Using GIS to Explore the Spatial Relationships between Wastewater Injection Wells and Earthquakes in Oklahoma, 2010-2014

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Abstract

The use of hydraulic fracturing technology to extract oil and natural gas has expanded in the last decade within the United States and elsewhere. The extraction process produces large volumes of wastewater as a byproduct, much of which is disposed of by injecting it into the deep subsurface through wells (known as Class II wells, or simply injection wells). Recently, increases in hydraulic fracturing and wastewater injection has seemingly coincided with an unprecedented rise in earthquake events in the state of Oklahoma, which are believed to be caused in part by wastewater injection and the subsequent increase in pressure on faults (Andrews, 2015). Locations of injection wells and earthquakes were analyzed and compared using a variety of spatial analysis tools to explore relationships between the seismic occurrences and injection well locations. Lithology data was used to examine the rock types in which significant earthquakes occurred and whether there was any dominant geology at these locations and similarities between the rock types associated with injection wells and earthquakes. Finally, earthquakes were examined in the context of major population centers within the study area, particularly Oklahoma City.

Introduction

Although the phenomenon of increasing mid-continent earthquakes has gained attention in recent years (Keranen, Savage, Abers, and Cochran, 2013), researchers found that injecting fluids into the subsurface could trigger earthquakes as early as the 1960s (Frohlich, 2012). Earthquakes were extremely uncommon in Oklahoma until hydraulic fracturing reached high levels in recent years. With the rapid rise in oil and gas development, earthquakes that are detectable by humans without instrumentation began to occur (Frohlich).

According to the Oklahoma Geological Survey, the rates of seismicity and changing geographic pattern are highly unlikely to be due to natural processes; rates of earthquake occurrence in the state is 600 times higher than historical background levels (Andrews, 2015). It is believed that earthquakes are being triggered not by the initial hydraulic fracturing process but by the subsequent wastewater injection into wells. Increased seismicity has been observed to follow large volumes of water injection; there is usually a time delay between injection and an earthquake event, varying between several weeks to a year or more (Andrews).

Holland (2013) notes fluid-induced seismicity can often be identified by spatial proximity and multiple temporal correlations between the wastewater injections and earthquake events. These

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cases involve fluid injection over a longer period of time than the average hydraulic fracturing event, lending more evidence to the idea that it is the wastewater injection process inducing earthquakes rather than the hydraulic fracturing process. Earthquake triggering caused by fluid injection occurs when the pore pressure exceeds a critical threshold (Keranen *et al*., 2013). This makes the volume of wastewater injected an important factor in the potential triggering of an earthquake. Frohlich (2012) found injection rates exceeded 150,000 barrels of water per month (BWPM) near most earthquakes in a Texas study. Figure 1 diagrams a generalized oil and gas production well and a brine disposal (injection) well.

Areas that experience suspected induced earthquakes are also at a higher risk of seismic activity from natural stresses and large remote earthquakes. Susceptibility to remote triggering can indicate that the fault system in the area is critically stressed (van der Elst, Savage, Keranen, and Abers, 2013). With the rise in earthquake frequency, Oklahoma has also experienced an increase in the magnitude of some earthquakes. The largest earthquake measured to date occurred near Prague, Oklahoma in November of 2011 with a magnitude of 5.7 M_w and two aftershock events both measured at 5.0 M_w (Keranen *et al*., 2013). The primary earthquake could be felt in 17 states and destroyed 14 homes, damaged numerous other buildings and caused injury to two people (Keranen *et al.*, 2013). The magnitude of induced earthquakes also appears to be related in large part to the overall volume wastewater injected into wells (McGarr, 2014). The greater the volume of water, the greater the pressure on faults. Figure 2 illustrates a schematic of a generalized reservoir response to injection pressure.

