Relating Wastewater Injection and Induced Seismicity in Ohio

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Table of Contents

Acknowledgements……..1

Abstract.....2

Introduction……..…3

Methods…….…...9

Results…….....11

Geographical Information Systems Maps…….….11

Ohio Department of Natural Resources Data……....15

Unites States Geological Survey Data……...…....19

Discussion……..…….23

References……...…...27

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Abstract

Hydraulic fracturing is the unconventional process by which natural gas is released from shale bedrock in the subsurface. In this process, hundreds of thousands of barrels of wastewater are produced. To dispose of it, it is injected into the ground at high pressures to essentially seal the fluid between layers of rock. Recently, this process of wastewater injection has been linked to induced seismic activity in the subsurface. The purpose of this study is to determine if there is a statistical correlation between wastewater injection and seismic activity. Increased seismic activity can cause damages to surface structures as well as subsurface pipelines.

Using data from the ODNR and USGS, this study explores the relationship between the volume of injected fluid per year in Ohio from 2010-2015 and seismic variables such as the number of earthquakes per year, average depth, and average magnitude. The strongest relationship ($R^2 = 0.608$) existed between fluid volume and average magnitude. The second strongest relationship ($R^2 = 0.159$) existed between fluid volume and average depth of earthquakes. Using these correlations, the distribution of injection wells across Ohio and seismic events, it is highly probable that the injection of wastewater has led and will continue to lead to induced seismic activity in Ohio and other parts of the United States.

Introduction

Oil and gas are two resources that have given humans the ability to make significant technological advancements. Since the development of the first automobile to the creation of the iPhone 7, the oil and gas industry has been transforming the way people live their lives since the 1850's (Hobart, 2005). As technology improves, scientists and engineers are continually looking for more efficient ways to extract natural resources from the Earth. States with large natural gas reservoirs such as Texas, Oklahoma, Kansas, Pennsylvania, Ohio, and North Dakota are currently leading the way for fracking development, making the United States the largest producer of natural gas in the world (Ridlington et. al, 2013; Chen, 2013). The Marcellus Shale, which directly underlies six states including much of Pennsylvania, Ohio, and West Virginia, is now the nation's largest recoverable source of natural gas (Lee, 2015). Although fracking is necessary to extract natural gas, this process can be accompanied by some adverse environmental impacts, including the disposal of wastewater fluid from hydraulic fracturing.

Hydraulic fracturing works by increasing the permeability of a rock layer to allow for easier flow of hydrocarbons (Carpenter, 2013). Hydrofracking combines two methods to work; horizontal drilling and the injection of fluids and chemicals into the well to increase pressure and create fractures in a particular rock layer. Modern fracking involves a vertical well that is drilled to a specific depth where there is a large concentration of hydrocarbons, usually oil or natural gas trapped in rock such as sandstone or limestone. Once the vertical pipe has reached the desired depth, the pipe is then curved, and drilling begins in a lateral motion to obtain as much of the natural resource as possible.

The waste produced during a fracking operation, which includes a mixture of water, proppant, and chemicals, must be extracted and transported to another site for subsurface

injection into a disposal well. When this waste fluid is injected into the subsurface at high pressures, it increases the chance of inducing seismic events, some of which have the potential to cause damage above ground. Specifically, Ohio has had earthquakes in the past and continues to experience them. Consequently, Ohio is one of the largest disposers of wastewater fluid in the Northeast. This raises questions as to what the root cause of seismicity throughout the state could be.

There are six different classes of disposal wells described by the Ohio Department of Natural Resources (ODNR). Different types of fluids are disposed of in different well classes. For example, wastewater from oil and gas operations can only be disposed of in class II injection wells (Underground Injection Wells, 2017). In Ohio specifically, 98% of the wastewater produced is injected back into the ground into brine-bearing or depleted oil and natural gas reservoirs (Chen et. al., 2013). The ODNR recently produced an interactive map that shows all the different wastewater disposal wells in the state (Zehringer, 2017). This map is extremely useful for locating specific disposal wells and for accessing well data.

In many areas within the U.S., wastewater injection is the most common form of disposal. Of the 144,000 class II injection wells in the United States, 20% are responsible for the disposal of wastewater from oil and gas production (Chen et. al., 2013). For a typical class II injection well, fluid is injected on average at a depth of 4,000 feet (Injection well disposal). On rare occasions, injection wells can reach 10-12,000 feet (Injection well data sheet, 2012). In general, wastewater disposal works by injecting waste into the ground to induce fractures. These fractures then allow for more waste fluid to be injected into the formation. In Ohio alone, there are 242 active class II injection wells that have the capability of disposing of hydraulic fracturing

waste (Auch, 2013). There are many chemicals and additives that compose wastewater fluid including metals, salts, oil and gas compounds, and radionuclides (Luek, 2017).

There are many rock formation characteristics that make an area suitable for wastewater disposal. Disposing of fluid into a highly permeable formation is the best form of injection when getting rid of large quantities of wastewater (Veil et. al., 2003). A permeable formation allows for the disposal fluid or slurry to spread out evenly across the formation which is known as rapid screen out. Desired permeable layers (sandstone, limestone) should be overlain by a rock layer with a very low permeability such as a shale, an evaporite, or a tight limestone layer (Veil et. al., 2003). This low permeability seal layer prevents the spread of wastewater upwards toward possible ground water aquifers. Regions with interbedded sandstone and shale units are ideal for wastewater disposal as the shale layers act as impermeable barriers both above and below the targeted high permeability layer. For a target layer, the desired formation would be at least 65 feet thick, and it would have been deposited relatively horizontal (Veil et. al., 2003). It would also stretch several miles laterally. This would allow for the most waste to be contained given the extent of the formation. A horizontal formation will also allow for the distribution of waste to occur much slower than a formation that was dipping at an angle.

There is a very detailed process for how wastewater disposal or slurry injection occurs. The solid waste from drilling operations must be condensed and broken down, so it can be injected down the disposal well. Large solids are removed from the disposal fluid as not to clog the pipe, while the rest of the waste is mixed with a chemical fluid to increase its viscosity (Fact sheet – Slurry Injection of Drilling Wastes). Before the slurry is injected, the target formation is prepped by injecting water down into the well, so the pressure is right at the formation's fracture pressure. Then, the slurry is injected into the well to surpass the rock's fracture pressure and

form new fractures in the rock layer to create more space for the slurry to flow (Fact sheet – Slurry Injection of Drilling Wastes). Once all the slurry is pumped down the well, additional water is injected down the wellbore to clean out any solid waste that may have been left behind. Injection can either occur as a single continuous process or in cycles; however, most disposal wells inject over the course of a few days.

The introduction of these fluids to a given area can become problematic for several reasons. First, fluids reduce the principle stresses that act on rock layers which in turn reduces the amount of stress needed to produce an earthquake if a fault plane is present in the area. Fluids compound the activation process of fault systems by acting as a lubricant for rock surfaces to slip past each other or by causing new faults to form (Davies, 2013). This process can cause induced seismicity which occurs when fluids are injected into the subsurface. Seismic activity is considered induced if a fault plane slips or a new plane is formed due to the introduction of fluids and an increase in stress on the system.

Induced seismicity has become more recognized in the past fifty years given the increase in wastewater disposal and the increase in seismicity in states such as California, Oklahoma, Arkansas, and Colorado. Each of these states have recorded a magnitude 4.0 or greater earthquake due to wastewater injection since 2008 (Auch, 2016). This relationship has caused scientists to examine the cause of seismic activity in other regions throughout the U.S. where wastewater disposal is prevalent. States, such as these, that have been tectonically active in the past or that are so currently are at greater risk for induced seismicity because of their tectonic history.

Several factors including pre-existing faults, changes in pore-pressure, and volume of injected fluid can contribute to induced seismic activity. The presence of pre-existing fault zones

is a very important variable to consider that may increase the risk of induced seismicity. For example, wastewater disposal operations are less likely to cause seismicity if they are occurring in a tectonically stable area or in an area that has not been tectonically active in the past (Muntendam-Bos et. al., 2015). When fluid is injected into the ground surface at high pressures, old faults can be reactivated causing seismic activity to occur (Wiprut and Zoback, 2000; Nicol, A. et. al., 2013: McClure et. al, 2017). Most of these events can only be recorded on a seismograph; however, there is potential for more severe earthquakes to occur as more fluid is injected into the subsurface.

