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The Housing Market Impacts of Wastewater Injection Induced Seismicity Risk [*]

Running Title: Injection Induced Seismicity Risk

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Abstract

Using data from a county severely affected by the increased seismicity associated with injection wells since 2009 in Oklahoma, we recover hedonic estimates of property value impacts from nearby shale oil and gas development that vary with earthquake risk exposure. Results suggest that the seismic activity has enhanced the perceived risks associated with wastewater injection but not shale gas production. This risk perception is limited to injection wells within 2 km of the properties.

Keywords: Earthquake; Wastewater Injection; Oil and Gas Production; Housing Market; Hedonic Pricing; Oklahoma

JEL classification: L71, Q35, Q54, R31

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1. Introduction

The injection of fluids underground has been known to induce earthquakes since the mid-1960s (Healy et al. 1968, Raleigh et al. 1976). However, few cases were documented in the United States until 2009. Since 2009, the central and eastern United States (CEUS) has seen an unprecedented increase in seismicity, and many earthquakes are believed to be induced by injection wells (Ellsworth 2013). Weingarten et al. (2015) examined the location and timing of earthquakes and their relationship to the location and operation of injection wells across the CEUS. They found that the number of earthquakes associated with injection wells has tripled since the year 2000 and that the entire increase in seismicity since 2009 is associated with fluid injection wells. Wells in Oklahoma, where unconventional oil and gas production methods generate large volumes of waste water which are injected at high rates, are the main contributors to the dramatic increase in associated seismicity (Weingarten et al. 2015, Walsch and Zoback 2015). Figure 1 depicts the exponential increase in the number of earthquakes of magnitude 3 or larger in Oklahoma since 2000.

Many factors are necessary for injection activity to induce earthquakes. The injection of large volumes of wastewater into the rock formation increases pore pressure; this pressure can spread from the injection site and trigger seismicity on a critically stressed fault (Walsh and Zoback 2015). Most injection wells are not associated with earthquakes, but in Oklahoma, the disposal reservoir– the highly permeable Arbuckle formation – sits directly above crystalline basement rock, in which there are faults large enough to cause earthquakes that can be felt and potentially cause damage. The fact that increasing pore pressure at depth from fluid injection can trigger a slip on a pre-existing, already-stressed fault is well documented (Healy et al. 1968, Raleigh et al. 1976, McGarr et al. 2002, 2014, Suckale 2009, National Research Council 2013), and the mechanisms by which the triggered fault slip occurs are generally well known - increased fluid pressure decreases the effective normal stress on a fault, potentially triggering the release of accumulated strain energy on a preexisting fault that is already close to failure (National Research Council 2013). Figure 1 shows a steady increase in the total number of injection wells over time, and a marked increase in the number of high rate injection wells and injection volumes since 2010.

Unconventional oil and gas production, also referred to as shale gas development, has experienced a boom since the mid-2000s that has revolutionized the energy sector (Bartik et al. 2016). Innovations in hydraulic fracturing (commonly known as “fracking” or “fracing”) and horizontal drilling, involving the injection of a mixture of water, sand, and chemicals at high pressure into deep rock formations, have allowed the extraction of oil and gas from shale resources previously believed to be commercially inaccessible. The dramatic increase in hydrocarbon production has been accompanied by a robust debate regarding the potential pros and cons of development. See Bartik et al (2016) and Mason et al. (2015) for recent reviews on the state of research on the economic benefits and negative externalities of the shale gas boom.

Krupnick and Echarte (2017) provide an overview of hedonic valuation studies which use changes in housing prices following shale gas development as indicators of community perceptions about the benefits and costs of such development. These studies have primarily estimated the net benefits of shale gas development (e.g., Bennett and Loomis 2015, Balthrop and Hawley 2017), the impacts of extraction moratoria (e.g. Boslett et al. 2016a), or focused on one important external cost of unconventional oil and gas production: groundwater contamination (e.g. Gopalakrishnan and Klaiber 2014, Muehlenbachs et al. 2015). Indeed, many of the substances involved in fracking operations have been linked to reproductive and developmental health problems and pose a serious threat if drinking water is contaminated (Elliott et al. 2016). Muehlenbachs et al. (2015) estimate that adjacency to shale gas wells (1.5 km or closer) reduces the value of groundwater-dependent homes from 9.9 to 16.5 percent. However, previous studies have mainly focused on the Marcellus shale play or other areas where an increase in seismicity has not been observed and thus have ignored the seismicity risk induced by injection wells.

Our study is the first to estimate the effects of unconventional oil and gas production on housing markets in Oklahoma, an area severely affected by the unprecedented increase in seismicity since 2009, and the first paper to monetize the earthquake risk induced by injection wells. While earthquake risk has been found to negatively affect housing values (Beron et al. 1997, Naoi et al. 2009, Hidano et al. 2015), existing studies consider single, massive earthquakes in large urban areas like San Francisco and Tokyo, with causes independent of wastewater injection activity. A notable exception is a paper by Cheung, Wetherell and Whitaker (2018) which estimates the impact of *experiencing* earthquakes on property values in Oklahoma.[1] Our paper tackles a different question, however. Our focus is on estimating the external cost of *injection wells* in terms of perceived seismicity risk. As we describe in more detail when we present our identification strategy, the risk of a *well inducing* an earthquake is different from the risk of a *house experiencing* an earthquake. Houses could in principle capitalize the seismicity risk associated with injection activity nearby even if they are not directly affected by an earthquake.

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[1] They find that property values decline 3 to 4 percent after a home has experienced a moderate earthquake measuring IV or V on the Modified Mercalli Intensity scale, and decline 9.8 percent after an earthquake above VI.

We use a difference-in-differences hedonic model framework exploiting the distance of properties to injection wells, but also the timing of earthquakes and earthquake characteristics, to estimate the impacts of injection-induced earthquake risk on property values in Oklahoma County. Hedonic pricing models show that the provision of hazard risk information creates price differentials between houses located in different risk zones (Brookshire et al. 1985, Bernknopf et al. 1990, McCluskey and Rausser 2001, Troy and Romm 2004). The occurrence of a hazardous event (e.g. a flood or an earthquake) heightens risk perceptions as reflected by increasing price differentials across risk zones (Bin and Polasky 2004, Carbone et al. 2006, Naoi et al. 2009, Skantz and Strickland 2009, Kousky 2010, Atreya et al. 2013, Bin and Landry 2013).

This finding is consistent with the "availability heuristic" (Tversky and Kahneman 1973), a cognitive heuristic whereby decision makers rely upon knowledge that is readily available (e.g. what is recent or dramatic) rather than searching alternative information sources. Under this explanation, the occurrence of a hazardous event acts as a source of new information, increasing salience and heightening risk perceptions. In a hedonic framework, this translates into a reduction in the value of properties with higher exposure to the risk; e.g. properties in the floodplain after a flood event or properties in earthquake prone areas after an earthquake, in our case. Accordingly, in our paper we use the occurrence of earthquakes, and the distance of properties to injection wells, whose activity is the proximate cause of seismicity in the region, to identify and monetize earthquake risks associated with injection activity.

We find, across multiple indicators of seismicity in the region, that earthquakes have depressed the value of those residential properties in Oklahoma County, OK with injection activity in close proximity (2 km). On average, the price of properties with one injection well within 2 km dropped by 2.4 percent after the 5.6-magnitude 2011 Oklahoma earthquake with epicenter in Prague, Lincoln County, OK. An additional earthquake of magnitude 3 or larger in Oklahoma county has a much smaller effect (0.2 percent), but earthquakes of magnitude 4 and above reduce the price of homes with one injection well in 2 km by 1.6 percent. Our estimates are not confounded by damages to structures which have been very small to date and, in the case of the Prague earthquake, nonexistent for properties in Oklahoma County. Results are also robust to controlling for injection volumes, oil and gas production activity, and drinking water sources. However, we present some evidence that potential groundwater contamination risk is related to injection wells while public water is perceived to be at risk from production wells. In addition, large earthquakes (of magnitude larger than 4) exacerbate the perception of both types of water contamination risk, estimated at 12.4 and 3.9 percent of the price of the average home on private groundwater and in public water serviced areas, respectively.

The rest of the paper proceeds as follows. Section 2 provides additional background on injection wells and their connection to earthquakes in Oklahoma. Section 3 discusses the methodology used to identify the induced-seismicity risk. Data sources are introduced in section 4 along with a brief descriptive analysis. We report the empirical results and robustness checks in section 5. Finally, we conclude with our major findings.

2. Background: Injection Wells and Earthquakes in Oklahoma

The oil and gas industry in Oklahoma dates back more than a century, and it accounts for 10% of the state's GDP (Oklahoma Chamber of Commerce 2014). In 2014 there were 15,560 oil and gas production wells and 8,891 injection wells (Class II underground injection control wells), most of which were concentrated in the east central region of the state.

It is estimated that over two billion gallons of Class II fluids (primarily brines - salt water- brought to the surface while producing oil and gas) are injected in the US every day (EPA

2016) for recovery of residual oil and sometimes gas, or for disposal.[2,3] Most of the injection wells in Oklahoma are injecting water coming not from hydraulic fracturing *per se* but from the "dewatering" of production wells. The water exists in the producing formation and comes up with the oil and natural gas in a recovery process developed in the last decade, known as dewatering (Chesapeake Energy Corporation 2009, OCC 2016). While Oklahoma has only 8% of all injection wells in the CEUS region,[4] it is home to 40% of all injection wells that can be linked to earthquakes. Wells injecting wastewater into the Arbuckle formation, a 7,000-foot-deep sedimentary formation under Oklahoma are the main contributors to the dramatic increase in associated seismicity in that region (Weingarten et al. 2015).

With the increase in seismic activity, much public and media attention has been paid to the connection between earthquakes and unconventional oil and gas production in Oklahoma. A simple keyword search of "Oklahoma earthquakes and fracking" results in over 8,000 news articles since 2010. However, the response from state government officials has lagged. On November 7, 2011, two days after the 5.6-magnitude Oklahoma earthquake with epicenter near Prague, OK, which was at the time the largest earthquake that affected the state since 2009, the governor of Oklahoma declined to address the cause of the earthquake despite multiple studies

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[2] There are two main types of Class II injection wells: saltwater disposal wells (SWD) and enhanced recovery wells (EOR). SWDs are used to dispose of the brines brought to the surface during oil and gas extraction. They make up about 20 percent of the total number of Class II wells in the US (EPA 2016), but in our sample they are about 35 percent. EORs are used to inject fluids to displace extractable oil and gas that are then available for recovery.

[3] The physical appearance of injection wells may vary depending on the injection fluid the well is built for. However, in general, EPA defines injections wells as "a bored, drilled, or driven shaft whose depth is greater than the largest surface dimension; or, a dug hole whose depth is greater than the largest surface dimension; or, an improved sinkhole; or, a subsurface distribution system" (EPA, 2015). For Class II injection wells, the well site usually contains a set of holding tanks for liquids to be injected and a pipe sticking out of the ground to connect the holding tanks with the drilled well. The pipe is typically around 5' to 6' tall. In contrast, production wells are much taller, have large horse heads, walking beams, and large pitman arms for counter weights that move up and down. Their height is typically above 15' to 30' tall. Production wells and injection wells are often near; the correlation between the number of production and injection wells within 2 km of a property in our sample is 0.2174.

