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Claudia Judele
cmj89@zips.uakron.edu

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Fracking and Induced Seismicity Mitigation in Ohio

Claudia Judele

The University of Akron

Abstract

This research analyzes the extent to which the hydraulic fracturing process contributes to seismic activity in the State of Ohio and compares Ohio's fracking induced seismicity with other case studies from the States of Texas, Pennsylvania, and Oklahoma. It distinguishes and addresses the differences in risks that fracking poses in conventional natural gas wells versus unconventional horizontal wells where natural gas is extracted from reservoirs with low permeability. Ohio's earthquake history, fracking history, current fracking regulations, and restrictions on local regulations were thoroughly investigated to determine just how much fracking has affected the state's seismicity rate. Since 2011, when unconventional natural gas development began occurring, Ohio has experienced a significant increase in both microseismicity and 2.0+ magnitude earthquakes. Earthquakes and hydraulic fracturing were studied from an emergency management perspective through the examination of local hazard mitigation plans from each of the state's 88 counties to determine what, if any, mitigative strategies were being implemented by local emergency management agencies. Potential mitigative strategies that local emergency management agencies could implement to reduce the risks that fracking poses have also been discussed.

Keywords: fracking, induced earthquakes, local emergency management agency, unconventional natural gas development, local hazard mitigation plan, conventional well, unconventional well, vertical drilling, horizontal drilling.

Table of Contents

CHAPTER 1: INTRODUCTION

Hazard, Risk, and Emergency Management Overview

At all levels, local, state, and federal, effective emergency management is dependent upon the effective identification of both current and potential hazards in an area. Hazards are events that could endanger an area or result in a disaster if they were to occur. Hazards can be categorized as natural, anthropogenic non-intentional (technological), or anthropogenic intentional. Natural hazards are biologically, atmospherically, geologically, and hydrologically sourced events that occur on Earth without human intervention and "pose a threat to human populations and communities" (Haddow, Bullock, & Coppola, 2014, p. 32). Anthropogenic non-intentional, also known as technological hazards, are unintentional events that are caused by the failure of man-made systems due to accident, negligence, or improper constriction. These events are often unpredictable in frequency and may be poorly understood due to a lack of research, which is the case for fracking induced earthquakes. Some examples of these hazards could be hazardous material spills and releases, nuclear power plant accidents, dam and levee failures, structural collapses due to improper construction or lack of maintenance, and hydraulic fracturing induced earthquakes (Gill & Malamud, 2017). Unlike the former man-made hazards, anthropogenic intentional hazards are those that are caused by people who want to cause harm to people and/or destroy property. These hazards include, but are not limited to, terrorist attacks, the sabotage of technological systems, and cyber-attacks (Drabek, 2013).

Regardless of their classification, all hazards have associated risks, which are based on the hazards' frequency of occurrence and their capability to negatively impact physical, social, and economic systems. Events that overwhelm and exceed the resource, personnel, and equipment response capabilities of local government and emergency managements agencies are classified as disasters and may require aid from state and federal partners to meet disaster response and recovery demands (Haddow, 2014). Therefore, it is vital for local emergency managers to be aware of and develop effective policies that are tailored to meet the needs of their county. Emergency management begins at the local level with the implementation of comprehensive policies that are tailored to the four phases of emergency management: mitigation, preparedness, response, and recovery.

Mitigation comprises activities such as hazards mapping, sustainable land use planning, creating and maintaining effective warning systems, enacting and enforcing building codes, and retrofitting structures that are designed to reduce or eliminate the risks that various hazards pose to the community. Preparedness focuses on activities that enhance a community’s response capacity and ability to recover from various hazards through all-hazard planning, acquiring equipment, training first responders and other response personnel, conducting exercises, and continuously revising exercises and planning strategies. Response activities take place just before, during, and immediately after a disaster occurs with the goal of reducing injuries, fatalities, and further public and private property loss. These activities include the evacuation of people, search and rescue, mass care, conducting damage assessments, and restoring communications, utilities, and other critical infrastructure (Haddow, 2014). Recovery focuses on returning the impacted communities back to normal as quickly as possible through implementing mitigation strategies when rebuilding and fixing damaged structures, debris management, providing shelter and temporary housing to residents until their homes are rebuilt, helping residents and business owners obtain federal and private disaster loans, and applying for federal recovery and mitigation grants (Phillips, 2016). For the purposes of this research, the focus will be on the mitigation phase of emergency management and how local Ohio emergency managers are planning to reduce the risks associated with hydraulic fracturing, primarily induced earthquakes.

Hydraulic Fracturing: An Emerging Technological Hazard

Although most earthquakes in Ohio have been low magnitude and tended to cause little damage to physical structures, seismic activity within the State of Ohio has been increasing. Multiple studies have attributed the increased use of fracking in conjecture with horizontal drilling to extract natural gas and oil to the increase in the quantity and magnitude of earthquakes in the state (Friberg, Besana-Ostman, & Ilya Dricker, 2014; Kozlowska et al., 2018; Harnetty, 2017; Skoumal, Brudzinski, & Currie, 2015). Since 1776, when earthquake documentation began in the state, Ohio has experienced over 200 earthquakes with magnitudes of 2.0 or greater on the Richter Magnitude Scale (Ohio History Central, 2012). However, since 2011, when hydraulic fracturing wells were permitted and drilled, the frequency of small scale seismological events has been increasing in areas located near fracking wells.

For instance, in 2014, Mahoning County, Ohio, experienced 77 earthquakes with magnitudes ranging from 1.0 to 3.0 from March 4 through March 12, a time span of just 8 days. These earthquakes' epicenters were located approximately 0.62 miles away from Hilcorp Energy Company's horizontal hydraulic fracturing wells in Poland Township (Skoumal, 2016). Additionally, numerous other counties in Ohio have experienced an increase in earthquakes with magnitudes of 3.0 or higher after the start of hydraulic fracturing and horizontal drilling in for natural gas in shale reservoirs (Kozlowska et al., 2018). Although most of Ohio's 88 Local Emergency Management Agencies (LEMAs) include earthquakes in their all-hazards mitigation plan, few of them mention hydraulic fracturing induced earthquakes let alone discuss potential mitigative strategies for this hazard. With the relatively recent emergence of this anthropogenic non-intentional hazard, this research stresses the importance of developing mitigative strategies at the local level. It seeks to determine what, if any, mitigative strategies are being implemented by Ohio local emergency management agencies to address hydraulic fracturing induced seismicity through an analysis of local hazard mitigation plans (LHMPs) that were submitted to Ohio Emergency Management Agency (OEMA)'s State Hazard Analysis, Resource, and Planning Portal (SHARPP). Additionally, a 20 question survey regarding fracking mitigation and induced seismicity was emailed to each of the 88 LEMA directors to obtain a better understanding of how this hazard is prioritized, public awareness and understanding of the hazard, as well as any current, proposed, or future mitigative measures in each county.

This paper is structured so that readers will first be introduced to the hazards, how they occur, and their potential impacts in Chapter 2. It then provides an analysis of various cases studies of documented induced seismicity that can be attributed to hydraulic fracturing in the states of Ohio, Pennsylvania, Texas, and Oklahoma in Chapter 3. Chapter 4 discusses Ohio's earthquake and fracking history. The primary focus is on the mitigation efforts undertaken by Ohio's LEMAs to reduce the risks that fracking poses to counties that have active fracking wells, which are discussed in Chapter 5. This section also discusses Ohio's fracking induced mitigation efforts, as well as potential mitigative strategies that could be implemented by local EMAs. Finally, the conclusion highlights the mitigative measures undertaken by Ohio's LEMAs and summarizes potential fracking mitigative strategies that could be implemented by LEMAs.

CHAPTER 2: EARTHQUAKE AND FRACKING BACKGROUND

Earthquakes: Processes, Causes, & Measurement

An earthquake is traditionally classified as a geologically sourced natural hazard that causes rapid movement and vibrations in the Earth's crust (Haddow et al., 2014). The movement of tectonic plates, brought about by natural or anthropogenic factors, results in the production of earthquakes. As illustrated in Figure 1, the Earth is comprised of three main sections: a core (inner and outer), mantle, and crust. Changes in the lithosphere, which is comprised of the crust and solid mantle, occur when individual plates move along the asthenosphere, a hot, weak, viscus region of the mantle (Hanks, 1999). These movements are driven by the planet's gradual heating and cooling cycle, when magma from the asthenosphere finds its way through plate boundary cracks in the lithosphere, reaches the surface as lava, cools, and hardens. When this occurs, new fault lines will form and these areas are highly susceptible to slipping due to the amount of pressure on the plates and the relatively weak connections at fault lines (Harris & Kiger, 2001).

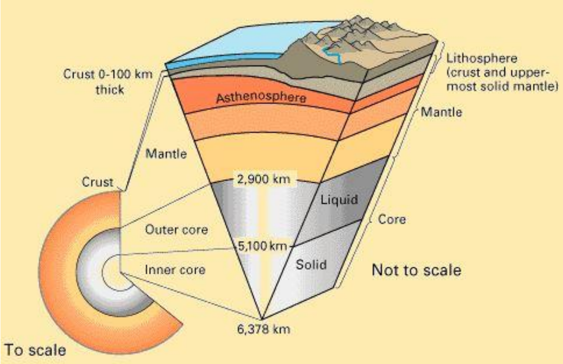

Figure 1: Sections of the Earth and their respective depths (Hanks, 1999).

The vast majority of earthquakes occur when faults, the weaker boundaries of the Earth's tectonic plates, slip due to stress levels that exceed the threshold of the respective fault system (Braile, 2009). Faults with depth ranging from fractions of an inch to miles long can be produced gradually, through repeated displacement, or suddenly, when plates slip. They are classified based on their angle, dip, and how it travels when it slips: north, south, east, or west (United States Geological Survey [USGS], n.d.). Reverse, thrust, strike-slip, and normal are the primary types of faults that can occur at convergent, divergent, and transform plate boundaries (Harris & Kiger, 2001). Reverse faults occur when the hanging wall is pushed over the footwall. A thrust fault is like a reverse fault, in that the hanging wall gets pushed over the footwall and both types of faults are caused by horizontal compression. However, thrust faults occur at an angle of 45° or lower, while reverse faults occur at an angle greater than 45 degrees (Unites States Geological Survey [USGS], n.d.). Strike-slip faults occur at transform boundaries when the rocks move away from each other horizontally, towards the right or left. Finally, normal faults occur at divergent boundaries when the headwall is pushed downward and the footwall gets pulled upward (Harris & Kiger, 2001).

Slipping along the fault plane results in the release of built up elastic energy in the form of seismic waves that travel outward in all directions from the earthquake's focus, see Figure 2 (Braile, 2009). Seismic waves fall into two categories: body waves, such as primary (P), the fastest traveling waves, and secondary (S) waves, and slower moving surface waves, such as love and Rayleigh waves (Ammon, 2001). These waves are measured by seismometers and plotted onto seismographs to help determine the earthquake's magnitude and the location of its epicenter (USGS, 2018a).

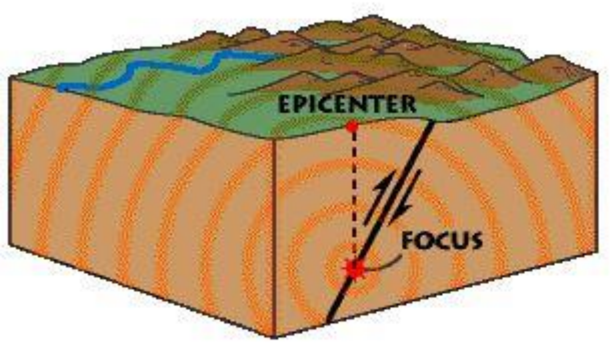

Figure 2: The focus of an earthquake is where the slip initially occurs and produces seismic waves. An earthquake's epicenter is located directly above the focus on the surface (United States Department of the Interior [DOI] & USGS 2017).

