FRACKING AND EARTHQUAKES IN OKLAHOMA: AN ANALYSIS OF THE LINKAGES

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DEDICATION

Dedicated to my family for all their love, support and patience.

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Over the last twenty years the number of earthquakes in the State of Oklahoma has increased significantly. This study investigates the relationship between hydraulic fracturing wastewater injection wells and the increase in seismicity. In this work SPSS (Statistical Program for Social Sciences) was used to analyze all the data for correlations between wastewater well injection volumes. And psi (pounds per square inch), and earthquakes. SPSS was also used to examine the relationship between the injection of wastewater and the time-delay of seismicity. ArcGIS 10.3.1 (Geographic Information System) was used to explore the density of earthquakes and their distance from wastewater injection wells. This study finds that there is a relationship between wastewater injection volume, distance and time-delay of the injections and earthquakes. Pore pressure was not found to be a contributor to seismicity. However, the depth of the wastewater wells, which was not one of the variables in this study, showed a positive correlation to the increase in earthquakes in Oklahoma. This study reveals some important practical suggestions for the wastewater disposal industry. By setting up industry standards, such as, keeping volume below 150,000 barrels/month, and shortening well depth to at least 1km from the Precambrian crystalline basement the wastewater disposal industry could be more confident that they are lowering their risk of inducing earthquakes and thereby reducing their risk of insurance liability claims and litigation.

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CHAPTER ONE: INTRODUCTION

Anthropogenic earthquakes have many different causes: dam impoundment, hydraulic fracturing, and disposal of wastewater into underground wells, which may cause nearby faults to shift and trigger an earthquake (Farahbod, Kao, Walker, & Cassidy, 2015; Walsh, III & Zoback, 2015). Faults in an area that are already near critical failure may not need much additional pressure, or release of pressure, to cause the fault to slip. Many times, this slippage is not felt; however, when the slippage is great enough to be felt people become concerned. The possibility of damage to buildings or injuries to people causes the local communities to question what has caused the earthquake. Was it a natural earthquake, and if not, who is responsible, the oil and gas companies perhaps? Most people do not carry earthquake insurance for their homes, automobiles or businesses. Consequently, if there is damage to any of their properties the owners will find themselves paying for the repairs out of their own pockets. This study will focus on the relationship between the injection of hydraulic fracturing wastewater into disposal wells and earthquakes in Oklahoma from 2011 to 2016.

Recently, there has been an increase in small earthquakes in many areas around the globe. Canada, England, and the interior of the U.S., are just a few of the places seeing increased seismic activity in areas that were once aseismic. They have also had an increase in hydraulic fracturing (fracking) for oil and gas in these same areas. As the fracking in these areas has increased so has the number and magnitude of the earthquakes.

Recent scientific research has shown a link between the fracking process and an increase in earthquake activity (Ellsworth, 2013; Keranen, Savage, Abers, & Cochran, 2013; Weingarten, Ge, Godt, Bekins, & Rubinstein, 2015). Part of the process of hydraulic fracturing is injecting water, with a mixture of hazardous chemicals, into the well and then allowing this water to flow back to the surface. When this water flows back, it contains not only the original chemicals but also oil and gas, as well as many of the natural minerals from the rocks, which may be highly saline and toxic. After the oil or gas has been removed, this water must be carefully disposed of due to its hazardous nature. The wastewater must be contained in a deep, impermeable underground disposal well. Studies have found that when the wastewater is injected into the disposal wells the volume and pressure of the injection has been found to cause earthquakes (Kim, 2013; Walsh, III & Zoback, 2015). Although this phenomenon has been studied in various places, such as Youngstown, Ohio, Horn River Basin, Canada, Blackpool, United Kingdom and Paradox Valley, Colorado, it has not been adequately studied in Oklahoma. Oklahoma has both wastewater disposal wells and enhanced oil recovery wells (EOR). EOR wells inject fluid into oil and gas formations to retrieve hard to reach oil and gas. These wells do not seem to trigger as many earthquakes as the wastewater disposal wells. This could be because the EOR wells inject and extract water, causing less sustained pressure in the well (Environmental Protection Agency [EPA] 2011). Another factor may be that many of the wastewater wells in Oklahoma are deep enough to be near faults that reach the Precambrian crystalline basement. Wastewater wells in less seismic areas may not be as deep as the wells in Oklahoma; therefore, they have fewer earthquakes. Because of the volume, pore pressure and depth of the wastewater wells, that are near faults that continue to the crystalline basement, I would expect the relationship between volume and pore pressure of wastewater and earthquakes to be stronger in Oklahoma. Kim (2013) found this to be the case with the earthquakes in Youngstown, Ohio. While Oklahoma has only 8% of all injection wells in the Central US, 40% of the injection wells in Oklahoma have been associated with earthquakes (Weingarten, Ge, Godt, Bekins, & Rubinstein, 2015).

Earthquake Damage in Oklahoma

Jones, Oklahoma, has had 2,547 small earthquakes since 2008. When these earthquakes first started, the people of Jones were frightened; they would call City Hall asking that the mayor do something to stop the earthquakes (Hand, 2014). At first, they were unsure what was causing the earthquakes, but it became clear that the earthquakes were caused by the injection of hydraulic fracturing wastewater fluid into deep disposal wells more than 20km away (Hand, 2014). Some people in Jones, Oklahoma experienced minor damage to their homes and businesses, mostly cracked ceilings (Hand, 2014). However, the Prague, Oklahoma earthquake of 2011 destroyed 14 homes and injured two people (Jackson, et al., 2014). One person injured in the 2011 Prague earthquake, Sandra Ladra, has filed a lawsuit for bodily injury against New Dominion, LLC and Spess Oil Company (Branstetter, 2015). Her 28-foot rock fireplace chimney collapsed during the earthquake, dropping a heavy stone into her lap and gashing her knee (Branstetter, 2015). Since the earthquake Sandra Ladra has had two surgical procedures on her knee and has been told by her physician she will need knee replacement (Branstetter, 2015). Ms. Ladra was also forced to move out of her home, for several months, while extensive repairs were made, including the replacement of all the plumbing in the structure (Branstetter, 2015). Sandra Ladra is only one of several people who have filed lawsuits against the oil companies for damages (Branstetter, 2015). With an increase in earthquakes, many people will be considering earthquake insurance for their homes and businesses. Earthquake insurance is not something most people carry, so many of the people that had their homes or businesses damaged had no coverage at the time of the earthquakes and must pay for the repairs themselves. Earthquake insurance is available, but the cost could be prohibitive for many people. In addition, the devaluation of homes in an earthquake area could make it difficult for people to sell their homes and move (Cheung, Wetherell, & Whitaker, 2018). People in earthquake prone areas will not only receive less money for their home, but they may also have difficulty selling their home (Cheung, Wetherell, & Whitaker, 2018).

Oklahoma has seen an increase in the disposal of hydraulic fracturing wastewater over the last twenty years, along with an increase in earthquakes. There is scientific evidence that the injection of hydraulic fracturing wastewater into injection wells is causing this increase in seismic activity (Ellsworth, 2013; Keranen, Weingarten, Abers, Bekins, & Ge, 2014; Walsh, III & Zoback, 2015). The oil and gas companies would benefit from this scientific research as it would give them valuable information on how to lower the risk of causing earthquakes and the risk of being sued for damages from earthquakes. Especially since many insurance companies have begun excluding hydraulic fracturing operations in their commercial general liability policies, leaving companies that perform hydraulic fracturing with higher insurance premiums or no insurance coverage for their daily operations. The hydraulic fracturing companies could find themselves paying for their own legal fees with no legal defense from their insurance company.

This thesis will be a case study that concentrates on the relationship between the injection of hydraulic fracturing wastewater into disposal wells and increased earthquakes in Oklahoma from 2011 to 2016. Specifically, the volume of wastewater, its injection pressure, the distance from the well to an unstable fault, and how long ago the injection was are hypothesized to impact the frequency of earthquakes. This case study poses initially that among these variables injection pressure will be the most influential factor.

CHAPTER TWO: LITERATURE REVIEW

Hydraulic fracturing was invented in 1947 and is still used today to retrieve hard-to-reach oil and gas found in low-permeability rock formations. In this process, a well is drilled to reach oil and gas trapped in shale and tight sand formations (Rubinstein, 2015). Once the well is drilled the fracking fluid, a mixture of water and chemicals, is injected into the well creating fractures along the borehole (Rubinstein, 2015). The propping agent (e.g., sand) in the fracking fluid holds open the fractures so that the oil and gas may be extracted to the surface (Rubinstein, 2015). Once the oil and gas is brought to the surface it is extracted from the fracking fluid. The leftover fracking fluid is wastewater that is either reused, in enhanced oil recovery operations, or disposed of in disposal wells. Due to the high saline content of the wastewater it must be disposed of properly into Underground Injection Control (UIC) Class II wells (see Figure 1) per the EPA's Safe Drinking Water Act of 1974. The UIC Class II wells are specifically for disposing of the high saline wastewater from oil and gas hydraulic fracturing operations and are deep wells situated in sedimentary rock formations with high porosity and high-permeability. The wells are usually at a depth deeper than the oil and gas deposits, and drinking-water wells per the US Environmental Protection Agency requirements (https://www.epa.gov/; Rubinstein, 2015; Walsh, III & Zoback, 2015).