[4] Injection wells are geographically clustered in basins and regions of major oil and gas operations; Texas, Oklahoma, Kansas and Wyoming contain approximately 85 percent of all Class II injection wells in the US (Weingarten et al. 2015).

linking the increased seismicity in Oklahoma to injection activity (e.g. Keranen et al 2013, Keranen et al 2014, McGarr 2014). The governor would not publicly link injection wells and earthquakes until early 2015 (Soraghan 2015).

Compared to other states, the response of Oklahoma's Corporation Commission (OCC) to address wastewater injection induced earthquakes has been less aggressive. Rules targeting operators in "areas of interest"[5] in the Arbuckle formation went into effect only in September 2014, merely requiring the provision of more detailed and frequent data on injection volume and pressure. Subsequent regulations in March 2015 expanded the definition of "areas of interest", and require operators to prove that their wells are not in contact with granite basement rock (a major risk factor for triggering earthquakes) (Wertz 2016). We note that the period covered by our analysis, 2010-2014, precedes the tightening of OCC regulations and that, during that period, none of the wells in our sample falls within an "area of interest".

The increase in seismic activity has not resulted in casualties, which are typically the result of earthquakes of magnitudes larger than the ones experienced in Oklahoma so far. The material damages to date have also been small. In our sample, the maximum intensity of the earthquakes experienced in Oklahoma County is 5.54 in the Modified Mercalli Intensity (MMI) scale. In this scale, which goes from I to X, it is only after an intensity of VI (Strong) where the shaking is considered "strong" and one starts experiencing slight physical damage (USGS 1989). For comparison, the earthquake in Prague in 2011, with a moment magnitude of 5.6 and a maximum MMI of VIII (Severe) in the area closest to the epicenter, buckled road pavement and damaged dozens of homes (Summars 2016). Because physical damage to structures has been small to date, it should not contaminate our interpretation of hedonic pricing estimates as reflecting changes in subjective risk perception of injection activity.

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[5] These include wells within 10 km of the epicenter of a magnitude 4 or larger earthquake.

While insurance claims have also been small, insurers have increased premiums and deductibles, and some have stopped writing new earthquake insurance altogether even as demand for earthquake insurance is soaring.[6] This reflects an increasing concern that insurers would be too exposed in the event of a "big one" (Cohen 2016).

3. Methodology

3.1. Impact Categories

We follow Muehlenbachs et al. (2015) categorization of impacts of nearby shale gas activity on housing values. There are *adjacency effects* - costs and benefits associated with close proximity to injection wells. Costs might include noise and light pollution, local air pollution, drinking water contamination, and visual disamenities associated with drilling and injection equipment and cleared land. (Table A.1. details the local external costs of production and injection wells and their drivers). The benefits are mainly royalty or lease payments for the use of the property for wastewater injection. In Oklahoma, it is possible to sever the mineral property rights from surface property rights. Without access to detailed data on leases and deeds, we do not know whether that is the case for the properties in our sample. Thus, like in virtually all previous papers, our estimates are of the overall net effect: the benefits of lease payments for those households who may be receiving them[7] (counterbalanced by those who do not receive them) and the negative externalities of being located near an injection well. We acknowledge, however,

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[6] Earthquake damage is not covered under a regular homeowner's policy. According to the Oklahoma Insurance Department, many Oklahomans have earthquake insurance policies but the coverage protects a home "from catastrophic damage." The typical earthquake insurance policy covers home repairs, replacement of personal property directly damaged by the earthquake, debris removal and living expenses while the home is being repaired or rebuilt. However, most policies do not cover replacement of brick, rock or stone covering the outside of the edifice, damage to the lot, vehicle damage or external water damage (Summars 2016).

[7] For hydraulic fracturing (oil and gas production) wells, the horizontal portion is approximately 1 mile (1.6 km) (US Energy Information Administration 2013). Lease payments would only be made to those households whose property is located above the well. Therefore, the overall effect of proximity is the combined impact on houses receiving payments and houses not receiving them.

that accounting for mineral rights ownership can make a big difference. Boslett et al. (2016b) estimate that houses in Colorado in areas of federal mineral ownership (i.e. without mineral rights) and within one mile of an unconventional drill site sell for 34.8% less than comparable properties without proximate drilling.

There are also *vicinity effects* from the drilling of injection wells. Muehlenbachs et al. (2015) define them as the impact of shale gas development on houses within a broadly defined area (e.g. 20 km) surrounding wells and possibly including increased traffic congestion and road damage from trucks, increased local employment and demand for local goods and services and impacts on local public finance. Considering that Oklahoma City is very spread out and that workers in the shale gas industry typically drive less than 20 miles (30 km) one way to work (Langston 2003), we define the vicinity effect to be in the neighborhood of 30 km of a well. Furthermore, *macro effects* (e.g. recovery of the national economy, mortgage availability) which are not specifically related to shale gas activity are assumed to be common to all properties.

As mentioned in the introduction, an important externality of living in proximity to injection wells, and the focus of our study, is an increase in *Seismicity Risk.* Hydrogeologists and geophysicists consider any earthquake within up to 15 km of an active injection well to be associated with that well (Weingarten et al. 2015). OCC uses a related but less conservative criterion in terms of distance. In its March 2015 regulations to deal with induced seismicity, OCC targeted wells within “areas of interest” covering a 10 km-radius area around the central mass of “seismic swarms.”[8]

Anecdotal evidence suggests that the perception of seismicity risk has been dramatically enhanced by the swarm of earthquakes since 2009. Because earthquakes have provided

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[8] Swarm is defined as an area consisting of at least two events with epicenters within 0.25 miles of one another, with at least one event of magnitude 3 or higher. Previous rules targeted wells within 10 km of the epicenter of an earthquake of magnitude 4 or larger.

information about the seismicity risk associated with active injection wells, we exploit the occurrence of earthquakes and the presence of active injection wells at differing distances of properties in Oklahoma County to identify the perceived seismicity risk of injection wells.

3.2. Identification Strategy

Figure 2 is useful in describing our strategy to identify seismicity risk. Area A represents a 2-km buffer drawn around an active well that defines *adjacency* – being in close proximity to injection wells. In Oklahoma, royalty and lease payments from hydraulic fracturing and wastewater disposal are typically distributed by square mile lines, which means that properties within 2.3 km of a well may be eligible for the benefits. This choice is also consistent with the finding by Muehlenbachs et al. (2015) that properties located less than 2 km from an active shale gas well are most affected by proximity.

We follow Weingarten et al. (2015) in considering any earthquake within 15 km of an active injection well to be associated with that well. Accordingly, a buffer of 15 km around an active injection well defines the "catchment area" for the epicenters of earthquakes *potentially* induced by that well. Area B in Figure 2, located outside the adjacency buffer but within 15 km from the well, helps to isolate the seismicity risk from injection activities from an adjacency effect. Finally, Area C is located outside of both the adjacency buffer and the 15 km spatially-associated earthquake buffer, but is within the vicinity (30 km) of an injection well.

Based on this intuition, in deriving our empirical specification, the price of house i at time t is a function of the number of injection wells surrounding the property at differing distances. Because we are interested in isolating the seismicity risk, which is associated to active injection wells, we consider the wells that were active in the last 3 months preceding the sale of the property. We chose this time window as the average homebuyer searches for approximately 3 months before purchasing a home.[9]

$$(1) \qquad lnP_{it} = \alpha_0 + \alpha_1(wells\ in\ 2\ km)_{it} + \alpha_2(wells\ in\ 2-15\ km)_{it} + \alpha_3(wells\ in\ 15-30\ km)_{it} + \mu_i + v_t + q_t + \epsilon_{it}$$

Equation (1) includes a house fixed effect μ_i to control for any time-invariant unobservable characteristics at the individual property level, temporal fixed effects v_t and q_t indicating the year and quarter of the transaction, respectively, to control for time-varying unobservables at the macro level. ϵ_{it} is the error term. Referring back to Figure 2, properties that fall within area A, i.e. properties with active injection wells within a 2-km buffer, experience adjacency, seismicity and vicinity effects captured by coefficient α_1; properties in the non-overlapping ring B (further than 2 km but closer than 15 km from an active injection well) experience seismicity and vicinity effects (α_2); and properties falling in ring C, beyond 15 km of an active injection well, experience only vicinity effects (α_3). Thus, $\alpha_2 - \alpha_3$ captures the seismicity risk from injection activities, assuming that a well within 15km has the same size impact of vicinity effects than a well within 15-30 km.

The seismic activity experienced in the region since 2009 provides another source of identification. Earthquakes have been felt (with differing intensity) by virtually all the residents in Oklahoma (the Prague earthquake, for example, was felt as far away as Tennessee and Wisconsin, ~1400 km away). We hypothesize that the occurrence of earthquakes has enhanced the perception of seismicity risk, particularly for those living in closer proximity of earthquake-

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[9] According to Zillow, the real estate website, the average buyer searches for 12 weeks before purchasing a home. According to the National Association of Realtors, in 2015 people under 50 spent an average 11 weeks, and those over 50 about 8 weeks searching for a home. (http://www.realtor.org/sites/default/files/reports/2015/2015-home-buyer-and-seller-generational-trends-2015-03-11.pdf). The results were robust to using longer time search windows, of 6 and 12 months, and to using the number of wells active on the day of sale.

inducing injection activity. Thus, we expand equation (1) to include an earthquake variable and its interaction with the number of injection wells:

$$(2) \qquad lnP_{it} = \alpha_0 + \alpha_1(wells\ in\ 2\ km)_{it} + \alpha_2(wells\ in\ 2 - 15\ km)_{it} + \alpha_3(wells\ in\ 15 - 30\ km)_{it} + \alpha_4 EQ_t + \alpha_5(wells\ in\ 2\ km)_{it} * EQ_t + \alpha_6(wells\ in\ 2 - 15\ km)_{it} * EQ_t + \alpha_7(wells\ in\ 15 - 30\ km)_{it} * EQ_t + \mu_i + v_t + q_t + \epsilon_{it}$$

In equation (2), *EQ* denotes *Earthquake* and is an indicator of the seismicity experienced in the area surrounding the property. As noted above, 15 km is the distance that defines the catchment area for the epicenters of earthquakes associated to injection activity (Weingarten et al. 2015), but there have been instances of earthquakes associated with wells at farther distances (Keranen et al 2014). Thus, we include interactions with injection wells at all distances within 30 km.

The first earthquake indicator (*EQ*) is a dummy variable that takes the value of one if the sale happened after Saturday, November 5, 2011, the date of the 2011 Oklahoma (“Prague”) earthquake. Prague is the largest event in our sample, and the largest ever experienced in Oklahoma until the M 5.8 Pawnee earthquake on September 3rd, 2016, garnering considerable national media attention. However, because earthquakes were increasingly being experienced statewide prior to this event (Figure 1), and home prices might have capitalized some of that risk,[10] we employ two alternative sets of seismicity indicators.

The first one is the number of earthquakes with epicenters in Oklahoma County with a magnitude equal to or greater than 3 (or 4) in the 3 months prior to the sale of the property.[11] Earthquakes with magnitude less than 3 are generally not felt, so we only consider those that can be felt by people to reveal their risk perception. The second set of seismicity indicators uses the

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[10] We investigate the anticipation and persistence of a “Prague effect” in more detail in Section 5.3.

[11] As noted above, the average homebuyer searches for approx. 3 months before purchasing a home (footnote 9).

MMI scale, developed by seismologists as a more meaningful severity measure to the nonscientist than magnitude, as it refers to the effects actually felt at a specific place. It is a function of both the distance to the epicenter and the earthquake's magnitude. We use an intensity prediction equation with attenuation coefficients specific to the CEUS region by Atkinson and Wald (2007),[12] which has been shown to provide a good fit for moderate events such as those experienced in Oklahoma (Hough 2014). It is worth noting that MMI is location specific. Accordingly, EQ_t in equation (2) should be replaced with EQ_{it} in specifications using this seismicity indicator.

