Unraveling the Mysteries of Seismicity in Oklahoma

A Story Map

Background

Why create a story map?

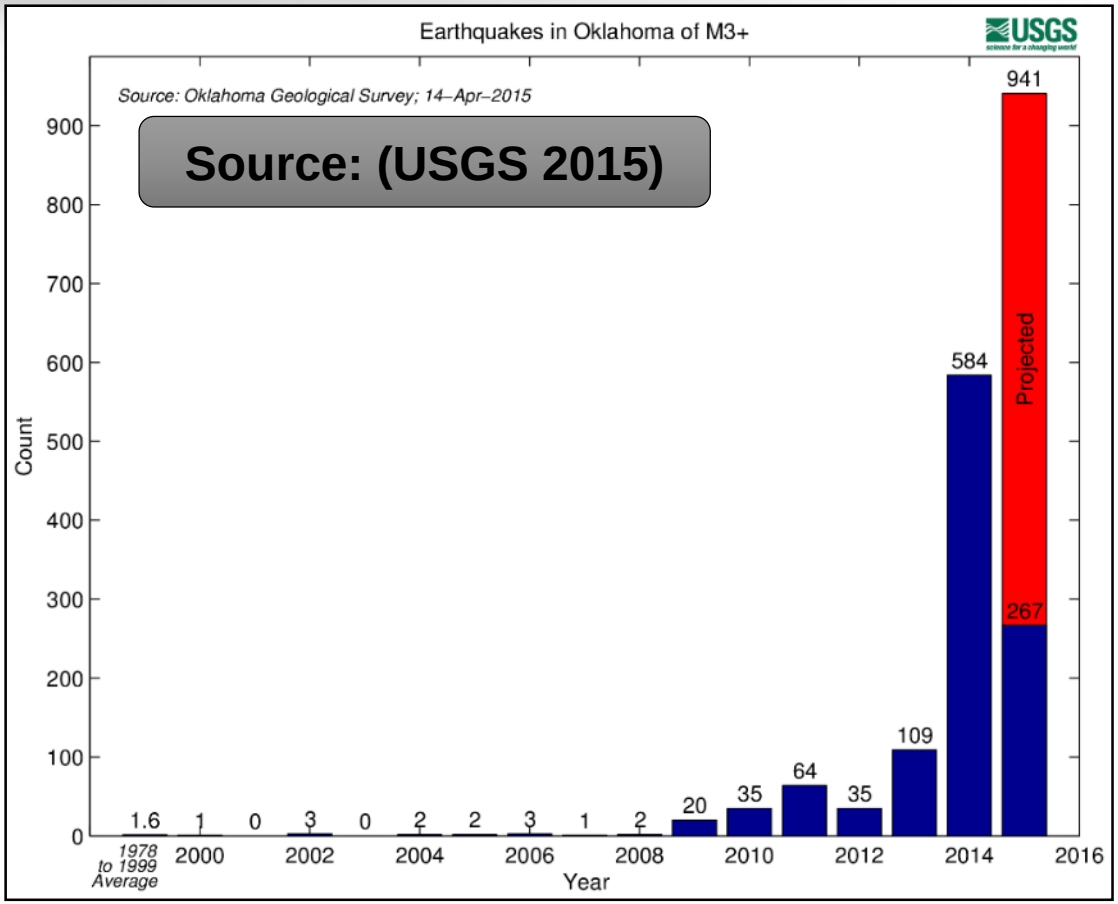
- Visualization of various types of data (graphics, text, symbols, etc.) within a geographical context to enhance story telling
- Allows for easier comprehension and conceptualization of complex problems
- Useful for identifying key patters in natural and human systems
  - Example: Sea level rise and storm surge effects on energy assets
- ArcGIS Online provides web application templates to create story maps

Background

As of 7/22/2015, now over **19,000**

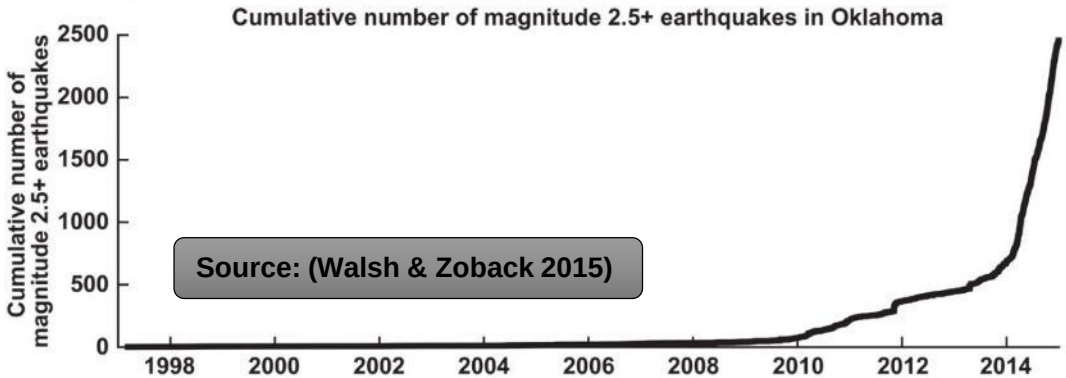
- **Over 17,000 earthquakes recorded in Oklahoma since 1882.**
- **Over 15,000 of these earthquakes were recorded after the beginning of 2008**
- **Seismicity rate is now 600 times greater than the background seismicity rate**
- **Most, but not all of these earthquakes are occurring as swarms**

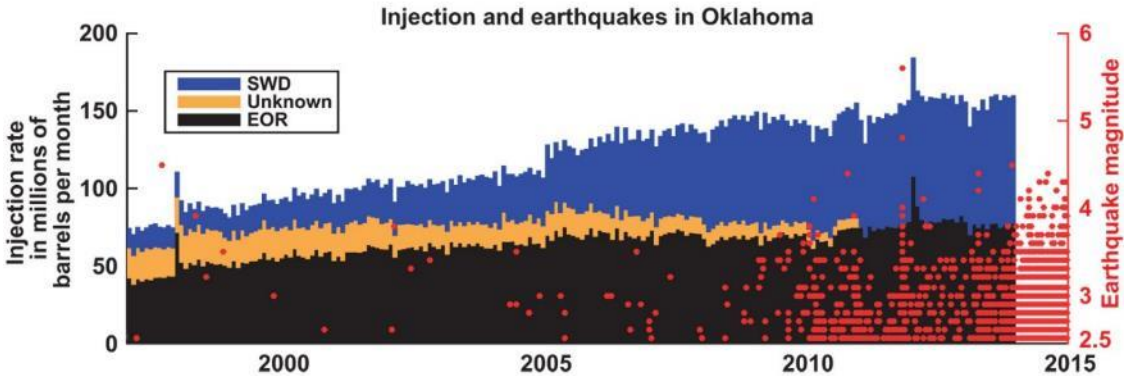
(Andrews & Holland 2015)



Suggests the increase in seismicity is <u>unlikely due to natural forces alone</u>

Background





- **Research suggests this is mainly caused by the increase in the amount of wastewater injected into the subsurface, <u>but does not account for all earthquake events</u>**
- **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