Earthquakes can be measured based on their magnitude, intensity, or acceleration. The Richter scale is a logarithmic scale that measures the amplitude of seismic waves to determine the strength or magnitude of an earthquake. On the other hand, the Modified Mercalli scale is more subjective and assigns rankings based on how much shaking people felt and the damages that structures sustained. Acceleration of the seismic waves is measured using the “g” force percentage (Baer, 2018). Most of the damages caused by earthquakes occur near its epicenter and the total amount of damage decreases as the waves decelerate and weaken as they are traveling further away from the epicenter. Earthquakes can threaten the health and safety of individuals in the impacted area both directly, by producing structural damages that cause injuries or deaths, or through the production of secondary events, such as landslides, dam failures, water and gas main breaks that result in flooding and fires, tsunamis, and hazardous material releases (Haddow et al., 2014, p. 34).

Natural vs. Induced Earthquakes

While most earthquakes occur due to natural geological processes, anthropogenic influences can also lead to slips in fault planes. From the early 1880s to 2018 over 775 earthquakes have been linked to human intervention worldwide, of which 188 or 24.3 % occurred in the U.S. alone (Wilson et al., 2018). The primary ways in which people can cause earthquakes are through activities that change the pore pressure or the amount of stress that is placed upon fault planes (Ellsworth, 2013). Human activities such as injecting large amounts of fluid into the crust through hydraulic fracking, enhanced recovery, and wastewater disposal can induce earthquakes by altering the pore pressure within faults (Satterlee, 2016). Furthermore, mining and mine collapses, some construction activities, and explosions can also lead to fault slips by increasing or decreasing the amount of stress on geological faults. In fact, activities related to mining are the leading cause of anthropogenic earthquakes worldwide, followed by water reservoir impoundment, such as dams, and gas and oil extraction methods (Wilson et al., 2018). Although natural and induced earthquakes may appear to be extremely similar, they often differ in their location of occurrence, effect on the crust, and magnitude.

Unlike natural earthquakes, which primarily occur along plate boundaries, the majority of the U.S.'s induced earthquakes have occurred in intraplate zones (Wilson et al., 2018). The majority of anthropogenic earthquakes, especially those that were induced by hydrologic fracturing, are low magnitude events that often cause little to no damage. Unlike natural earthquakes, these earthquakes tend to have magnitudes that range from 1.0 to 3.0 and they often result in little to no damage (Mulargia1 & Bizzarri, 2014). Oftentimes, these low magnitude events result in plaster cracks and other minor types of non-structural damage (Seismol, 2015, p. 628). However, moderate and high magnitude earthquakes can and have resulted from human activity, such as wastewater injection. Wastewater injection has resulted in the triggering of moderate earthquakes with magnitudes of 5.0 in Oklahoma. These earthquakes can cause a substantial amount of structural damage in highly populated areas and lead to injuries, as well as fatalities, from falling debris (Tucker, 2017). Furthermore, since induced earthquakes tend to be shallower than natural earthquakes, less than 1.2 miles versus 6.2 miles, they could actually cause more damage, even at lower magnitudes, than normal earthquakes due to their close proximity to the Earth's surface (Nikiforuk, 2015, p. 57).

Hydraulic Fracturing Mechanisms & Risks

The hydraulic fracturing, commonly referred to as fracking, process begins after a site containing a profitable reservoir has been identified. A common site surveying method used to determine if gas reservoirs exist and their location is the use of vibroseis trucks. These trucks are equipped with large baseplates that are lowered to the ground and repeatedly struck by the trucks to emit sound waves that penetrate underground rock formations. Then the sound waves reverberate back to the surface, where they are picked up by geophones that are placed around the potential drilling site (Harnetty, 2017). Once a site has been selected, supplies, such as cement, fracking fluid components, and casings are brought to the site. Then the well is drilled hundreds to thousands of feet underground and a number of casings are cemented in place, each state has their own requirements pertaining to the types of casings used and cement thickness (EPA, 2016). A perforating gun is then used to place explosive charges within the casing. Up to "15 million psi," are produced when the charges are detonated, making numerous cracks in the casing, cement, and target reservoir (Hansen, 2017, p. 8). After the fractures are made, the fracking process can be initiated.

Hydraulic fracturing is a hydrocarbon extraction method where a fracking fluid is forced downward through the wellbore of a horizontal or vertical well at pressures that exceed the pressure gradient of the shale rocks, resulting in fractures. Fracking fluid, which consists of a proppant, a mixture of sand, water, and chemicals, that keeps the fractures open and allows trapped gas to flow upward through the production casing, is injected into the well by high pressure fracking pumps connected to trucks that are situated near the well. Water became the primary fluid base in 1953 and continues to be the main component of fracking fluid today, along with proppant, and trace amounts of chemicals and acids that are used to either enhance the extraction rate, reduce the amount of mineral contaminants, or keep the steel casings from corroding. No two reservoirs are alike, so the chemical composition of the fracking fluids must be altered to ensure the most efficient extraction of natural gas (Gandossi & Von Estorff, 2015). Once the reservoir has been drained of natural gas, the well will be abandoned and sealed off

(EPA, 2016). Figure 3 provides an estimated timeline of fracking operations from the time that a location is selected to the time that a well is plugged and abandoned.

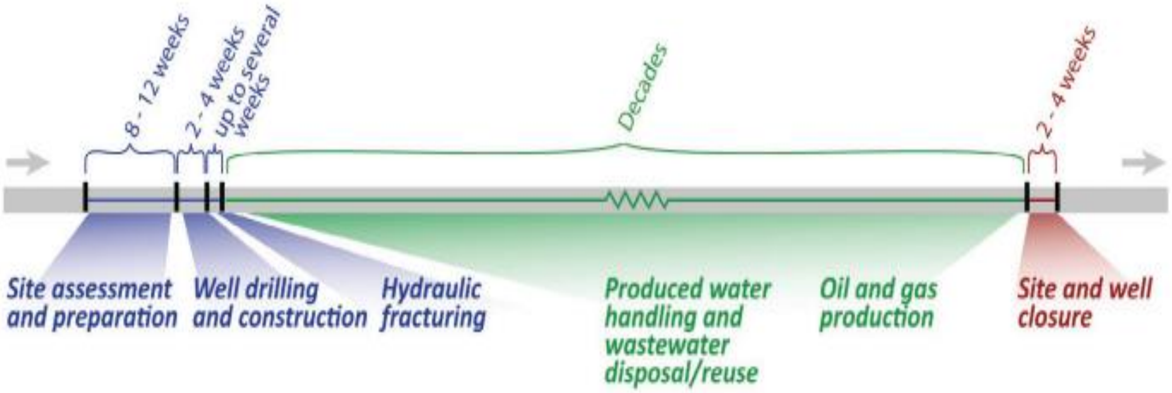

Figure 3: This image shows the average timeline for the hydraulic fracturing process from the amount of time needed to select and prepare a site to the time needed to retire a well once it stops producing gas or oil (EPA, 2016, p. 4).

Vertical versus Horizontal Drilling

There are two primary types of wells, illustrated in Figure 4 that can be drilled to extract oil and natural gas: vertical wells and horizontal wells, which are a type of directional well. When drilling a vertical well, the borehole is angled and drilled in one straight line, or as close to straight as possible, to reach underground natural gas or oil deposits. This method has been utilized since 1859, when it was successfully used to extract oil in Titusville, Pennsylvania, and aided in the initiation of the oil rush. Vertical wells are cheaper to drill, maintain, and are shallower in depth, only reaching a few hundred feet, in comparison to horizontal wells, which can reach depths of thousands of feet (Ma, Chen, & Zhao 2016; Houston, Dougherty, Shaner, & Johnson 2013). However, a significant disadvantage of these wells is the fact that multiple wells would have to

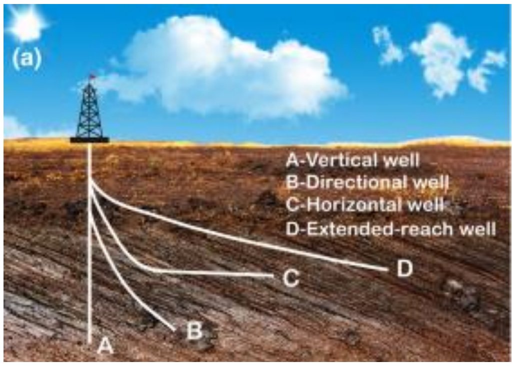

Figure 4: Differences between vertical wells (A) and other types of wells. This illustration shows that all wells originate as vertical wells before the drills are angled (Ma et al., 2016, p. 367).

be drilled to reach various oil and natural gas deposits due to their depth range and inability to extract large amounts of natural gas and oil from target reservoirs (Norris, Tucotte, & Rundle, 2014).

Unlike horizontal wells, these wells are often utilized when extracting natural gas and oil from conventional rock sources, such as sandstone, where gas and oil flow up through the production tubing once the well is drilled (Alcorn, Rupp, & Graham, 2017). With conventional fracking used in vertical wells, high viscosity fracking fluid used to create a few large fractures in the rock and proppant is pumped down the borehole to keep the fractures from closing, thereby allowing oil and natural gas to travel up the borehole. Hydraulic fracturing can be used to speed up the production of these wells when their extraction rate and profitability of the vertical wells decreases (Norris et al., 2014). In comparison to vertical wells, horizontal wells are drilled above the reservoir then the borehole is turned more than 60° from the kickoff point, the potion of a vertical well when drilling is angled (Ma et al., 2016). These wells require the use of hydraulic fracturing and they are used to access a greater amount of trapped oil and natural gas, which often lie horizontally. This results in fewer wells having to be drilled to access the same amount of natural gas or oil due to the fact that they can over “10,000 lineal feet” can be fractured by one well hundreds with vertical wells (Huston et al., 2013, p. 2).

Additionally, these wells utilize low viscosity fracking fluid or slickwater, which is when chemicals are added to water to increase its flow rate, to fracture the rocks and prevent them from closing. This allows trapped gas to travel up the borehole (Norris et al., 2014). These wells can also be drilled at depths of over 5,000 ft. and they can extract natural gas and oil at higher rates than vertical wells (Joshi, 2003). Hydraulic fracturing and horizontal drilling are utilized to extract trapped natural gas from unconventional low permeability sources, such as shale rocks.

These wells surpass vertical wells in their ability to extract oil and natural gas from reserves, which resulted in the nationwide predominance of these methods in 2011. In 2016, “670,000 of the 977,000 producing wells were hydraulically fractured and horizontally drilled” in the U.S. (Cook, Perrin, & Van Wagener, 2018, para. 6). In conjecture, these technological advancements have allowed the U.S. to become the world’s top producer of natural gas and provided the country with a steady domestic energy supply, thereby reducing international energy dependence (Alcorn, Rupp, & Graham, 2017).

While there are many advantages to utilizing these wells, they also have substantial disadvantages. For instance, horizontal wells are up to 2.5 times more expensive to drill than vertical wells and they also require a greater amount of fracking fluid to extract the natural gas. Furthermore, it is difficult for one well to access reservoirs that have significant depth or permeability variations (Joshi, 2003). The use of horizontal drilling and hydraulic fracturing to extract natural gas from low permeability rocks also requires a larger amount of water than traditional fracking in conventional reservoirs. In 2014, a national average of 5.1 million gallons of water was required to frack one horizontal well, while one vertical well only required an average of less than “671,000 gallons” (Wade & Cooper, 2015, para. 2). Fracking in unconventional reservoirs, those that contain low permeable rocks, may be more likely to cause intraplate earthquakes due to the increase in stress on both recently developed faults in clastic rocks and mature, deep, faults in crystalline rocks (Kozlowska et al., 2018).

