# The Housing Market Impacts of Wastewater Injection Induced Seismicity Risk

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**Abstract**

Using data from Oklahoma County, an area severely affected by the increased seismicity associated with injection wells, 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 2011 Oklahoma earthquake in Prague, OK, and generally, earthquakes happening in the county and the state have enhanced the perception of risks associated with wastewater injection but not shale gas production. This risk perception is driven by injection wells within 2 km of the properties.

**Keywords:** Earthquake, Wastewater Injection, Oil and Gas Production, Housing Market, Oklahoma

**JEL classification:** L71, Q35, Q54, R31

## 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.

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). It arose from new techniques to extract oil and gas from shale resources previously believed to be commercially inaccessible. These techniques (commonly known as hydraulic fracturing, “fracking”, or “fracing”) involve the injection of a mixture of water, sand, and chemicals at high pressure into deep rock formations to enhance oil and gas recovery. The injection wells associated with oil and natural gas production (Class II injection wells) include wells used for enhanced oil recovery and those for used for wastewater disposal.

Existing studies estimating the external costs of unconventional oil and gas production (Boslett et al. 2016a; Gopalakrishnan and Klaiber 2014; Muehlenbachs et al. 2013, 2015) have mainly analyzed activity on the Marcellus shale play where an increase in seismicity has not been observed and, thus, have ignored the seismicity risk induced by injection wells. These studies have estimated the net benefits of shale gas development or focused on one important external cost of unconventional oil and gas production: groundwater contamination. Indeed, many of the substances involved in the unconventional oil and gas production process 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. (2013) 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.

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; Hidano et al. 2015; Naoi et al. 2009), existing studies have focused on single, massive earthquakes in San Francisco Bay and Tokyo, with causes independent of wastewater injection activity.

We use a difference-in-differences hedonic model framework exploiting the timing of earthquakes, earthquake characteristics, and the distance of properties to injection wells to estimate the impacts of injection-induced earthquake risk on property values in Oklahoma County. Estimates of risk perceptions from hedonic pricing models show that providing information that identifies areas of varying risk creates price differentials between houses located in different risk zones (Bernknopf et al. 1990; Brookshire et al. 1985; 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 (Atreya et al. 2013; Bin and Landry 2013; Bin and Polasky 2004; Carbone et al. 2006; Kousky 2010; Naoi et al. 2009; Skantz and Strickland 2009).

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. 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 seismic activity in the region) to identify and monetize earthquake risks associated with unconventional oil and gas production.

We find, across multiple indicators of seismic activity in the region, that earthquakes have depressed the value of those residential properties in Oklahoma County with injection activity in close proximity (2 km). On average, the price of properties with one injection well within 2 km dropped by 2.2 percent after the 5.6-magnitude 2011 Oklahoma earthquake with epicenter in Prague, Lincoln County, OK. 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 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 12.5 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 background on injection wells and their connection to earthquakes in Oklahoma. Section 3 discusses the methodology used to identify the different types of impacts of injection wells on housing prices and isolate 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 its GDP (Oklahoma Chamber of Commerce 2014). In 2014 there were 15,560 oil and gas production wells and 14,705 Class II injection wells, most of which were concentrated in the east central region of the state.

Class II injection wells are used to inject fluids associated with oil and gas production. 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.[1] 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; Oklahoma Corporation Commitession 2016).

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

While Oklahoma has only 8% of all injection wells in the CEUS region,[2] it is home to 40% of all earthquake-associated injection wells. 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 the 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's officials has lagged. In 2011, two days after the 5.6-magnitude Oklahoma earthquake with epicenter near Prague, OK, which was at the time the largest in the swarm of earthquakes that affected the state since 2009, the governor of Oklahoma declined to address the cause of the earthquake since injection wells had not been scientifically linked to the earthquakes at that time. The governor would not publicly link the activity of 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"[3] 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 expand 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

[2] 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).
[3] These include wells within 10 km of the epicenter of a 4.0-magnitude or larger earthquake.

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”.[4]

The increase in seismic activity has not resulted in casualties, but has been blamed for structural damage to buildings (Reith and Stewart 2016). In one instance, earthquakes were given partial blame for the collapse of a building (Hermes 2015). In general, the material damages to date have been relatively small. The 5.6-magnitude earthquake in Prague in 2011 buckled road pavement and damaged dozens of homes. According to State Farm spokesman Jim Camoriano, 50 claims were filed throughout the state following the 5.8-magnitude Pawnee earthquake (the largest ever in the state) and its aftershocks in 2016 (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.

Despite small claims, insurers are hiking premiums and deductibles, and some have stopped writing new earthquake insurance altogether.[5] This reflects an increasing concern that insurers would be too exposed in the event of a "big one" even as demand for earthquake insurance is soaring(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

[4] There were only three earthquakes with a magnitude larger than 4.0 in Oklahoma County, and they occurred before July 2014.
[5] Earthquake damage is not covered under a regular homeowner's policy. According to the Oklahoma Insurance Department (OID), 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).

to injection wells (or generally oil and gas wells). Costs might include noise and light pollution, local air pollution, drinking water contamination, and visual disamenities associated with drilling equipment and cleared land. The benefits are mainly royalty or lease payments from the oil and gas company for the use of the property for wastewater injection or oil and gas extraction or for the mineral rights owner's share of proceeds. In Oklahoma, it is possible to sever the mineral property rights from the 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 Muehlenbachs et al. (2015), our estimates are of the overall net effect: the benefits of lease payments for those households who may be receiving them[6] (tempered by those who do not receive them) and the negative externalities of being located near an injection well. We acknowledge, however, that accounting for mineral rights ownership can make a big difference. Boslett et al. (2016b) estimate that houses in Colorado within one mile of an unconventional drill site and in areas of federal mineral ownership (i.e. without mineral rights) 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. Oklahoma City is very spread out; it is the largest city (whose government is not consolidated with that of a county or borough) by land area in the U.S. Together with the consideration that workers in the shale gas industry generally do not drive

[6] 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.

more than 20 miles (30 km) in one direction to work in a day, and that they operate in port-to-port contracts (Langston 2003), we define the vicinity effect to be in the neighborhood of 30 km of a well. Furthermore, there are *macro effects* (e.g. recovery of the national economy, interest rates, mortgage availability) which are not specifically related to shale gas activity and are assumed to be common to all the properties in the sample.

