Unraveling the Mysteries of Seismicity in Oklahoma
A Story Map
Why create a story map?

- Visualization of various types of data (graphics, text, symbols, etc.) within a geographical context to enhance story telling

- Allows for easier comprehension and conceptualization of complex problems

- Useful for identifying key patterns in natural and human systems
  - Example: Sea level rise and storm surge effects on energy assets

- ArcGIS Online provides web application templates to create story maps
• Over 17,000 earthquakes recorded in Oklahoma since 1882.
• Over 15,000 of these earthquakes were recorded after the beginning of 2008.
• Seismicity rate is now 600 times greater than the background seismicity rate.
• Most, but not all of these earthquakes are occurring as swarms (Andrews & Holland 2015).

Suggests the increase in seismicity is unlikely due to natural forces alone.
Research suggests this is mainly caused by the increase in the amount of wastewater injected into the subsurface, but does not account for all earthquake events.

What are these other earthquake factors that are present within Oklahoma?
Objectives

The goal of this project is to create a story map through ArcGIS Online to provide a better understanding of the recent increase in seismicity in Oklahoma. This will be accomplished by reviewing literature, exploring, and performing analyses on key datasets to explain:

1. The onset of the increase of seismic activity after 2008
2. Earthquake history (before 2008)
3. The risk to the population
4. How earthquakes happen
5. What natural and anthropogenic earthquake factors have been known to cause earthquakes within and outside of Oklahoma
6. If any of the earthquake factors have any spatial correlation with the earthquake data, individually or cumulatively
# Key Datasets

<table>
<thead>
<tr>
<th>Natural</th>
<th>Earthquake Factors</th>
<th>Relevant dataset(s) and sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>Surficial geology (United States Geological Survey) Faults (Oklahoma Geological Survey)</td>
<td></td>
</tr>
<tr>
<td>Hydrologic conditions</td>
<td>Aquifers (Oklahoma Water Resources Board) Rivers and Streams (Oklahoma Water Resources Board) Lakes (Oklahoma Water Resources Board) Heavy rain events (National Oceanic Atmospheric Administration)</td>
<td></td>
</tr>
<tr>
<td>Earthquake triggering</td>
<td>Remote earthquakes- layer covering state that represents uniform spatial influence (US Census Bureau) Local earthquakes- Oklahoma earthquakes before 2008 (Oklahoma Geological Survey)</td>
<td></td>
</tr>
<tr>
<td>Regional stress field</td>
<td>layer covering state representing uniform spatial influence (US Census Bureau)</td>
<td></td>
</tr>
<tr>
<td>Solid earth tides</td>
<td>layer covering the state representing uniform spatial influence (US Census Bureau)</td>
<td></td>
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</tbody>
</table>
## Key Datasets

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<th>Anthropogenic</th>
<th>Earthquake Factors</th>
<th>Relevant datasets and sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fluid injection</td>
<td>Class II injection wells (Oklahoma Corporation Commission)</td>
</tr>
<tr>
<td></td>
<td>Hydraulic Fracturing</td>
<td>Hydraulic fracturing wells (IHS Inc.)</td>
</tr>
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<td></td>
<td>Groundwater extraction</td>
<td>Groundwater wells (Oklahoma Water Resources Board)</td>
</tr>
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<td></td>
<td>Mineral resource operations</td>
<td>Coal Mines (Energy Information Administration)</td>
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<td></td>
<td>Oil and gas production</td>
<td>Mines and mineral plants (United States Geological Survey)</td>
</tr>
<tr>
<td></td>
<td>Reservoir impoundment</td>
<td>Dams (Oklahoma Water Resources Board)</td>
</tr>
<tr>
<td></td>
<td>Urban areas</td>
<td>Urban areas (US Census Bureau)</td>
</tr>
</tbody>
</table>
Application Structure

- Overall framework (yellow box): Tabbed story map series
- Tabs representing story elements in order (green arrows)
- Application templates embedded within tab (light blue)
- Pages or “Sections” within application (light pink)
- Sections explaining the natural (dark blue boxes) and anthropogenic (orange boxes) factors

Earthquake factors that have data overlaid with earthquake density and a hotspot analysis for earthquake magnitude are outlined in red.
Implementation Results

“The Problem”

Landing page for application, discusses
- the recent seismicity
- the problem with current research
Implementation Results

“Earthquake History”

Discusses earthquake history through analysis:

- Directional distribution tool applied on each decade of earthquake occurrences (1950 – 7/22/2015)
- Figure shows table displaying number of earthquakes per decade and a plot displaying earthquake per year (colors correspond to ellipses)
“Earthquake History”

“Before and After 2008”
- 2 heat maps for earthquake location density
  - 1882 - 2007
  - 2008 - 2015
- Plot displays annual earthquake data (1882 – 2015) by:
  - cumulative count
  - earthquake count
  - average magnitude
  - maximum magnitude for entire earthquake catalog

“2008 - 2015”
- 4 heat maps for earthquake location density and same plot for:
  - 2008 - 2009
  - 2010 - 2011
  - 2012 - 2013
  - 2014 - 2015
Used “impact summary” application template to:
- Display interactive map where users can obtain earthquake and population statistics by county on a dashboard (bottom of the screen)
Implementation Results

“How do earthquakes happen?”