Unconventional natural gas and oil extraction also releases more methane gas into the atmosphere than traditional fracking. High methane emissions from unconventional fracking and gas reservoirs also contribute to global climate change due to the fact that methane is a powerful greenhouse gas that can absorb more energy than carbon dioxide and exacerbate the rate of global climate change (Alcorn et al., 2017; Hoffman, 2018; United States Environmental Protection Agency [EPA] 2017). Furthermore, this is particularly problematic due to the fact that this combustible gas can easily explode if it comes in contact with a heat source, at concentrations of just 5%, which poses a risk to nearby workers, residents, and structures (Sutherland, 2018). Additionally, the increase in hydraulic fracking and horizontal drilling has led to the development of more injection wells for wastewater disposal. Multiple studies have linked Class II wastewater injection wells to increases seismicity and the number of felt earthquakes (Satterlee, 2016; Kim, 2013).

Although wastewater disposal is not the primary focus of this study, it is important recognize the positive relationship between the increase in fracking, which leads to an increase in Class II wells, and ultimately results in an increase in seismicity. A noteworthy example is the impact that the Northstar 1 Class II injection well had on seismicity spike in the City of Youngstown, Ohio. Youngstown is located in Mahoning County, Ohio, an area which was devoid of any historical seismic events prior to the operation of the Northstar 1 wastewater injection well on December 29, 2010. Since the well's operation began, the city experienced approximately 169 earthquakes directly under or in close proximity to the well. These earthquakes ranged in magnitude form 0.0 to 3.9 and occurred between January 2011 and February 2012 (Kim, 2013).

Health Effects of Hydraulic Fracturing

In addition to its environmental effects, including but not limited to: induced seismicity, air pollution, groundwater contamination, and high demand for water, fracking can have unintended impacts on people's heath and quality of life. While the primary focus of this research is on the role that hydraulic fracturing plays in induced seismicity, it is important to note that fracking can also threaten the health of workers and residents living near the wells. These risks are exacerbated if the well casings are not properly constructed or maintained, which can cause toxic fracking fluid, along with highly flammable methane, to leak into the groundwater. Additionally, equipment failures and traffic accidents can release chemical laden fracking fluid into the environment (Jabbari, Aminzadeh, & de Barros, 2017; Elliott et al. 2017; Sumner, 2014). Groundwater contamination could occur if the cement encircling the well casing or the casing itself cracks and allows franking fluid to seep into groundwater (Jabbari et al., 2016). Additionally, unconventional natural gas development releases numerous volatile organic compounds, such as benzene, cadmium "C2−C8 alkanes, aromatic hydrocarbons, methyl mercaptan, and carbon disulfide" that have been linked to various cancers, such as leukemia and lymphoma respiratory illnesses, birth defects, and cardiovascular illnesses (Adgate, Goldstein, & McKenzi, 2014, p. 8311).

Overall, there are relatively few studies that examine the relationship between the chemicals utilized during the hydraulic fracturing process, over 1177 distinct chemicals, and the 143 air pollutants that are released during unconventional drilling and extraction. The International Agency for Research on Cancer (IARC) only reviewed 20 % of these chemicals so far. Through their analysis of the EPA's list of fracking fluid chemicals and the IARC's carcinogen designations, Elliott et al. (2017) found that of the 1177 chemicals found in fracking fluid and wastewater, 111 could potentially lead to cancer and other adverse health effects, while 29 of the 143 air pollutants could be carcinogens. They also found that 11 air pollutants and 17 fracking fluid chemicals were known carcinogens that increased the risk of developing leukemia and lymphoma (Elliott et al. 2017). Furthermore, exposure to groundwater contaminates and air pollution from fracking operations could produce gastrointestinal issues and irritate the eyes, nose, skin, and throat (Weinberger, Greiner, Walleigh, & Brown, 2017). The risk of experiencing adverse health effects is highest for residents who live less than half a mile away from an unconventional natural gas extraction well (McKenzie, Witter, Newman, & Adgate, 2012).

Hydraulic fracturing can also negatively alter residents' quality of living by producing acoustic pollution, increasing traffic during well drilling and development, and damaging the roads through the use of heavy supply and vibroseis trucks (Adgate et al., 2014; Harnetty, 2017; Goodman et al., 2016). Construction of the wells often takes anywhere from three to five months before the drilling preparations at the site are completed, the well is drilled, and the proper tests are conducted (EPA, 2016). During this time period, traffic increases as the employees and contractors of energy companies are tasked with transporting steel, cement, water, and other supplies to the site. Increased traffic, construction, and production well noises can increase residents' stress, hinder their ability to fall asleep, and even contribute to the development of tinnitus, ringing of the ears, due to prolonged noise exposure (Weinberger, 2017). Goodman et al. (2017) found that fracking production noises resulted in an increase in about 2.5 to 3.4 dBA, a measurement of perceived loudness, at night in communities near producing wells. Additionally, hydraulic fracturing can result in short term rental rate increases of up to 300 percent, as well as increased in housing demand from workers. This could cause lower-income renters to be evicted and have to relocate due to the rent increases. However, as fracking operations decrease and production companies leave the area, housing demands and rental prices start to decrease (Williamson & Kolb, 2015).

The aforementioned risks and health effects are exacerbated for workers who are in close proximity to these wells. Unconventional natural gas drilling and production poses numerous health risks for employees due to their frequent exposure to fracking fluid chemicals, as well as air pollutants from equipment and the production well themselves. Improper safety protocols or failure to follow established protocols also significantly increase the risk of equipment malfunctions, hazardous material spills and releases, explosions, and transportation accidents, which can seriously injure workers or result in fatalities. The occupational fatality rate for individuals employed by the oil and natural industry from 2005 to 2009 was more than eight times than the national average individuals in other occupations and seven times higher than other industry workers. Approximately 33.33 % of fatalities occurred due to traffic accidents and vehicle rollovers. Interestingly, smaller oil and natural gas companies had the highest occupational fatality rate (Adgate, 2014). This may be due to a lack of proper supervision, equipment, protocols, and compliance with national safety standards.

CHAPTER 3: CASE STUDIES

Relationship between Fracking and Earthquake Prevalence: State Selection

As of 2016, 21 states, which are shown in Figure 5, were actively fracking for natural gas: California, Utah, Montana, Wyoming, Colorado, New Mexico, North Dakota, Nebraska, Kansas, Oklahoma, Texas, Arkansas, Louisiana, Mississippi, Alabama, Indiana, Michigan, Ohio, Pennsylvania, West Virginia, and Virginia (Horn, 2016). While hydraulic fracturing has the potential to increase seismicity wherever it occurs, some states have experienced this negative effect to a greater degree than others.

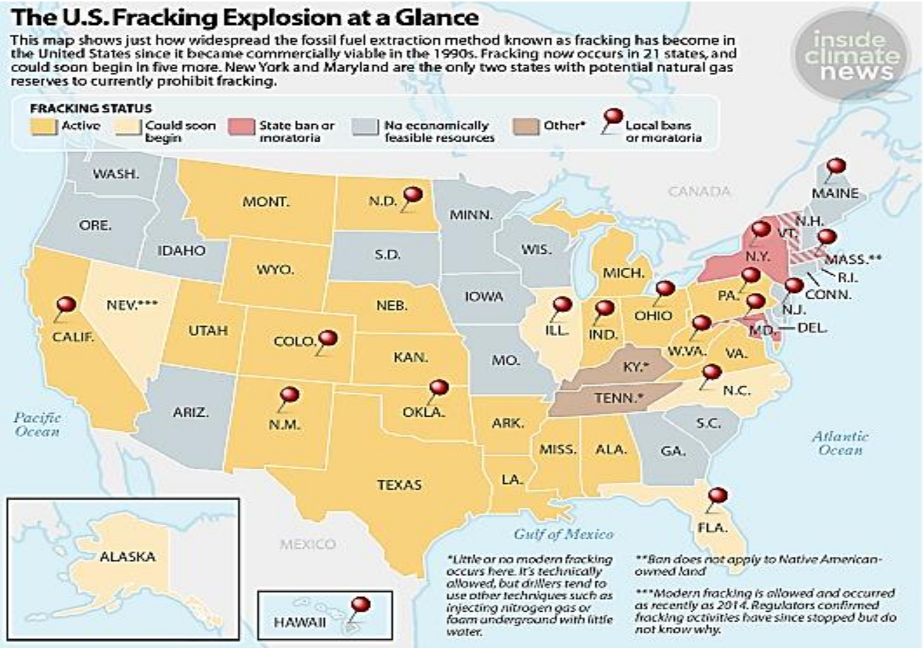

Figure 5) The following map shows each of the states that have active fracking wells, are considering natural gas development, or have enacted legislation to restrict or ban fracking (Horn, 2016).

Oklahoma was selected due to the state's exponentially increasing rate of magnitude 3.0 or higher earthquakes from 2009 to 2015, primarily due to a byproduct of fracking: wastewater injection (Virginia Tech Seismological Observatory [VTSO], 2014). Oklahoma surpassed California in magnitude 3 or higher earthquake prevalence in 2014, with 585 events to California's 200 earthquakes. As of 2015, Oklahoma still had the second highest risk of experiencing a magnitude 3 or higher earthquake in all of the states, with Alaska being the first

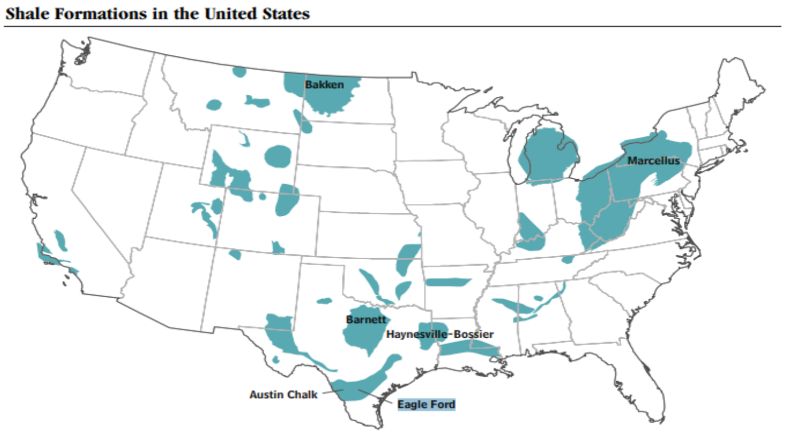

Figure 6) This map shows profitable shale formations throughout the US that would most likely require the use of fracking and horizontal drilling to extract (CBO, 2014, p. 4).

(USGS, 2018b). Texas was chosen due to its numerous shale reservoirs (see Figure 6), such as the Barnett, Haynesville-Bossier, Austin Chalk, and Eagle Ford, as well as its historical support and development of oil and natural gas wells that utilized fracking. Additionally, it was the start of horizontal drilling and fracking in shale reservoirs for natural gas during the 1990s. Pennsylvania was chosen due to the fact that it borders Ohio and also contains part of the Marcellus Shale region, a profitable reservoir of unconventional natural gas (Congressional Budget Office [CBO], 2014). The state also has the largest number of fracking wells in the eastern United States, with about 10,924 unconventional wells and 192,969 vertical wells (Pennsylvania Department of Environmental Protection [Pennsylvania DEP], 2017; Ridlington, Norman, & Richardson, 2016). Finally, Ohio was selected due to the fact that this state is the primary focus of the study of LEMA hydraulic fracturing mitigation. However, the impact that fracking has had on seismicity in Ohio will be discussed in Chapter 4, which will also contain a more in depth analysis of fracking induced earthquakes in the state.

Oklahoma

Since 2009, Oklahoma has experienced a surge in earthquakes with magnitude of 3.0 or higher (3.0+ earthquakes) and resulted in the state having the second highest seismic risk in the nation as of 2014 (USGS, 2018b). These earthquakes are believed to be the primarily the result of wastewater injection, a byproduct of hydraulic fracturing, due to that fact that the state has historically experienced about an average of 1.5 magnitude 3.0+ earthquake(s) per year from 1950 through 2005 (Petersen et al., 2016). As of 2008, the state's earthquake risk drastically increased to an average of 2.5 magnitude 3.0+ earthquakes occurring per day and hundreds of felt earthquakes occurring annually (Herskovitz, 2016; Petersen et al., 2016; Roach, 2018). This represents an increase of 300 percent from the state's historical seismicity rate that correlates with the significant increase in the amount of wastewater injected into the ground, from 849 million barrels per month in 2009 to 1.54 million in 2014 (Kuchment, 2016; Roach, 2018). In Oklahoma, most of the induced seismicity research has focused on the impact that fluid injection and removal wells have had on the decreasing frictional stability of faults.