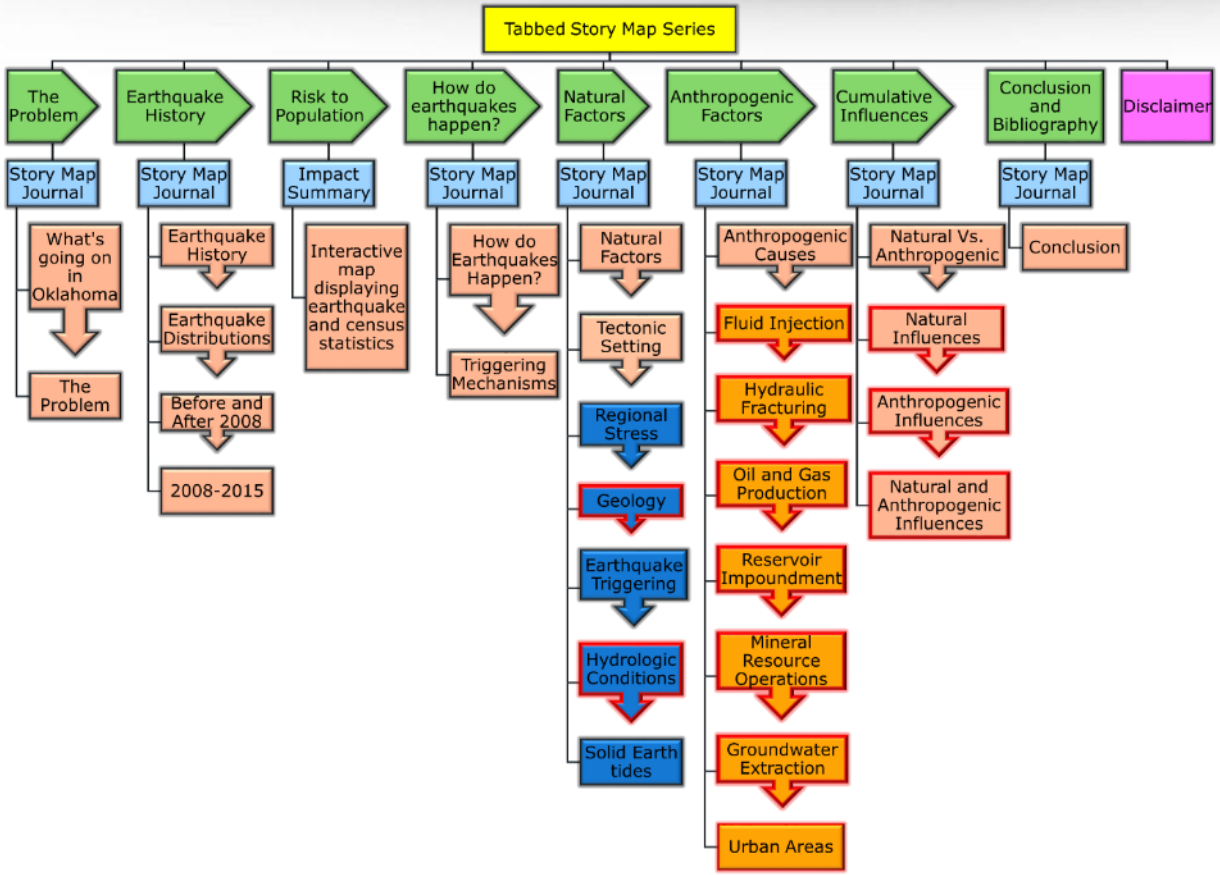
Key Datasets

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

Key Datasets

	Earthquake Factors	Relevant datasets and sources
Anthropogenic	Fluid injection	Class II injection wells (Oklahoma Corporation Commission)
	Hydraulic Fracturing	Hydraulic fracturing wells (IHS Inc.)
	Groundwater extraction	Groundwater wells (Oklahoma Water Resources Board)
	Mineral resource operations	Coal Mines (Energy Information Administration)
		Mines and mineral plants (United States Geological Survey)
	Oil and gas production	All oil and gas production wells (minus injection and hydraulic fracturing) (IHS Inc.)
	Reservoir impoundment	Dams (Oklahoma Water Resources Board)
	Urban areas	Urban areas (US Census Bureau

Application Structure

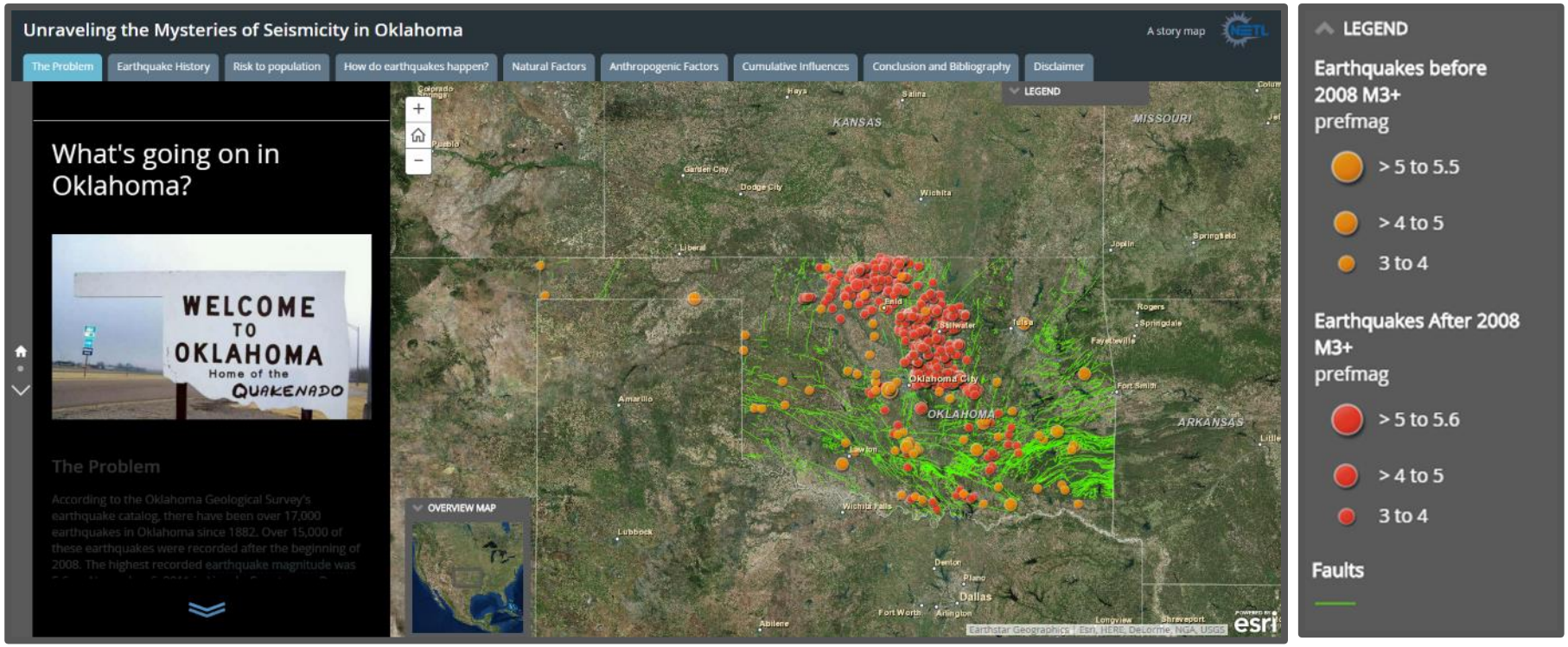


Earthquake factors that have data overlaid with earthquake density and a hotspot analysis for earthquake magnitude are outlined in red.

- **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**

Implementation Results

“The Problem”

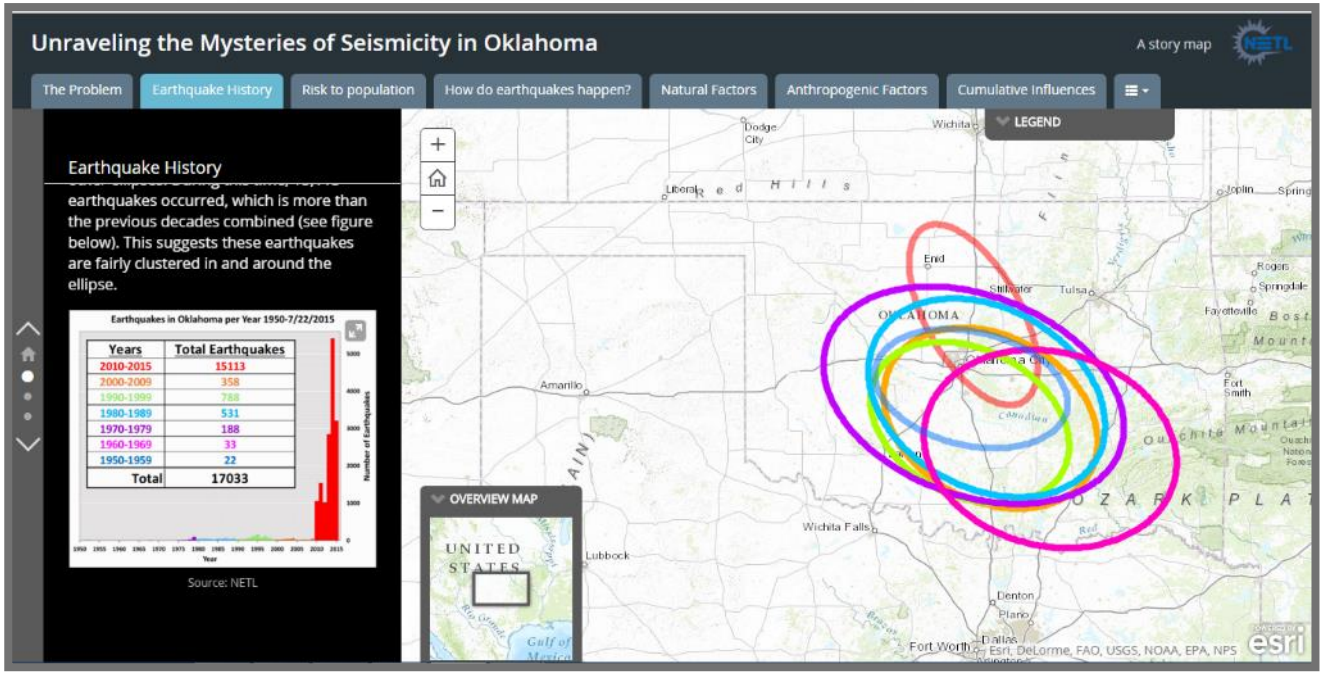


Landing page for application, discusses

- **the recent seismicity**
- **the problem with current research**

Implementation Results

"Earthquake History"

