SPATIAL DISTRIBUTION OF WATER POLLUTION INCIDENTS REPORTED TO THE OKLAHOMA CORPORATION COMMISSION

By

NELLY J. RUIZ

Bachelor of Science in Geology
Oklahoma State University
Stillwater, Oklahoma
2008

Master of Science in Biosystems Engineering
Oklahoma State University
Stillwater, Oklahoma
2015

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2019

SPATIAL DISTRIBUTION OF WATER POLLUTION INCIDENTS REPORTED TO THE OKLAHOMA CORPORATION COMMISSION

Dissertation Approved:

Dr. Paul Weckler

Dissertation Adviser

Dr. Glenn Brown

Dr. Todd Halihan

Dr. Javier Vilcaez

ACKNOWLEDGEMENTS

Many thanks to Dr. Brown for believing in me and teaching me to believe in myself among other subjects such as Fluid Mechanics and Groundwater Contamination. To the members of my committee thank you for keeping an open door and providing valuable advice.

I would also like to thank my children for sleep training me and preparing me for this task. To my husband, for supporting me through my crazy and unreachable dreams. To my mother and brother for making my children happy with their company in Stillwater. To the Robberson Summer Dissertation Fellowship for providing me with the funds and the opportunity to complete this dissertation.

Lastly and most importantly, I thank the members of the Oklahoma Corporation Commission who gathered data and took the time to meet with me to discuss ideas and provide feedback.

Name: NELLY J. RUIZ

Date of Degree: MAY, 2019

Title of Study: SPATIAL DISTRIBUTION OF WATER POLLUTION INCIDENTS
REPORTED TO THE OKLAHOMA CORPORATION COMMISSION

Major Field: BIOSYSTEMS ENGINEERING

Abstract: The increase in high volume hydrocarbon production in Oklahoma raised concern about the potential adverse environmental effects and more specifically the contamination to surface and ground waters. Despite the complexity of the debate encompassing this topic, there has been limited quantitative information presented to the public on actual impacts. Publicly available databases in Oklahoma indicate very infrequent or no contamination of groundwater has been reported alluding responsibility to the oil and gas industry. However, firm conclusions are hindered by the gaps and uncertainties in the raw data. The goal of this research was to manually sort through five years of state data to quantify and evaluate the spatial distribution of actual occurrences. In order to facilitate interpretation of the raw disorganized database it was necessary to classify the incidents into five categories including accidents, misconduct, non-producing, health and other. These categories were further divided into 12 subcategories of which the affected surface and ground waters were extracted for evaluation. The literature suggests that these waters may be directly affected by unplugged wells and produced fluid spills. For this reason, the locations of these two subcategories were geocoded to assess the spatial distribution in ESRI Geographic Information System (GIS). It was found that 203 water wells were reported polluted in five years from 2008 to 2012, of which 84 were referred for continuation and additional analysis. Produced fluid spills had occurred in 1,805 instances of which 18% were located within a vulnerable aquifer and 10% within a protected watershed. The number of unplugged wells was 1,090 with an annual average of 218. The unplugged wells and the polluted water wells were clustered in north-central Oklahoma, which coincides with the locations of historical hydrocarbon fields. Detailed and organized data is necessary to calculate the effects to water resources in the state.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Background

The accentuated concern for the environment and the resulting water management challenges of high volume hydrocarbon production emerged with the exponential increase in production and the economic success of the mid-2000s. While earlier forms of hydraulic fracturing by US energy companies date back to the late 1940s, the recent upsurge in its use was prompted by the discovery of large new reserves of coal or shale bound gas throughout the US and by technological improvements such as the inclusion of horizontal drilling techniques adopted from deepwater oil and gas wells operating in the Gulf of Mexico (US Energy Information Administration, 2011). Estimated reserves in the United States increased 35% between 2006 and 2009 (Navigant Consulting 2008; Gregory et al. 2011). The rapid increase in production left a gap or uncertainty in the management of the successive wastewater production and a growing public concern for the environment. To date there is no federal law that protects water resources from oil and gas production. The Energy Policy Act of 2005 exempts fluids used in hydraulic fracturing from regulatory action under the Clean Water Act, the Safe Drinking Water Act, and the Comprehensive Environmental Response, Compensation, and Liability Act (Kosnik, 2007). For the most part state, and in some cases regional authorities, have taken the lead role in regulation of shale gas developments in the US (GWPC, 2009). Water protection from oil and gas production and hydraulic fracturing is a highly debated active research field. More studies are needed across a broader geographic area, particularly because many shale gas developments occur in areas that have been historically exploited for conventional oil and gas (Vengosh et al., 2014). At this point, the issue of well age addresses a critical question: Are recently drilled wells safer than older wells? Intuitively, the answer should be “yes.” Materials are often better, regulations are often stricter, and people learn as they go, tailoring practices to local geology (Jackson, 2014). However, as stated by Meng (2016):

> “It is still critical and needed for scientists from environmental sciences, geosciences, engineering, and other disciplinary to conduct pure environmental assessment and at the same time avoid conflicts of interest; and thereafter, a neutral, unbiased, and overall assessment of the impacts of fracking on the environment and society could be provided to the public.”

Research Objectives

The most recent increase in high volume natural gas production in Oklahoma might leave an environmental footprint in fresh water supplies. It is important to quantify the reported pollution and to identify the source of the pollution that could lead to potential detrimental long-term effects. This self-funded, objective, and impartial study examines actual occurrences reported in the state to observe the trends and spatial distribution of the complaints. The objectives of this research focus on incidents reported to the Oklahoma Corporation Commission (OCC) as complaints or violations related to hydrocarbon production extracted from *Incident and Complaint Investigation Reports* (1085 forms) dating from 2008 to 2012. The first objective of this study is to quantify the environmental impacts by sorting, classifying, and categorizing the reported events. Secondly, the incidents related to water resources will be evaluated by determining the proximity of produced fluid spills to vulnerable aquifers (ground waters) and protected watersheds (surface waters). Lastly, affected water supply wells will be correlated to unplugged production wells in close proximity and studied based on age of the hydrocarbon play; whether the old conventional plays may have affected the reported water supply wells in comparison to the newer contemporary shale play.

The specific research tasks are focused on the state of Oklahoma and include:

1. Identify and assess the occurrence potential of the most commonly reported oil and gas complaints.
2. Identify surface areas or geographic locations that need improved quality control and best management practices in hydrocarbon production operations, especially near riparian zones, surface waters, and shallow aquifers.
3. Locate the most vulnerable aquifers in the state and associate the recurrence of produced fluid spills in these areas.
4. Locate the protected watershed and surface waters in the state and relate the recurrence of produced fluid spills in proximity to these.
5. Determine the spatial occurrence of affected water supply wells in relation to unplugged wells.
6. Observe the trends through spatial statistical analysis amongst the affected water wells and unplugged wells.

Dissertation Format

The research in this dissertation is presented as a collection of a three series paper formatted for submission to an Oklahoma journal. Preceding the three series paper is an introduction and a literature review and the last chapter includes the dissertation conclusions.

References

EIA, U. (2011). Review of emerging resources: US Shale gas and shale oil plays. *Energy Information Administration, US Department of Energy*.

Jackson, R. B. (2014). The integrity of oil and gas wells. *Proceedings of the National Academy of Sciences*, 201410786.

Meng, Q. (2017). The impacts of fracking on the environment: a total environmental study paradigm. *Science of the Total Environment*, *580*, 953-957.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental science & technology*, *48*(15), 8334-8348.

Gregory, K. B., Vidic, R. D., & Dzombak, D. A. (2011). Water management challenges associated with the production of shale gas by hydraulic fracturing. *Elements*, *7*(3), 181-186.

Rahm, B. G.; Riha, S. J. Toward strategic management of shale gas development: Regional, collective impacts on water resources. Environ. Sci. Policy. 2012, 17, 12−23.

CHAPTER II

LITERATURE REVIEW

Introduction

Analysis of newspaper and popular press coverage of hydraulic fracturing has shown it to be largely negative and focused on environmental issues, particularly water quality impacts (Evensen et al., 2013). The furor over fracturing and frac water disposal was largely driven by lack of chemical disclosure and the pre-2008 laws of some states (King, 2012).

> "The ability to economically produce natural gas from unconventional shale gas reservoirs has been made possible recently through the application of horizontal drilling and hydraulic fracturing. This new technique has radically changed the energy future of the United States. The U.S. has shifted from a waning producer of natural gas to a growing producer. The Energy Information Administration forecasts that by 2035 nearly half of U.S. natural gas will come from shale gas." (Rahm, 2012).

The number of horizontal and vertical wells completed statewide in the United States is portrayed in Figure 2.1 reprinted from Murray (2013). An increase in production is evident in the 2000s followed by a steep decrease in 2009 from nearly five thousand wells to just over two thousand wells completed in Oklahoma.

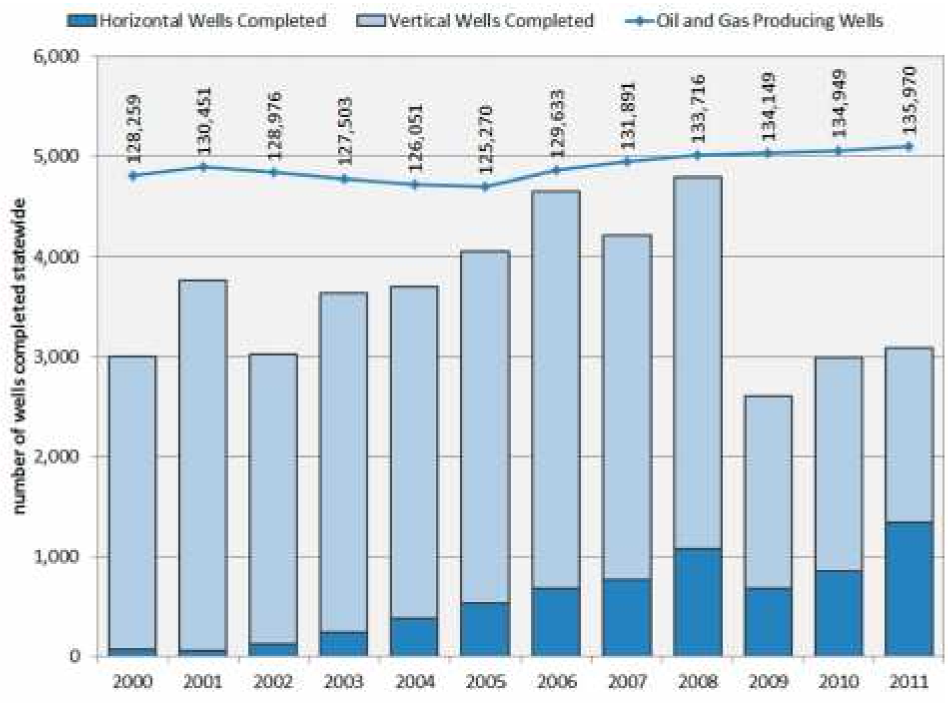


Figure 2.1: Well completions and number of oil or gas producing wells in Oklahoma, 2000 to 2011. Reprinted from "State-Scale Perspective on Water Use and Production Associated with Oil and Gas Operations, Oklahoma, U.S.", K. Murray, *Environ. Sci. Technol.*, pp 4918–4925. Copyright 2013 by the American Chemical Society.

Directional Drilling and Hydraulic Fracturing

According to historic records, hydraulic fracturing (HF) took place for the first time in 1857 when Preston Barmore created a downhole explosion at Canadaway Creek, NY. Barmore placed gunpowder into a well and dropped a red-hot iron down a tube. The explosion fractured the rock and increased the flow of gas from the well. In the past drillers used explosives downhole instead of water to free hydrocarbons from non-producing wells. In 1865 Colonel Edward Roberts and his brother developed a technique known as "superincumbent fluid-tamping" in which an oil well would be filled with water and a nitroglycerine (NG) "explosive torpedo" would be lowered and detonated upon impact (Montgomery and Smith, 2010). In 1949, Floyd Farris of Stanolind Oil proposed that fracturing a rock formation through hydraulic pressure might increase well productivity. That same year, Halliburton Oil Well Cementing Company obtained an exclusive license for the hydraulic fracturing process. In the first year of operations, 332 oil wells were treated with crude oil or a combination of crude oil, gasoline, and sand. The wells on average increased production by 75% (Morton, 2013). This practice was transformed when it combined with horizontal drilling and other new technologies, such as 3D seismic imaging. In the mid-1970s, the US Department of Energy (DOE) and the Gas Research Institute (GRI), in partnership with private operators, began developing techniques to produce natural gas from shale. These include the use of horizontal wells, multi-stage fracturing, and "slick" water fracturing (Pal et al., 2010). Between 1981 and 1998, a Texas company, Mitchell Energy and Development, experimented with these techniques in testing the Barnett Shale formation. Commercial success started when Nicholas Steinberger, a Mitchell engineer, diluted the gel creating a low viscous mixture that could be rapidly pumped down a well to deliver a much higher pressure to the rock (Smith, 2016). In 2002, a merger between Mitchell Energy and Devon Energy brought rapid increase in the use of hydraulic fracturing with horizontal drilling. Figure 2.2 presents a simple schematic of this chronology.

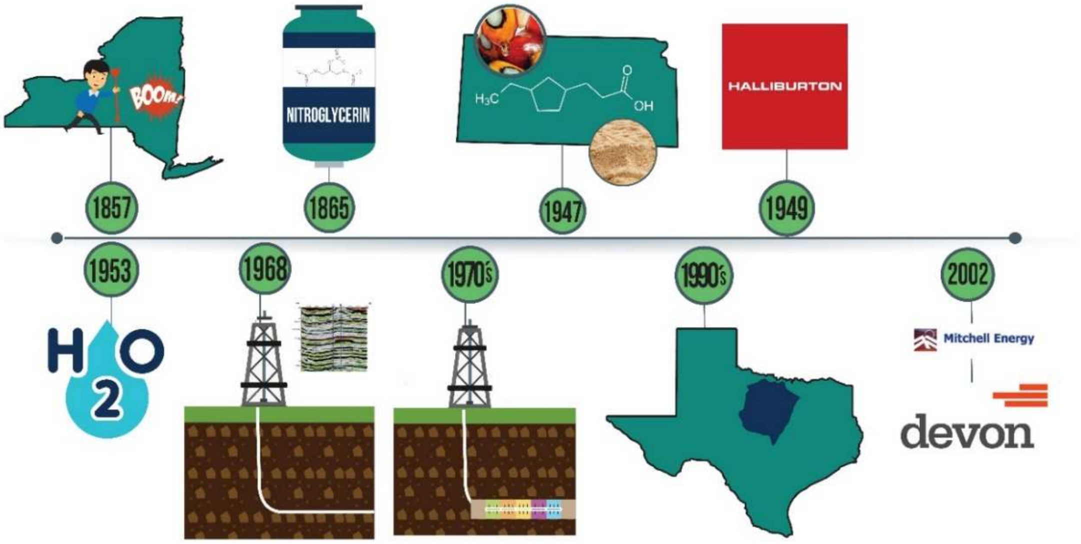


Figure 2.2: Hydraulic fracturing chronology

In conventional traditional drilling the drill string extends vertically, whereas in unconventional drilling the drill string extends vertically until it approaches the formation of interest where it bends and it proceeds to extend horizontally (Figure 2.3).

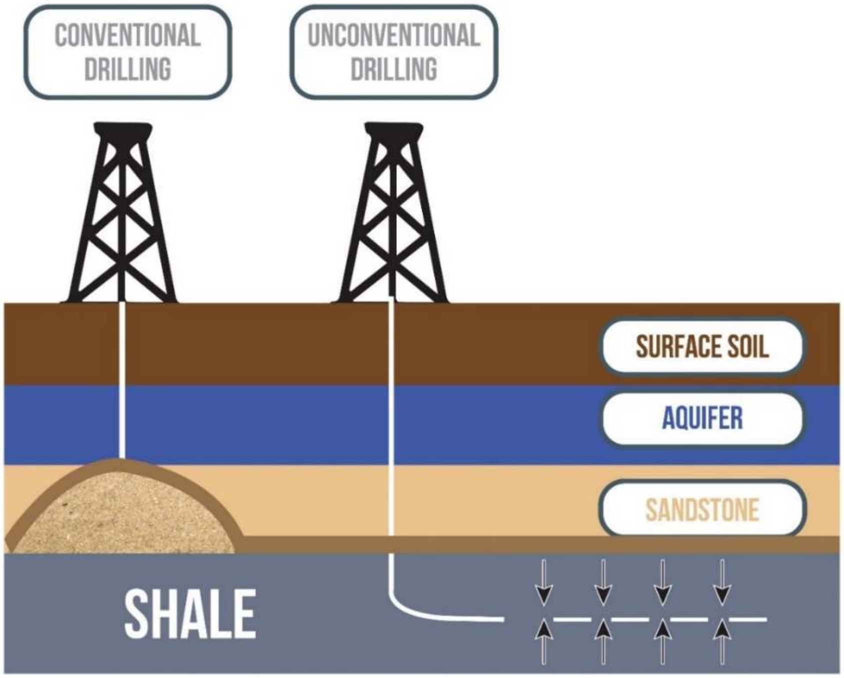
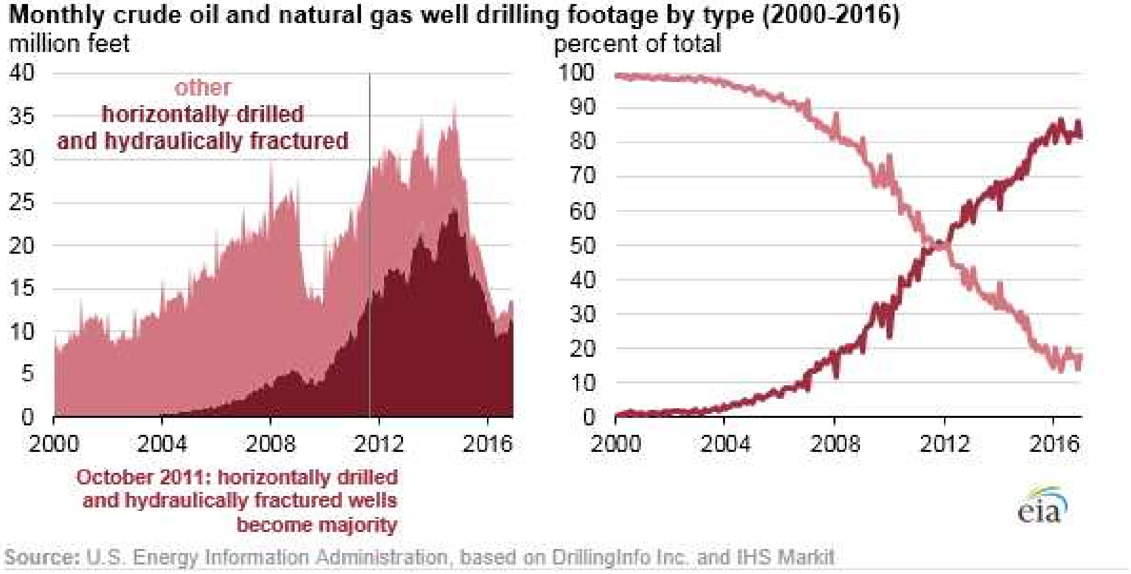


Figure 2.3: Conventional and unconventional drilling schematic

Directional drilling reaches into horizontal or slanted formations to better access low porosity unconventional reservoirs and increase the productivity of the well. The technology consists of a single well pad installed at the surface from which rotary vertical drilling takes place until it reaches the “kickoff point” located a few hundred feet above the formation of interest. From this point, the trajectory of the borehole begins to build an angle by rotating the drill bit with the hydraulic motor mounted above the drill bit. This allows the drill bit to continue its path without turning the drill string at the surface. The angle of a drill bit is controlled with real-time technologies and two-way communication between the operators and the downhole assembly. Adjustment and steering is conducted without interrupting the drilling. Horizontal and vertical control is maintained by a bend that steers the bit toward its target formation. The surface adjustable bend can be set between 0 and 3 degrees. “This seemingly minor deflection determines the rate at which the motor builds angle to establish a new wellbore trajectory. By orienting the bend in a specific direction, the driller can change the inclination and azimuth of the well path” (Duplantis, 2016). Directional drillers alternate between rotating and sliding modes of drilling. In drilling mode, the drill string rotates providing power to the drill bit and enabling the bend to point equally in all directions to maintain a straight drilling path. Included within the drill bit are a number of logging while drilling (LWD) sensors for advanced capabilities in guiding the drill string. Downhole sensors transmit various readings to operators at the surface including the azimuth and inclination of the drilling assembly. There are also sensors that provide information on the downhole environment such as temperature and pressure, weight on the bit, bit rotational speed, and rotational torque. The physical characteristics of the surrounding rock such as natural radioactivity and electrical resistance are obtained in real time while drilling ahead (Haugen, 1998). Petrophysical data is collected and stored to ultimately steer using real-time evaluation of the surrounding reservoir structure. After drilling operations have been completed and the drilling crew has left the site, a HF company takes over the well pad to inject fluids at high pressure. Water mixed with sand and other inert solids, such as ceramic beads, or “proppants”, are injected into the formation to fracture the rock and provide support, which prevents the fractures from closing once the well pressure is released. In addition to proppants, other chemicals are added to the injected HF fluids. These chemicals are typically blended at the wellhead and serve various functions in the process such as preventing the growth of bacteria, facilitating the pumping of proppant, and minimizing mineral scaling of the well (Stringfellow et al., 2014). Since Stanolind Oil introduced hydraulic fracturing in 1949, close to 2.5 million fracture treatments have been performed worldwide (Montgomery and Smith, 2010). As stated by Donaldson et al. (2014) hydraulic fracturing is a process to open new or existing cracks in the rock structures to produce oil and gas, also known as petroleum hydrocarbons. With the application of this technique, low permeability formations are capable of releasing hydrocarbons at economical rates. In other words, fracturing is a process of improving permeability of a tight rock formation such as shale to stimulate production of oil and gas (Donaldson et al., 2014). Many fields would not exist today without hydraulic fracturing (Montgomery and Smith, 2010). The advent of horizontal drilling coupled to hydraulic fracturing has changed unproductive shale gas deposits into large natural gas fields all over the world (Donaldson et al, 2014).



Source: U.S. Energy Information Administration, based on DrillingInfo Inc. and IHS Markit

Figure 2.4: Monthly crude oil and natural gas well drilling footage by type. Reprinted from U.S. Energy Information Administration by T. Cook et al., 2018. Available at: https://www.eia.gov/todayinenergy/detail.php?id=34732

Hydraulically fractured horizontal wells became the predominant method of new U.S. crude oil and natural gas development in October 2011, when total footage (in linear feet) surpassed all other drilling and completion techniques (Cook et al., 2018). Figure 2.4 shows the increase in horizontally drilled hydraulic fractured wells in the United States coupled with the decrease in other forms of drilling. Figure 2.5 shows the well count in the United States by type, according to this figure reprinted from the EIA, horizontally drilled and hydraulic fractured wells became majority on September 2014.

