Energy Policy 121 (2018) 365–373

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Oklahoma earthquakes and the price of oil☆

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ARTICLE INFO

JEL classification:
H71
L51
L71
Q35
Q51

Keywords:
Earthquakes
Hydraulic fracturing
Oil and gas extraction
Regulation

ABSTRACT

The process of hydraulic fracturing has unlocked an unprecedented amount of oil and gas in the United States. Hydrocarbons are not the only output from this process, though, as billions of barrels of "produced" water are extracted and subsequently pumped back underground. This process of injecting produced water into disposal wells has been causally linked to the rise in earthquakes. Here I show how the amount of earthquakes in Oklahoma are positively linked to the price of oil, and further find that the decrease in earthquake activity in Oklahoma is due to both the drop in oil prices and the regulatory directives of regional authorities. The estimated impact of the various shut-in policies have been small compared to the reduction in earthquakes due to the broad price decline, though. I find that the drop in oil prices that began in mid-2014 led to as large of a reduction in earthquakes as the combined effect f new policies that started in March of 2015.

1. Introduction

The surge in oil and gas supply due to hydraulic fracturing or 'fracking' has transformed markets and industries with wide ranging effects impacting coal burning facilities' retirement dates and the follow-through on nuclear power plant additions. Interestingly enough, though, oil and gas are not the primary outputs of this type of production – water is. At the nascent stages of modern unconventional extraction, circa 2007, onshore oil and gas wells contributed as much as 17.82 billion barrels of 'produced water' (Clark and Veil, 2009). This water is later separated from the oil and gas and re-injected into disposal wells that are often at greater depth than the water originated.[1] Alongside the surge in U.S. oil and gas supply, and the disposal of produced water, there has been a staggering increase in the amount of earthquakes felt in areas where waste-water injection is taking place (Ellsworth et al., 2015). Although wastewater-induced earthquakes have been felt in other areas,[2] the state of Oklahoma has witnessed a striking increase in earthquake activity. Figure one shows just how unprecedented the change in earthquake activity has been. In the top panel all earthquakes from January 1 2000 through the end of 2009 are plotted; in the bottom panel the amount of earthquakes witnessed through 2016 are shown. Clearly, there has been a distinct increase over these seven years. In this paper I discuss the economic drivers of induced seismicity and further explore how effective regional authorities have been in reducing the amount of included earthquakes.

Seismicity in Oklahoma serves as a very unique case because the current earthquake rate is 300 times higher than the historical rate (Weingarten, 2015). In fact, the seismicity rate in Oklahoma has increased so drastically that it is now more common to have a magnitude 3.0 or larger earthquake in a single day than in entire years prior to 2008. Specifically, Weingarten (2015) shows that the rate of magnitude 3.0+ earthquakes was $1\frac{1}{2}$ *per year* prior to 2008, and $2\frac{1}{2}$ magnitude 3.0 + earthquakes *per day* after 2008. Linking now to the amount of produced water, the advent of hydraulic fracturing has significantly increased the amount of disposal because the targeted formations often have a large amount of 'associated' water that is high in salinity and is brought to the surface as a bi-product. For example, Nicot et al. (2014) find that there was a five fold increase in produced water disposal in the Barnett shale between 2000 and 2011 – from 8.8 thousand acre feet per year to 45.7 thousand acre feet per year. In Oklahoma, approximately 849 million barrels[3] of produced water per month were injected into disposal wells at the beginning of the fracking boom. By 2014 this amount had grown to 1.54 billion barrels per month. For comparison, produced water in the state of Texas increased from 33.8 million barrels

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☆ This research was supported through funding from the NSF Oklahoma EPSCoR ROA+ program.

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[1] Hydraulic fracturing is a water-intensive practice, however wastewater from the production process is a small percentage of the total amount of water that is ultimately injected into disposal wells.

[2] As shown in Hornbach et al. (2015) and Llenos and Michael (2013).

[3] A barrel is 42 U.S. gallons.

https://doi.org/10.1016/j.enpol.2018.05.040
Received 6 November 2017; Received in revised form 13 May 2018; Accepted 15 May 2018
0301-4215/ Published by Elsevier Ltd.

per month in 2007–81.1 million barrels per month in 2014 (Kuchment and Kuchment ()). For context, this means that nearly 19 times more produced water was injected within Oklahoma than Texas; even though Texas has more than three times the land area.

In this article, I use the sudden and dramatic increase in seismic activity witnessed in Oklahoma and determine how this rise in earthquakes is related to the economic viability of oil production while controlling for aftershock effects and policy efforts. I do this by considering time-series data on daily earthquake counts from January 2009 to July 2016. This date range includes a time period before earthquakes were common in Oklahoma, and this sample period includes a large amount of price variation - the wholesale price of oil, the West Texas Intermediate (WTI) price, ranged from $26 to $145 per barrel. I am also able to use state policy interventions to identify the effect of price changes on earthquake activity and, further, determine whether or not these policy interventions are responsible for the recent decline in earthquake activity. While earthquake activity drastically increased after 2009, local policymakers were slow to act and the first directive intended to reduce wastewater disposal occurred in March of 2015. Thus, there is a clear pre-policy era in which no policy or disposal directive had been passed, and a clear post-policy era in which multiple well shut-ins and disposal limits were set. Across many model specifications I find that a 10% decrease in the wholesale price of oil leads to a more than 3.4% decrease in earthquakes per day. Further, I find that there has been a statistically discernible decrease in daily earthquakes in the era of policy measures. Specifically, I find that the policy-era is associated with 2.7 fewer earthquakes per day Fig. 1.