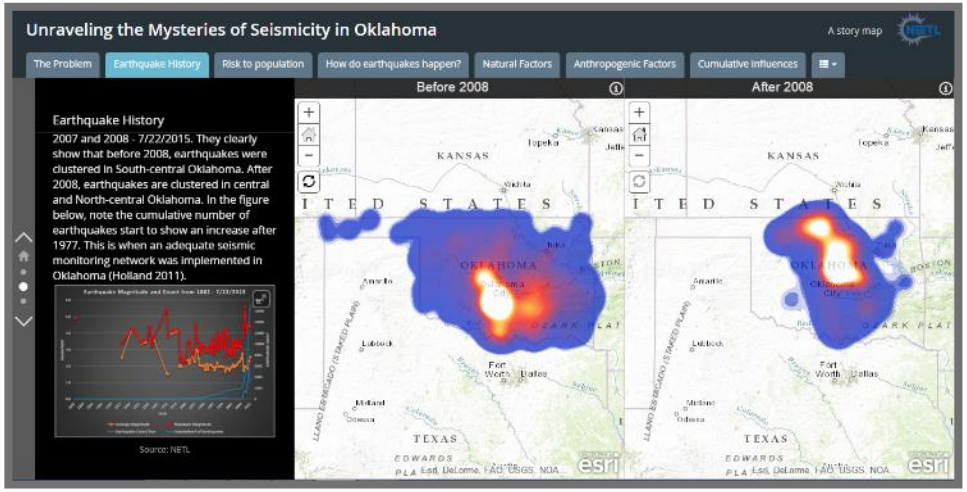


Discusses earthquake history through analysis:

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

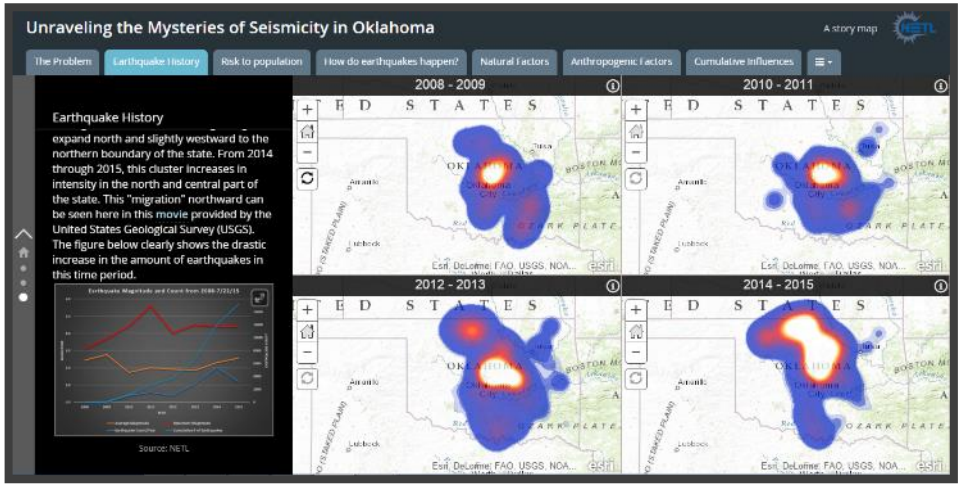
Implementation Results

"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

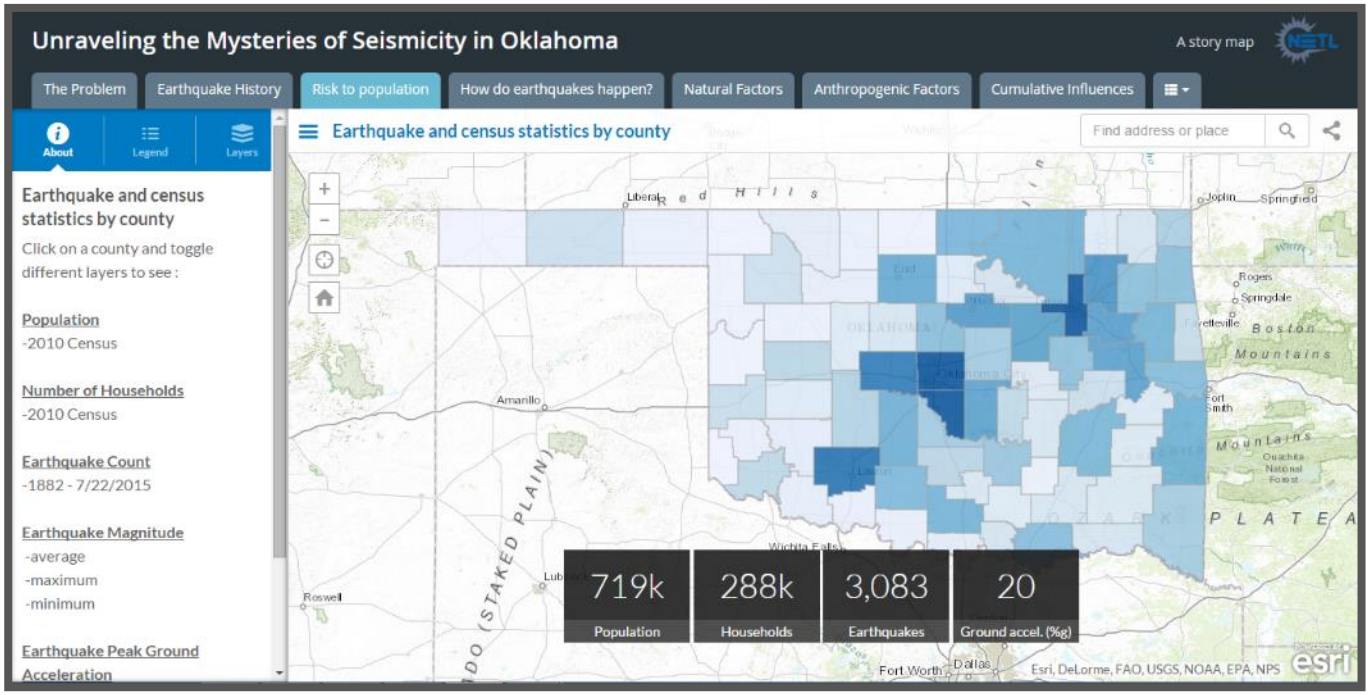


"2008 - 2015"

- 4 heat maps for earthquake location density and same plot for:
  - 2008 - 2009
  - 2010 - 2011
  - 2012 - 2013
  - 2014 - 2015

Implementation Results

"Risk to Population"



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)

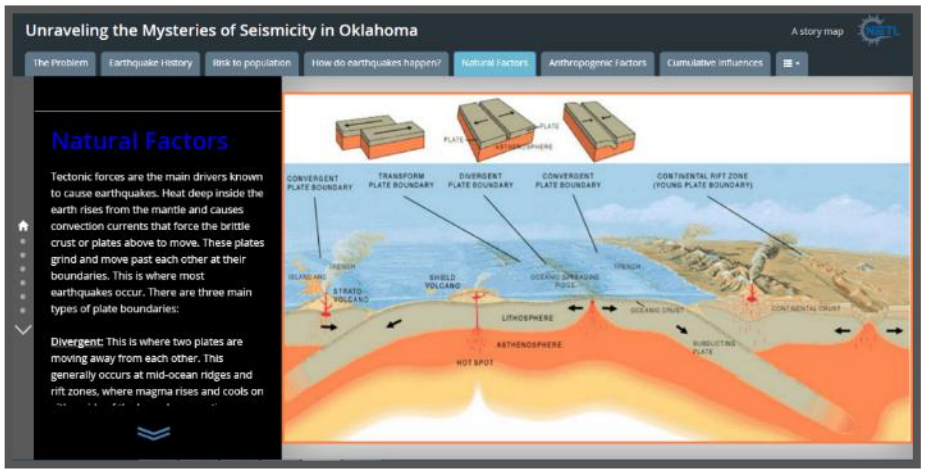
Implementation Results

“How do earthquakes happen?”