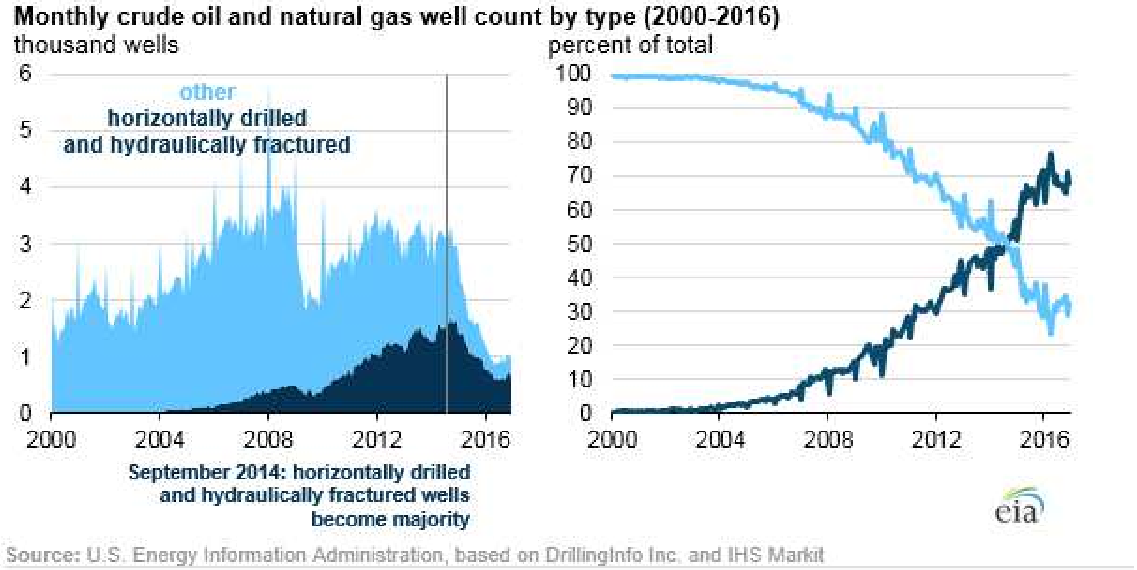


Figure 2.5: Monthly crude oil and natural gas well count by type. Reprinted from U.S. Energy Information Administration by T. Cook et al., 2018. Available at: https://www.eia.gov/todayinenergy/detail.php?id=34732

There are many stages or processes within the exploration and production of hydrocarbons from drilling the borehole to injecting fluids at high pressure that have the potential of polluting the environment. The complex nature of this distributed extractive industry with limited impact data makes establishing possible effects and designing appropriate regulatory response challenging (Rahm and Riha, 2012). However, according to Porter (1991) strict environmental regulations do not inevitably hinder competitive advantage against foreign rivals; indeed, they often enhance it. Challenging uniform standards trigger innovation and upgrading. The “shale rush” has received much attention throughout the last decade, but the advent of natural gas originated centuries ago.

Oklahoma Production

While conventional sources of natural gas are declining, unconventional sources like shale gas are rapidly increasing due to the accessibility and feasibility that the contemporary technologies have provided. Oklahoma is a major player of the shale revolution in the United States and prior to the development of the technology and discovery of new reservoirs, it was listed six times amongst the 509 giant oil and gas fields in the world. A giant is defined as having 500 million barrels of recoverable oil or equivalent gas (Carmalt and St. John, 1986). Following the success of the Barnett Shale in the Fort Worth Basin of Texas, Kuuskraa (2011) recognized the Woodford Shale of Oklahoma as one of the "magnificent seven" (Barnett, Fayetteville, Haynesville, Marcellus, Woodford, Horn River, and Montney) gas shale plays in North America. Being a hydrocarbon source rock and having a brittle (silica-rich) lithologic character makes the Woodford Shale (Late Devonian to Early Mississippian) an important oil and gas shale in Oklahoma (Cardott, 2012). Beginning in 2004, Woodford Shale plays centered on producing thermogenic (heat generated) methane in the western Arkoma Basin in eastern Oklahoma. The plays later occurred in other geologic provinces in Oklahoma expanding to include oil, condensate, and biogenic methane (formation from methanogenic bacteria) production (Cardott, 2012). Crude oil in Oklahoma has been produced from the Cherokee Platform in the northeastern part of the state since early in the 20th century. However, the largest single source of hydrocarbons was gas produced from the Anadarko Basin as it can be depicted in Figure 2.6 retrieved from Boyd (2005).

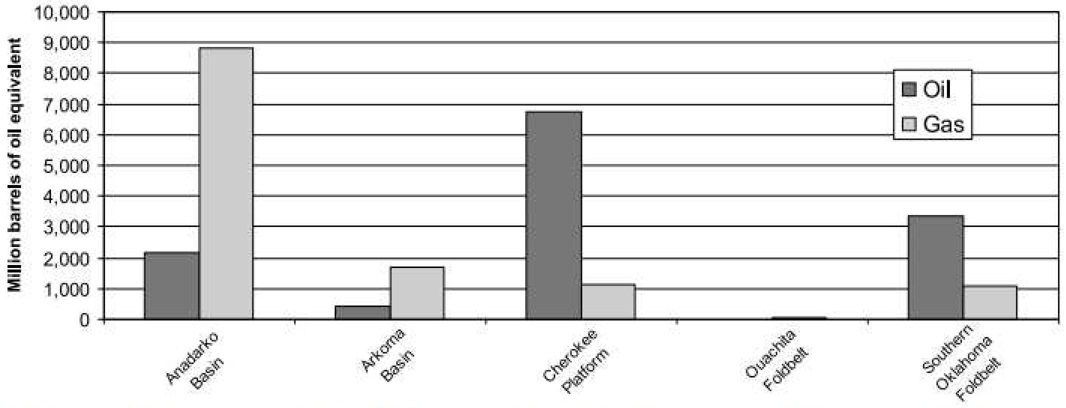


Figure 3. Cumulative production of oil and gas in Oklahoma, in equivalent energy (1 barrel of oil = 6,000 cubic feet of gas). IHS Energy (2004).

Figure 2.6: Cumulative production of oil and gas in Oklahoma. Reprinted from "Oklahoma oil and gas production: Its components and long-term outlook", by D.T. Boyd, 2005, Oklahoma Geology Notes, 65(1), 4-23. Retrieved from http://www.ogs.ou.edu/fossilfuels/pdf/LongTermOutlook.pdf

While HF has been described, it is important to mention that the data that will be presented in this research includes oil and gas drilling from conventional and unconventional formations that may or may not have been hydraulically fractured. The socio-economic issues related to the topic of HF will not be discussed in this study.

Quantification and Occurrence Potential

Identification of risk, the potential for occurrence of an event and impact of that event, is the first step in improving a process by ranking risk elements and controlling potential harm from occurrence of a detrimental event (King, 2012). There is minimal research focusing on the spatial study of environmental and human risks of high volume hydraulic fracturing process, which is necessary for state and federal governments to administer, regulate, and assess fracking (Meng, 2015). It is therefore time for decision makers and scientists to pay closer attention to the spatial planning of hydraulic fracking, prioritizing the issue of distance to a hydraulic fracking well in environmental impact assessments (Meng, 2014)

Spills

The most commonly reported accidents leading to environmental contamination are surface spills, which can happen on-site (including well blowouts and casing failures) or during transportation to or off the site via pipelines, trains, or trucks (Kahrilas et al., 2014). Spills or leaks of hydraulic fracturing and flowback fluids can pollute soil, surface water, and shallow groundwater with organics, salts, metals, and other constituents (Vengosh et al., 2014). A 2013 publication by Walton and Woocay affirm that the primary threat to surface and shallow groundwater from hydraulic fracturing is from spilled or released material on the earth's surface. They further express that wells are normally completed far below the depth of groundwater aquifers by about a factor of 10 (thousands of feet for gas versus hundreds of feet for useful water). The 2016 EPA report indicates that the severity of impacts on water quality from spills of hydraulic fracturing fluids or additives depends on the identity and amount of chemicals that reach groundwater or surface water resources, the toxicity of the chemicals, and the characteristics of the receiving water resource. Accidents will result in localized contamination of surface and shallow groundwater with any of the chemicals associated with drilling, hydraulic fracturing, and gas production (Walton and Woocay, 2013). For this reason, identifying the most susceptible surface and ground waters in the state is imperative in order to better protect these. Because prevention is the key to helping ensure that future practices do not result in ground-water contamination, it is now more important than ever to use planning and management tools to help recognize the places where certain activities pose a higher risk (Aller, 1985).

Unplugged Wells

Petroleum production, drilling operations, and improperly sealed abandoned wells have the potential to cause major contamination of groundwater in petroleum-producing states (Kharaka et al., 2013). Locating historical unplugged wells should be a priority at the time. With regard to the impact pathways involved, a distinction has to be made between production wells and old wells, such as wells from other explorations and uses (Bergmann et al., 2014). According to Gass et al., (1977) unplugged old wells are considered a threat to ground water reservoirs and the total impact of the hazard is not fully understood, nor apparent. The same study reviews cases of ground water pollution caused by unplugged wells.

> “A classic example of problems that can arise from abandoned wells has occurred in Colorado. In 1915, an oil test hole was drilled in west-central Colorado to a depth of 560 m (1,837 ft.). This well encountered warm, mineralized water. Fifty-three years later, on May 9, 1968, the well was found to be discharging 7,338 cu m/d (1,350 gpm) of brackish water with a concentration of 19,200 mg/l dissolved solids. It was estimated that this flow contributed 52,000 metric tons (57,000 tons) of dissolved solids per year to the White River. The well was subsequently plugged, after which the hydrostatic pressure built up,

> causing other non-flowing wells in the area to flow, and creating saline seeps in the vicinity of these wells." (Miller, et., 1974, Gass et al., 1977).

Two decades ago, the US EPA estimated that there were at least 1.2 million abandoned oil and gas wells in the United States (EPA, 1987). Also, about a million oil and gas wells were drilled prior to a formal regulatory system (IOGCC, 2008). Unplugged or improperly plugged wells act as natural conduits for the movement of oil, gas, salt water, or other deleterious substances into any groundwater strata through which the well may have been drilled (Wright, 1986). Ground water contamination caused by abandoned wells could be reduced with increased awareness and education of state and federal regulatory agencies. Increased awareness of the problem should lead to new regulations and more stringent enforcement of these regulations (Gass et al., 1977, p. 3).

Regulation and Data Management

Fracturing wastes are not regulated as a hazardous waste under the Resource Conservation and Recovery Act, and fracturing wells are not covered under the Safe Drinking Water Act. Only recently has the Environmental Protection Agency asked fracturing firms to voluntarily report the constituents in the fracturing fluids based on the Emergency Planning and Community Right-to-Know Act (Osborn et al., 2011). Greater stewardship, knowledge, and possibly regulation are needed to ensure the sustainable future of shale-gas extraction (Osborn et al., 2011). These laws have shortcomings including nondisclosure of proprietary or "trade secret" mixtures, insufficient penalties for reporting inaccurate or incomplete information, and timelines that allow for after-the-fact reporting (Maule et al., 2013). Interagency and interstate coordination of activity is also increasingly critical, alongside the need for data integration between disparate data systems that will lead to better data analysis capability and increase transparency. (GWPC, 2009). Effective management will likely come down to an ability to recognize key characteristics of a region, and to learn and adapt over time (Rahm and Riha, 2012). Bergmann et al. (2014) argue that new data is needed to answer questions related to hydraulic fracturing. Enhanced data management of the reported complaints could translate data into information that would aid in calculating the effects of these practices and infringe regulation accordingly.

Concluding Comment

Analyzing the spatial distribution of water related incidents and delineating the most vulnerable aquifers and surface waters would be more meaningful for administrators and planners to understand how water might be affected at a specific location. It is necessary for data to be collected, stored, and managed in a way that achieves maximum productivity in order to quantify the annual impact of hydrocarbon production.

References

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US Environment Protection Agency, Ada, Oklahoma, EPA/60012-87/035.

Bergmann, A., Weber, F. A., Meiners, H. G., & Müller, F. (2014). Potential water-related environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natural gas reservoirs in Germany. *Environmental Sciences Europe*, *26*(1), 10.

Boyd, D. T. (2005). Oklahoma oil and gas production: Its components and long-term outlook. *Oklahoma Geology Notes*, *65*(1), 4-23.

Cardott, B. J. (2005). Coalbed-methane activity in Oklahoma, 2004 update. In *Unconventional energy resources in the southern Midcontinent, 2004 symposium: Oklahoma Geological Survey Circular* (Vol. 110, pp. 69-81).

Cardott, B. J. (2012). Thermal maturity of Woodford Shale gas and oil plays, Oklahoma, USA. *International Journal of Coal Geology*, *103*, 109-119.

Donaldson, E. C., Alam, W., & Begum, N. (2014). *Hydraulic fracturing explained: Evaluation, implementation, and challenges*. Elsevier.

EPA, 1987. Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy. Office of Solid Waste and Emergency Response, Washington, D.C. http://nepis.epa.gov/Exe/ZyPDF. cgi?Dockey¼20012D4P.PDF

Evensen, D. T., Clarke, C. E., & Stedman, R. C. (2014). A New York or Pennsylvania state of mind: social representations in newspaper coverage of gas development in the Marcellus Shale. *Journal of Environmental Studies and Sciences*, *4*(1), 65-77.

Haugen, J. (1998). Rotary steerable system replaces slide mode for directional drilling applications. *Oceanographic Literature Review*, *8*(45), 1471.

Gass, T. E., Lehr, J. H., & Heiss, H. W. (1977). *Impact of abandoned wells on ground water*. US Robert S. Kerr Environmental Research Laboratory.

Kharak, Y. K., Thordsen, J. J., Conaway, C. H., & Thomas, R. B. (2013). The energy-water nexus: potential groundwater-quality degradation associated with production of shale gas. *Procedia Earth and Planetary Science*, *7*, 417-422.

Kahrilas, G. A., Blotevogel, J., Stewart, P. S., & Borch, T. (2014). Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation, and toxicity. *Environmental science & technology*, *49*(1), 16-32.

King, G. E. (2012, January). Hydraulic fracturing 101: what every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. In *SPE hydraulic fracturing technology conference*. Society of Petroleum Engineers.

Maule, A. L., Makey, C. M., Benson, E. B., Burrows, I. J., & Scammell, M. K. (2013). Disclosure of hydraulic fracturing fluid chemical additives: analysis of regulations. *New Solutions: A Journal of Environmental and Occupational Health Policy*, *23*(1), 167-187.

Meng, Q., & Ashby, S. (2014). Distance: A critical aspect for environmental impact assessment of hydraulic fracking. *The Extractive Industries and Society*, *1*(2), 124-126.

Meng, Q. (2015). Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA. *Science of the Total Environment*, *515*, 198-206.

Miller, D. W., DeLuca, F. A., & Tessier, T. L. (1974). *Groundwater Contamination in the Northeast States. US Environmental Protection Agency publication no*. EPA-660/2-74--056.

Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing: history of an enduring technology. *Journal of Petroleum Technology*, *62*(12), 26-40.

Morton, M. Q. (2013). Unlocking the Earth: A Short History of Hydraulic Fracturing.

Murray, K. E. (2013). State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, US. *Environmental science & technology*, *47*(9), 4918-4925.

Oil, I. Gas Compact Commission (IOGCC). 2008. Protecting Our Country's Resources: The States' Case; Orphaned Well Plugging Initiative. Report prepared for US Department of Energy, National Energy Technology Laboratory.

Osborn, S. G., Vengosh, A., Warner, N. R., & Jackson, R. B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences*, *108*(20), 8172-8176.

Rahm, B. G.; Riha, S. J. Toward strategic management of shale gas development: Regional, collective impacts on water resources. Environ. Sci. Policy. 2012, 17, 12−23.

U.S. EPA. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F, 2016.

Smith, S.V. (2016, September 27). How an Engineer's Desperate Experiment Created Fracking. Retrieved from https://www.npr.org/2016/09/27/495671385/how-an-engineers-desperate-experiment-created-fracking

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology*, *48*(15), 8334-8348.

Walton, J., & Woocay, A. (2013). Environmental issues related to enhanced production of natural gas by hydraulic fracturing. Journal of Green Building, 8(1), 62-71.

Wright III, H. W. (1986). Oklahoma's Groundwater: Reducing the Pollution Caused by Improperly Plugged Oil and Gas Wells. *Tulsa LJ*, *22*, 581.

CHAPTER III

QUANTIFYING HYDROCARBON PRODUCTION COMPLAINTS IN OKLAHOMA USING ENVIRONMENTAL COMPLIANCE REPORTS

Abstract

A great deal of speculation has been generated following the most recent “shale rush” as it became one of the most significant energy developments of the last two decades. Different scholarly views have contemplated and hypothesized about the various components of both practices and the potential environmental effects. However, minimal effort has been invested in quantifying the reported impacts or actual occurrences. This paper represents the first comprehensive inventory of the reported oil and gas incidents and complaints in the state of Oklahoma. This was accomplished by obtaining a list of compliance environmental reports, sorting through 11,144 incidents, classifying them manually in order to quantify the different occurrences and determine the distribution of the most accountable complaints in the state. It was found that almost half of the incidents reported (48%) were accidents and 35% of the incidents indicate the diligence of the state to address and remediate historical sites. Misconduct was observed in 9% of the total incidents and complaints that could affect health represented 5% of the total reported incidents in five years. It was also observed that data entries need to be more consistent and follow a defined framework in order to facilitate data management and environmental record tracking.

Introduction

Trends in Energy Prices and Production

Oil and gas or hydrocarbons are the most used energy source worldwide, accounting for 36.4% of primary energy consumption (EIA, 2006) and 94.5% of global energy used for transportation (OECD/IEA, 2008a, Maggio and Cacciola, 2009). In 2003, the price of a barrel of oil increased from 30 USD to 60 USD by 2005. Based on data from the Energy Information Administration (EIA) the price of oil per barrel peaked in July 2008 at 145 USD and within six months by December 2008 dropped to 32 USD. Given the uncertainty in the drastic fluctuations in price, drilling activity plunged in mid-2009 but started steadily increasing in 2010 until it leveled near the end of 2011 as shown in Figure 3.1. It is evident that the number of active rigs was correlated to the price of the barrel of oil with a lag in rig count of about six months.

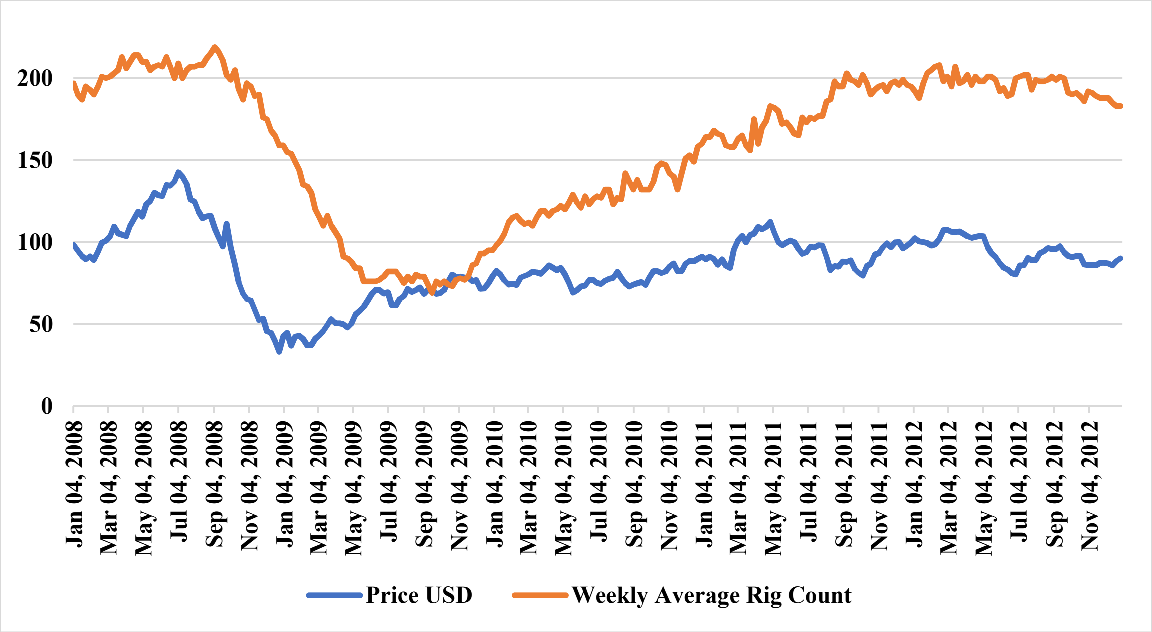


Figure 3.1: Oklahoma weekly average rig count data obtained from Baker Hughes (2018) and weekly average price of oil data obtained from EIA (2018).

The price of oil has since decreased to an annual average of 43 USD in 2016 as has the number of active drilling rigs. Since then, oil prices have increased slowly but steadily to up to an annual average of 67 USD for 2018 as shown in Figure 3.2. The consequent number of active rigs in the state continued to decline up to 2013 when production activity re-emerged to an annual average of 199 active rigs. From this point on towards 2016, a second plunge in production is evident reaching an annual average of 69 rigs, which is even lower than the 2009 plunge with an annual average of 94 active rigs. The number of active rigs has been increasing since 2016 and is currently at an annual average of 134 for 2018.

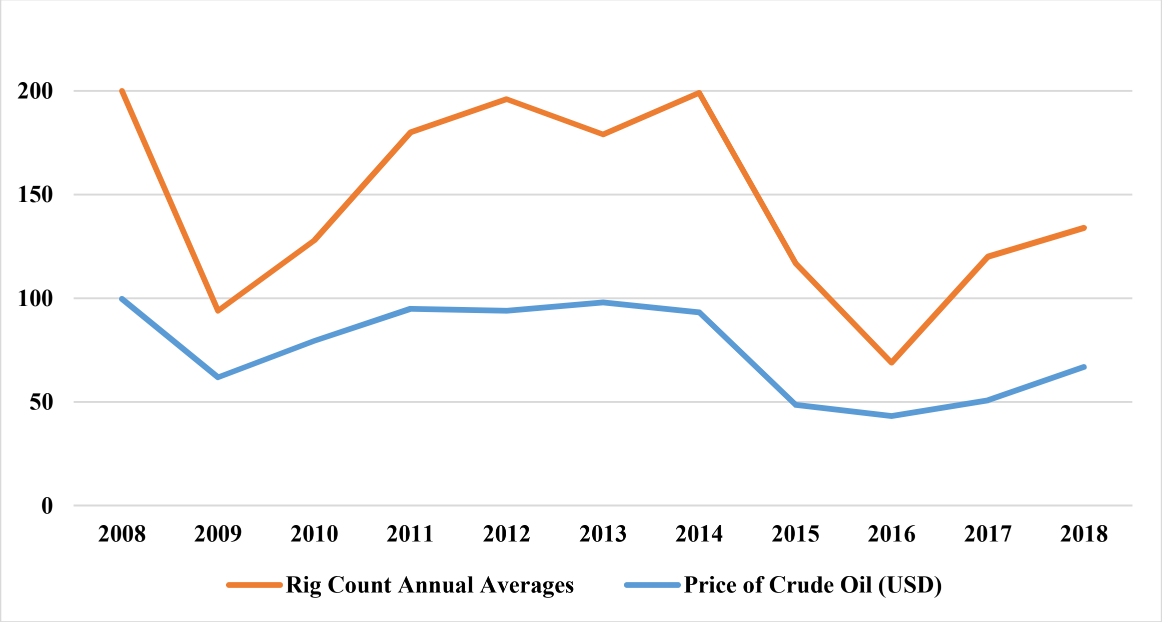


Figure 3.2: Oklahoma annual average count of rigs obtained from Baker Hughes and annual average price of oil obtained from EIA.