Assuming that the perception of seismicity risk increases with the frequency and intensity of earthquakes, we sum the MMI of the earthquakes that happened in the 3 months prior to the sale date. It is also possible that people simply ignore or do not even notice smaller earthquakes, thus, we alternatively use the maximum of the MMIs over the same period. Furthermore, the perception of seismicity risk is likely to be shaped by the diffusion of news about earthquakes in local news outlets and through informal interactions with friends and colleagues. We therefore calculate the intensity measures in relation to the earthquakes in both Oklahoma County and the state of Oklahoma.

Between January 2010 and December 2014, all earthquakes with M ≥ 3 in Oklahoma County were associated with at least one active injection well according to the 15-km buffer criterion by Weingarten et al. (2015). However, they do not fall in an "area of interest" as defined by OCC rules enacted in September 2014. Subsequent regulations in March 2015 expanding the definition of "areas of interest", and closures of injection wells in the aftermath of

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[12] $\mathrm{MMI} = 12.08 + 2.36(M-6) + 0.1155(M-6)^2 - 0.44\log_{10}R - 0.002044R + 2.31B - 0.479M\log_{10}R$, where $R = \sqrt{D^2 + 17^2}$, $B = \begin{cases} 0, & R \leq 80 \\ log10(R/80), & R > 80 \end{cases}$. M is the magnitude of an earthquake, D is the distance between the epicenter of the earthquake and the location where it was felt, R is the transition distance in the attenuation shape.

the M 5.8 Pawnee earthquake on September 3rd, 2016 (MMI of V at the population weighted centroid of Oklahoma County) are outside of our study period. Moreover, the Prague earthquake's epicenter in Lincoln County is about 60 km from Oklahoma County, and 34 km from the closest active well in our sample. Thus, we do not believe that the threat of closure of injection wells associated with earthquakes affects the interpretation of our estimates as reflecting the loss of potential rents (for those properties with mineral rights over injection wells). We further note that the legislature and the executive branch in Oklahoma's state government have remained friendly to shale gas development. In May 2015, Oklahoma's governor signed Senate Bill 809 which prohibits cities from enacting oil and gas drilling bans, and allows "reasonable" restrictions for setbacks, noise, traffic issues and fencing.

4. Data

With the increase in the number of earthquakes as well as injection wells concentrated in central and north-central Oklahoma, we focus on Oklahoma County which has experienced the largest number of earthquakes of magnitude 3 or larger since 2010 in this region. As of the 2010 census, its population was 718,633, making it the most populous county in Oklahoma, accounting for 19% of the total population. Oklahoma County is also the most urbanized county in the state being at the heart of the Oklahoma City Metropolitan Statistical Area. This ensures that the property market is sufficiently thick, with enough transactions of relatively uniform properties to help recover unbiased estimates of seismicity risk.

We obtained transaction records of all properties sold in Oklahoma County between January 2010 and December 2014 from PVPlus, a local real estate data provider. The records contain information on the transaction date and price, exact address, and property characteristics (square footage, year built, lot size, number of rooms, etc.) of single family residences. We start with 70,438 unique observations of sale transactions with information on the location of the property. After excluding properties with no list price, a price in the top or bottom 1%, or sold more than once in a single year, we are left with 55,362 observations. We consider only arm's length transactions (i.e., exclude made-to-order homes), thus we drop 6,834 properties sold in the year built. We only include the remaining 48,015 sales of single family residences in our main specifications in order to estimate the impact on (likely) owner-occupied residential homes, rather than properties that are more likely transient or rented. Of these, 8,662 are repeated sales[13] – a necessary condition for including property fixed effects to control for unobserved heterogeneity at the property level.

Data on production and injection activity (location, year and month reported, well type, well status) come from OCC[14] and Weingarten et al. (2015). During the period of analysis (January 2010 to December 2014), there were a total of 189 active Class II injection wells and 368 shale gas production wells in and within 30 km of Oklahoma County. About 65% of the active injection wells operated for the purposes of enhanced oil recovery (EOR), whereas the remaining 35% wells were designated as salt water disposal (SWD) wells. Active SWD wells are more than 1.5 times as likely as active EOR wells to be associated with an earthquake. However, most earthquakes in the CEUS region (66%) are associated with EOR wells (Weingarten et al. 2015). Moreover, it is difficult for a layman to distinguish the two types of wells and we are interested in people's risk perception towards injection activity in general. Thus, the count of injection wells within each buffer includes both types of wells. We count wells that were active in the 3 months prior to the sale of the property.

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[13] Compared with homes sold only once during the sample period, homes sold more than once are slightly more expensive ($6,476 more), larger (133 more square feet), have 0.1 more bedrooms and 0.13 more bathrooms, and a lower proportion (0.6 vs. 1.1 percent) have forced air heating. However, there is no statistical difference between them in terms of total property area, roof and foundation type, and whether there is an attached garage.

[14] http://www.occeweb.com/og/ogdatafiles2.htm.

Earthquake data (origin time, location of epicenter, depth, and magnitude) come from the Oklahoma Geological Survey. During our sample period there were 864 earthquakes with magnitude $M \geq 3$ in the state of Oklahoma. Among these quakes, 24 were of $M \geq 4.0$, and one, in Prague, Lincoln County on November 5, 2011 was of M 5.6. There was a sharp jump in the number of earthquakes in year 2013 with 109 earthquakes of $M \geq 3.0$, and in year 2014 with 578 earthquakes of $M \geq 3.0$, accounting for 70% of all the earthquakes of $M \geq 3.0$ since 2010. Out of the 864 earthquakes with $M \geq 3.0$ in the state, 121 (14%) originated in Oklahoma County. There were only 3 earthquakes with $M \geq 4.0$ in the county and they all took place after 2013. Locations of properties with repeated sales, oil and gas production wells, injection wells, and epicenters of earthquakes with $M \geq 3$ are shown in Figure 3, overlaying with public water serviced areas.

Table 1 displays the summary statistics of the properties in our sample. The average selling price was $159,781. There were 0.84 active injection wells within 2 km of a property in the past 3 months before the house was sold, with a maximum of 15 wells. Between 2 and 15 km of a property, there were 40 injection wells on average, with a maximum of 93. For the outer buffer between 15 and 30 km, 64 injection wells were operating in the past 3 months on average, and the maximum exceeded 100. Homeowners in Oklahoma County experienced an average of 6.65 earthquakes with $M \geq 3$ in the 3 months before they sold the house, while earthquakes with $M \geq 4$ were much less frequent. 75 percent of the properties with repeated sales between 2010 and 2014 were sold after the Prague earthquake.

5. Results

5.1 Main Results

We estimate models (1) and (2) with repeated sales of owner-occupied residential properties in Oklahoma County, controlling for property, year, and quarter fixed effects. Results are presented in Table 2. In the baseline model (equation 1), we estimate the net impacts of having injection wells nearby without accounting for earthquake activity. In the results, reported in column (1), we do not observe any statistically significant impacts of injection wells on housing prices regardless of their proximity, suggesting that the positive effects are offsetting the negative external costs at all distances. However, when we add in earthquake activity in the specification to explicitly estimate how earthquakes enhance the perceived seismicity risk from wastewater injection (equation 2), we find a statistically significant and negative impact brought by the occurrence of earthquakes, that manifests for properties with injection wells in close proximity (in the 2-km buffer), suggesting that earthquakes heighten the perception of seismicity risk associated with injection wells, but only for wells within 2 km of a property, not at farther distances. This impact is robust across alternative seismicity indicators.

In column (2), one additional injection well within 2 km of a property induces a 2.43% lower value for a property sold after the Prague earthquake. As we would expect, an additional earthquake of magnitude 3 or larger (column 3) has a much smaller impact on housing prices than one more earthquake of magnitude 4 or larger (column 4). The former reduces the price of properties with one injection well within 2 km by 0.22% while the latter reduces them by 1.56%.[15] However, there are many more earthquakes with $3 \leq M < 4$ than with $M \geq 4$ in a year, so cumulatively $M \geq 3$ earthquakes have a much larger impact over the course of a year. Using the average price of houses sold in 2014 with one injection well within 2 km, we estimate the per house loss from induced earthquakes with $M \geq 3$ in Oklahoma County to be $19,325 in that year, and $5,831 from $M \geq 4$ earthquakes.

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[15] The two estimates are statistically different from each other at 10% significance level (p-value = .0771). Recall that the average property has 0.84 (almost one) injection wells within 2 km (Table 1).

The two MMI measures in columns (5) and (6), which account for both earthquake magnitude and proximity to the epicenter, are also highly statistically significant when interacted with the number of wells within 2 km. Not surprisingly, the impact for Max(MMI) is larger than for Sum(MMI) suggesting, again, that property prices react more strongly to stronger earthquakes. Overall, results in Table 2 suggest that earthquake activity has altered the perception of seismicity risks associated with wastewater injection, but that homeowners are myopic, only associating these risks to injection wells within 2 km of the property, not at further distances. However, because earthquakes might also increase the saliency of adjacency effects, we check the robustness of our results to this potential confounding effect, as described below.

5.2 Robustness

In this section, we present several robustness checks of our results. We first re-estimate equations (1) and (2) using all the earthquakes with epicenters in the state of Oklahoma (not just in the county). We hypothesize that residents pay more attention to local earthquakes than to those that do not directly affect their lives, but it could be that local earthquakes are smaller and larger earthquakes happen in other counties. Given that information nowadays spreads fairly rapidly and broadly through television, newspapers and social media, we surmise that earthquakes in a broader area are also important in shaping risk perceptions.

Second, we test the impact of using only injection wells that have been associated with earthquakes. Non-associated injection wells entail seismicity risk as they could induce an earthquake in the future even if they have not so far. Nonetheless, we speculate that currently associated injection wells (92 percent of injection wells in our sample) are perceived to be riskier.

Third, we investigate if the estimated impacts (which we interpret as reflecting an increased perception of seismicity risk) are robust to controlling for injection and production volumes which drive adjacency effects. Finally, we compare the main results with those from a pooled OLS model (i.e. a regression that does not include property fixed effects).

5.2.1 All Earthquakes in Oklahoma

Table A.2 reports the results of estimating models (1) and (2) using all the earthquakes in Oklahoma State. Estimates are qualitatively similar to those in Table 2. We do not observe statistically significant effects from proximity to injection wells in the baseline specification. A significant impact associated with seismic activity is observed in the estimates of equation (2), reported in columns (2) - (6), for those properties with injection wells within 2 km. In column (2), the model is the same as that in column (2) of Table 2, therefore, the estimates are identical. The impact of max(MMI) is also almost unchanged. The occurrence of earthquakes with $M \geq 3$, $M \geq 4$, and the sum(MMI), however, all have much smaller impacts on housing prices than before. An additional earthquake of magnitude $M \geq 4$ in the state depresses the value of properties with one injection well within 2 km by 0.51 percent, which is about one third of the effect of a local earthquake of the same magnitude. Although there were more earthquakes with larger magnitude throughout the state, they were farther from the properties in Oklahoma County, thereby, the marginal effects are smaller overall.