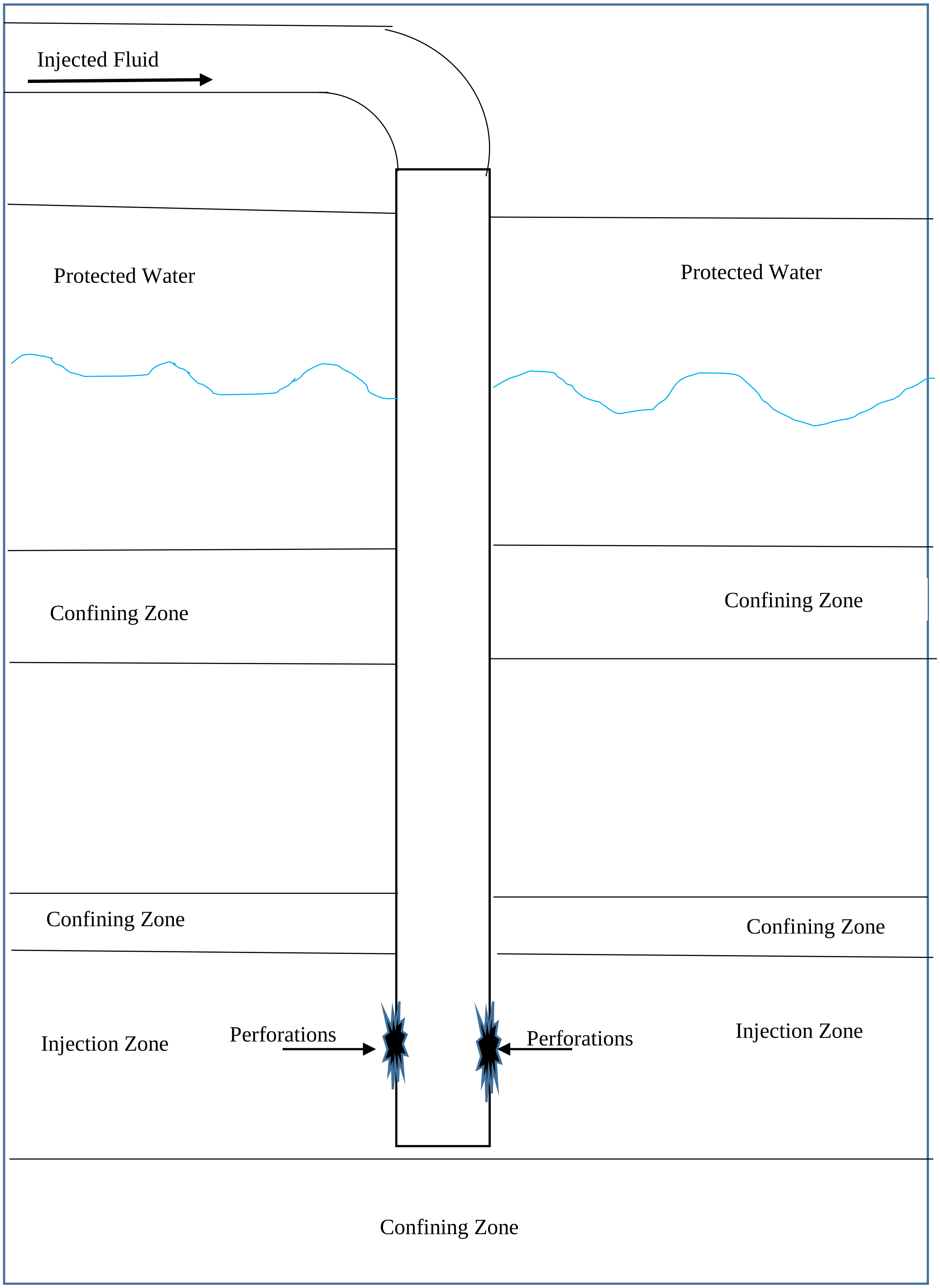

Figure 1: UIC Class II Wastewater Injection Well (created by Susan Muñiz, July 22, 2018)

Fracking and Seismic Events: a US and Global Perspective

Over the last nine years the number of earthquakes in the central United States has increased dramatically from 21 earthquakes per year to more than 300 per year (Ellsworth, 2013). Research suggests that this increased seismic activity is associated with the injection of hydraulic fracturing wastewater into deep sedimentary formations (Ellsworth, 2013; Kim, 2013; Rubinstein, 2015). There have been several seismic events associated with hydraulic fracturing wastewater disposal (Ellsworth, 2013; Rubinstein, 2015). In 1967, an M_W 4.8 event occurred near Denver, Colorado. This event was considered the largest seismic event induced by wastewater injection, until the M_W 5.7 event in Prague, Oklahoma in 2011 (Ellsworth, 2013). The Youngstown, Ohio, area had no recorded seismic activity from 1776 until 2011. During this same time, the entire state of Ohio had only 200 earthquakes, the largest an M 5.4 on 9 March 1937. Then from January 2011 to February 2012 there were 109 small earthquakes reported in the Youngstown area (Kim, 2013). The increase in seismicity corresponded with the increase in the disposal of hydraulic fracturing wastewater into UIC Class II wells in the Youngstown area (Kim, 2013). Since 2008, there have been several earthquakes of $M \geq 3$ in the Ellenburger Formation near Fort Worth, Texas (Frohlich, 2012a; Hornbach, et al., 2016). The Barnett Shale area has approximately 2,458 injection wells, which inject into the Ellenburger Formation; 128 of these wells have experienced nearby seismic activity (Frohlich, 2012a; Hornbach, et al., 2016).

The United States is not the only country experiencing seismic activity suspected to be due to hydraulic fracturing operations. Horn River Basin in northeast British Columbia, Canada, experienced increased seismic activity after hydraulic fracturing operations began in an aseismic area in 2006 (Farahbod, Kao, Walker, & Cassidy, 2015). In 2011, the British Geological Survey

(BGS) detected an M_L of 2.3 near the Cuadrilla Resources hydraulic fracturing operations near Blackpool in the United Kingdom; the earthquakes began the day after hydraulic fracturing operations had ceased (Clarke, Eisner, Styles, & Turner, 2014). When operations resumed a few weeks later a second earthquake of M_L 1.5 was detected 1km from the well and again a day after operations had ceased (Clarke et al., 2014). The BGS recorded 52 earthquakes in this area ranging from M_L -2 to M_L 2.3 (Clarke et al., 2014)

Injection of water not associated with hydraulic fracturing is also associated with earthquakes. For example, in 1991, the Bureau of Reclamation began operations at a deep injection well near Paradox Valley, Colorado (King, Block, & Wood, 2016). Seismicity was monitored in the area from 1985 until the start of operations in 1991 and no earthquakes were detected within 18km of the injection wells during this time (King et al., 2016). Once operations began seismic activity was detected within days of the injections (King et al., 2016). Southwest China has experienced induced earthquakes from the water injection into the Changning salt mines (Sun, Yang, & Zhang, 2017). Wastewater injection is obviously associated in some way with increased earthquake activity. One unanswered question, however, is what characteristics of this water are most associated with seismic events, as indicated in the literature. Below, I will investigate four such factors: volume, pore pressure, location of the injection well in relation to vulnerable geological strata and time between the injection and the seismic event.

Wastewater Volume and Seismic Events

One possible cause of earthquakes, near wastewater wells, is the volume of wastewater injected into wells (Clarke, Eisner, Styles, & Turner, 2014; Kim, 2013; Rubinstein, 2015; Walsh, III & Zoback, 2015). There have been several large earthquakes that have been identified as being the result of fluid injection into deep, underground wells. They are the 1960 M 4.9 in

Denver, Colorado, the 2011 M 5.3 in Trinidad, Colorado, and the 2011 M 5.6 in Prague, Oklahoma. Injection rates can vary from 100 barrels per month to as much as one million barrels per month. Maximum monthly injection rates of 150,000 barrels of water per month or greater may be the cause of injection-triggered earthquakes. The Ellenburger Formation in the Barnett Shale, Texas area has injection rates that have exceeded a maximum rate of 150,000 barrels of water per month for a year or more, which has corresponded with an increase in seismic activity (Frohlich, 2012a; Frohlich, 2012b; Rubinstein, 2015). While this rate of injection has triggered earthquakes in some areas, other areas comparable rates of injection did not experience any earthquakes. This could be because many of the wastewater disposal wells in Oklahoma are deep enough to reach faults that extend into the Precambrian basement, bypassing shallower faults in the area. The sedimentary rocks in Central Oklahoma extend to 2 to 3km; however, the earthquakes in this area are occurring at an average depth of 5 to 6 km which extends into the crystalline basement (Walsh, III & Zoback, 2015).

Wastewater Pore Pressure and Seismic Events

Another probable cause of earthquakes is the change in pore pressure, the pressure of fluid on rock at the micro-level. Earthquakes may be induced by wastewater injection into disposal wells, which increases pore pressure along pre-existing faults (Ellsworth, 2013; Kamei, Nakata, & Lumley, 2015; Kim, 2013). These micro seismic events, usually a “moment magnitude” M_W of no more than 3 or 4, are created when the fluid injection changes the reservoir pressure a few hundred psi (pounds per square inch), which equals a few MPa (mega Pascal) (Kamei et al., 2015). One mega Pascal (MPa) equals 145.038 pounds per square inch (psi) (Convert psi to MPa-Conversion of Measurement Units, 2017). The US Geological Survey (USGS) experiment at Rangely oil field, Colorado concluded that an increase in pore pressure could increase the rate of seismic activity (Ellsworth, 2013). In 1967, a M_W 4.8 seismic event occurred due to the injection of water with a pressure front of 3.2 MPa (Ellsworth, 2013). In 2011, the earthquakes recorded in Youngstown, Ohio were believed to be due to the injection of hydraulic fracturing wastewater at pressures up to 17.2 MPa; the seismic activity in the area increased as the injection pressure increased (Kim, 2013). The fluids injected into disposal wells do not have to travel from the well to the fault to induce an earthquake (Rubinstein, 2015). The change in fluid pressure in the reservoir can be spread farther than the fluids themselves (Rubinstein, 2015). Ellsworth (2013) found that the earthquakes at the Paradox Valley wastewater injection sites would quickly subside if there were occasional shutdowns of the wastewater injection. These 20-day shutdowns allowed the fluid pressure to equalize reducing the potential for seismic activity. Even pouring wastewater down the well with no pressure could still cause faults to slip due to the rise of the water table, which would still increase pore pressure on the faults (Ellsworth, 2013); Weingarten, Ge, Godt, Bekins, & Rubinstein, 2015).

Wastewater Disposal and Distance to Critical Faults and Time Delay of Earthquakes

Another effect of wastewater disposal is the possibility that the earthquakes triggered could be several kilometers from the disposal well. King, Block and Wood (2016) believe this is due to pore-pressure diffusion. Increased subsurface pore pressure is more likely to trigger seismic activity up to 20km away from the well. The presence of injectate may not be the cause of the seismicity; it may be caused by the pore pressure in the original fluid in the reservoir (King et al., 2016). Ellsworth (2013) found that deep reservoirs in active tectonic zones are susceptible to induced earthquakes, such as the 1967 Rocky Mountain Arsenal seismic event that occurred 10 km from the injection well. The Paradox Valley operation has seen several changes in volume and pore pressure of wastewater injection into wastewater disposal wells (King et al., 2016). Although the volume and pressure was decreased after seismic activity, the activity continued sometimes as much as 10km from the wellhead (King et al., 2016). In 1995, seismic activity was registering 3 to 4km from the injection well at Paradox Valley, but by mid-1997, the activity was 6 to 8km and by mid-2000, earthquakes were detected 12 to 14km from the injection well (King et al., 2016).