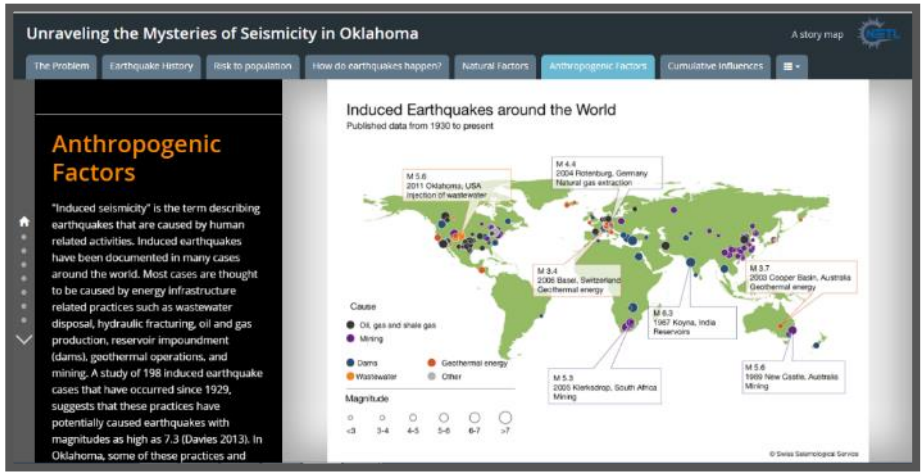
Discusses physics and triggering mechanisms earthquakes

Implementation Results

“Natural Factors”



“Anthropogenic Factors”

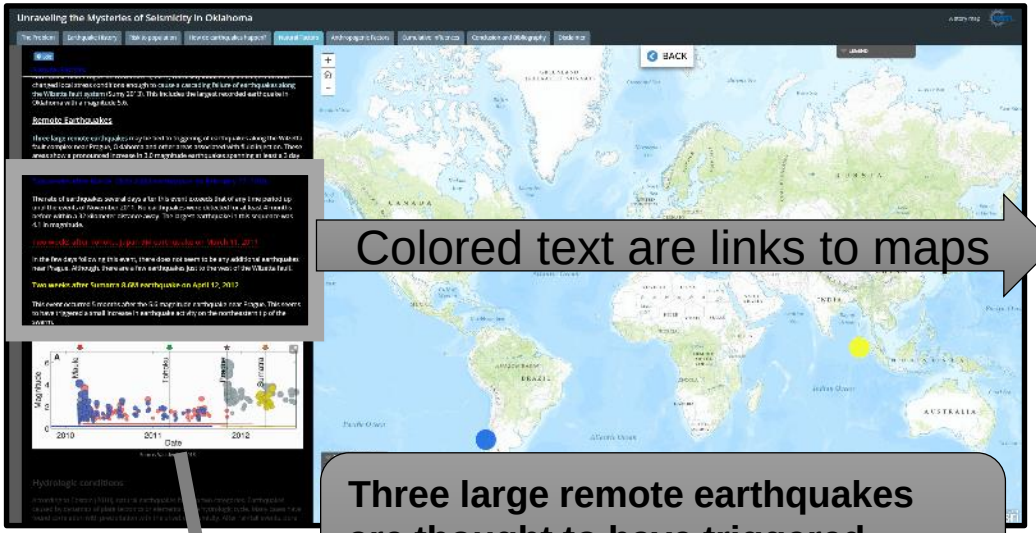


Natural and anthropogenic earthquake factors are examined in their respective tabs by exploring their background, datasets, and case studies through maps and analysis.

Implementation Results- case study example

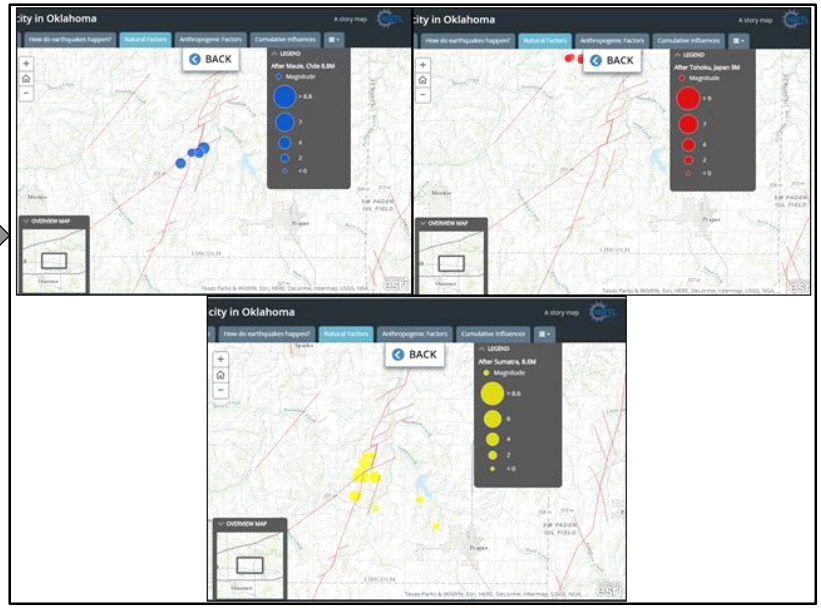
“Natural Factors”

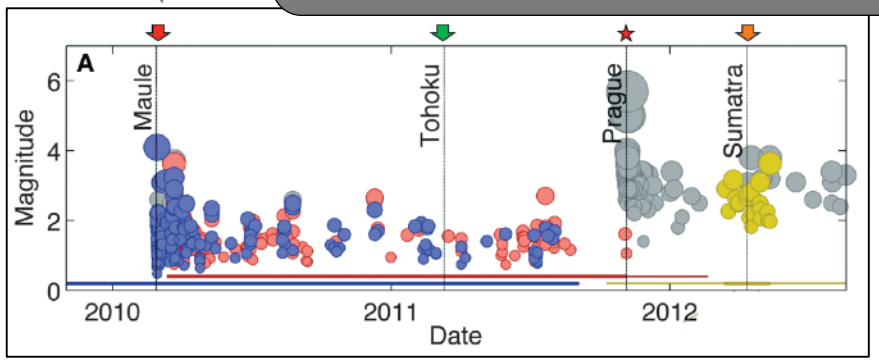
Case study (Van der Elst 2013) for remote earthquake triggering in “Earthquake Triggering” section