5.2.2 Associated Injection Wells

Table 2 reports results for all injection wells, both earthquake-associated and non-associated. We thus re-estimate models (1) and (2) with only associated injection wells. Considering that there were only 3 earthquakes with $M \geq 4$ in Oklahoma County during 2010 – 2014, potentially lacking variation, we re-estimate the models with all earthquakes throughout the state of Oklahoma. Results are presented in Table A.3.[16]

As in previous results, seismic activity depresses housing prices for those properties with injection activity within 2 km. The effects are similar in magnitude to those in Table A.2, although their statistical significance is slightly lower, which might be due to there being fewer associated wells at all distances. Another explanation might be that people perceive injection wells that have already been associated with earthquakes to be less likely to cause more earthquakes and therefore to be less dangerous (i.e., the gambler's fallacy). However, the effects continue to be statistically significant at the 5% level (except for the less frequent $M \geq 4$ earthquakes for which the effect is significant at the 12% level). Moreover, we see a statistically significant impact of associated injection wells within 2 to 15 km of the property (in levels).

Together, these findings suggest that people perceive associated injection wells to be related to seismicity risk. In the baseline specification in column (1), the negative coefficient on wells between 2 and 15 km suggests that there is a seismicity effect (given the insignificance of vicinity effects for wells 15-30 km from the property). A negative seismicity effect is not apparent for wells within 2 km of the property in the baseline model, as this effect is possibly counterbalanced by positive adjacency effects (e.g. royalty receipts). It does become apparent, however, in model (2) that explicitly includes earthquake activity (columns 2-6). For example, after Prague, one additional earthquake-associated injection well within 2 km of a property reduces the value of the property by 2.29%.

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[16] The results for models with only earthquakes in Oklahoma County are comparable, except that the coefficients on seismicity risk for wells within 2 km brought by earthquakes are larger, and earthquakes with $M \geq 4$ are not statistically significant at conventional levels.

5.2.3 Injection and Production Volume

In addition to the perception of seismicity risk, earthquakes might also increase the saliency of adjacency effects. Moreover, both local negative externalities (air, water, noise and light pollution) and earthquakes are driven by injection volumes. To rule out that our interaction estimates are driven by adjacency effects, rather than by an increased perception of seismicity risk, we include in our main specification the injection volume of the wells in each distance buffer in the three months preceding the sale. We also estimated models that control for production volume, and both production and injection volumes. The results for the latter set of models are presented in Table A.4. We do not observe much significance on the injection and production volumes. Only injection volume for wells within 2 km and production volume for wells in 15-30 km are marginally significant (suggesting negative adjacency and positive vicinity effects, respectively), but the interaction terms remain remarkably robust compared to the baseline specification. This increases our confidence that we are indeed identifying a seismicity risk effect, and that our results are not driven by injection activity *per se* but by injection wells being perceived as possibly triggering earthquakes.[17]

Finally, Table A.5 reports results from pooled regressions including all single-family homes. These models control for property characteristics and school district fixed effects, but not for property fixed effects. The results indicate a consistently negative and significant adjacency effect and, in most specifications, negative seismicity and positive vicinity effects. In columns (2) - (6) seismicity *per se* negatively affects all properties, with the effects somewhat exacerbated for properties with injection wells within 2 km and mitigated for those with injection wells at farther distances. We do not place much weight in these results, however. The location of wells can be strategic on the part of oil and gas companies and must be agreed to by the property owner, so it

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[17] Results for the models that included only production volume or only injection volume were similar.

is important to account for all the unobservable attributes that may be correlated with both the property and the proximity to the well (Muehlenbachs et al. 2015, p. 3640). We accomplish that in specifications that control for property fixed effects.

5.3 Placebo Tests: The Anticipation and Persistence of a "Prague" Effect

The evidence presented so far suggests that the occurrence of earthquakes has enhanced the perception of seismicity risk reflected by a price discount for those properties in closer proximity (2 km) of earthquake-inducing injection activity. To identify this effect, we use a range of seismicity indicators, including a Prague-earthquake dummy. In this section we investigate if Prague did indeed mark a before and after or if the price for properties neighboring injection wells was dropping before then given the increasing seismicity trend since 2009, and if the "Prague" effect persisted. We do this by considering fake earthquake dates spanning one year before and one year after November 5, 2011. In total we create twenty-four placebo earthquake dummies in addition to the (real) Prague-earthquake dummy: twelve dummies for the preceding 12 months (sale after 10/5/2011, sale after 9/5/2011, and so on until sale after 11/5/2010), and twelve dummies for the 12 months after Prague (sale after 12/5/2011 all the way until sale after 11/5/2012). We then re-estimate equation (2) and plot the coefficient of the interaction term "Injection wells in 2 km × *Earthquake*" for each of the twenty five regressions in Figure 4.

Figure 4 shows a downward trend in the price differential before Prague. However, the price differential becomes consistently statistically negative (and the trend stabilizes) only around the date of the Prague Earthquake. The effect persists, and the point estimates become even larger for further dates after Prague. This suggests that housing markets were reacting to the increase in earthquake activity before the Prague earthquake, and that this reaction persists afterwards.[18]

5.4 Further Exploration: Mechanisms

The literature posits several links between shale gas development and real estate markets, notably royalties from oil and gas production and water contamination. In this section, we explore the impacts of nearby production wells, water contamination risk, and their interaction with seismicity risk on housing prices.

5.4.1 Impacts of Production Wells

Although only injection (not production) wells are associated with seismicity risk, the public might not know this and might therefore have an incorrect perception that production wells also induce earthquakes, or incorrectly assume that production wells are always in close proximity to injection wells. Production wells are much larger and more conspicuous than injection wells (see footnote 3), adding a potentially strong visual disamenity effect to the suite of external effects of injection wells discussed in Section 3.1. Thus, we expand model (2) with a set of variables indicating the proximity of production wells to isolate the effects of injection-induced seismicity from these potentially confounding effects.[19]

$$(3)\quad lnP_{it} = \alpha_0 + \alpha_1(injection\ wells\ in\ 2\ km)_{it} + \alpha_2(injection\ wells\ in\ 2-15\ km)_{it} + \alpha_3(injection\ wells\ in\ 15-30\ km)_{it} + \alpha_4(production\ wells\ in\ 2\ km)_{it} + \alpha_5(production\ wells\ in\ 2-15\ km)_{it} + \alpha_6(production\ wells\ in\ 15-30\ km)_{it} + \alpha_7 EQ_t + \alpha_8(injection\ wells\ in\ 2\ km)_{it} *$$

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[18] The statistically negative coefficients and trend after the Prague earthquake in Figure 4 suggest the effects might be additional. However, the confidence intervals overlap. Moreover, re-estimating model (2) with a triple interaction of the count of injection wells within 2 km, earthquakes with M ≥ 3 (4), and an after-Prague dummy finds an insignificant triple interaction effect, suggesting that the effects shown by count of earthquakes with magnitude greater than 3 or 4 do not increase after Prague.

[19] See Table 1 for their descriptive statistics. Production wells are more common than injection wells at any distance.

$$EQ_t + \alpha_9(injection\ wells\ in\ 2-15\ km)_{it} * EQ_t + \alpha_{10}(injection\ wells\ in\ 15-30\ km)_{it} * EQ_t + \alpha_{11}(production\ wells\ in\ 2\ km)_{it} * EQ_t + \alpha_{12}(production\ wells\ in\ 2-15\ km)_{it} * EQ_t + \alpha_{13}(production\ wells\ in\ 15-30\ km)_{it} * EQ_t + \mu_i + v_t + q_t + \epsilon_{it}$$

Results are presented in Table 3. Like for injection wells, we do not detect statistically significant impacts of production wells on housing prices regardless of their proximity (in levels), suggesting that the positive and negative effects associated with shale gas production offset each other at all distances. This is also the case in the specifications that include earthquake activity, except for a marginally significant effect of -1.82% for production wells within 2 km in column (6).

The coefficients for injection wells are strikingly similar to those in Table 2 in both significance and magnitude. Seismic activity significantly decreases property prices of houses with injection wells within 2 km across specifications, and in column (2) also marginally for those with wells at farther distances. The statistically indistinguishable estimates of seismicity risk in Tables 2 and 3, and the lack of significance of effects associated with production wells suggest that people correctly perceive production wells as independent from injection wells in triggering earthquakes.

5.4.2 Water Contamination Risk

Earthquakes might disrupt infrastructures, change the pressure beneath the surface and cause underground injection wells to leak, threatening aquifer and in turn drinking water quality. In March 2016, an underground pipe broke and released over 700,000 gallons of wastewater from drilling activities in Oklahoma (Rangel 2016). This pipe belonged to a wastewater injection well and contaminated a nearby public water supply. With some residents on private groundwater especially in rural areas, the contamination risk posed by dewatering techniques and fluid injection may be exacerbated by the occurrence of earthquakes. Muehlenbachs et al. (2015) find an economically and statistically significant groundwater contamination risk from shale gas development in Pennsylvania, where induced earthquakes have not been observed. While the results of Table A.4 suggest that earthquakes do not exacerbate adjacency effects, in this section, we further explore whether earthquakes have intensified water contamination risk. We estimate this effect separately by water source: private groundwater dependent area and public water serviced area (PWSA), and denote the risk as *Groundwater Water* (*GW*) *Contamination Risk* and *Public Water* (*PW*) *Contamination Risk*, respectively.[20]

There is a slight difference in the way we measure water contamination risk for the two types of areas. The distance between injection wells and water supply wells is what is relevant for creating this risk. For private groundwater areas, we do not have exact locations of the private wells, so we simply use a groundwater dummy and the well intensity around the property to reflect groundwater contamination risk. This is a reasonable approximation given that people normally drill groundwater wells on/near their property. For PWSAs, we more accurately measure the intensity of injection wells around the closest public water supply (PWS) well for a property.[21] According to relevant official documents and communication with experts, we

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[20] Private water wells access groundwater, while public water wells access either groundwater or surface water. We use the term groundwater to denote only private groundwater and GWCR for private groundwater contamination risk henceforth. We acknowledge that this is a slightly abuse of the terms.

[21] We understand that some homes may get water from a public water well that is not the closest due to geography or zoning. However, considering that people want to minimize the cost of laying down pipeline, they would prefer the closest public water well. We acknowledge that there may be some measurement error, yet we believe that this assumption is plausible.

choose 1.5 km as the buffer size.[22] We then calculate the number of injection wells within 1.5 km of the closest PWS well to a property to determine the potential public water contamination risk. According to Oklahoma Department of Environmental Quality (ODEQ)[23], there are currently 1,465 public water supply wells in the state of Oklahoma, with Oklahoma County owning the highest number (19%). Sixty percent of the wells in Oklahoma County are groundwater wells that are not under the influence of surface water, 31% are surface water wells, and the remaining 9% are groundwater wells that are under the influence of surface water or surface water wells where the public water authority purchases the rights to the water.