Not only do pre-existing faults and fractures lead to an increase in induced seismicity, but changes in pore-pressure have also been linked to seismic activity and fault reactivation (Wiprut et. al., 2000). Fluids are very incompressible meaning they need to have room to spread out in the subsurface, filling up space that normally would not be filled with anything other than air. As fluid moves in and out of the pores of the rock at high velocities, pressure in the pore spaces changes (Talwani et. al., 1985). These changes can cause unnecessary stress to be placed upon fault systems in the surrounding area (Holland, 2013). Relaxation of stress and pore pressure that initially came with the injection of wastewater can also induce seismicity (Bao, 2012; Hajati, 2015; Muntendam-Bos, A. et. al., 2015). Increases in pore-fluid pressure reduce the amount of effective stress on the system, and in turn lowers the amount of shear-stress that is needed for an earthquake to occur (Mechanisms of induced seismicity, 2017).

Finally, the volume of injected fluid is an important variable to consider because it directly affects the fluid pressure and subsequent fracture-induced permeability (Bolton, 2016). That is, higher fluid volumes lead to more fracture and larger fractures in the subsurface. The larger amounts of injected fluid increase the vertical stress on the underlying bedrock. If

underlying layers have faults or pre-existing fractures within them, the added weight of the disposal fluid could cause slip beneath the injection area (Bolton, 2016).

One of the reasons Ohio injects so much wastewater into the subsurface is because of its geology. Most of Ohio's primary geology consists of shale and dolostone with some stretches of sandstone, siltstone, mudstone, and limestone throughout the state (Auch, 2013). Shale and dolostone act as great reservoirs for waste because they are not very porous which means fluids do not flow very easily through them. Injecting waste into these layers is beneficial because the non-porous nature of the formations keeps the wastewater in place and stores it. Furthermore, small fractures are made in these formations during the injection process to open more space for the waste to flow. The waste is stored in the space between the grains of the rock and within the fractures created from injection.

Between Quarter 3 of 2010 and quarter 1 of 2016, Ohio's Class II injection wells have seen an exponential increase in injection activity. This increase may have contributed to the eastward movement of the Ohio seismic center in recent years as most disposal activity has been in the eastern part of the state (Auch, 2013). Using publicly available well data and seismic data, this paper analyzes the correlation between disposal activity and seismic activity using factors such as time, location, magnitude of seismicity, and earthquake depth as well as volume of injected fluid.

Methods

The Ohio Department of Natural Resources (ODNR) has publicly available well data that show the location of wells, the company that owns them, pressure measurements, and more (Zehringer, 2017). Using the lease name and saltwater injection well (SWIW) numbers, I was able to look at volumes of injected fluid from 2010-2015 for each well on a website called FracTracker. The volume of injected fluid for each well was broken down into four quarters, which constitutes a full year of injection (3 moths/quarter), so I added each well's quarterly injection volumes together to estimate total volume per quarter and total averages per year for each of the five years.

In conjunction with well data, I collected seismic data from both the Ohio Department of Natural Resources (ODNR) and the United States Geological Survey (USGS). From each webpage, I recorded the number of seismic events, magnitude, depth, and location of each event all between 2010 and 2015. Averaging the number of seismic events, magnitudes, and depths by year allowed me to make a comparison with the annual volumetric fluid data I had from the FracTracker website.

Two separate series of graphs were created because the USGS data accounted for earthquakes greater than 1.0 magnitude whereas the ODNR data only accounted for earthquakes that were greater than 2.0 in magnitude. Both sets of data were used because this study is looking to see if a relationship exists between seismicity and injected fluid; therefore, even if the earthquakes that are occurring don't cause much damage (< 2.0 mag), they are still important to the purpose of this study. Trend lines and calculated R^2 values were used to determine the kinds of relationships present and the strength of the relationships between different variables.

Accompanying these graphs are two maps created using Geographic Information Systems (GIS) software that show the spatial distribution of class II injection disposal wells and the location of earthquakes throughout the state of Ohio. The first map shows earthquakes that range from 1950 to the present, because the process of deep waste water injection was first used in Ohio during the 1950s (Wickstrom, et.al.). Only seismic events greater than and equal to 2.0 in magnitude were plotted, as anything below that is usually not felt at the ground surface and can only be picked up by seismometers (Zehringer, 2010). The second map shows the spatial distribution of injection wells to earthquakes that occurred between 2010 and 2015 to show the relationship between both variables over the same time period.

Results

Geographic Information Systems Maps

Most of the active class II injection wells throughout Ohio are located in the Eastern half of the state. Consequently, most of the earthquakes that have occurred since 1950 (Figure 1) and that have occurred in the past five years (Figure 2) have also occurred in the eastern half of Ohio. Earthquakes especially in the Western half of the state seem to occur around or near major Precambrian fault systems (Zehringer, 2013). Surprisingly, most of the clusters of earthquakes present on the map are not generally near areas with the largest volumes of injected fluid from 2010-2015.

Two exceptions to this observation occur in Mahoning county (Northeastern Ohio) and Washington county (Southeastern Ohio) represented by circles on Figure 1. The Southernmost tip of Washington County contains a series of 13 earthquakes that have all occurred in the last seven years. Spatially, all 13 earthquakes are within 13 km of a series of four major injection wells located near the Ohio River and the West Virginia Border. Another example of this correlation exists in Northern Mahoning county, where a series of eight earthquakes occurred within a four-kilometer radius between 2010 and 2015. The farthest of these eight earthquakes was located just 4.5 kilometers from the closest major injection well and under 10 km away from two other injection wells in the area.

The largest and most apparent cluster of earthquakes is located in the northeastern most part of Ohio along the coast of Lake Erie in the counties of Lake and Ashtabula. While there aren't significant volumes of wastewater being disposed here, there are a series of 18 injection wells present across both counties. Also, there is a major Precambrian fault that runs almost

parallel to the shoreline of Lake Erie. This is significant because Ohio earthquakes are shallow-focus events meaning they occur in Precambrian age rock about three to six kilometers in the subsurface (Hansen, 2015). The deepest wells in Ohio are around 10,000 to 12,000 feet which means there are some wells that could be drilled into Precambrian rock. Most wells however; are drilled into the Paleozoic sedimentary rock overlying the Precambrian basement rock.

