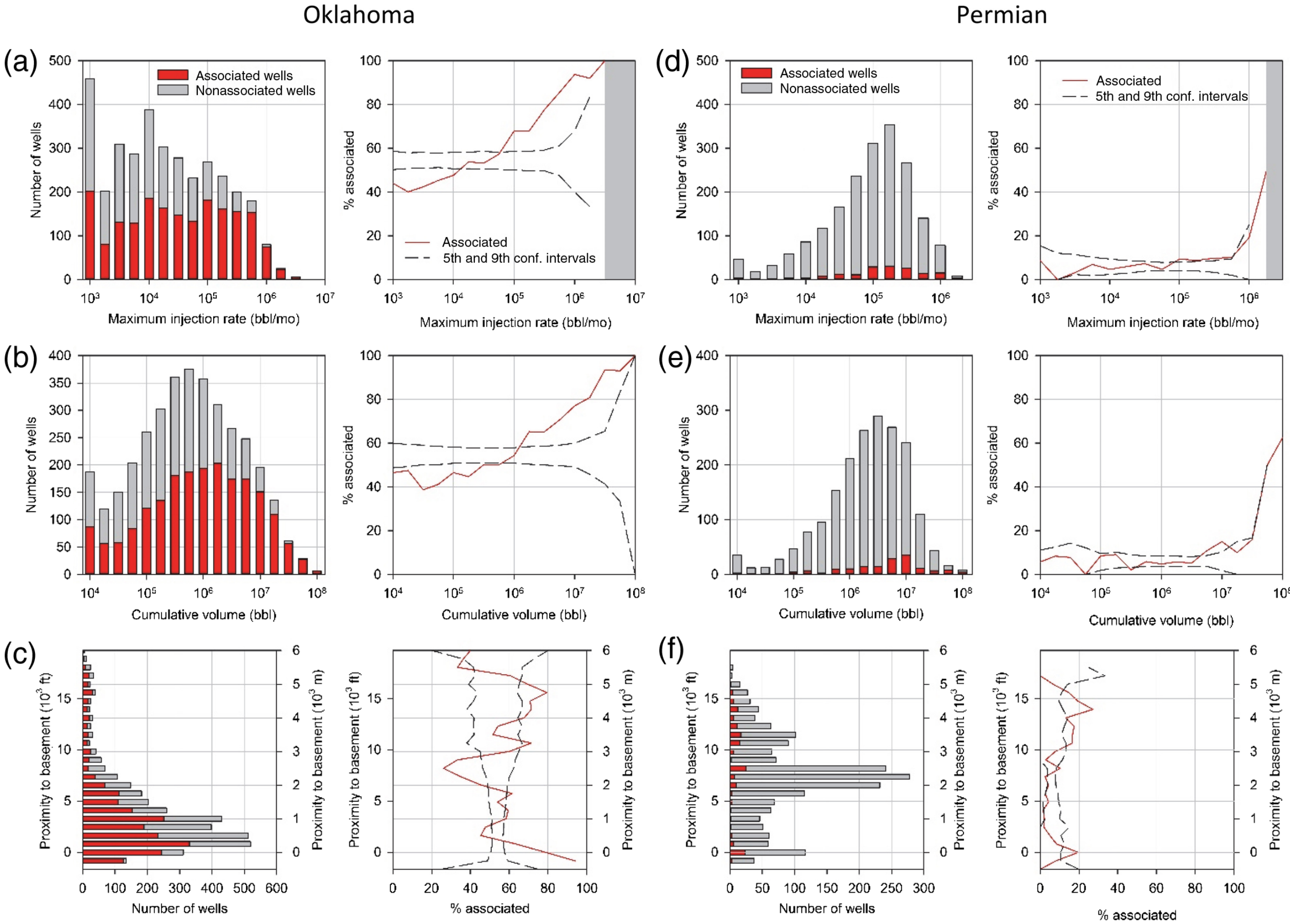
Potential controls on PW management and seismicity include:

1. PW injection rate at the well level,
2. regional cumulative injection volume, and
3. proximity of injection to basement.

10 In (1), using a first-order spatiotemporal filter, about 55% of SWD wells (~1900 out of ~3500 SWD wells) are potentially associated with earthquakes (M ≥ 3.0) within a 15 km radius in the area of interest (AOI) in central and north-central Oklahoma (OK) (2009–2017; Figs. 1 and 5a). Individual injection rates for wells associated with earthquakes vary by a few orders of magnitude (~10,000 to 4 million bbl/month [mo]) with a median of ~16,000 bbl/mo. PW injection rate in SWD wells plays an important role in induced seismicity because the like- 11
lihood of association between SWD wells and earthquakes increases with increasing injection rate: specifically, from ~50% of wells at injection rates ≤ 30,000 bbl/mo (1000 bbl/day) to 85%–100% at rates ≥ 300,000 bbl/mo (10,000 bbl/day) (Fig. 5a). The increasing percentage of higher-injection-rate wells associated with earthquakes exceeds the 5%–95% confidence bounds, based on a bootstrapped resampling method (see the Ⓔ Estimating Confidence Intervals based on Bootstrapped Resampling section). These results are consistent with earlier findings from the U.S. mid-continent that linked injection rate with seismicity (Oklahoma, Colorado, New Mexico, and Arkansas), based on data up through 2013 (Weingarten *et al.*, 2015).