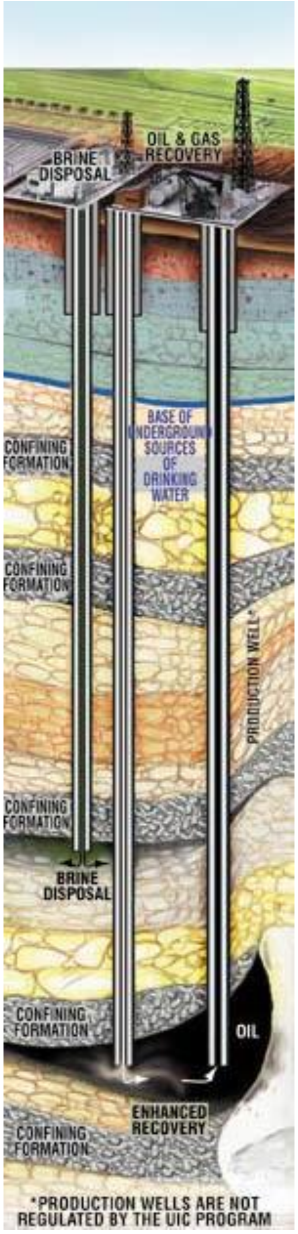

Figure 1. Diagram showing a production well and a class II injection well (Environmental Protection Agency, 2016). On the right side of the figure is the oil and gas production well and on the left a slightly shallower Class II disposal well where brine water and other fluids are injected underground.

Even though the injection pressure remains the same at the wellbore (surface pressure), the pressure at the fault will continue to rise until it is released in an earthquake unless fluid injections are not ceased before the fault reaches this critical point.

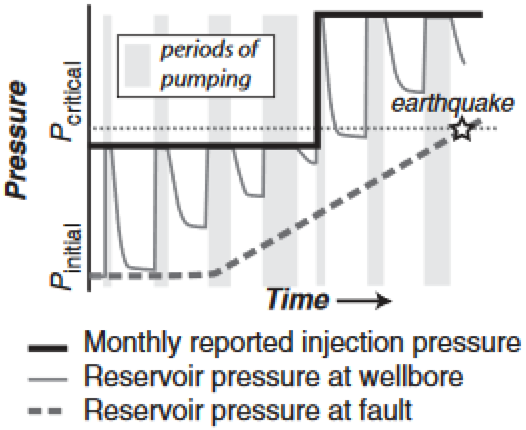

Figure 2. Injection Pressure and Reservoir Pressure at Fault (Reproduced with permission Keranen *et al.*, 2013). The graph shows pressure at the fault increasing over time and as injection pressure increase.

Study Area

The state of Oklahoma was selected for the study area due to the high levels of hydraulic fracturing as well as increased seismic events in the area. The time-period of the data analyzed is 2010-2014. This timeline was selected because it covers the beginning and peak of the phenomenon. The Great Plains region seismicity makes this an interesting location and time-period to explore with spatial analysis.

Methods

This study examines fundamental spatial relationships between wastewater injection wells and earthquakes. This study does not address other factors of geologic nature that could influence seismic events. As such, the methodology contained in this work examines only a few variables for consideration. Hydraulic fracturing occurs in areas across the United States, but only a few areas have experienced earthquakes associated with the activity. The major datasets used for this analysis were point data – the location of disposal wells and the location of earthquakes. Tabular data included in these shapefiles were also important in the data preparation process and performing analysis in GIS. Additionally, lithology and populated areas data were utilized in the study.

Data Preparation and Software

Spatial analysis required two primary datasets: the locations of class II wells and earthquakes recorded in Oklahoma during the study period. Class II wells are used to inject fluids associated with oil and gas production into the subsurface (Frohlich, 2012). These data were acquired from the University of Oklahoma and the Oklahoma Geological Survey Observatory.

The Oklahoma geologic shapefile was acquired from the United States Geological Survey (USGS, 2005). This shapefile includes the lithology across the entire state, including the primary rock type. The lithology was symbolized using the style file provided by the USGS.

Population center data (specifically urban areas) were acquired from Natural Earth (2016) in order to examine the most vulnerable populated areas based on the location of earthquake events in the study period.

Data Pre-Processing

Injection well location data were acquired as a spreadsheet plotted in Esri’s ArcMap software using coordinate data and then transformed into a shapefile. The earthquake shapefile was then reduced to seismic events which had a magnitude of 3 M_w or greater (Figure 2). This was done to select only those earthquake events that are detectable by humans and could cause significant damage (Frohlich, 2012).