The time delay of earthquakes, triggered by wastewater disposal, is another unusual effect. King, Block and Wood (2016), observed that seismic activity created by pore pressure diffusion displays a characteristic space-time trend. Keranen, Savage, Abers and Cochran (2013) suggest that some of the fluid injected into disposal wells was injected into isolated pockets, which may delay seismicity by nearly 20 years from the date of initial injection. An example of this time delay happened at the Rocky Mountain Arsenal, a defense plant, in Colorado (Ellsworth, 2013). The hazardous chemicals from the plant were injected into 3.6km deep wastewater wells, and six years later an M_W 4.8 seismic event occurred (Ellsworth, 2013). Rubinstein (2015) found that the longer the duration and the larger the injection volume the more likely the earthquakes will occur farther from the injection site and over a longer period of time.

Oklahoma, like many of the previously mentioned places, has also experienced an increase in earthquakes. The earthquakes in Oklahoma may be related to hydraulic fracturing operations and the increased amount of wastewater generated and injected into wastewater wells. The literature shows that the causes of these earthquakes in Oklahoma may be due to the volume, pore pressure, or distance to critical faults near the wastewater injection wells. Some of the earthquakes caused by wastewater injection may not be triggered for days, months or even years after the initial injection. This case study will reinforce previous literature that argues that the earthquakes in Oklahoma are caused by the injection of hydraulic fracturing wastewater into UIC Class II wells.

Geology and Fracking

The EPA (https://www.epa.gov/) states that the injection of wastewater must be into the same or similar formations from which it was extracted. The previously mentioned locations of hydraulic fracturing and wastewater disposal sites all tend to be found in sedimentary formations from the Paleozoic Era. The Horn River Basin, Canada formation is part of the Mississippian to Early Carboniferous period (Farahbod et al., 2015). Blackpool, UK hydraulic fracturing extended into the Late Carboniferous formations in the area (Clarke et al., 2014). The wastewater sites near Youngstown, Ohio were injecting water into Middle Cambrian to Lower Ordovician formations, but the earthquakes occurred in the Precambrian crystalline basement (Kim, 2013). Hornbach, et al. (2016), found that wastewater disposal sites were in the Ellenburger Formation, part of the Lower Ordovician; however, like Ohio, the earthquakes were occurring in the Precambrian granitic basement underlying the Ellenburger Formation. The hydraulic fracturing and wastewater sites in Oklahoma are found in the Middle Cambrian to Lower Ordovician formations (Walsh, III & Zoback, 2015). Both Walsh, III and Zoback (2015) and Ellsworth (2013) found that the largest seismic events caused by wastewater injection were in deep wells that increased pressure into the crystalline basement. The more important factor may be the depth of the well and its proximity to nearby faults that extend into the crystalline basement.

Fracking and Seismic Events in Oklahoma

Oklahoma is one of the high-production oil and gas areas in the United States and it has had a sharp increase in earthquakes within the last 10 years (Keranen, Weingarten, Abers, Bekins, & Ge, 2014). Twenty percent of the seismic activity in the central US region, in 2008, was a single swarm of earthquakes near Jones, Oklahoma. The Jones, Oklahoma single swarm of earthquakes, along with the other earthquakes, from 2008 to 2013, are part of a 40-fold increase, compared to the number of earthquakes from 1976 to 2007 for the state of Oklahoma (Keranen et al., 2014). This increase in earthquakes corresponds with an increase in hydraulic fracturing wastewater disposal in the area (Keranen et al., 2014). This increase in earthquakes corresponds with an increase in hydraulic fracturing wastewater disposal in the area (Keranen et al., 2014).

Natural earthquakes occur when there is tectonic movement caused by an increase or reduction in stress which can cause slippage along a fault line releasing stored energy (Ellsworth, 2013; Kamei et al., 2015). Oklahoma has 45% of M 3 or greater earthquakes, the highest number in the central US. The largest earthquake recorded in the area is the Prague, Oklahoma earthquake of 2011, which registered at M_W 5.7 (Ellsworth, 2013; Keranen et al., 2014). Prior to 2009, the north central region of Oklahoma experienced one M_W 4 event per decade; however, in 2015 to 2016 this area experienced M_W 4 or larger seismic events weekly (Alt, II & Zoback, 2017). This increase in earthquakes corresponds with an increase in injection rates at wastewater disposal sites (Walsh, III & Zoback, 2015).

Oklahoma Wastewater Volume and Seismic Events

Prior to 2008, Oklahoma experienced one $M \geq 3$ event a decade, but in 2014 there were 24 $M \geq 3$ events (Walsh, III & Zoback, 2015). The monthly injection rate in Oklahoma doubled from 80 million barrels per month in 1997 to 160 million barrels per month in 2013; this increase in the volume of injected wastewater injected into wells corresponds with an increase in earthquakes (Walsh, III & Zoback, 2015). By 2013, the rate of injection at the disposal wells near Perry, Oklahoma was 10 times higher than it had been in early 2000. The injection well located near Perry, Oklahoma had increased the volume of injection from almost nothing to about 500,000 barrels per month; Cherokee, Oklahoma has also seen an increase in its disposal rates followed by an increase in seismic events (Walsh, III & Zoback, 2015).

Oklahoma Wastewater Pore Pressure and Seismic Events

The pressure of the wastewater being injected into a disposal well is believed to be the cause of earthquakes in various locations in the US. Oklahoma is no different. The Jones, Oklahoma earthquakes occurred in an area that was disposing of ~4 million barrels per month of wastewater. The pore pressure models indicated that the four disposal sites near Jones were capable of causing nearly 20% of the earthquakes in central and eastern U.S. from 2008 to 2013 (Keranen et al., 2014).

Oklahoma Wastewater Disposal and Distance to Critical Faults

The Jones, Oklahoma earthquake swarm was less than 20km from the wastewater disposal wells, this seismic activity continued to move northeast away from Jones, Oklahoma at 0.1 to 0.15km per day (Keranen et al., 2014). This migration of activity continued for nearly a year after the initial earthquake swarm, some of the last recorded activity was more than 30 km from the disposal wells in the area (Keranen et al., 2014).

Oklahoma Wastewater Disposal Wells and Time Delay of Earthquakes

Walsh, III and Zoback (2015), found that the time delay between the increased injection rate and seismicity could be due to the type of formation the wastewater is injected into; if the underlying layers are more permeable the pressure changes would be more likely to spread out quickly, causing a shorter time delay between pore pressure increase and seismicity. Walsh, III and Zoback (2015) also found that because the pore pressure is spreading out from the injection site to the depth of the crystalline basement, it takes time before an earthquake is triggered in the basement.

Oklahoma Geology and Fracking

The sedimentary rocks in central Oklahoma extend to 2 to 3km; however, almost all the earthquakes are occurring at the crystalline basement which is 5 to 6km deep (Walsh, III & Zoback, 2015). In central Oklahoma, the Arbuckle Group, a Cambrian-Ordovician formation, is the formation used for hydraulic fracturing wastewater disposal (Keranen et al., 2014; Walsh, III & Zoback, 2015) (see Figure 2 below). This formation appears to be connected with the underlying crystalline basement and the pressure changes from the wastewater injection can cause earthquakes to spread to this depth (Walsh, III & Zoback, 2015). The Prague, Oklahoma earthquake in November 2011 included a main shock of M5.7 with many aftershocks as great as M5; these aftershocks extended into the crystalline basement and along the north-northeast trending Wilzetta fault (Walsh, III & Zoback, 2015). The March 7, 2016 Oklahoma Corporation Commission Media Advisory includes a letter to companies within the area of triggered seismicity, which states that wells injecting into the Reagan Sand or Granit Wash are considered to be in communication with the crystalline basement rock and these wells must be plugged back (i.e., reduced in depth) (Baker, 2016). This study will more closely investigate the seismic and aseismic wastewater wells in Oklahoma, and the location of nearby earthquakes to better clarify the reason why some wastewater wells create earthquakes and others do not. The information obtained from this research would benefit not only the oil and gas industry, but also the people of Oklahoma, giving them a greater insight into this problem and helping to lessen the danger of a catastrophic seismic event.

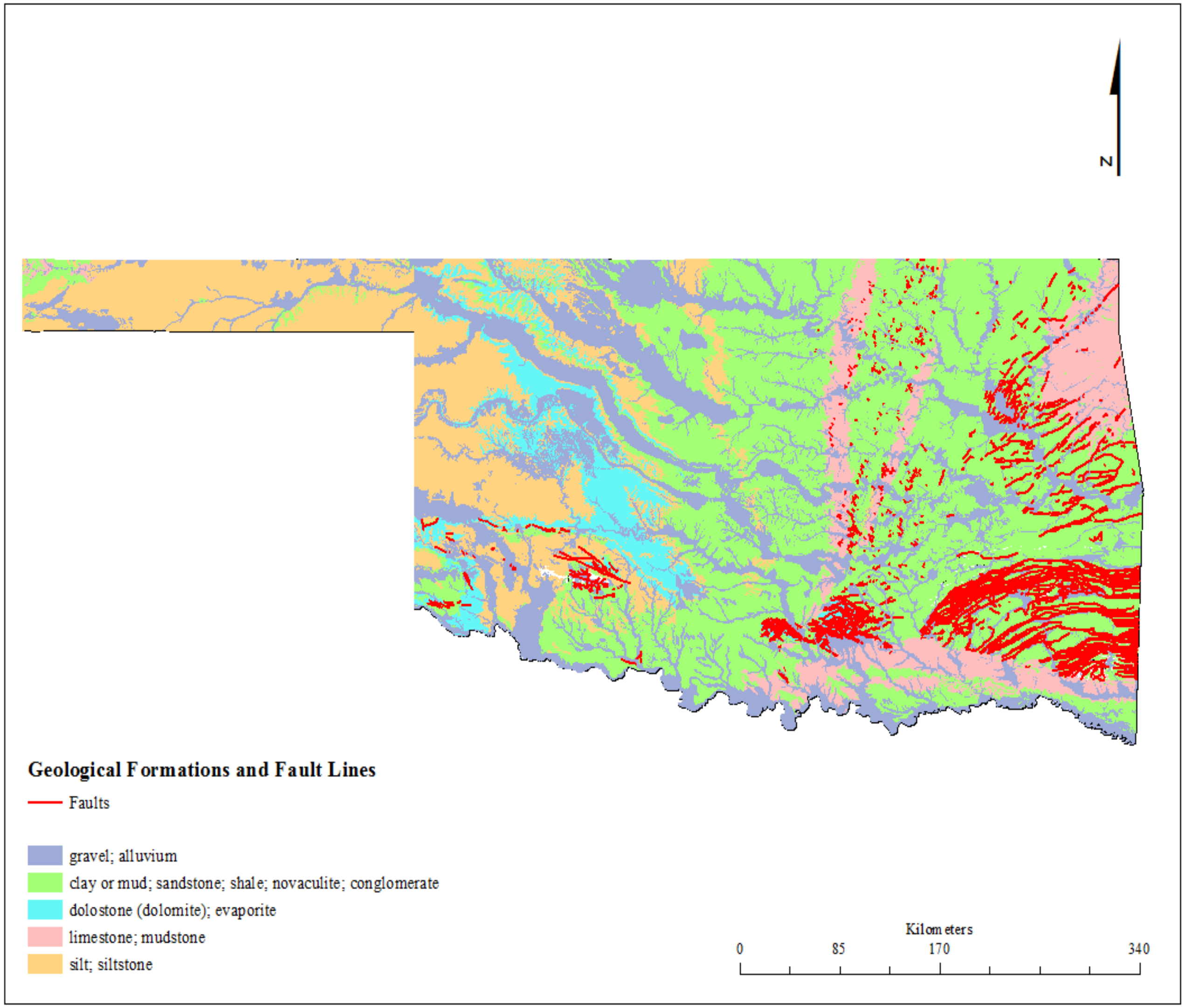

Figure 2: Map of the Geological Formations and Fault Lines in the State of Oklahoma (created by Susan Muñiz; data source: US Census Bureau, Oklahoma Corporation Commission and Oklahoma Geological Survey)