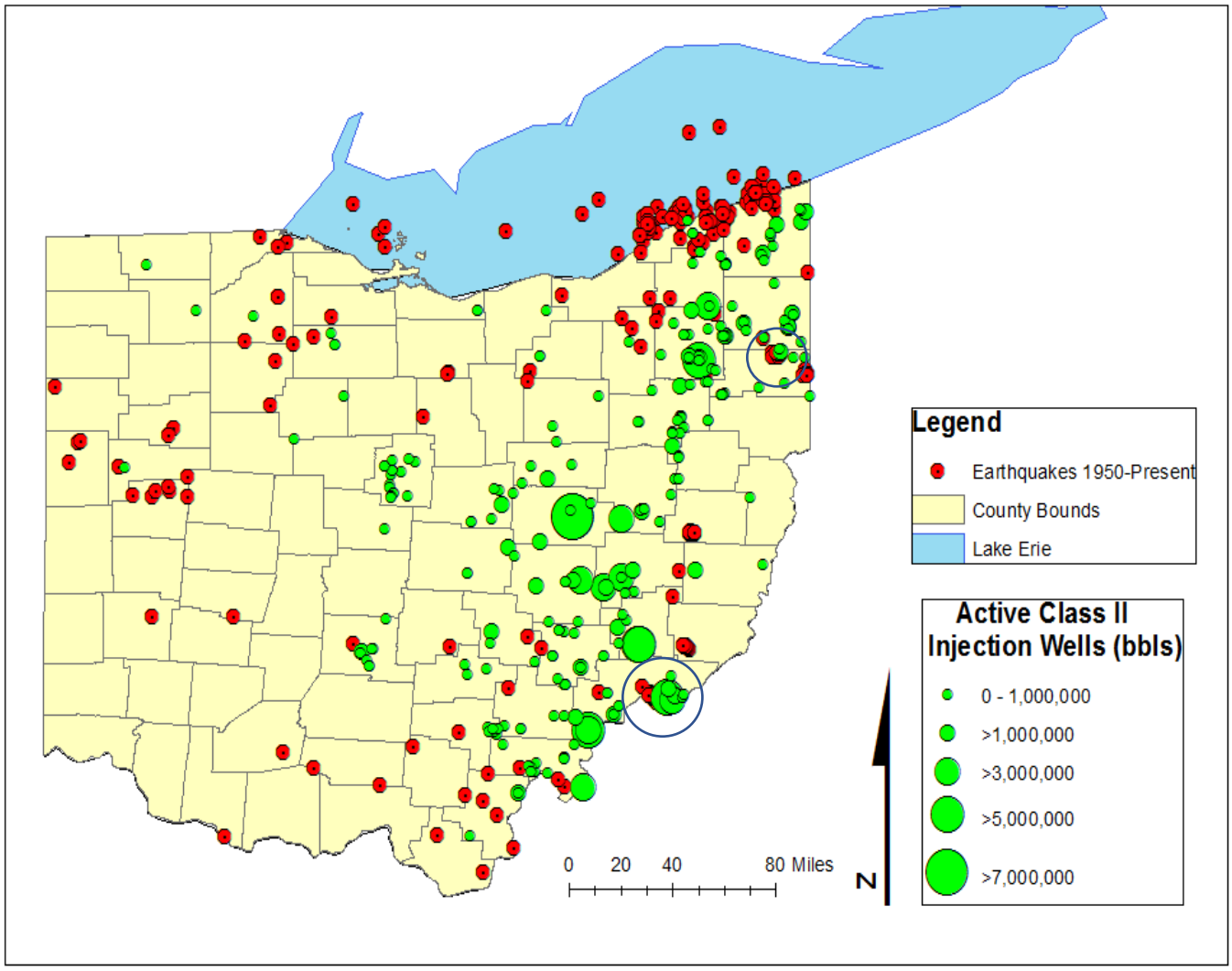


Figure 1. Distribution of class II injection wells by volume and the location of earthquakes in Ohio (1950 – Present) using data from the ODNR. Circles represent tightly packed clusters of injection wells and earthquakes within 20 kilometers of one another in Mahoning County (northernmost circle) and Washington County (southernmost circle).

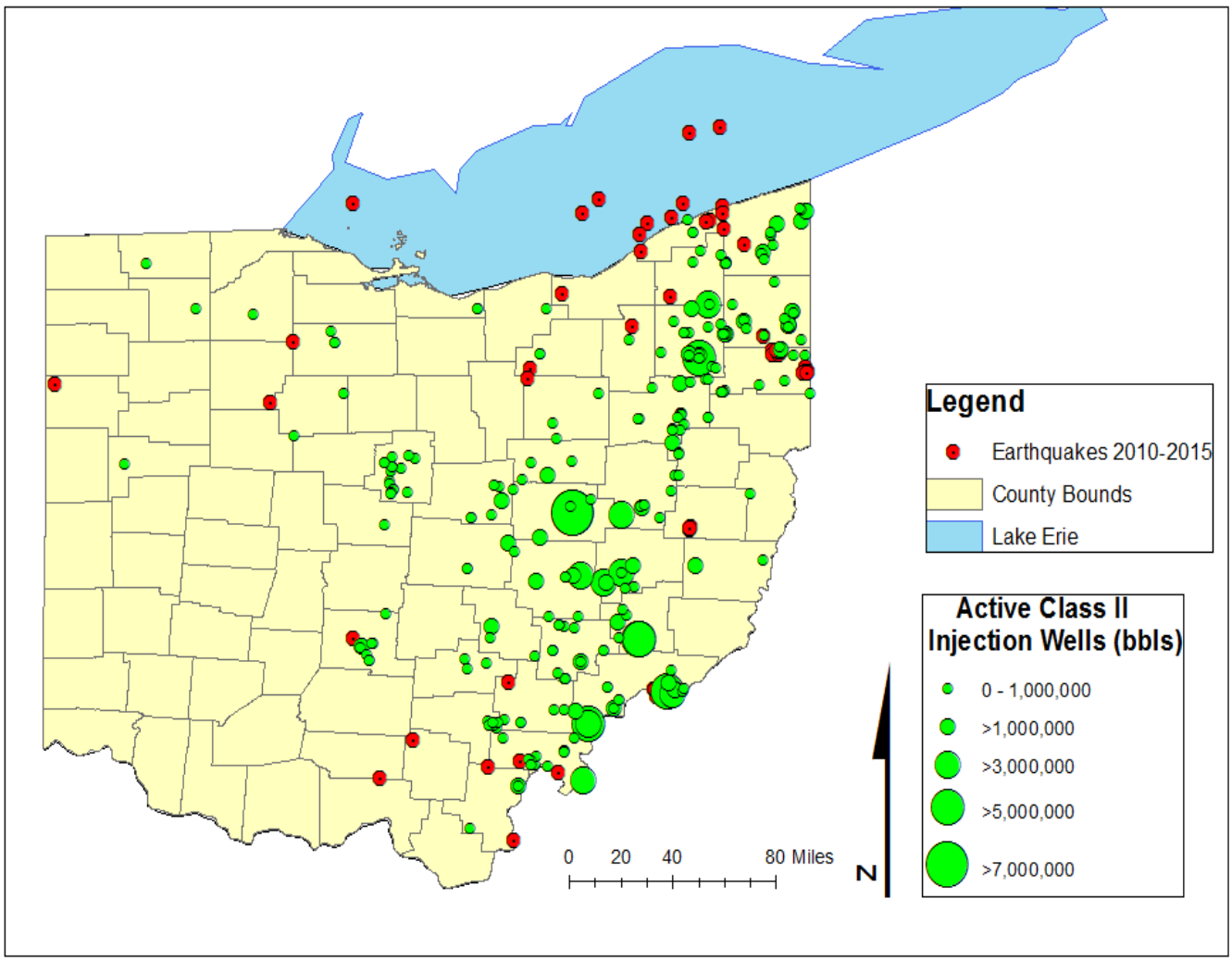


Figure 2. Distribution of class II injection wells by volume and the location of earthquakes in Ohio (2010-2015) using data from the ODNR.

Ohio Department of Natural Resources Data

Overall, there was no relationship between the volume of injected fluid and all three seismic variables (number of earthquakes, magnitude, depth) with data from the ODNR. Figure 3 shows a weak inverse correlation between the volume of injected fluid and the number of seismic of events that occurred over a period of five years (2010-2015) because as volume increases, the number of earthquakes slightly decrease. The volume of injected fluid ranged between approximately 24,000 and 60,000 barrels of waste annually, and in general volume increased over time. The number of seismic events ranged from 5 to 18; however, there was no real pattern over time, as the trendline's slope is close to zero. Figure 4 shows a positive relationship given by its positive sloping trendline; however, there is no relationship shown here given its R^2 value of 0.02.

Figure 5 shows no real correlation between volume of injected fluid and magnitude. Magnitude values range from approximately 2.2-2.6 and remain relatively constant over time. Figure 6 shows a negative relationship between volume and magnitude given by its negative sloping trendline; however, there is no relationship shown here because of its extremely low R^2 value of 0.05. Figure 7 shows a positive correlation between volume and earthquake depth. Depth ranged from 3.9-9.1 km, and generally increased over time. Figure 8 shows no relationship between volume and depth with an R^2 value of 0.09.