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). The OCC uses a related but less conservative criterion. In its March 2015 regulations to deal with induced seismicity, the OCC has targeted wells within "areas of interest" covering a 10 km-radius area around the central mass of "seismic swarms."[7]

Anecdotal evidence suggests that the perception of seismicity risk has been dramatically enhanced by the swarm of earthquakes since 2009, especially after the 5.6- magnitude "Prague" earthquake in November 5, 2011, that until September 2016 was the largest in Oklahoma history. Because earthquakes have provided 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 perceived seismicity risk.

[7] 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 a 4.0-magnitude or larger earthquake.

*3.2. Identification Strategy*

Figure 1 is useful in describing our strategy to identify seismicity risk. Area A represents a 2 km buffer drawn around a 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 squared 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 *potentially* induced earthquakes. Area B in Figure 1, 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, and this is associated to active injection wells, we consider the wells that were operational 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.[8]

[8] 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)

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

Equation (1) includes a house fixed effect $\mu_i$ 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 to control for time-varying unobservables at the macro level. $\epsilon_{it}$ is the error term. Referring back to Figure 1, 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 $\alpha_1$; 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 ($\alpha_2$); and properties falling in ring C, beyond 15 km of an active injection well, experience only vicinity effects ($\alpha_3$). Thus, $\alpha_2 - \alpha_3$ captures the seismicity risk from injection activities.

We note that the risk of *inducing* an earthquake, which is associated with nearby (within 15 km) injection activity is different from *experiencing* an earthquake. For example, the 5.8-magnitude Pawnee earthquake in September 2016 was felt across the state and in neighboring states. We allow the occurrence of earthquakes to alter the perception of induced seismicity risk in the following specification:

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

where *Earthquake* is an indicator of the seismicity experienced in the area surrounding the property. *Earthquake* is interacted with the variables reflecting injection activity at distances up to 15 km from the home, which is the distance that defines the "catchment area" for the epicenters of potential earthquakes induced by injection activity.

Anecdotal evidence suggests that the 2011 Oklahoma ("Prague") earthquake marked a before and after in the perception of seismicity risk (and possibly other adjacency effects) associated with oil and gas operations in the state of Oklahoma. We formally test this hypothesis, and estimate the model with a dummy variable: afterprague = 1 as our first *Earthquake* indicator. It takes the value of one if the sale happened after Saturday, November 5th, 2011, the date of the earthquake shock, and zero otherwise.

We employ two alternative sets of seismicity indicators. The first one is the number of earthquakes with a magnitude equal to or greater than 3 (or 4) in the 3 months prior to the sale of the property.[9] 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 uses the Modified Mercalli Intensity (MMI), an intensity scale developed by seismologists as a more meaningful measure of severity to the nonscientist than the magnitude as it refers to the effects actually experienced at a specific place. It is a function of both the distance of the property 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), [10] which has been shown to provide a good fit for moderate events such as those experienced in Oklahoma (Hough 2014).

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[9] As noted above, the average homebuyer searches for approximately 3 months before purchasing a home (see footnote 10). The results were robust to using longer time search windows, of 6 and 12 months.

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

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 of the property. It is also possible that people barely note and ignore smaller earthquakes, thus, we use an alternative indicator constructed as the maximum of the MMIs over the same time period. Furthermore, the perception of seismicity risk is likely to be shaped by the diffusion of news about earthquakes in local news outlets and informal interactions with friends and colleagues. We therefore, calculate the intensity measures in relation to the earthquakes in both Oklahoma County and Oklahoma State.

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 the Pawnee M 5.8 earthquake on September 3rd, 2016 are outside of our study period. Moreover, the Prague earthquake's epicenter in Lincoln County is about 60 km from Oklahoma County (as the crow flies), 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 to 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 the state government have remained friendly to shale gas development activity. 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. These guarantees that the property market is sufficiently thick, with enough transactions of relatively uniform properties to recover 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 that have information on the location of the property. After excluding properties without a listed price, a price in the top or bottom 1% of all prices, and properties sold more than once in a single year, we are left with 55,362 observations. We consider only homes that were sold from one person to another (i.e., excluding made-to-order homes), thus we drop approximately 6,834 properties that were sold in the year built. Of these, there are 48,249 sales of properties designated as a residential use, and 48,015 sales were single family residences. We only include these 48,015 properties 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 this remaining 48,015 sales, 8,662 are repeated sales – 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[11] 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 459 shale gas production wells in 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.

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, 121 (14%) originated in Oklahoma County, 24 were of M $\geq 4.0$, and one, in Prague, Lincoln County on November 5th 2011 was of M = 5.6. There was a sharp jump in the number of earthquakes in Oklahoma 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 the year 2010. Of the 121 quakes with M $\geq 3.0$ in Oklahoma County, 3 were of M $\geq 4.0$ and they all took place after year 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 2, overlaying with public water serviced areas.

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

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. Home owners 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 highly 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). This impact is robust across alternative seismicity indicators.

In column (2), one additional injection well within 2 km of a property induces a 2.21% lower value for the property after the Prague earthquake, suggesting that Prague altered home owners' perception of wastewater injection in close proximity to the property dramatically. 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 earthquakes 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 later reduces them by 1.55%.[12] 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 with one injection well within 2 km that sold in year 2014, we estimate the loss from induced earthquakes with $M \geq 3$ in Oklahoma County to be $6,282 over that year, and the loss from earthquakes with $M \geq 4$ to be $2,229. 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.

*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 in the state of Oklahoma (not just in the county). Second, we test the impacts on the results of using only injection wells that have been associated with earthquakes.

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

### 5.2.1 All Earthquakes in Oklahoma

We hypothesize that residents pay more attention to the local earthquakes than to the ones 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. Thus, we re-examine the estimates using all the earthquakes that occurred in Oklahoma during the sample period. Results are reported in Table 3.

Estimates are qualitatively similar to those in Table 2. We do not observe any 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. Because the epicenter of Prague is in Lincoln County, the estimates in column (2) are identical to the corresponding ones in Table 2. 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 0.52 percent, which is 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 much farther from the properties in Oklahoma County, thereby, the marginal effects are smaller overall.