Regulations

The Energy Policy Act of 2005 exempts fluids used in hydraulic fracturing from regulatory action under the Clean Water Act, the Safe Drinking Water Act, and the Comprehensive Environmental Response, Compensation, and Liability Act (Kosnik, 2007). The lack of federal regulatory authority has led to fractured and fragmented regulatory policy nationwide, increased court action, and interstate conflict over the transport of fracking waste across state lines (Warner and

Shapiro, 2013). It is the responsibility of each state to develop regulations, rules and procedures to protect the environment as energy growth opportunities stem in the absence of applicable federal law and regulation. It is also the state responsibility to oversee oil and gas operations, ensure policy implementation and disclose information to the public.

The Oklahoma Corporation Commission (OCC) was formed in 1907 to regulate public service corporations, railroads, telephones, and telegraphs, and has jurisdiction in 76 of the 77 counties. Under the Oklahoma Enabling Act of 1906, the OCC lacks jurisdiction over Osage county, which is governed by the Osage Nation. In 1914, the OCC started regulating oil and gas. At the time, the organization was significantly understaffed and the lack of inspectors forced it to rely on an honor system in which the industry would self-regulate. Numerous oil spills and fires were unreported and unattended because each producer would gauge the consequences of their actions in the field. Gas was flared and coal was wasted in large amounts, this alerted the federal government to extend its authority over Oklahoma (Boyd, 2008). In 1914, the Oklahoma Independent Petroleum Association advocated regulation of the industry, with the focus on portioning, dividing and distributing funds and responsibilities. Nowadays, as stated in Title 165: Corporation Commission, Chapter 10: Oil and Gas Conservation; "it is the duty of the Conservation Division to administer and enforce the statues of this State and the rules, regulations, and orders of the Commission relating to the conservation of oil and gas and the prevention of pollution in connection with the exploration, drilling, producing, transporting, purchasing, processing, and storage of oil and gas, and to administer and enforce the applicable provisions of the Natural Gas Policy Act of 1978". The Conservation Division of the OCC has the right at all times to inspect any oil and gas properties, pipelines, tank farms, refineries, and other processing plants and pump stations. Some of these facilities may require testing or retesting of any oil, gas, injection, or disposal well for which the conservation division will provide with a 48-hour notice. It is mandatory for an initial mechanical test for enhanced recovery injection wells and disposal wells to take place. This is a pressure test of the casing tubing annulus according to the minimum testing standards that are set by an authorized injection pressure permit Form 1075. Any operator that fails to comply with initial mechanical integrity testing of the well may be fined up to $500 (OAC 165:10-5, p. 77).

Data Management

The Oil and Gas division of the corporation records and addresses drilling complaints through the Environmental Compliance Reporting System (ECRS), which was in place until May 2013, and the present Risk Based Data Management System (RBDMS). Data is open to the public and can be obtained with an open records request but comprehensive and inclusive environmental information is limited. Cheng and Han (2016) on the topic of big data and hydroinformatics state that utilization of the currently available data is challenging due to the uncertainties of the data, the challenges of processing and the lack of ideas of data utilization. All of these three factors were evident when sorting through the database. There is a clear need and opportunity to use the existing OCC databases to quantify the impacts of oil and gas production in Oklahoma. In this research, the data has been put to work by manually organizing five years of nominal data including over 10,000 records of incidents and complaints. This is the largest and most detailed analysis of the database according to members of the OCC. An enormous amount of data has been collected by state agencies and used for narrow, specific purposes of the present-day but the data has not been examined in its entirety. The purpose of this study is to interpret, sort and classify five years of data to integrate it into a useful visual display of information. This will encourage the utilization of related or proximate incidents and the correlation amongst data points to discover the big trends. Mining through countless data entries could unleash knowledge discovery and innovative scientific exploration through information-based research. The next two following chapters will uncover spatial distribution trends derived from the data processed in this study.

Methods

Data Sorting

An Excel spreadsheet containing a list of *Incident and Complaint Investigation Reports* (1085-forms) was obtained in August of 2013 through direct contact with staff of the OCC. The list contained 94,546 records dating from July 1993 to May 2013 and 100 different fields containing information about the reported complaint. A 10-digit and 4-letter complaint number identifies each distinct record, and each individual record or complaint could be classified as multiple categories depending on the reported information. Most of the description of the complaint was contained in the field titled “allegations” but when this field was inconclusive or difficult to interpret the “findings” and “recommendations” fields would in most cases include information that would aid in categorizing the event. The raw nominal data was at times missing, inconclusive, or difficult to interpret impending the proper identification of incidents for potential remediation continuation and environmental policy record tracking.

Data Classification

The last five full calendar years of incidents were selected from the extended list for sorting and classification. The selected list contained 11,144 incidents reported from January 2008 to December 2012. With the purpose of facilitating interpretation, these occurrences were manually classified into 5 categories and 12 sub-categories included in Table 3.1;

Table 3.1: Categories and subcategories created for incidents and complaints

1. Accidents	1a. Produced Fluid Spill
	1b. Hydrocarbon Spill
	1c. Undefined Leak/Discharge
	1d. Soil Contamination
2. Misconduct	2a. Permit Violations
	2b. Unpermitted Discharges
3. Non-producing	3a. Trash and Debris
	3b.Unplugged Wells
	3c. Unattended Facilities
4. Health	4a. Surface Water
	4b. Ground Water
	4c. Odor
5. Other	5. Vandalism, Fires, Cattle intrusion, etc

The logic behind the five different categories is that a*ccidents* will tend to happen in any of the energy development industries; however, *misconduct* could be almost eradicated with stricter disciplinary action, *non-producing* shows the diligence of the state to address and restore old sites and *health* may well be promoted by identifying the source and recurrence of the detriment. The state of Pennsylvania is an example in which a revision of the regulations decreased and eventually eradicated water pollution from 0.7% of total incidents reported in 2010 to 0 events reported in 2015 (Raimi, 2018). The sub-categories are defined as follows:

Accidents:

Produced fluid spills and oil spills refer to spills where the discharged fluid was reported. These spills might have occurred due to human error, equipment malfunction, weather changes or during transportation. The inspector's description in the raw data or 1085 form includes at times the reason or cause of the spill. The spills in this category have been reported and an immediate attempt to remediate has taken place.

Soil contamination refers to soil that has been contaminated because of an accidental discharge, leak or spill.

Undefined Leak/Discharge refers to leaks in the equipment or from underground or surface piping, tubing or casing. This category also includes discharges for which the fluid differs from oil or water, and in some occasions the fluid was not disclosed. The events in this category have been reported and an immediate attempt to remediate has taken place.

Misconduct:

Permit violations refers to the failure to obtain permits or operating with expired permits. It also includes cases in which signs are not properly posted and/or illegal activities are taking place such as unlined pits, failure to close reserve pits within the required period, and land application violations. It will also include cases related to pressure limits and mechanical integrity tests (MIT), in which an injection well is tested to insure there are no leaks and pressure limits.

Unpermitted Discharge refers to the intentional discharge or dumping of fluids. It also includes spills that have not been reported and have not been attended after notification. Discharges and spills that lack further information, but have been referred to the pollution abatement department of the OCC, are classified into this category.

Non-producing:

Trash and debris refers to reported trash and debris that have been left on site.

Unplugged wells refers to oil and/or gas wells that are not producing and have not been plugged and are at times seeping or purging (a term often used in the raw database for leaking and/or bubbling).

Unattended facilities refers to equipment, storage tanks, and tools left on site. It also includes wells for which the status is uncertain as they appear to have been abandoned and sites that have not been restored after completion and/or sites that need maintenance and are referred to the Oklahoma Energy Resources Board (OERB) for remediation.

Health:

Surface water refers to surface water bodies that have been compromised by spills.

Ground water refers to domestic water wells that had been reported polluted.

Odor refers to air pollution from venting, foul air smell from the ongoing hydrocarbon activity and from soil farming or land applications of waste. Those activities in and of themselves, may be permitted and legal, but such operations are reported as a nuisance to people that live in close proximity.

Other:

This category includes all other violations that do not repeat with enough frequency to merit a singularized classification such as vandalism and fires.

Results

Quantification and Distribution of Incidents

The results of the analysis through sorting and manual classification of the reported environmental complaints is included in Figure 3.3. Within the five years that were manually classified from 2008 to 2012, and focusing solely on the five created categories, it was observed that the health-related incidents were relatively constant. Misconduct was at its highest on 2008 with the accelerated production, decreased in 2010 and continued to increase through 2012. Accidents is the category with the highest amount of reports in 2008 and 2012. The number of incidents reported decreased in 2009 and 2010 with an evident lag in reporting between these two years as drilling activity significantly decreased. The amount of active rigs are comparable in 2008 and 2012 with annual averages of 200 and 196, respectively; however, the amount of incidents decreases from 3,354 to 3,073.

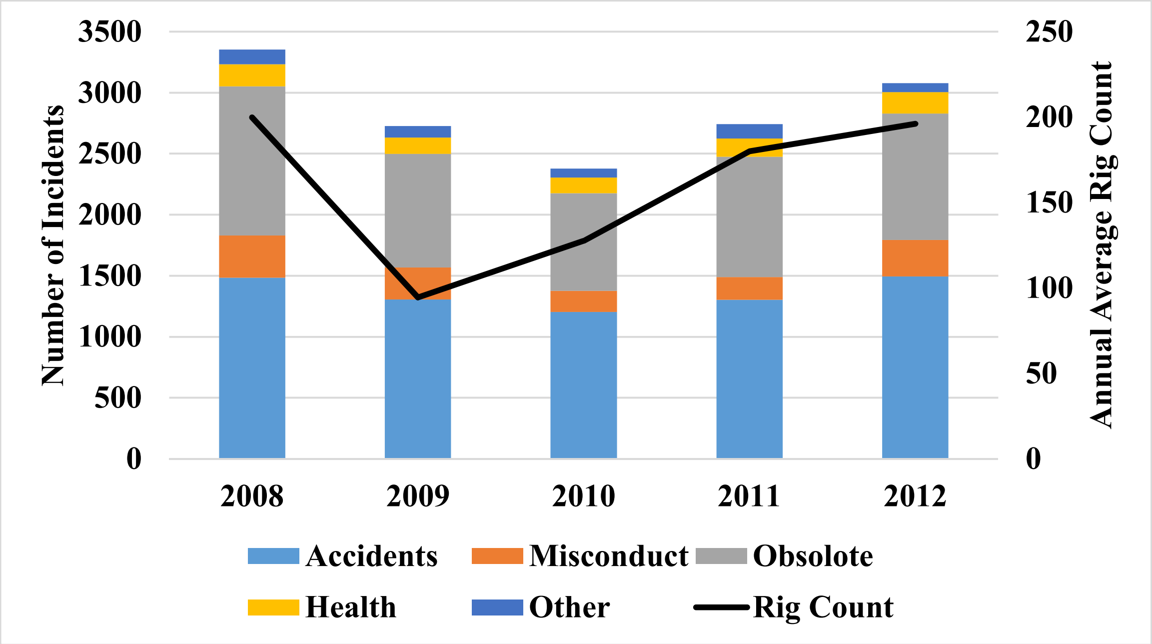


Figure 3.3: Comparison of the assigned categories from 1085 forms and the drilling activity (Baker Hughes) through the years

As it has been mentioned before, one complaint number could be classified under more than one subcategory based on the description of the data entry. A decrease in the number of reported incidents is evident in 2010 which slowly upraises onto 2012. The amount of complaints for each year shows a lag in time of about a year compared to the annual average rig count. The reason for the lag in the number of complaints might be alluded to a decrease in site security and/or attendance, the stage of the well pad, or suggest greater oversight. The percent distribution of the categories is represented as Figure 3.4 which shows a constant percentage in the distribution of incidents throughout the years. The five-year percentage distribution of incidents is included as Figure 3.5 and shows that a great majority of the incidents are accidents at 48%, followed by non-producing at 35%. Misconduct and health account for 9% and 5% of the total incidents reported.

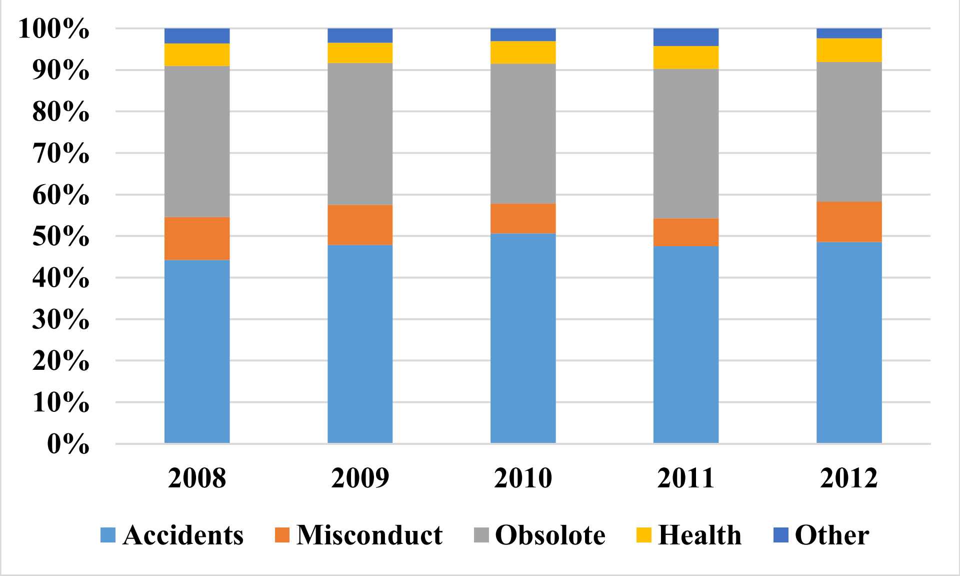


Figure 3.4: Percentage distribution of reported incidents by year.

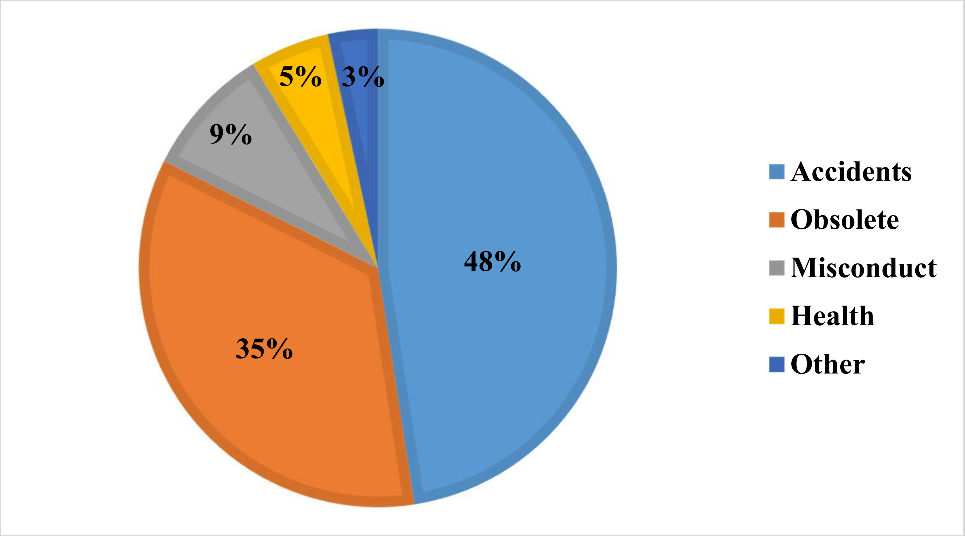


Figure 3.5: Five-year percentage distribution of incidents

Each complaint number was classified within the created subcategories and reckoned in Table 3.2. The most persistent accident was *undefined leak/discharge* with an annual average of 507 incidents. The second most counted accident is *produced fluid spills* with an annual average of 362 incidents. For the misconduct category, the most frequent subcategory was *permit violations* with an annual average of 214 incidents. For the health category, the most recurrent subcategory was *surface water* contamination with an annual average of 81 incidents.

Table 3.2: Classified incidents reported in Oklahoma from 2008 to 2012

		2008	**2009**	**2010**	**2011**	**2012**
1. Accidents	1a. Produced Fluid Spill	375	368	319	351	396
	1b. Hydrocarbon Spill	261	302	247	265	324
	1c. Soil Contamination	254	184	202	199	209
	1d. Undefined Leak/Discharge	593	451	435	489	565
2. Misconduct	2a. Permit Violations	311	237	151	159	211
	2b. Unpermitted Discharges	36	26	21	25	88
3. Non-producing	3a.. Unattended facilities	395	372	306	436	471
	3b.Trash and Debris	544	359	325	347	329
	3c. Unplugged Wells	281	200	169	204	236
4. Health	4a. Surface Water	94	65	77	74	96
	4b. Ground Water	44	32	31	46	51
	4c. Odor	43	36	21	29	29
5. Other	5. Vandalism, Fires, etc	123	94	73	117	73

The distribution of the accidents reported from 2008 to 2012 is illustrated in Figure 3.6 where undefined leak/discharge takes the lead at 37% followed by produced fluid spill at 27%, hydrocarbon spill at 21% and soil contamination at 15%.

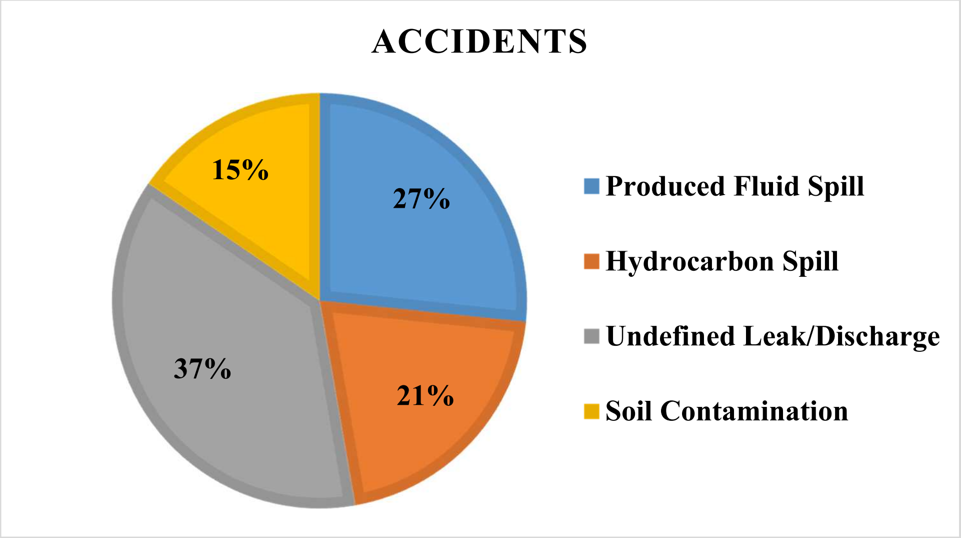


Figure 3.6: Percent distribution of accidents reported from 2008 to 2012

The distribution of misconduct splits 85% for permit violations and 15% for unpermitted discharges as shown in Figure 3.7.

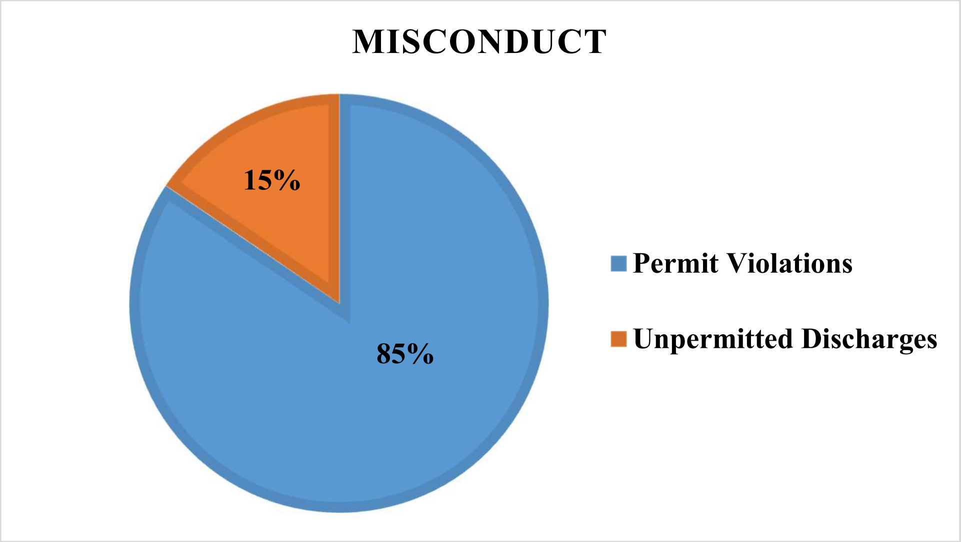


Figure 3.7: Percent distribution of misconduct reported from 2008 to 2012

The percent distribution of non-producing events reported between 2008 to 2012 is shown in Figure 3.8. The most reported incidents within this category is *unattended facilities* at 40%. These sites have been referred to OERB for remediation. *Trash and debris* account for 38% and *unplugged wells* for 22% of the incidents within this category. The unplugged well incidents are plugged in most cases with state funds.

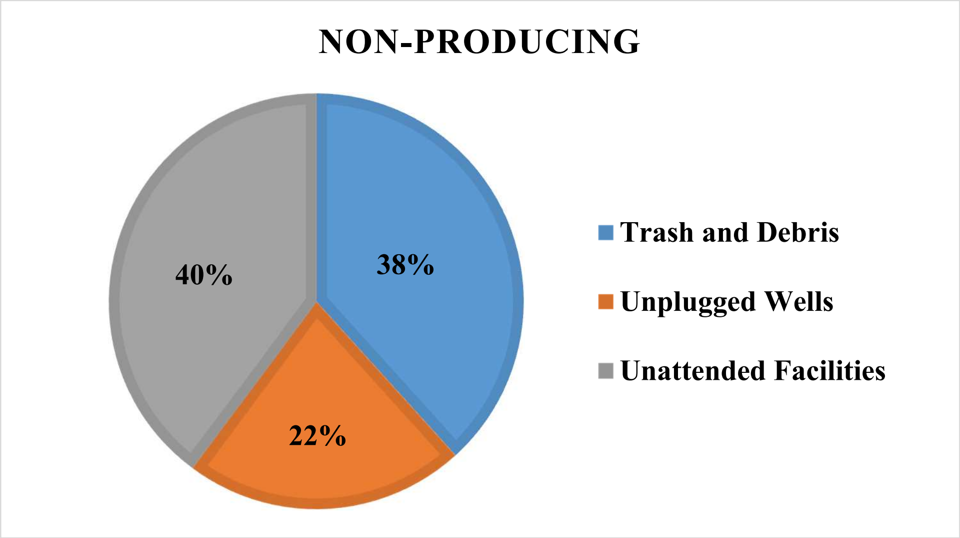


Figure 3.8: Percent distribution of non-producing incidents reported from 2008 to 2012

The percent distribution for health is include as Figure 3.9. Most of the incidents in this category are surface water contamination at 53% of all incidents reported followed by ground water at 26% and odor at 21%.