CHAPTER THREE: METHODOLOGY

This thesis concentrated on the relationship between the injections of hydraulic fracturing wastewater into UIC Class II disposal wells and earthquakes in Oklahoma for the inclusive years 2011 to 2016.

Hypotheses:

- Hypothesis 1: As the well's wastewater volume increases, the number of earthquakes, in the vicinity, increases.
- Hypothesis 2: As the well's wastewater injection pressure increases, the number of earthquakes, in the vicinity, increases.
- Hypothesis 3: As the distance of the wastewater injection from the well increases, the number of earthquakes decreases.
- Hypothesis 4: As the time from the date of injection of wastewater into the well increases, the number of earthquakes decreases.

The unit of analysis was the approximately 800,000 hydraulic fracturing wastewater injections into Class II UIC (underground injection control) wells in Oklahoma over the 72-month period of January 2011 to December 2016. For hypotheses 1, 2, and 4, the volume, pressure, and the time-delay between injections and earthquakes were the independent variables; they were recorded for grid cells of approximately 100 sq. km. each, covering the entire state of Oklahoma. Whether there was an earthquake in the same grid cell (in the same month or in subsequent months), was the dependent variable. For hypothesis 3, the number earthquakes (the dependent variable) was measured by distance zones from each injection. Thus, for this hypothesis, distance zone from the well was the independent variable. The number of magnitude 2 or greater was my operational definition for the dependent variable. Geology was an exogenous control. Most of the hydraulic fracturing wastewater disposal takes place in central Oklahoma were the wastewater is injected into the Arbuckle Group, a Cambrian-Ordovician formation (Walsh, III and Zoback, 2015). These variables were chosen as the independent variables for this research because of the literature on this subject. Several peer-reviewed articles discussed how the wastewater injection volume, pore pressure, distance from wastewater wells, and time since the last injection are related to the increase in earthquakes experienced near wastewater wells (see Figure 3).

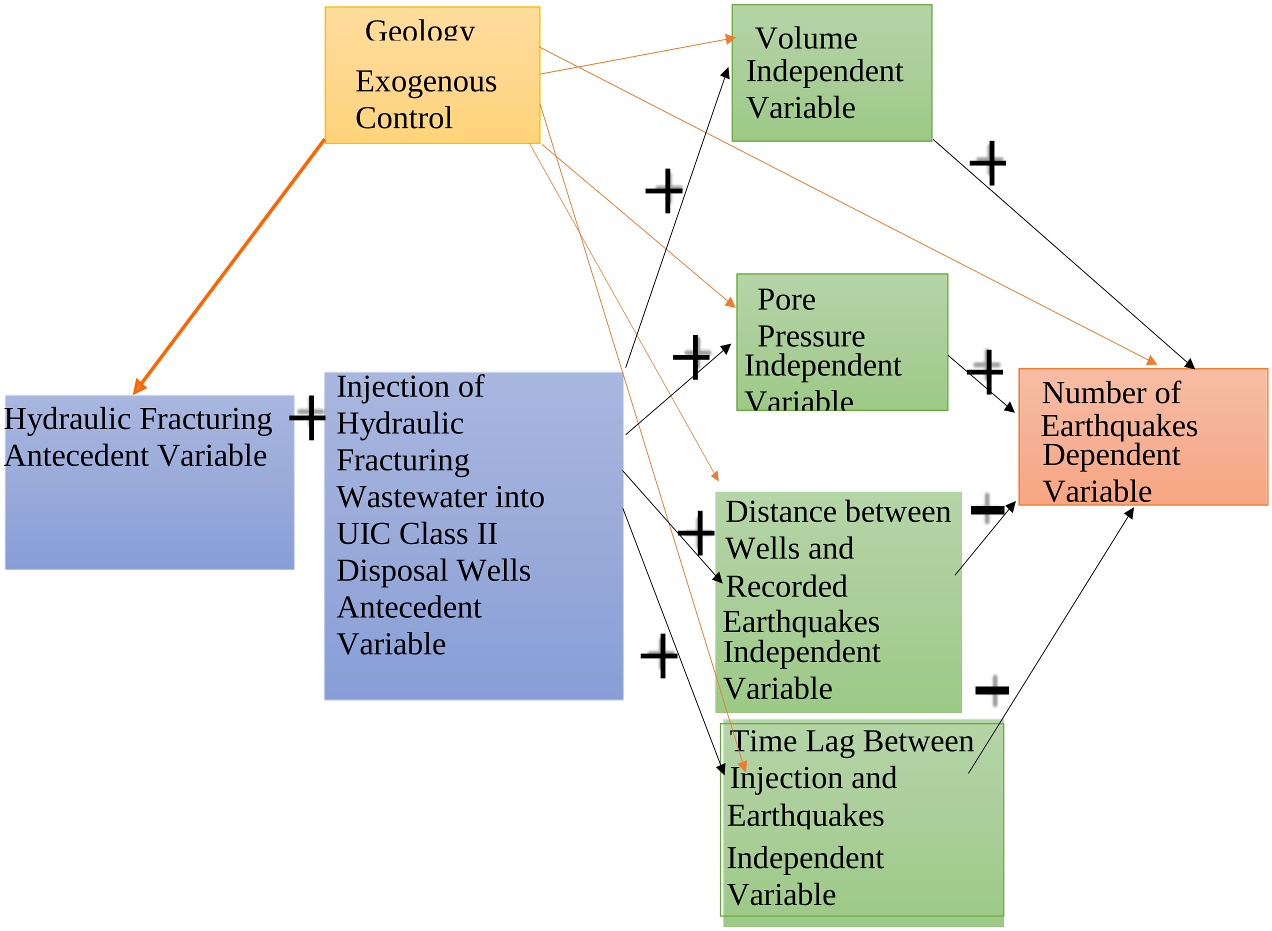

Figure 3: Diagram of Relationships (Muñiz, 2017)

Data

The earthquake data for this research were obtained from the Oklahoma Geological Survey (OGS) and the Oklahoma UIC Class II wastewater well information was been obtained from the Oklahoma Corporation Commission (OCC) (Muñiz, 2016). Vector layers of the State of Oklahoma were downloaded from the U.S. Census Bureau's Topologically Integrated Geographic Encoding and Referencing data sets (TIGER), found in the geography portion of the census.gov website; this data included a base map of Oklahoma and Oklahoma's geology and fault information (Muñiz, 2016).

Well data prior to 2011 was not very reliable; it consisted of scanned documents sent in from well owners. Many of these documents were difficult to read, incomplete and some of them appeared to be the same document sent in year after year. The Oklahoma Corporation Commission had excellent well data from 2011-2016 showing monthly psi and volume information, depth of wells, along with latitude and longitude, for each well.

The well data from 2011-2016 were cleaned up to include just the information needed for this research, deleting all wells showing zero or null for psi, barrels, depth, latitude, longitude, any duplicate entries, and extremely high or low values, e.g. volume had one entry of 3,864,144 barrels injected in a single month, and the next highest volume was 2,528,313 per month.

Earthquake information for Oklahoma from 2011-2016 was used to coincide with the years of well information. The earthquake data was also cleaned up by deleting any earthquakes showing zero or null for latitude and longitude, and by deleting any earthquakes with a magnitude less than 2mg. Most earthquakes less than 2mg are not felt and do not cause property damage. While the earthquake data gave, the actual date and time of the earthquake the well data only showed monthly average for psi and monthly total volume for each well for each year, therefore, the earthquake times were grouped into months for each year to correspond with the well data.

Well and earthquake data were entered into SPSS and ArcGIS. Hypotheses 1, 2, and 4 used SPPS; hypothesis 3 used ArcGIS. The first hypothesis involved the total monthly volume of wastewater injected into UIC Class 2 wells and the number of earthquakes found in the vicinity of the well after the injections. The wastewater volume and earthquakes were aggregated into variables for SPSS, which included all months and years for the wastewater injections and earthquakes. The wastewater volume was divided into eight categories by using SPSS frequencies and percentiles. The earthquake information was divided into two categories, earthquakes or no earthquakes. With these new categories cross-tabulations were run, along with symmetric measures of Cramer’s V, Pearson’s R, and Spearman Correlation to determine if there was any correlation between the amount of wastewater injected into the wastewater wells and the number of earthquakes nearby. Pearson’s R was also run separately between total earthquakes and total wastewater volume to determine if there was any significant correlation between the two variables.

The second hypothesis involved the monthly average of psi (pounds per square inch) of wastewater injected into UIC Class II wells and the number of earthquakes found in the vicinity of the well after the injections. The wastewater psi and earthquakes were aggregated into variables for SPSS, which included all months and years for the wastewater injections and earthquakes. The psi was divided into four categories by using SPSS frequencies and percentiles. The earthquake information was divided into two categories, earthquakes or no earthquakes. With these new categories cross-tabulations were run, along with symmetric measures of Cramer’s V, Pearson’s R, and Spearman Correlation to determine if there was any correlation between the monthly psi of injected wastewater and the number of earthquakes nearby. Pearson's R was also run separately between total earthquakes and the monthly average of psi of wastewater to determine if there was any significant correlation between the two variables.