### 5.2.2 Associated Injection Wells

Tables 2 and 3 report results for all injection wells, both earthquake-associated and non-associated. 92 percent of our sample injection wells are earthquake associated. It is possible that non-associated injection wells could induce an earthquake in the future even if they have not so far, so they are associated with potential seismicity risk as well. Nonetheless, we speculate that currently associated injection wells are perceived to be riskier. 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 in Oklahoma State. Results are presented in Table 4.[13]

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 the specification with all injection wells in Table 3, although their statistical significance is slightly lower. One explanation might be that people perceive injection wells that have already induced earthquakes to be less likely to cause more earthquakes and therefore less dangerous (gambler's fallacy). However, the effects continue to be statistically significant at a 5% level (except for the less frequent $M \geq 4$ earthquakes for which the effect is significant at a 10% 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 with 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,

[13] We did estimate the models with only earthquakes in Oklahoma County; the results 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.

after Prague, one additional earthquake-associated injection well within 2 km of a property reduces the value of the property by 2.14%.

*5.3 Common trends and "Prague" Falsification Tests*

Our difference-in-differences identification strategy relies on the assumption that there are not distinct preexisting trends in the prices of houses located at different distances of injection wells. If, for example, houses within 2 km of an injection well were experiencing slower growth in prices relative to homes located further from injection activity, this could lead to estimating a spurious negative effect of earthquakes in our difference-in-differences analysis.

Figure 3 illustrates the evolution of housing prices for those properties with and without injection activity within 2km. Both lines follow the same trends. As an additional analysis, we run two separate regressions – for properties with and without active injection wells within 2km – of the log price on property characteristics controlling for year and quarter. We then estimate two price functions with local polynomial regressions using as dependent variables the residuals from the previous regressions. Figure 4 depicts the results from the local polynomial regressions. The two lines show that the residuals are generally close to zero, and that, consistent with the evolution of prices in Figure 3, they follow similar trends. Both figures suggest that prices of houses in closer proximity to injection wells are slightly more volatile before the Prague earthquake; then the residuals compress until they are nearly identical in recent times. Thus, this graphical analysis bolsters the argument that our difference-in-differences estimates are causal.

Another check for whether the decrease in housing price for properties with active injection wells within 2km after Prague is due to differential trends in housing prices in these areas is to conduct a falsification test. We do this by estimating equation (2) using three randomly selected false earthquake dates during our study period, one before Prague and two after Prague: February 1st, 2011, July 15th, 2012, and October 31st, 2013. The results presented in Table 5 show that there was not a statistically significant price differential between houses with and without injection wells in 2km after the first fake earthquake in 2011. This insignificance provides no evidence of a spurious effect driven by different housing price trends *before* the earthquake and thus supports the causal interpretation of our DD model estimates of the impact of Prague on housing prices.

In contrast, we estimate statistically significant price differentials for houses with injection activity within 2 km for the two false earthquakes dates after Prague and the impacts are slightly larger than that of Prague. This suggests that the impact of Prague is persistent and possibly enhanced by the increasing incidence of earthquakes, locally and across the state.

### *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 production wells, water contamination risk, and the interaction between them and 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 difference 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, 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.[14]

(3) $$lnP_{it} = \alpha_0 + \alpha_1(injection\ wells\ in\ 2\ km)_{it} + \alpha_2(injection\ wells\ in\ 2 - 15\ km)_{it} + \alpha_3(injection\ wells\ in\ 15 - 30\ km)_{it} + \alpha_4(production\ wells\ in\ 2\ km)_{it} + \alpha_5(production\ wells\ in\ 2 - 15\ km)_{it} + \alpha_6(production\ wells\ in\ 15 - 30\ km)_{it} + \alpha_7 Earthquake_{it} + \alpha_8(injection\ wells\ in\ 2\ km)_{it} * Earthquake_{it} + \alpha_9(injection\ wells\ in\ 2 - 15\ km)_{it} * Earthquake_{it} + \alpha_{10}(production\ wells\ in\ 2\ km)_{it} * Earthquake_{it} + \alpha_{11}(production\ wells\ in\ 2 - 15\ km)_{it} * Earthquake_{it} + \mu_i + v_t + q_t + \epsilon_{it}$$

Results with only earthquakes in Oklahoma county are presented in Table 6. Like for injection wells, we do not detect statistically significant impacts of production wells on housing prices regardless of their proximity, suggesting that the positive and negative effects associated with shale gas production offset each other all distances. This is also the case in the specifications that include earthquake activity.

The coefficients for injection wells are strikingly similar to those in Table 2 in both significance and magnitude. Seismic activity decreases property prices of houses with injection wells within 2 km. The statistically indistinguishable estimates of seismicity risk in Tables 2 and 6, 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 then drinking water quality. In

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

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 many residents on private groundwater especially in rural areas, the contamination risk posed by dewatering techniques and fluid injection may factor into the perceived risk of buying a property. Such risk perception on water contamination may also 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. In this section, we investigate whether earthquakes have intensified water contamination risk or not for residents in Oklahoma County. 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.[15]

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 in engendering 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 measure this risk more accurately by using the intensity of injection wells around the closest public water supply (PWS)

[15] 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 in this paper. We acknowledge that this is a slightly abuse of the terms.

well for a property.[16] According to relevant official documents and communication with experts, we choose 1.5 km as the buffer size.[17] We then calculate the number of injection wells within 1.5 km of the closest PWS well to a property to determine the potential PW contamination risk.

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

(4) $$lnP_{it} = \alpha_0 + \alpha_1(wells\ in\ 2\ km)_{it} + \alpha_2(wells\ in\ 2 - 15\ km)_{it} + \alpha_3(wells\ in\ 15 - 30\ km)_{it} + \alpha_4(wells\ in\ 2\ km)_{it} * GW_i + \alpha_5(wells\ in\ 1.5\ km\ of\ PWS\ well)_{it} *$$

[16] 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.

[17] 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 to keep 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.

$$PWSA_i + \alpha_6 Earthquake_{it} + \alpha_7 (wells\ in\ 2\ km)_{it} * Earthquake_{it} + \alpha_8 (wells\ in\ 2 - 15\ km)_{it} * Earthquake_{it} + \alpha_9 (wells\ in\ 2\ km)_{it} * Earthquake_{it} * GW_i + \alpha_{10} (wells\ in\ 1.5\ km\ of\ PWS\ well)_{it} * Earthquake_{it} * PWSA_i + \mu_i + v_t + q_t + \epsilon_{it}$$

*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 both injection wells and production wells. $\alpha_4$ and $\alpha_5$ are the measures of GW and PW contamination risk associated with the proximity of wells without earthquakes, and $\alpha_9$ and $\alpha_{10}$ measure the additional water contamination risk perception brought by earthquakes to GW-dependent and PWSA-dependent homes, respectively.