Risk perception of water contamination may be exacerbated by the occurrence of earthquakes; thus, we include interaction terms of water source dummies, number of injection wells in close distance to the water supply well/house, and earthquake indicators. Although we find no evidence that oil and gas production wells are related to seismicity risk in the last section, they might be related to water contamination risk since the extraction process uses substantial amounts of water and produces even larger amounts of wastewater to recycle or dispose, during which pollutants might flow to drinking water sources and cause contamination. Therefore, we

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[22] The hydrogeological literature does not provide a distance for reference, so we resort to official regulations for wellhead protection. The Oklahoma Water Resource Board (OWRB) suggests keeping potential sources of contamination (e.g. septic system and composting areas) at least 50 feet down-gradient from the water supply well location, but does not give a reference distance for injection or shale gas production wells. University of Hawaii at Manoa suggests ¼ mile (0.4 km) as the minimum distance from potable water wells to treated effluent injection wells (Cooperative Extension Service 2000) in December 2000. Michigan's Department of Environmental Quality recommends a 2,000 feet (0.61km) minimum isolation distance between brine wells/injection wells and private and public water wells. We also consulted a groundwater pollution expert at Princeton Groundwater Inc. - Robert W. Cleary - and were told that the State of Florida requires a minimum of 1,500 feet radius from wells in an unconfined aquifer with no known contamination. When there is contamination from a known contamination threat, wells must be located using a 5-year travel time or 2,500 feet (0.76km), whichever is greater from the source of contamination (depends on hydrogeology factors). Finally, according to Advanced Purification Engineering Corp (APEC), the leading manufacturer of residential reverse-osmosis drinking water filtration systems in the United States, the water we drink probably entered the ground less than a mile (1.6km) from our water supply wells if they are on ground water. Given that public water supply wells are either on surface water or ground water, we choose the largest distance from these regulations and company suggestions and use 1.5km as the approximate buffer to calculate the injection well intensity around public water supply wells to measure the risk of injection activities on public water sources.

[23] http://gis.deq.ok.gov/maps/.

include the set of variables related to production wells in model (4) as well. The extended model can then be written as:

$$(4) \qquad lnP_{it} = \alpha_0 + \boldsymbol{\alpha_1}(wells\ in\ 2\ km)_{it} + \boldsymbol{\alpha_2}(wells\ in\ 2-15\ km)_{it} + \boldsymbol{\alpha_3}(wells\ in\ 15-30\ km)_{it} + \boldsymbol{\alpha_4}(wells\ in\ 2\ km)_{it} *\ GW_i + \boldsymbol{\alpha_5}(wells\ in\ 1.5\ km\ of\ PWS\ well)_{it} * PWSA_i + \alpha_6 EQ_t + \boldsymbol{\alpha_7}(wells\ in\ 2\ km)_{it} * EQ_t + \boldsymbol{\alpha_8}(wells\ in\ 2-\ 15\ km)_{it} *\ EQ_t + \boldsymbol{\alpha_9}(wells\ in\ 15-\ 30\ km)_{it} *\ EQ_t + \boldsymbol{\alpha_{10}}(wells\ in\ 2\ km)_{it} *\ EQ_t *\ GW_i + \boldsymbol{\alpha_{11}}(wells\ in\ 1.5\ km\ of\ PWS\ well)_{it} *\ EQ_t * PWSA_i +\ \mu_i + v_t + q_t +\ \epsilon_{it}$$

GW and *PWSA* denote whether the property relies on private groundwater or is on a PWSA. The other variables are defined as in model (3), and *wells* refers to either injection wells or production wells. $\boldsymbol{\alpha_4}$ and $\boldsymbol{\alpha_5}$ capture groundwater and public water contamination risk associated with the proximity of wells without earthquakes, and $\boldsymbol{\alpha_{10}}$ and $\boldsymbol{\alpha_{11}}$ measure the additional water contamination risk perception brought by earthquakes to groundwater dependent and public water dependent homes, respectively.

We obtained the GIS boundaries of the PWSAs in Oklahoma from the Oklahoma Comprehensive Water Plan and assume that any property outside these boundaries is groundwater dependent. Public water service is available in most of the regions in Oklahoma County (Figure 2); only 13% of our properties are dependent on groundwater. We further acquired the locations of each PWS well in Oklahoma from Oklahoma Department of Environmental Quality.

Table 4 presents the regression results. For groundwater contamination risk, estimates from both wastewater injection and shale gas production activity are statistically insignificant regardless of model specification. There seems to be some significant public water contamination risk associated with production activity, however. One more production well within 1.5 km of a house's PWS well reduces its value by ~5% in the baseline specification. This effect is not observed for injection wells around PWS wells, suggesting that pollution to public water is perceived to be most likely through surface water, such as partially-treated wastewater to rivers or streams or accidental releases of contaminants, while injection wells operate deep underground and are seen as less likely to contaminate surface water.

We find that the additional water contamination risk brought by earthquakes is generally small and not significant except for large ($M \geq 4$) earthquakes. One thing worth noting is that this additional risk is much larger for homes dependent upon private groundwater than for those on public water. For groundwater dependent homes with one injection well within 2 km, the occurrence of a $M \geq 4$ earthquake reduces their value by 12.39% on average, whereas, for a public water serviced home, the risk is associated with production wells and is much smaller (a reduction in value of 3.9%). This suggests that injection wells are perceived to be a substantial threat to groundwater but not surface water. The effect is much larger than the average effect in the main specification. The results are, however, exploratory, due to the small number of observations. Only 0.37% of the repeated sales are from homes that are simultaneously (i) on groundwater, (ii) located within 2 km of at least one active injection well, and (iii) had at least one magnitude 4+ earthquake in the 3 months preceding the sale. Using these estimated impacts from GWCR and PWCR (column 4 in Table 4, triple interaction terms) and the average price of houses sold in year 2014 with one injection well within 2 km (one production well within 1.5 km from the PWS well), we calculate that the average loss per home resulting from the perception of water contamination risk brought by $M \geq 4$ earthquakes is \$23,157 and \$7,200 for homes on groundwater and in public water serviced areas, respectively.

Finally, we note that the estimates of seismicity risk resulting from injection wells in proximity (2 km) of the property are very similar to those in Tables 2 and 3. Production wells are overall not perceived to be associated with seismicity, regardless of the distance between the wells and the properties, and the occurrence of earthquakes does not alter risk perceptions.

6. Conclusion

Development of shale deposits has increased dramatically due to advances in technology, generating substantial debate about the benefits of a relatively cleaner domestic fuel and the local negative impacts associated with the extraction technology. Bartik et al. (2016) estimate positive net benefits at the local level; the mean willingness-to-pay for allowing fracking equals about $1,300 to $1,900 per household annually among original residents of counties with high fracking potential. However, there is abundant heterogeneity in the WTP measures among homeowners and across shale plays.

A big concern in the Central and Eastern US since 2009 is the increase in seismicity induced by fluid injection wells (Ellsworth 2013, Weingarten et al. 2015). Our paper is the first to identify the induced seismicity risk and specifically measure the net capitalization of benefits and costs of shale gas development at various levels of proximity and seismicity exposure in housing prices in Oklahoma County.

Our identification strategy exploits the timing of earthquakes, earthquake intensity and location, the distance of properties to injection wells (and production wells), and drinking water sources. We find that seismic activity has lowered housing prices in Oklahoma County, but the impact is limited to houses with injection wells within 2 km distance. The results are robust to using a variety of earthquake indicators – a “Prague” shock, the number of earthquakes with $M \geq 3$ and $M \geq 4$, and the sum and max of Modified Mercalli Intensity of earthquakes in both

Oklahoma County and throughout the state of Oklahoma. Further, the estimated effects are not confounded by damages caused by earthquakes, and are robust to controlling for injection activity, oil and gas production activity, and the type of drinking water source. Using data on houses with one injection well within 2 km and sold in the most recent year (2014), we calculate the average loss for properties in Oklahoma County to be $4,541 (2.4%) after the Prague earthquake. Similarly, we calculate the average property value loss due to one additional $M \geq 3$ and $M \geq 4$ earthquake in Oklahoma County to be $411 (0.2%) and $2,916 (1.6%), respectively.

In contrast, our results suggest that shale oil and gas production wells are not perceived to induce earthquakes. The science makes clear that injection wells increase earthquake risk, and it seems that people are actually able to differentiate injection wells from production wells as the trigger of earthquakes. We also find that large earthquakes ($M \geq 4$) exacerbate water contamination risk, both for properties dependent upon private and public water services. Interestingly, residents in Oklahoma County seem to be able to distinguish the causes of water contamination associated with shale gas development. They correspond wastewater injection wells with groundwater contamination, and oil and gas production wells with potential public water contamination.

Overall, we believe that our findings can be interpreted as evidence of availability heuristic bias in the perception of risks associated with injection activity. A negative impact of injection wells in hedonic prices is observed only when accounting for seismic activity, suggesting that earthquakes provide information that updates the subjective perception of injection risks and only for properties in close proximity of injection wells.

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Table 1. Summary Statistics

Description			Obs	Mean	SD	Min	Max
Properties	Selling price (k $ 2010 Q4)		8662	159.78	128.61	2.92	827.41
	Injection wells in 2 km		8662	0.84	1.8	0.00	15.00
	Injection wells in 2 -15 km		8662	39.71	24.07	6.00	93.00
	Injection wells in 15 - 30 km		8662	64.4	27.79	15.00	127.00
	Associated injection wells in 2 km		8662	0.78	1.71	0.00	14.00
	Associated injection wells in 2 -15 km		8662	36.66	21.87	4.00	88.00
	Associated injection wells in 15 - 30 km		8662	59.53	26.38	14.00	127.00
	Production wells in 2 km		8662	1.57	2.06	0.00	27.00
	Production wells in 2 -15 km		8662	86.32	30.26	10.00	247.00
	Production wells in 15 - 30 km		8662	165.27	66.85	52.00	721.00
	Injection volume of wells in 2 km (million blue barrels)		8662	0.13	0.81	0.00	15.46
	Injection volume of wells in 2 - 15 km (million blue barrels)		8662	5.42	6.53	0.03	24.17
	Injection volume of wells in 15 - 30 km (million blue barrels)		8662	9.80	6.91	0.09	26.26
	Production volume of wells in 2 km (billion cubic feet)		8662	0.01	0.02	0.00	0.25
	Production volume of wells in 2 - 15 km (billion cubic feet)		8662	0.02	0.03	0.00	0.28
	Production volume of wells in 15 - 30 km (billion cubic feet)		8662	0.55	0.24	0.06	3.76
	1 = Public water serviced (PWS) area		8662	0.87	0.34	0.00	1.00
	Injection wells in 1.5 km of PWS well		8662	0.66	1.57	0.00	13.00
	Production wells in 1.5 km of PWS well		8662	0.60	1.06	0.00	10.00
	1 = Sale after November 5, 2011		8662	0.75	0.43	0.00	1.00
Earthquakes	In Oklahoma County	Earthquakes with M ≥ 3	8662	6.65	6.85	0.00	26.00
		Earthquakes with M ≥ 4	8662	0.20	0.56	0.00	2.00
		Sum(MMI)	8662	23.56	24.91	0.00	100.06
		Max(MMI)	8662	3.48	1.31	0.00	5.54
	In Oklahoma State	Earthquakes with M ≥ 3	8662	43.50	53.17	0.00	195.00
		Earthquakes with M ≥ 4	8662	1.30	1.72	0.00	6.00
		Sum(MMI)	8662	124.45	148.55	0.00	538.60
		Max(MMI)	8662	3.90	0.94	0.00	6.06

Table 2. Log(Price) on Number of Injection Wells

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0012	0.0244	0.0160	0.0051	0.0156	0.0359
	(0.0293)	(0.0298)	(0.0294)	(0.0294)	(0.0294)	(0.0303)
Injection wells in 15 km	0.0008	0.0032	0.0021	0.0005	0.0022	-0.0022
	(0.0037)	(0.0043)	(0.0044)	(0.0040)	(0.0044)	(0.0047)
Injection wells in 30 km	-0.0012	-0.0002	-0.0004	-0.0008	-0.0003	-0.0011
	(0.0027)	(0.0034)	(0.0030)	(0.0028)	(0.0030)	(0.0035)
Earthquake		0.1008	0.0049	0.0102	0.0015	-0.0401
		(0.1844)	(0.0129)	(0.1550)	(0.0035)	(0.0589)
Injection wells in 2 km × *Earthquake*		-0.0243**	-0.0022***	-0.0156**	-0.0006***	-0.0123***
		(0.0095)	(0.0007)	(0.0078)	(0.0002)	(0.0035)
Injection wells in 2 - 15 km × *Earthquake*		-0.0017	-0.0000	0.0004	-0.0000	0.0006
		(0.0019)	(0.0001)	(0.0015)	(0.0000)	(0.0006)
Injection wells in 15 - 30 km × *Earthquake*		-0.0014	-0.0000	-0.0001	-0.0000	0.0002
		(0.0017)	(0.0001)	(0.0014)	(0.0000)	(0.0005)
Constant	11.4801***	11.3082***	11.3643***	11.4641***	11.3549***	11.6170***
	(0.2746)	(0.3193)	(0.3095)	(0.2836)	(0.3089)	(0.3646)
Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.170	0.172	0.173	0.171	0.173	0.175

Notes: (1) Each column represents a separate regression. The dependent variable in all regressions is the log sale price. The price is adjusted using the housing price index (HPI) from the Federal Housing Finance Agency. We use the HPI for Metropolitan Statistical Areas and Divisions for sales of properties in Oklahoma City, and the HPI for Oklahoma State Nonmetropolitan Areas for all the other sales. We set the price index in quarter 4, year 2010 as 100.