1.1. Background

Induced seismicity is by no means new. Beginning as early as 1894 there are accounts of induced seismicity in Johannesburg due to gold mining operations (McGarr, 2002). There are also historical accounts of people close to the oil and gas industry applying for earthquake insurance curiously prior to earthquakes occurring (Hough and Page, 2016). Since then, rigorous methods have been applied to linking fluid injection and the rise in earthquakes, and there is broad scientific consensus that swarms of induced earthquakes are due to injection activities as measured by pumping volumes and rates (McGarr et al., 2015; Ellsworth, 2013; Weingarten et al., 2015; among others). Specific to the earthquakes in Oklahoma, Keranen et al. (2013) show that the surge in earthquake activity is due to wastewater injection. Llenos and Michael (2013) and McNamara et al. (2015) provide even further evidence linking injection wells to induced seismicity in Oklahoma. The distinction between naturally occurring and induced earthquakes is also well researched. Studies have shown that the maximum magnitude of induced earthquakes may be smaller than what is seen with natural earthquakes, but they also suggest that induced earthquakes can trigger larger earthquakes on known or unknown faults (McGarr, 2014; Petersen et al., 2016). Additionally, induced earthquakes tend to occur in swarms (many happening in the same area in quick succession) and they tend to happen at shallower depths than natural earthquakes (Gomberg and Wolf, 1999; van der Elst et al., 2016). While the causal link between wastewater disposal and earthquakes is established, the exact mechanism and dynamics are still under debate. For example, we do not know with certainty how much time it takes for disposal to trigger an earthquake, nor do we know with certainty the distance between where wastewater disposal occurs and where a triggered event could occur. New research by Peterie et al. (2018) shows that earthquakes could be triggered up to 90 kilometers away - more than 10 times further than prior research suggested. Terry-Cobo (2018) shows that researchers in the geology field have called this result into question, though. While there has clearly been a flurry of research associated with induced seismicity given the recent phenomena of earthquakes in traditionally non-seismic areas, the fact that injection can cause earthquakes has actually been established within the scientific literature for nearly 50 years. Healy et al. (1968) showed how high pressure injection caused earthquakes to occur in the Denver area. Following the Denver earthquakes, scientists were later able to control the amount of earthquakes by changing fluid pressure at four wells in Rangely, Colorado (Raleigh et al., 1976).

Policymakers and regulating authorities were slow to act in regulating disposal well volumes in Oklahoma, but following a litany of published scientific literature, and complaints from constituents, the state authority in charge of regulating oil and gas operations did begin to issue directives and limit disposal volumes in areas that witnessed large or frequent earthquakes in 2015. Armed with information, the Oklahoma Corporation Commission (OCC) issued several policy directives aimed at combating the dramatic increase in earthquake activity between 2015 and 2016 with the first, and most wide-ranging of these directives, issued on March 25th of 2015. In the March 25th directive, the Corporation Commission defined what they refer to as an “area of interest” which largely coincided with the Arbuckle formation and determined an action plan for disposal wells within this area. The Arbuckle formation is the basement layer formation that operators injected produced water into, and published research indicates that fluid pressure differences at this great of a depth are what cause induced earthquakes. Following the March 25th directive the next substantial directive was issued on July 17th, 2015. Between the two of these directives a total of 558 disposal wells were told to check the depth that they were disposing water and either: reduce daily volume disposed, ‘plug back’ and reduce the depth that they were disposing, a combination of these two actions, or to cease operations entirely.[4] Following the first two major directives the OCC has mostly issued smaller, targeted directives in response to large scale events or earthquake swarms and they have coordinated actions with disposal well operators in close proximity to the swarm or large tremblor. Since the original, large-scale directives more than 15 other individual directives have been issues forming a patchwork of policy prescriptions throughout the state of Oklahoma. A complete list of directives dates and actions is shown in Box 1.

Since the era of wastewater regulation began the amount of daily earthquakes has declined. Fig. 2 shows the change in earthquake activity over time with the four week moving average of daily earthquake counts (top panel). Following the first directive for plugging back and reducing disposal volumes by the OCC, shown with the vertical bar on March 25th, earthquake activity seemed to wane. At first glance, the top panel of Fig. 2 seems to show that the policy-era of shut-in policies have been successful in reducing the amount of earthquakes - the four-week moving average broadly declines after this date. However, the effect of the Corporation Commission's policies must be taken in context with the broader oil market. Although these policies are clear in their direction and definition of risk-prone areas, they have an unfortunate lack of generality in reducing disposal at wells outside of specified areas or target wells. The list of all OCC directives shows just this, that actions and directives have been issued following major events or earthquake swarms in order to limit disposal volumes in affected areas or at specific disposal wells. Thus, the directives issued by the OCC are, by nature, purely reactive and form a patchwork of policies regulating disposal-induced seismicity. It is not surprising, then, that market dynamics and wholesale price changes can more immediately impact drilling activities and the quantity supplied of oil and gas (and hence produced water and disposal) than these policies. The bottom panel of Fig. 2 shows the wholesale price of oil with the same vertical line for March 25th indicated. All else equal, when oil prices fall the amount of oil production also declines as it becomes less economically viable to produce. Thus, while the policy-era of new disposal directives seems to have reduced the amount of daily earthquakes, it is just as likely that there is simply

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[4] A list of all directives, press releases, etc. is available from Oklahoma Corporation Commission ().