Population center data was clipped to Oklahoma state boundaries to simplify further analysis. Next, ArcGIS 10.3.1 and QGIS 2.14.3 software were utilized to run analysis tools on the shapefile data. Below is a map of the study area plotted with injection well locations and earthquake events (Figure 3).

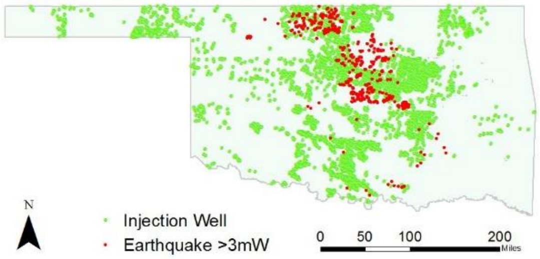

Figure 3. Injection well and earthquake distribution, 2010-2014. Injection wells are displayed in green and earthquakes are displayed in red.

Density Analysis

Point Density

The Point Density tool was accessed from ArcGIS. It creates a raster surface by calculating the magnitude of points within a "neighborhood" or a number of individual cells. This tool was run twice – once for earthquake events and another time for the injection wells layer. This resulted in two raster layers: one displaying the density of wells in the study area, and another showing the density of significant earthquakes in the same area. By eliminating earthquakes with magnitudes below 3 M_w in the analysis, the density of the more powerful earthquakes is revealed. All of the injection wells were used in this analysis.

Kernel Density

The Kernel Density tool is another option available in ArcGIS. It works slightly differently than Point Density in that it computes the density of points in a neighborhood surrounding each point. This tool was used on both the injection well and earthquakes in order to compare differences between results of the Point Density tool. This tool was utilized in order to examine whether the calculation method delivered a more or less conservative approximation of density in the output using the same input data as used in the Point Density analysis.

Rock Type Analysis

In order to gain a better understanding of the geological composition where significant earthquakes occurred, a spatial join was performed between the significant earthquakes layer and the Oklahoma geology layer. This produced a layer consisting of the rock type of each significant earthquake in the attribute table; summary statistics were calculated from this data. A spatial join was also performed between the lithology layer and the injection well layer. This allowed for comparison between the two datasets by making it possible to calculate the number of injection wells and earthquakes present in each lithologic type in the study area.

Microsoft Excel was used to process the data produced through the spatial join. The count of earthquakes and injection wells were added to pivot tables with the rock type for each record. From here, percentage contributions of each rock type were calculated. The percentage contribution of rock types could then be compared between the earthquake and well layers to see whether they are similar or dissimilar.

Urban Area Analysis

In order to explore the greatest potential threats (loss of life, damage to property) posed by earthquakes, an intersection was applied to the significant earthquakes layer and the urban areas layer to identify earthquake events that occurred in densely populated areas. This analysis used urban areas as a proxy for potential damages as these areas have higher concentrations of populations and structures. These earthquakes were also compared to the underlying lithology.

Results

Density Analysis

The four rasters created by the density tools showed appreciably different extents using the same input data; by visually comparing the Point Density and Kernel Density outputs, it is evident that the Kernel Density tool uses a more conservative approach to calculating density. Individual results are discussed in greater detail in the following sections.

Injection Well Point Density

Results of the Point Density analysis of injection wells yielded a few clusters with medium to high density, with the greatest density occurring in the far south-central part of the study area (Figure 4).

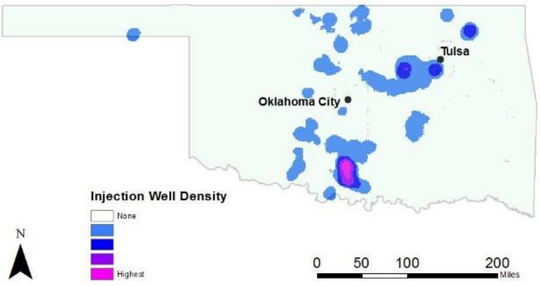

Figure 4. Injection Well Density. The colored polygons represent the degree of injection well density, where the purple and pink areas indicate the greatest concentration of wells.