(2) *Earthquake* = Prague, Number of Earthquakes with M ≥ 3, Number of Earthquakes with M ≥ 4, Sum(MMI), and Max(MMI), as indicated by the column headings. Only earthquakes with epicenters in Oklahoma County in the previous 3 months before the sale are included in specifications (3) – (6).

(3) Property, Year and Quarter fixed effects are included in all specifications. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

Table 3. Log(Price) on Number of Injection Wells and Shale Gas Production Wells

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0002	0.0276	0.0143	0.0053	0.0139	0.0385
	(0.0293)	(0.0299)	(0.0298)	(0.0298)	(0.0298)	(0.0304)
Injection wells in 2 -15 km	-0.0001	0.0032	0.0016	0.0002	0.0017	-0.0017
	(0.0038)	(0.0044)	(0.0044)	(0.0041)	(0.0044)	(0.0048)
Injection wells in 15 - 30 km	-0.0013	-0.0021	-0.0009	-0.0011	-0.0008	-0.0024
	(0.0027)	(0.0035)	(0.0030)	(0.0028)	(0.0030)	(0.0036)
Production wells in 2 km	-0.0048	-0.0069	-0.0079	-0.0052	-0.0080	-0.0182*
	(0.0094)	(0.0109)	(0.0094)	(0.0095)	(0.0094)	(0.0109)
Production wells in 2 -15 km	0.0002	-0.0009	0.0002	0.0004	0.0002	0.0001
	(0.0009)	(0.0009)	(0.0009)	(0.0009)	(0.0009)	(0.0010)
Production wells in 15 - 30 km	0.0005	0.0001	0.0006	0.0005	0.0006	0.0007
	(0.0004)	(0.0005)	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Earthquake		0.0856	0.0044	-0.0143	0.0014	-0.0432
		(0.1851)	(0.0131)	(0.1571)	(0.0036)	(0.0598)
Injection wells in 2 km × *Earthquake*		-0.0319***	-0.0023***	-0.0187**	-0.0007***	-0.0135***
		(0.0097)	(0.0007)	(0.0082)	(0.0002)	(0.0036)
Injection wells in 2 - 15 km × *Earthquake*		-0.0035*	-0.0000	0.0001	-0.0000	0.0006
		(0.0020)	(0.0001)	(0.0015)	(0.0000)	(0.0006)
Injection wells in 15 - 30 km × *Earthquake*		-0.0033*	0.0000	-0.0004	-0.0000	0.0005
		(0.0018)	(0.0001)	(0.0014)	(0.0000)	(0.0006)
Production wells in 2 km × *Earthquake*		0.0061	0.0002	0.0067	0.0001	0.0038
		(0.0080)	(0.0006)	(0.0074)	(0.0002)	(0.0025)
Production wells in 2 - 15 km× *Earthquake*		0.0021***	0.0000	0.0009	0.0000	0.0001
		(0.0007)	(0.0001)	(0.0007)	(0.0000)	(0.0002)
Production wells in 15 - 30 km× *Earthquake*		0.0001	-0.0000	-0.0001	-0.0000	-0.0001
		(0.0004)	(0.0000)	(0.0003)	(0.0000)	(0.0001)
Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.171	0.174	0.174	0.172	0.174	0.175

Notes: Constants not reported to save space. See notes to Table 2.

Table 4. Log(Price) on Number of Injection and Production Wells Accounting for Water Contamination Risk

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0115	0.0406	0.0283	0.0182	0.0284	0.0678*
	(0.0340)	(0.0360)	(0.0356)	(0.0352)	(0.0356)	(0.0390)
Injection wells in 2 -15 km	0.0006	0.0032	0.0023	0.0005	0.0024	-0.0011
	(0.0038)	(0.0044)	(0.0044)	(0.0041)	(0.0044)	(0.0049)
Injection wells in 15 - 30 km	-0.0021	-0.0033	-0.0019	-0.0022	-0.0018	-0.0031
	(0.0028)	(0.0035)	(0.0030)	(0.0028)	(0.0030)	(0.0036)
Production wells in 2 km	0.0072	0.0001	-0.0006	0.0054	-0.0008	-0.0073
	(0.0121)	(0.0137)	(0.0124)	(0.0123)	(0.0124)	(0.0140)
Production wells in 2 -15 km	0.0007	-0.0005	0.0007	0.0009	0.0007	0.0007
	(0.0009)	(0.0010)	(0.0009)	(0.0009)	(0.0009)	(0.0011)
Production wells in 15 - 30 km	0.0003	0.0000	0.0003	0.0002	0.0003	0.0004
	(0.0004)	(0.0005)	(0.0005)	(0.0004)	(0.0005)	(0.0005)
GW × Injection wells in 2 km	-0.0911	-0.0741	-0.0595	-0.0783	-0.0567	-0.0102
	(0.1355)	(0.1492)	(0.1434)	(0.1280)	(0.1422)	(0.1538)
GW × Production wells in 2 km	0.0398	0.0465	0.0369	0.0329	0.0361	0.0184
	(0.0532)	(0.0566)	(0.0552)	(0.0537)	(0.0550)	(0.0667)
PWSA × Injection wells in 1.5 km of PWS well	-0.0053	-0.0186	-0.0086	-0.0044	-0.0100	-0.0460
	(0.0486)	(0.0555)	(0.0512)	(0.0502)	(0.0512)	(0.0554)
PWSA × Production wells in 1.5 km of PWS well	-0.0517**	-0.0308	-0.0363	-0.0492**	-0.0362	-0.0521*
	(0.0240)	(0.0276)	(0.0252)	(0.0242)	(0.0251)	(0.0316)
Earthquake		0.0403	0.0046	-0.0218	0.0014	-0.0454
		(0.1899)	(0.0130)	(0.1542)	(0.0036)	(0.0595)
Injection wells in 2 km × *Earthquake*		-0.0324**	-0.0025***	-0.0137	-0.0007***	-0.0188***
		(0.0132)	(0.0009)	(0.0103)	(0.0003)	(0.0054)
Injection wells in 2 - 15 km × *Earthquake*		-0.0030	-0.0000	0.0002	-0.0000	0.0006
		(0.0020)	(0.0001)	(0.0015)	(0.0000)	(0.0006)
Injection wells in 15 - 30 km × *Earthquake*		-0.0026	0.0000	-0.0002	0.0000	0.0004
		(0.0019)	(0.0001)	(0.0014)	(0.0000)	(0.0006)
Production wells in 2 km× *Earthquake*		0.0050	0.0008	0.0160*	0.0002	0.0034
		(0.0098)	(0.0007)	(0.0093)	(0.0002)	(0.0030)

Production wells in 2 - 15 km× *Earthquake*		0.0021***	0.0000	0.0007	0.0000	0.0001
		(0.0007)	(0.0001)	(0.0007)	(0.0000)	(0.0002)
Production wells in 15 - 30 km× *Earthquake*		-0.0000	-0.0000	-0.0001	-0.0000	-0.0001
		(0.0004)	(0.0000)	(0.0003)	(0.0000)	(0.0001)
GW × Injection wells in 2 km × *Earthquake*		0.0263	-0.0041	-0.1239**	-0.0012	-0.0230
		(0.0902)	(0.0053)	(0.0535)	(0.0014)	(0.0256)
GW × Production wells in 2 km× *Earthquake*		0.0336	0.0007	0.0101	0.0002	0.0064
		(0.0294)	(0.0022)	(0.0264)	(0.0006)	(0.0116)
PWSA × Injection wells in 1.5 km of PWS well × *Earthquake*		0.0050	0.0006	-0.0022	0.0002	0.0110*
		(0.0174)	(0.0010)	(0.0146)	(0.0003)	(0.0064)
PWSA × Production wells in 1.5 km of PWS well × *Earthquake*		-0.0085	-0.0024*	-0.0390**	-0.0007*	0.0024
		(0.0208)	(0.0014)	(0.0187)	(0.0004)	(0.0063)
Constant	11.3945***	11.5413***	11.3094***	11.3933***	11.2976***	11.5521***
	(0.2791)	(0.3323)	(0.3077)	(0.2873)	(0.3077)	(0.3618)
Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.172	0.175	0.175	0.174	0.175	0.177

Notes: See notes to Table 2.

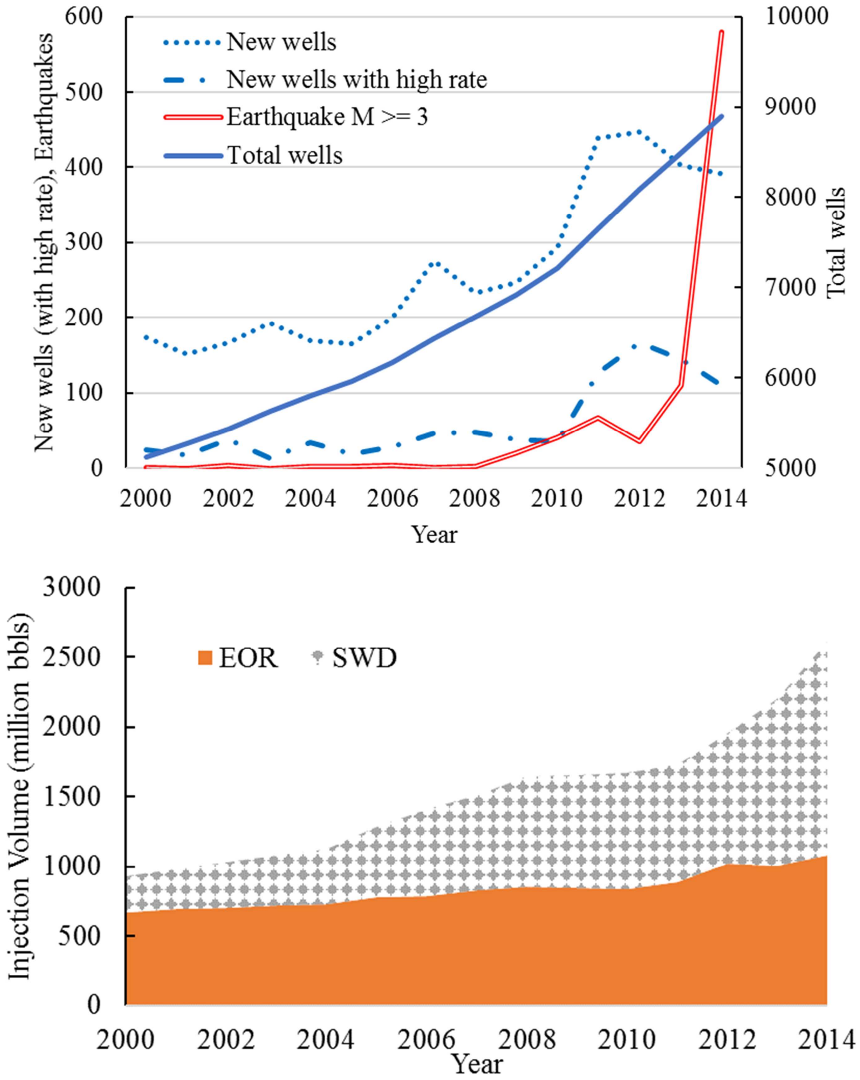

Figure 1. Number of Injection Wells, Injection Volume, and Earthquakes of Magnitude 3+ in Oklahoma since 2000

Notes: Injection wells in the State of Oklahoma are Class II injection wells, including saltwater disposal wells (SWD) and enhanced recovery wells (EOR). New wells are the number of injection wells newly approved each year. New wells with high rate are injection wells with annual injection rates of more than 5,000 blue barrels. Total wells are the accumulated number of all injection wells.