In (2), we find the cumulative injection volume for SWD wells in Oklahoma from 2009 to 2017 to be statistically associated with earthquakes (Fig. 5b). The percentage of SWD wells associated with earthquakes increases with increasing cumulative injection volumes. Cumulative injection volumes range from ~10,000 bbl/well (5th percentile) to almost 84 million bbl/well (1 well 139 million bbl). Wells with 12
cumulative injection volumes ≤ ~1 million bbl exhibit statistically random association with earthquakes. The percentage association generally increases from ~60% at cumulative volumes of ~1 million bbl to ~90%–100% at ≥ 30 million bbl. This increase is statistically significant, based on the bootstrap resampling method. A prior study did not find a statistically significant relationship based on data from the U.S. mid-continent through 2013 (Weingarten *et al.*, 2015). With 3.5 yrs of additional injection data, a given well's cumulative injection volume is now correlated with its maximum monthly injection rate (coefficient of determination, $r^2 = 0.83$; Ⓔ Fig. S4a). Therefore, cumulative injection volume is now expected to also be statistically associated with earthquakes.

In (3), using a newly developed basement map (Crain 13
et al., 2018) and PW injection database for the state of Oklahoma (Murray, 2015), the proximity of the injection interval of the SWD wells to the crystalline basement is found to be related to earthquake association (Fig. 5c). The median injection depth for Oklahoma SWD wells is 3400 ft (~1 km) (range: 1000–8000 ft [0.3–2.4 km], 5th–95th percentile). Between ~60% and 90% of SWD wells with injection intervals within 800 ft (~240 m) of the basement are associated with earthquakes, which is statistically significant (Fig. 5c). This result also contrasts with the previous findings at the U.S. mid-continent scale that did not find a statistically significant relationship between proximity of SWD injection interval to basement and seismicity (Weingarten *et al.*, 2015). The previous analysis utilized a basement map that contained much larger uncertainties in basement depth (±15% in depth to



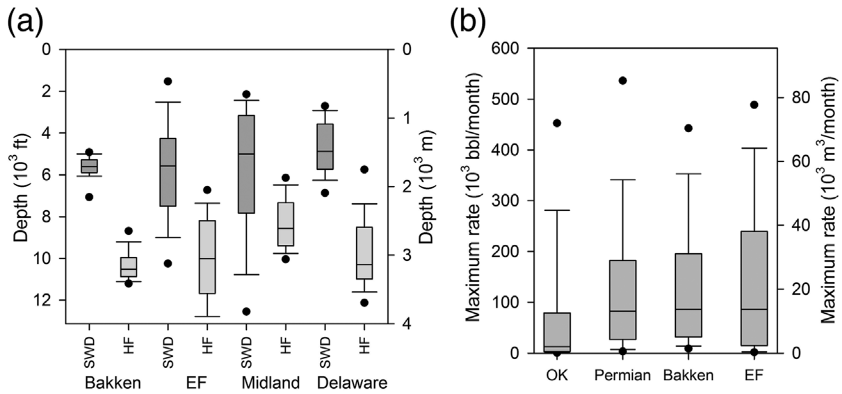
▲ **Figure 5.** Assessment of linkages between SWD and seismicity in Oklahoma and Permian basin. Output includes histogram of (a,d) maximum monthly injection rate in SWD wells in Oklahoma and the Permian basin. The bars show the number of wells operating at a given maximum monthly injection rate for all SWD wells and SWD wells spatiotemporally associated with an earthquake. (b,e) Histogram showing cumulative injected volume at all wells in the same states as those in (a). The percentage of all wells that are associated 29
with an earthquake in each histogram bin is plotted as a function of (a,d) maximum monthly injection rate and (b,e) cumulative injected volume. Dashed lines represent the 5% and 95% confidence bounds in each bin from 10,000 bootstrap resamples assuming rate of
30 association are random. The color version of this figure is available only in the electronic edition.

basement) than the present study, thus no statistically significant relationship was found when taking this uncertainty into
14 account (Mooney and Kaban, 2010).

Bakken, Eagle Ford, and Permian Basin Plays

The number of earthquakes M ≥ 3.0 in the Bakken (2), Eagle Ford (12), and Permian basin (53) is much less than that in the Oklahoma AOI (2642) (2009–2017; Fig. 1; Ⓔ Table S1). The percentage of SWD wells potentially associated with earthquakes is also much lower in those plays (5% in the Bakken; 9%, Permian; 20%, Eagle Ford) relative to Oklahoma (56%) (Fig. 5a,d and Ⓔ Fig. S5a,d). There is no regional-scale, statistically significant linkage between seismicity and PW injection rates, cumulative injection volumes, or proximity to basement in these plays because all of the data plot within the confidence bounds of random association (Fig. 5d–f and Ⓔ Fig. S5).