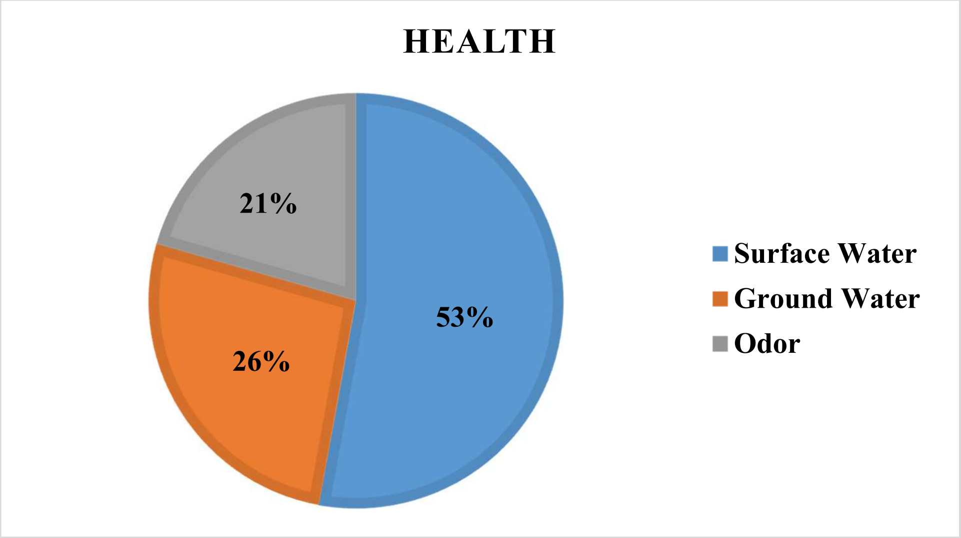


Figure 3.9: Percent distribution of health incidents reported from 2008 to 2012.

The data was analyzed up to the last date included in the list (May 31, 2013). However, the 2013 portion was not included to keep consistency and to only incorporate full calendar years. It should be furthermore noticed that the data from May 2013 to December 2013 was requested for the OCC, but the format was different as it has been entered into a different system (RBDMS). To ensure reliability only ECRS records are compared in this study.

Data Management Observations

Substantial divergence was observed in the nominal data as different field inspectors had entered, in their own words, a description of the site visit they were assigned after a complaint had been reported. At this point, as the inspector entered the information, the incident was individualized in the database. It was also observed that many of the incidents were repeated entries that in some cases shared the same complaint number while in others a new complaint number had been opened for the same site. Site locations were at times not included at all, and in other cases, the longitude was offset to the east, which suggests some systematic error. Incident reporting was highly variable between inspectors and numerous errors in data entry were present. These types of errors are to be expected when data is manually entered without real-time quality control.

Limitations and Discussion

There was not a well-defined conceptual framework set in place to be followed by inspectors when entering data into the database. Incongruent data was created at the time of entering the description of the occurrence which may include more than one of the aforementioned categories. As such, the author had to use her best judgement with the manual classification on many entries.

Isolated applications, such as ECRS and RBDMS, processing data in a standalone fashion are insufficient and an approach is needed to make it easier to combine knowledge with Big Data analysis to provide an integrated enterprise level solution (Tekiner and Keane, 2013). Moreover, Oklahoma is not alone, as some states collect or store data in hard copy or image pdfs, inhibiting analysis unless personnel later digitize the data (Patterson et al., 2017). The 2016 EPA report indicates that data gaps and uncertainties in the available data prevented the calculation or estimation of the national frequency of impacts on drinking water resources from activities in the hydraulic fracturing water cycle. The same EPA report emphasizes on the urgent need to reduce the data gaps and uncertainties to better protect current and future drinking water resources. Thorough scientific investigations are often necessary to narrow down the list of potential causes to a single source at site-specific cases of alleged impacts (EPA, 2016). The database itself presents a real opportunity for improvement in data management that would ultimately address future environmental regulations that would be on the best interest of the public and the industry. Because the information is more valuable than the data it is important to assure consistent data entry and processing to reduce duplicated or incongruous data as well as gaps within the database. The flow of data could strongly benefit from a cycle management that starts at input creation and initial storage to the time when the incident is addressed and dismissed through tiers. These tiers would automate data migration from one tier to another based on specified policies and criteria amongst the linked institutions. For instance, if a reportedly polluted ground water well needs to be referred to the “pollution abatement” department within the OCC or if an unrestored site needs to be referred to OERB the information would automatically and immediately transfer to the corresponding department or institution updating a holistic master state database. As, an example, it was noted that over 30 water supply wells are reported as polluted by hydrocarbon activity annually. These water wells are physically inspected but lack the evidence that the archives and the surroundings could provide. A continuation plan through data management needs to be set in place for some of these water supply wells so that the long-term impacts to ground water reservoirs could be understood. Although, regulations have been set in place by the OCC to protect ground water it is important to keep record track, link nearby reports and investigate deeper into the source and cause of the pollution. It is imperative to track the environmental reported activity until the most probable explanation for the trends is proven. Substantial observational support could be accumulated just by systemizing and digitizing the reported data because “verifiable facts always take precedence”.

The results in this study suggest that the inconsistent wording arises in the context that every field inspector is different and there is currently not a well-defined conceptual framework to be followed. In this rapidly evolving world, it is necessary to match the accelerated progress of the technologies applied in the field for exploration, exploitation and production to those of incident reporting and environmental record tracking. It is time for automated approaches, such as software applications, to be adopted as a more effective method of managing incident reporting, tracking corrective and preventive actions, and allowing for a real-time interface to interconnect the field and the state environmental offices. Tracking up-to-date environmental concerns and actual occurrences in the state with a finger tap or the click of a button could lead to more informed policy decisions with perhaps more rigorous penalties. Information-based and site-specific research is needed to unravel the trends of this highly debated topic. Incidents classified as affecting water resources, such as surface and ground waters, could be extracted from the structured dataset and further evaluated to assess the localized frequency and recurrence of these impacts and implement protection policies. Likewise, the locations of incidents classified as unplugged wells could be evaluated as potential contamination conduits. The entire raw database from July 1993 to May 2013 has been automatically classified based on query language derived from the manual classification of these five years (2008-2012). The trends observed in the five years that were manually classified could expand to 20 years and provide more insight. It is the responsibility of researchers to direct future studies into information-based, focused, site-specific actual impacts to demarcate tangible occurrences and set objectives based on real events.

Conclusions

The OCC database, while inconsistent, did provide a reasonable visual display of the types of incidents that were reported in this period of time. Incidents were categorized and quantified to discover the trends that led to the selection of certain categories to be evaluated in the next chapters. From 2008 to 2012 the incidents reported were mostly *accidents* representing 48% of total incidents reported. The second category with the most incidents reported was *non-producing* with 35%. *Misconduct* and *health* account for 9% and 5%, respectively.

References

Boyd, Dan T. (2008). Oklahoma: The ultimate oil opportunity. The Shale Shaker 58 (6):205-221.

Cardott, B. J. (2012). Thermal maturity of Woodford Shale gas and oil plays, Oklahoma, USA. *International Journal of Coal Geology*, *103*, 109-119.

Carmalt, S. W., & John, B. S. (1986). Giant oil and gas fields.

Chen, Y., & Han, D. (2016). Big data and hydroinformatics. *Journal of Hydroinformatics*, *18*(4), 599-614.

Oklahoma. 2018. "Administrative Code. Title 165: Corporation Commission. Chapter 10: Oil and Gas Conservation." Available at: https://www.occeweb.com/rules/Ch10eff091418searchable.pdf

Duplantis, 2016. Slide Drilling-Farther and Faster, Steven Duplantis Houston, Texas, USA, Oilfield Review, 28, no. 2, pg 50 (May 2016).

EIA, 2006. World Consumption of Primary Energy by Energy Type and Selected Country Groups, 1980–2006. In: International Energy Annual 2006. Available at: /http://www.eia.doe.gov/pub/international/iealf/table18.xlsS.

Kosnik, R. L. (2007). The oil and gas industry's exclusions and exemptions to major environmental statutes. Oil and Gas Accountability Project/Earthworks, 41.

Kuuskraa, V.A., 2011. Worldwide assessment underscores vast potential of gas shale resources. American Oil & Gas Reporter 54 (5), 40–46

Lord C., Niskern D. & Billingsley P. (2009) Using Geologic Data and GIS to Make Base of Treatable Water Maps that Protect Fresh Water Aquifer, Oklahoma Corporation Commission. http://water.okstate.edu/activities/symposium/2009-symposium/2009-abstracts/Lord2009.pdf.

Maggio, G., & Cacciola, G. (2009). A variant of the Hubbert curve for world oil production forecasts. *Energy Policy*, *37*(11), 4761-4770.

Managi, S., Opaluch, J. J., Jin, D., & Grigalunas, T. A. (2005). Environmental regulations and technological change in the offshore oil and gas industry. *Land Economics*, *81*(2), 303-319.

Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing: history of an enduring technology. *Journal of Petroleum Technology*, *62*(12), 26-40.

Oklahoma Corporation Commission Title 165: 10 Oil and gas conservation rules (Available at: http://www.occeweb.com/rules/CH10eff08-27-15searchable.pdf)

OECD/IEA, 2008a. World Energy Outlook 2008, Paris. ISBN: 978-92-64-04560-6.

Pal, A., Gin, K. Y. H., Lin, A. Y. C., & Reinhard, M. (2010). Impacts of emerging organic contaminants on freshwater resources: review of recent occurrences, sources, fate and effects. *Science of the total environment*, *408*(24), 6062-6069.Porter ME (1991) America’s green strategy. Sci Am 264(4):168.

Panel on Scientific Responsibility and the Conduct of Research, National Academy of Engineering National Academy of Sciences (Institute of Medicine), Institute of Medicine, National Academy of Sciences, & National Academy of Engineering. (1992). *Responsible Science. Volume 1: Ensuring the Integrity of the Research Process*. National Academies Press.

Patterson, L. A., Konschnik, K. E., Wiseman, H., Fargione, J., Maloney, K. O., Kiesecker, J., ... & Saiers, J. E. (2017). Unconventional oil and gas spills: Risks, mitigation priorities, and state reporting requirements. *Environmental science & technology*, *51*(5), 2563-2573.

Raimi, D. (2018, February 14) The Fracking Debate [Audio podcast] Retrieved from https://sanford.duke.edu/articles/fracking-debate-podcast.

Tekiner, F., & Keane, J. A. (2013, October). Big data framework. In *Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on* (pp. 1494-1499). IEEE.

US Environmental Protection Agency. (2016). Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States.

Warner, B., & Shapiro, J. (2013). Fractured, fragmented federalism: A study in fracking regulatory policy. *Publius: The Journal of Federalism*, *43*(3), 474-496.

Data

Hughes, B. (2018). North America Rig Counts.

Oklahoma Corporation Commission (2013). Incident and Complaint Investigation Reports (1085 forms).

U.S Energy Information Administration (2018). Cushing, OK WTI Spot Price (Dollars per Barrel).

CHAPTER IV

EVALUATING THE SPATIAL DISTRIBUTION OF UNPLUGGED WELLS AND POLLUTED WATER WELLS IN OKLAHOMA

Abstract

Unplugged wells are unsealed exploration boreholes that could act as conduits of contaminants to groundwater reservoirs. The objectives of this study were to locate and quantify unplugged wells and polluted water supply wells reported in Oklahoma annually, and to examine the spatial relationship between those wells. This was accomplished by integrating geospatial analysis in GIS and the locations of compliance state records (1085 forms). The patterns of localization and distribution of unplugged wells were examined with geo-information technology to bring out the influence of spatial factors in the reporting of affected water supply wells. Up to now, information about the spatial relationships of reported groundwater pollution is limited in Oklahoma. It was found that 204 water wells were reported polluted within five years, of which 84 were referred for further evaluation and analysis after the initial site visit. The spatial distribution of the referred water wells was correlated to the spatial occurrence of reported unplugged wells. Spatial clusters for both types of wells were identified in the north-central region of the state showing elevated numbers of unplugged wells concurrent with the locations of historical oil and gas fields. Groundwater contamination caused by the transport of pollutants through unplugged wells could be eliminated with increased awareness of the spatial patterns and occurrences of these conduits.

Introduction

Numerous scholarly sources suggest a direct connection between unplugged wells and the pollution of ground water reservoirs. According to IHS data over 500,000 oil and gas wells have been drilled in Oklahoma, and there are 107,079 groundwater wells reported by the Oklahoma Water Resources Board (OWRB) on November 2018. The number of oil and gas wells is five times greater than the number of groundwater wells that have been drilled in the state throughout the years. As stated by Jackson et al. (2013), the rapid expansion of the unconventional gas industry has been accompanied by public concern regarding protection of environmental and human health particularly over possible pollution of shallow groundwater by migration of natural gas, formation water, and/or fracturing fluids from deep formations induced by hydraulic fracturing. Furthermore, King and Valencia (2014) add that there is no question that un-plugged or improperly plugged oil and gas wells, dating from 1860's to 1930's and later, are a potential threat. Unmarked wellbores still exist and pose a pollution pathway to aquifers from surface spills and a lesser risk from oil or gas well developments. For this reason, the issue of well age addresses a critical question: Are recently drilled wells safer than older wells? Intuitively, the answer should be "yes." Materials are often better, regulations are often stricter and people learn as they go, tailoring practices to local geology (Jackson, 2014). Two decades ago, the US EPA estimated that there were at least 1.2 million abandoned oil and gas wells in the United States (EPA, 1987); more than 200,000 of these wells appear to be unplugged (EPA, 1987). Improper plugging operations result in orphaned or unplugged wells in which the leakage pathways, natural seepage and cross flow of hydrocarbons and/or formation fluids can occur between the geologic formations. Unplugged or improperly plugged wells act as natural conduits for the movement of oil, gas, salt water, or other deleterious substances into any groundwater strata through which the well may have been drilled (Wright, 1986). To prevent this and to ensure the integrity of the geologic formations and the protection of ground water at the end of the wells useful life, plugging and abandonment operations take place. Well completion must follow statutory regulations and industry best practice (Cheremisinoff and Davletshin, 2015). States in the USA report that somewhere between 828,000 and 1,060,000 oil and gas wells were drilled prior to a formal regulatory system, most of which have no information available in the state databases (IOGCC, 2008). Usealed, abandoned wells and exploration holes constitute a hazard to public health, safety, and welfare, and to the preservation of ground water resources (Gass, et al,. 1977, p.40). It is critical to identify the locations of these unplugged wells and to generate the information needed to assist decision-makers in adopting suitable measures to prevent and reduce ground water pollution.

Study Area

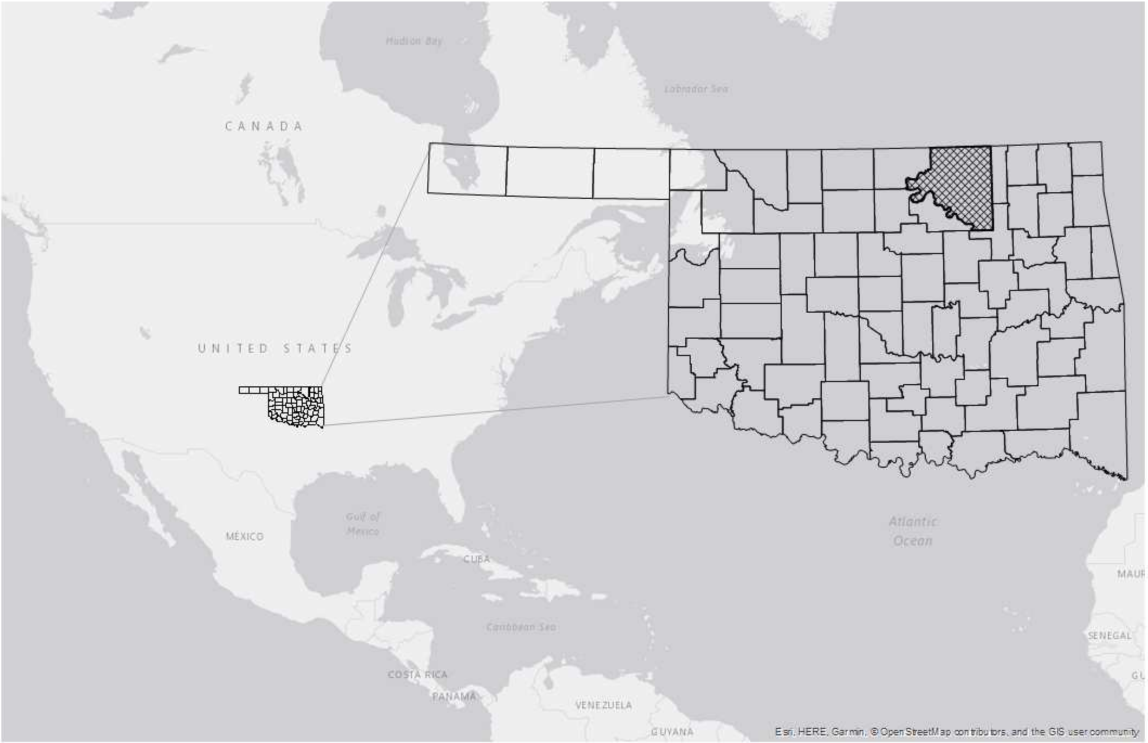


Figure 4.1: Map of Oklahoma within the United States

Oklahoma is one of the 50 states in the United States of America and it is located in the south-central region of the country (Figure 4.1). The state is divided into 77 counties of which the Oklahoma Corporation Commission (OCC) regulates oil and gas activity in 76 of these counties. It lacks jurisdiction over Osage county under the Osage Allotment Act and the Oklahoma Enabling Act of 1906. According to Carney (1981) the total hydrocarbon output of the Cushing field in Oklahoma led the nation in total production of crude oil from 1915 through 1917. The map included below as Figure 4.2 has been digitized and clipped to include only Oklahoma. The original version is archived at the Oklahoma Historical Society (OHS) and it illustrates the locations of historic conventional oil and gas development in the United States.

Figure 4.2: Historical oil and gas fields in Oklahoma. Map clipped from OHS https://www.okhistory.org/research/hl_map5.php#page/0/mode/1up

Currently, Oklahoma is included among the major shale plays rating as the fifth largest crude oil producer in the United States supplying over 4,000 trillion BTUs a year (EIA, 2016). Given the long history of hydrocarbon production in the state, it is now more important than ever to locate all the reported information and zoom out to see the spatial trends and clusters that may lead regulators and decision-makers to instill regulations and best management practices that protect ground water. As stated by Wright (1986) a source of pollution and contamination of Oklahoma groundwater comes from abandoned, unplugged, or improperly plugged oil and gas wells leaking oil, gas, salt water, and other deleterious substances into the groundwater. The state of Oklahoma has been very diligent at locating these wells and plugging them with state funds.

Oklahoma Hydrocarbon Basins

Anadarko: The Anadarko basin extends from west-central Oklahoma into the Oklahoma panhandle and the northern Texas panhandle (Figure 4.3). It is one of the giant oil and gas provinces in North America, with exploration and development activities having started more than 75 years ago (Wang and Philp, 1997). It is a petroliferous basin with a complex history that has benefited from applied aerial geology, remote sensing, advances in deep-drilling technology, and seismic exploration (Trollinger, 1968; Petzel, 1974; Brewer et al, 1983). The water basins with very high vulnerability that included within this basin are the North Canadian River, Washita River, North Fork River, Red River and Canadian River.

Ardmore: The Ardmore basin is located in the south central part of the state covering an area of 80 km by 10 km. It was not until 2005 that the Ardmore Woodford Shale play began to gain interest, and from 2005 to 2011, shale wells produced roughly 662 million cubic feet of gas (MMCF) and 7 thousand barrels of oil (MBO) (Boyd, 2011). The Woodford Shale has historically been considered a mature source rock throughout much of Oklahoma and parts of Texas and New Mexico, and gained reputation as a prolific oil and gas reservoir since the onset of the shale boom in the early 2000’s. It is estimated that the field holds four trillion cubic feet of natural gas (TCF) (Ballotpedia, 2015). In 2010, the USGS conducted an assessment of the Woodford shale in the Arkoma Basin. They estimated that the total undiscovered resource is between 6,065 and 14,036 billion cubic feet (BCF), with a mean of 10,068 BCF. The shale gas resource in the Ardmore Basin has not been evaluated by USGS (Ryan, 2017). The water basin with very high vulnerability that are within the Ardmore is the Red River.

Arkoma: The Arkoma Basin in southeastern Oklahoma and west-central Arkansas is one of the most prolific petroleum-producing basins in North America (Suneson, 2012). The Arkoma Basin consists of Cambrian to Pennsylvanian age rocks that are rich in hydrocarbons (Denison et al., 1989; Walper, 1976). The typical thermal maturity range of oil is 0.5 to 1.35% Rv; condensate is 0.85 to 2.0% Rv; dry gas is 1.0-3.0% Rv (Dow, 1977). Exploratory wells in the deepest part of the Arkoma Basin, still within the Woodford Shale, have Rv values of 3.0% and are known to contain saturated gas (Houseknecht, 2014). The Woodford Shale within the Arkoma Basin is Kerogen type II (Cardott, 2013). The water basins with very high vulnerability located in the Arkoma are the Canadian River and the North Canadian River.

Northeastern Oklahoma/Cherokee Basin: The Cherokee basin in southeastern Kansas, a northern shelf extension of the Arkoma/Anadarko basin complex located farther south in Oklahoma, is part of the American Mid-Continent region (Förster et al., 1998). Geological evidence indicates that this is a field of very active research by the petroleum industry and one that apparently was considered fairly promising (Baker, 1962). The drilling completion reports (1002 A forms) indicate that this basin has been drilled prior to the 1920s and as stated by Baker (1962) continued to be active through the sixties and onto current time. The lower Cherokee is thought to be represented in the Ardmore basin by the relatively thin section of sediments between the Pumpkin Creek limestone and the base of the Bostwick conglomerate, which is something of the order of 400 feet (Lowman, 1933). The water basins located in the Northeastern Oklahoma basin are the Arkansas River, Cimarron River and North Canadian River.