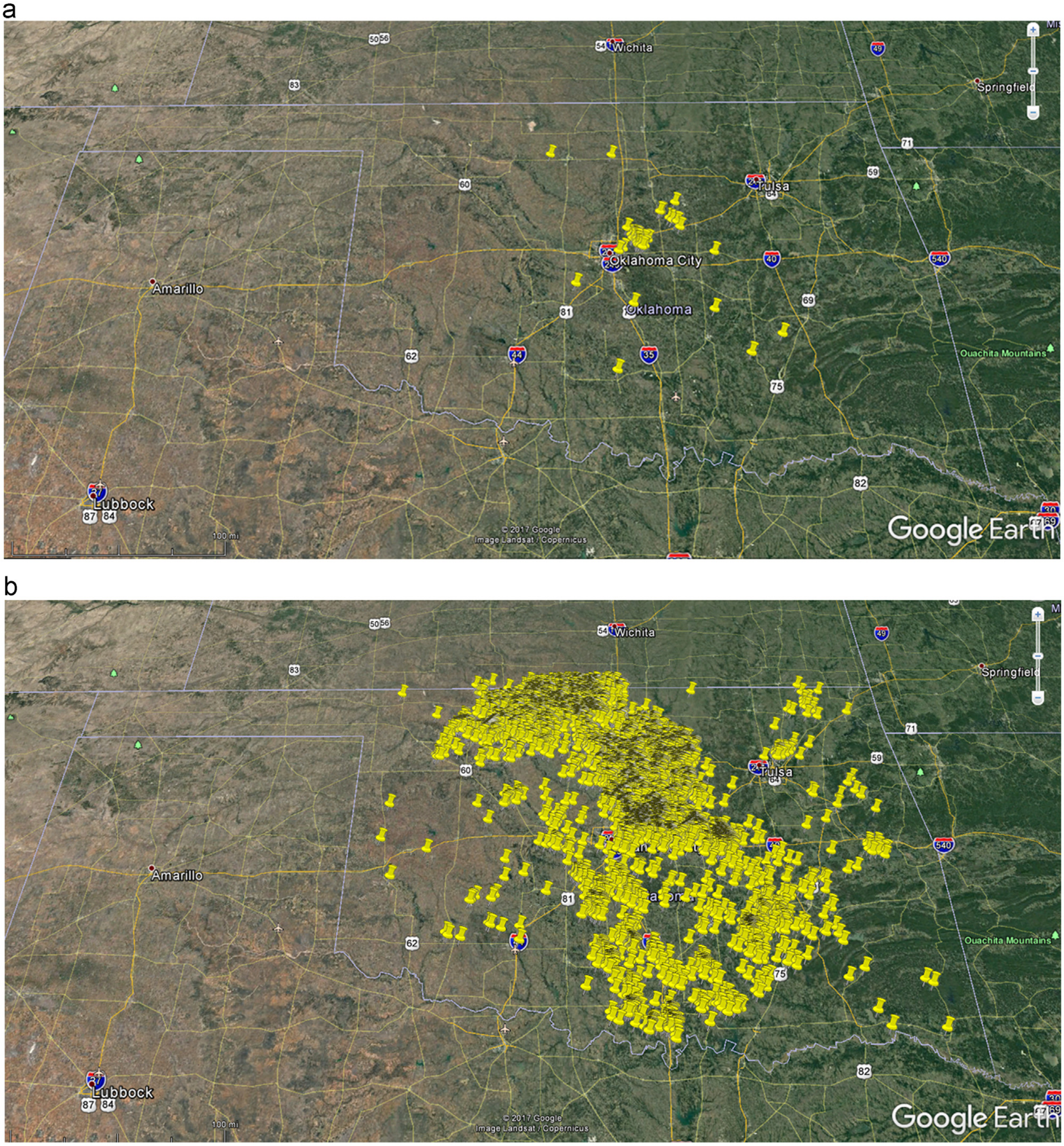

Fig. 1. Total amount of earthquakes: through 2009 (top), through 2016 (bottom).

less production taking place (and hence less wastewater). The findings of this paper indicate that the efforts of policy-makers have reduced the daily amount of earthquakes, but that the low price environment has had as large of an impact as the regulating authorities.

The results of this paper are complementary to a growing literature on the positive and negative externalities of hydraulic fracturing and shale gas development in the United States (Fry et al., 2015; Muehlenbachs et al., 2015; Boslett et al., 2016, among others). Many exploit natural experiment settings and state-to-state policy differences in disallowing hydraulic fracturing. Regarding induced earthquakes, McComas et al. (2016) finds that the public perceives induced earthquakes more negatively than naturally occurring earthquakes. This negative perception has even filtered into observed home prices in Oklahoma as shown in the hedonic studies of Cheung et al. (2016) and Metz et al. (2017). Obviously, earthquake risks and risks from shale gas development in general (real or perceived) will also have impacts on insurance decisions. Wetherell and Evensen (2016) explicitly discuss the gap that exists in insurance markets regarding hydraulic fracturing and shale development and offer potential remedies. The present paper contributes to the debate and discussion regarding externalities from hydraulic fracturing in general, and specifically contributes with regard to induced earthquakes. The results of this paper not only aid in the understanding and predictability of earthquakes for insurance purposes, but further aids in understanding how policies intended to limit earthquakes have had limited impact and why there are still earthquakes occurring despite the effort.

Box 1
List of Wastewater Disposal Directives.

- **March 25, 2015 Original directive establishing an “area of interest” and calling for 347 wells in the Arbuckle to check depth, reduce depth, cut injection rate.
- ** July 17, 2015 Directive for 211 disposal wells in the Arbuckle to check depth. Must prove that depth is not in communication with basement rock, or a plug back operation is completed to bring the bottom of the well at least 100 feet up into the Arbuckle.
- July 28, 2015 Crescent: 2 wells shut in, 1 reducing volume 50%.
- August 3, 2015 vol cutback plan for area that includes portions of northern Oklahoma, Logan, Lincoln, and Payne counties. Goal is to bring total disposed volume in area to 30% below 2012 total (pre seismicity). Plan covers 23 wells.
- October 19, 2015 Cushing: 13 wells either ceasing operations or cutting volume disposed 25%.
- November 10, 2015 Medford: 10 wells reducing volume disposed 25–50%.
- November 16, 2015 Fairview: 2 wells reduce volume 25%, 1 well stop operations and reduce depth.
- November 19, 2015 Cherokee: 2 disposal wells shut-in, 23 others reduce volume 25–50%.
- November 20, 2015 Crescent: 4 disposal wells shut-in, 7 others reduce volume 50%.
- December 3, 2015 Medford area: 3 disposal wells shut-in and cuts of 25–50% in disposed volumes for 19 other wells. The total net volume reduction for the area in question is 42%.
- December 3, 2015 Byron/Cherokee area: 4 disposal wells shut-in, volume cuts of 25–50% for 47 other disposal wells.
- January 4, 2016 - Edmond area: 5 disposal wells to reduce volumes by 25–50%. Wells 15 miles from epicenter to conduct reservoir pressure testing. (Two disposal wells ceased operation as part of the action)
- January 4, 2016 - Edmond area: 5 disposal wells to reduce volumes by 25–50%. Wells 15 miles from epicenter to conduct reservoir pressure testing. (Two disposal wells ceased operation as part of the action)
- January 20, 2016 Medford, Byron-Cherokee areas: 8 wells to stop disposal, 9 wells to be used by researchers. 36 wells to reduce volume. Total volume reduction: 191,327 barrels/day, (40%).
- January 13, 2016 - Fairview area: 27 disposal wells to reduce volume. Total volume reduction for the area in question: 54,859 barrels a day or (18%).
- February 16, 2016 Western Oklahoma Regional Volume Reduction Plan
- March 7, 2016 Central Oklahoma Regional Volume Reduction Plan and Expansion of Area of Interest
- August 19, 2016 Luther/Wellston area: 2 wells shut in, 19 wells to further reduce volume.
- September 3, 2016 Pawnee area: 37 wells directed to shut in (cease operations) under emergency directive as immediate response to Pawnee-area 5.8 magnitude earthquake. (Superseded by September 12, 2016 directive).
- September 12, 2016 Pawnee area: Directive modifying operations at 48 Arbuckle disposal wells under OCC jurisdiction in a 1116 square mile area. 32 to shut in, remainder to reduce volume. EPA follows OCC lead in its area of jurisdiction (Osage County), shutting down 5 Arbuckle disposal wells, and reducing volumes at 14 others
- November 3, 2016 Pawnee area: Directive covering 38 Arbuckle disposal wells under OCC jurisdiction and 26 Arbuckle disposal wells under sole EPA jurisdiction.
- November 8, 2016 Cushing area: Directive modifying operations of 54 Arbuckle disposal wells.