For hypothesis 3 wastewater well and earthquake data were entered into ArcGIS and plotted. Buffers of 5km, 10km, and 15km were generated around each wastewater well. For each buffer layer the earthquakes were selected by location to show just those earthquakes that fell within the buffer. The density of earthquakes was determined for each buffer layer.

Finally, for hypothesis 4 the total monthly barrels of injected wastewater, average monthly psi of injected wastewater and the total number of earthquakes with a magnitude of 2 or greater, for all months and years were entered into SPSS. The time series function in SPSS was used to lead (move forward) the earthquake variable by one month, up to eight months. Spearman's Correlation was run on all of these variables to determine if there was a significant correlation. Depth of wastewater wells and total number of earthquakes were included in the Spearman's Correlation. Total earthquakes was included to see if the correlation between total earthquakes and the other variables diminished over time. Depth of wastewater wells was used to see if there was a correlation between depth of wells and earthquakes.

Hypothesis 1

As the well's wastewater volume increases, the number of earthquakes in the vicinity increases.

Operational Definitions of Variables

The first hypothesis used total, monthly barrels (1 barrel equals 42 gallons) of hydraulic fracturing wastewater injected into each UIC Class II well, each month for the years 2011 to 2016, inclusively, and the total number of magnitude 2 earthquakes or greater, in the same grid cell as the wells, for the same months and years.

Data Extraction

Hypothesis 1 used the total wastewater volume injected into the wastewater wells in relation to the total number of earthquakes for the same month, year, and grid cell. The methodology for the first, second and fourth hypotheses used a grid cell of 1/10th of a degree of latitude by 1/10th of a degree of longitude (approximately 104 km^2) which covered the entire state of Oklahoma. Using this grid the earthquakes for a given month and year were matched to volume for the same month and year in the same grid cell.

Using SPSS a dichotomy for the earthquake variable was created: "Yes" if an earthquake occurred (in that grid cell for that month and year) and "No" if there was no earthquake. This earthquake variable was used in hypotheses one, two and four.

Statistical Techniques

Since there was such a wide range of volume injections, from 0 to 2,528,313 barrels per month, volume was divided into eight equal percentiles. Wastewater injections were the total monthly volume of injected wastewater which was divided into eight categories extremely low, very low, low, medium low, medium high, high, very high, and extremely high. Volume ranged from 0 barrels to 2,528,313 barrels. Volume was measured by barrels; one barrel equals 42 gallons. The mean for monthly injection of wastewater was 26,557.20 barrels per monthly injection and the standard deviation was 70,305.391. For earthquakes, a dichotomy category was created; yes, for whether an earthquake occurred and no if, no earthquake occurred. Earthquakes of 2mg or greater were used.

Using the dichotomy variable for earthquakes, volume was broken up into eight equal divisions in order to run cross-tabulations with the earthquake dichotomy variable; Cramer's V was run along with the cross-tabulations. Pearson's correlation was run between volume and earthquakes.

Criteria for Acceptance of Hypothesis

In order to accept this hypothesis there needs to be a low probability that the statistical results are random, the level of significance should be 0.001 or greater, and there should be a positive correlation.

Hypothesis 2

As the well's wastewater injection pressure increases, the number of earthquake in the vicinity increases.

Operational Definitions of Variables

The second hypothesis used average pounds per square inch (psi) of pressure of hydraulic fracturing wastewater injected into each UIC Class II well, each month for the years 2011 to 2016, inclusively, and the total number of magnitude 2 earthquakes or greater, in the same grid cell as the wells, for the same months and years, a grid cell being defined as above (hypothesis 1). Using this grid the earthquakes for a given month and year were matched to psi for the same month and year in the same grid cell.

Data Extraction

The grid cell methodology mentioned in hypothesis one and the dichotomy earthquake variable were used for this hypothesis. Using this grid the earthquakes for a given month and year were matched to psi for the same month and year within the same grid cells. Using frequencies in SPSS psi was broken up into four equal divisions in order to run crosstabs with the earthquake dichotomy variable.

Statistical Techniques

Research shows that a change of 1.5 to 14.5 psi was capable of triggering an earthquake if nearby faults are near critical failure (Keranen, et al, 2014). There does not seem to be a specific psi level that increased the chance of an earthquake; it was the change in psi, even a small change, that could trigger an earthquake (Kim, 2014).

The categories for the variables in the second hypothesis were the dichotomy category for earthquakes and the average psi of injected wastewater, divided into four categories low, medium, high, and very high.

Using the dichotomy variable for earthquakes and the four divisions of psi cross-tabulations were run with the earthquake variable; Cramer’s V was also run. Pearson’s correlation was run between psi and earthquakes.

Criteria for Acceptance of Hypothesis

In order to accept this hypothesis there needs to be a low probability that the statistical results are random, the level of significance should be 0.001 or greater, and there should be a positive correlation.

Hypothesis 3

As the distance of the wastewater from the well increases, the number of earthquakes decreases.

Operational Definitions of Variables

The third hypothesis used total monthly barrels of injected wastewater for each month for the years 2011 to 2016, inclusively, and the total number of magnitude 2 earthquakes or greater, in the vicinity of the wastewater UIC Class II wells, for the same months and years to show the distance (in kilometers) the earthquakes traveled after the injection of the wastewater into the wells.

Data Extraction

Since, many of the wastewater wells were less than a kilometer apart 5km, 10km, and 15km buffers were established around the wastewater wells. Pi r square was used to find the area of each buffer ring. Five kilometers (0 kilometers to 5 kilometers) contained 78.54 square kilometers, the 10-kilometer buffer (5 kilometers to 10 kilometers) contained 235.62 square kilometers and the 15-kilometer buffer (10 kilometers to 15 kilometers) contained 392.70 square kilometers. The number of earthquakes in each buffer was divided by the appropriate area shown above for each of its corresponding buffers to determine the density of earthquakes in each buffer. Earthquakes were selected by location to the wells, so only those earthquakes that fell within the buffer zones were plotted on ArcGIS.

Statistical Techniques

The categories for this hypothesis were the number of earthquakes found within 5km, 10km, and 15km of wastewater injection wells both percent and density of earthquakes was calculated for each of these zones. The total number of earthquakes, of 2mg or greater, for all years and all zones were used.

In ArcGIS, buffer was used to create 5km, 10km and 15km buffers around each wastewater well. Selection by location was used to select only those earthquakes within the different buffer zones. These thresholds of 5, 10, and 15km were used to show the pore-pressure diffusion which King et al, (2016) described as extending out at least 10km. Using 5km and 15km allowed the data to show how much the density of earthquakes changed as the distance from the well increased.

The percentages of total earthquakes and the density of the earthquakes within 5km, 10km, and 15km for all years of the study were calculated to show the density of earthquakes that occurred as you moved farther from the wastewater well. Kernel density was used to create a raster to help show the density of wastewater wells and earthquakes in Oklahoma for the years 2011 to 2016, inclusively.

Criteria for Acceptance of Hypothesis

For the third hypothesis, the criteria for accepting the hypothesis would be low probability that the statistical results are random and a clear, statistical decrease in density of earthquakes as you move farther away from the wells.

Hypothesis 4

As the time from the date of injection of wastewater into the well increases, the number of earthquakes decreases.

Operational Definitions of Variables

Finally, the fourth hypothesis used the total monthly barrels of injected wastewater, average psi of injected wastewater each month for the years 2011 to 2016, inclusively, and the total number of magnitude 2 earthquakes or greater, in the vicinity of the wastewater wells, for the same months, years and within the same grid cells, as well as for earthquakes that were one, two, …up to eight months into the future.

Data Extraction

Hypothesis 4 used the same methodology as the first two hypotheses, but the data were aggregated to show total earthquakes, total volume, and average psi by month over all grid cells within the state of Oklahoma to examine time-delayed earthquakes due to volume and psi. This hypothesis examined time-delayed earthquakes as an effect of volume and psi. Grid cells were as defined for hypothesis 1 and 2. Using this grid the earthquakes for a given month and year were matched to volume for the same month and year in the same grid cell

Statistical Techniques

Using the time series function in SPSS the earthquake variable was led (moved forward) by one month, for up to 8 months. Categories for psi, monthly average pressure of wastewater for all years, monthly total injection of wastewater in US barrels (1 barrel equals 42 gallons) for all years, depth of wastewater wells in kilometers for all years, and earthquakes that were one, two,…up to eight months into the future were created.

Spearman’s rho was run for all years, and all months for psi and volume, and 8 months of lead-time of earthquakes, for all years.

Criteria for Acceptance of Hypothesis

A low probability that the statistical results are random, a level of significance of 0.001 or greater, and a negative correlation between the variables would be needed in order to accept this hypothesis.

CHAPTER FOUR: RESULTS

Hypothesis 1: As the well's wastewater volume increases, the number of earthquakes in the vicinity increases.

Pearson's correlation was run between volume and earthquakes and showed a weak, positive correlation of 0.029 between the increase in wastewater volume and earthquakes, while Cramer's V showed a weak, positive correlation of 0.055. However, there was a strong probability, which is significant at better than 0.001 probability, that the correlation between wastewater volume and earthquakes was not random due to the large number of cases. Nearly every well injection in Oklahoma was included in the number of cases used in tabulating the statistics, approximately 695,454 cases. Spearman's correlation was not run as there were too many cases. The number of valid cases was 526,627. The cross tabulations (see below) show a non-monotonic relationship, with the number of earthquakes increasing dramatically, once volume reaches a monthly injection of 46,360 barrels. The percentage of earthquakes initially increased as the volume increased. However, when the volume level reached the medium range of volume, approximately 9,000 barrels, the earthquakes began to decrease until the volume reached its extreme limit and then the earthquakes dramatically increased. Previous research suggests there is a threshold at which the number of earthquakes will increase; that threshold, according to Frohlich (2012a) is when the maximum injection rate exceeds 150,000 barrels per month. The number of wastewater injections was 613,061 with a mean of 26,557.20 barrels injected per well in the state of Oklahoma, with a large standard deviation of 70,305, as shown in Table 1 below.

Table 1: Volume^a Statistics

N	Valid	613061
	Missing	192122
Mean		26557.20
Std. Deviation		70305.391

a-Volume (barrels)-monthly total injection of wastewater (1 barrel = 42 gallons

Table 2 shows the cross-tabulations between the eight categories for volume and the two categories for earthquakes. There was an increase in earthquakes for the first two categories and then the percentage of earthquakes dropped off until the last category of extremely high wastewater volume. Frohlich (2012a) and Weingarten et al (2015) both found that the number of earthquakes increased when extremely high volumes of wastewater was injected into wastewater wells.