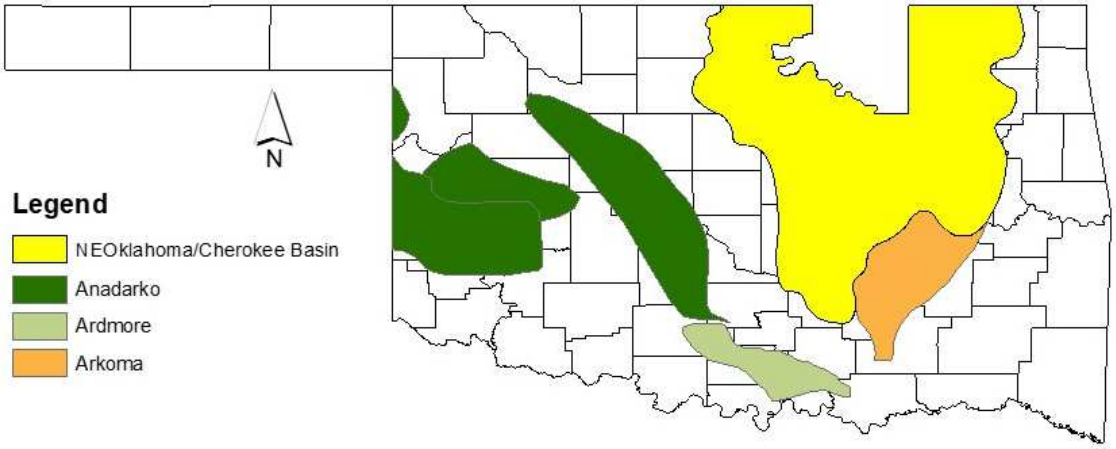


Figure 4.3: Hydrocarbon basins in Oklahoma

Methods

Data Processing

Incidents and Complaints Investigation Reports (1085 forms) were obtained from the OCC. The list of reports included 94,546 of all complaints related to oil and gas activity in the state from July 1993 to May 2013. The last five years in the list were sorted and classified to identify the origin of the complaints. After classifying and quantifying the events, the affected water wells and unplugged wells were selected for this study for further evaluation through spatial analysis. The locations of these incidents were geocoded as x and y coordinates for spatial processing in ArcGIS 10.2. Prior to applying spatial statistics analyses Osage county was extracted from the map due to the lack of oil and gas data. The location coordinates were prepared through data management tools in ArcMap to *integrate* the vertices to a distance of 50 meters and converted to a weighted point feature class through the *collect events* tool to combine coincident points. Given that these data points or counts could not be statistically evaluated individually or as counts of 1, the data points were aggregated by polygons representing each county in the state.

The OHS map included as Figure 4.2 was digitized and a shapefile was created by freehand drawing the portion that included the cluster of historical oil and gas fields. This shapefile and basin delineation is what is referred as the Northeastern Oklahoma/Cherokee basin.

Spatial Autocorrelation

The Incremental Spatial Autocorrelation tool calculates a Moran's I value and produce a z-score to test the null hypothesis that the attribute being analyzed is randomly distributed among the features (Ord and Getis, 1995). Z-scores reflect the intensity of spatial clustering, and statistically significant peak z-scores indicate distances where spatial processes promoting clustering are most pronounced. A positive local Moran's I value refers to the location under study which has similarly high or low values as its neighbors and then the location is called a "spatial cluster". On the other hand, a negative local Moran's I value indicates a potential spatial outlier which is different from the values of its surrounding locations (Lalor and Zhang, 2001). Moran's I is one of the oldest indicators of global spatial autocorrelation and is still used for determining spatial autocorrelation (Mitchell, 2005; Haning, 2003). The attribute similarity of severity indices of two points is defined as the difference between each value and the global mean value (Wong and Lee, 2005).

The Moran's I statistic for spatial autocorrelation is given as (Equation 4.1):

$$I = \frac{n}{So} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i \, z_j}{\sum_{i=1}^{n} z_i^2} \tag{4.1}$$

Where z_i is the deviation of an attribute for feature I from its mean, $w_{i,j}$ is the spatial weight between feature I and j, n is equal to the total number of features, and S_o is the aggregate of all the spatial weights (Equation 2).

$$S_o = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \tag{4.2}$$

The statistical significance for Moran's I can be calculated using z-score methods. Based on the expected values for a random pattern and the variances, the standardized Z-score can be mathematically represented as follows (Equation 4.3):

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \tag{4.3}$$

where:

$$E(I) = \frac{-1}{(n-1)} \tag{4.4}$$

$$VAR(I) = E(I^2) - E(I^2) \tag{4.5}$$

In this study, the Incremental Spatial Autocorrelation tool was used to compute Moran's I statistics and z-scores. Since each data point is analyzed in terms of its neighboring data points defined by a distance threshold, it is necessary to find an appropriate distance threshold where spatial autocorrelation is maximized. This distance is used to evaluate the existence of hot spots which are locations or a small areas within an identifiable boundary that show a concentration of incidents. A weighted point feature was used as the input for running the hotspot function (Getis-Ord GI*) to identify whether features with high values or features with low values tend to cluster in the state without any preconceptions about their locations. Lastly, the Inverse Distance Weighted (IDW) interpolation was applied to estimate values at unsampled points using weighted average of the sampled points within a selected number of neighbors of the unsampled location (Robinson and Metternicht, 2006). The IDW is determined through the following equation

$$W_i = \frac{1/d_i^p}{\sum_{i-1}^{n} 1/d_i^p}$$

Where n is the number of neighboring points used for the calculation, and p is the power parameter, di is the distance between the sampled location and the un-sampled location for which an interpolated value is sought (Isaaks and Srivastava, 1989).

Results

Characteristics of Incidents

A total of 203 incidents of water well pollution occurred within the five-year window between 2008 and 2012. It was found that after the initial inspection of the allegedly polluted water wells, only a portion of these were referred to a different department or state agency for continuation and further evaluation. Some of the reasons for the dismissal of incidents included: solutes consistent with agriculture pollution, wells drilled deeper than the base of treatable water, wells distant from oil and gas production and no observable free hydrocarbons. The year with the highest percentage of water wells referred for additional investigation was 2009 at 69%. The year with the least percentage of water wells referred was 2011 at 24%. The least number of referred water wells was 2010 with eight of these being referred, as can be seen in Table 4.1.

Table 4.1: Annual amounts of reported and referred water wells

Year	Water wells	Referred water wells	Percentage
2008	44	28	64%
2009	32	22	69%
2010	31	8	26%
2011	45	11	24%
2012	51	15	29%

The annual reported and referred water wells is illustrated in Figure 4.4. The 2010 year presents the least amount of reported and referred water wells followed by 2009 and 2012 has the most reported polluted water with only 29% of these being referred. These values could be attributed to a decrease in hydrocarbon production in 2009 and an increase in production in 2012.

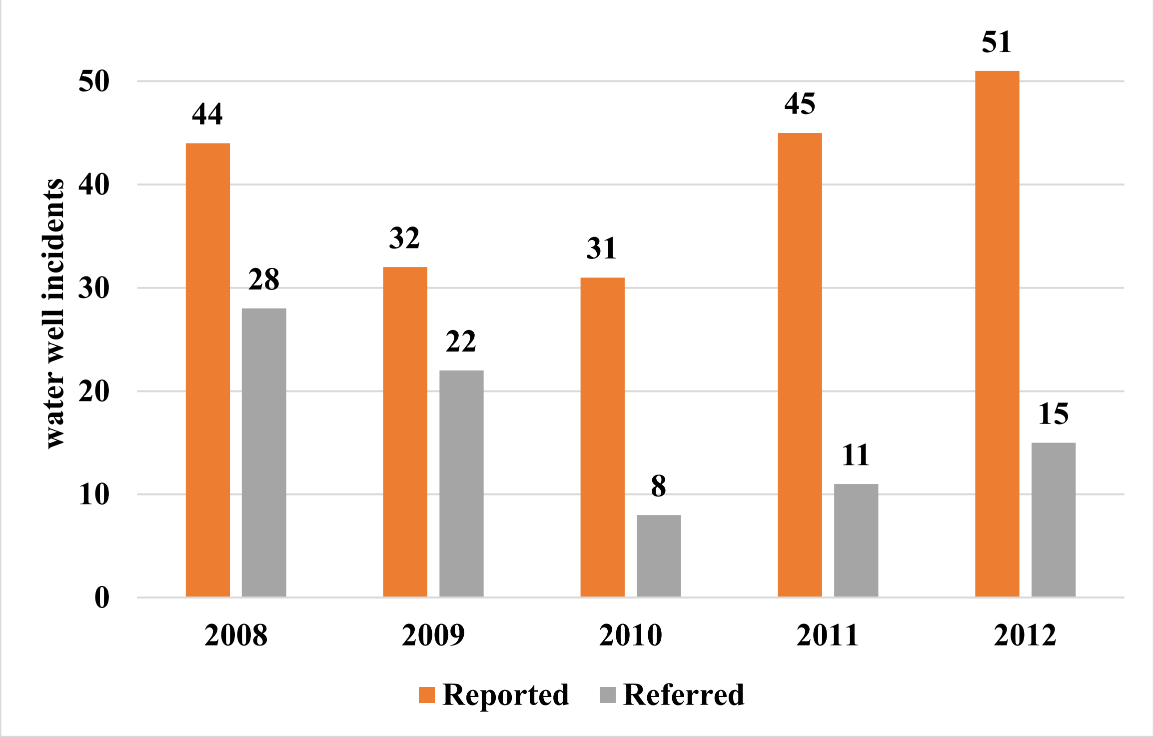


Figure 4.4: Reported and referred water wells by year.

In the same manner, the amount of unplugged wells were quantified and tallied to 1,090 reported between 2008 and 2012 as illustrated in Figure 4.5. The year with the most unplugged wells was 2008 and the year with the least unplugged wells 2010.

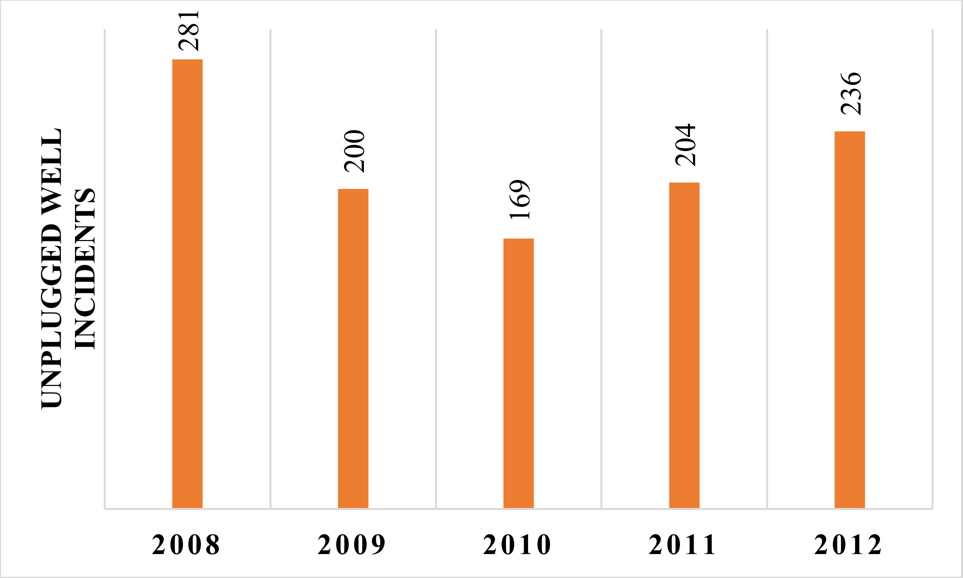


Figure 4.5: Reported unplugged wells by year

Spatial Characteristics of Incidents

Water well incidents were reported in 45 counties in of which Creek County had the most incidents. The referred water well incidents were spread amongst 33 counties with significant spatial clustering in the east-central part of the state as can be seen in Figure 4.6.

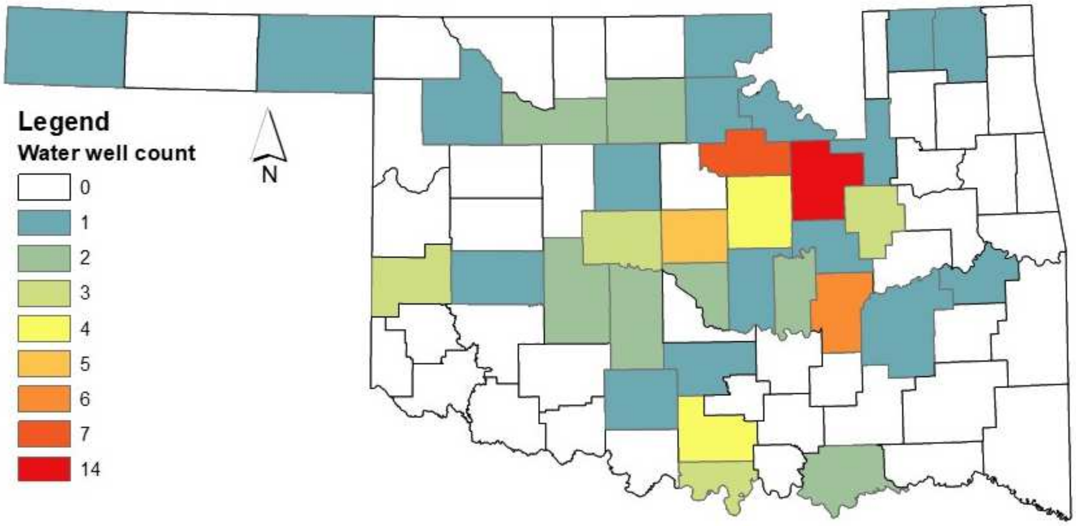


Figure 4.6: Count of affected water wells at the county level

The spatial distribution of affected water through the Oklahoma basins is depicted in Figure 4.7. The majority of these incidents are located in the Northeastern Oklahoma/Cherokee basin and a few are located in between this basin and the Anadarko basin to the east. There are locations that are not contained within a basin and are included in the map.

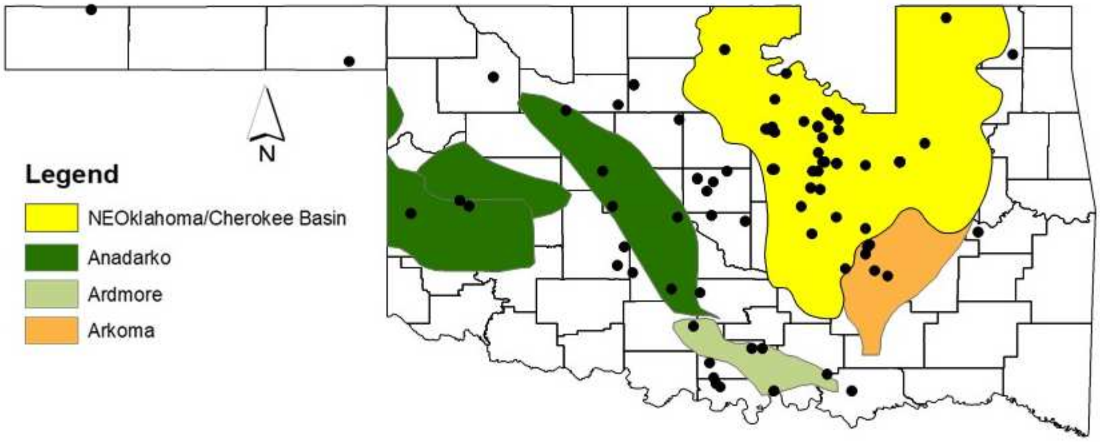


Figure 4.7: Spatial distribution of affected water wells at the basin level

The majority of affected water wells are located in the Northeastern Oklahoma/Cherokee Basin as portrayed in Figure 4.8. Nearly half of the incidents, 46%, are located within this basin while 33% are not located within a basin.

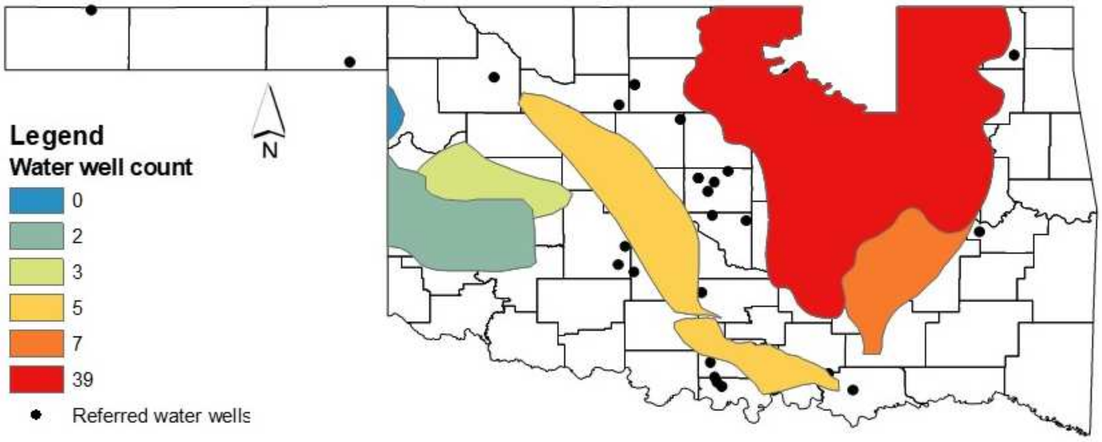


Figure 4.8: Spatial distribution of affected water wells within the basins

The amount of unplugged wells was spread throughout 59 of the 76 counties and mostly clustered through the north-central region of the state (Figure 4.9).

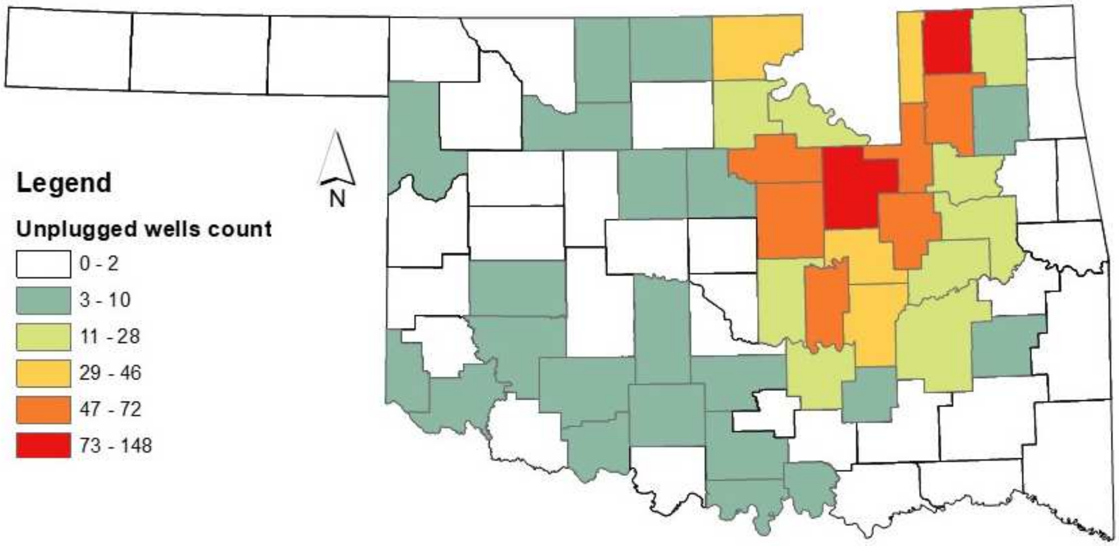


Figure 4.9: Count of unplugged wells at the county level

The locations of unplugged wells within the basins is depicted in Figure 4.10. As it can be seen the majority of these incidents are location within the Northeastern Oklahoma/Cherokee basin.

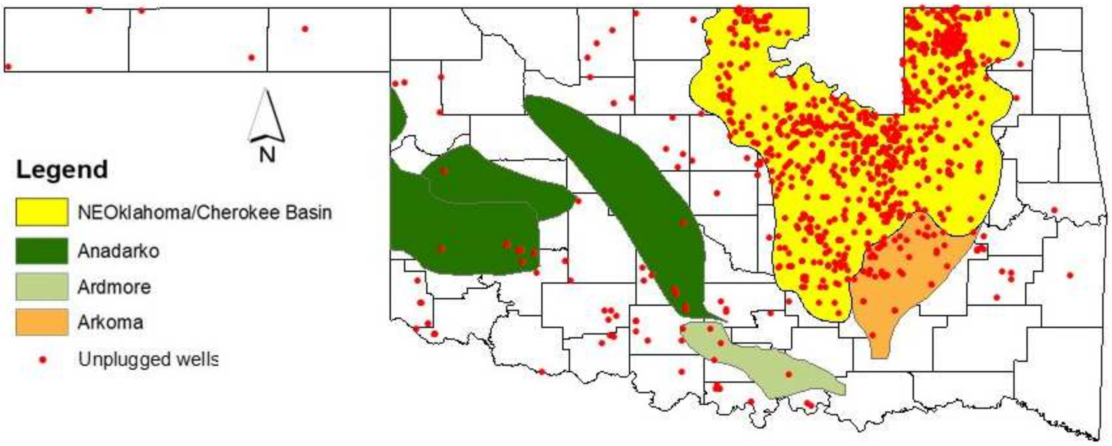


Figure 4.10: Spatial distribution of unplugged wells within the basins

A total of 907 unplugged wells were located within the Northeastern Oklahoma/Cherokee basin which represents 83% of the total unplugged wells reported from 2008 to 2012. The second basin with the most unplugged wells is the Arkoma basin located immediately south. The location of unplugged wells that are not contained within a basin are depicted as red dots.

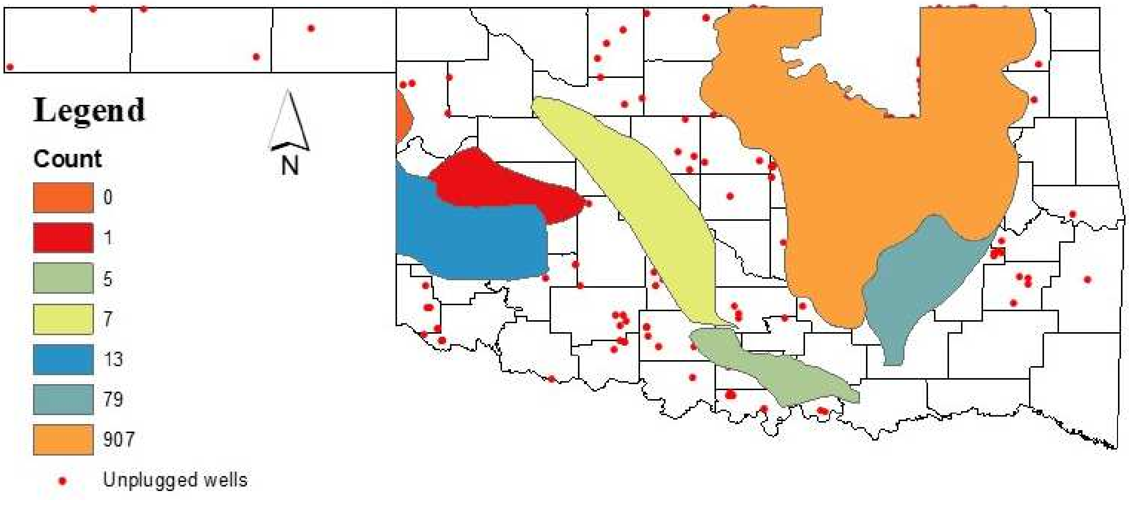


Figure 4.11: Count of unplugged wells by basin

Spatial Statistics Characteristics

The Incremental Spatial Autocorrelation indicated that the peak for the distance threshold was located at about 112 kilometers with a z-score of 6.5 as can be seen in Figure 4.12.