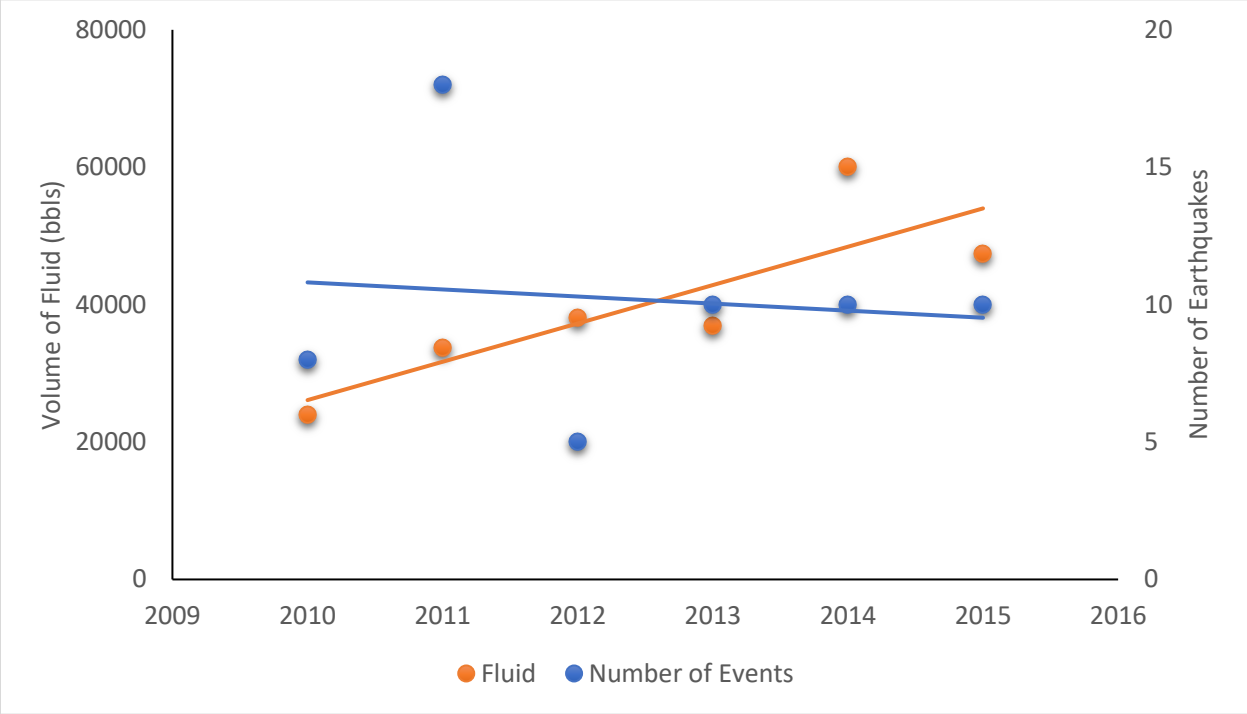


Figure 3. Volume of fluid and number of earthquakes using seismic data from the ODNR in Ohio. Graph depicts an inverse correlation between barrels of fluid and earthquakes.

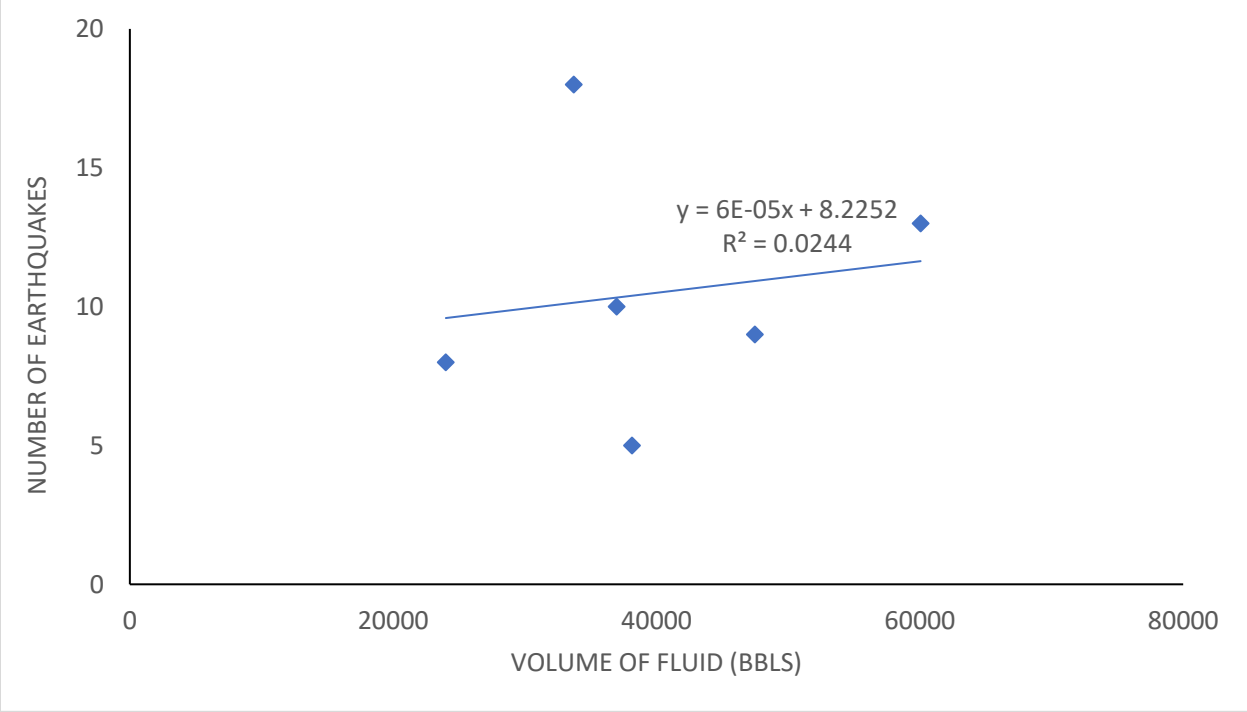


Figure 4. Volume of fluid and number of earthquakes from 2010-2015 in Ohio using ODNR seismic data. R^2 value (0.0244) depicts no relationship between barrels of fluid and earthquakes.

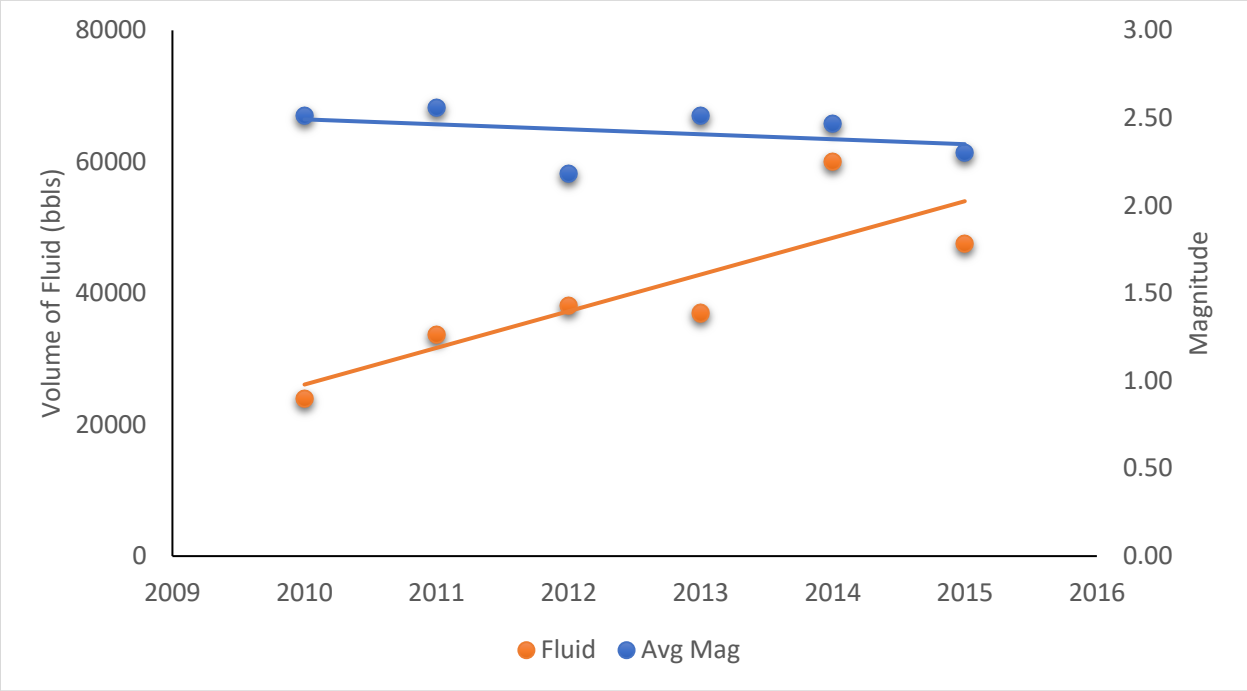


Figure 5. Volume of fluid and average magnitude from 2010-2015 in Ohio using ODNR seismic data. Graph depicts no significant correlation between barrels of fluid and average magnitude.