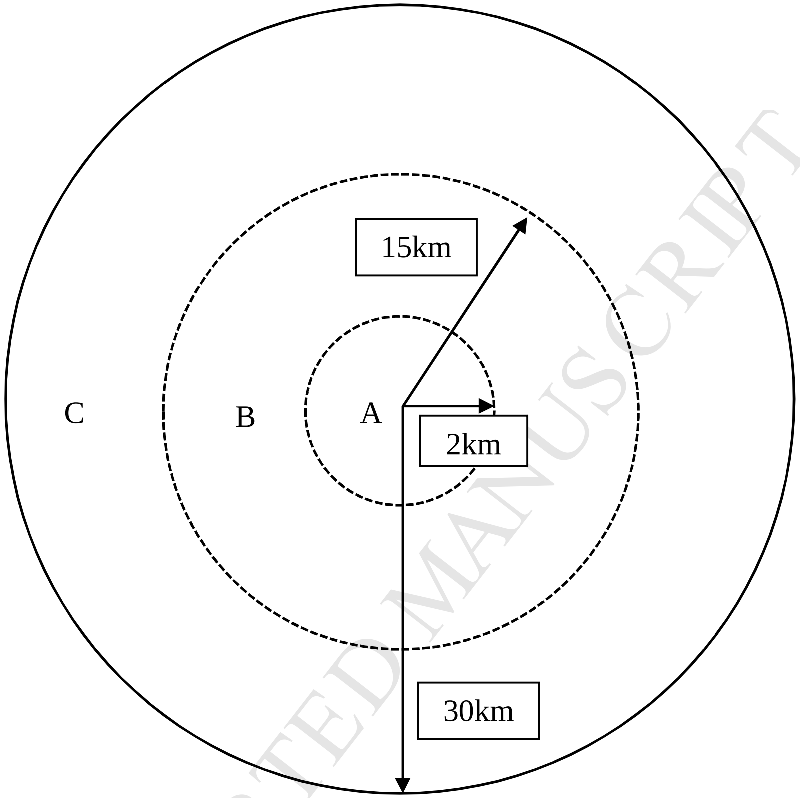

Figure 2. Types of Areas Examined

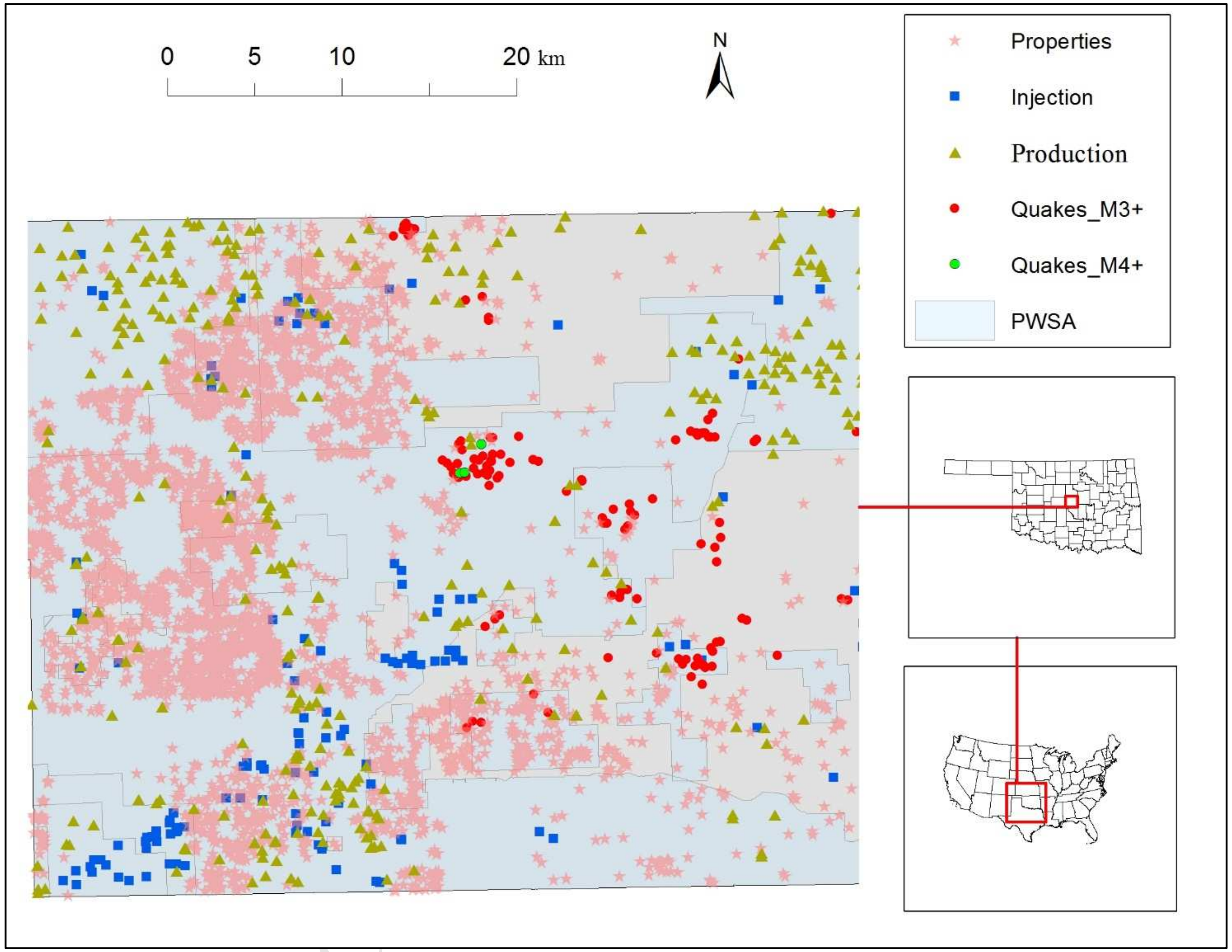

Figure 3. Location of Properties, Wells, Earthquakes, and Public Water Service Areas

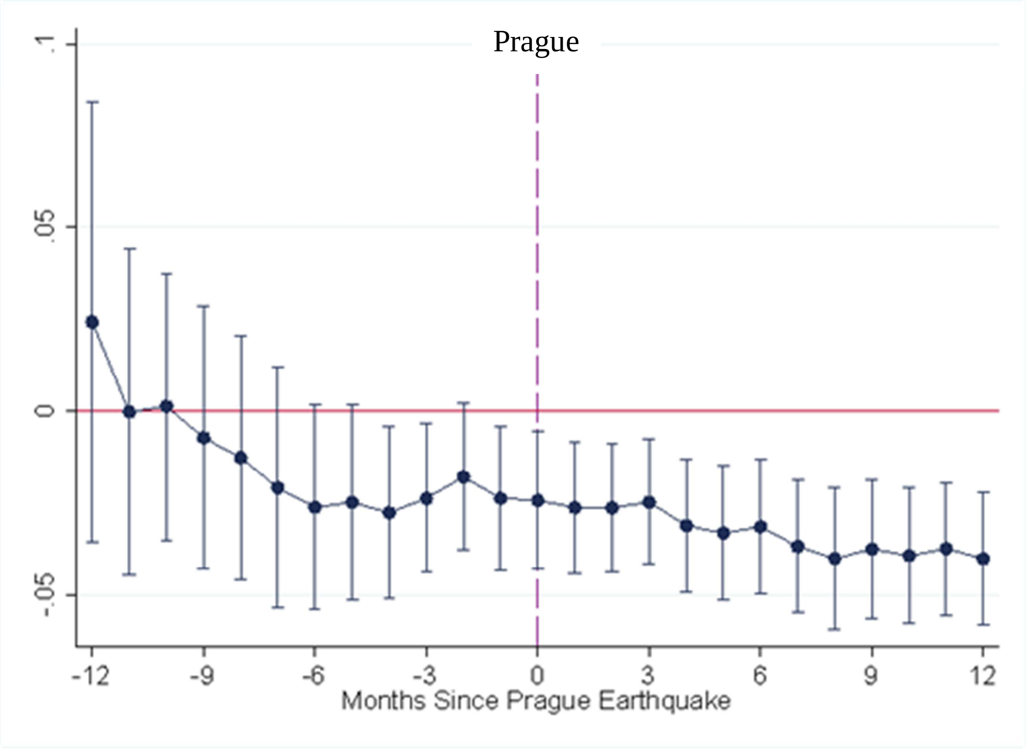

Figure 4. Prague Earthquake Effect -Placebo exercise

Notes: The connected dots are coefficients on the variable (Injection wells in 2 km × *Earthquake*) from the main model (eq. (2)), estimated with alternative dates for the Prague earthquake. Each coefficient corresponds to a separate regression. In the horizontal axis, at 0, *Earthquake* corresponds to the Prague earthquake, and it is a dummy that takes a value of 1 after November 5, 2011. For other values, they are placebo/fake earthquake dummies before or after Prague. For example, if the value on the x-axis is -6, then the *Earthquake* dummy equals 1 if the home was sold after May 5, 2011, 0 otherwise (that is, as if Prague had taken place on May 5, 2011). If the value is 3, then the placebo earthquake dummy equals 1 if the home was sold after February 5, 2012, 0 otherwise. The bars are the 95% confidence intervals.

Appendix A

Table A.1. Major Environmental Impacts of Production and Injection Wells and their Drivers

Impact Categories	**Production Wells**	**Injection Wells**
Noise	Site preparation Heavy transport equipment of fracking fluids, wastewater, oil and gas Fracking operation (drilling, hydraulic fracturing, flaring, compressor stations)	Site preparation Heavy transport equipment wastewater/residual oil Injecting operation (pump and fluid handling noise)
Light pollution	Producing sites Increased traffic	Injecting sites Increased traffic
Air pollution (volatile organic compounds, oxides of nitrogen tropospheric ozone, diesel particulate matter, airborne silica)	Emissions from gas-processing equipment Emissions from heavy transport equipment Underground methane leakage	Emissions from heavy transport equipment Emissions from wastewater injection equipment
Visual disamenities	Land clearance to build fracking sites and for road expansion Above ground storage infrastructure Above ground equipment	Land clearance to build injection wells and for road expansion Above ground storage infrastructure Above ground equipment
Water pollution (benzene, hydrocarbons, endocrine-disrupting chemicals, heavy metals)	Surface spills and leakage from above ground-storage Fracking fluid leak, oil and methane leak, wastewater	Surface spills and wastewater leakage from above ground and underground storage
Seismic activities	Rarely	Mainly wastewater injection, enhanced oil recovery causes fewer earthquakes

Notes: (1) Table focuses on local externalities; we omit the contribution of fracking to greenhouse gas emissions (a global externality). (2) Assessment of potential local risks has been difficult in the U.S. because drilling operators are not required to disclose which chemicals are used (Kovats et al 2014). (3) Production wells include both vertical and horizontal producing wells. (4) Sources:

Litovitz et al. (2012); McKenzie et al. (2012); Miller et al. (2013); Warner et al. (2013); Hays et al. (2017); Roy and Robinson (2014); Kovats et al (2014); Rubinstein and Mahani (2015).