Earthquake Point Density

Results suggest significant earthquakes occurred in a relatively limited geographic extent in the study area, with the greatest density occurring near Oklahoma City (Figure 5). The Point Density analyses reveal some interesting differences between the injection well and earthquake layers. Based on the density of injection wells in Figure 4, one may expect the area around Oklahoma City would be unlikely to experience earthquakes, whereas the area west of Tulsa and the southern portion of the state would likely experience more earthquakes.

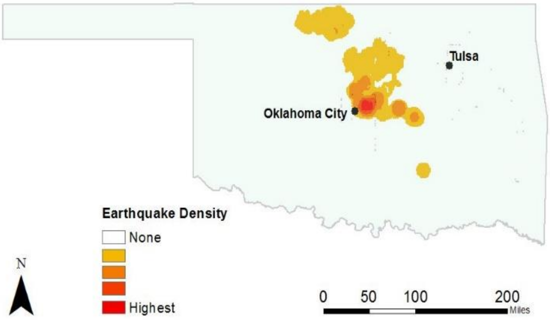

Figure 5. Earthquake Point Density Results (events ≥ 3 M_w in magnitude). The figure shows the earthquake density in the study area as calculated by the Point Density tool.

However, results seem to support an opposite effect. This seems to indicate there are more factors to explore relating to the relationship of localized earthquakes than just the density of injection wells in an area.

Injection Well Kernel Density

Figure 6 highlights results of the Kernel Density analysis conducted on the injection well layer (Figure 6). The Kernel Density tool produced a much smaller area of high density areas than the Point Density tool. However, the greatest density of clustering of injection wells shared some spatial consistency between the Point Density and Kernel Density results – particularly in the location of the cluster in the south-central portion of the study area. The distinct results are significant whether they are used to produce maps which communicate relative earthquake risk to the public or are used to perform further analysis with the calculated datasets.

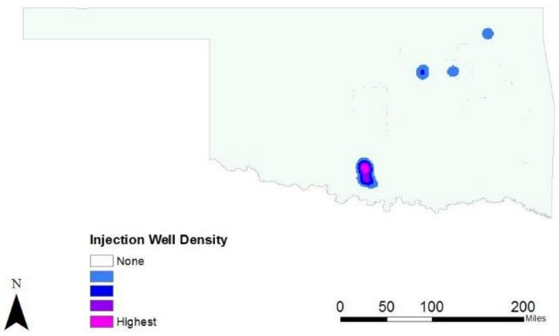

Figure 6. Injection Well Kernel Density Results. The purple and pink clusters represent the highest density of Class II wells as calculated by the Kernel Density tool in ArcMap.

Earthquake Kernel Density

Figure 7 illustrates the output of the Kernel Density analysis on the earthquakes layer.

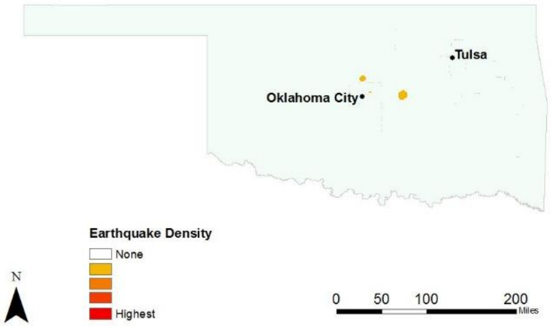

Figure 7. Earthquake Kernel Density Results (events ≥ 3 M_w in magnitude). The Kernel Density output contains only two small clusters with a relatively low density.

The Kernel Density produced a smaller area with a high occurrence of earthquakes compared to the Point Density analysis due to the distance between earthquakes. This result is meaningful for the example of communicating data through maps discussed earlier, as well as for any further analysis which uses the raster data as an input.

Rock Type Analysis

Figure 8 illustrates the significant earthquakes layer overlaid on a map of Oklahoma lithology. Based on the spatial join, summary statistics were generated in Microsoft Excel.