The biggest difference between PW management in the other plays relative to Oklahoma is proximity to basement, with much shallower injection in the Bakken, Eagle Ford, and Permian basin SWD wells relative to crystalline basement depths than the predominantly deep disposal in Oklahoma (Fig. 5c,f, and Ⓔ Fig. S5c; Table 1). In the Permian basin, most of the increase in SWD between 2009 and 2016 occurred in the shallow zone above oil-producing intervals (factor of 4.3 increase in volume) relative to the deep zone below oil-producing intervals (factor of 2.0 increase) (Fig. 4). PW injection in the Midland and Delaware basins within the Permian basin is mostly shallower than the oil-producing intervals, as shown by the contrast in SWD well depths (median



▲ **Figure 6.** (a) Depths of PW injection using SWD wells in the Bakken and Eagle Ford plays and in the Midland and Delaware basins within the Permian basin relative to the oil-producing zones. (b) Comparison of maximum monthly injection rate distributions for SWD wells completed in the different plays. Median (solid) and mean (dashed line) are shown along with 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers), and 5th and 95th percentiles (points). (a) Injection of PW in Bakken SWD wells is in the Dakota formation (median depth 5600 ft) relative to oil production from the Bakken Petroleum System (Bakken and underlying Three Forks, median depth of HF wells, 10,500 ft). Wastewater injection in Eagle Ford SWD wells is primarily in multiple shallower formations (median depth, 5600 ft) relative to oil production from the Eagle Ford (median depth of HF wells, 10,000 ft). Injection of PW in Midland basin SWD wells is primarily in the San Andres formation (median depth, 5000 ft) relative to oil production from the Wolfcamp, as reflected in HF well depths (median depth of HF wells, 8600 ft). Injection of PW in Delaware basin SWD wells is primarily in the Delaware Mountain Group (median depth, 4900 ft) relative to oil production from the Wolfcamp (median depth of HF wells, 10,300 ft). The appearance of overlap between Eagle Ford SWD and HF distributions results from the dip and increased formation depths toward the southeast of the Eagle Ford play geology. Median (solid) and mean (dashed line) are shown along with 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers), and 5th and 95th percentiles (points). The data are provided in Ⓔ Table S11. The color version of this figure is available only in the electronic edition.

~5000 ft [1.5 km] for both basins) relative to HF well depths (corresponding to the oil reservoir, 8600–10,300 ft [2.6–3.1 km]; Fig. 6a). The percentage of SWD wells associated with earthquakes in the Permian basin is slightly elevated in the shallow zone (~1500 ft [4.6 km] from basement; Fig. 5f), consistent with the large increase in injection through SWD wells into this zone. Disposal of PW in the Bakken and Eagle Ford plays is also much shallower than the oil-producing intervals (median SWD well depths ~5600 ft [1.7 km] for both plays relative to HF well depths, oil reservoir, ~10, 000 ft [3 km] in both plays) (Table 1; Fig. 6a). These reservoirs are also much shallower than the crystalline basement (Ⓔ Fig. S5).

Maximum monthly injection rates alone cannot explain the differences in seismicity among the plays (Fig. 6b). Although Oklahoma has similar numbers of wells injecting at high rates to the other plays (Oklahoma = 85%–100% at 95th percentile), Oklahoma has many more wells injecting at lower rates, as evidenced by the median maximum monthly injection rate being ~15% of the median maximum rates in the other plays. Lower seismicity in the other plays relative to Oklahoma may be partially attributed to the lower regional-scale cumulative PW injection volumes in the Permian and much lower volumes in the Bakken and Eagle Ford plays relative to volumes in Oklahoma (2009–2016, Fig. 3).

In summary, the much lower levels of seismicity in the other plays relative to Oklahoma may be related to shallower disposal far from basement and to lower regional-scale cumulative injection volumes.

Managing Produced Water to Reduce Induced Seismicity

Large volumes of PW in many plays indicate that managing PW is a critical issue. We can learn from the experiences in Oklahoma related to mitigating seismicity, and we can explore various options for reducing future seismicity in different plays.

Table 1
Comparison between Horizontal Hydraulic Fracturing (HF) Well Depths, Saltwater Disposal (SWD) Well Depths, and Crystalline Basement Rock Depths at the SWD Well Locations in the Different Plays

Value (ft)	Statistic	Bakken	Eagle Ford	Permian: Delaware	Permian: Midland	Oklahoma
HF well depth	Range	8,500–11,500	6,500–13,000	6,000–12,000	6,000–10,000	4000–8000
	Median	10,500	10,000	10,000	8,500	5400
SWD well depth	Range	5,000–7,000	1,500–10,000	2,500–8,500	2,000–13,000	1500–9000
	Median	5,600	5,600	5,300	4,600	6400
Basement depth	Range	12,400–15,200		14,000–21,000	8,200–13,600	4000–9800
	Median	14,300		20,000	11,300	6000

Mitigating Induced Seismicity in Oklahoma

The OCC, the regulatory body responsible for permitting disposal wells, took direct action to mitigate induced seismicity in Oklahoma in early 2016. The OCC issued the following directives related to PW management to reduce seismicity in the AOI where intense earthquakes were recorded in central/
15 north-central Oklahoma (see Data and Resources):

1. reduction in maximum PW injection (SWD disposal) rate at the well level to $\leq 10{,}000$–$15{,}000$ bbl/day per well;
2. reduction in regional-scale injection by 40% from the 2014 total injection; and
3. application of directives to wells completed in the Arbuckle Group adjacent to the basement, impacting ~700 Arbuckle wells.