For instance, on September 3, 2016, Oklahoma experienced its largest recorded earthquake, a 5.8 magnitude earthquake near Pawnee County. This earthquake is believe to be the largest fluid injection induced earthquake in the world, and it resulted in moderate structural damage near the epicenter and could be felt from Texas all the way through South Dakota (Foulger et al., 2018; Urken, 2017). Increases in fluid pore pressure from the numerous nearby injection wells, some of which were only 1.5 miles away from the fault, led to a downward failure along the Sooner Lake Fault, a blind fault that was discovered after the Pawnee County earthquake. These injection wells pumped large quantities of wastewater into the ground since 2006, which slowly decreased the stability of the fault (Barbour, Norbeck, & Rubinstein, 2017). Additionally, both the 2011 magnitude 5.7 Prague and the 2016 magnitude 5.0 Fairview earthquakes were believed to have resulted from fluid injection (Kuchment, 2016; Satterlee, 2016; USGS, 2016; Yang et al., 2017). Notably, the Prague earthquake could be felt in 17 surrounding states, injured two individuals, and resulted in the destruction of "over a dozen homes" (USGS, 2016, para. 5). On the other hand, the Fairview earthquakes only caused minor structural damage to homes located near the epicenter (Kuchment, 2016; USGS, 2016).

As a result of the numerous earthquakes near fluid injection wells, the Oklahoma Corporation Commission, which is responsible for regulating injection wells as well as oil and natural gas extraction wells, began implementing new mitigative standards for injection wells in 2015. For instance, wells near critical facilities, such as the Crushing Oil Hub complex, were shut down and the total amount of fluid that could be injected by well could be limited by up to 25 percent (Satterlee, 2016). Additionally, 37 wells near the Pawnee earthquake epicenter were shut down (Herskovitz, 2016). With increasing regulations and decreasing injection wells, Oklahoma has seen a significant reduction in magnitude 3.0+ earthquakes. However, the state's earthquake hazard risk remains high due to the consistent rate of weaker earthquakes. These earthquakes are believed to be related to fracking in the state (Petersen et al., 2018). For instance, Holland (2011) found that 43 earthquakes, ranging from 1.0 to 2.8 magnitude, occurred just hours after fracking operations ended at well that was 2.2 miles away. This could have been due to the abrupt changes in stress and pore pressure. Overall, most of the research on induced seismicity examines the relationship between wastewater injection and earthquake prevalence (Murphy, Greer, & Wu, 2018).

The effects of hydraulic fracturing on induced seismicity are often overlooked due to the fact that these earthquakes are often weaker, unfelt events that typically do not result in substantial structural damages, unlike earthquakes that are induced by fluid injection. Additionally, the USGS (2018c) reported that fracking has only been linked to less than 2 percent of Oklahoma's induced earthquakes. However, these earthquakes can reactivate dormant faults, weaken the frictional strength of existing faults, and cause structural damages. Further research is needed on the impact that fracking has on induced seismology in Oklahoma. Unfortunately, the Oklahoma Corporation Commission’s mitigation and research efforts are often stifled by political incentives to minimize the relationship between oil and natural gas development and any negative environmental effects. Energy sector lobbyists persuaded state legislators to pass numerous laws that lessened regulations and restrictions for oil and natural gas development, while simultaneously preventing local governments from passing laws that hinder production operations. It is important to note that oil and gas development makes up a significant portion of the state’s GDP and hires more individuals than any other industries, so many residents also object to development reductions and restriction (Murphy et al. 2018; Satterlee, 2016). Therefore, it is not surprising that Murphy et al. (2018) found that over half of residents in their study region, the Cities of Shawnee and Sapulpa, did not believe that their local government officials would do anything to mitigate induced seismicity. Effective mitigation in Oklahoma is primarily dependent upon political change and increased support for oil and natural gas regulations.

Texas

Induced earthquakes are a phenomena that Texas has experienced ever since 1925, just 24 years after oil drilling began in the state (Frohlich et al., 2016). Up until George Mitchell, who pioneered commercial fracking, began to use fracking and horizontal drilling as an economically beneficial way to extract tight shales in the Barnett Shale play during the early 1990s, fracking was used to accelerate production in shallow vertical wells. With the increasing use horizontal drilling and fracking during the shale boom, the state’s earthquake prevalence has also increased (Beebeejaun, 2017; The Academy of Medicine, Engineering and Science of Texas [TAMEST], 2017). Similar to Oklahoma, Texas has experienced a spike in magnitude 3.0+

earthquakes since the widespread increase in fluid extraction and injection wells, as well as hydraulic fracturing in shale reservoirs for natural gas. For instance, until 2008 the state only experienced an average of 2 of these events per year. The rate jumped to 12 3.0+ earthquakes per year in 2016 (Magnani, Blanpied, DeShon, & Hornbach, 2017; TAMEST, 2017). For example, the state experienced a 4.8 magnitude earthquake in its most profitable shale play, Eagle Ford, on October 20, 2011, due to increases in water and oil extraction at nearby wells (Frohlich & Brunt, 2013).

In the Barnett Shale reservoir, fluid injection has been attributed to 67 earthquakes with magnitude ranging from 1.4 to 3.0 from 2009 through 2011. While the majority of the 2,458 wells in the area injected an average of 1,500 barrels of water a month, earthquake increases tended to correlate with increases in the amount of water injected. Earthquakes occurred approximately 2.5 miles away from wells that had average monthly injection rates of over 150,000 barrels (Frohlich, 2012). Similarly, 30 earthquakes have occurred in the Fort Worth area from 2013 to 2014, an area were earthquakes have not been prevalent historically (Beebeejaun, 2017). On May 7, 2017, the Barnett Shale region of Jackson County experienced its largest earthquake, 4.0 magnitude. This earthquake was believed to have resulted from nearby injection wells, which continuously injected large quantities of wastewater into the ground and activated a nearby faults (Hornbach et al., 2016; Magnani et al., 2017). Overall, research in Texas, as in Oklahoma, on the topic of induced seismicity mainly focused on the effects that wastewater injection and fluid extraction had on anthropogenic earthquakes.

Mitigating induced earthquakes in Texas has been difficult for the Railroad Commission of Texas (RCT), which is responsible for regulating oil and gas production and wastewater injection, due to large influence of the energy sector. Texas is the nation’s top oil producer, accounting for more than 33.33 percent of the U.S.'s oil production, and it was the seventh largest global producer of oil. Residents have historically supported natural gas and oil production in the state (TAMEST, 2017). Furthermore, the majority of land that contains producing fracking wells is not publically owned, making it harder to study induced seismicity along with other risks posed by unconventional oil and natural gas production. Additionally, it is harder to monitor and regulate wells on individually owned private property (TAMEST, 2017). Notably, it is difficult to study the historic rate of natural and induced seismicity in Texas due to its lack of seismograph stations. For instance, the state only had six stations in 2005.

However, increasing concerns about induced earthquakes prompted the state to enact House Bill 2 in 2015. The bill provided $4.47 million in funding to install 22 stations and funded the creation of the TexNet seismic monitoring program. (Frohlich et al., 2016; TAMEST, 2017). In the previous year, the RCT hired a state seismologist and increased regulations for oil and natural gas production, as well as wastewater disposal, in response to the increase in earthquakes near fluid injection and extraction wells. Under these new regulations, the RTC regulate injection well fluid volumes or even halt wastewater injection altogether. Additionally, production companies have to supply "data (for a 100-mile radius) about the region's historical levels of seismicity when seeking to drill an injection well" to the RTC (Davis & Fisk, 2017, p. 8). While Texas has taken numerous steps to mitigate the risks associated with Class II injection wells, little has been done to specifically address the risk of induced seismicity for hydraulic fracturing. Future fracking mitigation could come about through the enhanced seismic monitoring provided by TexNet.

Pennsylvania

Unconventional natural gas drilling started in January 2004, in Pennsylvania, and the state in the second largest producer of unconventional natural gas in the U.S., surpassed by Texas (Chow, 2017; Jacobs, 2017). Unlike Oklahoma, Texas, and Ohio, Pennsylvania has not had history of fracking induced earthquakes. In fact, the state's first reported fracking induced earthquakes occurred between April 25 and 26, 2016, in Lawrence County, Pennsylvania, where four horizontal wells were drilled in the Utica Shale zone at depths of 7,900 ft. It is believed that drilling too close to basement rocks in the region resulted in the five earthquakes, ranging in magnitude from 1.8 to 2.3, which occurred in three of the county's Townships: Mahoning, North Beaver, and Union. After the earthquakes, Hilcorp Energy, the company that owned the wells, decided to shut down one the unconventional production wells that was believed to be responsible for the earthquakes until further testing near the site could be completed to determine if the well actually triggered the earthquakes. Researchers discovered that it was in fact responsible for the minor earthquakes in Lawrence County (Chow, 2017; Conti, 2016; Pacchioli, 2017). Interestingly, out of the approximately 10,924 unconventional wells in the state, earthquakes have only been attributed to one of four unconventional well in Lawrence County (Pennsylvania DEP, 2017). This data might indicate that fracking induced earthquakes are not significant hazard in the state.

There are a few potential explanations for this phenomena. Induced earthquakes surpass natural earthquakes in the state, with quarry and mine blasting accounting for approximately 99 percent of earthquakes (Pacchioli, 2017). Due to the prevalence of blasting in coal mines and quarries, semiologists and emergency managers are likely to be devoting most of their time to studying these earthquakes and monitoring ground movements near blasting sites with seismometers. Minor blasting is also used to identify and map out shale gas reservoirs in unpopulated or rural areas, while vibroseis trucks are used in urban areas. It should be noted that the blasting used in seismic exploration is only intended to be strong enough to cause vibrations that can be picked up by geophones (Pennsylvania DEP, 2014). However, this may further weaken any faults in the vicinity of the blasts, making them more susceptible to failure from other sources. Furthermore, Pennsylvania only has 12 Class II injection wells and transports the vast majority of fracking wastewater to Ohio for underground injection (Quigley, 2016; Pennsylvania DEP, 2017). As previously noted, (Ellisworth 2013; Kim, 2013; Satterlee, 2016…) numerous studies have found that fluid injection wells significantly increase the probability of small to moderate earthquakes occurring relatively close to the disposal well. With Pennsylvania having fewer Class II injection wells that pump larger quantities of water for longer periods of time than fracking does, it is not surprising that the state has also experienced fewer earthquakes than the other examined states.

CHAPTER 4: OHIO EARTHQUAKE AND FRACKING BACKGROUND

Ohio's Earthquake History

From 1776 through 1998, Ohio is believed to have had a total of approximately 229 earthquakes with magnitudes of or greater than 2.0. One hundred twenty-nine earthquakes had epicenters located in the State of Ohio, 76 impacted Ohio, but had epicenters that were located in adjacent states, and 24 events had "questionable seismic origins" and could have been falsely identified as earthquakes when the shaking may have been caused by something else, such as an explosion (Hansen, 2017, p. 53). The majority of earthquakes that originated in Ohio have been relatively shallow, low magnitude events, with the most powerful earthquake being a 5.4 magnitude earthquake. This earthquake's epicenter was located near the town of Anna in Shelby County and it occurred on March 9, 1937. However, the true magnitude of this earthquake, along with other historical earthquakes was difficult to determine due to the lack of seismometers that could accurately measure the amplitude of seismic waves (Hansen, 2012).