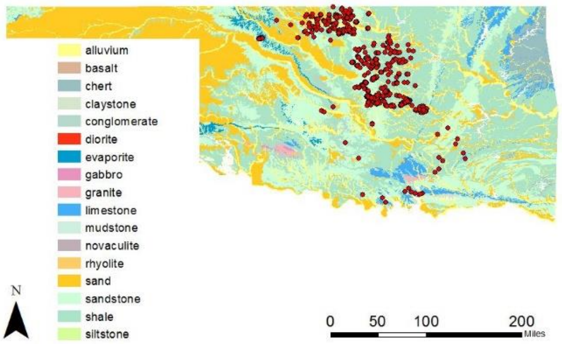

Figure 8. Oklahoma Lithology Map and Significant Earthquakes. This figure displays earthquake events as points and the major rock types in which they occur.

Table 1 displays summary statistics tallying the number of earthquakes found within percentages of rock type.

Table 1. Count of Earthquakes by Major Rock Type.

Rock Type	Earthquake Count	% of Total
Shale	370	41.86
Sandstone	304	34.39
Alluvium	123	13.91
Sand	71	8.03
Siltstone	7	0.79
Claystone	3	0.34
Evaporite	3	0.34
Limestone	2	0.23
Water	1	0.11

Shale was the largest percent in which earthquakes were present. Shale and sandstone accounted for over 75% of significant earthquake events during the study period, while alluvium and sand accounted for just over 20% with the remaining rock types contributing a negligible amount. The same process was repeated with the injection wells layer to explore the proportion of geology types. Figure 9 shows the injection wells distribution across lithology.

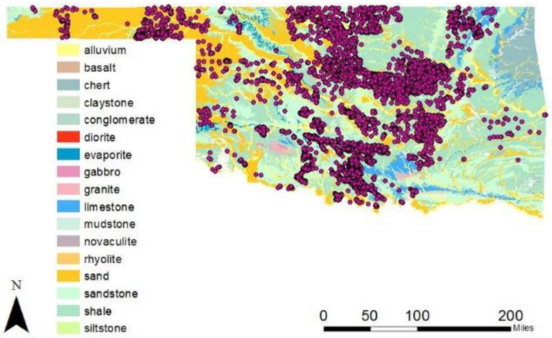

Figure 9. Oklahoma Lithology Map and Injection Well Distribution. The figure shows locations of Class II wells and the underlying rock type in the study area.

Since there are more injection wells over a wider spatial extent, the results were expected to be more diverse than the earthquake layer. Using Microsoft Excel, the same summary statistics were generated with a pivot table (Table 2).

Table 2. Count of Injection Wells by Major Rock Type.

Rock Type	Count of Injection Wells	% of Total
Shale	7775	47.58
Sandstone	4796	29.35
Alluvium	1774	10.86
Sand	1523	9.32
Limestone	210	1.29
Evaporite	95	0.58
Water	67	0.41
Conglomerate	47	0.29
Siltstone	45	0.28
Dolostone (dolomite)	6	0.04
Carbonate	1	0.01
Claystone	1	0.01

The percentage makeup of injection wells per rock type was quite similar to the results of the earthquake analysis. The four largest rock type contributors to the total were the same, and followed the same respective order. Injection wells were more common within the shale rock type; shale formations are frequently associated with hydraulic fracturing.

Urban Area Analysis

During the five-year study period, seven earthquakes occurred within two urban areas in the state: six in Oklahoma City (metro population of 1,358,452 in 2015) and one earthquake in the city of Stillwater (micropolitan statistical area population of 78,399 according to the 2012 census) (United States Census Bureau, 2015). Figure 10 displays the six earthquakes within the Oklahoma City metropolitan area and their magnitudes.

The central yellow polygon represents the Oklahoma City metropolitan area (the polygon just to the south is Norman, Oklahoma). All six of the earthquake events ≥3 M_w that occurred during the study period are clustered in a relatively small area in the eastern part of the city, raising questions about the geology in this region. The location of these earthquakes was compared to the underlying lithology (Figure 11). Fault lines were plotted in ArcMap (not pictured) and there were none in this particular region.