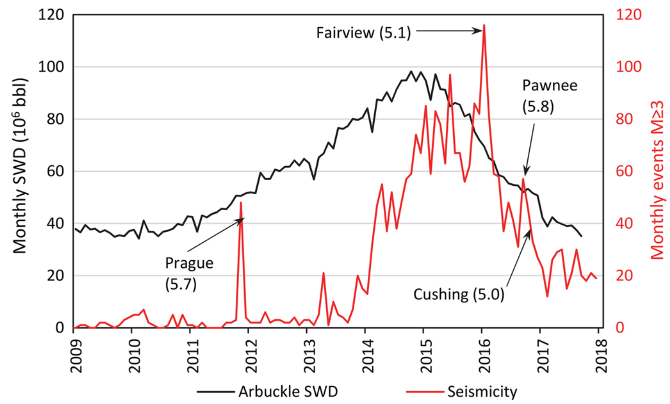
In addition, the OCC (2014–present) requested that operators plug back SWD wells completed in the basement. These directives are consistent with the findings from this analysis related to the importance of PW injection rate with large increases in seismicity rates at rates $\geq 10{,}000$ bbl/day (300,000 bbl/mo; Fig. 5a), cumulative injection volume
16 (Fig. 5b), and proximity to basement (Fig. 5c). These directives consider both local (well level) and regional (AOI) impacts of injection on seismicity. Changes in SWD disposal were phased over several months to avoid rapid pressure changes and potential additional earthquakes (Segall and Lu, 2015).

Seismicity has markedly decreased in response to the reduction in PW injection in SWD wells. The annual number of earthquakes $M \geq 3$ decreased by 67% from the peak in 2015 (901 earthquakes) to 2017 (298 earthquakes) in the AOI (Fig. 7; Ⓔ Table S1). The peak month was in June 2015 with 104 earthquakes $M \geq 3$. The marked decline in seismicity is consistent with the forecasted seismicity rate from decreased stresses computed using a rate-and-state modeling approach that was originally developed for natural seismicity (Norbeck and Rubinstein, 2018).

Reducing Potential Future Induced Seismicity

A variety of approaches can be used to reduce potential induced seismicity associated with PW in the future. Historical data from plays in the United States suggest that shallow disposal may help reduce seismicity; however, the trade-offs between shallow versus deep disposal should be considered. Reducing subsurface disposal by managing PW in different ways should also reduce potential induced seismicity.

Shallow versus Deep Disposal. The strong linkage between induced seismicity and PW injection into the Arbuckle Group adjacent to the basement in Oklahoma suggests that injecting into shallower zones that are hydraulically isolated from the crystalline basement faults should reduce the likelihood of seismicity. About 60% of PW in Oklahoma is injected into the Arbuckle Group with the remaining ~40% into shallower intervals. However, the Arbuckle Group is up to 2000 ft (600 m) thick, subdivided into three main zones: high-permeability upper Arbuckle (27% of thickness), low-permeability middle Arbuckle (41% of thickness), and high-permeability lower



▲ **Figure 7.** Comparison between monthly SWD rates and the monthly number of seismic events with $M \geq 3.0$ in the Oklahoma area of interest. The timings of seismic events with $M \geq 5.0$ are indicated. The color version of this figure is available only in the electronic edition.

Arbuckle (32% of thickness) (Carrell, 2014; Morgan and 17
Murray, 2015). We cannot dispose into low-permeability zones 18
because of low injectivity; however, disposing into shallower intervals in the Arbuckle Group might reduce seismicity if they are hydraulically disconnected from the basement.

PW injection in the Bakken, Eagle Ford, and Permian basin has been primarily into zones stratigraphically far from basement, mostly above the oil-producing intervals (Figs. 4 and 5f, Ⓔ Fig. S5c; Table 1). While stratigraphically far from basement, earthquakes can occur in shallow intervals because hypocenters for some earthquakes in the Permian Basin are located in the sediments rather than in the basement, even considering the general ±2 km uncertainty in hypocentral depths in this region (see Data and Resources; Savaidis, personal comm., 19
2018).

The trade-offs between shallow versus deep PW injection need to be considered (Table 2). Shallow disposal has been favored in many plays because of low cost, whereas deep disposal wells, extending below oil reservoirs, may cost 2–3 times more. Disposal of PW into shallow intervals has a higher likelihood of impacting overlying aquifers. Overpressuring caused by disposal can result in upward migration of PW through faults or fractures or through abandoned oil wells that have not been properly plugged. There are over half a million oil wells drilled in the Permian basin within the past century, with many abandoned or orphaned wells that could provide pathways for overpressured fluids, that is, pressures exceeding hydrostatic pressure. Airborne electromagnetic surveys have been used to link salinity to leaking wells in west Texas (Paine *et al.*, 1999). Potential contamination is exacerbated in the Permian basin because of thick halite and anhydrite deposits (up to 4000 ft [1200 m] thick, Castile, Salado, and Rustler formations) that can result in highly saline fluids corroding well casings. Surface subsidence can also result from dissolution of these salts (Paine *et al.*, 2012). Aquifer impacts from PW injection in the Bakken play are likely lower because the primary disposal reservoir,