Colored text are links to maps

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

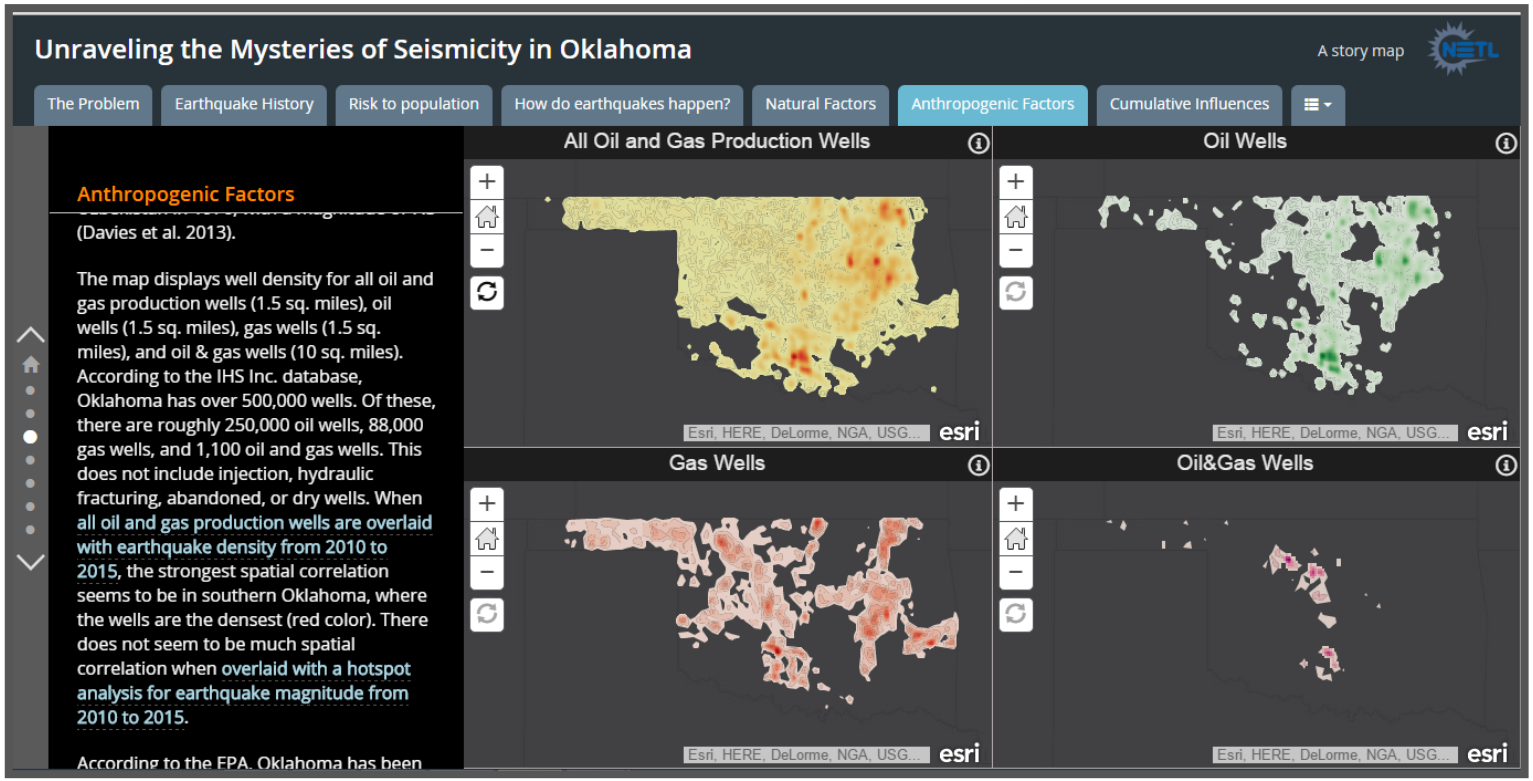




- **Maps zoomed into area around Prague, OK.**
- **Resulting seismicity up to two weeks after 3 large remote earthquakes**

Implementation Results- analysis example

“Anthropogenic Factors”

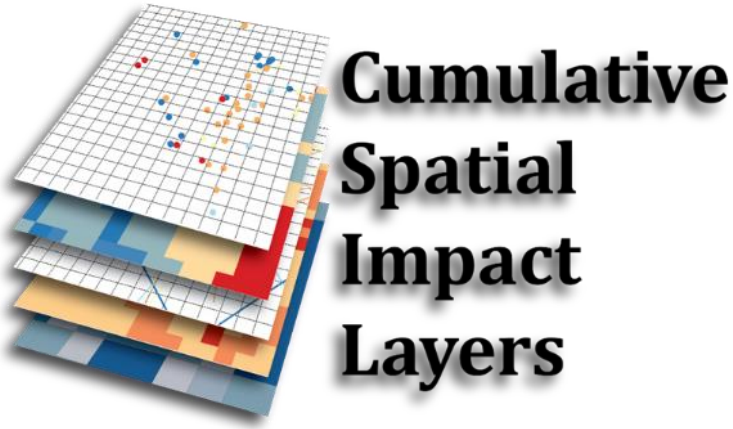


Four maps displaying well density in the “oil and gas production” section using “Compare Analysis” application template

Cumulative Analysis

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:

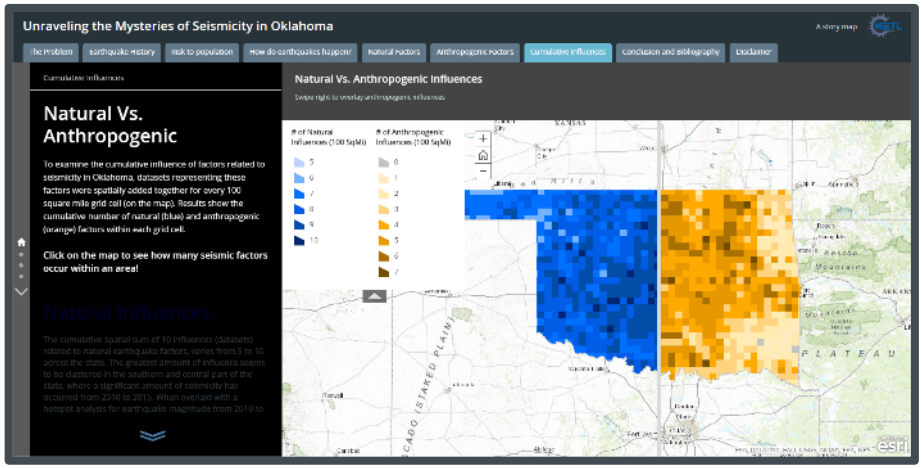
- Natural earthquake factors
- Anthropogenic earthquake factors
- All earthquake factors



Implementation and Cumulative Analysis Results

"Cumulative Influences"

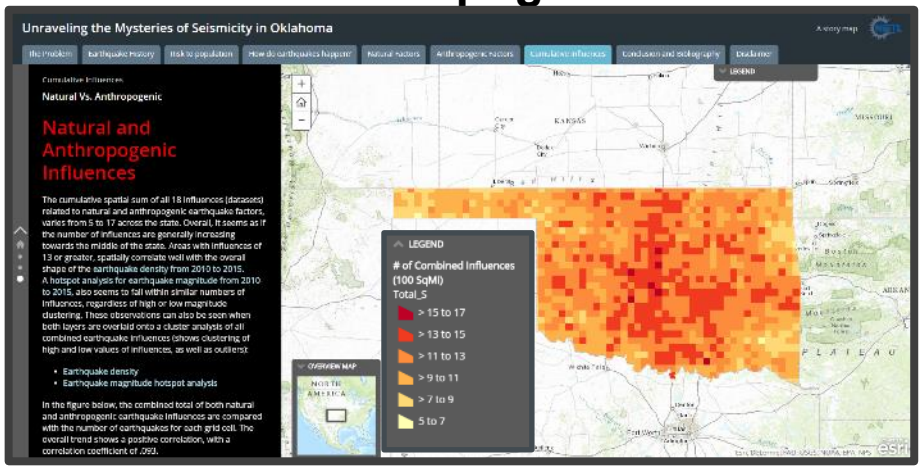
"Natural Vs. Anthropogenic"



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**

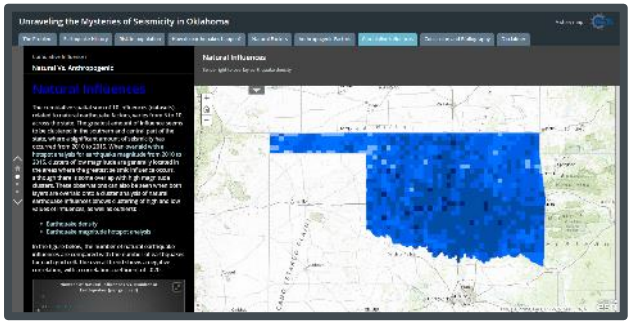
<u>For every 100 square mile grid cell</u>