We obtained the GIS boundaries of the PWSAs in Oklahoma from the Oklahoma Comprehensive Water Plan (OCWP) 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 the Oklahoma Department of Environmental Quality.

Table 7 presents the regression results with earthquakes only in Oklahoma county. For GW 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 PW 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 partiallytreated 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 and are thus not considered to be a risk to public drinking 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 GW than for those on PW. For GW-dependent homes with one injection well within 2 km, the occurrence of a $M \geq 4$ earthquake reduces their value by 12.53% on average, whereas, for a PW-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. Using these estimated impacts from GWCR and PWCR (columns 4 in Table 7, 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 loss resulting from the perception of water contamination risk brought by $M \geq 4$ earthquakes is $24,870 and $7,748 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 Table 6. Production wells are overall not perceived to be associated with seismicity, regardless of the distance between the wells and the properties, and the occurrence or earthquakes does not alter risk perceptions.

## 6. Conclusion

Development of shale deposits has become increasingly widespread due to advances in technology, generating plentiful 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 a magnitude equal to or greater than 3 (and 4), and the sum and max of Modified Mercalli Intensity of earthquakes in both Oklahoma County and Oklahoma State. Further, the estimated effects are not confounded by damages caused by earthquakes, and are robust to controlling for 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 $4,378 (2.2%) 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 $434 (0.2%) and $3,082 (1.6%), respectively.

In contrast, our results suggest that shale oil and gas production wells are not perceived to induce earthquakes. Pondering on the science that it is injection wells that are associated with the increase in recent earthquakes, it seems that people are actually able to differentiate injection wells from production wells in triggering 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 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 |
| 1 = Public water serviced 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 $M \geq 3$ | 8662 | 6.65 | 6.85 | 0.00 | 26.00 |
| Earthquakes with $M \geq 4$ | 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 $M \geq 3$ | 8662 | 43.50 | 53.17 | 0.00 | 195.00 |
| Earthquakes with $M \geq 4$ | 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, Earthquakes in Oklahoma County**

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Baseline | Prague | M>=3 | M>=4 | Sum(MMI) | Max(MMI) |
| Injection wells in 2 km | 0.12 | 2.06 | 1.51 | 0.50 | 1.46 | 3.80 |
| | (2.93) | (2.92) | (2.89) | (2.92) | (2.89) | (2.90) |
| Injection wells in 2 -15 km | 0.08 | 0.23 | 0.19 | 0.05 | 0.19 | -0.14 |
| | (0.37) | (0.40) | (0.43) | (0.39) | (0.42) | (0.42) |
| Injection wells in 15 - 30 km | -0.12 | -0.21 | -0.06 | -0.08 | -0.06 | -0.03 |
| | (0.27) | (0.29) | (0.29) | (0.28) | (0.29) | (0.28) |
| *Earthquake* | | - | 0.19 | 0.45 | 0.06 | -1.93 |
| | | | (0.27) | (2.73) | (0.07) | (1.27) |
| Injection wells in 2 km × | | -2.21*** | -0.22*** | -1.55** | -0.06*** | -1.27*** |
| *Earthquake* | | (0.86) | (0.06) | (0.75) | (0.02) | (0.32) |
| Injection wells in 2 - 15 km | | -0.06 | 0.00 | 0.05 | 0.00 | 0.04 |
| × *Earthquake* | | (0.07) | (0.00) | (0.05) | (0.00) | (0.03) |
| Constant | 1,148.01*** | 1,146.11*** | 1,138.63*** | 1,146.58*** | 1,138.15*** | 1,153.49*** |
| | (27.46) | (27.47) | (29.42) | (27.85) | (29.30) | (28.29) |
| 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 $M \geq 3$, Number of Earthquakes with $M \geq 4$ Sum(MMI), and Max(MMI), as indicated by the column headings. Only earthquakes that happened in Oklahoma County are included in specifications (3) – (6). In the Prague model, the earthquake dummy is perfectly collinearly related with the two interaction terms, therefore, it drops out.
(3) Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. Property, Year and Quarter fixed effects are included in all specifications. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

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

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Baseline | Prague | M>=3 | M>=4 | Sum(MMI) | Max(MMI) |
| Injection wells in 2 km | 0.12 | 2.06 | 0.81 | 0.66 | 0.78 | 4.17 |
| | (2.93) | (2.92) | (2.92) | (2.93) | (2.93) | (3.02) |
| Injection wells in 2 -15 km | 0.08 | 0.23 | -0.24 | 0.03 | -0.22 | -0.42 |
| | (0.37) | (0.40) | (0.53) | (0.46) | (0.53) | (0.46) |
| Injection wells in 15 - 30 km | -0.12 | -0.21 | 0.11 | -0.05 | 0.11 | -0.09 |
| | (0.27) | (0.29) | (0.29) | (0.29) | (0.30) | (0.28) |
| *Earthquake* | | - | 0.02 | 0.04 | 0.01 | -3.82** |
| | | | (0.05) | (1.15) | (0.02) | (1.75) |
| Injection wells in 2 km × | | -2.21*** | -0.02*** | -0.52** | -0.01*** | -1.29*** |
| *Earthquake* | | (0.86) | (0.01) | (0.26) | (0.00) | (0.42) |
| Injection wells in 2 - 15 km × | | -0.06 | 0.00 | 0.02 | 0.00 | 0.06* |
| *Earthquake* | | (0.07) | (0.00) | (0.02) | (0.00) | (0.03) |
| Constant | 1,148.01*** | 1,146.11*** | 1,146.81*** | 1,145.27*** | 1,145.85*** | 1,173.00*** |
| | (27.46) | (27.47) | (30.12) | (30.22) | (30.36) | (30.14) |
| 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: Each column represents a separate regression. The dependent variable in all regressions is log sale price. Property, County-year and Quarter fixed effects are included in all specifications. Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