Table 2: Volume^a and Earthquakes Cross-Tabulation

			Extremely Low Less than 806	Very Low 807 to 2400	Low 2401 to 4836	Medium -Low 4837 to 9000	Medium-High 9001 to 14927	High 14928 to 24949	Very High 24950 to 46360	Extremely High 46361 or more	Total
Earthquakes	No	Count	64934	65244	64177	64816	64999	65035	65038	63518	517761
		65951	1017	1057	1059	1013	829	791	790	2310	8866
	Yes	100.0%	1.5%	1.6%	1.6%	1.5%	1.3%	1.2%	1.2%	3.5%	1.7%
			100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	

a-Volume in U.S. Barrels-monthly injection of wastewater (1 barrel = 42 gallons)

Table 3: Volume Symmetric Measures

		Value	Asymptotic Standard Error[a]	Approximate T[b]	Approximate Significance
Nominal by Nominal					
	Cramer's V	.055			.000
Interval by Interval	Pearson's R	.022	.002	15.777	.000[c]
Ordinal by Ordinal	Spearman Correlation	.022	.002	15.783	.000[c]
N of Valid Cases		526627			

a. Not assuming the null hypothesis.
b. Using the asymptotic standard error assuming the null hypothesis.
c. Based on normal approximation.

Pearson's correlation below shows a weak, positive relationship between earthquakes and wastewater volume, which is significant at better than 0.001.

Table 4: Pearson Correlations Volume and Earthquakes

		Earthquakes[a]	Volume[b]
Earthquakes	Pearson Correlation	1	.029**
	Sig. (2-tailed)		.000
	N	695455	526627
Volume	Pearson Correlation	.029**	1
	Sig. (2-tailed)	.000	
	N	526627	526627

**. Correlation is significant at the 0.01 level (2-tailed).
a-Total number of earthquakes for all years; b-Volume in U.S. Barrels-monthly injection of wastewater (1 barrel = 42 liquid gallons)

Walsh, III and Zoback (2015) found that the earthquakes in the Jones, OK area began after the maximum rate of injection reached about 12.5 million barrels/month. In Perry, OK earthquakes occurred in 2013 after the rate of injection increased from nearly zero to about 500,000 barrels/month. Frohlich (2012a) stated that of the eight study areas, in Oklahoma, that experienced earthquakes, all of them had a maximum injection rate that exceeded 150,000 barrels/month. Injection rates can vary from 100 barrels per month to as much as one million barrels per month. Maximum monthly injection rates of 150,000 barrels of water per month or greater may be the cause of injection-triggered earthquakes. The Ellenburger Formation in the

Barnett Shale, Texas area has injection rates that have exceeded a maximum rate of 150,000 barrels of water per month for a year or more, which has corresponded with an increase in seismic activity (Frohlich, 2012a; Frohlich, 2012b; Rubinstein, 2015).

Even though the relationship between volume and earthquakes is non-linear, there is a clear relationship between the increase in wastewater volume and the increase in earthquakes near the wastewater wells. The findings for the first hypothesis meet the criteria for acceptance. There is a low probability of the results being random, the significance level shown on the Pearson's correlation is 0.001 and there is a weak, but positive correlation between the two variables.

Hypothesis 2: As the well's wastewater injection pressure increases, the number of earthquakes in the vicinity increases.

Surprisingly, the cross-tabulations between psi and earthquakes shows a negative, monotonic relationship. The cross tabulations for psi shows the percentage of earthquakes steadily decreases as the wastewater pressure increases in a linear, monotonic decline (see table 6 below). Cramer's V shows a stronger, positive relationship of 0.064. The number of cases for psi was 417,431, with a mean monthly psi for all wells in Oklahoma of 628.10 and a standard deviation of 696.60, as shown in table five, below.

Table 5: PSI[a] Statistics

Statistics

PSI-monthly average pressure of wastewater

N	Valid	417431
	Missing	278024
Mean		628.0951
Std. Deviation		696.59698

a-PSI- (pounds per square inch) monthly average pressure of wastewater

Table 6: PSI[a] and Earthquakes Cross-Tabulation

			Low Less than 200	Medium 201 to 440	High 441 to 900	Very High 901 or greater	Total
Earthquakes	No	Count	104162	100873	103556	102845	411436
	Yes	Count	2669	1656	1286	382	5993
			2.5%	1.6%	1.2%	0.4%	1.4%
Total			100.0%	100.0%	100.0%	100.0%	100.0%

a-Monthly average pressure of wastewater for all years

Table 7: PSI Symmetric Measures

		Value	Asymptotic Standard Error[a]	Approximate T[b]	Approximate Significance
Nominal by Nominal					
	Cramer's V	.064			.000
Interval by Interval	Pearson's R	-.064	.001	-41.346	.000[c]
Ordinal by Ordinal	Spearman Correlation	-.064	.001	-41.354	.000[c]
N of Valid Cases		417429			

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

Pearson's R correlation between the increase in wastewater pressure and earthquakes showed a significant, better than 0.001 probability that the relationship is not random due to the large number of cases, but has a weak, negative correlation at -0.006.

Table 8: Pearson Correlations PSI and Earthquakes

		Total Earthquakes[a]	PSI[b]
Total Earthquakes	Pearson Correlation	1	-.006**
	Sig. (2-tailed)		.000
	N	695455	417431
PSI	Pearson Correlation	-.006**	1
	Sig. (2-tailed)	.000	
	N	417431	417431

**. Correlation is significant at the 0.01 level (2-tailed).

a-Total number of earthquakes for all years; b-Monthly average of pressure (psi=pounds per square inch) of wastewater for all years.

I did not expect this relationship; I thought this would be the stronger variable for causing earthquakes. However, the low relationship may be due to the dispersion of the pressure front as it moves through the geologic containing layer and the distance from the nearest critical fault. Although the literature does show that with an increase in psi there is an increase in earthquakes, there does not seem to be any single threshold amount. At Rangely, CO a critical fluid pressure of 25.7MPa (3,727.47 psi) was enough to trigger earthquakes (Ellsworth, 2013). Northstar 1 well in Youngstown, OH experienced peak seismicity after peak pressure, with psi ranging from 1890 to 2,509 (Kim, 2013). The Raton Basin, in central Colorado and northern New Mexico experienced earthquakes as great as 5.3mg even with zero injection pressure, also known as gravity feed (Rubinstein, 2015). Ellsworth (2013) stated that gravity feed could induce earthquakes by raising the pressure along fault lines. However, the lower pore pressure could open fractures, which initially caused an earthquake, but once the fracture was open, the fluid was able to flow into the spreading fractures (Raleigh, Healy, & Bredehoeft, 1976). Even though the psi may be increased, there are now open areas that allowed the fluid to continue to flow dropping the pore pressure due to diffusion and lessening the chance of an earthquake.

Hypothesis 2 is not accepted. Although there is a low probability that the correlation between psi and earthquakes is not random with a significance level of 0.001 or better, the correlation was negative, not positive as would be needed to accept this hypothesis.

Hypothesis 3: As the distance of the wastewater from the well increases, the number of earthquakes decreases.

The density of earthquakes found in each of the 15km buffers decreased from the number found in the 5km and 10km buffers.

Table 9: Percentage of Earthquakes within 5km, 10km, and 15km of Wastewater Wells

Percentages of Earthquakes near Wastewater Wells, within 5km, 10km, and 15km		
Earthquakes - Total 18,070	# of Quakes	% of Quakes
5km	8,019	43%
10km	7,291	40%
15km	2,465	14%

Table 10: Density of Earthquakes within 5km, 10km, and 15km of Wastewater Wells

Density of Earthquakes near Wastewater Wells, within 5km, 10km, and 15km		
Earthquakes - Total 18,070	# of Quakes	Density of Quakes per km^2
5km	8,019	102.10%
10km	7,291	30.94%
15km	2,465	6.28%

This decrease in earthquakes over distance may be due to the earthquake's energy wave front dispersing as it gets farther from the earthquake's epicenter (see Figure 4 below). Ellsworth (2013) reported earthquakes at Rocky Mountain Arsenal were sometimes found many kilometers from the injection site. The pore pressure diffusion may trigger earthquakes farther from the injection site, but since the pressure continues to decrease over time and distance there are fewer earthquakes the farther the pore pressure gets from the injection site. King et al (2016) found that pore-pressure diffusion extended out to a least 10km, which would help to explain the earthquakes found 15km from the well and the decrease in the density of earthquakes.