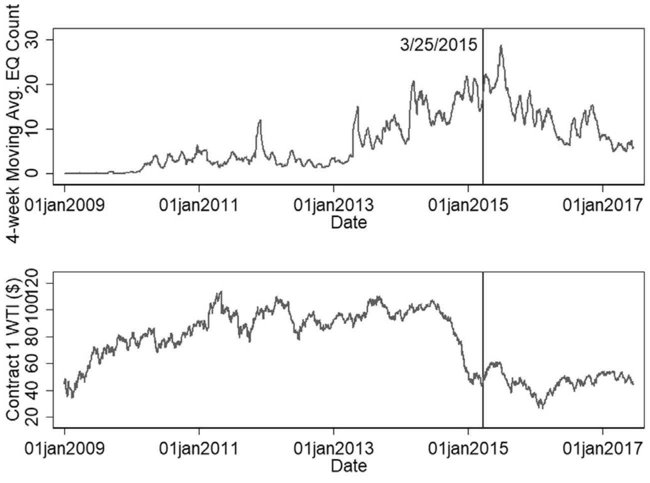

Fig. 2. Earthquake activity (top) and the WTI price (bottom).

The balance of this paper continues as follows: Section 2 describes the empirical strategy and develops the price-taking behavior benchmark model; Section 3 displays the results of the primary model and expands on the empirical model by allowing for asymmetric error-correction between wholesale prices and midstream prices as well as other robustness checks; Section 4 concludes with a policy discussion.

2. Empirical strategy

The wholesale price of oil is greatly affected by global events, energy policies, and even news stories of either of the former two factors potentially changing. As an example, this can be seen when the WTI price or the Brent crude price jump on news of action (or inaction) by countries in the OPEC cartel. These exogenous price fluctuation still have an impact on firm-level production decisions, though.

The firm model adopted here is that of price-taking behavior. Consider a representative constant cost extraction firm, i, that chooses their output level in each period to maximize profit according to the following

$$\Pi_i = P(Q)\cdot q_i - C\cdot q_i \tag{1}$$

where the price of oil, P is exogenously determined in global commodity exchanges, but is impacted by the sum of all foreign (Q_f) and domestic oil production (Q_d).

$$Q = Q_d + Q_f = \sum_{i=1}^{N} q_i + Q_f \tag{2}$$

with

$$P'(Q) < 0 \tag{3}$$

to satisfy the law of demand

It is further assumed that individual domestic oil and gas producers do not produce a large enough volume to impact the price of oil. In other words, firms are small compared to the global market and take the price of oil as given when making production decisions. This is a common characteristic among individual commodity producers (e.g. corn or cotton production). Simple profit maximization yields the familiar law of supply result that

$$\frac{\partial q_i}{\partial P} > 0 \tag{4}$$

Linking now to produced water and disposal wells, let us assume that the amount of produced water is a function of the amount of oil and gas produced according to the following

$$d_i = \delta \cdot q_i \tag{5}$$

where d_i represents the amount of disposed water by firm i and δ is any real number greater than zero. It follows, then, that the amount of produced water is positively related to the price of oil.

$$\frac{\partial d_i}{\partial P} > 0 \tag{6}$$

Hence, the price of oil is a simple measure of oil-field activity that is directly related to the amount produced water that will be injected into disposal wells. Given the received literature on disposal volumes and earthquake rates, we should then expect that induced seismicity will increase as the price of oil increases.

2.1. Data description

The primary data for this study are collected from the Oklahoma Geological Survey and cover daily earthquake records in the state of Oklahoma from January 1, 2009 through June 16, 2017. Over this sample period the daily average amount of earthquakes is 7.34 earthquakes.[5] Since March 25th, 2015, the date of the first shut-in directive, the daily average is 11.94 earthquakes. In addition to the amount of daily earthquakes, I use information on the maximum strength of an earthquake on a given day. The maximum earthquake strength is used to control for any aftershock effects.[6] All else equal, the amount of earthquakes on a given day will be higher following a magnitude 5.0 earthquake than a magnitude 2.0 earthquake. The economic variable of interest is the price of oil. Here, I use the one month futures price for the West Texas Intermediate price as it is the major wholesale clearinghouse price for U.S. onshore production. This 'Contract 1′ price is the price accepted for delivery one-month from the day the contract is executed.[7] I later use Contact 2, 3, and 4 prices which represent the agreed price for oil delivered two, three or four months from the date that contract is agreed upon, respectively. I use this variable as it reflects current market conditions as well as any hesitation on the part of the producer or consumer sides of the market. These price series are available at a daily resolution from the Energy Information Administration. In later robustness specifications I instrument Oklahoma-specific midstream prices with the West Texas Intermediate price to control for potential endogeneity due to locational advantage. These data are taken from the Rose Rock daily price bulletin and are available since 2001. Descriptive statistics for these variable are shown below in Table 1.