Table 2
Trade-Offs between Shallow versus Deep SWD

Shallow Disposal	Deep Disposal
Low cost	High cost
Could impact overlying aquifer	Little or no impact on aquifers
Impact oil well drilling (overpressuring, extra casing)	Little or no direct impact on oil well drilling
Can impact oil production	Little direct impact on oil production
Less seismicity	More seismicity
	31 Underpressuring, high injectivity
Inexpensive, drill many wells	Expensive, few wells, high rates

the Dakota formation (~5600 ft [1.7 km] deep), is much deeper than the Fox Creek confined aquifer or the shallow alluvial aquifers in this region (Scanlon *et al.*, 2016; Table 1). Rising interest in deep, brackish, groundwater resources in Texas increases concerns about shallow SWD, with zones containing SWD wells excluded from consideration (Young *et al.*, 2016).

Shallow disposal of PW can also affect oil production because wells have to penetrate disposal intervals. Shallow disposal in the Permian basin created health and safety concerns related to drilling through overpressured zones, requiring additional casing in some regions (see the Ⓔ Shallow versus Deep Disposal section).

20 Although disposal into deep intervals adjacent to basement has been linked to seismicity in Oklahoma, there are some advantages to disposing into these deep units (Table 2). Deep disposal should not impact oil production directly because the units are generally below the oil-producing intervals. Potential impacts on overlying aquifers should be greatly reduced because of the depth of these units. The Arbuckle in Oklahoma and corresponding Ellenburger in the Permian basin are both underpressured, that is, pressures less than hydrostatic pressure (Nelson *et al.*, 2015). Therefore, injection into these units can largely be conducted under gravity without pumping water into the subsurface. Both units are potentially karstified, as seen in surface exposures of the Arbuckle Group in the Arbuckle Mountains of south-central Oklahoma; however, the extent of fracturing, secondary porosity, and karstification is unknown because of the depths of the rock below the land surface and limited geologic characterization of the disposal zone.

Reusing Produced Water for Hydraulic Fracturing. An alternative approach to managing the net fluid balance is to reuse PW to hydraulically fracture new producing wells. PW reuse would accomplish a number of goals, including reducing PW disposal and also reducing water demand for HF from other water sources. The potential for this approach to work depends in part on the ability to match PW supplies with HF water demand both spatially and temporally. Comparison of cumulative water volumes (2009–2016) indicates that PW supplies, estimated from SWD volumes, are about nine times HF water demand in Oklahoma (Fig. 3); therefore, even if all of the HF water was sourced with PW reuse, 90% of the PW would still need to be managed. There is also a spatial disconnect because PW supplies in north-central Oklahoma (e.g., Woods and Alfalfa counties) are not collocated with the large HF water demands in central Oklahoma (e.g., Blaine County in the STACK [Sooner Trend Anadarko Canadian Kingfisher] play). Despite these issues, a current study is investigating the potential for developing a pipeline system to transfer minimally treated PW, referred to as a clean brine (~220,000 mg/L TDS) from Alfalfa County in the north to the HF demand 21
center in Blaine County, ~35 miles (56 km) to the south (Dunkel, 2017). Too little PW relative to HF water demand can also be an issue. For example, historical PW in the Eagle Ford represents ~50% of HF water demand (Figs. 1 and 3). Previous efforts to reuse PW in this play encountered logistical issues with trying to capture sufficient PW to support HF. PW supply versus HF water demand issues would need to be resolved at a much more granular spatial and temporal scale than at the play level to assess feasibility of reuse.

Cumulative PW volumes match HF water demands better in the Bakken and Permian basin plays (Fig. 3). Although the quality of some of the PW in the Bakken is extremely saline, greater than 10 times that of seawater, studies suggest that advances in HF fluid chemistry can accommodate such saline water with minimal treatment (McMahon *et al.*, 2015). The ratio of cumulative PW from unconventional wells to HF water demand in the Permian is ~2.0 (2009–2016; Fig. 3). PW (12-month cumulative) to HF ratios are ~3 times higher in the Delaware basin than in the Midland basin (2015; Scanlon *et al.*, 2017). Therefore, even if all the HF water was sourced from PW in the Delaware basin, there would still be a large excess of PW to manage. Additional approaches will need to be considered to manage this PW such as treatment for use in other sectors (e.g., irrigation or municipal use) or evaporation ponds.

DISCUSSION

This study focuses on quantifying the net fluid balance in the major tight-oil plays and dewatering reservoirs in the United States because of the impacts on subsurface pressures and potential induced seismicity. The data from conventional reservoirs provide context for more recent unconventional reservoir development. The emphasis on conventional oil development and subsequent reinjection of PW into producing intervals throughout the latter half of the twentieth century can explain the relatively low levels of seismicity associated with this development. This net fluid balance is achieved by matching oil and PW extraction with injection using EORI and SWD wells into oil-producing intervals. Pressure maintenance and EOR are key goals for conventional reservoir operations.