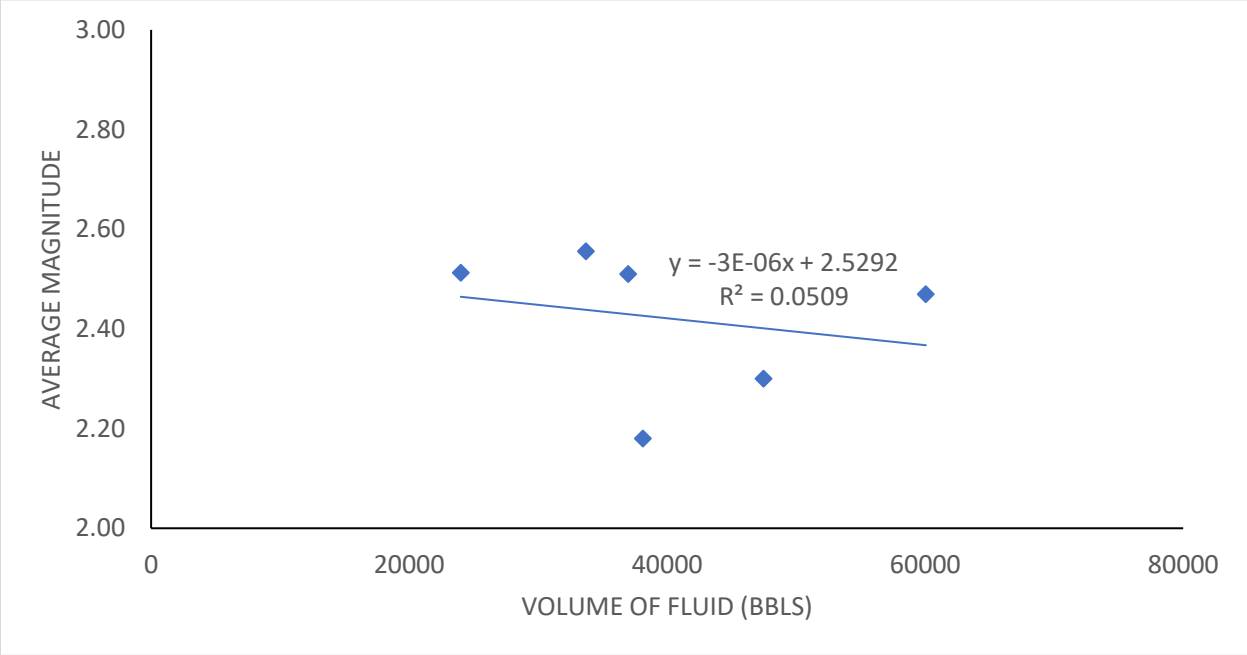


Figure 6. Volume of fluid and average earthquake magnitude from 2010-2015 in Ohio using ODNR seismic data. R^2 value (0.0509) depicts no relationship between barrels of fluid and average magnitude.

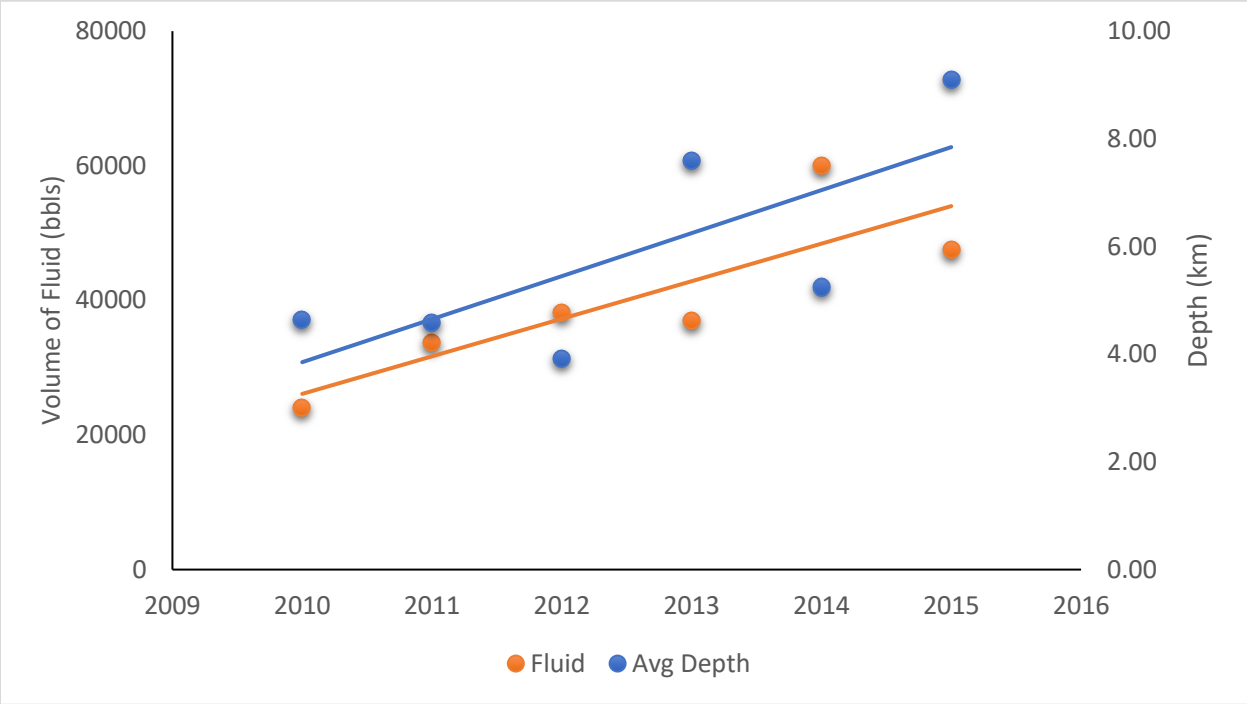


Figure 7. Volume of fluid and average earthquake depth from 2010-2015 in Ohio using ODNR seismic data. Graph depicts a direct correlation between barrels of fluid and average depth.

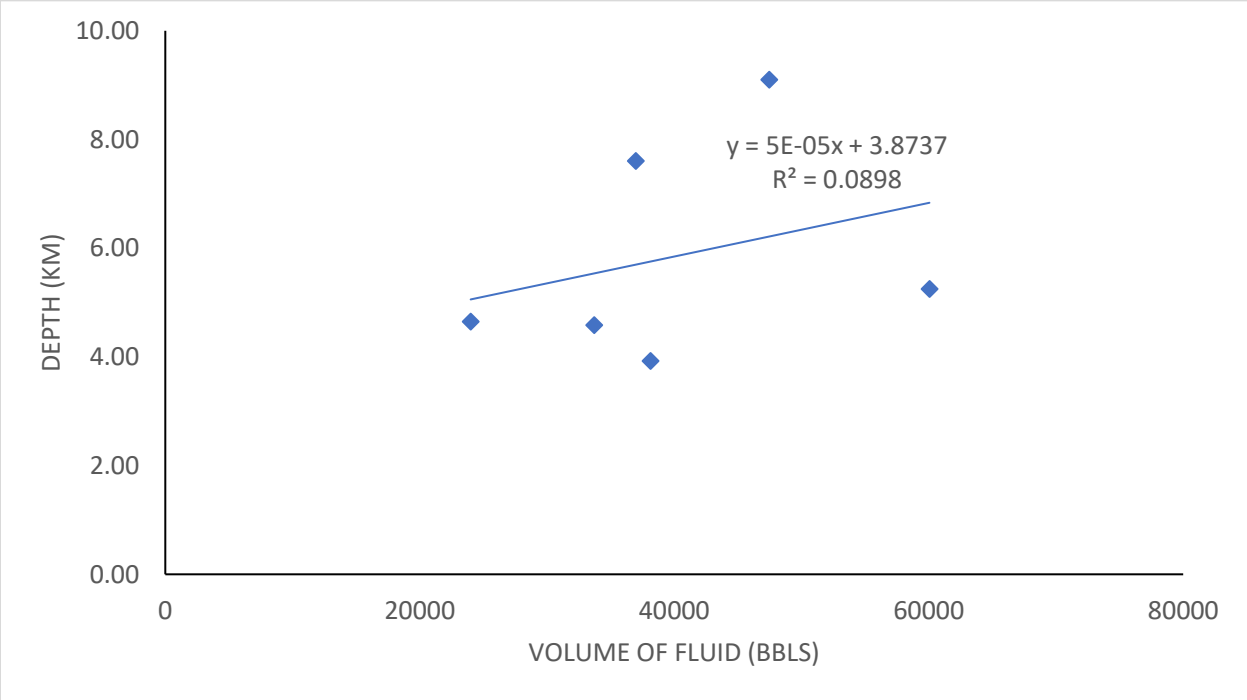


Figure 8. Volume of fluid and average earthquake depth from 2010-2015 in Ohio using ODNR seismic data. R^2 value (0.898) depicts no relationship between barrels of fluid and average depth.