Discusses physics and triggering mechanisms earthquakes
“Natural Factors” and “Anthropogenic Factors”

Natural and anthropogenic earthquake factors are examined in their respective tabs by exploring their background, datasets, and case studies through maps and analysis.
Implementation Results - case study example

“Natural Factors”

Case study (Van der Elst 2013) for remote earthquake triggering in “Earthquake Triggering” section

Three large remote earthquakes are thought to have triggered seismicity near Prague, OK

Colored text are links to maps

- Maps zoomed into area around Prague, OK.
- Resulting seismicity up to two weeks after 3 large remote earthquakes
“Anthropogenic Factors”

The map displays well density for all oil and gas production wells (1.5 sq. miles), oil wells (1.5 sq. miles), gas wells (1.5 sq. miles), and oil & gas wells (10 sq. miles). According to the IHS Inc. database, Oklahoma has over 500,000 wells. Of these, there are roughly 250,000 oil wells, 88,000 gas wells, and 1,100 oil and gas wells. This does not include injection, hydraulic fracturing, abandoned, or dry wells. When all oil and gas production wells are overlaid with earthquake density from 2010 to 2015, the strongest spatial correlation seems to be in southern Oklahoma, where the wells are the densest (red color). There does not seem to be much spatial correlation when overlaid with a hotspot analysis for earthquake magnitude from 2010 to 2015.

According to the EPA, Oklahoma has been

Four maps displaying well density in the “oil and gas production” section using “Compare Analysis” application template
The CSIL (Cumulative Spatial Impact Layers) tool (Bauer et al. 2015), developed at the National Energy Technology Laboratories (NETL), was used to examine the cumulative spatial extents for key data sets related to:

- Natural earthquake factors
- Anthropogenic earthquake factors
- All earthquake factors
Implementation and Cumulative Analysis Results

“Cumulative Influences”

“Natural Vs. Anthropogenic”

Map shows cumulative spatial sum of the:

- 10 key datasets relating to 5 natural earthquake factors (left in blue)
- 8 key datasets relating to 7 anthropogenic earthquake factors (right in orange)

“Natural and Anthropogenic Influences”

Map shows cumulative spatial sum of:

- All 18 key datasets related to natural and anthropogenic earthquake factors

For every 100 square mile grid cell
To examine the relationship between the number of earthquakes and the number of earthquake influences (datasets per grid cell) correlation coefficients were determined.

- Earthquake count per grid cell was calculated by spatially joining earthquakes from 2010 – 7/22/2015 to each “influence” grid layer.
Cumulative Results – Cluster Analysis

Examines how sum of influences accumulate spatially:

- Cluster of higher sums of influences in red
- Clusters of lower sums of influences in blue
- High value outlier surrounded by cluster of low values in orange
- Low value outlier surrounded by cluster of high values in green

Legend

- Not Significant
- High-High Cluster
- High-Low Outlier
- Low-High Outlier
- Low-Low Cluster
To visually examine any spatial correlations on individual natural and anthropogenic factors and the three spatial cumulative results, the two following layers were created:

**Earthquake Density (100 Square Miles) from 2010 - 7/22/2015**

**Hotspot Analysis for Earthquake Magnitude from 2010 - 7/22/2015**
Data overlay example

Example showing heavy rainfall events from 1997 to June 2015

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Natural Factors

Precipitation

From 1997 through June of 2015, more heavy rainfall events seem to be located in the western part of the state, as well as Tulsa county in the northeast region. When this is overlaid with earthquake density from 2010 to 7/22/2015, there does seem to be some spatial correlation between the number of heavy rainfall events and the number of earthquakes, especially in central and north-central Oklahoma and Tulsa County. When overlaid with a hotspot analysis for earthquake magnitudes from 2010 to 2015, higher magnitude clusters (in red) may be associated with more heavy rainfall events.

In August 2007, Tropical Storm Erin dropped heavy rain in Oklahoma, flooding many areas. As the volume of groundwater increased in depth over time, decreases in normal stresses or increases in pore

Legend

Earthquake Density

1
2 - 10
10 - 100
100 - 1000
1000 - 2000

Legend

Coldspots
Hotspots

Heavy rain events

Count

> 6 to 7
> 4 to 6
> 3 to 4
> 2 to 3
> 1 to 2
> 0 to 1
0 to 0
Discusses conclusions and lists references for project
Discussion and Conclusion

• The final application presents an interactive story map providing information related to the probable factors related to the recent increase in seismicity in Oklahoma.

• Natural and human systems can act together and independently to increase the likelihood of seismic activity (Klose 2013).

• The difficulty lies in determining which factors have the greatest influence on seismicity, in a given area.

• Based on this examination via story map, further analyses and investigation are needed to help root out the risks and causes of the recent increase in seismicity in Oklahoma.

Link to complete story map application
Key References