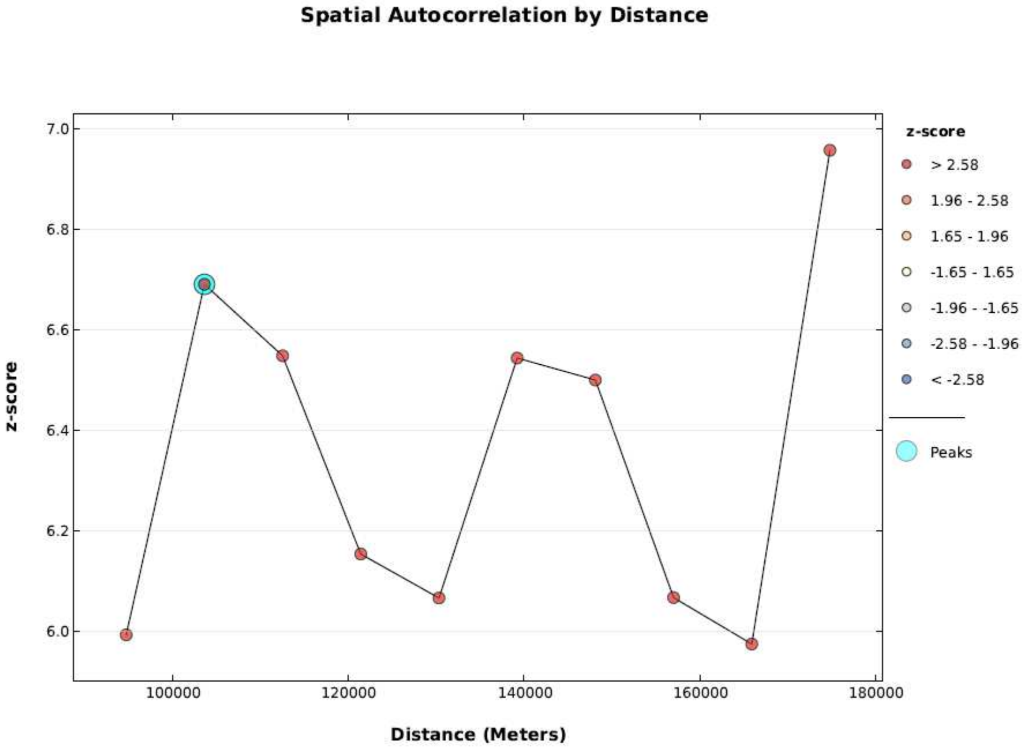


Figure 4.12: Spatial autocorrelation output from ArcGIS 10.2

This distance threshold was applied to the unplugged wells through the Getis-Ord Gi* Hot Spot Analysis in ArcGIS 10.2. A significant hot spot with a localized cluster of unplugged wells was evident in the Northeastern Oklahoma basin. The hot spot map was overlaid by the historical oil and gas fields map for Oklahoma which demarcates a coincident area for unplugged wells and affected water wells (Figure 4.13).

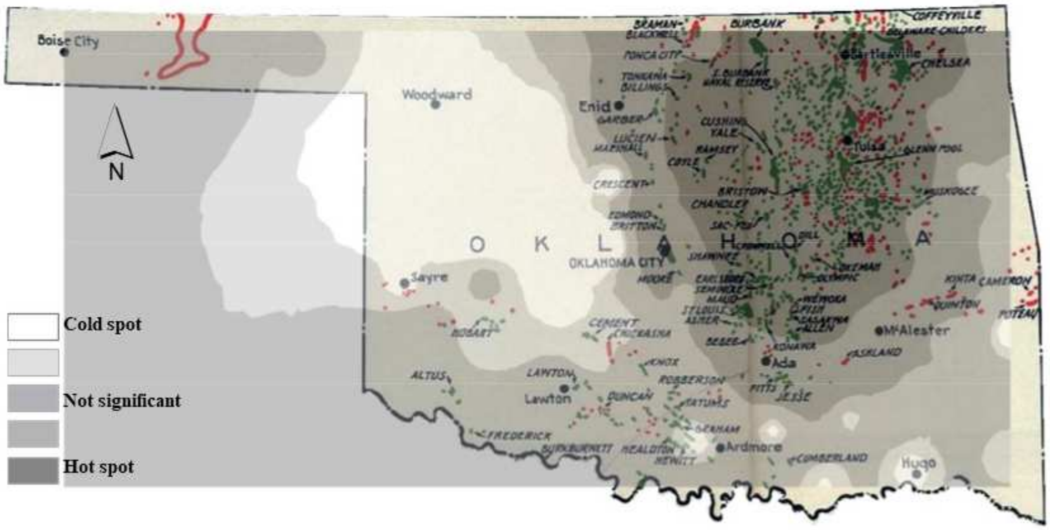


Figure 4.13: OHS map overlaid by hot spot analysis of unplugged wells

Data Management Observations

The affected water wells are physically inspected, but lack the evidence that the archives and the surroundings could provide. A continuation plan through data management needs to be set in place for these water supply wells so that the long-term impacts to ground water reservoirs could be understood. It is imperative to track the environmental reported activity until the most probable explanation is proven. Some of these water wells are tested for analytes such as nitrate, chloride, sulfate, boron, sodium, calcium, magnesium, potassium as well as pH and total dissolved solids. However, the laboratory results are archived in the corresponding district office. Substantial observational support and trends could be accumulated just by systemizing and digitizing the reported data beyond county borders. The lack of clarity for the *undefined leaks/discharges* subcategory described in Chapter III prevented the inclusion of these sites into this analysis. Casing and cement leaks have also proven to create migration of fluids. As it has been mentioned before in this document, the database and data entry could benefit from an automated defined conceptual framework to be followed by inspectors with an option to add comments as needed.

Discussion and Conclusions

It is evident that the spatial distribution of affected water wells and unplugged wells coincides. Spatial distribution mapping is the key to understanding the spatial occurrence of environmental variables related to historical and contemporary oil and gas fields. This shows that Moran's I, combined with geostatistics and GIS, could be used to study spatial patterns of environmental variables related to oil and gas developments. The Getis-Ord Gi* statistics indicate that the hot spots and cold spots are clustered around specific sectors with isolated highs and lows of which both separate reported incidents (water wells and unplugged wells) seem to cluster in the north-central part of the state which concurs with the locations of historical hydrocarbon fields. Clusters of affected water wells and unplugged wells were identified around specific sectors and mostly pronounced in the north-central region of the Oklahoma, which concurs with the locations of historical hydrocarbon fields within the Northeastern Oklahoma/Cherokee basin. The spatial analysis of these reported incidents sustains the literature that suggests the importance of actively pursuing unplugged wells from historical hydrocarbon production to prevent pollution of groundwater. Groundwater contamination caused by the transport of pollutants through unplugged wells could be eliminated with increased awareness of the spatial patterns and occurrences of these conduits.

References

ESRI Arc GIS 10.2

Oklahoma Corporation Commission Environmental Compliance Reports (1085 forms)

Baker, D. R. (1962). Organic geochemistry of Cherokee Group in southeastern Kansas and northeastern Oklahoma. *AAPG Bulletin*, *46*(9), 1621-1642.

Besag, J., & Newell, J. (1991). The detection of clusters in rare diseases. *Journal of the Royal Statistical Society. Series A (Statistics in Society)*, 143-155.

Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., & Kaufman, S. (1983). COCORP profiling across the Southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko Basin. *Geology*, *11*(2), 109-114.

Carney, G. O. (1981). *Cushing Oil Field: Historic Preservation Survey*. Department of Geography, College of Arts and Sciences, Oklahoma State University.

Cheremisinoff, N. P., & Davletshin, A. (2015). *Hydraulic fracturing operations: Handbook of environmental management practices*. John Wiley & Sons.

Committee on Science, Public Policy (US). Panel on Scientific Responsibility, & the Conduct of Research. (1993). *Responsible Science: Ensuring the integrity of the research process* (Vol. 2). National Academies Press.

Da Wang, H., & Philp, R. P. (1997). Geochemical study of potential source rocks and crude oils in the Anadarko Basin, Oklahoma. *AAPG bulletin*, *81*(2), 249-275.

Denison, R. E. (1984). Basement rocks in northern Arkansas. *Contributions to the Geology of Arkansas*, *2*, 33-49.

EIA State rankings <https://www.eia.gov/state/rankings/?sid=US#/series/101>

EPA, 1987. Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy. Office of Solid Waste and Emergency Response, Washington, D.C. http://nepis.epa.gov/Exe/ZyPDF. cgi?Dockey¼20012D4P.PDF

Förster, A., Merriam, D. F., & Hoth, P. (1998). Geohistory and thermal maturation in the Cherokee basin (mid-continent, USA): results from modeling. *AAPG bulletin*, *82*(9), 1673-1693.

Gass, T. E., Lehr, J. H., & Heiss, H. W. (1977). *Impact of abandoned wells on ground water*. US Robert S. Kerr Environmental Research Laboratory.

Haining R. Spatial Data Analysis: Theory and Practice. New York: Cambridge University Press.2003.

Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics* (No. BOOK). Oxford university press.

Jackson, R. B. (2014). The integrity of oil and gas wells. *Proceedings of the National Academy of Sciences*, 201410786.

Jackson, R. E., Gorody, A. W., Mayer, B., Roy, J. W., Ryan, M. C., & Van Stempvoort, D. R. (2013). Groundwater protection and unconventional gas extraction: The critical need for field-based hydrogeological research. *Groundwater*, *51*(4), 488-510.

Lalor, G. C., & Zhang, C. (2001). Multivariate outlier detection and remediation in geochemical databases. *Science of the total environment*, *281*(1-3), 99-109.

Lowman, S. W. (1933). Cherokee structural history in Oklahoma.

Mitchell, A. (2005). The ESRI guide to GIS analysis II: spatial measurements and statistics ESRI Press. *Redlands CA*.

OHS, Map Collection, Oil & Gas Journal https://www.okhistory.org/research/hl_map5.php#page/0/mode/1up

Ord, J. K., & Getis, A. (1995). Local spatial autocorrelation statistics: distributional issues and an application. *Geographical analysis*, *27*(4), 286-306.

Patterson, L. A., Konschnik, K. E., Wiseman, H., Fargione, J., Maloney, K. O., Kiesecker, J., ... & Saiers, J. E. (2017). Unconventional oil and gas spills: Risks, mitigation priorities, and state reporting requirements. *Environmental science & technology*, *51*(5), 2563-2573.

Perry, W. J. (1989). *Tectonic evolution of the Anadarko Basin region, Oklahoma* (No. 1866). Department of the Interior, US Geological Survey.

Petzel, G. J. (1974). *Evaluation of data from the first earth resources technology satellite for the purpose of structural analysis in the Anadarko Basin, Oklahoma and Texas* (Doctoral dissertation, University of Oklahoma).

Robinson, T. P., & Metternicht, G. (2006). Testing the performance of spatial interpolation techniques for mapping soil properties. *Computers and electronics in agriculture*, *50*(2), 97-108.

Ryan, B. (2017). *Petrophysical Properties of the Woodford Formation in the Ardmore Basin in Oklahoma, USA* (Doctoral dissertation).

Suneson, N. H. (2012). Arkoma Basin Petroleum-Past, Present, and Future.

Trollinger, W. V. (1970). Surface evidence of deep structure in the Anadarko basin.

Walper, J. L. (1976). Geotectonic evolution of the Wichita aulacogen. *Oklahoma (abs.): AAPG Bull*, *60*, 327-328.

Wong, D. W. S., and J. Lee. 2005. Statistical Analysis of Geographic Information with ArcView GIS and ArcGIS. Hoboken: Wiley

Wright III, H. W. (1986). Oklahoma's Groundwater: Reducing the Pollution Caused by Improperly Plugged Oil and Gas Wells. *Tulsa LJ*, *22*, 581.

CHAPTER V

SPATIAL ANALYSIS AND OCCURRENCE POTENTIAL OF PRODUCED FLUID SPILLS IN OKLAHOMA

Abstract

In spite of various modeling attempts, it is currently difficult to assess or estimate the impact to water resources due to the lack of actionable data. However, it is possible to delineate the most susceptible surface and ground waters in the state and evaluate the spatial distribution of contaminant spills. This will motivate focused and site-specific research and the opportunity to anticipate constructive modifications to existing state regulations. This paper represents the first attempt to obtain a data-driven analysis of the spatial distribution of produced fluid spills in Oklahoma. The main objective of this paper is to find the surface and ground water vulnerable zones using the DRASTIC model in GIS. It was found that 524 produced fluid spills had occurred within susceptible water resources from 2008 to 2012. Spatial clustering of produced fluid spills was evident in the south-central part of the state and in the panhandle. The most impacted watershed was Lake Overholser, the most affected sensitive water supply was Beaver Creek and the aquifer with the most counts of produced fluid spills was the North Canadian River alluvium aquifer. There is room for improvements in data entry and management to better protect fresh water supplies from the accidental release of produced fluids during hydrocarbon production in the state of Oklahoma.

Introduction

Because prevention is the key to helping ensure that future practices do not result in ground-water contamination, it is now more important than ever to use planning and management tools to help recognize the places where certain activities pose a higher risk (Aller et al., 1985). Identification of risk, the potential for occurrence of an event and impact of that event, is the first step in improving a process by ranking risk elements and controlling potential harm from occurrence of a detrimental event (King, 2012). In 2016, the Environmental Protection Agency (EPA) published a report that discusses the impact from the hydraulic fracturing water cycle on drinking water resources in the United States. The report recognizes that the severity of impacts on water quality from spills of hydraulic fracturing fluids or additives depends on the identity and amount of chemicals that reach groundwater or surface water resources, the toxicity of the chemicals, and the characteristics of the receiving water resource. A 2013 publication by Walton and Woocay affirm that the primary threat to surface and shallow groundwater from hydraulic fracturing is from spilled or released material on the earth's surface. They further express that wells are normally completed far below the depth of groundwater aquifers by about a factor of 10 (thousands of feet for gas versus hundreds of feet for useful water). Concomitant with the "shale rush" of 2008, when the price of a barrel of oil was set at $142, surged the concern over the quality of drinking water resources from accidental spills of the fluids used and produced during the extraction of hydrocarbons. Walton and Woocay (2013) indicate that the frequency and consequences of these accidents will depend upon the safety standards applied by industry and regulatory agencies, but they will periodically occur given the high number of wells anticipated and the complex nature of the subsurface environment.

Chemical Composition of Produced Fluids

Water mixed with sand and other inert solids, such as ceramic beads, are injected into the formation to fracture the rock and provide support, or "proppant", which prevents the fractures from closing once the well pressure is released. In addition to proppant, other chemicals are added to the injected fluids. These chemicals are typically blended at the wellhead and serve various functions in the process such as preventing the growth of bacteria, facilitating the pumping of proppant down-hole and into the fractured formation, and minimizing mineral scaling of the well (Stringfellow et al., 2014). Injected chemicals include gelling and foaming agents, friction reducers, crosslinker, breakers, pH adjusters, bioagents, corrosion inhibitors, scale inhibitors, iron control chemicals, clay stabilizers, and surfactants. The practice of hydraulic fracturing uses more than 2,500 products containing 750 chemicals along with other components. Methanol is the most widely used as it applied as a component in 342 hydraulic fracturing products. Isopropyl alcohol, ethylene glycol, and crystalline silica (silicon dioxide) are some of the most used chemicals (Waxman et al., 2011). HF companies have used 2-butoxyethanol (2-BE) as a foaming agent or surfactant. Exposure to this organic compound could cause destruction of red blood cells and damage to the spleen, liver, and bone marrow. 2-BE has recently been found in drinking water wells tested by the EPA in Pavillion, Wyoming where HF has been linked to groundwater contamination (DiGiulio and Jackson, 2016). The Safe Drinking Water Act (SDWA) regulates the most hazardous chemicals to human health used in HF. Six hundred and fifty-two (652) products used in HF contain at least one chemical of concern. Under the SDWA, EPA regulates 53 chemicals that may have an adverse effect on human health and are known to or likely to occur in public drinking water systems at levels of public health concern. HF companies used 67 products containing at least one of the eight SDWA-regulated chemicals. The majority of these SDWA-regulated chemicals were the BTEX compounds, benzene, toluene, xylene, and ethylbenzene (Waxman et al., 2011). In HF there is a wide variety of chemicals and mixtures that are formation dependent and are often held as trade secrets by HF practitioners that prefer not to disclose the constituents in their formulations. Diesel and petroleum distillates have been used as carrier fluids for dissolving additives. For example, crosslinkers and pH adjusters have been dissolved or suspended in hydrophobic carrier fluids before being mixed into aqueous fracturing fluids during well-injection in order to overcome the limitations of dry chemical blending and uncontrolled premature crosslinking (Stringfellow et al., 2014). The EPA has worked with major HF contractors and unconventional gas producers to eliminate the use of diesel fuel in fracturing fluid due to environmental and toxicity concerns. Reporting of the chemicals used in HF is voluntary through the online chemical disclosure registry FracFocus. Oklahoma is among some of the states with disclosure requirements in effect.

Spill Characterization

The EPA has categorized spills according to the following causes: equipment failure, human error, failure of container integrity, other (e.g., well communication, weather, vandalism), and unknown as represented in EPA Figure 5.1. This figure includes the distribution of the causes for in Oklahoma before the advent of high-volume hydraulic fracturing from 1993 to 2003.

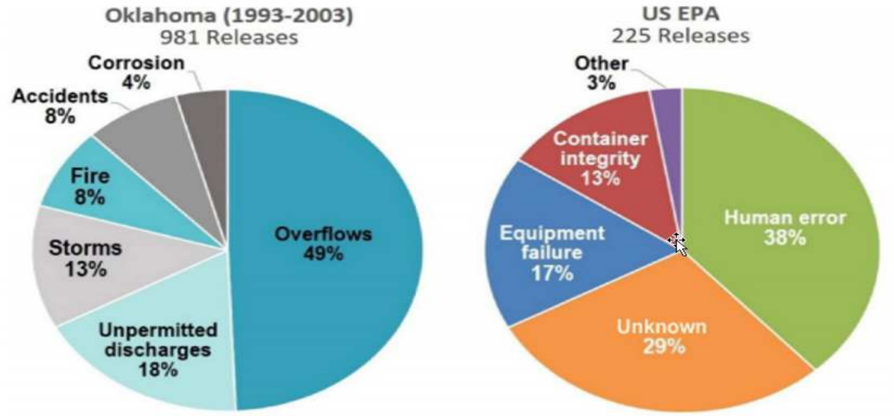


Figure 5.1: Distribution of spill causes in Oklahoma. "Reprinted from U.S. EPA. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F, 2016.

The following figure (Figure 5.2) presents the percent distribution of causes of hydraulic fracturing-related spills and for spills associated specifically with chemicals or fracturing fluid. It is important to note that the ECRS database does not include an input field for the cause of the spill but it is at times included within the description of the allegation.

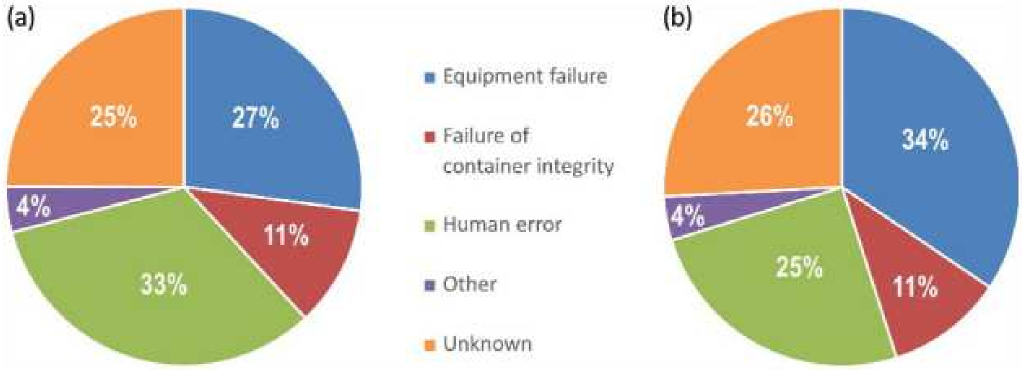


Figure 5-10. Percent distribution of the causes of spills.
Percent distribution by spill type for (a) 457 hydraulic fracturing-related spills (all spills) and (b) 151 chemical mixing-related spills. Data from U.S. EPA (2015m). Legend shows categories in clockwise order, from the top left of each pie chart.

Figure 5.2: Percent distribution of the causes of spills. "Reprinted from U.S. EPA. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F, 2016.

Produced fluids are stored in tank batteries or storage tanks that can leak or can be fully discharged at the surface because of lightning or tornado, as well as tank corrosion or valve malfunction as has been observed through the manual classification of incidents. There are also cases in which the equipment and machinery have failed leading to blowouts or leaking valves, pipes and pumps. “Accidents will result in localized contamination of surface and shallow groundwater with any of the chemicals associated with drilling, hydraulic fracturing and gas production” (Walton and Woocay, 2013). According to the United States Department of Energy, produced water can have different potential impacts depending on where it is discharged. They also state that there are numerous variables that determine the actual impacts of produced water discharge on water resources such as the physical and chemical properties of the constituents, temperature, content of dissolved organic material, humic acids, presence of other organic contaminants, and internal factors such as metabolism, fat content, reproductive state, and feeding behavior (Frost et al. 1998).

Environmental Fate and Transport

Spills and leaks from oil and gas production pollute the surface soil and may allow pollutants to travel laterally to nearby surface waterbodies as storm-water runoff and vertically into the aquifer through infiltration. There are preferential flow paths representative of the geology of the site that determine the transport of the spilled water by infiltration, into the soil subsurface, or by runoff, over the land surface. The porosity and permeability of the receiving soil or rock will determine the velocity and direction of the spilled fluid into the subsurface and/or over the land surface. Receiving surfaces with low permeability will allow the spilled fluid to travel laterally over the land surface onto surface waters. Ultimately, the fate and transport of the spilled produced fluids will be dependent on the volume of the spill and the distance to the receiving waters (above or below ground). As stated by the EPA report on drinking water resources:

> “Characteristics of the receiving groundwater or surface water resource (e.g., water resource size and flow rate) can affect the magnitude and duration of impacts by reducing the concentration of spilled chemicals in a drinking water resource. Impacts on groundwater resources have the potential to be more severe than impacts on surface water resources because it takes longer to naturally reduce the concentration of chemicals in groundwater and because it is generally difficult to remove chemicals from groundwater resources.”

Regulations

The Energy Policy Act of 2005 exempts fluids used in hydraulic fracturing from regulatory action under the Clean Water Act, the Safe Drinking Water Act, and the Comprehensive Environmental Response, Compensation, and Liability Act (Kosnik, 2007). Furthermore, congress exempted oil and gas derivatives, including produced water, from the hazardous waste management requirements of Subtitle C of the Resource Conservation and Recovery Act (RCRA). Congress; however, did require the EPA to study these wastes and submit a report on the status of their management to promulgate regulations under Subtitle C of RCRA or make a determination that such regulations were unwarranted. In 1988, the EPA published its regulatory determination in the Federal Register (FR) in which produced water ranks first on the list of wastes that are exempt and warrant no regulation under Subtitle C of RCRA. The EPA states in the Code of Federal Regulations (CFR) that “produced wastewater” is among “solid wastes which are not hazardous wastes” (40 CFR §261.4(b)(5)). For this reason, each producing state regulates these discharges and infringe penalties. The Oil and Gas division of the OCC records and addresses drilling complaints through the preceding Environmental Compliance Reporting System (ECRS), which was in place until May 2013. After that date, complaints were recorded in the Risk Based Data Management System (RBDMS). A list of oil and gas related incidents was obtained in an effort to understand potential contamination sources and magnitudes. The ECRS list obtained was an extensive database that covered two decades of reported complaints. Produced fluids spills are reported to the OCC and an inspector fills out an *Incident and Complaint Investigation Report* (1085-form) which describes the incident.