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Table A.2. Log(Price) on Number of Injection Wells, All Earthquakes in Oklahoma

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0012	0.0244	0.0125	0.0062	0.0126	0.0331
	(0.0293)	(0.0298)	(0.0298)	(0.0298)	(0.0299)	(0.0318)
Injection wells in 2 -15 km	0.0008	0.0032	-0.0021	0.0003	-0.0018	-0.0075
	(0.0037)	(0.0043)	(0.0053)	(0.0046)	(0.0054)	(0.0055)
Injection wells in 15 - 30 km	-0.0012	-0.0002	0.0019	-0.0006	0.0019	-0.0046
	(0.0027)	(0.0034)	(0.0030)	(0.0029)	(0.0030)	(0.0043)
Earthquake		0.1008	0.0021	-0.0044	0.0008	-0.1253
		(0.1844)	(0.0017)	(0.0533)	(0.0006)	(0.0783)
Injection wells in 2 km ×		-0.0243**	-0.0003***	-0.0051*	-0.0001***	-0.0113**
Earthquake		(0.0095)	(0.0001)	(0.0028)	(0.0000)	(0.0044)
Injection wells in 2 - 15 km ×		-0.0017	-0.0000	0.0002	-0.0000	0.0014*
Earthquake		(0.0019)	(0.0000)	(0.0006)	(0.0000)	(0.0008)
Injection wells in 15 - 30 km ×		-0.0014	-0.0000	0.0000	-0.0000	0.0008
Earthquake		(0.0017)	(0.0000)	(0.0005)	(0.0000)	(0.0007)
Constant	11.4801***	11.3082***	11.4014***	11.4561***	11.3844***	12.0913***
	(0.2746)	(0.3193)	(0.3094)	(0.3070)	(0.3125)	(0.4480)
Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.170	0.172	0.173	0.171	0.173	0.174

Notes: All the earthquakes with epicenters in the State of Oklahoma in the previous 3 months before the sale are included. See notes to Table 2.

Table A.3. Log(Price) on Number of Associated Injection Wells, All Earthquakes in Oklahoma

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0112	0.0306*	0.0177	0.0115	0.0176	0.0493**
	(0.0154)	(0.0164)	(0.0158)	(0.0159)	(0.0158)	(0.0208)
Injection wells in 2 -15 km	-0.0038**	-0.0025	-0.0019	-0.0063***	-0.0020	-0.0074**
	(0.0015)	(0.0024)	(0.0027)	(0.0023)	(0.0027)	(0.0037)
Injection wells in 15 - 30 km	-0.0004	0.0008	0.0014	-0.0015	0.0014	-0.0028
	(0.0011)	(0.0019)	(0.0018)	(0.0016)	(0.0019)	(0.0032)
Earthquake		0.0664	0.0016	-0.0575	0.0006	-0.0863
		(0.1841)	(0.0015)	(0.0453)	(0.0006)	(0.0738)
Injection wells in 2 km ×		-0.0229**	-0.0003**	-0.0055	-0.0001**	-0.0120**
Earthquake		(0.0097)	(0.0001)	(0.0035)	(0.0000)	(0.0049)
Injection wells in 2 - 15 km ×		-0.0012	-0.0000	0.0006	-0.0000	0.0009
Earthquake		(0.0019)	(0.0000)	(0.0005)	(0.0000)	(0.0008)
Injection wells in 15 - 30 km ×		-0.0011	-0.0000	0.0006	-0.0000	0.0006
Earthquake		(0.0017)	(0.0000)	(0.0004)	(0.0000)	(0.0007)
Constant	11.6001***	11.4659***	11.4243***	11.7615***	11.4263***	11.9572***
	(0.1078)	(0.1985)	(0.2026)	(0.1777)	(0.2083)	(0.3322)
Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.172	0.173	0.173	0.173	0.173	0.175

Notes: All the earthquakes with epicenters in the State of Oklahoma in the previous 3 months before the sale are included. See notes to Table 2.

Table A.4. Log(Price) on Number of Injection Wells, and Injection and Production Volume

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	0.0138	0.0367	0.0305	0.0180	0.0301	0.0502*
	(0.0292)	(0.0297)	(0.0294)	(0.0293)	(0.0294)	(0.0303)
Injection wells in 2- 15 km	-0.0007	0.0024	0.0016	-0.0010	0.0016	-0.0025
	(0.0039)	(0.0045)	(0.0046)	(0.0042)	(0.0046)	(0.0050)
Injection wells in 15 - 30 km	-0.0023	-0.0018	-0.0016	-0.0018	-0.0015	-0.0021
	(0.0028)	(0.0035)	(0.0031)	(0.0029)	(0.0031)	(0.0037)
Earthquake		0.0848	0.0068	0.0164	0.0020	-0.0329
		(0.1848)	(0.0128)	(0.1541)	(0.0035)	(0.0592)
Injection wells in 2 km × *Earthquake*		-0.0238**	-0.0023***	-0.0160**	-0.0007***	-0.0125***
		(0.0095)	(0.0007)	(0.0078)	(0.0002)	(0.0035)
Injection wells in 2 - 15 km × *Earthquake*		-0.0018	-0.0000	0.0003	-0.0000	0.0005
		(0.0019)	(0.0001)	(0.0015)	(0.0000)	(0.0006)
Injection wells in 15 - 30 km × *Earthquake*		-0.0012	-0.0000	-0.0002	-0.0000	0.0002
		(0.0017)	(0.0001)	(0.0013)	(0.0000)	(0.0005)
Injection volume wells in 2 km	-0.0508*	-0.0520*	-0.0507*	-0.0510*	-0.0506*	-0.0500*
	(0.0295)	(0.0292)	(0.0296)	(0.0295)	(0.0296)	(0.0296)
Injection volume wells in 2 - 15 km	-0.0005	-0.0016	-0.0013	-0.0008	-0.0013	-0.0014
	(0.0044)	(0.0044)	(0.0044)	(0.0044)	(0.0044)	(0.0045)
Injection volume wells in 15 - 30 km	0.0034	0.0031	0.0033	0.0031	0.0033	0.0028
	(0.0036)	(0.0037)	(0.0037)	(0.0037)	(0.0037)	(0.0037)
Production volume wells in 2 km	0.8035	0.8386	0.7537	0.7882	0.7524	0.6940
	(0.9197)	(0.9119)	(0.9173)	(0.9182)	(0.9171)	(0.9141)
Production volume wells in 2 - 15 km	-0.1579	-0.1027	-0.2140	-0.1875	-0.2134	-0.2646
	(0.6298)	(0.6307)	(0.6299)	(0.6304)	(0.6299)	(0.6302)
Production volume wells in 15 - 30 km	0.2182**	0.2325**	0.2320**	0.2217**	0.2313**	0.2256**
	(0.1003)	(0.1016)	(0.1005)	(0.1008)	(0.1006)	(0.1003)
Constant	11.4319***	11.2674***	11.2853***	11.4172***	11.2797***	11.5313***
	(0.2860)	(0.3264)	(0.3161)	(0.2945)	(0.3153)	(0.3769)

Observations	8,662	8,662	8,662	8,662	8,662	8,662
Adjusted R-squared	0.173	0.174	0.175	0.173	0.176	0.177

Notes: See notes to Table 2.

Table A.5. Log(Price) on Number of Injection Wells, Pooled Regression with School District Fixed Effects

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Baseline	Prague	M>=3	M>=4	Sum(MMI)	Max(MMI)
Injection wells in 2 km	-0.0517***	-0.0529***	-0.0500***	-0.0518***	-0.0499***	-0.0395***
	(0.0019)	(0.0033)	(0.0025)	(0.0020)	(0.0025)	(0.0049)
Injection wells in 2 - 15 km	-0.0002	-0.0002	-0.0016***	-0.0006	-0.0014**	-0.0031***
	(0.0005)	(0.0009)	(0.0006)	(0.0005)	(0.0005)	(0.0010)
Injection wells in 15 - 30 km	0.0017***	0.0018**	0.0003	0.0013***	0.0005	-0.0003
	(0.0004)	(0.0008)	(0.0005)	(0.0004)	(0.0005)	(0.0008)
Earthquake		-0.0726	-0.0171***	-0.0681**	-0.0042***	-0.0832***
		(0.0878)	(0.0032)	(0.0315)	(0.0009)	(0.0225)
Injection wells in 2 km × *Earthquake*		0.0015	-0.0004	-0.0028	-0.0001	-0.0038***
		(0.0038)	(0.0003)	(0.0035)	(0.0001)	(0.0014)
Injection wells in 2- 15 km × *Earthquake*		-0.0001	0.0002***	0.0004	0.0000***	0.0009***
		(0.0009)	(0.0000)	(0.0005)	(0.0000)	(0.0002)
Injection wells in 15 - 30 km × *Earthquake*		-0.0001	0.0002***	0.0015***	0.0001***	0.0006***
		(0.0008)	(0.0000)	(0.0003)	(0.0000)	(0.0002)
Property Characteristics	YES	YES	YES	YES	YES	YES
Constant	10.3687***	10.3643***	10.4854***	10.4041***	10.4721***	10.6478***
	(0.1836)	(0.1973)	(0.1852)	(0.1841)	(0.1852)	(0.1989)
Observations	48,015	48,015	48,015	48,015	48,015	48,015
Adjusted R-squared	0.5159	0.5160	0.5166	0.5163	0.5164	0.5164

Notes: (1) Each column represents a separate regression. The dependent variable in all regressions is the log sale price. The price is adjusted using the housing price index (HPI) from the Federal Housing Finance Agency. We use the HPI for Metropolitan Statistical Areas and Divisions for sales of properties in Oklahoma City, and the HPI for Oklahoma State Nonmetropolitan Areas for all the other sales. We set the price index in quarter 4 year, 2010 as 100.

(2) *Earthquake* = Prague, Number of Earthquakes with M ≥ 3, Number of Earthquakes with M ≥ 4, Sum(MMI), and Max(MMI), as indicated by the column headings. Only earthquakes with epicenters in Oklahoma County are included in specifications (3) – (6).

(3) Property characteristics include square feet, number of bedrooms, number of bathrooms, property area (acres), roof type, foundation type, whether there is an attached garage, and heating type. The coefficients on these variables are all significant and have correct signs in all models.

(4) Robust standard errors are shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

Highlights

- We recover hedonic estimates of property value impacts from shale gas development.
- We focus on Oklahoma and identify the impacts of injection induced seismicity risk.
- Nearby earthquakes enhanced the perception of risks from wastewater injection.
- This risk perception was limited to injection wells within 2 km of the properties.
- Shale gas production was not considered to be associated with seismic activities.