Table 1
Summary Statistics.

	Mean	Std. Dev.	Min	Max
Earthquake Count	7.53	8.37	0.00	133.00
Max Magnitude EQ	2.30	1.22	0.00	5.80
Contract 1	75.33	22.80	26.21	113.93
Contract 2	75.92	22.38	28.35	114.43
Contract 3	76.40	21.98	29.69	114.71
Contract 4	76.75	21.62	30.83	114.83
Oklahoma Sweet	68.56	23.41	18.12	108.38
Oklahoma Panhandle	68.11	23.41	17.67	107.93
Oklahoma Sour	57.46	23.41	7.02	97.28

Notes: 3089 observations. Contract 1–4 and Oklahoma Midstream prices are in dollars per barrel.

2.2. Specification

We are interested in the daily amount of earthquakes and their economic causes. This type of data, count data, is typically modeled using a maximum likelihood Poisson regression model due to zero lower-bound truncation.

$$E(EQCount_t | X_t) = e^{X'_t \beta + \varepsilon_t} \tag{7}$$

Where $X'_t\beta$ is the price of oil and relevant earthquake determinants, discussed below. A common issue with Poisson models is "overdispersion", when the standard deviation of the count variable is greater than the average, which leads to inefficient parameter estimates (Ver Hoef and Boveng, 2007). The data at hand clearly exhibits overdispersion - the average daily earthquake count is only 7.5 events while the standard deviation of earthquake events is 8.4. The maximum amount of earthquakes in a single day was 133. A more general version of the Poisson model, the negative binomial regression model, corrects the overdispersion problem and leads to unbiased and efficient parameter results.[8] The full model specification is shown below in Eq. (8).

$$\begin{aligned} X'_t\beta = {} & \beta_0 + \beta_1 Price_t + \beta_2 MarchShutin_t + \beta_3 JulyShutin_t \\ & + \sum_{j=0}^{J} \beta_{4+j} MaxEQ_{t-j} \\ & + \lambda_1 Trend_t + \sum_{j=1}^{51} \lambda_{1+j} Week_t \end{aligned} \tag{8}$$

The primary estimates of interest are the coefficient for $Price_t$ and the coefficients on the shut-in policy indicator variables, $MarchShutin_t$ and $JulyShutin_t$. The shut-in variables are binary indicator variables that are equal to 1 from the beginning of the policy start date (March 25th and July 17th, respectively) to the end of the sample. These two shut-in policies are used because, (i) they mark the beginning of any policy within the state that was intended to reduce earthquakes from disposal volumes, and (ii) these are the policies that affected the widest range of disposal wells.[9] The addition of these coefficients yields the cumulative effect of the shut-in policies relative to the time period before any action was taken by the Oklahoma Corporation Commission. Taken together, these variables represent the entire 'policy-era' in Oklahoma. In the primary model the one month futures price (Contract 1) is used as the wholesale price of oil at time t. Later robustness exercises use two-four month futures contract prices (Contracts 2–4). From the model of price-taking behavior we expect this to be positively related to the amount of produced water, and, hence, water that is injected into disposal wells. Based on the received literature on wastewater injection we expect the price of oil to be positively related to the amount of earthquakes, ceteris paribus.

The variable, $MaxEQ_{t-j}$ accounts for contemporaneous and lagged values of the maximum magnitude earthquake witnessed for up to J

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[5] Since January 1, 2000 the daily average amount of earthquakes is 3.7 earthquakes.

[6] Augmented Dickey-Fuller tests reject the null of a unit-root for the dependent variable as well as for the maximum magnitude.

[7] This series is stationary at the 95% confidence level when a drift term is included in the ADF test.

[8] The dependent variable does not exhibit any time-series persistence that would suggest the use of modeling strategies that account for temporal dependence in the daily count of earthquakes.

[9] Box 1 includes a full listing of actions taken by the Oklahoma Corporation Commission.

prior days. Various lag lengths for $MaxEQ_t$ are considered to control for seismic activity that is due to triggered aftershocks from a large-scale event (and not the prevailing price of oil or any policy variables). The models presented here extend to a 7 day lag length because further lags do not aid in the predictability of the model. To accommodate for production differences that are not caused by changes in the wholesale price of oil I include fixed effects for each week of the year. These variables are able to capture changes in production that are due to seasonality and not the prevailing price of oil, hence also capturing changes in disposal volumes that are due to seasonality. Unfortunately, data on wastewater injection is only available on an annual basis, and this information is only available beginning in 2006. Clearly this prohibits the use of disposal volumes within an estimating equation. One could also use oil or natural gas production as a proxy for the amount of wastewater that is disposed, though there are an array of confounding issues with using this as a proxy. First, according to the Oklahoma Corporation Commission, Oklahoma actually imports wastewater for injection from surrounding states.[10] It is possible, then, that oil and gas production could be falling within the state while disposal volumes are increasing. Using the wholesale price of oil as I do here can actually account for changes in wastewater from neighboring states because, at the margin, it becomes more feasible to drill for oil or gas in a state that bans or limits wastewater injection and ship the wastewater elsewhere as the price of oil and gas increase (and vice versa). Second, production data is available at monthly intervals and the time lag between production and wastewater disposal differs by the operator and may fall unevenly around month cutoffs (e.g. October production, November and December wastewater injection). Finally, I include a linear time trend and report robust standard errors.[11]

3. Results

Table 2 shows select estimates from Eq. (8).[12] To aid interpretation the coefficients for the Contract 1 price and the maximum magnitude earthquake are shown in elasticity form.[13] These coefficients should be interpreted as the percentage change in earthquakes per day following a one percent increase for each variable, holding all others constant. Table 2 also shows the effect of the shut-in policies on earthquake counts as well as the cumulative effect of these policies ($\beta_2 + \beta_3$). The coefficient presented here reflects the change in daily earthquake counts in the policy era while controlling for the price of oil and past earthquake magnitudes. Five different specifications are included for completeness. Specification (1) is the baseline specification in which the maximum magnitude earthquake over the prior seven days, and the present day, are used to account for aftershock activity. Additionally, the Contract 1 price over the prior seven days is included. Specification (2) removes lagged price effects but continues to control for the maximum magnitude earthquake over the prior week. Specification (3) allows for lagged prices, but removes prior days' maximum magnitude earthquakes. Specifications (4) and (5) are similar to the baseline specification, but in (4) all fixed effects and trends are removed, and in (5) the linear trend is replaced with yearly fixed effects.