To ensure that earthquakes in the state could be properly measured and identified, the Ohio Emergency Management Agency (OEMA) and FEMA funded the establishment of the Ohio Seismic Network (OhioSeis) in 1999. OhioSeis consisted of a network of 15 broadband seismometers that were placed throughout the state in areas that were considered to be seismologically active historically. These stations are operational 24/7 and can immediately record any seismic waves in the area. Data from the stations can then be used to help discover new faults in the state or enhance seismologists' understanding of existing faults (Hansen, 2012). Earthquakes in Ohio are difficult to identify and predict due to the fact that most of state's faults are blind faults that are not visible at the surface. In addition to the limited understanding of Ohio's faults, most of the state's earthquakes are intraplate earthquakes, which have longer recurrence intervals, as well as poorly understood origins and causes. These factors make intraplate earthquakes harder to predict by seismologists (Hansen, 2012).

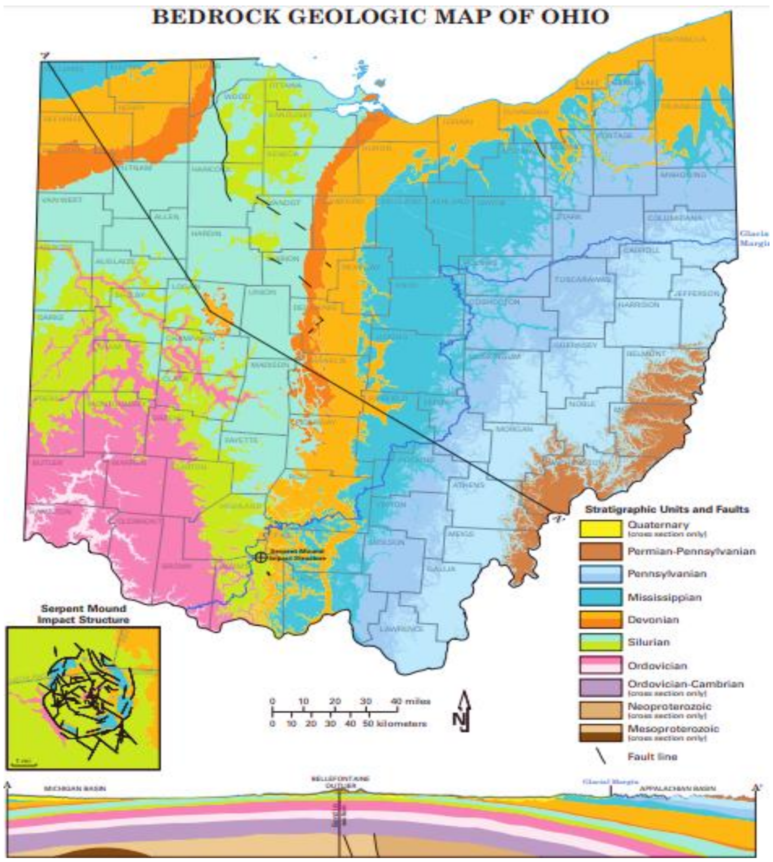

Figure 7: This map shows the distribution of Ohio's bedrock, most of which (Permian- Pennsylvanian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, Ordovician-Cambrian, and Mesoproterozoic) primarily consists of sedimentary rock. Neoproterozoic formations primarily consist of metamorphic rocks and Mesoproterozoic formations are primarily made up of igneous rocks (ODNR, 2017, p. 1-2).

Interestingly, the bedrock geology of Ohio actually increases its susceptibility to seismic waves, by enhancing the amplitude of seismic waves and their destructive potential (see Figure 7). Approximately "two-thirds of Ohio is covered by unconsolidated sediments," which are more prone to distortion and can actually help amplify the seismic waves of minor earthquakes (ODNR, 2019a, para 20). Most of Ohio's earthquakes are shallow and occur in crystalline Precambrian rocks at depths of three to six miles below the Earth's surface. Given the facts that shallower earthquakes tend to cause more damage and the state's bedrock geology can increase the earthquake's vibrations, it is surprising that only 15 of Ohio's earthquakes resulted in relatively minor and injuries. So far, no fatalities have resulted from an earthquake in Ohio (Hansen, 2015).

These factors have caused earthquakes to be viewed as a low frequency, low impact hazard by most of the state's 88 LEMAs. Therefore, it is not prioritized in local or state disaster mitigation planning and members of the general public are often surprised when they discover that Ohio does experience earthquakes (Hansen, 2015). However, since 2011, when the first horizontal well was drilled and fracked to extract natural gas from the Utica and Point Pleasant shales, Ohio's earthquake frequency has been increasing (Wickstrom, 2013). For instance, from 2000 through 2009 there have been 63 earthquakes with a magnitude of 2.0 or higher (ODNR, 2014). From 2010 through September 20, 2018, there have been 91 earthquakes with a magnitude of 2.0 or higher, with 18 of these earthquakes occurring in 2011 (ODNR, 2018a). This illustrates that Ohio has had more earthquakes in eight years than it has in the previous decade, suggesting that there is a correlation between unconventional drilling and fracking to increases in seismicity.

However, it is important to note that just because hydraulic fracturing and earthquake prevalence are correlated doesn't necessarily mean that fracking was primarily responsible for this increase in earthquakes. As has been observed in the previous case studies, the fracking byproduct of wastewater injection has been primarily responsible for the anthropogenic triggering of earthquakes in Ohio, as will be thoroughly discussed in the following section. Overall, the data shows that the frequency of earthquakes is increasing in the state. This alarming trend could potentially cause LEMAs to allocate more time and resources to developing mitigative strategies for this emerging anthropogenic non-intentional hazard. Furthermore, LEMAs should examine the risks that active fracking wells pose to their county and/or attempt to understand the impact that proposed wells may have on seismicity by analyzing the bedrock geology and fault structures in the vicinity of proposed wells. .

Ohio's Fracking & UNG Development Origins and Seismicity Spikes

Ohio has had an extensive history of oil and natural gas development dating back to 1814, when oil was first discovered from a well in Noble County, and 1860, when the first commercial vertical well began extracting oil in Washington County's Village of Macksburg. Just 24 years later, in 1884 commercial natural gas drilling began in Ohio (Ohio Oil and Gas Association [OOGA], 2003). While Texas is now known as the country's leader in oil and gas production, Ohio was at the forefront of the industry from 1895 to 1902 and surpassed the oil and natural gas production of all of the other states (Aller, Zwierschke, & Weatherington-Rice, 2013). In Ohio, the use of fracking to increase production in vertical wells began in 1952, after a successful simulation in sandstone reserves in 1951 (ODNR, 2015; OOGA, 2003). Morrow County took advantage of this technological advancement and constructed more oil and natural gas wells than any other county in the United States, during the early 1960's (Aller et al., 2013). As previously drilled wells decreased in productivity or completely depilated reservoirs, the inability to effectively retrieve natural gas from the deep shale reservoirs with vertical wells limited the state's natural gas production capabilities. However, the use of horizontal drilling, coupled with hydraulic fracturing, resulted in a new energy boom in 2011 (ODNR, 2011a).

Unconventional natural gas (UNG) development, where hydraulic fracturing is combined with horizontal drilling in tight shale formations, started in 2011 in the Utica/Point Pleasant and Marcellus shale reservoirs (Wickstrom, 2013). Permits were issued as early as 2009 for the Marcellus and 2010 for the Utica/Point Pleasant shale reservoirs. As of January, 8, 2019, there are 468 permitted and 2,137 producing wells in the Utica/Point Pleasant shale reservoir, along with 23 permitted and 22 producing wells in the Marcellus shale reservoir (ODNR, 2019b). Hydraulic fracturing has be utilized in over 80,000 vertical and horizontal wells to increase natural gas production since the 1950s (ODNR, 2015). The fracking boom in UNG reservoirs resulted in a natural gas output increase of “1,715.5 percent from 79.2 billion cubic feet in 2006 to 1,437.3 billion in 2016,” which subsequently resulted in the skyrocketing increase in annual revenue generated from natural gas from $964 million in 2011, when drilling started, to $10,755 million in 2016. (Larrick, 2018, p. 35). While the state initially saw a significant economic boom, UNG development also correlated with increases in another area: earthquake frequency.

Microseismicity, the production of earthquakes that are less than 1.0 in magnitude, is a typical part of the fracking process in UNG reservoirs that occurs during well simulation, when fracking is used to enhance the flow of hydrocarbons. The vast majority of fracking induced earthquakes were unfelt events, but these large clusters of small earthquakes near active UNG production wells increase the amount of stress placed on faults and the potential of triggering a larger earthquake. While rare, fracking has been responsible for larger earthquakes that were greater than 2.0 in magnitude (Ellsworth, 2013; Kozłowska et al., 2018; Skoumal et al., 2015; Skoumal, 2016…). As noted by the ODNR (2018a), Ohio experienced 28 more magnitude 2.0+ earthquakes in eight years than it did during the previous decade, correlating with the increase in UNG. Additionally, the fact that the majority of Ohio’s bedrock geology consists of unconsolidated sediments also promotes the amplification of seismic waves and enhances the damage potential of weaker earthquakes (ODNR, 2017).

Since the use of horizontal drilling and fracking in UNG reservoirs, Ohio’s microseismicity and overall seismicity rates have increased. For instance, from October 2 to October 19, 2013, Harrison County, as area that has had virtually no reported earthquakes before

2010, experienced six earthquakes ranging in magnitude from 1.6 to 2.2 (Friberg, Besana-Ostman, & Dricker, 2014; Kozłowska et al., 2018) These earthquakes occurred along an unknown fault less than 0.62 miles away from three active fracking wells, Ryser-2, Ryser-3, and Ryser-4, which began stimulations in September 7, 2013 (Friberg et al, 2014). Additionally, there were no Class II injection wells within 6.21 miles of the earthquake hypocenters, indicating that fluid injection was not responsible for inducing these earthquakes (Skoumal et al., 2015). It should be noted that Harrison County started UNG development in the Utica/Point Pleasant shale reservoirs just a year ago in 2012 (Kozłowska et al., 2018). Due to the cluster like pattern of these earthquakes near the three wells, along with the area's lack of earthquakes, ODNR placed four seismic stations in the area where the swarms occurred to determine if the wells were responsible for inducing the earthquakes. From October 30th through December 13th, the stations identified 30 earthquakes near the wells with magnitude of up to 0. 7 (Friberg et al., 2014). These findings strongly suggested that the Harrison County earthquakes were induced by the fracking wells.

A year later, from March 2 through 14, 2014, Mahoning County's Poland Township experienced 77 earthquakes. (Wines, 2015). While the majority of the earthquakes were around 1.0, five of them had magnitudes ranging from 2.1 to 3.0. The epicenters of the five larger earthquakes was located approximately 0.62 miles away from Hilcorp Energy's CLL2 1H well, which was undergoing fracking stimulations during the same period as the earthquake swarms were occurring (Skoumal et al., 2015; Skoumal, 2016). Although these earthquakes' epicenters were less than 12.42 miles away from those that occurred in Youngstown due to the Northstar 1 Class II injection well, which will be briefly addressed at the end of this section, there were no injection wells present for about 6.84 miles from the location of the Poland Township earthquakes (Skoumal et al., 2015). As with the Harrison County earthquakes, fluid injection could not be blamed for inducing the earthquake sequences and the county did not have an extensive earthquake history. Therefore, UNG development was discovered to have induced these earthquakes. In response, ODNR suspended operations at the well believed to induce the earthquakes, but allowed Hilcorp to continue operations at the other five wells that were drilled on the well pad. However, on April 11, 2014, ODNR issued an article stating that the Poland Township earthquakes prompted the development of more stringing permit requirements for any horizontal well proposals that would be located near faults or in areas that have experienced earthquakes in the past. As per the new permit requirements, "horizontal drilling within 3 miles of a known fault or area of seismic activity greater than a 2.0 magnitude would require companies to install sensitive seismic monitors" (ODNR, 2011b, para. 2). ODNR would than investigate any earthquakes greater than 1.0 magnitude and halt operations until the probable cause is identified. If it is found that hydraulic fracturing induced the earthquakes, than well operations would be terminated (ODNR, 2011b).