**Table 4. Log(Price) on Number of Associated Injection Wells, All Earthquakes in Oklahoma**

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Base | Prague | M>=3 | M>=4 | Sum(MMI) | Max(MMI) |
| Injection wells in 2 km | 1.12 | 2.88* | 1.57 | 1.42 | 1.56 | 5.42*** |
| | (1.54) | (1.59) | (1.55) | (1.56) | (1.55) | (1.96) |
| Injection wells in 2 -15 km | -0.38** | -0.35** | -0.35** | -0.41*** | -0.36** | -0.47*** |
| | (0.15) | (0.16) | (0.17) | (0.16) | (0.17) | (0.18) |
| Injection wells in 15 - 30 km | -0.04 | -0.03 | 0.06 | -0.02 | 0.05 | -0.02 |
| | (0.11) | (0.11) | (0.13) | (0.12) | (0.13) | (0.11) |
| Earthquake | | - | 0.05 | 0.41 | 0.02 | -2.58* |
| | | | (0.05) | (1.06) | (0.02) | (1.56) |
| Injection wells in 2 km × | | -2.14** | -0.03** | -0.64* | -0.01** | -1.32*** |
| Earthquake | | (0.88) | (0.01) | (0.35) | (0.00) | (0.47) |
| Injection wells in 2 - 15 km × | | -0.04 | 0.00 | -0.00 | 0.00 | 0.03 |
| Earthquake | | (0.06) | (0.00) | (0.02) | (0.00) | (0.03) |
| Constant | 1,160.01*** | 1,157.48*** | 1,153.35*** | 1,160.28*** | 1,154.52*** | 1,169.74*** |
| | (10.78) | (10.88) | (13.26) | (12.41) | (12.96) | (11.99) |
| Observations | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 |
| Adjusted R-squared | 0.172 | 0.173 | 0.173 | 0.172 | 0.173 | 0.175 |

Notes: Each column represents a separate regression. Dependent variables in all regressions are log sale price. Property, County-year and Quarter fixed effects are included in all specifications. Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

**Table 5. Falsification Tests: Hypothetical Earthquake Dates**

| VARIABLES | (1)<br>Feb2011 | (2)<br>Prague | (3)<br>Jul2012 | (4)<br>Oct2013 |
|---|---|---|---|---|
| Injection wells in 2 km | -0.21 | 2.06 | 2.91 | 0.60 |
| | (3.38) | (2.92) | (2.83) | (2.85) |
| Injection wells in 2 -15 km | 0.39 | 0.23 | 0.25 | -0.37 |
| | (0.41) | (0.40) | (0.42) | (0.43) |
| Injection wells in 15 - 30 km | -0.16 | -0.21 | -0.09 | 0.08 |
| | (0.27) | (0.29) | (0.28) | (0.29) |
| Injection wells in 2 km × *Earthquake* | 0.38 | -2.21*** | -3.54*** | -2.77*** |
| | (1.69) | (0.86) | (0.92) | (0.92) |
| Injection wells in 2 - 15 km × *Earthquake* | -0.21* | -0.06 | 0.00 | 0.19** |
| | (0.11) | (0.07) | (0.06) | (0.07) |
| Constant | 1,139.10*** | 1,146.11*** | 1,136.60*** | 1,153.00*** |
| | (28.30) | (27.47) | (27.84) | (27.60) |
| Observations | 8,662 | 8,662 | 8,662 | 8,662 |
| Adjusted R-squared | 0.171 | 0.172 | 0.174 | 0.173 |

Notes: Each column represents a separate regression. Dependent variables in all regressions are log sale price. *Earthquake* = 1 if the transaction happened on or after February1$^{st}$, 2011 (or November 5$^{th}$, 2011; July 15$^{th}$, 2012; October 31$^{st}$, 2013), and 0 otherwise. Property, Year and Quarter fixed effects are included in all specifications. Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

**Table 6. Impacts of Shale Gas Production Wells**

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Baseline | Prague | M>=3 | M>=4 | Sum(MMI) | Max(MMI) |
| Injection wells in 2 km | 0.02 | 2.05 | 1.44 | 0.47 | 1.38 | 4.09 |
| | (2.93) | (2.93) | (2.91) | (2.94) | (2.91) | (2.91) |
| Injection wells in 2 -15 km | -0.01 | 0.19 | 0.13 | 0.00 | 0.13 | -0.17 |
| | (0.38) | (0.41) | (0.43) | (0.40) | (0.42) | (0.42) |
| Injection wells in 15 - 30 km | -0.13 | -0.45 | -0.08 | -0.12 | -0.07 | -0.07 |
| | (0.27) | (0.31) | (0.29) | (0.28) | (0.29) | (0.29) |
| Production wells in 2 km | -0.48 | -0.94 | -0.82 | -0.54 | -0.84 | -1.91* |
| | (0.94) | (1.09) | (0.94) | (0.95) | (0.94) | (1.09) |
| Production wells in 2 -15 km | 0.02 | -0.02 | 0.01 | 0.04 | 0.01 | 0.01 |
| | (0.09) | (0.09) | (0.09) | (0.09) | (0.09) | (0.10) |
| Production wells in 15 - 30 km | 0.05 | 0.05 | 0.06 | 0.05 | 0.06 | 0.05 |
| | (0.04) | (0.04) | (0.04) | (0.04) | (0.04) | (0.04) |
| *Earthquake* | | - | 0.21 | -6.75 | 0.06 | -2.21 |
| | | | (0.56) | (6.58) | (0.15) | (2.48) |
| Injection wells in 2 km × | | -2.63*** | -0.23*** | -1.76** | -0.07*** | -1.39*** |
| *Earthquake* | | (0.87) | (0.07) | (0.78) | (0.02) | (0.33) |
| Injection wells in 2 - 15 km × | | -0.13 | 0.00 | 0.06 | 0.00 | 0.03 |
| *Earthquake* | | (0.08) | (0.01) | (0.06) | (0.00) | (0.03) |
| Production wells in 2 km× | | 0.70 | 0.02 | 0.68 | 0.01 | 0.40 |
| *Earthquake* | | (0.80) | (0.06) | (0.74) | (0.02) | (0.25) |
| Production wells in 2 - 15 km× | | 0.08 | 0.00 | 0.08 | 0.00 | 0.00 |
| *Earthquake* | | (0.05) | (0.01) | (0.07) | (0.00) | (0.02) |
| Constant | 1,136.56*** | 1,155.79*** | 1,127.12*** | 1,134.67*** | 1,126.32*** | 1,144.90*** |
| | (28.00) | (29.45) | (29.86) | (28.37) | (29.80) | (30.16) |
| Observations | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 |
| Adjusted R-squared | 0.171 | 0.173 | 0.174 | 0.172 | 0.174 | 0.175 |

Notes: Each column represents a separate regression. Dependent variables in all regressions are log sale price. Property, County-year and Quarter fixed effects are included in all specifications. Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