In regressions of the type used here the standard R-squared approach to gauge model fit is not appropriate. Instead, I present McFadden's R-squared and adjusted R-squared statistic (McFadden, 1973) which can be interpreted with the same intuition as traditional R-squared measurements. The upper bound of McFadden's R-squared, however, is much lower than the traditional R-squared statistic due to how it is calculated. McFadden notes that models with a (McFadden's) R-squared between 0.2 and 0.4 indicate a model with excellent fit.

Across all specifications I find that the WTI Contract 1 futures price is positively related with the daily amount of earthquakes. In the baseline specification that controls for past maximum magnitude events I find that a 10% increase in the price of oil results in a 3.45% increase in earthquake activity.[14] In specifications that do not account for past maximum magnitudes the effect of price changes are more muted. In these models a 10% increase in the WTI price results in approximately 2.3% more earthquakes. These specifications are not preferred, however, as indicated by the lower McFadden's adjusted R-squared statistics.

The coefficients for each of the shut-in directives show the change in daily earthquakes within each policy period while holding all other factors constant. The combined effect of these policies capture the full effect of the directives issued by the OCC since the beginning of the policy-era. I find across all specifications that these policies have had a discernible effect on the amount of daily earthquakes. Specifically, I find that these policies are associated with a reduction in daily earthquakes with the preferred model indicating a decrease of 2.7 earthquakes per day. Note, that the least preferred specification (adjusted R-squared of only 0.216) attributes the largest decline in earthquake activity to policy effects because it does not account for prior maximum magnitude events. In all other specifications I find that the policy-era is related to a decrease of 1.8–3.01 daily earthquakes.

While the elasticities and point estimates listed in Table 2 are informative, a more clear picture of how the price of oil affects seismicity is shown in Fig. 3. This figure shows the predicted amount of earthquakes for a range of Contract 1 WTI prices. Further, this figure shows the impact that prices have on daily earthquake counts in both the pre and post policy periods. For both eras, Fig. 3 clearly shows an upward trend with higher oil prices triggering further seismicity. This finding makes intuitive sense given that as the price of oil increases, drilling and hydraulic fracturing increases, and thus the amount of produced water increases.[15] This figure further shows that in low price environments we expect fewer daily earthquakes - an indication that shut-in policies may not be the primary cause for the reduction in daily earthquake amounts. When we compare the price decline that occurred prior to any disposal policy (a price drop from more than \$100 to approximately \$50) we can see that earthquakes decreased by more than two per day; about the same amount that is associated with policy interventions. Put another way, we can see that if present oil prices were to recover to their 2013 levels we expect to have as many daily earthquakes as in the low price environment that existed when the policy-era began. Comparing the slope of predicted daily earthquakes between policy periods does offer interesting evidence that the impact of price increases is more muted now that disposal directives have been issued.

3.1. Two-four month futures contracts

While the estimates presented above do account for contemporaneous production decisions based on future delivery, they may not fully account for the time to delivery that some well-operators face. That is to say, some operators may make production decisions based on a longer window of development to eventual dispatch. To account for this possibility I estimate the same baseline specification from above using contract 2–4 prices instead of the contract 1 price. These price series are the average executed price for delivery two, three, and four months ahead, respectively. The column headings indicate which

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[10] Data on water imports are not available, but multiple news accounts and interviews of corporation commissioners confirm this (Report, 2016).

[11] In robustness specifications yearly fixed effects are substituted for the linear time trend. I find that the major results of this paper are unchanged with the addition or removal of these fixed effects or trends.

[12] All model coefficients are available on request.

[13] As opposed to the logarithm of the odds ratio.

[14] Or, equivalently, a 10% decrease in price results in 3.45% fewer earthquakes.

[15] See Eq. (6), above.

Table 2
Model estimates.

	(1)	(2)	(3)	(4)	(5)
Contract 1 Price	0.345 ***	0.303 ***	0.228 ***	0.401 ***	0.228*
	(0.070)	(0.068)	(0.074)	(0.066)	(0.122)
Max EQ	3.111 ***	3.100 ***	2.082 ***	3.229 ***	2.514 ***
	(0.076)	(0.076)	(0.051)	(0.047)	(0.097)
March Shutin	1.988 ***	1.737 ***	1.976 ***	1.961 ***	1.431 ***
	(0.470)	(0.470)	(0.499)	(0.381)	(0.517)
July Shutin	− 4.687 ***	− 4.749 ***	− 7.064 ***	− 3.772 ***	− 3.500 ***
	(0.408)	(0.413)	(0.413)	(0.341)	(0.454)
Combined Effect ($\beta 2 + \beta 3$)	− 2.698 ***	− 3.012 ***	− 5.088 ***	− 1.811 ***	− 2.069 ***
	(0.451)	(0.450)	(0.464)	(0.335)	(0.498)
Weekly FE	Y	Y	Y	N	Y
Trend	Y	Y	Y	N	N
Year FE	N	N	N	N	Y
Lags of Max_EQ	7	7	–	7	7
Lags of Price	7	–	7	7	7
McFadden's R2	0.242	0.241	0.223	0.235	0.225
McFadden's Adjusted R2	0.234	0.234	0.216	0.232	0.221
Obs	3089	3089	3089	3089	3089

Notes: Coefficients for Contract 1 Price and Max EQ are in elasticity form. Coefficients for policy variables are in number of earthquakes. ***, **, * denotes statistical significance at the 1%, 5%, and 10% level, respectively.