Four earthquakes occurred in a sandstone subsurface, while two occurred within an alluvium subsurface. It is interesting that no documented earthquakes occurred within the shale formations to the west of the earthquake cluster, as this is the most common rock type where earthquakes occurred.

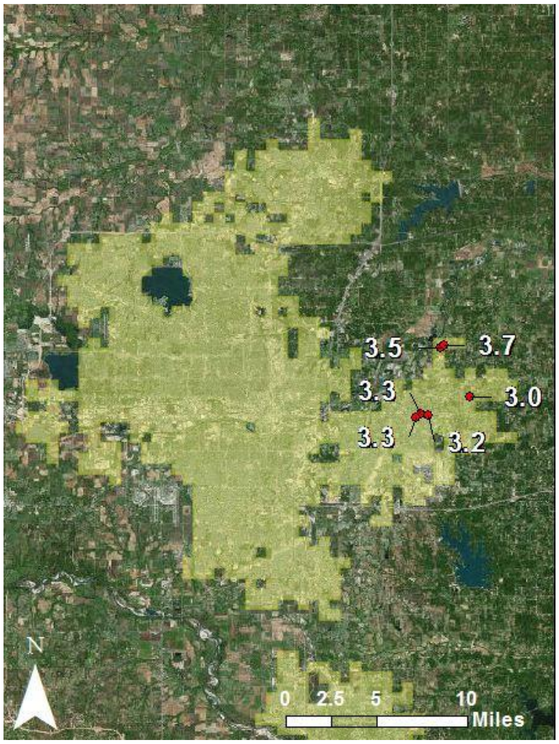

Figure 10. Earthquakes in Oklahoma City, 2010-2014. The light green areas represent urbanized areas; in this figure, the major polygon is the Oklahoma City metropolitan area. Values displayed are the magnitude (Mw) of seismic events (red points).

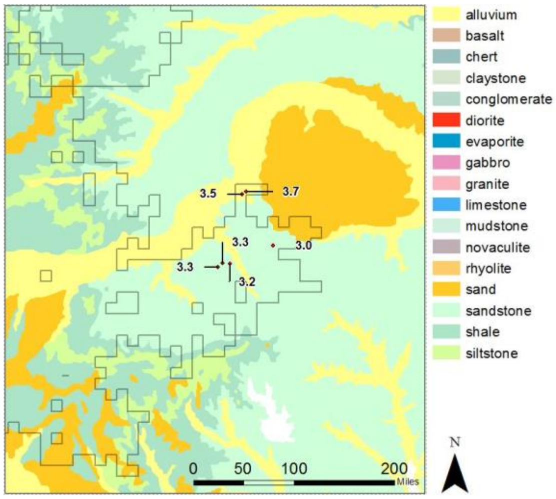

Figure 11. Local lithology of earthquakes within Oklahoma City metropolitan area. The earthquakes occurred in or near a sandstone rock formation.

Discussion

Spatial Analysis

Various spatial analysis tools from ArcGIS were used to characterize the spatial relationships between injection wells and selected earthquake events.

Density Tools

There are many factors that were not taken into account in this analysis, including volume of wastewater injected, frequency of injections, and specific geologic conditions at both the well and earthquake sites. Point Density analysis has some limitations, but is useful for visualizing the overall geographic distribution of injection wells and earthquake events.

Point Density analysis may be useful in helping to explore future seismic events within a more robust model. A density analysis should be used in conjunction with additional spatial and geologic analysis in order to produce more robust results. Accessed literature did not provide well defined methodology to achieve this, which provides opportunity for further studies.

Kernel Density analysis produced a significantly different result from the earthquake dataset than Point Density did. Prior to the analysis, it was expected that the two density methods would produce relatively similar results. If the study period were extended adding additional earthquakes, it would likely increase the extent of the density. Depending on the purpose of the analysis, it would be beneficial to consider which tool is most appropriate for the data involved.