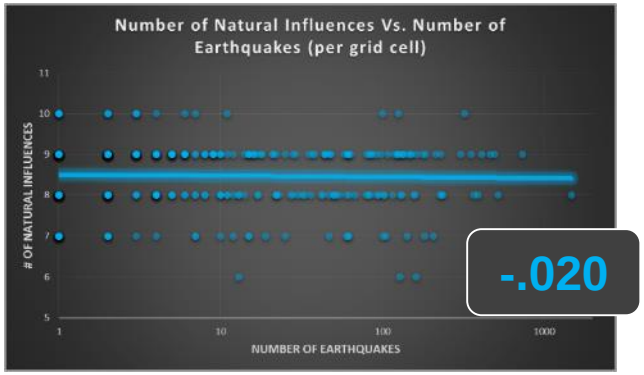
Cumulative Analysis Results continued

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

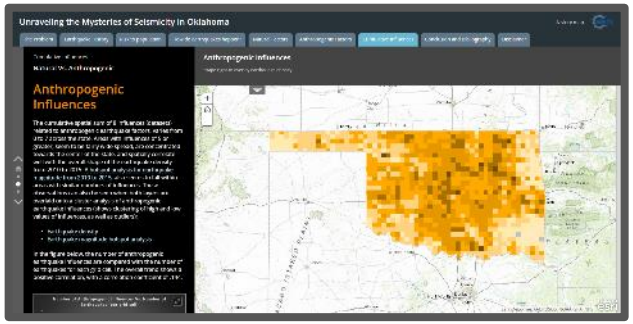
- **Earthquake count per grid cell was calculated by spatially joining earthquakes from 2010 – 7/22/2015 to each "influence" grid layer**

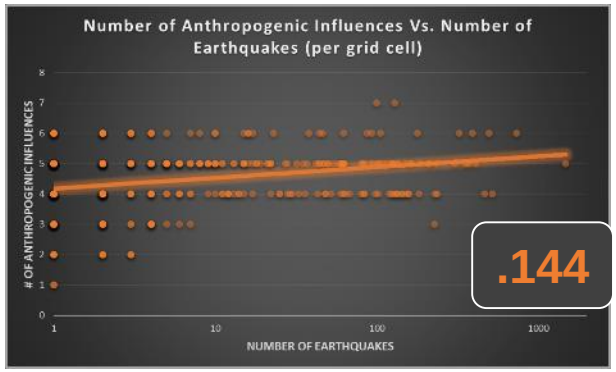
"Natural Influences"



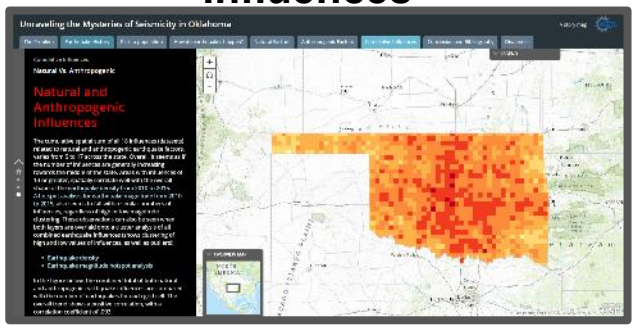


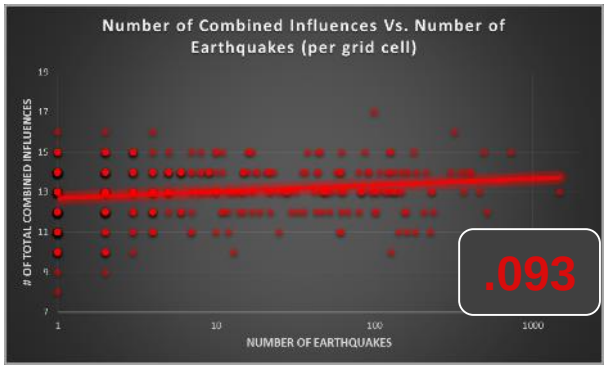
"Anthropogenic Influences"



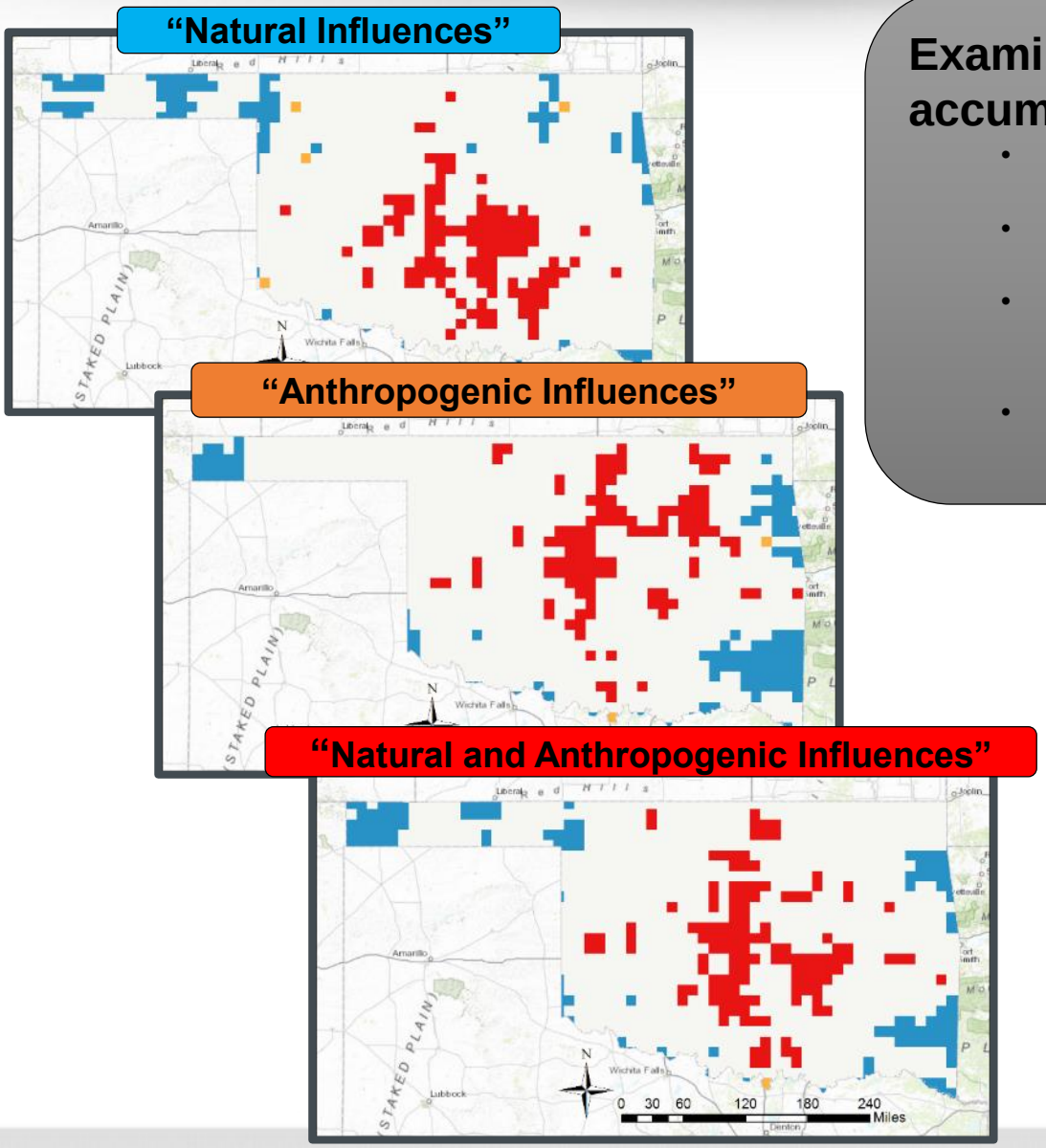


"Natural and Anthropogenic Influences"