United States Geological Survey Data

The correlations and relationships defined by the graphs using the ODNR seismic data are very similar to the ones present in the graphs using the USGS seismic data. The main difference is that the strength of these relationships is much greater in the data from the USGS, because there is a wider range of data used. This difference is most prevalent in the graphs comparing volume and earthquake magnitude and volume and earthquake depth.

Similar to figures 3 and 4, figure 9 shows an inverse correlation between the number of earthquakes and the volume of fluid. The number of earthquakes range from 5 to 13 and generally decrease over time. There is no relationship among these variables as the trendline in figure 10 is close to zero and the R^2 value is extremely low at 0.02. Figure 11 also shows an inverse correlation but between volume of injected fluid and the average magnitude of earthquakes annually. Generally, average magnitude decreases over time but only slightly as the values only range from 2.1-2.8. Figure 12 shows a very strong negative relationship ($R^2 = 0.608$) between these two variables as average magnitude decreases as more fluid is injected. Similar to figure 7, figure 13 shows a direct correlation between fluid volume and average earthquake depth with a range of 5.0-8.9 km. Consequently, Figure 12 shows a moderately positive relationship between these two variables with an R^2 value of 0.159.

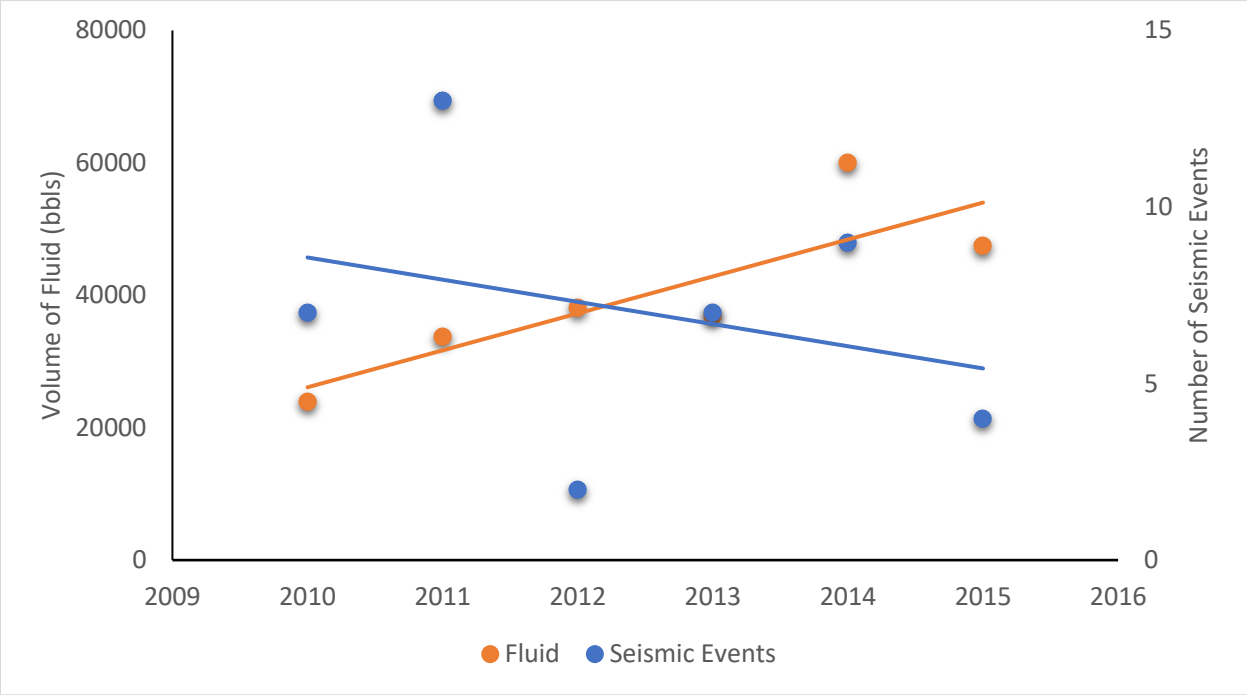


Figure 9. Volume of fluid and number of seismic events using USGS seismic data from 2010-2015 in Ohio. Graph depicts an inverse correlation between barrels of fluid and seismic events.

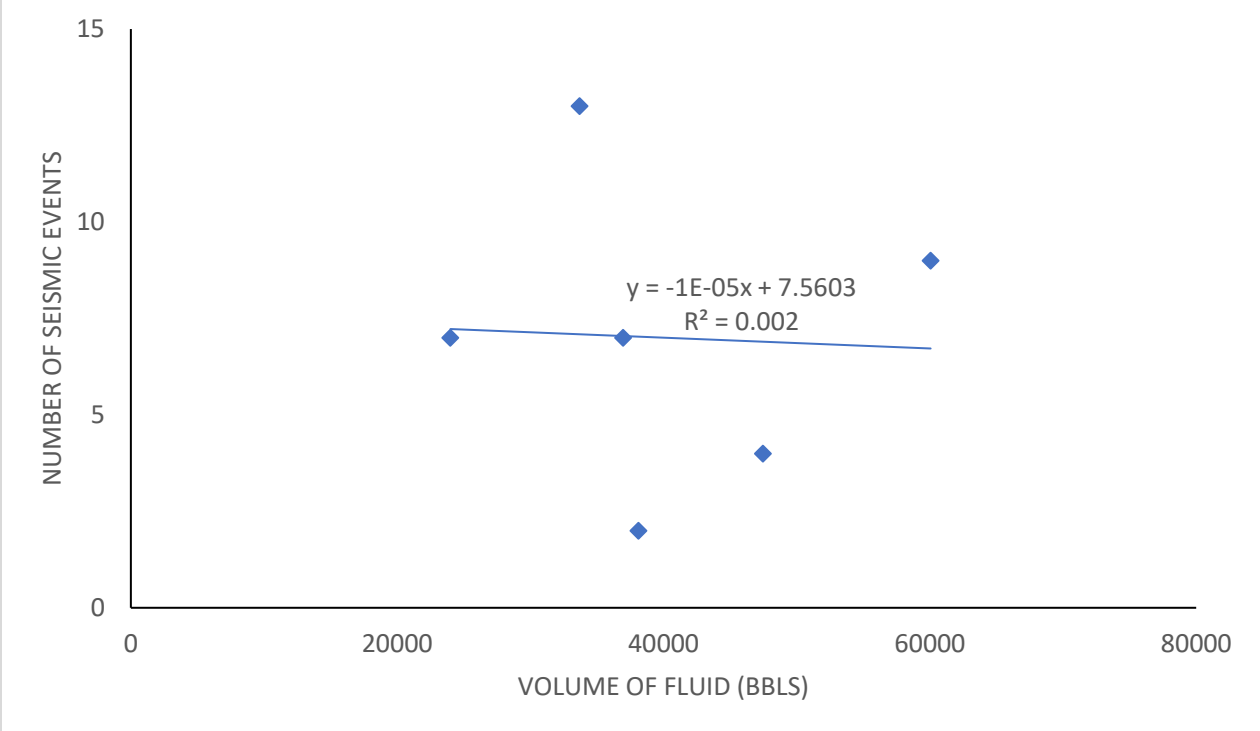


Figure 10. Volume of fluid and number of earthquakes from 2010-2015 in Ohio using USGS seismic data. R^2 value (0.002) depicts no relationship between barrels of fluid and seismic events.