The updated analysis of linkages between PW injection and induced seismicity for Oklahoma shows that not only PW injection rate but also cumulative injection volume and proximity to crystalline basement all contribute to induced seismicity in this region. Statistically significant associations between active Oklahoma SWD wells and nearby earthquakes (within 15 km) were found for maximum injection rates exceeding ~300, 000 bbl/mo, cumulative disposal volumes $\sim \geq 1$ million bbl/well, and in wells operating within ~1000 ft [300 m] of crystalline basement. Seismicity in the Bakken, Eagle Ford, and Permian basin plays is much less than that in Oklahoma but has been increasing in the Delaware basin within the Permian basin. At present, relationships between SWD well operations and seismicity in the Bakken, Eagle Ford, and Permian basin plays fell within the bounds for statistically random association. However, these relationships can change through time. Much lower seismicity in the other plays may be attributed to much shallower injection stratigraphically far from the basement and lower cumulative PW injection volumes through SWD wells (10%–60% of volumes in Oklahoma, 2009–2016; Figs. 1 and 3; Table 1).

Our original goal was to determine what lessons we could learn from injection and seismicity in Oklahoma and how we might apply those lessons to the other plays to reduce the potential for induced seismicity. The obvious lesson from the Oklahoma data is that induced seismicity can be mitigated by reducing injection rates and regional injection volumes in wells operating near the basement. Injection into shallow zones far from the basement is a potential mitigation strategy. However, this has been occurring in the other plays with some drawbacks. Some of the negative factors include impacts on oil-well drilling and production complications from shallow zone overpressuring and the potential to affect overlying aquifers. Reducing injection rates has had a positive effect on managing induced seismicity in Oklahoma, but it is important to note that there is a time lag in seismicity response to reductions in injection, with some of the largest-magnitude earthquakes occurring in 2016 after the reduction in PW injection (Fig. 7).

Maintaining a balance between extraction and injection in unconventional reservoirs can be partially achieved by reusing PW for HF in these reservoirs. This approach may be most effective where the PW volumes generally match HF water demands. The large mismatch in Oklahoma, with a factor of 9:1 ratio between SWD and HF, limits the value of PW reuse in this region (Fig. 3). However, the volumes are more closely matched in the Bakken play and the Midland basin within the Permian basin, suggesting greater potential in these regions. However, the trade-offs associated with potentially increased risks of contamination during storage and transport of PW (e.g., TDS in the 100,000–200,000 mg/L range in the Permian basin and 250,000–500,000 range in the Bakken play; Scanlon *et al.*, 2016) need to be considered.

Implications for Regulators and Policy Makers

Although the EPA has authority over the Underground Injection Control (UIC) program (SWD and EORI wells) under the Safe Drinking Water Act, the authority has been delegated 22
to the states in most cases. The state agencies grant permits for SWD and EORI wells. A number of reports have been developed to provide guidance to UIC regulators for evaluating, managing, and minimizing injection-induced seismicity (U.S. EIA, 2014; GWPC, 2017).

The directives issued by the OCC in early 2016 are consistent with the findings from this analysis in terms of injection rates, regional cumulative injection volumes, and proximity to basement. Although permits are generally granted for individual SWD wells, the importance of net fluid budgets at local to regional scales suggests that the regulators should consider individual well permits within a larger context of the net fluid balance, as is done in Oklahoma. No new SWD permits are being granted in Oklahoma for wells in the Arbuckle Group adjacent to the basement. In addition, permits for shallow (Delaware Mountain Group) or deep (Ellenburger Group) disposal in New Mexico are restricted to individual operators, rather than for commercial wells, to reduce potential seismicity. Although EORI wells in conventional reservoirs are managed as a system, groups of SWD wells in unconventional reservoirs may benefit from larger scale management, similar to current practices in Oklahoma.

CONCLUSIONS

The rapid increase in unconventional oil production is associated with an increase in coproduced water that cannot be reinjected into the low-permeability tight-oil reservoirs. This PW is managed primarily by subsurface injection into nonproducing geologic intervals through SWD wells. Reanalysis of Oklahoma data with an additional 3.5 yrs of data and a newly developed basement map (Crain *et al.*, 2018) reveals that induced seismicity is not only linked to PW injection rates but is also related to cumulative injection volume and proximity to basement. Quantifying the water budgets of the main tight-oil plays in the United States indicates that the major difference between Oklahoma, with intensive induced seismicity, and the other plays (Bakken, Eagle Ford, and Permian basin) is disposal depths, with shallow disposal above oil-producing reservoirs in most plays relative to deep disposal near the basement in Oklahoma. There are problems with shallow disposal also, including overpressuring affecting oil well drilling and potential contamination of overlying aquifers, particularly in the Permian basin. A variety of management strategies will need to be considered, including reuse of PW, to support increasing demand for HF as an alternative approach to subsurface disposal. This analysis provides a comprehensive assessment of PW issues related to tight-oil production that can be used to guide future seismic monitoring and feed into regulatory and decision-making processes.