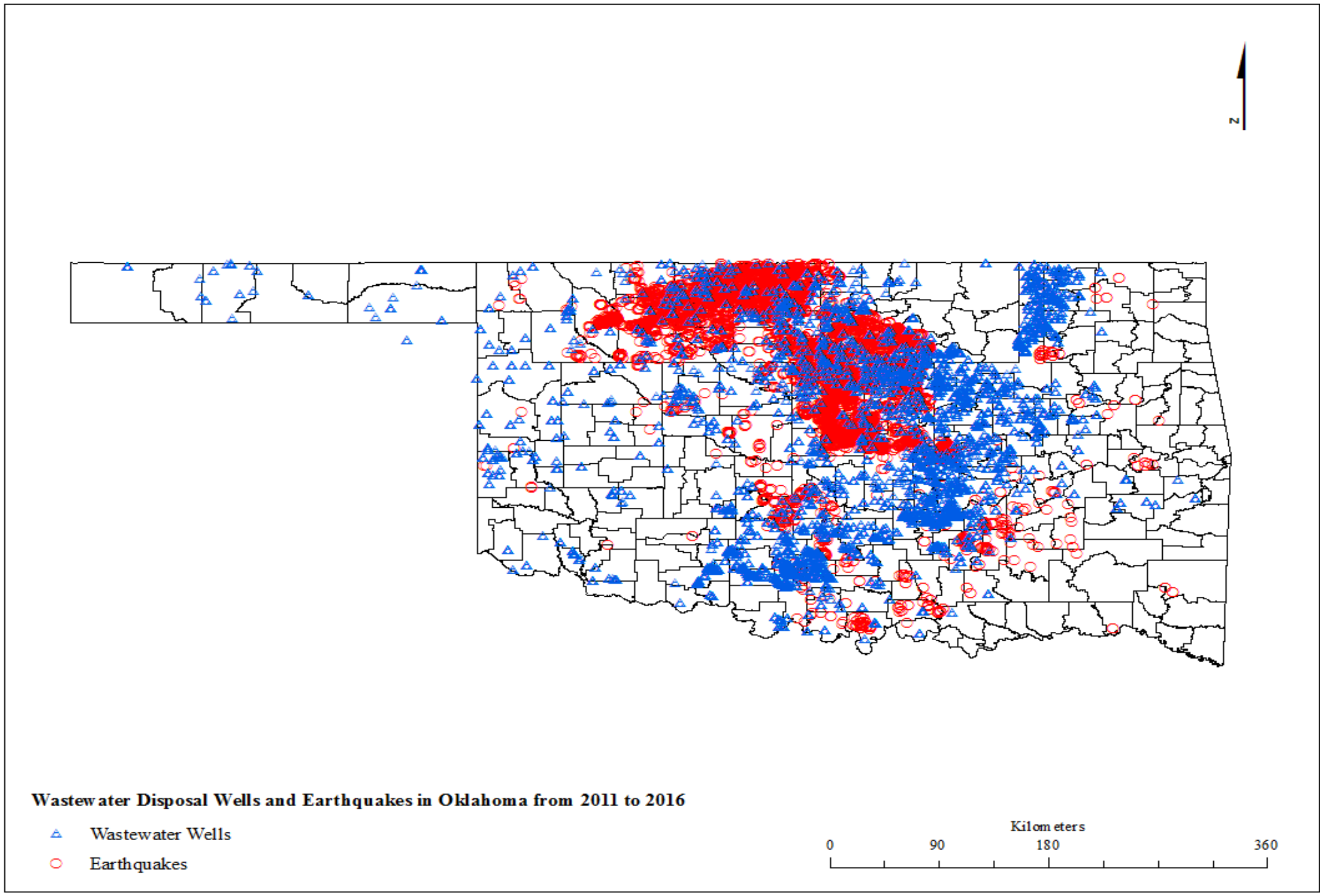

Figure 4: Map of Density of Earthquakes and Wastewater Injection Wells (created by Susan Muñiz; data source: US Census Bureau, Oklahoma Corporation Commission and Oklahoma Geological Survey)

Due to the large case number there was a low probability that the results in tables 9 and 10 were random, and with a strong decrease in density of earthquakes at the 15km buffer, this hypothesis will be accepted.

Hypothesis 4: As the time from the date of injection of wastewater into the well increases, the number of earthquakes decreases.

When the earthquakes lead, by up to 8 months, (see Appendix A) the relationship between PSI and earthquakes is a weak, non-linear relationship. It begins with a negative, direct relationship until the fourth month of lead-time then the relationship fluctuates up and down for 2 months and then drops again in the seventh and eighth month. Volume has a much stronger, non-linear, relationship which was significant at better than 0.001 probability, as shown by the Spearman's rho correlation coefficient that fluctuates between 0.622 and 0.720. The aggregated total of earthquakes and the earthquakes at each lead month has a strong, positive, non-linear relationship with a significant probability of better than 0.001. The volume and psi fluctuations may be due to gaps in pumping. There are days when there is no injection of wastewater due to holidays, injection tests, and pump maintenance (Kim, 2015). Kim (2015) found that the correlation between peak seismicity and peak pressure was not symmetrical and that because of this lack of symmetry seismicity was delayed by approximately five days.

Table 11: Correlation between Psi, Volume, and Well Depth in a given Month, and Number of Earthquakes in that Month and in Subsequent Months

Spearman's rho		# of Quakes in the Month	Psi in a Given Month	Depth in a Given Month	Volume in a Given Month	# of Quakes 1 Month Later	# of Quakes 2 Months Later	# of Quakes 3 Months Later	# of Quakes 4 Months Later
# of Quakes in the Month	Correlation Coefficient	1.000	-.085	.459**	.776**	.734**	.641**	.536**	.508**
	Sig. (2-tailed)	.	.474	.000	.000	.000	.000	.000	.000
	N	73	73	73	73	72	71	70	69
Psi in a Given Month	Correlation Coefficient	-.085	1.000	-.165	-.122	-.104	-.061	-.038	-.034
	Sig. (2-tailed)	.474	.	.163	.303	.384	.614	.758	.780
	N	73	73	73	73	72	71	70	69
Depth in a Given Month	Correlation Coefficient	.459**	-.165	1.000	.474**	.463**	.497**	.534**	.456**
	Sig. (2-tailed)	.000	.163	.	.000	.000	.000	.000	.000
	N	73	73	73	73	72	71	70	69
Volume in a Given Month	Correlation Coefficient	.776**	-.122	.474**	1.000	.720**	.695**	.707**	.644**
	Sig. (2-tailed)	.000	.303	.000	.	.000	.000	.000	.000
	N	73	73	73	73	72	71	70	69
# of Quakes 1 Month Later	Correlation Coefficient	.734**	-.104	.463**	.720**	1.000	.760**	.683**	.588**
	Sig. (2-tailed)	.000	.384	.000	.000	.	.000	.000	.000
	N	72	72	72	72	72	71	70	69
# of Quakes 2 Months Later	Correlation Coefficient	.641**	-.061	.497**	.695**	.760**	1.000	.756**	.682**
	Sig. (2-tailed)	.000	.614	.000	.000	.000	.	.000	.000
	N	71	71	71	71	71	71	70	69
# of Quakes 3 Months Later	Correlation Coefficient	.536**	-.038	.534**	.707**	.683**	.756**	1.000	.749**
	Sig. (2-tailed)	.000	.758	.000	.000	.000	.000	.	.000
	N	70	70	70	70	70	70	70	69
# of Quakes 4 Months Later	Correlation Coefficient	.508**	-.034	.456**	.644**	.588**	.682**	.749**	1.000
	Sig. (2-tailed)	.000	.780	.000	.000	.000	.000	.000	.
	N	69	69	69	69	69	69	69	69

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The unit of analysis for this table is the month, from January 2011 to December 2016

Psi in the above table shows a steady downward trend over subsequent months (up to four months). This downward trend could be due to pore pressure diffusion over time. The strongest relationship was between volume and earthquakes in the same month, this relationship decreased over the following months (up to four months). Depth has an interesting relationship with the number of quakes. The number of earthquakes increases in strength until the third month and then decreases. It is possible that by the third month the wastewater has spread out away from the crystalline basement, lowering the number of earthquakes.

Ellsworth (2013) also found a similar time lag between earthquakes and pore pressure at Rocky Mountain Arsenal. As the pressure increases and diffuses away from the well over time, critically stressed faults may slip triggering an earthquake. Since many of the wells in Oklahoma extend 2 to 3 km, the earthquakes are occurring in the crystalline basement, which can create a time lag between the time of the wastewater disposal and seismicity (Walsh, III and Zoback, 2015). Walsh, III and Zoback (2015) also found that increases in wastewater injection increases the pore pressure, which then spreads out away from the wells over time. Eventually, the pressure triggers a critically stressed fault in the crystalline basement (see below).

Although there is some fluctuation in the correlations between the various variables and delayed earthquakes, the general trend was negative with most correlations showing a level of significance of 0.001. Again, due to the large case, number there is a low probability that the statistical results above are random; therefor this hypothesis will be accepted.

An Unexpected Finding

Hypothesis 5: As the depth of the wastewater well increases, the number of earthquakes increases.

Even though the depth of the wastewater wells was not one of my variables the relationship between well depth and earthquakes was mentioned in several articles. Using the dichotomy variable for earthquakes, well depth was broken up into four equal divisions in order to run crosstabs with the earthquake variable. Pearson correlation was run between well depth and earthquakes. There were 659,316 wastewater wells with an average depth of 1.192 km; the standard deviation was 0.765.

Pearson's correlation (table 15) showed a 0.015 weak, direct relationship between the increase in well depth and earthquakes, and the cross tabulations (table 14) showed a positive, direct relationship. This relationship may be due to the fact that the deeper the well is the closer it may be to the crystalline basement. It is believed that deep, unknown faults may be shifting due to the injection of wastewater into deep wells.

Table 12: Well Depth[a] Statistics

N	Valid	659316
	Missing	36139
Mean		1.192
Std. Deviation		0.76531

a-Depth of wastewater wells in kilometers

The cross-tabulations in table 13 shows a strong increase in earthquakes as the depth of the wastewater well increases. This may be caused by the well bottom being too close to the Precambrian crystalline basement and the wastewater encountering fractures in the basement and triggering earthquakes.

Table 13: Depth[a] of Wastewater Wells and Earthquakes Cross-Tabulations

			Shallow 0.5749km or less	Moderate 0.5750km to 1.0385km	Deep 1.0386km to 1.6145km	Very Deep 1.6146km or more	Total
Earthquakes	No	Count	164323	163745	161185	158205	647458
	Yes	Count	545	1111	3563	6567	11786
			0.30%	0.70%	2.20%	4.00%	1.80%
Total			100.00%	100.00%	100.00%	100.00%	100.00%

a-Depth of wastewater wells in kilometers

Table 14: Depth of Wastewater Wells Symmetric Measures

Symmetric Measures		Value	Asymptotic Standard Error[a]	Approximate T[b]	Approximate Significance
Nominal by Nominal	Cramer's V	0.109			0.000
Interval by Interval	Pearson's R	0.105	0.001	85.786	.000[c]
Ordinal by Ordinal	Spearman Correlation	0.105	0.001	85.786	.000[c]
N of Valid Cases	659244				

a Not assuming the null hypothesis.

b Using the asymptotic standard error assuming the null hypothesis.

c Based on normal approximation.

Table 15: Pearson's Correlation Depth of Wells[a] and Earthquakes[b]

		Earthquakes	Depth of Wells
Total number of earthquakes for all years	Pearson Correlation	1	.015*
	Sig. (2-tailed)		.020
	N	695455	23419
Calculated depth of earthquake in kilometers	Pearson Correlation	.015*	1
	Sig. (2-tailed)	.020	
	N	23419	23419

*. Correlation is significant at the 0.05 level (2-tailed).

a-Depth of wastewater wells in kilometers; b-Total number of earthquakes

Kim (2013) found that the earthquakes that were occurring in Youngstown, OH were occurring in the Precambrian crystalline basement. The Northstar 1 well was 2,802 meters deep; the Precambrian crystalline basement was encountered at 2,741 meters. Walsh, III and Zoback (2015) also found that many of the earthquakes occurring in Oklahoma were in the crystalline basement. Research by Skoumal et al (2018) found that wastewater injection activity within less than 1km of the Precambrian basement were more likely to trigger induced earthquakes than those farther from the basement.