**Table 7. Water Contamination Risk**

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Baseline | Prague | M>=3 | M>=4 | Sum(MMI) | Max(MMI) |
| Injection wells in 2 km | 1.15 | 3.69 | 2.84 | 1.81 | 2.84 | 7.11* |
| | (3.40) | (3.57) | (3.53) | (3.49) | (3.53) | (3.82) |
| Injection wells in 2 -15 km | 0.06 | 0.25 | 0.20 | 0.04 | 0.21 | -0.09 |
| | (0.38) | (0.41) | (0.43) | (0.40) | (0.43) | (0.43) |
| Injection wells in 15 - 30 km | -0.21 | -0.52* | -0.18 | -0.22 | -0.18 | -0.15 |
| | (0.28) | (0.31) | (0.30) | (0.28) | (0.30) | (0.29) |
| Production wells in 2 km | 0.72 | 0.06 | -0.08 | 0.53 | -0.10 | -0.82 |
| | (1.21) | (1.38) | (1.23) | (1.23) | (1.23) | (1.40) |
| Production wells in 2 -15 km | 0.07 | 0.03 | 0.07 | 0.09 | 0.07 | 0.08 |
| | (0.09) | (0.09) | (0.09) | (0.09) | (0.09) | (0.11) |
| Production wells in 15 - 30 km | 0.03 | 0.02 | 0.04 | 0.02 | 0.04 | 0.02 |
| | (0.04) | (0.04) | (0.04) | (0.04) | (0.04) | (0.04) |
| GW × Injection wells in 2 km | -9.11 | -7.72 | -6.09 | -8.01 | -5.83 | -0.74 |
| | (13.55) | (15.25) | (14.42) | (12.95) | (14.31) | (15.39) |
| GW × Production wells in 2 km | 3.98 | 4.49 | 3.72 | 3.28 | 3.63 | 2.38 |
| | (5.32) | (5.83) | (5.51) | (5.37) | (5.49) | (6.77) |
| PWSA × Injection wells in 1.5 km of PWS well | -0.53 | -1.98 | -0.82 | -0.43 | -0.97 | -4.69 |
| | (4.86) | (5.41) | (5.09) | (5.01) | (5.09) | (5.56) |
| PWSA × Production wells in 1.5 km of PWS well | -5.17** | -4.14 | -3.65 | -4.93** | -3.64 | -5.24* |
| | (2.40) | (2.72) | (2.52) | (2.42) | (2.51) | (3.16) |
| *Earthquake* | | - | 0.26 | -5.06 | 0.07 | -2.31 |
| | | | (0.57) | (6.62) | (0.16) | (2.55) |
| Injection wells in 2 km × *Earthquake* | | -2.76** | -0.25*** | -1.33 | -0.07*** | -1.96*** |
| | | (1.26) | (0.09) | (1.00) | (0.03) | (0.53) |
| Injection wells in 2 - 15 km × *Earthquake* | | -0.13 | 0.00 | 0.05 | 0.00 | 0.03 |
| | | (0.08) | (0.01) | (0.06) | (0.00) | (0.03) |
| Production wells in 2 km× *Earthquake* | | 0.54 | 0.08 | 1.62* | 0.02 | 0.35 |
| | | (0.99) | (0.07) | (0.93) | (0.02) | (0.30) |
| Production wells in 2 - 15 km× *Earthquake* | | 0.08 | -0.00 | 0.07 | -0.00 | 0.00 |
| | | (0.05) | (0.01) | (0.07) | (0.00) | (0.02) |

| | | | | | | |
|---|---|---|---|---|---|---|
| GW × Injection wells in 2 km × *Earthquake* | | 1.78 | -0.42 | -12.53** | -0.13 | -2.45 |
| | | (9.19) | (0.53) | (5.43) | (0.14) | (2.55) |
| GW × Production wells in 2 km× *Earthquake* | | 2.93 | 0.05 | 0.93 | 0.02 | 0.47 |
| | | (2.99) | (0.23) | (2.69) | (0.06) | (1.19) |
| PWSA × Injection wells in 1.5 km of PWS | | 0.56 | 0.07 | -0.17 | 0.02 | 1.16* |
| well × *Earthquake* | | (1.74) | (0.10) | (1.44) | (0.03) | (0.65) |
| PWSA × Production wells in 1.5 km of PWS | | -0.54 | -0.24* | -3.90** | -0.07* | 0.26 |
| well × *Earthquake* | | (2.05) | (0.14) | (1.87) | (0.04) | (0.63) |
| Constant | 1,139.45*** | 1,157.52*** | 1,131.06*** | 1,139.73*** | 1,130.27*** | 1,146.64*** |
| | (27.91) | (29.40) | (29.70) | (28.23) | (29.64) | (30.23) |
| Observations | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 | 8,662 |
| Adjusted R-squared | 0.172 | 0.174 | 0.175 | 0.174 | 0.175 | 0.177 |

Notes: Each column represents a separate regression. Dependent variables in all regressions are log sale price. Property, County-year and Quarter fixed effects are included in all specifications. Coefficients are in percentage terms. Robust standard errors are clustered by property and shown in parentheses. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