Another notable earthquake sequence that is believed to have been induced by hydraulic fracturing occurred along the western border of Belmont County and the eastern border of Guernsey County from May 18 to 19, 2014 (Skoumal et al., 2015). Five earthquakes, with the larger earthquake having a magnitude of 2.6, occurred less than three miles away from four horizontal wells that were undergoing hydraulic fracturing operations at the time. However, the data on these earthquakes had a higher degree of uncertainty than that of the previous fracking induced earthquakes due to a lack of adequate seismic station coverage. Therefore, operations were allowed to continue (Brudzinski & Kozłowska, 2018). On June 02, 2017, less than 9 miles away from this earthquake sequence, Noble County experienced the largest fracking induced earthquake. This 3.4, initially estimated at 3.7 magnitude earthquake occurred less than a mile away from the Wolf 2H well, a horizontal well that was being stimulated during the time that the earthquake occurred. Operations were not suspended at the well after this felt earthquake due to the fact that its microseismicity only consisted of 18 minor earthquakes, rather than 50 plus or hundreds. It did not have a large enough swarm of minor earthquakes associated with it to confidently assume that the fracking well directly induced it (Brudzinski & Kozłowska, 2018; USGS 2017).

Class II Injection Well Induced Earthquakes

Like the other states examined, Ohio has also experienced numerous wastewater injection induced earthquakes. While wastewater injection is not the focus of this study, the issue of induced seismicity regarding oil and gas operations was brought to the forefront in 2011 after a 4.0 magnitude earthquake occurred on December 31 in the City of Youngstown, Mahoning County (ODNR, 2012). The earthquake occurred less than 0.62 miles away from the Northstar 1 Class II injection well (Skoumal et al, 2015). Northstar 1 was drilled in December 2010 and minor earthquakes started occurring in January 2011 (Kim, 2013). The frequency of these minor earthquakes increased in March 2011, coinciding with increases in the well's maximum surface injection pressure from 1,890 psi to 2,250 psi on March 19th following the approval of D & L Energy Inc.'s request by ODNR's Division of Oil & Gas Resources Management. Additionally, they approved a second request from the company on May 3, 2011, and permitted the well to have a maximum injection pressure of 2,500 psi (ODNR, 2012). On December 24, 2011, a 2.7 magnitude earthquake occurred near the well and ODNR immediately investigated the event and sent a request to D & L Energy Inc. to stop all injection at the well on December 29. The company willingly halted all operations on the 30th, a day before the 4.0 earthquake struck

Youngstown (Kim 2013; ODNR 2012).Prior to the activity of the injection well, Mahoning County did not any reported earthquakes, yet the county experienced 109 earthquakes ranging in magnitude from 0.4 to 4.0 due to the fluid injection well. Seismicity in the county significantly decreased just one week after Northstar 1 ceased its operations (Kim, 2013).

After the Youngstown earthquake news sources began to highlight the dangers of fracking and its potential to induce earthquakes. For instance, the *Cleveland Plain-Dealer* only published one article regarding induced seismicity in 2011, but published 17 articles in 2012. Unlike in Texas and Oklahoma, news sources in Ohio tended to focus more on these events and hold energy companies responsible rather than claiming that the induced earthquakes occurred due to accident or were just a natural part of the fracking process (Frisk et al., 2017). Due to increased public pressure to address fracking related hazards, Governor John Kasich signed Senate Bill 315 on June 11, 2012. The bill contained many provisions that increased industry transparency, such as requiring operations to publicize the chemicals that they utilize thought the lifespan of the well and provide this information to medical facilities. It also increased the area from which water samples had to be collected and tested from 300 feet within the vicinity of the well to 1,500 feet for both urban and rural areas, no water testing had to occur in rural areas before the bill was passed. ODNR could also inspect the sites every 12 weeks without notifying operators in advance. Furthermore, the bill encouraged energy companies to develop RUMAs, road use maintenance agreements, with local jurisdictions (ODNR, 2019c).

CHAPTER 5: LEMA FRACKING & INDUCED SIESMICITY MITIIGATION IN OHIO

Method

Ohio Emergency Management Agency (OEMA)’s State Hazard Analysis, Resource and Planning Portal (SHARPP) was initially referenced to determine how local EMAs are currently mitigating or planning to mitigate both hydraulic fracturing and earthquake hazards. SHARPP is a database that allows the public to view each county’s mitigation plan, disaster declarations, as well as the total cost of public and individual disaster assistance. It contains each of the 88 counties’ local hazard mitigation plans (LHMP). Data regarding horizontal drilling Utica/Point Pleasant and Marcellus drilling was obtained from ODNR Division of Oil & Gas’s “Shale Well Drilling & Permitting” data (2019b). Furthermore, ODNR Division of Oil & Gas’s “Oil & Gas Well Locator” was used to identify all permitted and producing wells in Ohio (2018b). Findings from each county’s LHMP were then compared to the ODNR- Division of Oil & Gas’s data on producing and permitted wells to determine if and how counties that have UNG wells are working on mitigating associated hazards.

In addition to the SHARPP and ODNR- Division of Oil & Gas data analysis, a survey was sent out to LEMA directors to determine how fracking has impacted their county regarding increases in induced seismicity. The survey consisted of both quantitative and qualitative questions that addressed the effect that fracking has had on their county, if and how they were educating residents and business owners about this hazard’s risk, as well as if and how they are or would mitigate its negative effects. The survey was utilized to determine if fracking was a prioritized hazard by the LEMAs and if not, why. Furthermore, the directors were also asked to speculate as to how residents in their county perceive fracking and if the economic benefits outweigh the risks of induced earthquakes.

SHARPP & ODNR- Division of Oil & Gas Findings

The complete SHARPP results and ODNR findings for the 88 counties are provided in Table I, located in Appendix A. Notably, 68 of the counties, 85%, have producing and 79, 89.7%, have permitted gas wells. Of these counties, 17 have producing UNG wells, 18 have permitted UNG wells, 18 have UNG wells that have been drilled, and nine have drilling UNG wells. After analyzing the SARPP results, very few of the LEMAs addressed hydraulic fracturing induced earthquakes or any fracking related hazards in their LHMP. In their LHMP, only six of them discussed induced earthquakes, two of which only mentioned explosion induced earthquakes, and three of them proposed strategies to mitigate fracking or wastewater induced earthquakes that focused on enhancing residents' knowledge about the hazard. Only one of these counties that both discussed induced earthquakes and proposed mitigative strategies, Washington, had UNGD, while the other two had conventional wells. The LHMPs from the other 16 counties that have UNGD did not discuss potential ways to mitigate this hazard, or fracking and/or injection well induced earthquakes. Although, Muskingum County's LHMP did discuss explosion induced earthquakes.

Thirty-nine counties, 44.3%, that have had earthquake epicenters within their boundary have producing fracking wells. However, some of these counties, such as Shelby County, have a history of seismic events, so the correlation does not necessarily suggest that fracking is to blame for seismicity. Eight of the 17 counties, 45.1%, with UNG wells have had with earthquake epicenters located within their boundaries. Since most county LHMPs did not distinguish between natural and induced earthquakes, it is difficult to determine the effect that UNGD had on the seismicity rate in the counties. Furthermore, there was a range of 13 years among plan submissions for the 88 counties, resulting in counties having outdated plans that may not accurately reflect the hazards that are present. LHMP SHARPP submission years ranged from 2005 to 2018, with an average submission year of 2014 and a mode of 2014. Interestingly, four of the 88 counties did not even have a mitigation plan submitted to SHARPP, making it more difficult for the public to know what their LEMAs are doing to mitigate the hazards that are present in their county.

When visiting the EMA websites of these four counties, they did provide disaster preparedness, response, recovery, and mitigation information. Interestingly, Champaign County EMA posted their 2012 Mitigation Plan on the EMA website, which discussed natural earthquakes and stated that the county experienced two earthquakes with epicenters in the county (Champaign County Emergency Management Agency, 2012). Green County's EMA also uploaded their 2015 Greene County Natural Hazard Mitigation Plan to their website. Their plan also discusses natural earthquakes and states that the county had 11 significant earthquake events, with no earthquake epicenters in the county, "over the past 204 years" (Green County Emergency Management Agency, 2015, p. 76). Since these plans could not be found in SHARPP, their mitigation data was not included in Table 1. Allen and Madison County did not have a mitigation plan uploaded to their websites or SHARPP. However, Allen County did have a substantial amount of information regarding anthropogenic non-intentional and intentional hazards, as well as their mass notifications systems and Local Emergency Planning Committee (LEPC). The fact that none of these four counties have any type unconventional natural gas development (UNGD) should be taken into consideration. Of these four, only Green County had one producing gas well, which was a conventional domestic well that has an insignificant risk of inducing earthquakes. Additionally, Madison County has absolutely no type of oil and gas wells in the county. Therefore, fracking induced earthquakes, which tend to occur near the wells, would be nearly impossible to occur in the county unless the surrounding counties had UNG wells right on its border, which they do not.

Limitations & Discussion.

From the time that all of the LHMPs were analyzed, throughout December 2018 and January 2019, 31 of the 88 county LHMPs, which have a five year review cycle, in SHARPP had expired. This means that the data in 35% of the plans is outdated for the counties. However, some counties may be working on updating their plans, especially those that have had their plan recently expire in 2017 or 2018. It is possible that counties may include this hazard in their updated plans. Additionally, some plans may be currently undergoing review by the State or by FEMA, a process which may take weeks or even months for the LHMPs to be approved, as the LEMAs may have to revises and resubmit their plans a few times. On the other hand, one of the counties had a plan that was adopted in 2005, with an expiration date of 2010, which suggests that the LEMA has a lack of funding, staff, and/or support from the private and public sectors for disaster mitigation. These three issues are often present in smaller, less populous counties in the state due to having less revenue generated from taxes that can be utilized for activities that enhance public safety, such as mitigation planning.

Furthermore, the LHMPs are primarily focused on the state's highest impact and frequency hazard, which is flooding. In addition, LEMAs also tailor their mitigation plans so that they can receive credit for it under the National Flood Insurance Program's (NFIP) Community Rating System (CRS). The more credits that a community accumulates, the higher the premium discounts that residents in counties could get on their annual NFIP premiums. It is also possible that LEMAs do not address fracking induced earthquakes due to the fact that the ruling in the 2015 case of *State ex rel. Morrison v. Beck Energy Corp.* prevents local governments from enacting fracking bans or restrictions that go against state laws (*State ex rel. Morrison v. Beck Energy Corp.*, 2015). Mitigation strategies could be primarily focused on public awareness and education about the hazard, since LEMAs and local government leaders have little say in how and where emergency companies can drill and frack. Furthermore, fracking induced earthquakes have not resulted in substantial property or infrastructure damage, nor have they cause injuries or deaths in Ohio. Therefore, it appears that most LEMAs consider them to be low priority hazards. Most county mitigation plans also have a tendency to focus more on natural hazards and only briefly discuss anthropogenic hazards, which usually include hazardous materials spills, terrorism, and dam failures in the plan.

However, some counties also have plans in place with energy companies to reduce fracking hazards, such as RUMAs, which are not discussed in LHMPs. For instance, soon after the start of UNGD in 2011 and the passage of Ohio Senate Bill 315 in 2012, oil and gas companies have developed RUMAs with local governments in the Counties of "Belmont, Carroll, Columbiana, Guernsey, Jefferson, Harrison, Monroe and Noble" to repair and improve any roadways that were damaged through the phases of unconventional oil and natural gas development (OOGA & Energy In Depth [EID], 2017, p.7). In these eight counties, energy companies have spent over $300 million to repair and improve approximately 639 miles of roadways (OOGA & EID, 2017). While RUMAs do not address the issues of induced seismicity, they do indicate that local governments have an interest in working with energy companies to mitigate the risks posed by unconventional oil and natural gas development.