Methods

Data Processing

A list of *Incident and Complaint Investigation Reports* (1085-forms) related to oil and gas production was obtained in August of 2013 from the staff of the OCC. After manually classifying the last five full calendar years in the list (2008 to 2012) it was evident that substances such as produced fluids, hydrocarbons, lubricants, acids and chemicals had been spilled on a drilling or producing site on numerous occasions. The produced fluid spills were selected for this study because of their potential transport and toxicity. The database does not include the nature or chemical composition of the produced fluids that were spilled in different instances and locations and the discharge volumes are not always entered in the database which impedes determination of the potential hazard of the fluid. There are significant gaps and uncertainties in the data that inhibit the calculation of the effects of produced fluid releases on surface and ground waters. Some of the most common reasons for produced fluids spills encountered in the database are represented in a simple schematic as Figure 5.3 and include discharges due to weather such as lightning and tornadoes, transportation accidents, equipment failure, surface and sub-surface pipeline releases and overflow. There is not an input field in the database to include the cause of the spill but in some cases the cause is included within the description or allegation of the incident.

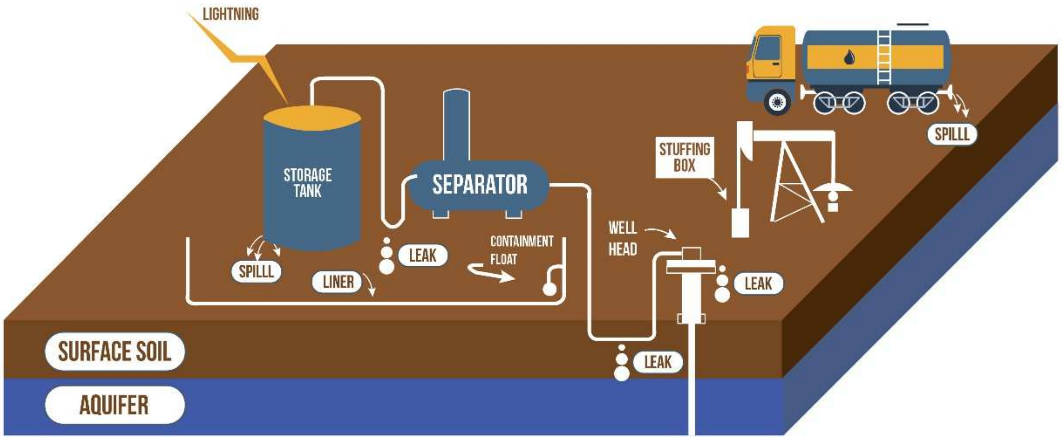


Figure 5.3: Schematic of potential sources for produced fluid spills

The locations of produced fluid spills were geocoded as x and y coordinates and plotted into the Oklahoma map in ArcGIS 10.2. As the latitude and longitude coordinates were plotted it was obvious some of the locations were not in Oklahoma, but rather appeared to have shifted east and were plotted in Arkansas. As has been mentioned, there have been several inconsistencies and incongruities in the ECRS dataset. To determine an approximate location, the legal description was converted to decimal latitude and longitude. As the converted decimal locations were compared to the provided decimal locations, the reported latitude match, but the longitude was offset to up to 1.979 degrees.

Aquifer Vulnerability

DRASTIC is a general index that has been commonly used as an aquifer sensitivity assessment method; however, it is not intended to predict the occurrence of ground water contamination (US EPA, 1987). By plotting the locations of produced fluid spills the contamination is integrated into the map. DRASTIC is an acronym standing for Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity. From these parameters a DRASTIC index or vulnerability rating can be obtained. The higher the value for the DRASTIC index, the greater the vulnerability of that location of an aquifer. The index is computed by,

$$Drastic\ Index = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

Where:

D = Depth to water

R = net Recharge

A = Aquifer media

S = Soil media

T = Topography

I = Impact of the vadose

C = hydraulic Conductivity

The subscripts:

w = weight

r = rating

For the weight, each DRASTIC factor was evaluated with respect to the other to determine the relative importance of each factor. The factors were rated in an ascending order from 1 to 5 being 5 the factors with the most significance (Table 5.1). These weights are constant and may not be changed (Aller et al., 1987)

Table 5.1: DRASTIC model parameters and weights (Aller et al., 1987)

Factor	**Description**	**Weight**
Depth to water	Depth from the ground surface to the water table	5
Net recharge	Infiltration from the ground surface to the water table	4
Aquifer media	Material properties of the saturated zone	3
Soil media	Uppermost weathered portion of the unsaturated zone	2
Topography	Slope of the land surface	1
Impact of the vadose zone	Materials of the unsaturated zone	5
Hydraulic conductivity	Ability of the aquifer to transmit water	3

Each one of the DRASTIC parameters was divided into ranges from which a variable rating was derived for the factors D, R, S, T and C. A and I could be assigned a variable or a fixed typical rating. For a complete description of the DRASTIC method, refer to the EPA publication DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings by Aller et al., (1987). The OWRB conducted a vulnerability assessment of the major Oklahoma aquifers and the USGS created grid layers to calculate the DRASTIC index. A conjunct effort between both entities and the work of Osborn and Hardy (1999) brought upon the aquifer vulnerability map will be used in this study to assess the spatial distribution of produced fluid spills on vulnerable aquifers.

Special Provisions Watersheds

The OWRB develops and propagates surface water protection plans through the Oklahoma Water Quality Standards (WQS) published in Oklahoma Administrative Code Title 785, Chapter 45 (OAC 785:45). As a requirement for the federal Clean Water Act, six different designations have been accounted for the beneficial use of water in the state. These include source water protection areas, high quality waters, sensitive water supplies, outstanding resource waters, scenic rivers, and nutrient-limited watersheds. The release of pollutants into these water bodies could be detrimental to human health, aquatic ecosystems, agriculture, and recreation. The Clean Water Act (CWA) amendments of 1972 instilled requirements from each state to set water quality standards for all contaminants in surface water. The Oklahoma Water Quality Standards (OWQS) include watershed provisions of the state approved by the EPA by assigning appropriate uses to each waterbody. Under designated beneficial water uses are high quality waters (HQW), nutrients limited watersheds (NLW), outstanding resource watershed (ORW), scenic river watershed (SR), sensitive public and private (SWS). This map was overlaid to the locations of the produced fluid spills to determine the spatial distribution of these spills in relation to protected watersheds.

Results

Characteristics of Incidents

In five years a total of 1,805 produced fluid spills were reported with an annual average of 361. Over 50% of these incidents do not include an estimation of the discharged volume as it can be seen in Table 5.2 and Figure 5.4. The nature and chemical composition of the produced fluid is unknown as it is not reported in the database.

Table 5.2: Produced fluid spills and reported volumes in Oklahoma

Year	# of spills	Volumes not reported	
		Amount	Percentage
2008	375	178	53
2009	367	159	57
2010	318	130	59
2011	350	128	63
2012	395	169	57

The year with the most produced fluid spills was 2012 with 395 cases and the year with the least produced fluid spills was 2010 with a count of 318 as can be seen in Figure 5.4. The decrease in incidents of 2010 may be attributed to the decrease in production.

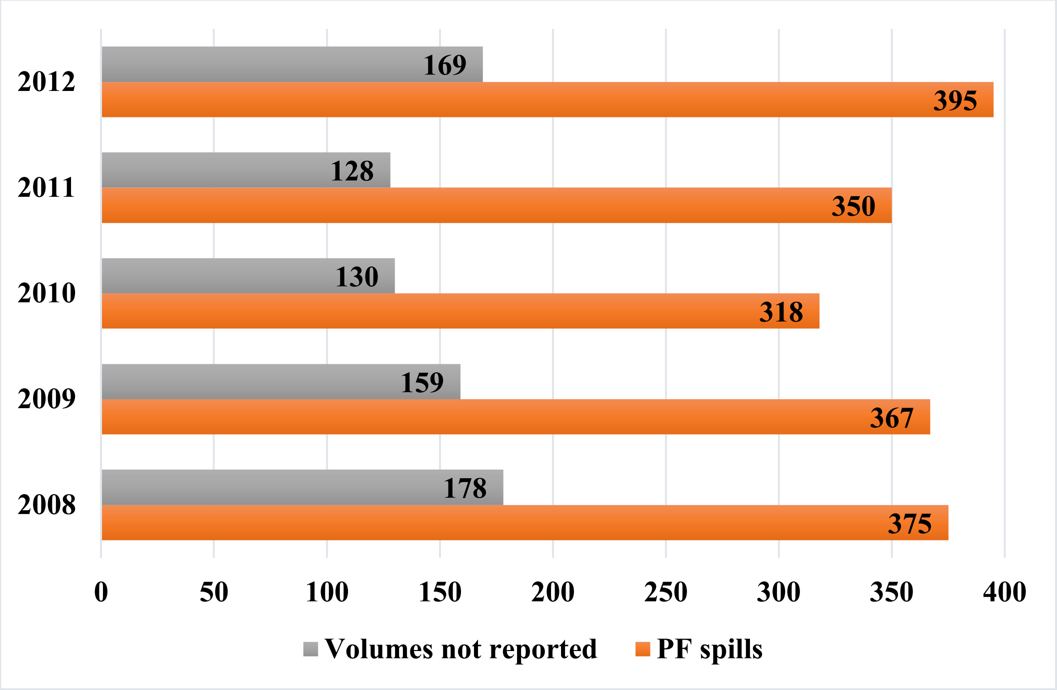


Figure 5.4: Reported volume for produced fluid spills from 2008 to 2012 in Oklahoma

Spatial Characteristics of Incidents

The spatial distribution of produced fluid spills reported in five years is illustrated in Figure 5.5. Osage county has been excluded from the map because of the lack of data. On the east of the state, several counties have not had any reports of produced fluid spills. However, there are several clusters of produced fluid spills represented in the orange and red in the south-central part of the state and in the panhandle.

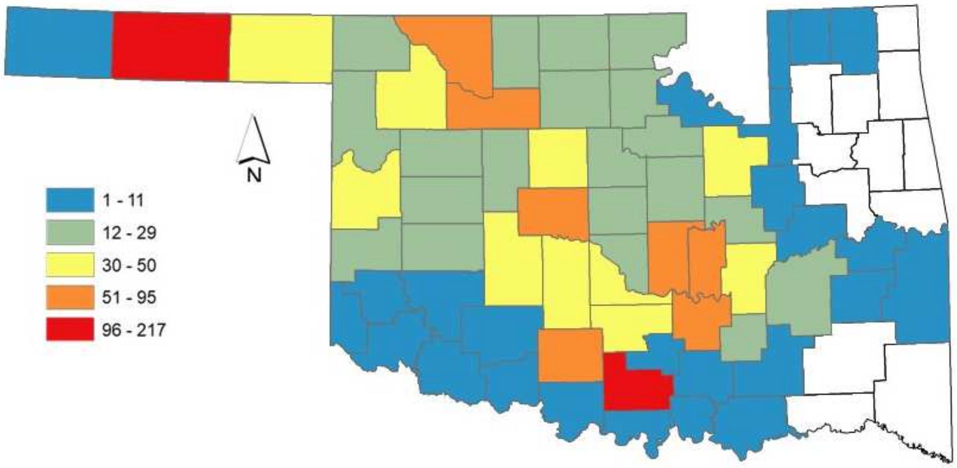


Figure 5.5: Spatial distribution and count of produced fluid spills per county

The extent of the state aquifers is illustrated in Figure 5.6, which also counts the amount of produced fluid spills that had occurred within that aquifer. A total of 330 produced fluid spills had occurred in five years from 2008 to 2012. The most affected aquifer was the North Canadian River with 116 produced fluid spills as can be seen in Table 5.3 followed by the Cimarron River to the north and the Washita River to the south.

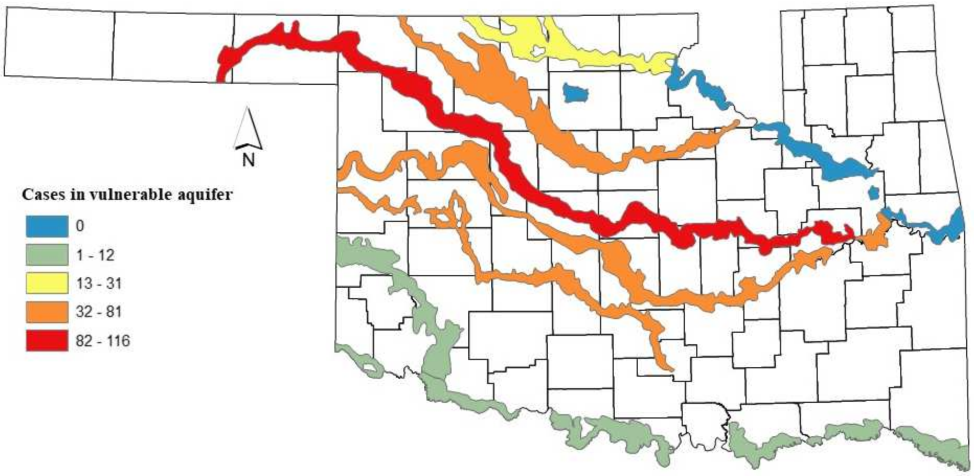


Figure 5.6: Spatial distribution and count of produced fluid spills in vulnerable aquifers

Table 5.3: DRASTIC index and produced fluid count

Basin name	Depth	Recharge	Aquifer Media	Soil Media	Topography	Impact	Conductivity	Drastic Index	PF spill count
Arkansas River	7	3	8	5	9	8	6	148	0
Canadian River	7	3	8	5	9	8	6	148	76
Cimarron River	7	3	8	6	10	8	4	145	81
Enid Isolated Terrace	7	3	8	5	10	8	6	149	0
North Canadian River	7	3	8	6	10	8	4	145	116
North Fork Red River	7	3	8	8	10	8	6	155	12
Red River	7	3	8	6	10	8	6	151	10
Salt Fork Arkansas	7	3	8	6	10	8	6	151	31
Washita River	7	3	8	5	10	8	6	149	57

The special provisions watershed map is included as Figure 5.7 along with a spatial join and count of the produced fluid spills that had occurred within these protected watersheds. A total of 177 produced fluid spills had occurred in 5 years within a protected watershed. The most impacted watershed was Lake Overholser in the center of the state followed by the Great Salt Plains Reservoir in the north.

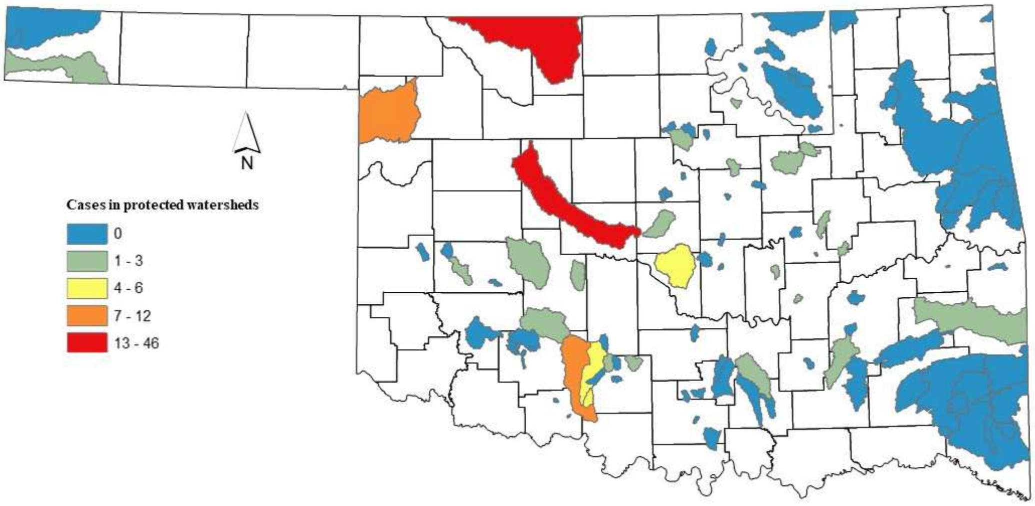


Figure 5.7: Spatial distribution and count of produced fluid spills in protected watersheds

The provision type for each watershed and the produced fluid spill count that had impacted each watershed within these five years is included as Table 5.4. It has been determined through GIS analysis that the most impacted protected surface water is Lake Overholser that connects with the North Canadian River through the Overholser Dam. Lake Overholser has been included as a special provision watershed because of its nutrient limited characteristics. The most affected sensitive water supply was Beaver Creek located in the southeast part of the state.

Table 5.4: Special provisions watersheds and produced fluid spills count

Watershed Name	Provision Type	PF spill count
Arcadia Reservoir and Watershed	SWS	1
Beaver Creek	SWS	11
Blue River	HQW	2
Buzzard Creek	SWS	1
Carl Blackwell and Watershed	SWS	1
Cushing lake and Watershed	SWS	3
Ellsworth Lake and Watershed	SWS	1
Fort Cobb Lake and Watershed	SWS, NLW	2
Fort Supply Reservoir	NLW	12
Fuqua Reservoir and Watershed	SWS	3
Great Salt Plains Reservoir	NLW	34
Hell Creek	SWS	1
Henryetta Lake and Watershed	SWS	1
Heyburn Lake and Watershed	SWS	3
Hobart Lake	SWS, NLW	2
Holdenville Reservoir and Watershed	SWS	1
Humpreys Lake and Watershed	SWS	1
Lake Chickasha	NLW	1
Lake Overholser	NLW	46
Lake Thunderbird	NLW	6
Little Beaver Creek	SWS	6
Little Wolf Creek	SWS	2
North Boggy Creek	SWS	1
Okmulgee Lake and Watershed	SWS	1
Pawnee Lake and Watershed	SWS	1
Sahoma Reservoir and Watershed	SWS	2
Thunderbird Lake and Watershed	SWS	6
Twentyfive Mile Creek	SWS	5
Walker Creek	SWS	4
Wewoka Lake and Watershed	SWS	2
Wister Reservoir and Watershed	NLW	1
Wolf Creek	SWS	12

The following figure (Figure 5.8) includes a count of the produced fluid spills that had occurred within a vulnerable aquifer or protected watershed. It also counts the number of times that such spill had affected both an aquifer and a watershed. The locations for which more than one incident had been reported within the same year are also illustrated in the same figure.

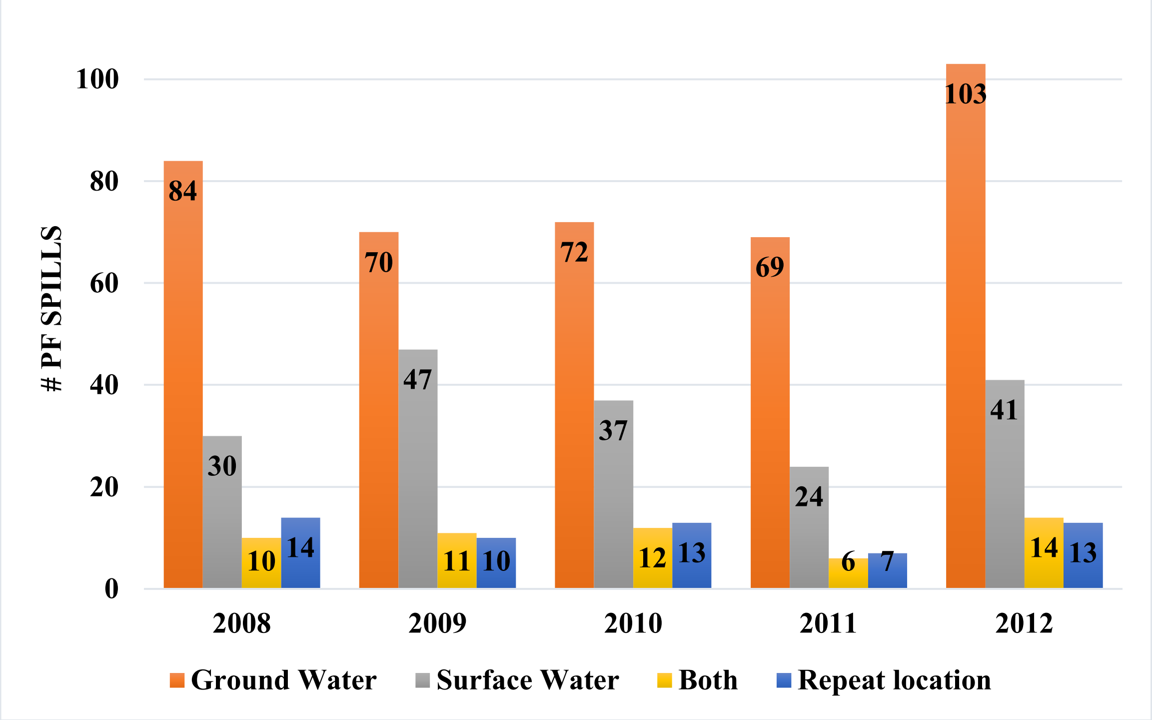


Figure 5.8: Annual count of produced fluid spills in susceptible waters

The very vulnerable aquifers and the protected watersheds that had been impacted the most by produced fluid spills are included in Table 5.5. Lake Overholser is amongst the most impacted surface water bodies along with the North Candian River alluvium aquifer. Both of these connect through the Overholser dam. The most impacted water sensity water supply was Beaver Creek located in the south central portion of the state.

Table 5.5: Most impacted protected surface water and vulnerable ground water by year.

Year	Most impacted surface water	Most impacted ground water	Most impacted water supply
2008	Lake Overholser	N. Canadian River	Beaver Creek
2009	Great Salt Plains	Cimarron River	Wolf Creek
2010	Lake Overholser	N. Canadian River	Beaver Creek
2011	Lake Overholser	N. Canadian River	Beaver Creek
2012	Lake Overholser	N. Canadian River	Thunderbird Lake and Watershed

The locations of the protected watersheds and vulnerable aquifers that have been most impacted by produced fluid spills are included in Figure 5.9.