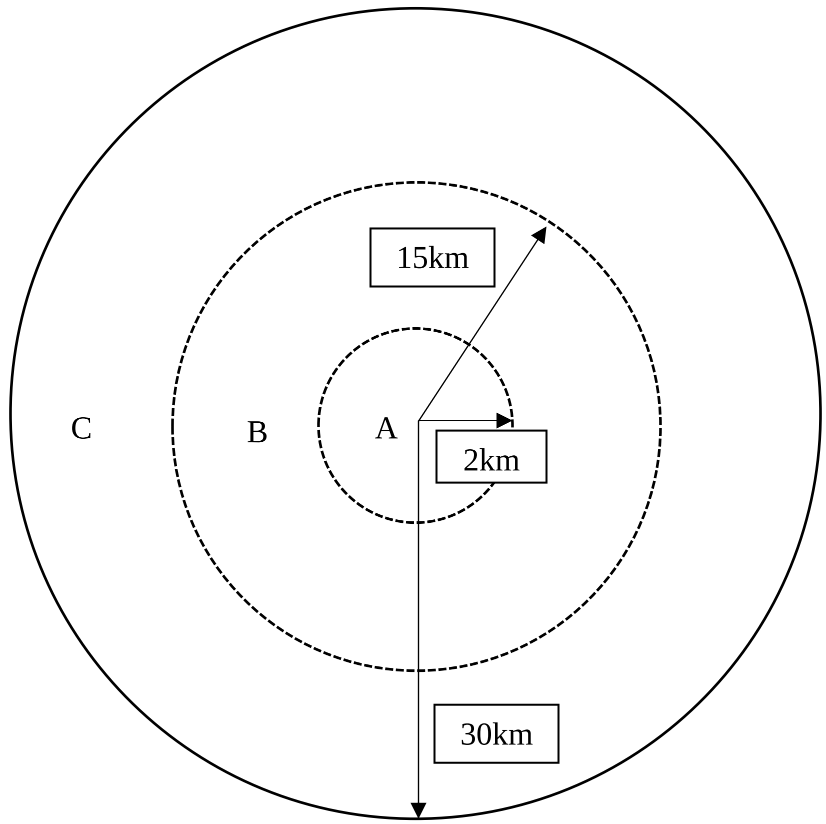


**Figure 1. Types of Areas Examined**

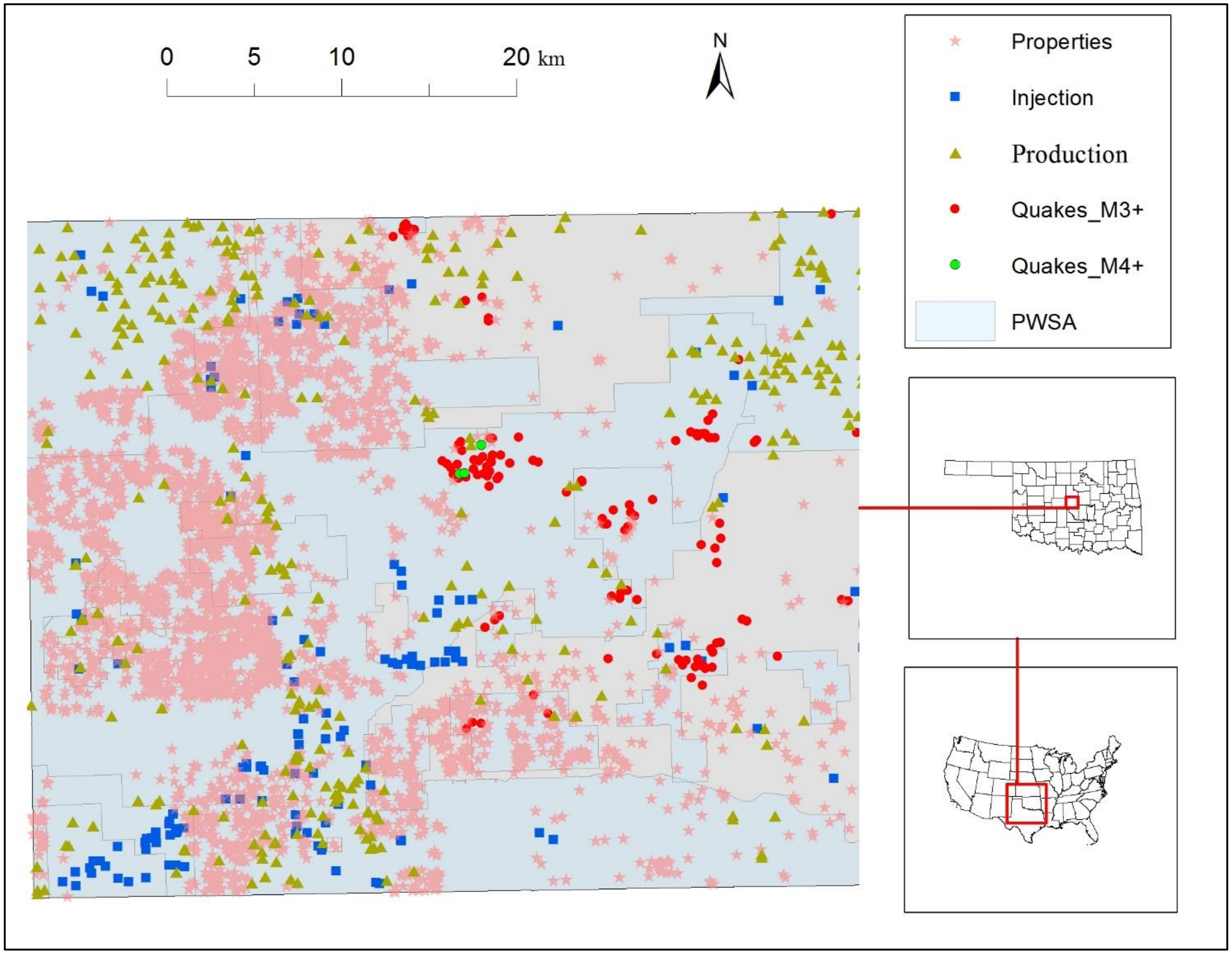


**Figure 2. Location of Properties, Wells, Earthquakes, and Water Service