DATA AND RESOURCES

Data on oil, gas, and water production were compiled from the IHS Enerdeq database for the Bakken, Eagle Ford, Permian basin, and Oklahoma. The IHS data are ultimately derived from data reported by operators to the various states and can be accessed from the state websites on a well by well basis. Water volumes used for hydraulic fracturing (HF) were also obtained from the IHS Enerdeq database, as well as well-completion data, including well depth and the length of horizontals. IHS increasingly obtains data on HF water volumes from the publicly accessible FracFocus database
23 (https://fracfocus.org) operated by the Groundwater Protection Council. Data on produced water (PW) management, including saltwater disposal (SWD) and enhanced oil recovery injection (EORI) volumes, were compiled from the IHS database. Well types (SWD vs. EORI) were determined from the Texas Railroad Commission Underground Injection Control (UIC) database, the New Mexico Oil Conservation Division, the North Dakota Industrial Commission, and the Montana UIC database. Data on earthquakes were obtained from the U.S. Geological Survey (USGS) Advanced National Seismic System (ANSS) Comprehensive Catalog (ComCat, https://earthquake.usgs.gov/earthquakes/search/). The stratigraphy in the Permian basin is based on analysis of formation tops derived from Geologic Data Systems (GDS) logs by the Bureau of Economic Geology. The depth to basement surface map was estimated from the same source based on 3075 data points using ordinary Kriging methods in ArcGIS. The depth to the basement in Oklahoma is based on the map provided in Crain and Chang (2018). Data on depth to basement in the North Dakota area of the Bakken play was provided by the North Dakota Industrial Commission (NDIC) for about 70 wells. In the Montana area of the Bakken play, basement depth was estimated using a contour map published by the Montana Bureau of Mines and Geology (Bergantino and Clark, 1985). There are no data on basement depths in the Eagle Ford play; however, basement is extremely deep in this region. The other relevant data can be found at www.occeweb.com (Hot Topics) and http://www.beg.utexas.edu/texnet.

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REFERENCES

Barbour, A. J., J. H. Norbeck, and J. L. Rubinstein (2017). The effects of varying injection rates in Osage County, Oklahoma, on the 2016 M_w 5.8 Pawnee earthquake, *Seismol. Res. Lett.* **88,** 1040–1053.

Bergantino, R. N., and M. Clark (1985). *Structure Contour Map on Top of Precambrian Crystalline Rocks*, Montana Bureau of Mines and Geology, MBMG, 158 pp. 24

Clark, C., and J. Veil (2009). Produced water volumes and management practices in the United States, *Rep. ANL/EVS/R-09/1*, Argonne Natl. Lab., Argonne, Illinois.

Crain, K. D., and J. C. Chang (2018). Elevation map of the top of the crystalline basement in Oklahoma and surrounding states, *Oklahoma Geol. Surv. Open-File Rept. OF1-2018*, 5 pp.

Davies, R., G. Foulger, A. Bindley, and P. Styles (2013). Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons, *Mar. Petrol. Geol.* **45,** 171–185.

Dieter, C. A., M. A. Maupin, R. R. Caldwell, M. A. Harris, T. I. Ivahnenko, J. K. Lovelace, N. L. Barber, and K. S. Linsey (2018). Estimated use of water in the United States in 2015, *U.S. Geological Survey Circular 1441*, 65 pp.

Drillinginfo (2012). Unconventional meets conventional—The Mississippi Lime, available at https://info.drillinginfo.com/unconventional-meets-conventional-the-mississippi-lime/. 25

Dunkel, M. (2017). Oklahoma water for 2060: Produced water reuse and recycling, *Report of the Oklahoma Produced Water Working Group*.

Frohlich, C., J. I. Walter, H. DeShon, B. Stump, C. Hayward, and M. Hornbach (2016). A historical review of induced earthquakes in Texas, *Seismol. Res. Lett.* **87,** 1022–1038.

Goebel, T. H. W., J. I. Walter, K. Murray, and E. E. Brodsky (2017). Comment on "How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?" by C. Langenbruch and M. D. Zoback, *Sci. Adv.* **3,** no. 8, e1700441.

Ground Water Protection Council (GWPC) (2017). *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*, Second Ed., Ground Water Protection Council and Interstate Oil and Gas Compact Commission, 181 pp.

Hincks, T., W. Aspinall, R. Cooke, and T. Gernon (2018). Oklahoma's induced seismicity strongly linked to wastewater injection depth, *Science* **359,** 1251–1255.

Kroll, K. A., E. S. Cochran, and K. E. Murray (2017). Poroelastic properties of the Arbuckle Group in Oklahoma derived from well fluid level response to the 3 September 2016 M_w 5.8 Pawnee and 7 November 2016 M_w 5.0 Cushing earthquakes, *Seismol. Res. Lett.* **88,** no. 4, 963–970.

Langenbruch, C., and M. D. Zoback (2016). How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?, *Sci. Adv.* **2,** no. 11, e1601542.

McMahon, B., B. Mackay, and A. Mirakyan (2015). First 100% reuse of Bakken produced water in hybrid treatments using inexpensive polysaccharide gelling agents, *SPE International Symposium on Oilfield Chemistry*, The Woodlands, Texas, 13–15 April, Society of Petroleum Engineers, SPE-173783-MS, Society of Petroleum Engineers, doi: 10.2118/173783-MS.