Survey Distribution & Analysis of Findings

A 20 question survey, consisting of three open ended questions and 17 closed ended questions, was sent out to each of the 88 LEMA Directors in Ohio. On October 23, 2018, the survey, which was created and distributed through Qualtrics, was emailed to the 88 directors. Within a week, three of the directors completed the survey. Reminders were sent out on October 30, 2018, November 15, 2018, and January 31, 2019 to the individuals who did not complete it. For the final reminder that was sent on January 31, 2019, the first question, which asked the directors to state their county, was removed in the hopes that it would encourage participation by increasing confidentiality. Unfortunately, this did not alter the final results, as no new directors responded to the survey. Throughout the process, 10 directors started the survey, but either only answered a few questions or did not answer any questions after opening it. For the purpose of this analysis, only complete surveys will be discussed.

All of the directors said that flooding was the hazard that their EMA devoted the majority of their resources towards mitigating and none of listed earthquakes as a hazard that their county was most susceptible to, which was not surprising given that most of the State's earthquakes were unfelt or caused little to no damage. Additionally, none of the participants were planning on devoting resources to mitigating fracking induced earthquakes. Two individuals had active fracking wells, while one stated that fracking never occurred in the county. One individual, whose county has producing, permitting and drilling wells, listed hydraulic fracturing as one of the hazards that that the county was most susceptible to and stated that the county EMA is planning to prepare educational handouts, posts, trainings, or exercises this year or the following year regarding hydraulic fracturing. Regarding fracking hazard knowledge, most directors believed that their residents, with the exception of individuals over 60 or under 18 years old, had a basic understanding of fracking's environmental impacts. They also noted that most industries either had a basic understanding or were very knowledgeable about fracking hazards, with members of energy sector being extremely knowledgeable. Regarding public complaints, results were across the board with one person stating that there were no fracking complaints, one claiming that their residents did complain, and one was uncertain if complaints were made. Two of the directors said that fracking operations have virtually no impact on traffic flow, note that one county never had fracking wells, while one said that it had a moderate impact with delays of 10 to 29 minutes and some lane or road closures.

Limitations & Discussion.

Unfortunately, only three directors completely answered all of the questions in the survey. Therefore, there is an extremely high margin of error and a low confidence interval for this study due to the fact that three directors only represents 3.41 percent of the sample population. Statistical significance cannot be accurately derived from this study due to the low number of responses. Additionally, the results of this study cannot accurately describe how fracking is prioritized in each of the 88 counties. For instance, the survey was sent out to the directors' county email addresses, which could have either marked the message as spam or prevented it from reaching their inbox due to file size restrictions. There are numerous reasons as to why only three individuals completely finished the survey.

For example, they may have been weary of sharing information about fracking or injection wells in their county due to concerns about how the data will be used and who will see the results. Some individuals may have been worried about their county being singled out and portrayed in a negative light for not having fracking and induced seismicity plans. Others may have plans that are not public for security reasons, such as containing sensitive information about well operations or personnel information. Finally, LEMA directors are extremely busy because they have a responsibility to enhance their county's public safety and reduce the impact that any hazard has on the community. The survey could have also been too long and time consuming for the directors to take time out of their schedule to answer an academic survey with seemingly minimal benefit to their county.

If this study were to be replicated in the future, it is advisable to consider alternative distribution methods. Conducting the survey over telephone could be a better alternative to email because any questions that participants have could be immediately addressed, plus it would reduce the amount of work that participants have to do. Meeting with the LEMA directors and conducting the survey in person may have yielded better results. However, with both of these methods, researchers would still have to find time that would work with both their own and their participants' schedule. Participants would also not have as much time develop their answers to the questions. In person meetings would also increase the time it takes to get responses because researchers would have to find a time that works for both parties and travel to the agreed upon location, which could be hours away.

Ohio's Attempts to Mitigate Fracking Induced Earthquakes

Currently, Ohio utilizes a traffic-light system to mitigate hydraulic fracturing induced earthquakes. This system was established by ODNR in April 2014, after the Poland Township earthquakes occurred 0.62 miles away from an active UNG well. Seismic monitors have to be set up before any horizontal drilling can occur within 3 miles of a seismically active region or known fault line. Operations at wells would be halted if any earthquakes greater than 1.0 magnitude, red light, are identified near the well until ODNR determines the cause of the earthquake. Well completions would be stopped if it is found that the well did in fact induce the earthquakes (ODNR, 2011b).While enhanced seismic monitoring near UNG and injection wells is a step in the right direction, the overall effectiveness of traffic-light systems is hindered by the fact that most of Ohio's faults are unknown and the composition of the State's crust is favorable for amplifying seismic waves. For instance, both Poland Township and Harrison County had no previous earthquakes history, which limits the effectiveness of ODNR's standard of monitoring seismicity in areas that have had earthquakes greater than 2.0 in magnitude. Additionally, no faults were identified in either of the regions prior to drilling (Wong, Nemser, Bott, & Dober, 2015).

Seismometers also have to be extremely sensitive and properly distributed to accurately detect potentially induced microseismicity. ODNR;s three mile standard is also relatively conservative, given that induced earthquakes have occurred further than three miles away from fracking wells and it does not take into account the margin of error for seismometer readings, which tends to be around + or – 6.21 miles (Wong et al., 2015). Arguably, the greatest issue regarding traffic light systems is the fact that they have not been able to prevent larger induced earthquakes or even predict the occurrence of larger earthquakes that may occur soon after fracking operations stop, such as the Youngstown earthquake. By design, these systems are retrospective in nature and only alert responders after earthquakes have occurred (Bommer, Crowley, & Pinho, 2015). Unfortunately, earthquakes, both natural and induced, are virtually unpredictable and Ohio's bedrock composition, coupled with a limited understanding of its all of the state's fault lines, makes mitigating induced earthquakes extremely difficult. Furthermore, since these induced earthquakes have been either unfelt or causes meniscal amounts of damage they are not a planning priority for LEMAs or even Ohio EMA. For instance, while Ohio EMA's 2011 Hazard Mitigation Plan discusses earthquakes and earthquake mitigation through increased awareness of this hazard, it does not mention induced earthquakes or hydraulic fracturing (Ohio Emergency Management Agency, 2011).

Additional LEMA Mitigative Measures

In Ohio, the state, specifically ODNR's Division of Oil & Gas Resources Management, has exclusive legislative and regulatory authority over oil and gas operations as per Ohio Revised Code (ORC) Chapter 1509.02. However, Ohio's Constitution permits local governments to establish ordinances, provided that they do not go against any state laws, through the Home Rule Amendment. In 2011, the City of Munroe Falls, Summit County, issued a Stop Work Order to Beck Energy Corporation, who had obtained a permit to drill within the city limits from ODNR, for violating five of the city's local ordinances: 1163.02, 1329.03, 1329.04, 1329.05, and 1329.06. Beck Energy Corporation claimed that the city's ordnances went against ORC Chapter 1509 and that they did not have to comply with the city's zoning or oil and gas ordinances since they fallowed all of ODNR's regulations. The case reached the State Supreme court and on February 17, 2015, the Court ruled in favor of Beck Energy Corporation. As per *State ex rel. Morrison v. Beck Energy Corp.*, local municipalities cannot use the Home Rule Amendment to enact and enforce fracking bans or other ordinances that go against the state's fracking laws (*State ex rel. Morrison v. Beck Energy Corp.*, 2015). This ruling significantly hinders the mitigative capabilities of LEMAs because they cannot propose and attempt to get support for stricter fracking regulations due to the precedent set forth by *State ex rel. Morrison v. Beck Energy Corp.* However, LEMAs can increase their community's awareness to the hazards associated with hydraulic fracturing.

For instance, none of the three responders have provided educational materials about hydraulic fracturing to residents and businesses, but two of the responders stated that there were producing and permitted wells or actively drilling, producing, and permitted wells in their county. Additionally, most of the participants stated that residents in their county, regardless of age group, had a basic understanding of fracking’s environmental impacts, while residents over 60 years old and under 18 had a limited understanding. Yet, none of the participants believed that residents in their county were unaware of the hazard, very knowledgeable, or extremely knowledgeable. LEMAs that have producing and permitted fracking wells, especially UNG wells, could host meetings to discuss fracking hazards or provide additional information on their websites or social media sites. Members of retail and communications industries were noted as having the least knowledgeable about fracking hazards. Therefore, LEMAs could tailor public awareness programs and campaigns to members of these industries. Although no clear indication of LEMA fracking induced earthquake mitigation could derived from the survey results due to the small number of participates, low fracking prioritization can be observed when analyzing the counties’ LHMP. For instance, only three of the counties that UNG wells both discuss the hazard and potential mitigative strategies in their LHMP, yet 17 counties have producing and 18 have permitted UNG wells. LEMAs that have producing or permitted UNG wells could incorporate information about fracking induced earthquakes and microseismicity into their LHMPs.

CHAPTER 6: CONCLUSION

Summary & Future Considerations

While the risk of induced seismicity from UNGD is lower than that of Class II wastewater disposal wells, it should still be addressed in research and members of the public should be aware of this hazard. In Ohio, microseismicity, along with the rate of 2.0+ magnitude earthquakes, has significantly increased since fracking was combined with horizontal drilling to extract natural gas, as well as oil, from tight shale reservoirs in 2011. The composition of Ohio’s bedrock geology is prone to amplifying seismic waves and most of the state’s faults are unknown, making it difficult to determine if and when seismometers should be place near wells that undergo fracking. While the state has been relatively proactive in increasing seismic monitoring and enacting legislation to enhance fracking regulations, the State Supreme Court case of *State ex rel. Morrison v. Beck Energy Corp.* has limited the authority of local governments to impose stringent regulations or issue fracking bans.

Unfortunately, due to the unpredictable nature of induced earthquakes, as well as natural earthquakes, there is little that can be done in Ohio to mitigate this hazard aside from enhanced seismic monitoring and educating the public about the hazard. Regarding public awareness of the hazard, LEMAs, especially those in counties that have UNG wells, should develop educational materials about fracking induced seismicity. This information could be presented at public safety events and posted onto the LEMAs' social media sites and websites. LEMAs could also briefly discus this risk in their LHMPs and ensure that they upload their LHMP on their webpages and on SHARPP to increase the chances that members of the public will be able to access this information.

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APPENDIX A

LHMP Mitigation and Ohio’s Oil and Gas Wells

County	Year of LHMP submission to SHARPP	Has experienced earthquake with epicenter(s) in county, according to LHMP	LHMP Discusses Earthquakes	LHMP Discusses Induced Earthquakes	Has Producing Fracking Wells	Has Permitted Wells (wells that could be developed)	Has UNGD Producing Wells	Utica/Point Pleasant Producing	Marcellus Producing	Total Number of UNGD Producing Wells	Number of UNG Permitted Wells	UNGD Wells that have been Drilled	UNGD wells that are being Drilled	LHMP Proposes Ideas to Mitigate Fracking and/ or Induced Earthquakes
Adams	2010	Yes	Yes	No	No	No	No	0	0	0	0	0	0	No
Allen	n/a	n/a	n/a	n/a	No	Yes	No	0	0	0	0	0	0	n/a
Ashland	2015	Yes	Yes	No	Yes	Yes	No	0	0	0	0	1	0	No
Ashtabula	2013	Yes	Yes	Yes-injection well	Yes	Yes	No	0	0	0	1	0	0	Discusses Class I Injection wells and EMA wants to promote public awareness
Athens	2013	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Auglaize	2008	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Belmont	2013	No	No	No	Yes	Yes	Yes	443	2	445	88	62	21	No
Brown	2017	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Butler	2017	No	Yes	No	No	No	No	0	0	0	0	0	0	No
Carroll	2006	No	Yes	No	Yes	Yes	Yes	468	1	469	49	7	1	No
Champaign	n/a	n/a	n/a	n/a	No	Yes	No	0	0	0	0	0	0	n/a
Clark	2013	Yes	Yes	No	Yes	No	No	0	0	0	0	0	0	No
Clermont	2014	Yes	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Clinton	2016	Yes	Yes	No	No	No	No	0	0	0	0	0	0	No
Columbiana	2015	Yes	Yes	No	Yes	Yes	Yes	71	0	71	73	15	0	No
Coshocton	2010	No	Yes	No	Yes	Yes	Yes	1	0	1	3	1	0	No
Crawford	2014	Yes	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Cuyahoga	2017	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Darke	2012	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Defiance	2017	Yes	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Delaware	2014	No	No	No	Yes	Yes	No	0	0	0	0	0	0	No
Erie	2014	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Fairfield	2012	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Fayette	2015	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Franklin	2013	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No