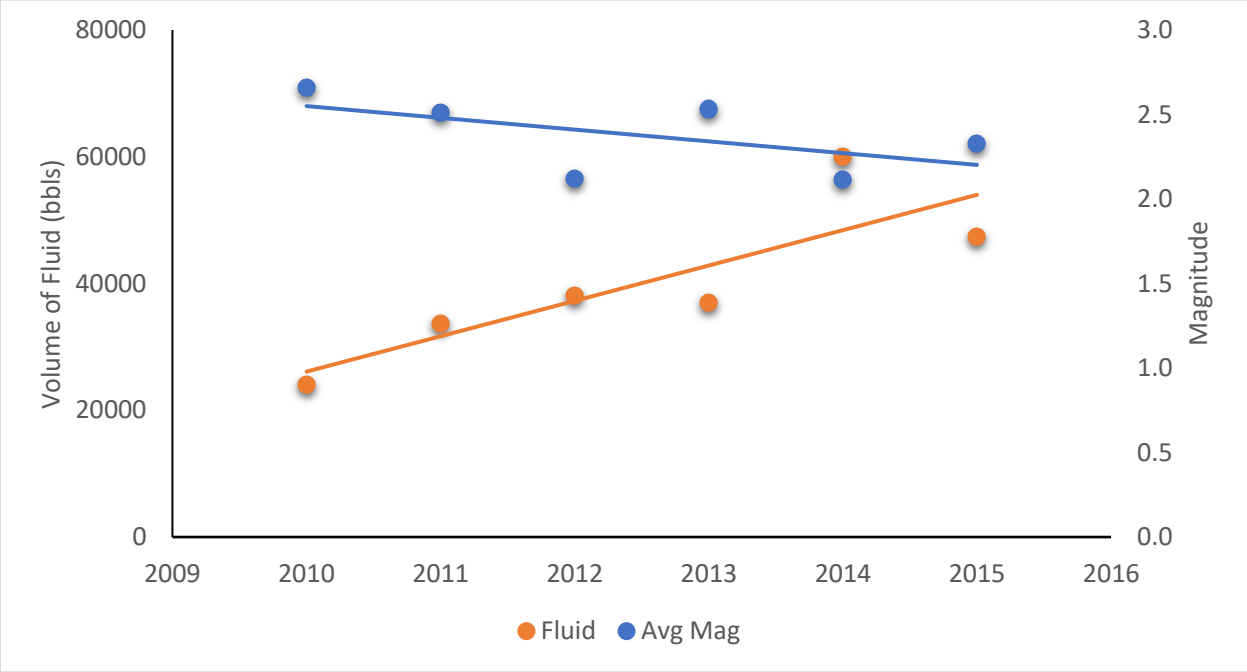


Figure 11. Volume of fluid and average magnitude from 2010-2015 in Ohio using USGS seismic data. Graph depicts an inverse correlation between barrels of fluid and average magnitude.

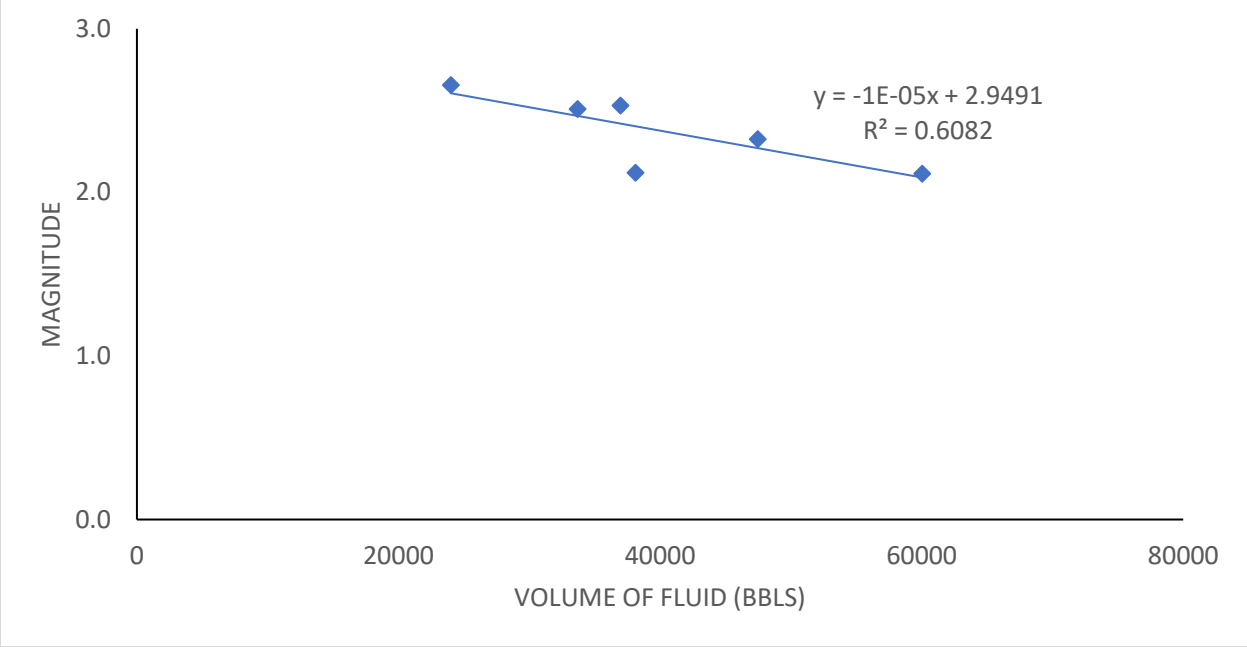


Figure 12. Volume of fluid and average earthquake magnitude from 2010-2015 in Ohio using USGS seismic data. R^2 value depicts a significant relationship between barrels of fluid and average magnitude.

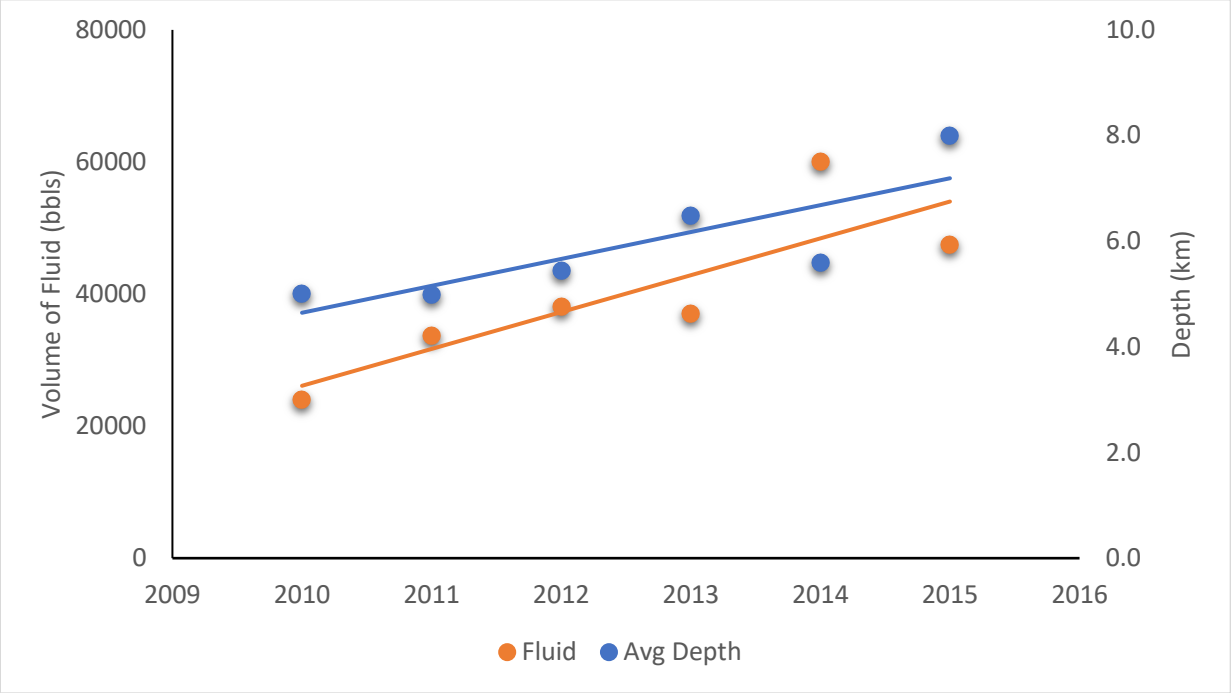


Figure 13. Volume of fluid and average earthquake depth from 2010-2015 in Ohio using USGS seismic data. Graph depicts a direct correlation between barrels of fluid and average depth.