When comparing the results of the two Density tools, the major difference is the spatial distribution of injection wells and earthquakes are dispersed enough across the study area that the search radii of each point do not overlap in the Kernel Density calculation, which would increase density in the output. The search radius is not a consideration in the Point Density tool, which leads to a greater portion of the study area covered by density clusters.

It is important to note the limitations of Density tools in ArcGIS. The most common use for these tools are to improve the visualization of data (Krause, 2013) by creating a raster layer from a larger set of individual points. The output from Density tools should be interpreted using qualitative terms, rather than a literal interpretation (Krause, 2013).

Interestingly, according to the Earthquake Hazard Map produced by the USGS (Figure 12) the density of injection wells (from both density tools) generally aligned spatially with the highest projected earthquake risk areas. It may be the case that examining earthquake phenomenon on a scale such as this may not be significant enough to draw conclusions from current or future events. Each instance may be a unique event and dependent on localized conditions in the subsurface and may or may not be linked to any other earthquakes.

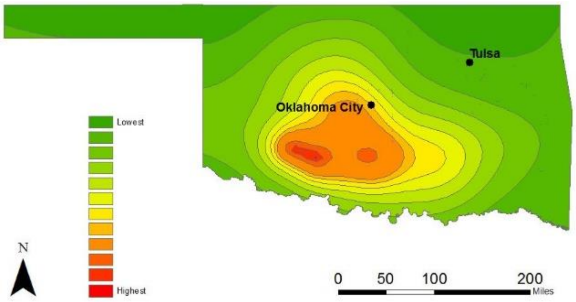

Figure 12. Adapted from USGS earthquake hazard map (United States Geological Survey, 2014). This map estimates the risk of earthquakes across the state.

Rock Type and Earthquakes

The rock type analysis provided some interesting exploratory results. Injection wells and earthquakes were most common within shale formations, with sandstone being the second most common subsurface type. It seems that the lithology chosen for hydraulic fracturing and wastewater injection also may promote fluid-induced earthquakes.

Potential Impacts to Populated Areas

Although Oklahoma is a largely rural state, there remains a potential threat to human life and property posed by fluid-induced earthquakes, particularly in the Oklahoma City metropolitan area, which experienced an average of more than one earthquake per year with a magnitude ≥ 3 M_W during the study period.

There has yet to be an earthquake of significant magnitude to cause severe widespread damage in the state. Understanding the spatial dimensions of fluid-induced earthquakes could provide valuable information on the potential threat levels across the study area.

Further Study

As the phenomenon of fluid-induced earthquakes is a relatively recent one, further studies are needed to gain a better understanding of the link between the two. Oil and gas producers have greatly cut back on production as the cost of oil has plummeted since the end of the study period. It would be interesting to compare the time period of this analysis with more recent data as it becomes available to see if induced earthquakes are occurring less frequently with a reduction in hydraulic fracturing and wastewater injection.

In addition to the surficial analysis performed, additional geologic information could be incorporated to potentially create a more predictive model of future seismic activity. There are no major active faults in Oklahoma, so it would require a more nuanced approach including measures of fault stress levels, soils and local hydrology.

Beyond the basic science, planners and emergency management officials should use spatial data analysis in order to determine areas of greatest risk to human life and property and to implement mitigation efforts. Vulnerable buildings and infrastructure could be identified and prioritized for retrofitting or replaced if necessary. Infrastructure such as gas and water lines could be included in this type of analysis as they could contribute to more dangerous outcomes such as fires and flooding if damaged during a seismic event.

Conclusion

The spatial analyses conducted in this study was not intended to specifically link occurrences of earthquakes to the use of wastewater injection wells, which is the current popular hypothesis of the Oklahoma Geological Survey (Andrews, 2015). However, GIS analysis did provide exploration for the visualization and general spatial characterization of the problem.

This study helped to narrow the direction of future spatial analysis on the topic. The use of lithology and spatial joins with injection wells and significant earthquakes provided some interesting results. Point Density analysis was an interesting method for characterizing the spatial distribution of features and events, but the density of injection wells did not correlate with the density of earthquake events.

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