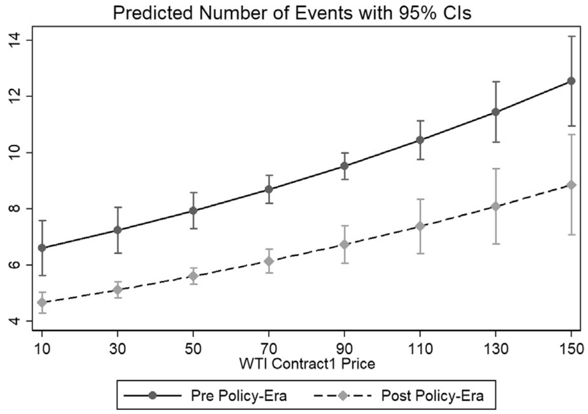

Fig. 3. Predicted EQs by WTI Contract 1 price.

Table 3
Longer futures contracts.

	Contract 1	Contract 2	Contract 3	Contract 4
Contract Price	0.345 ***	0.359 ***	0.369 ***	0.376 ***
	(0.070)	(0.073)	(0.075)	(0.077)
Max EQ	3.111 ***	3.114 ***	3.114 ***	3.114 ***
	(0.076)	(0.076)	(0.076)	(0.076)
March Shutin	1.988 ***	1.930 ***	1.911 ***	1.887 ***
	(0.470)	(0.477)	(0.475)	(0.474)
July Shutin	− 4.687 ***	− 4.707 ***	− 4.709 ***	− 4.712 ***
	(0.408)	(0.414)	(0.414)	(0.415)
Combined Effect ($\beta 2 + \beta 3$)	− 2.698 ***	− 2.778 ***	− 2.798 ***	− 2.825 ***
	(0.451)	(0.452)	(0.452)	(0.450)
Weekly FE	Y	Y	Y	Y
Trend	Y	Y	Y	Y
Lags of Max_EQ	7	7	7	7
Lags of Price	7	7	7	7
McFadden's R2	0.242	0.242	0.242	0.242
McFadden's Adjusted R2	0.234	0.234	0.234	0.234
Obs	3089	3089	3089	3089

Notes: Column headings indicate contract month price. Coefficients for Contract Price and Max EQ are in elasticity form. Coefficients for policy variables are in number of earthquakes. ***, **, * denotes statistical significance at the 1%, 5%, and 10% level, respectively.

futures contract is used in each specification. Column 1 of Table 3 repeats the findings from before, and columns 2–4 show the estimates from each separate futures price, respectively.

The major findings of this paper remain unchanged in this robustness check. I continue to find a more than 3% increase in earthquake activity following a 10% change in price. Further, I continue to find that the directives issued by the OCC are associated with a 2.8 decrease in daily earthquakes.

3.2. Endogenous comparative advantage

Thus far I have assumed that firms are ‘price-takers’ and that the price of oil can reasonably be modeled as exogenous. This modeling approach has it's advantages empirically, and also helps to proxy for the effects and incentives that lead to produced water being shipped into Oklahoma from outside states. All else equal, as the wholesale price of oil rises it is more cost-effective to ship produced water greater distances - for example from areas with stringent regulations into areas with less stringent regulations. However, the bulk of produced water that is injected within Oklahoma is likely produced from shale plays within the state. These producers may be able to exert some form of local market power due to the quality of oil in Oklahoma, for example ‘sweet’ crude compared to more sulfuric ‘sour’ crude that requires more refining to be ready for consumption domestically. Moreover, local producers may have a competitive advantage over other domestic producers due to the close proximity to Cushing, Oklahoma - the nation's largest oil hub and where West Texas Intermediate (WTI) is priced. That is to say, the break-even price for Oklahoma producers could be lower than other domestic producers due to transportation costs alone. If either of these issues arise, then the Contract 1 WTI price does not accurately reflect the price producers receive and results may suffer from endogeneity. To account for this possibility I instrument midstream prices for the three major oil grades that are produced in Oklahoma, the Oklahoma Sweet, Oklahoma Sour, and Oklahoma Panhandle prices, and substitute these in place of the futures contract price.[16] Fig. 4 shows these three midstream price series along with the WTI price. The cointegrated nature of midstream and wholesale prices can clearly be seen, thus one must account for error correction between these prices series.

The midstream pricing model used here is common in capturing

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[16] This method is akin to two-stage least squares.

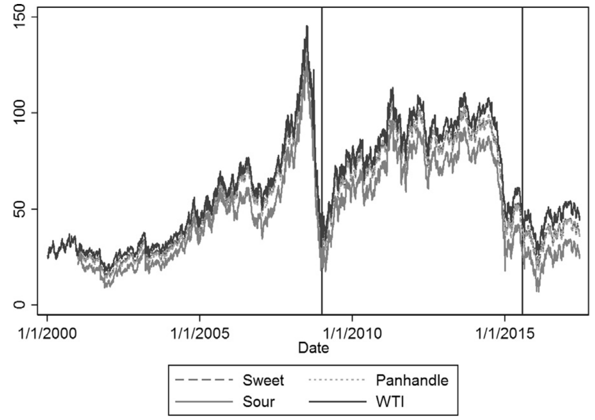

Fig. 4. Midstream and WTI prices.

downstream price shocks in the retail gasoline literature (Noel, 2007; Tappata, 2009; Noel, 2009; and Lewis and Noel, 2011) and captures the transmission of upstream prices to downstream markets and any error correction that may occur. Further, this model allows for asymetric error correction between wholesale and midstream prices because price increases may have different a different transmission into downstream prices than price decreases. The asymetric vector error correction model is shown below in Eq. (9).

$$\Delta PRICE_t = \delta_0 + \sum_{i=1}^{I} \delta^{+}_{1+i}\Delta WTI^{+}_{t-i} + \sum_{i=1}^{I} \delta^{-}_{1+i}\Delta WTI^{-}_{t-i} + \sum_{j=1}^{J} \delta^{+}_{1+I+i}\Delta PRICE^{+}_{t-j} + \sum_{j=1}^{J} \delta^{-}_{1+I+i}\Delta PRICE^{-}_{t-j} + \theta Z_t + \upsilon_t \tag{9}$$

with

$$\Delta WTI^{+} = \max(0, \Delta WTI) \tag{10}$$

$$\Delta WTI^{-} = \min(0, \Delta WTI) \tag{11}$$

$$\Delta PRICE^{+} = \max(0, \Delta PRICE) \tag{12}$$

$$\Delta PRICE^{-} = \min(0, \Delta PRICE) \tag{13}$$

and the error correction term, θZ_t, measures the long run, steady state relationship in levels between midstream prices and the wholesale (WTI) price.