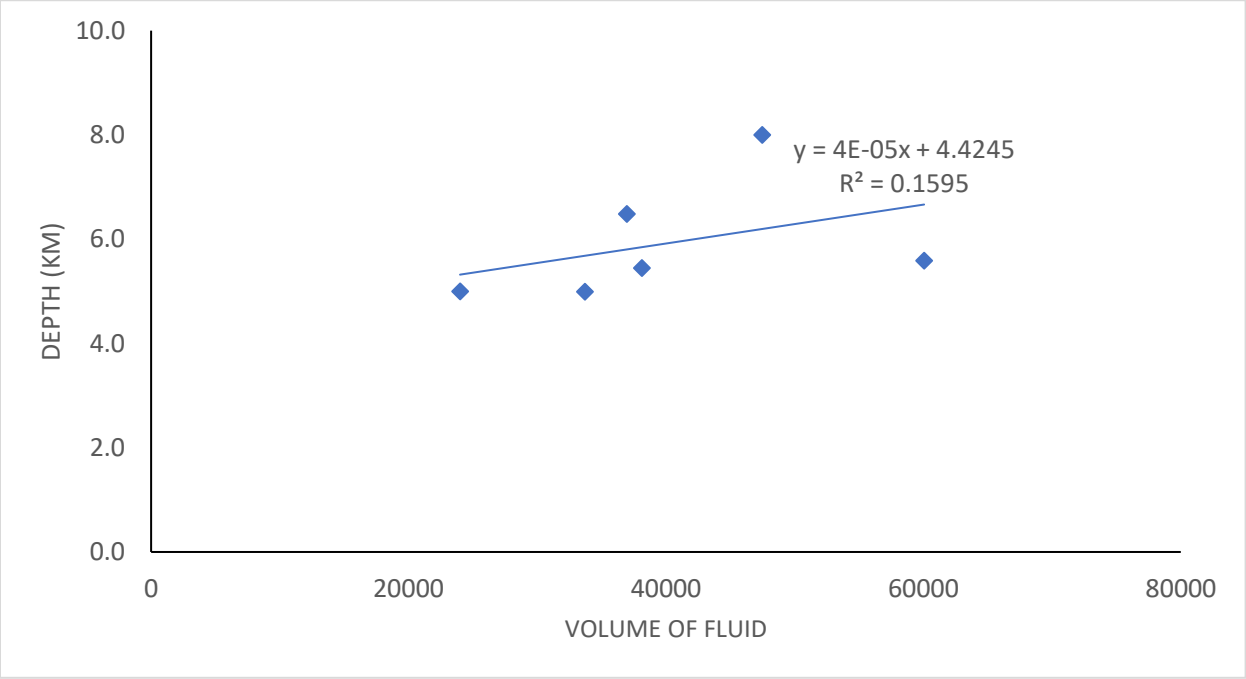


Figure 14. Volume of fluid and average earthquake depth from 2010-2015 in Ohio using USGS seismic data. R^2 value (0.1595) depicts a moderate relationship between barrels of fluid and average depth.

Discussion

The spatial distribution of wells to earthquakes exhibited by figures 1 and 2 is important to consider because it pinpoints specific locations throughout Ohio that may be more prone to induced seismicity than others. The depth of wells in relation to the subsurface geology is important to consider as well. Precambrian basement faults run throughout the state of Ohio and in general coincide with the location of earthquakes. Some of the deeper wells in the state could very possibly be drilled into this basement fault which could in turn reactivate basement faults. For most wells drilled into the Paleozoic sedimentary rock, which overlies the Precambrian age rock, overburden stress from the weight of the wastewater could also reactivate deeper faults. This is significant because while most of what is directly injected into the wastewater wells may not reach the Precambrian faults, the weight of the fluid could indirectly cause earthquakes to occur deeper in the subsurface. These maps also allow for future hypothesis to be made about where seismic events could likely occur in the future based on well location and subsequent wastewater volumes. Specifically, small regions in Mahoning and Washington counties show clusters of earthquakes in close proximity to a series of injection wells.

The area in Mahoning county is centered around the town of Youngstown which has seen induced seismic events in the past. In 2011, twelve events greater than magnitude 1.8, the highest being magnitude 3.9, were documented in the Youngstown area where no known earthquakes had occurred in the past (Kim, 2013). It was concluded that the injection of wastewater increased pore pressure along a fault system located close to a specific well that caused a series of induced seismic events over a 14-month time span (Kim, 2013). This is significant because it shows that wastewater injection can cause induced seismicity in areas that have not seen seismicity in the past. This also suggests that the cluster of earthquakes centered around four disposal wells in

southern Washington County likely were due to the injection of wastewater. Earthquake magnitudes in Ohio on average range anywhere from 1.0 to 2.8 which suggests that not much damage is associated with these events.

This relationship is also present in other parts of the United States. Oklahoma has seen more large magnitude earthquakes due to deep injection drilling than any other area recently. In November of 2011, a magnitude 5.7 earthquake was documented in Oklahoma that was felt across 17 states (Keranen et. al., 2013). It was concluded that the increase in injected fluid volume over an 18-year period decreased the effective stress on faults in the area, producing two earthquakes greater than 5.0 and a large sequence of aftershocks (Keranen et. al., 2013). This is indicative of what could potentially happen in Ohio in the future because from 2010-2015, Ohio also saw an increase in injection volume. This is a much shorter period than what was observed in the Oklahoma study; however, if injection volumes continue to rise, Ohio could see significant earthquakes in the future. It is important to note; however, that the subsurface geology of Ohio and Oklahoma are drastically different. Rocks formed at every geologic time period throughout history are exposed at the surface in Oklahoma which shows just how tectonically active this region has been (Johnson, 2008). This tectonic activity indicates that there is more risk for earthquakes to occur in general regardless of if wastewater is being disposed of or not

To better predict these earthquakes, it is important to look at how injection volume affects certain seismic variables such as the number of earthquakes, magnitude, and depth. There were no significant relationships that occurred between fluid volume and any of the seismic variables based on data from the ODNR given the extremely low R^2 values. Conversely, the data from the USGS produced two significant relationships when compared to the volume of injected fluid over time. As volume increased, the magnitude of earthquakes decreased over time (Fig 12)

which was surprising because McGarr (2014) suggests that as the volume of injected fluid increases over time, so does the magnitude of earthquakes. McGarr looked at 18 different events from around the world to see the affect of volume of injected fluid on magnitude. He compared earthquakes that were scientifically proven to have been caused by fluid injection. This difference can be explained using the next significant relationship between fluid volume and depth (Fig 14), Over time, as fluid volume increases, the depth of earthquakes also increase. So, an earthquake that occurs at a deeper depth will cause less shaking at the Earth's surface than the same earthquake would at a shallower depth resulting in a lower recorded magnitude by seismometers (Open Hazards Group, 2009).

Ohio is at risk for induced seismicity due to wastewater injection, and there have already been documented cases of this relationship in areas such as Youngstown, Ohio. One way to mitigate this effect would be to put caps on injection volumes and injection rates (Ellsworth, 2013). Since induced seismicity is strongly correlated with higher fluid volumes and greater depths, regulations on these factors could help prevent earthquakes in the future. Also, having a magnitude threshold for certain wells could be beneficial, meaning if a certain injection well is associated with producing an earthquake above a certain magnitude in an area, then it should be shut down (Ellsworth, 2013).

One limiting factor of this study was that it only included fluid data from 2010-2015, because that was the only data publicly available provided by FracTracker. This is a small sample size considering waste water disposal has been occurring since the 1950's (Wickstrom et. al.). Another possible limiting factor was the accuracy of earthquakes prior to the establishment of modern seismometers in Ohio. Seismic events from the 1950's 60's and 70's may not have exact values for magnitude, depth, and location because the instrumentation wasn't as advanced

as it is in the modern day. Finally, the last limiting factor was that USGS seismic data included a smaller number of earthquakes that the ODNR data did even though it included earthquakes from a wider range of magnitudes (everything greater than 1.0). This discrepancy occurred because I did not clearly define the Ohio state line that ran through Lake Erie when taking data from the ODNR and USGS sites.

Earthquakes in Ohio have occurred for centuries and will continue to occur along faults throughout the state. This correlative paper discusses the extent to which wastewater injection causes seismicity and the implications that go along with it. Future studies should be done to further explore how wastewater injection further influences seismicity.

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