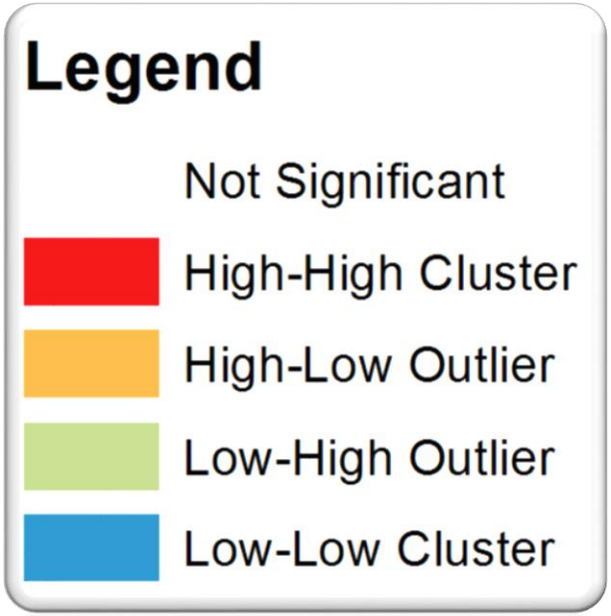


Cumulative Results – Cluster Analysis



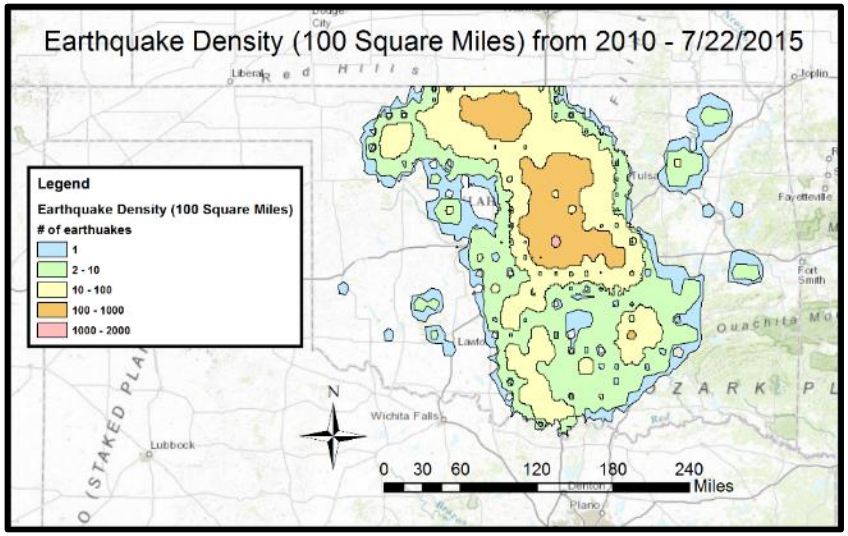
Examines how sum of influences accumulate spatially:

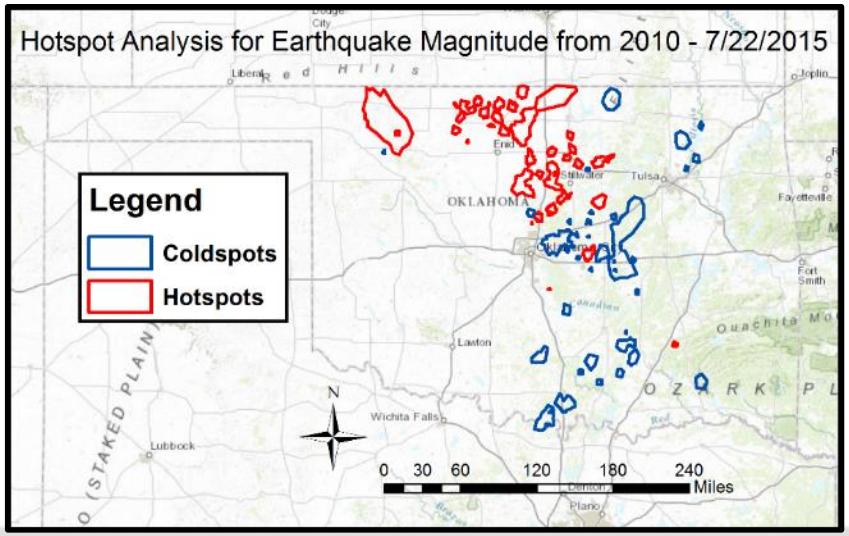
- Cluster of higher sums of influences in red
- Clusters of lower sums of influences in blue
- High value outlier surrounded by cluster of low values in orange
- Low value outlier surrounded by cluster of high values in green

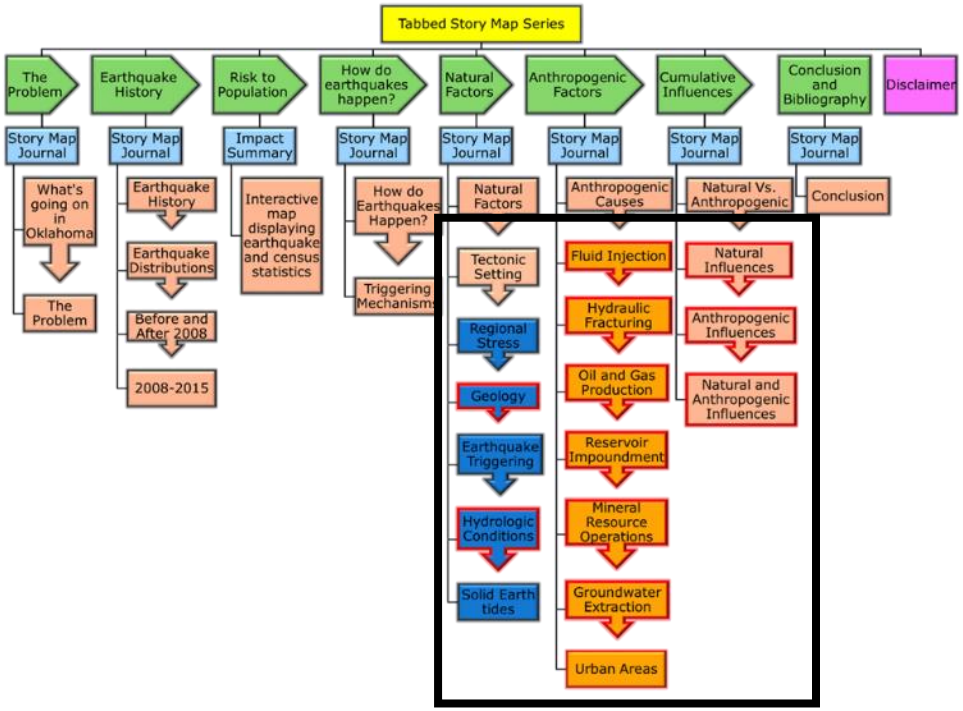


Data overlay

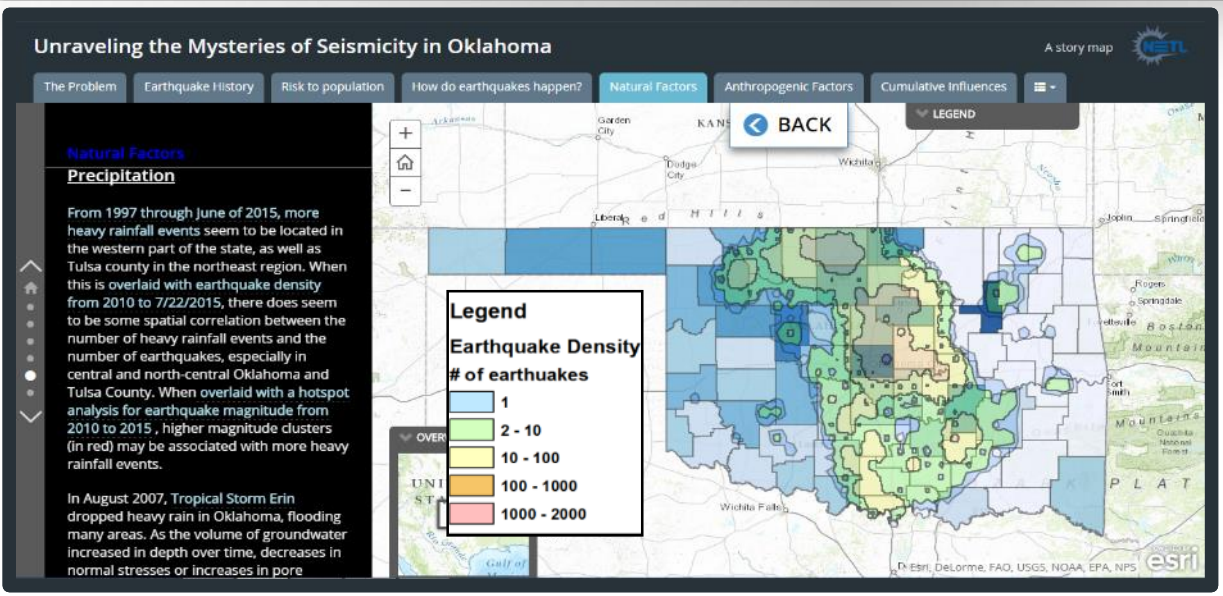
To visually examine any spatial correlations on **individual natural and anthropogenic factors** and the **three spatial cumulative results**, the two following layers were created:

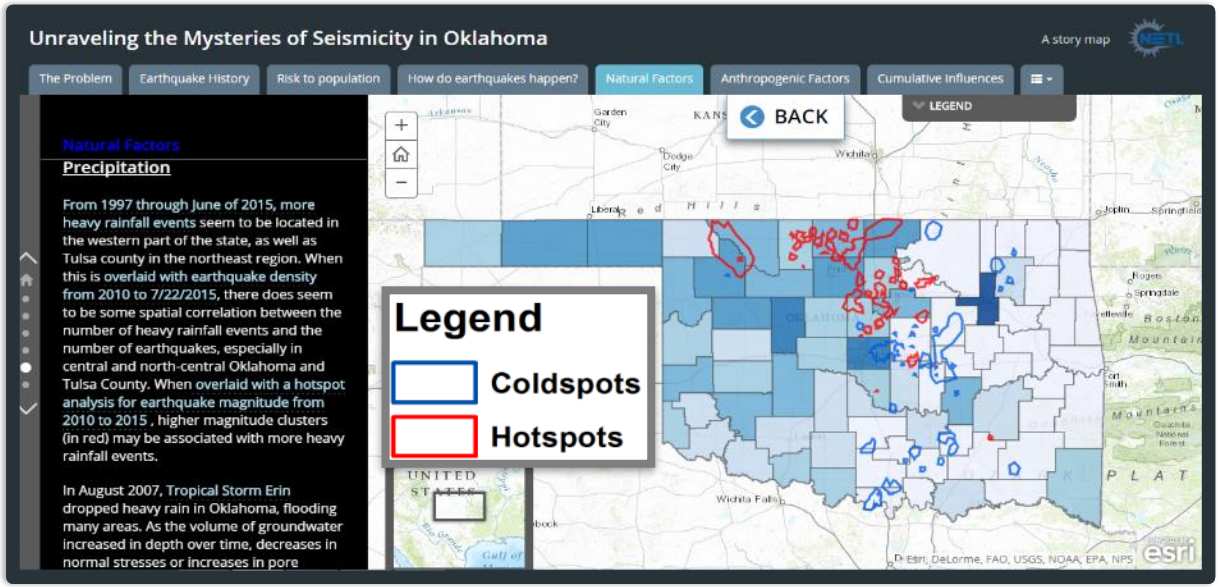




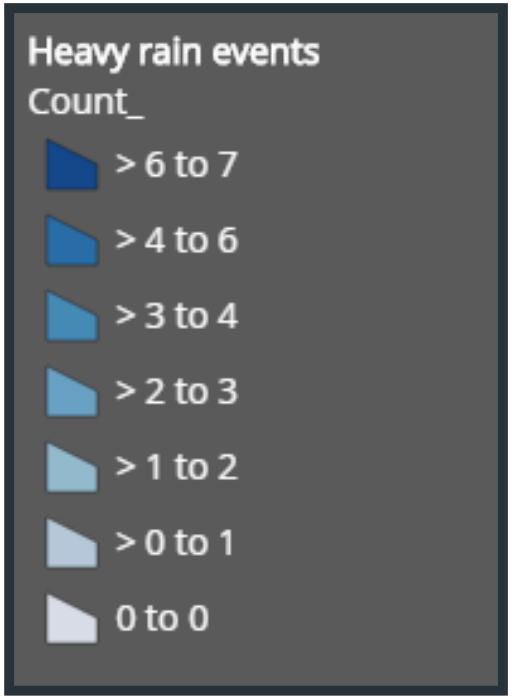


Data overlay example



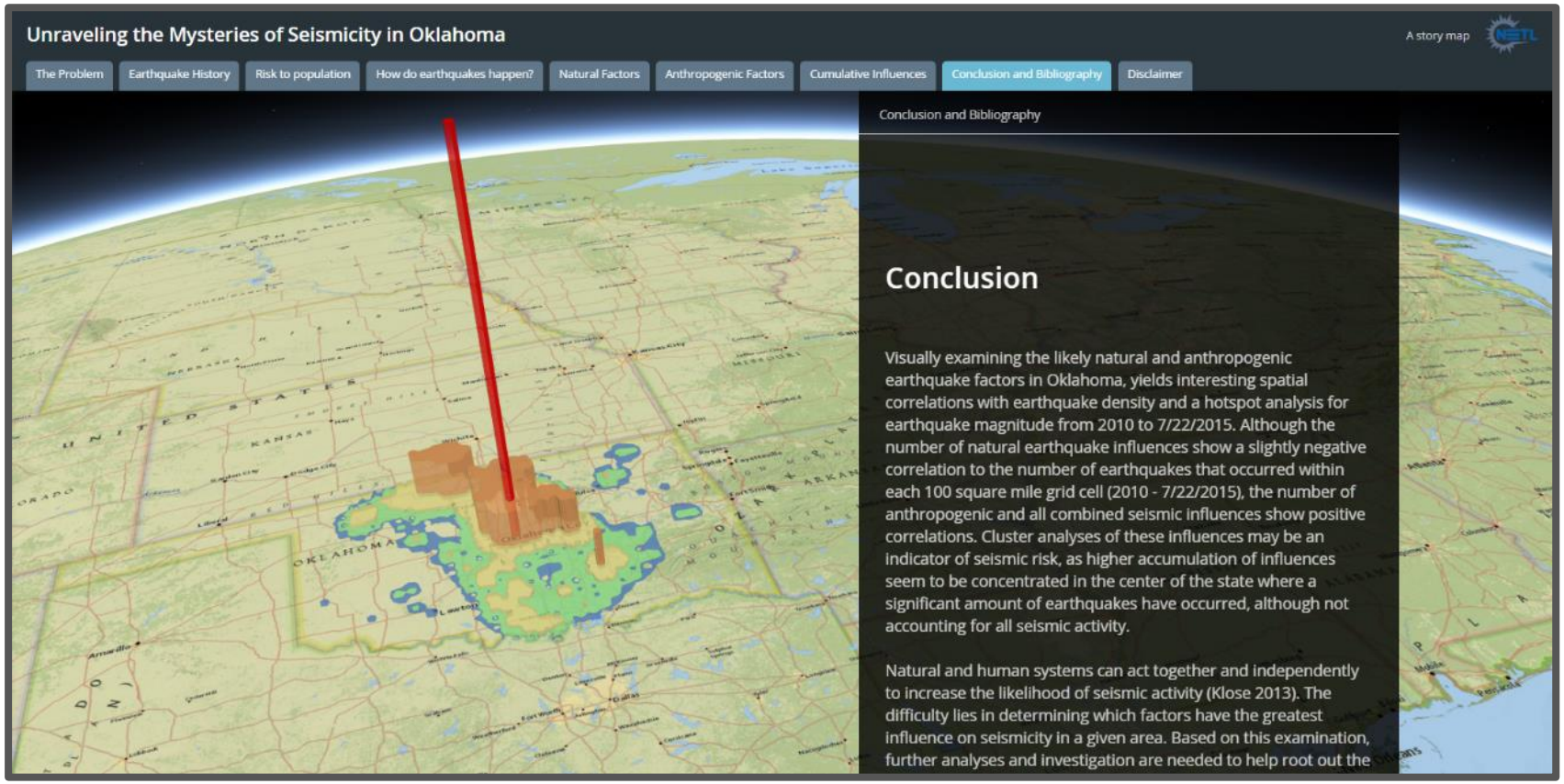


Example showing heavy rainfall events from 1997 to June 2015



Implementation Results

“Conclusion and Bibliography”



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

Andrews, Richard D., Holland, A. (2015). Statement on Oklahoma and Seismicity: April, 21 2015. *Oklahoma Geological Survey*.

Bauer, J . R. et al (2015). A Spatio-Temporal Approach to Analyze Broad Risks Potential Impacts Associated with Uncontrolled Hydrocarbon Release Events in the Offshore Gulf of Mexico; NETL-TRS-2-2015; EPAct Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2015; p 60.

Klose, C. D. (2013). Mechanical and statistical evidence of the causality of human-made mass shifts on the Earth's upper crust and the occurrence of earthquakes. *Journal of Seismology*, *17*(1), 109-135.

Nicks, Denver. (2014, June 17). Earthquake Insurance Becomes Boom Industry in Oklahoma. *Time.*

United States Geological Survey (USGS). (2015). *Graph of the Number of Oklahoma Earthquakes 1978 to Present*.

Walsh, F. R., & Zoback, M. D. (2015). Oklahoma's recent earthquakes and saltwater disposal. Science Advances, 1(5), e1500195.

Wertz, Joe. (2014, January 14). Oklahoma Earthquake Rate is High, But Holding Steady. *StateImpact*.