Murray, K. E. (2013). State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, U.S., *Environ. Sci. Technol.* **47,** 4918–4925.

Murray, K. E. (2015). Class II saltwater disposal for 2009–2014 at the annual-, state-, and county-scales by geologic zones of completion, Oklahoma, *Oklahoma Geol. Surv. Open-File Rept. OF5-2015*, Norman, Oklahoma, 18 pp.

National Research Council (NRC) (2013). *Induced Seismicity Potential in Energy Technologies*, National Research Council, Washington, D.C., 248 pp., doi: 10.17226/13355.

Nelson, P. H., N. J. Gianoutsos, and R. M. Drake (2015). Underpressure in Mesozoic and Paleozoic rock units in the Midcontinent of the United States, *AAPG Bulletin* **99,** 1861–1892.

Norbeck, J. H., and J. L. Rubinstein (2018). Hydromechanical earthquake nucleation model forecasts onset, peak, and falling rates of induced seismicity in Oklahoma and Kansas, *Geophys. Res. Lett.* **45,** doi: 10.1002/2017GL076562.

26 Oklahoma Corporation Commission (OCC) (2017). Managing risk, OGS, OCC, industry collaboration bears fruit, 27 June 2017 News, available at %http://www.occeweb.com/News/2017/06-27b-17Seismicity-well%20completion.pdf.

Paine, J. G., S. M. Buckley, E. W. Collins, and C. R. Wilson (2012). Assessing collapse risk in evaporite sinkhole-prone areas using microgravimetry and radar interferometry, *J. Environ. Eng. Geophys.* **17,** 75–87.

Paine, J. G., A. R. Dutton, and D. A. Blum (1999). Using airborne geophysics to identify salinization in west Texas, *Univ. Texas at Austin, Rept. Inv. No. 257*, Bureau of Economic Geology, 69 pp.

Petersen, M. D., C. S. Mueller, M. P. Moschetti, S. M. Hoover, A. M. Shumway, D. E. McNamara, R. A. Williams, A. L. Llenos, W. L. Wllsworth, A. J. Michael, *et al.* (2017). 2017 One-year seismic-hazard forecast for the central and eastern United States from induced and natural earthquakes, *Seismol. Res. Lett.* **88,** 772–783.

Rubinstein, J. L., and A. B. Mahani (2015). Myths and facts on wastewater injection, hydraulic fracturing, enhanced oil recovery, and induced seismicity, *Seismol. Res. Lett.* **86,** 1060–1067.

Scanlon, B. R., R. C. Reedy, F. Male, and M. Hove (2016). Managing the increasing water footprint of hydraulic fracturing in the Bakken play, United States, *Environ. Sci. Technol.* **50,** 10,273–10,281.

Scanlon, B. R., R. C. Reedy, F. Male, and M. Walsh (2017). Water issues related to transitioning from conventional to unconventional oil production in the Permian basin, *Environ. Sci. Technol.* **51,** 10,903–10,912.

Schenk, C. J., and R. M. Pollastro (2002). Natural gas production in the United States: National assessment of oil and gas series, *U.S. Geological Survey Fact Sheet FS-0113-01*, 2 pp.

Segall, P., and S. Lu (2015). Injection-induced seismicity: Poroelastic and earthquake nucleation effects, *J. Geophys. Res.* **120,** 5082–5103.

U.S. Energy Information Administration (EIA) (2014). *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, Underground Injection Control National Technical Workgroup, U.S. Environmental Protection Agency, Washington, D.C., Revised November 2014.

U.S. Energy Information Administration (EIA) (2018a). *How Much Shale (Tight) Oil Is Produced in the United States?*, Energy Information Administration, Frequently Asked Questions, available at https://www.eia.gov/tools/faqs/faq.php?id=847&t=6 (last accessed January 2018).

27 U.S. Energy Information Administration (EIA) (2018b). *Crude Oil Pro-*
28 *duction*, Energy Information Administration, available at https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm; https://www.eia.gov/naturalgas/data.php#production.

U.S. Energy Information Administration (EIA) (2018c). *Natural Gas*, Energy Information Administration, available at https://www.eia.gov/naturalgas/data.php#production.

Van der Baan, M., and F. J. Calixto (2017). Human-induced seismicity and large-scale hydrocarbon production in the USA and Canada, *Geochem. Geophys. Geosys.* **18,** 2467–2485.

Veil, J. (2015). U.S. produced water volumes and management practices in 2012, *Report Prepared for the Groundwater Protection Council*, April 2015.

Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, and J. L. Rubinstein (2015). High-rate injection is associated with the increase in US mid-continent seismicity, *Science* **348,** 1336–1340.

Young, S. C., M. Jigmond, N. Deeds, J. Blaine, T. E. Ewing, and D. A. Banerji (2016). *Final Report: Identification of Potential Brackish Groundwater Production Areas—Gulf Coast Aquifer System Prepared by INTERA Inc. for TWDB (Contract No. 1600011947)*, 636 pp.

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