I re-estimate Eq. (8) by replacing the Contract 1 price with the predicted ('instrumented') local prices to account for endogeneity that may be due to transportation cost efficiencies, grade specific market-power, or some other factor. For all three oil grades I find that the major results of this paper are unchanged. Specifically, I find an elasticity of 0.311, 0.260, and 0.309 for the Oklahoma Sweet, Panhandle, and Sour prices, respectively. Each of these elasticities are statistically significant at the 1% level. Again, this elasticity estimate concludes that a 10% price decrease will reduce earthquakes by approximately 3%. Looking now to the effect of the shut-in policies, I find that the policy-era is associated with approximately 2.74 fewer daily earthquakes.[17] Thus, after instrumenting the price that producers face we can still see that the effect of policy is muted in the face of higher prices.

3.3. Including 'pre-fracking' observations

As a final robustness check I expand the data range through January 1, 2000. Importantly, this data predates the advent of hydraulic fracturing which allows for 'natural' earthquakes to be included within the data sample, and also includes a substantial degree of price volatility. The only amendment I make to the baseline specification is the inclusion of a binary indicator variable that is equal to 1 for the time period since 2009. This is done to account for the change in production technology and subsequent increase in production that is not due to the prevailing price of oil. Using this extended time range I find that a 10% increase in prices result in 3.1% more earthquakes per day, similar to the elasticity found before. The effect of the disposal policy-era is more muted when the longer time frame is used. I find that the shut-in directives are associated with 1.51 fewer earthquakes per day. Both the elasticity and the effect of the policies are statistically significant at the 1% level.

4. Conclusion and policy implications

This research has shown that the price of oil is a major determining factor in the amount of earthquakes witnessed in the state of Oklahoma. This finding makes intuitive sense because as the price of oil increases, further exploration and production is incentivized, and as more oil and gas are produced, so too is the amount of 'produced' water which is subsequently pumped deep underground into injection wells. The causal link between wastewater disposal and earthquake activity has been established in the geological literature, and the present research aids in establishing a correlation between the economic viability of oil production (and hence wastewater production) and the amount of earthquakes in Oklahoma.

In an effort to curb earthquake activity in Oklahoma, state regulators issued directives and established areas of interest in which the daily volume and depth of disposal was limited. While at first these policy measures seemed effective, one must also consider that these policies were issued when the price of oil was reaching new lows. I find that there has been a statistically discernible effect on the daily amount of earthquakes in the time-period of policy prescriptions. However, the decrease in earthquake activity has as much to do with the low price environment as the policies. In total, I find that the era of disposal directives is associated with about 2.7 fewer earthquakes per day. This finding is robust to modeling assumptions and remains true when longer futures contracts are considered, local competitive advantages are accounted for by using an asymmetric error correction model, and when the sample period is extended to include observations from 2000 to 2009.

The issue of induced seismicity clearly poses a negative externality on affected communities which has already been seen through changes in the home prices of affected areas (Cheung et al., 2016; Metz et al., 2017). While the actions of the state regulatory authority were obviously intended to reduce this negative externality effect, the results of the present research indicate that their actions may have had limited impact. This is mostly due to the fact that the policies that were put in place were responsive in nature and not forward-looking. For lack of a better term, the method for reducing earthquake activity has been much like playing a game of 'whack-a-mole', with directives issued and disposal volumes limited specifically in areas in which a 'mole' popped up. There does not exist a state-wide statute limiting or taxing disposal.

The findings of this research indicate that a price-based instrument ought to be used to internalize the externality effect of earthquakes because producers, and hence earthquakes, have shown to be price-responsive. A per-barrel fee for wastewater disposal would function as any Pigouvian tax would, and would put the market more in line with the socially efficient outcome. Moreover, by establishing a per-barrel fee for all wastewater disposal two latent issues could be addressed and an important source of revenue could be established. First, this type of policy would incentivize the use of wastewater for 'enhanced oil recovery' techniques and wastewater recycling in agricultural and industrial practices. Existing efforts in these areas are still in the early stages of development and are not necessarily cost-competitive with simple disposal. Second, a per-barrel fee would reduce or limit state-to-

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[17] These estimates are from models analogous to specification 1 from before with lags for both the price and past earthquake magnitudes.

state transportation of wastewater which may be occurring because other regulatory bodies have encoded or enforced more strict regulation on disposal, or because the geologic features in Oklahoma make disposal more cost-effective than elsewhere. Lastly, any revenues received from this type of policy could be used to pay for existing or future damages caused by earthquake activity.

While the standard economic logic of a Pigouvian tax is instructive, the political feasibility of such an action in the state of Oklahoma is extremely low. This is due to two major factors: regulatory capture by the oil and gas industry, and a requirement in the state constitution that a 75% majority must be reached for any new tax or tax increase.[18] Taken together, these factors yield very little hope for an externality-correcting tax. Instead, at a minimum the efforts of policy makers to target and limit wastewater disposal ought to continue while efforts are made to bolster the legal system that allows for litigation of damages due to wastewater induced seismicity. Konschnik (2016) comments on the long process of pending litigation in Oklahoma and advocates for an induced seismicity compensation fund. Such a fund would ensure recovery of damages for lost property and simultaneously account for the "looming" liability and insurance coverage risks that oil and gas operators in the state face. Konschnik (2016) notes that there are several sources of revenue for a fund like this including license or registration fees, and that multiple other states and entities have successfully established similar funds (e.g. coastal protection funds). McComas et al. (2016) show that the public perception and acceptance of induced earthquakes is assuaged when they believe they have a voice in the decision to use the technology that caused the earthquake. The establishment of an induced seismicity compensation fund would allow for public comment and action with regards to further disposed water. If current disposal practices continue, and if wholesale oil prices increase enough to incentivize new drilling and disposal, then establishing such a fund would be prudent step for all parties while also allowing the public to be engaged in the policy-making process.

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[18] Oklahoma is one of only two states that requires such a high threshold for any new tax.