Fulton	2015	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Gallia	2013	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Geauga	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Greene	n/a	n/a	n/a	n/a	Yes	Yes	No	0	0	0	0	0	0	n/a
Guernsey	2013	No	No	No	Yes	Yes	Yes	188	0	188	30	14	19	No
Hamilton	2018	Yes	Yes	No	No	No	No	0	0	0	0	0	0	No
Hancock	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Hardin	2018	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Harrison	2016	Yes	Yes	No	Yes	Yes	Yes	349	0	349	63	16	20	No
Henry	2013	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Highland	2007	Yes	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Hocking	2005	No	No	No	Yes	Yes	No	0	0	0	0	0	0	No
Holmes	2014	No	Yes	No	Yes	Yes	No	0	0	0	3	0	0	No
Huron	2012	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Jackson	2012	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Jefferson	2014	Yes	Yes	No	Yes	Yes	Yes	130	1	131	19	29	33	No
Knox	2016	No	Yes	No	Yes	Yes	No	0	0	0	1	1	0	No
Lake	2017	Yes	Yes	Yes-injection well	Yes	Yes	No	0	0	0	0	0	0	Yes, a town hall meeting was hosted by Lake County EMA to educate residents about hazards associated with wastewater injection wells
Lawrence	2015	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Licking	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Logan	2018	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Lorain	2015	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Lucas	2013	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Madison	n/a	n/a	n/a	n/a	No	No	No	0	0	0	0	0	0	n/a
Mahoning	2018	Yes	Yes	Yes-injection well & fracking	Yes	Yes	No	0	0	0	0	0	0	No, but discussed the Youngstown earthquakes of 2011 caused by the Northstar 1 injection well.

Marion	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Medina	2012	Yes	Yes	No	Yes	Yes	No	0	0	0	0	1	0	No
Meigs	2013	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Mercer	2017	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Miami	2017	No	Yes	No	Yes	No	No	0	0	0	0	0	0	No
Monroe	2014	No	Yes	No	Yes	Yes	Yes	281	18	299	61	69	46	No
Montgomery	2014	Yes	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Morgan	2013	Yes	Yes	No	Yes	Yes	Yes	2	0	2	0	1	0	No
Morrow	2018	No	No	No	Yes	Yes	No	0	0	0	0	0	0	No
Muskingum	2018	No	Yes	Yes-explosion	Yes	Yes	Yes	1	0	1	2	0	0	No
Noble	2014	No	No	No	Yes	Yes	Yes	162	0	162	44	5	12	No
Ottawa	2017	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Paulding	2017	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Perry	2006	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Pickaway	2013	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Pike	2007	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Portage	2017	Yes	Yes	No	Yes	Yes	Yes	1	0	1	6	7	1	No
Preble	2013	No	Yes	No	No	No	No	0	0	0	0	0	0	No
Putnam	2015	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Richland	2017	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Ross	2011	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Sandusky	2015	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Scioto	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Seneca	2015	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Shelby	2017	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Stark	2017	Yes	Yes	No	Yes	Yes	Yes	2	0	2	6	5	0	No
Summit	2014	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Trumbull	2011	No	Yes	No	Yes	Yes	Yes	7	0	7	4	3	1	No
Tuscarawas	2017	No	Yes	No	Yes	Yes	Yes	6	0	6	11	3	0	No
Union	2013	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Van Wert	2014	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Vinton	2017	No	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Warren	2015	No	Yes	Yes - explosion	No	No	No	0	0	0	0	0	0	No
Washington	2016	Yes	Yes	Yes-injection well & fracking	Yes	Yes	Yes	11	0	11	10	1	0	EMA plans to work with ODNR and promote public education and awareness about the

														hazard. The findings of Skoumal et al. (2015) regarding fracking induced earthquakes in the county were discussed in the plan.
Wayne	2018	Yes	Yes	No	Yes	Yes	Yes	1	0	1	0	0	0	No
Williams	2013	No	Yes	No	No	Yes	No	0	0	0	0	0	0	No
Wood	2018	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No
Wyandot	2005	Yes	Yes	No	Yes	Yes	No	0	0	0	0	0	0	No

APPENDIX B

Survey Questions

Q1 Please type the name of the county you work for.

○ County Name ____

Q2 What are the primary natural, technological, and anthropogenic intentional hazards that your county is most susceptible to?

Anthropogenic Non-Intentional Hazards: Also known as technological hazards, these potential events result from human errors and accidents. The people who cause these events did not wish to do so and had no desire to cause the accidents, local emergencies, or disasters that may have occurred due to their mistake.

Anthropogenic-Intentional Hazards: Hazards caused by human activities that are not accidental in nature such as: arson, acts of terrorism (CBRNE), workplace violence & shootings, company or equipment sabotage, riots, or the release of classified information.

☐ Flooding

☐ Severe Storms

☐ Tornadoes

☐ Severe Winter Weather

☐ Land Subsidence

☐ Landslides

☐ Earthquakes

☐ Hazardous Material Spills & Releases

☐ Wildfires

☐ Coastal Erosion

☐ Invasive Species

☐ Infectious Diseases

☐ Power or Utility Failures at Critical Facilities (Hospitals, Police Stations, Fire Stations, Nursing Homes, etc.)

☐ Nuclear Power Plant Accidents

☐ Cyber Attacks

☐ Hydraulic Fracturing

☐ Terrorism

☐ Riots and Civil Disturbances

☐ Cyanobacteria

☐ Other ____

Q3 With regards to question 1, what is the primary hazard that your EMA devotes most of its mitigative efforts towards?

○ Highest Ranking Hazard ____

Q4 Is your EMA currently or planning to mitigate fracking hazards, such as induced earthquakes?

☐ No

☐ Yes, planning to mitigate

☐ If currently mitigating against the hazard, what are some of the EMA's mitigative strategies? Please provide the name(s) or a link to your EMA's fracking mitigation plans (this information could be contained in a hazard specific plan, all-hazards mitigation plan, EOP, etc). Note: I have examined each county's LHMP through Ohio EMA's State Hazard Analysis, Resource and Planning Portal.
____

Q5 If you answered "No" to question 3, do you think that developing and implementing plans that reduce the risks that hydraulic fracturing may pose to residents, industry, and the environment would be beneficial to your county?

- ○ Yes
- ○ No, fracking does not occur in my county, nor are drilling wells permitted
- ○ No, the frequency and impact of this hazard in my county don't warrant the reallocation of resources, such as grant funding, from higher frequency and impact hazards in my county.

Q6 To your knowledge, has your county ever experienced any induced earthquakes?

Induced Earthquakes: Induced earthquakes refer to any earthquakes that could be attributed to anthropogenic activities that include, but are not limited to: hydraulic fracturing, wastewater disposal, mining operations, construction, explosions, impoundment of reservoirs, etc.

- ○ Yes
- ○ No
- ○ Unsure

Q7 Did the frequency of earthquakes experienced in your county increase after 2011?

- ○ Yes
- ○ No
- ○ Unsure

Q8 Does your county have actively drilling, producing, or permitted fracking wells?

- ○ Yes, actively drilling, producing, and permitted fracking wells
- ○ Yes, producing and permitted wells

○ Yes, drilling and producing wells

○ No, wells were already drilled and/or are inactive

○ No, fracking has never occurred in this county

○ Unsure

Q9 Does your county have any Class II Injection Wells?

○ Yes

○ No

○ Unsure

Q10 To your knowledge, has any groundwater contamination occurred as a result of fracking in your county?

○ Yes

○ No

○ Unsure

○ Not applicable

Q11 How knowledgeable do you think that residents in your county are about the potential environmental and safety risks of hydraulic fracturing? Please select "Not Applicable" if hydraulic fracturing does not occur in your county.

	Extremely knowledgeable about the process, economic benefits, and risks to the environment	Very knowledgeable about the process, benefits, and risks to the environment	Basic understanding about what fracking is and its associated positive and negative	Limited understanding about what fracking is.	Unaware about the hazards associated with fracking and/or	Not Applicable

	and human health.	and human health.	impacts on the economy, environment, and human health.		fracking in the county.	
Residents under 18 years old	○	○	○	○	○	○
Residents between 18 - 30 years old	○	○	○	○	○	○
Residents between 30 - 40 years old	○	○	○	○	○	○
Residents between 40 - 50 years old	○	○	○	○	○	○
Residents between 50 - 60 years old	○	○	○	○	○	○
Residents between 60 - 70 years old	○	○	○	○	○	○
Residents over 70 years old	○	○	○	○	○	○

Q12 In your county, how knowledgeable do you think that owners & workers in the following industries are about the potential environmental and safety risks of hydraulic fracturing? Please select "Not Applicable" if hydraulic fracturing does not occur in your county.

	Extremely knowledgeable about the process, economic benefits, and risks to the environment and human health.	Very knowledgeable about the process, benefits, and risks to the environment and human health	Basic understanding about what fracking is and its associated positive and negative impacts on the economy, environment, and human health.	Limited understanding about what fracking is.	Unaware about the hazards associated with fracking and/or fracking in the county	Not Applicable
Agriculture and Food Processing	○	○	○	○	○	○
Transportation	○	○	○	○	○	○
Healthcare	○	○	○	○	○	○
Energy	○	○	○	○	○	○
Education	○	○	○	○	○	○
Legal	○	○	○	○	○	○
Manufacturing	○	○	○	○	○	○
Communication	○	○	○	○	○	○
Retail	○	○	○	○	○	○

Communication	○	○	○	○	○	○
Insurance	○	○	○	○	○	○

Q13 Has your EMA provided any educational materials about hydraulic fracturing hazards to residents and businesses in the county?

○ Yes

○ No

○ Unsure

Q14 If so, what mediums were used to present the information?

☐ Social Medina Sites (Facebook, Twitter, YouTube, etc.)

☐ Brochures

☐ Flyers

☐ EMA Trainings and Exercises

☐ Lectures

☐ Discussions at Public Safety Events

☐ Not Applicable

☐ Other ____

Q15 Is your EMA planning to prepare educational handouts, posts, trainings, or exercises this year or the following year regarding hydraulic fracturing? If not, why?

○ Yes

○ No, hydraulic fracturing is a low frequency/low impact hazard in my county

○ No, hydraulic fracturing has not occurred in my county

○ Other ____

Q16 How have hydraulic fracturing operations impacted the flow of traffic in your county?

○ Significant Impact: delays of up to and over half an hour and multiple lane or road closures

○ Moderate Impact: delays between 10 to 29 minutes and some lane or road closures

○ Slight Impact: less than 10 minute delays and very few or no lane or road closures

○ Minimal to No Impact: while supply trucks and/or vibroseis trucks were present at the sites and travelling to the site(s), they did not have a noticeable impact on traffic flow in the jurisdictions near the site(s)?

○ Not Applicable

Q17 Have any residents in your county complained about the hydraulic fracturing operations in your county?

○ Yes

○ No

○ Uncertain

Q18 If you answered "Yes" to question 16, what was the nature of the resident's or residents' complaints?

☐ Traffic delays, lane or road closures, flaggers, etc.

☐ Noise pollution near the drilling site(s): increase in traffic related noises, well operation noises during hydrocarbon extraction, noises from compressor stations, etc.

☐ Visual pollution from the drilling site(s): dislike the appearance of the compressor stations, fracking well, supply trucks, etc.

☐ Environmental concerns: air pollution, water contamination, potential for explosions, etc.

☐ Royalty disputes among landowners and fracking companies in the county

☐ Heath Concerns

☐ Not Applicable

Q19 In your opinion, do residents in your county view hydraulic fracturing favorably?

○ Yes

○ No

○ Uncertain

Q20 Do you think that residents in your county view fracking as economically beneficial and a good source of both energy and employment opportunities?

○ Yes

○ No

○ Uncertain