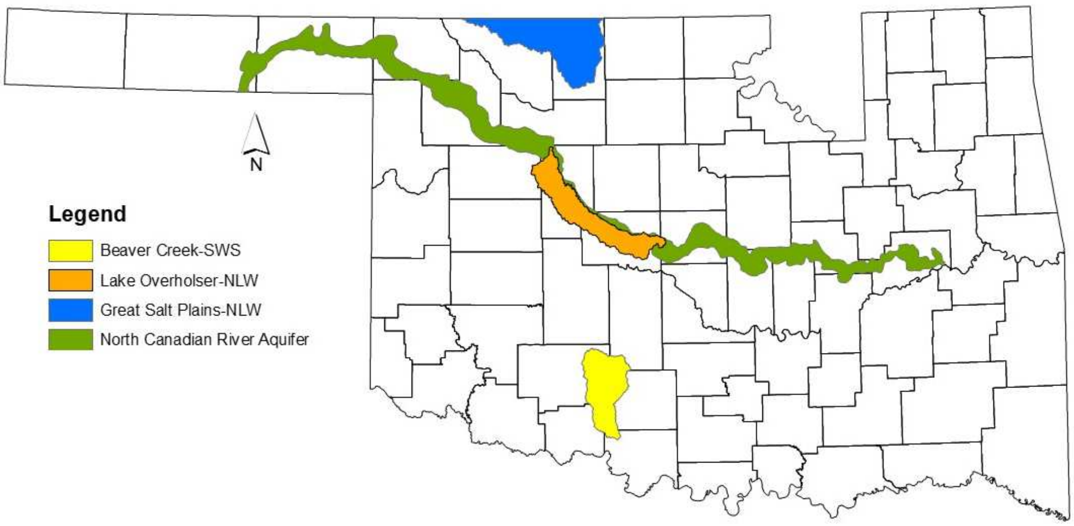


Figure 5.9: Locations of most impacted susceptible surface and ground waters

Data Management Observations

The EPA report persists in the data gaps and uncertainties that hinder the calculation of the pollution to surface and ground waters from hydrocarbon production. It is evident that the data entries in Oklahoma are missing an estimated volume of the discharged fluid in nearly 50% of the reported produced fluid spills. Also, there is not a precise definition of “produced fluid” as it has been interchangeably used in the database as “salt water”. The data entry is not explicit about the nature of the fluid, the chemical composition of the fluid or the cause of the spill. The inclusion of these data inputs added to these susceptible waters maps could define future remediation approaches.

Discussion

It is important to delineate the water resources that need to be protected and the areas that have most been impacted to direct future studies into collecting data to evaluate the localized effects of these spills through time. It is also imperative to implement a reporting system that demands the inclusion of spilled volumes within the database and a more in depth description of the spilled fluid with hopefully a laboratory analyzed sample. These susceptible areas have been delineated and highlighted to direct the need to remediate immediately and infringe regulations without uncertainty. The available data and information allowed for a qualitative study to delineate the most susceptible areas and the frequency in which these are being impacted. However; detailed and organized data is necessary in order to estimate or calculate the actual direct impacts on water resources in the state. It is important to address these data entry and management issues to better protect drinking water resources from hydrocarbon production in the state.

Conclusions

After locating 1,805 produced fluid spills reported within five years from 2008 to 2012 it was determined, that over 50% of these incidents do not include an estimation of the discharged volume. The database also does not require data inputs such as the chemical composition of the produced fluid or the nature and cause of the spill. These data entries would facilitate future site-specific research into calculating the spatial and temporal transport of produced fluid. The surface and ground water reservoirs that require the most attention in Oklahoma due to the re-occurrence of produced fluid spills are Lake Overholser, the North Canadian River alluvium and the Beaver Creek water supply.

References

SRI, E. (2014). ArcGIS 10.2. 2 for Desktop. *Redlands: ESRI*.

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US Environment Protection Agency, Ada, Oklahoma, EPA/60012-87/035.

DiGiulio, D. C., & Jackson, R. B. (2016). Impact to underground sources of drinking water and domestic wells from production well stimulation and completion practices in the Pavillion, Wyoming, field. *Environmental science & technology*, *50*(8), 4524-4536.

FracFocus Chemical Disclosure Registry / About Us, http://fracfocus.org/welcome

Frost T.K., S. Johnsen, and T.I. Utvik, 1998, “Environmental Effects of Produced Water Discharges to the Marine Environment,” OLF, Norway. (Available at http://www.olf.no/static/ en/rapporter/producedwater/summary.html.)

King, G. E. (2012, January). Hydraulic fracturing 101: what every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. In *SPE hydraulic fracturing technology conference*. Society of Petroleum Engineers.

Kosnik, R. L. (2007). The oil and gas industry’s exclusions and exemptions to major environmental statutes. Oil and Gas Accountability Project/Earthworks, 41.

Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing: history of an enduring technology. *Journal of Petroleum Technology*, *62*(12), 26-40.

Osborn, N. I., & Hardy, R. H. (1999). *Statewide Groundwater Vulnerability Map of Oklahoma*. Oklahoma Water Resources Board.

Pal, A., Gin, K. Y. H., Lin, A. Y. C., & Reinhard, M. (2010). Impacts of emerging organic contaminants on freshwater resources: review of recent occurrences, sources, fate and effects. *Science of the total environment*, *408*(24), 6062-6069.

Stringfellow, W. T., Domen, J. K., Camarillo, M. K., Sandelin, W. L., & Borglin, S. (2014). Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing. *Journal of hazardous materials*, *275*, 37-54.

Stringfellow, W. T., Camarillo, M. K., Domen, J. K., Sandelin, W. L., Varadharajan, C., Jordan, P. D., ... & Birkholzer, J. T. (2017). Identifying chemicals of concern in hydraulic fracturing fluids used for oil production. *Environmental Pollution*, *220*, 413-420.

Title 785. Oklahoma water resources board chapter 45. Oklahoma's water quality standards (Available at: http://www.owrb.ok.gov/rules/pdf/current/Ch45.pdf)

U.S.EPA, (1987). DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings, United States Environmental Protection Agency, Ada, OK, EPA/600/2-87/035.

U.S. EPA. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F, 2016.

Walton, J., & Woocay, A. (2013). Environmental issues related to enhanced production of natural gas by hydraulic fracturing. Journal of Green Building, 8(1), 62-71.

Waxman, H. A., Markey, E. J., & DeGette, D. (2011). Chemicals used in hydraulic fracturing. *United States House of Representatives Committee on Energy and Commerce Minority Staff*.

CHAPTER VI

CONCLUSIONS

Findings

This study was conducted to assess the impacts of hydrocarbon production on surface and ground water resources. It was difficult to estimate the direct impacts due to gaps and uncertainties in the data. However, chapter III provided the general distribution and organized classification of reported incidents from 2008 to 2012. The nominal data has been classified into five categories: accidents, misconduct, non-producing, health and other. It has been subdivided into 12 subcategories: produced fluid spill, hydrocarbon spill, undefined leak/discharge, soil contamination, unpermitted discharges, permit violations, trash and debris, unplugged wells, unattended facilities, surface water, ground water and odor.

The major findings from chapter III are:

1. Incongruent data is created consistently in the OCC database as there is not a well-defined conceptual framework set in place to aid inspectors input the data in the database. One complaint number may include more than one category and subcategory. Also, repeated entries were observed in which the same incident may or may not share the same complaint number. Some incident descriptions include more detail than others. The decimal longitude is often offset to the east and some incents did not include a location.

2. The total number of incidents were reported in five years was 11,144. The distribution of incidents included: 48% accidents. 35% non-producing, 9% misconduct and 5% are health related.
3. The most recurrent subcategories for each category were: produced fluid spill, permit violations, trash and debris and surface water.
4. The database presents a real opportunity for improvement in data management that would ultimately address future environmental regulations that would be on the best interest of the public and the industry.

Chapter IV showed the location and recurrence of affected water supply wells as well as the proximity of these to clusters of unplugged wells. The finding of this chapter include:

1. The number of water supply wells that were reported polluted from 2008 to 2012 was 203.
2. After the initial inspection of the allegedly polluted water wells, only a portion of these were referred to a different department or state agency for continuation and further evaluation. Some of the reasons for the dismissal of incidents included: solutes consistent with agriculture pollution, wells drilled deeper than the base of treatable water, wells distant from oil and gas production and no observable free hydrocarbons (rainbow sheen).
3. Water well incidents were reported in 45 counties, with Creek the county with the most incidents. The referred water well incidents were spread amongst 33 counties with significant spatial clustering in the east-central part of the state along the northeastern Oklahoma basin.
4. Unplugged wells are spread through 59 counties and Creek was again the most impacted. The clusters of unplugged wells coincide with the location of historical oil and gas developments.

Chapter V quantified and located produced fluid spills in relation to vulnerable aquifers and protected watersheds. It was found that:

1. The number of produced fluid spills reported in five years was 1,805 with an annual average of 361.
2. The volume of the discharge produced fluid is not reported or disclosed for over 50% of these incidents. Also, the nature and chemical composition of the produced fluid is unknown as it is not reported in the database. Without these information is difficult to calculate the direct impacts. It is imperative to implement a reporting system that demands the inclusion of spilled volumes within the database and a more in depth description of the spilled fluid with a laboratory analyzed sample.
3. The most impacted watershed was Lake Overholser in the central part of the state followed by the Great Salt Plains Reservoir to the north.
4. The most impacted aquifer was the North Canadian River followed by the Cimarron River to the north and the Washita River to the south.
5. The most affected sensitive water supply was Beaver Creek located in the south-east part of the state.

Broader Impacts

There is no completely risk-free energy development scheme, and all activities (renewable and nonrenewable) pose some degree of risk to the environment. According to the GWPC, state oil and natural gas regulatory agencies are diligent in addressing the technological, legal and practical changes that occur in oil and gas. The OCC operates and regulates with the information they have available as a state agency. The areas that need improved quality control near riparian zones, surface waters and shallow aquifers have been identified. These maps quantified at different levels of occurrence and risk assessment provide critical insight for communities, local and state governments to implement regulations. The areas in Oklahoma that require increased governmental attention and investigation have been delineated to develop effective regulations at the county and state level that address environmental and health administrative concerns. It is imperative to develop a defined framework that would guide inspectors into inputting the needed information without room for uncertainty. It is also important to establish monitoring plans for affected water wells and to require continuation through post-operation periods. This will aid in determining the existence of long-term impacts and to calculate the annual and/or overall impacts of these practices.

Recommendations for Future Work

The data entry and data management issues need to be addressed. It is necessary to match the innovation applied in the field for exploration and production with that of environmental record tracking and record keeping. Technologies such as automated systems in the form of software applications with real-time quality control need to be implemented. A query language and a conceptual framework that prompts the succeeding data entry has been developed based on the manual classification of five years of incidents. Some of the areas to evaluated on future research include:

1. Hot spot analysis applied to spills to determine if there are clusters of these occurring and concurring in certain areas. These same spills could be quantified by operator to infringe penalties according to the annual recurrence
2. Hot spot analysis for health related issues could be determined and correlated to information from local health care providers and survey polls.
3. A comparative analysis to other producing states could be executed to see where Oklahoma stands and how could regulations be improved or extended beyond borders.

REFERENCES

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US Environment Protection Agency, Ada, Oklahoma, EPA/60012-87/035.

Baker, D. R. (1962). Organic geochemistry of Cherokee Group in southeastern Kansas and northeastern Oklahoma. *AAPG Bulletin*, *46*(9), 1621-1642.

Bergmann, A., Weber, F. A., Meiners, H. G., & Müller, F. (2014). Potential water-related environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natural gas reservoirs in Germany. *Environmental Sciences Europe*, *26*(1), 10.

Besag, J., & Newell, J. (1991). The detection of clusters in rare diseases. *Journal of the Royal Statistical Society. Series A (Statistics in Society)*, 143-155.

Boyd, D. T. (2005). Oklahoma oil and gas production: Its components and long-term outlook. *Oklahoma Geology Notes*, *65*(1), 4-23.

Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., & Kaufman, S. (1983). COCORP profiling across the Southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko Basin. *Geology*, *11*(2), 109-114.

EIA, U. (2011). Review of emerging resources: US Shale gas and shale oil plays. *Energy Information Administration, US Department of Energy*.

EPA, 1987. Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy. Office of Solid Waste and Emergency Response, Washington, D.C. http://nepis.epa.gov/Exe/ZyPDF. cgi?Dockey¼20012D4P.PDF

Evensen, D. T., Clarke, C. E., & Stedman, R. C. (2014). A New York or Pennsylvania state of mind: social representations in newspaper coverage of gas development in the Marcellus Shale. *Journal of Environmental Studies and Sciences*, *4*(1), 65-77.

FracFocus Chemical Disclosure Registry / About Us, http://fracfocus.org/welcome

Förster, A., Merriam, D. F., & Hoth, P. (1998). Geohistory and thermal maturation in the Cherokee basin (mid-continent, USA): results from modeling. *AAPG bulletin*, *82*(9), 1673-1693.

Frost T.K., S. Johnsen, and T.I. Utvik, 1998, "Environmental Effects of Produced Water Discharges to the Marine Environment," OLF, Norway. (Available at http://www.olf.no/static/ en/rapporter/producedwater/summary.html.)

Gass, T. E., Lehr, J. H., & Heiss, H. W. (1977). *Impact of abandoned wells on ground water*. US Robert S. Kerr Environmental Research Laboratory.

Gregory, K. B., Vidic, R. D., & Dzombak, D. A. (2011). Water management challenges associated with the production of shale gas by hydraulic fracturing. *Elements*, *7*(3), 181-186.

Haining R. Spatial Data Analysis: Theory and Practice. New York: Cambridge University Press.2003.

Haugen, J. (1998). Rotary steerable system replaces slide mode for directional drilling applications. *Oceanographic Literature Review*, *8*(45), 1471.

Hughes, B. (2018). North America Rig Counts.

Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics* (No. BOOK). Oxford university press.

Jackson, R. B. (2014). The integrity of oil and gas wells. *Proceedings of the National Academy of Sciences*, 201410786.

Jackson, R. E., Gorody, A. W., Mayer, B., Roy, J. W., Ryan, M. C., & Van Stempvoort, D. R. (2013). Groundwater protection and unconventional gas extraction: The critical need for field-based hydrogeological research. *Groundwater*, *51*(4), 488-510.

Jackson, R. B. (2014). The integrity of oil and gas wells. *Proceedings of the National Academy of Sciences*, 201410786.

Kahrilas, G. A., Blotevogel, J., Stewart, P. S., & Borch, T. (2014). Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation, and toxicity. *Environmental science & technology*, *49*(1), 16-32.

Kharak, Y. K., Thordsen, J. J., Conaway, C. H., & Thomas, R. B. (2013). The energy-water nexus: potential groundwater-quality degradation associated with production of shale gas. *Procedia Earth and Planetary Science*, *7*, 417-422.

King, G. E. (2012, January). Hydraulic fracturing 101: what every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. In *SPE hydraulic fracturing technology conference*. Society of Petroleum Engineers.

Kosnik, R. L. (2007). The oil and gas industry's exclusions and exemptions to major environmental statutes. Oil and Gas Accountability Project/Earthworks, 41.

Kuuskraa, V.A., 2011. Worldwide assessment underscores vast potential of gas shale resources. American Oil & Gas Reporter 54 (5), 40–46.

Lalor, G. C., & Zhang, C. (2001). Multivariate outlier detection and remediation in geochemical databases. *Science of the total environment*, *281*(1-3), 99-109.

Lowman, S. W. (1933). Cherokee structural history in Oklahoma.

Lord C., Niskern D. & Billingsley P. (2009) Using Geologic Data and GIS to Make Base of Treatable Water Maps that Protect Fresh Water Aquifer, Oklahoma Corporation Commission. http://water.okstate.edu/activities/symposium/2009-symposium/2009-abstracts/Lord2009.pdf.

Maggio, G., & Cacciola, G. (2009). A variant of the Hubbert curve for world oil production forecasts. *Energy Policy*, *37*(11), 4761-4770.

Managi, S., Opaluch, J. J., Jin, D., & Grigalunas, T. A. (2005). Environmental regulations and technological change in the offshore oil and gas industry. *Land Economics*, *81*(2), 303-319.

Maule, A. L., Makey, C. M., Benson, E. B., Burrows, I. J., & Scammell, M. K. (2013). Disclosure of hydraulic fracturing fluid chemical additives: analysis of regulations. *New Solutions: A Journal of Environmental and Occupational Health Policy*, *23*(1), 167-187.

Meng, Q., & Ashby, S. (2014). Distance: A critical aspect for environmental impact assessment of hydraulic fracking. *The Extractive Industries and Society*, *1*(2), 124-126.

Meng, Q. (2015). Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA. *Science of the Total Environment*, *515*, 198-206.

Meng, Q. (2017). The impacts of fracking on the environment: a total environmental study paradigm. *Science of the Total Environment*, *580*, 953-957.

Miller, D. W., DeLuca, F. A., & Tessier, T. L. (1974). *Groundwater Contamination in the Northeast States. US Environmental Protection Agency publication no*. EPA-660/2-74--056.

Mitchell, A. (2005). The ESRI guide to GIS analysis II: spatial measurements and statistics ESRI Press. *Redlands CA*.

Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing: history of an enduring technology. *Journal of Petroleum Technology*, *62*(12), 26-40.

Morton, M. Q. (2013). Unlocking the Earth: A Short History of Hydraulic Fracturing.

Murray, K. E. (2013). State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, US. *Environmental science & technology*, *47*(9), 4918-4925.

OECD/IEA, 2008a. World Energy Outlook 2008, Paris. ISBN: 978-92-64-04560-6.

OHS, Map Collection, Oil & Gas Journal https://www.okhistory.org/research/hl_map5.php#page/0/mode/1up

Oil, I. Gas Compact Commission (IOGCC). 2008. Protecting Our Country's Resources: The States' Case; Orphaned Well Plugging Initiative. Report prepared for US Department of Energy, National Energy Technology Laboratory.

Oklahoma Corporation Commission (2013). Incident and Complaint Investigation Reports (1085 forms).

Oklahoma Corporation Commission Title 165: 10 Oil and gas conservation rules (Available at: http://www.occeweb.com/rules/CH10eff08-27-15searchable.pdf)

Ord, J. K., & Getis, A. (1995). Local spatial autocorrelation statistics: distributional issues and an application. *Geographical analysis*, *27*(4), 286-306.

Osborn, N. I., & Hardy, R. H. (1999). *Statewide Groundwater Vulnerability Map of Oklahoma*. Oklahoma Water Resources Board.

Osborn, S. G., Vengosh, A., Warner, N. R., & Jackson, R. B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences*, *108*(20), 8172-8176.

Pal, A., Gin, K. Y. H., Lin, A. Y. C., & Reinhard, M. (2010). Impacts of emerging organic contaminants on freshwater resources: review of recent occurrences, sources, fate and effects. *Science of the total environment*, *408*(24), 6062-6069.

Panel on Scientific Responsibility and the Conduct of Research, National Academy of Engineering National Academy of Sciences (Institute of Medicine), Institute of Medicine, National Academy of Sciences, & National Academy of Engineering. (1992). *Responsible Science. Volume 1: Ensuring the Integrity of the Research Process*. National Academies Press.

Patterson, L. A., Konschnik, K. E., Wiseman, H., Fargione, J., Maloney, K. O., Kiesecker, J., ... & Saiers, J. E. (2017). Unconventional oil and gas spills: Risks, mitigation priorities, and state reporting requirements. *Environmental science & technology*, *51*(5), 2563-2573.

Perry, W. J. (1989). *Tectonic evolution of the Anadarko Basin region, Oklahoma* (No. 1866). Department of the Interior, US Geological Survey.

Petzel, G. J. (1974). *Evaluation of data from the first earth resources technology satellite for the purpose of structural analysis in the Anadarko Basin, Oklahoma and Texas* (Doctoral dissertation, University of Oklahoma).

Porter ME (1991) America's green strategy. Sci Am 264(4):168.

Rahm, B. G.; Riha, S. J. Toward strategic management of shale gas development: Regional, collective impacts on water resources. Environ. Sci. Policy. 2012, 17, 12−23.

Raimi, D. (2018, February 14) The Fracking Debate [Audio podcast] Retrieved from https://sanford.duke.edu/articles/fracking-debate-podcast.

Robinson, T. P., & Metternicht, G. (2006). Testing the performance of spatial interpolation techniques for mapping soil properties. *Computers and electronics in agriculture*, *50*(2), 97-108.

Ryan, B. (2017). *Petrophysical Properties of the Woodford Formation in the Ardmore Basin in Oklahoma, USA* (Doctoral dissertation).

Smith, S.V. (2016, September 27). How an Engineer's Desperate Experiment Created Fracking. Retrieved from https://www.npr.org/2016/09/27/495671385/how-an-engineers-desperate-experiment-created-fracking.

SRI, E. (2014). ArcGIS 10.2. 2 for Desktop. *Redlands: ESRI*.

Stringfellow, W. T., Domen, J. K., Camarillo, M. K., Sandelin, W. L., & Borglin, S. (2014). Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing. *Journal of hazardous materials*, *275*, 37-54.

Stringfellow, W. T., Camarillo, M. K., Domen, J. K., Sandelin, W. L., Varadharajan, C., Jordan, P. D., ... & Birkholzer, J. T. (2017). Identifying chemicals of concern in hydraulic fracturing fluids used for oil production. *Environmental Pollution*, *220*, 413-420.

Suneson, N. H. (2012). Arkoma Basin Petroleum-Past, Present, and Future.

Tekiner, F., & Keane, J. A. (2013, October). Big data framework. In *Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on* (pp. 1494-1499). IEEE.

Title 785. Oklahoma water resources board chapter 45. Oklahoma's water quality standards (Available at: http://www.owrb.ok.gov/rules/pdf/current/Ch45.pdf)

Trollinger, W. V. (1970). Surface evidence of deep structure in the Anadarko basin.

U.S Energy Information Administration (2018). Cushing, OK WTI Spot Price (Dollars per Barrel).

U.S.EPA, (1987). DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings, United States Environmental Protection Agency, Ada, OK, EPA/600/2-87/035.

U.S. EPA. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F, 2016.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology*, *48*(15), 8334-8348.

Walper, J. L. (1976). Geotectonic evolution of the Wichita aulacogen. *Oklahoma (abs.): AAPG Bull*, *60*, 327-328.

Walton, J., & Woocay, A. (2013). Environmental issues related to enhanced production of natural gas by hydraulic fracturing. Journal of Green Building, 8(1), 62-71.

Warner, B., & Shapiro, J. (2013). Fractured, fragmented federalism: A study in fracking regulatory policy. *Publius: The Journal of Federalism*, *43*(3), 474-496.

Waxman, H. A., Markey, E. J., & DeGette, D. (2011). Chemicals used in hydraulic fracturing. *United States House of Representatives Committee on Energy and Commerce Minority Staff.*

Wong, D. W. S., and J. Lee. 2005. Statistical Analysis of Geographic Information with ArcView GIS and ArcGIS. Hoboken: Wiley

Wright III, H. W. (1986). Oklahoma's Groundwater: Reducing the Pollution Caused by Improperly Plugged Oil and Gas Wells. *Tulsa LJ*, *22*, 581.

VITA

Nelly J. Ruiz

Candidate for the Degree of

Doctor of Philosophy

Dissertation: SPATIAL DISTRIBUTION OF WATER POLLUTION INCIDENTS REPORTED TO THE OKLAHOMA CORPORATION COMMISSION

Major Field: Biosystems Engineering

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2019.

Completed the requirements for the Master of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in 2015.

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in 2008.

Experience:

Teaching Assistant at Oklahoma State University in Oklahoma
Project Manager at HSA Engineers and Scientists in Florida
Field Geologist at HSA Engineers and Scientists in Florida
Geologist and International Liaison at Faulkner Exploration in Peru
Geology Intern at PetroEcuador in Ecuador
Geology Intern at Goldmarca Mining in Ecuador and Peru

Professional Memberships:

Society of Petroleum Engineers