Areas**

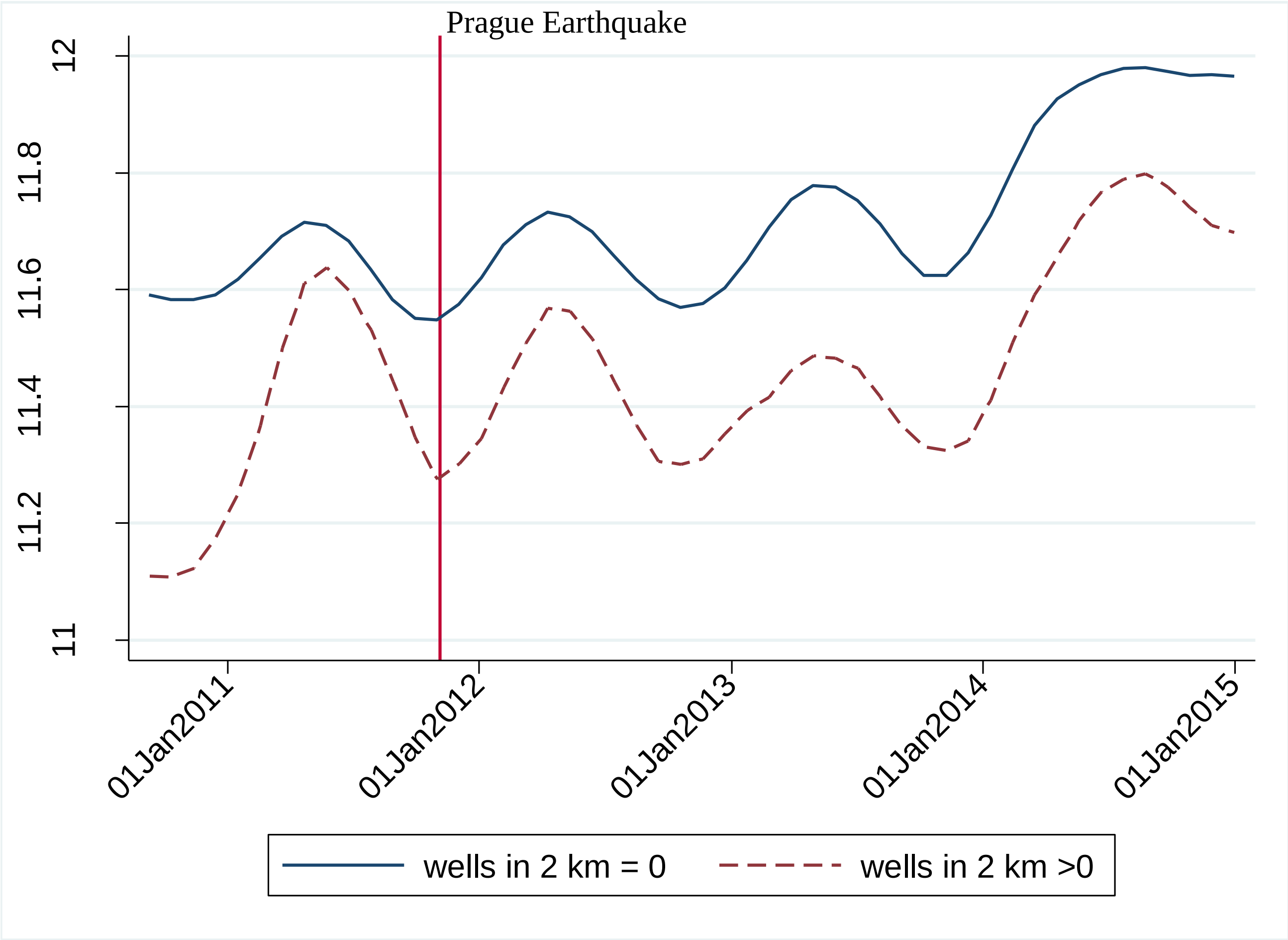


**Figure 3. Plot of Log Price over time**

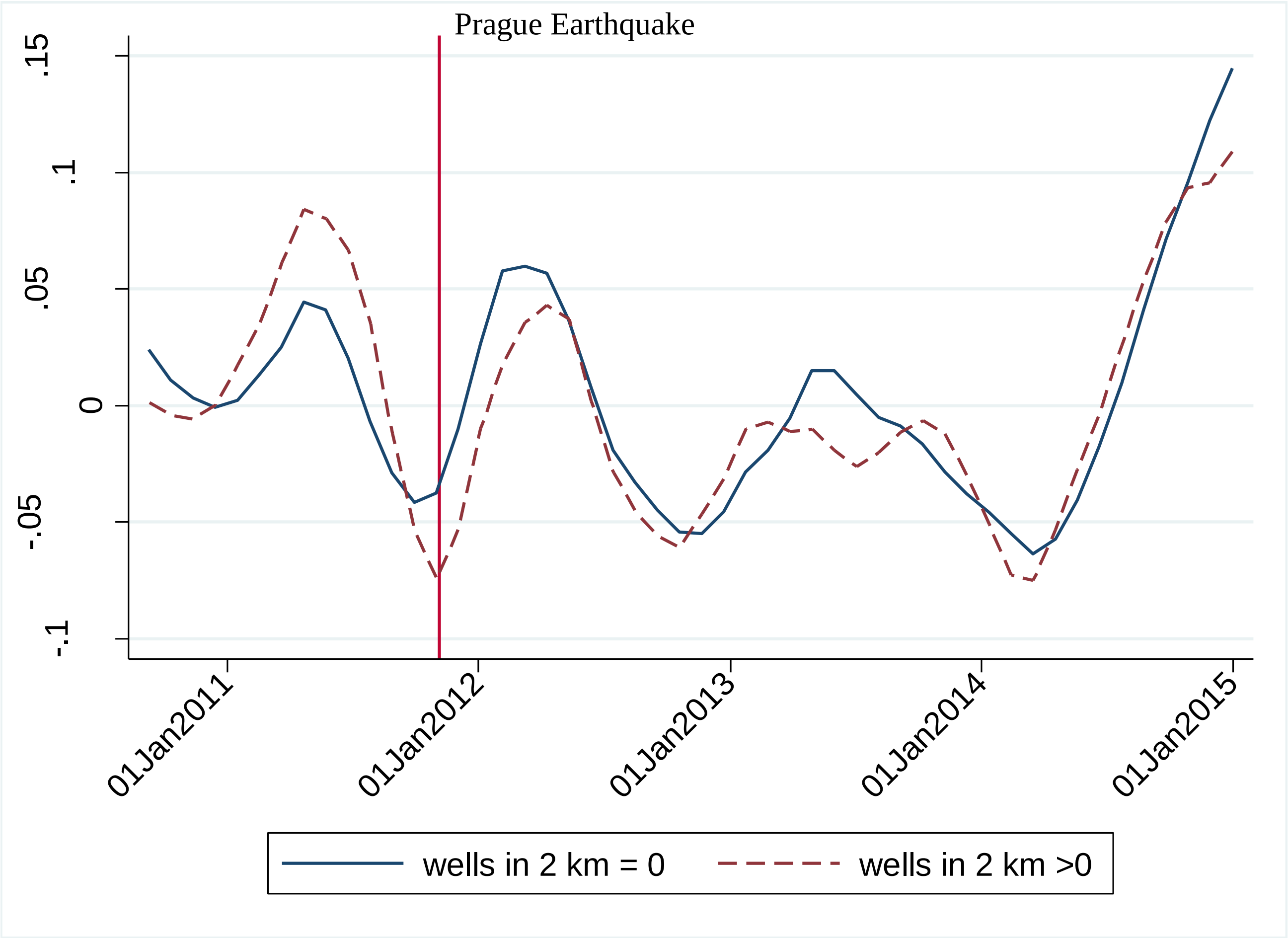


**Figure 4. Residual Plot of Log Price Regression over time**