CHAPTER FIVE: DISCUSSION

There has been significant scientific evidence that the injection of hydraulic fracturing wastewater injected into UIC Class II wastewater wells has caused an increase in seismic activity (Ellsworth, 2013; Keranen, et al., 2014; Walsh, III & Zoback, 2015). This increase in seismic activity has happened not just in the US but also, around the world. However, the greatest increase in seismic activity in the US has been in the state of Oklahoma. Forty-percent of the injection wells in Oklahoma have been associated with earthquakes, even though Oklahoma accounts for only 8% of all the injection wells in the central US (Weingarten, et al., 2015). This increase in seismicity, in Oklahoma, coincides with an increase in hydraulic fracturing wastewater injection, especially between 2011 and 2016. The specific variables that could cause this increase in seismicity are the volume of wastewater, its injection pressure, the distance from the well to an unstable fault, and the length of time from the injection.

Due to the large number of cases (695,455), the probability that the results were random was statistically low. Despite the fluctuations shown in the cross-tabulations between volume and earthquakes there was still a clear, positive correlation between an increase in volume and an increase in earthquakes, especially at the extremely high level of 46,361 barrels per month. Although psi would seem to be a more determining factor, the data did not show this; earthquakes diminished as the psi increased. However, the data did confirm that as the distance from the wastewater well increases the density of earthquakes diminished, especially at the 10-15km distance. Finally, the data established that as the time from injection increased the number of earthquakes decreased; there were a few fluctuations, but the overall trend was negative.

The well data from the Oklahoma Geological Survey was very well documented and easy to download from their website. However, the Oklahoma Corporation Commissions (OCC) well data prior to 2011 was not well organized. Many of the records appeared to be duplicates, data was missing, and many of the records were copies of hand written reports and were difficult to read. The OCC information from 2011 forward was entered into excel spreadsheets and easy to download. However, even the data from 2011 to 2016 had many errors, latitude and longitude were entered incorrectly or missing, some well data information appeared to be duplicate entries, and some data was missing. There were over 800,000 cases, but only 695,455 were usable.

Although many previous studies, such as Keranen et al. (2014), showed a direct, positive relationship between psi and earthquakes, the data in this study simply did corroborate that finding. Volume seemed to be a more important variable as a cause for earthquakes. Walsh, III and Zoback (2015) stated that when the monthly injection rate in Oklahoma doubled there was an increase in earthquakes. The results of this study also showed that the greatest increase in earthquakes corresponded with a higher volume. While some research shows that earthquakes, caused by wastewater injection, may increase as the distance from the wastewater wells increases, the findings in this research do not support that conclusion. This study shows that there are fewer earthquakes 10-15km from the wastewater wells. Walsh, III and Zoback (2015), and Kim (2013) all found that there was a time delay between injection of wastewater and seismicity. Research shows that the number of earthquakes decreases as the time after an injection increases, this study concurs with this finding.

While many previous studies stated that wastewater injection near the Precambrian crystalline basement could trigger earthquakes, the depth of the wastewater wells was not one of the variables in this study. However, statistics were run on this variable and the findings confirmed that there is an increase in earthquakes when there is an increase in well depth.

Oklahoma seems to be particularly susceptible to this phenomenon as many of the wastewater wells extend to the crystalline basement.

The data supported the first hypothesis, that an increase in volume would cause an increase in earthquakes. Volume was determined to have a weak, positive relationship with seismicity. The second hypothesis was not supported by the data, pore pressure, was not as important a factor in triggering earthquakes as volume; it had a weak, negative relationship with seismicity. This study clearly shows that as the distance from the wells increased the density of earthquakes diminished, especially at the 10-15km range. The fourth hypothesis was supported by the data, using SPPS to lead the number of earthquakes forward one month up to eight months, the number of earthquakes continued to diminish as the time from the injection increased. Well depth was not one of the original variables in this study, but since the well depth information was available statistics were run to determine if there was a correlation between well depth and earthquakes. The data does support this hypothesis with a weak, positive relationship. The findings of this study, specifically the first, third, fourth and additional fifth hypothesis, coincided with previous studies, which helps to confirm those findings. Even though the findings for the second hypothesis, pore pressure, contradicted some of the published research, this contradiction highlights the complexity of the problem of triggered earthquakes and their exact causes. Additional research is needed to find a more exact combination of what causes earthquakes near wastewater injection wells.

Some practical implications from this study would be an industry standard for injecting wastewater, such as, keeping volume below 150,000 barrels/month, and shortening well depth to at least 1km from the Precambrian basement especially, in areas where the sedimentary layers are not very deep. This would make it easier for the wastewater disposal companies to be confident that they are doing everything possible to help lower the risk of earthquakes near their well sites, while lowering risk of insurance liability claims and litigation. Industry standards would also give policy makers a template for their own procedures and laws. Knowing what the requirements are for any wastewater disposal site would give the communities some negotiating power when dealing with these companies. The monthly reports showing volume, psi, and well depth should be made available to the municipalities near the wells sites for greater transparency. This would allow policymakers to monitor the well injections and have a record of what is happening giving them the information, they need to hold the wastewater disposal companies accountable. Being able to lower the risk of earthquakes, would lower the risk of injury, help prevent property loss and the loss of property values, and decrease the potential for litigation between those who have had a loss due to an earthquake and the hydraulic fracturing wastewater disposal.

This study helps to confirm some of the causes of seismic activity near wastewater disposal sites. In Oklahoma, the Oklahoma Corporation Commission (OCC) has already begun to make new procedures for wastewater disposal wells. Many of the owners of wastewater wells, in an area of increased seismicity, were advised to reduce the volume of wastewater being injected and to plug back (shorten) the depth of the wells to at least 30 meters (Baker, 2016). Other areas in the US and around the world would benefit from the OCC's new procedures. However, depth and volume are not the only triggers for seismicity. There needs to be more research to understand the role psi plays in triggering earthquakes and how the different variables combined generates these earthquakes. With further research, the causes of these earthquakes could be more exactly determined, thus reducing the liability for the wastewater well companies, the risk of property damage, and the risk of injury of those living and working near these wastewater wells.

APPENDIX A

Correlation between Psi, Volume, and Well Depth in a given Month, and Number of Earthquakes in that Month and in Subsequent Months

Spearman’s rho		# of Quakes in the Month	Psi in a Given Month	Depth in a Given Month	Volume in a Given Month	# of Quakes 1 Month Later	# of Quakes 2 Months Later	# of Quakes 3 Months Later	# of Quakes 4 Months Later	# of Quakes 5 Months Later	# of Quakes 6 Months Later	# of Quakes 7 Months Later	# of Quakes 8 Months Later
# of Quakes in the Month	Correlation Coefficient	1.000	-.085	.459**	.776**	.734**	.641**	.536**	.508**	.509**	.519**	.473**	.517**
	Sig. (2-tailed)	.	.474	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
	N	73	73	73	73	72	71	70	69	68	67	66	65
Psi in a Given Month	Correlation Coefficient	-.085	1.000	-.165	-.122	-.104	-.061	-.038	-.034	-.075	-.074	-.042	-.032
	Sig. (2-tailed)	.474	.	.163	.303	.384	.614	.758	.780	.546	.552	.739	.802
	N	73	73	73	73	72	71	70	69	68	67	66	65
Depth in a Given Month	Correlation Coefficient	.459**	-.165	1.000	.474**	.463**	.497**	.534**	.456**	.368**	.355**	.420**	.278*
	Sig. (2-tailed)	.000	.163	.	.000	.000	.000	.000	.000	.002	.003	.000	.025
	N	73	73	73	73	72	71	70	69	68	67	66	65
Volume in a Given Month	Correlation Coefficient	.776**	-.122	.474**	1.000	.720**	.695**	.707**	.644**	.648**	.677**	.641**	.622**
	Sig. (2-tailed)	.000	.303	.000	.	.000	.000	.000	.000	.000	.000	.000	.000
	N	73	73	73	73	72	71	70	69	68	67	66	65
# of Quake 1 Month Later	Correlation Coefficient	.734**	-.104	.463**	.720**	1.000	.760**	.683**	.588**	.573**	.567**	.546**	.508**
	Sig. (2-tailed)	.000	.384	.000	.000	.	.000	.000	.000	.000	.000	.000	.000
	N	72	72	72	72	72	71	70	69	68	67	66	65
# of Quake 2 Months Later	Correlation Coefficient	.641**	-.061	.497**	.695**	.760**	1.000	.756**	.682**	.588**	.571**	.558**	.538**
	Sig. (2-tailed)	.000	.614	.000	.000	.000	.	.000	.000	.000	.000	.000	.000
	N	71	71	71	71	71	71	70	69	68	67	66	65
# of Quake 3 Months Later	Correlation Coefficient	.536**	-.038	.534**	.707**	.683**	.756**	1.000	.749**	.675**	.576**	.561**	.548**
	Sig. (2-tailed)	.000	.758	.000	.000	.000	.000	.	.000	.000	.000	.000	.000
	N	70	70	70	70	70	70	70	69	68	67	66	65
# of Quake 4 Months Later	Correlation Coefficient	.508**	-.034	.456**	.644**	.588**	.682**	.749**	1.000	.741**	.665**	.569**	.549**
	Sig. (2-tailed)	.000	.780	.000	.000	.000	.000	.000	.	.000	.000	.000	.000
	N	69	69	69	69	69	69	69	69	68	67	66	65
# of Quakes 5 Months Later	Correlation Coefficient	.509**	-.075	.368**	.648**	.573**	.588**	.675**	.741**	1.000	.731**	.663**	.559**
	Sig. (2-tailed)	.000	.546	.002	.000	.000	.000	.000	.000	.	.000	.000	.000
	N	68	68	68	68	68	68	68	68	68	67	66	65

APPENDIX A continued

Correlation between Psi, Volume, and Well Depth in a given Month, and Number of Earthquakes in that Month and in Subsequent Months continued

# of Quakes 6 Months Later	Correlation Coefficient	.519**	-.074	.355**	.677**	.567**	.571**	.576**	.665**	.731**	1.000	.728**	.656**
	Sig. (2-tailed)	.000	.552	.003	.000	.000	.000	.000	.000	.000	.	.000	.000
	N	67	67	67	67	67	67	67	67	67	67	66	65
# of Quake 7 Months Later	Correlation Coefficient	.473**	-.042	.420**	.641**	.546**	.558**	.561**	.569**	.663**	.728**	1.000	.720**
	Sig. (2-tailed)	.000	.739	.000	.000	.000	.000	.000	.000	.000	.000	.	.000
	N	66	66	66	66	66	66	66	66	66	66	66	65
# of Quake 8 Months Later	Correlation Coefficient	.517**	-.032	.278*	.622**	.508**	.538**	.548**	.549**	.559**	.656**	.720**	1.000
	Sig. (2-tailed)	.000	.802	.025	.000	.000	.000	.000	.000	.000	.000	.000	.
	N	65	65	65	65	65	65	65	65	65	65	65	65

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

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