

HYDRAULIC FRACTURING IN THE BARNETT SHALE REGION: IDENTIFYING
POTENTIAL PATHWAYS FOR THE POLLUTION OF SURFACE WATER
RESOURCES

by

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CHAPTER I

INTRODUCTION

Through the second half of the 20th century and moving into the 21st century, we humans are beginning to face numerous environmental problems and concerns. From global warming or climate change, to overfishing the oceans, decreasing biodiversity due to land cover change, and deforestation, and ever increasing land and water pollution. There is no question that the Earth's environment is beginning to be in some dire straits. One of these growing concerns, particularly here in the United States is the energy situation. In terms of total primary energy consumption the U.S. ranks second only to China, and in terms of natural gas and petroleum consumption the U.S. ranks first (U.S. EIA 2012). The U.S. has long been a top consumer of energy due to its large population, well developed economy, and infrastructure. However, coming out of the 20th century the United States' energy production tapered off as conventional resources were becoming depleted. Yet, today the U.S. is back on top of the world in terms of energy production, especially in terms of petroleum and natural gas. The primary driver of this newly increased energy production in the U.S. is due to technological advancements in hydraulic fracturing and horizontal drilling techniques. The technological revolution seen in hydraulic fracturing over the past ten years will make the U.S. a leader in world production of natural gas and petroleum moving into the future; however, these rigs are springing up at unprecedeted rates, and due to a lack of regulations the environmental impacts of these new drilling techniques are largely unknown, and highly debated. Through covering many of the different aspects of hydrofracking operations, some of the different environmental impacts they can create, and the evidence to support these claims

with a focus on possible pathways for surface and groundwater contamination; this paper will outline the emergence of the fracking industry, particularly in Texas, and the potential of the Barnett shale region in north Texas. Focusing on the four core counties (Denton, Johnson, Tarrant, and Wise) of the Barnett shale region, the paper will discuss how water resources could be impacted by the burgeoning fracking industry in the area, and why research must be conducted as to whether or not surface waters in this region may have become contaminated in conjunction with the recent increases seen in the hydraulic fracturing industry in the area. The paper will conclude with an examination of pH levels of surface waters in the core counties of the Barnett shale in order to determine if there has been a significantly measureable decline in pH levels of surface waters in conjunction with the rise of the fracking industry in north Texas; as well as what these findings mean for the people living in the Barnett shale, and suggestions for future research in Texas.

CHAPTER II

BACKGROUND AND HISTORY OF THE FRACKING INDUSTRY

It is well known that over the second half of the 20th century oil and natural gas production in the United States tapered off as conventional sources, which are exploited through vertically drilled wells became less productive. However, improvements in hydraulic fracturing and horizontal drilling technologies have emerged which have made unconventional sources like oil shales and tar sands economically viable for drilling; additionally, drilling companies are using these technological advancements to extract more oil from previously depleted conventional wells. Hydraulic fracturing, fracing, or fracking is a process which involves pumping various fluids at extremely high pressures underground to fracture rock formations which then releases tapped oil or natural gas reserves (Wiseman 2009).

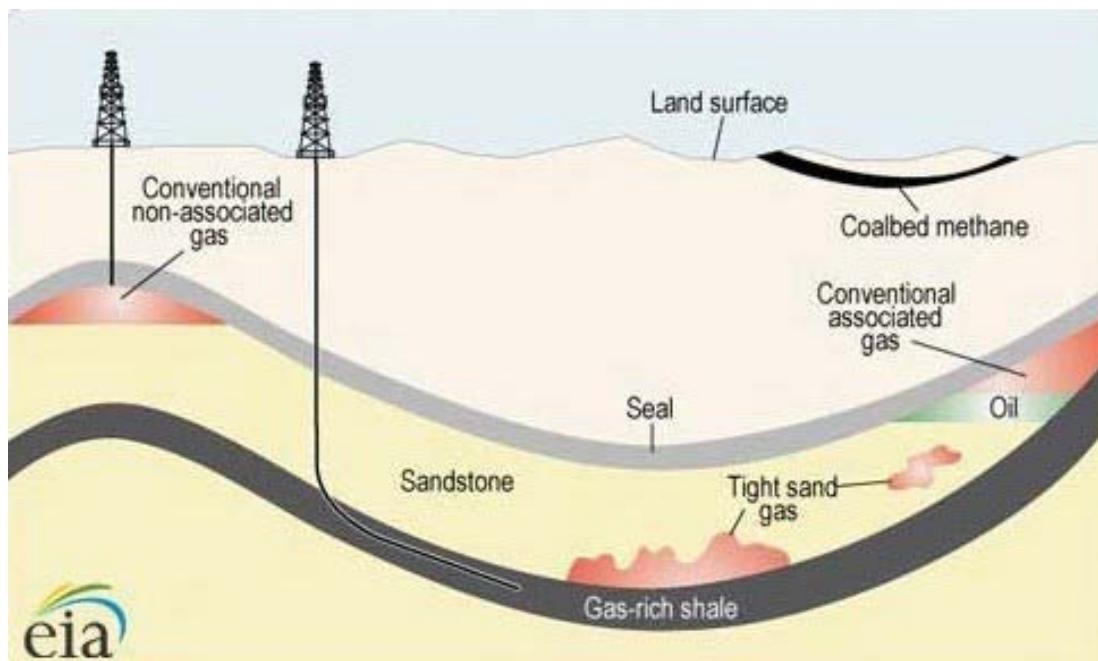


Figure 1: Differences between conventional vertical wells and horizontally drilled reserves: Cooley and Donnelly 2012

Although there are shale plays throughout the lower 48 states, in Texas alone there are 4 major shale plays: Eagleford, Haynesville, Barnett, and the Barnett-Woodford. These emerging areas are the main contributors for the booming natural gas industry in Texas which is already a leading natural gas producer in the United States; today Texas produces 30 percent all the natural gas produced in the U.S.. The most prolific of these Texas sites is the Barnett Shale; the Barnett Shale play alone produces 6 percent of all natural gas produced in the lower forty-eight states (Rahm 2011; Davis 2012). What's more is that the Barnett Shale as prolific as it already is, is also among one of the fastest growing plays in the U.S., and within this play resides one of the largest populations in the United States; the Dallas/Fort Worth metroplex. These factors make this region a prime area for investigation into the possible impacts of the fracking industry.

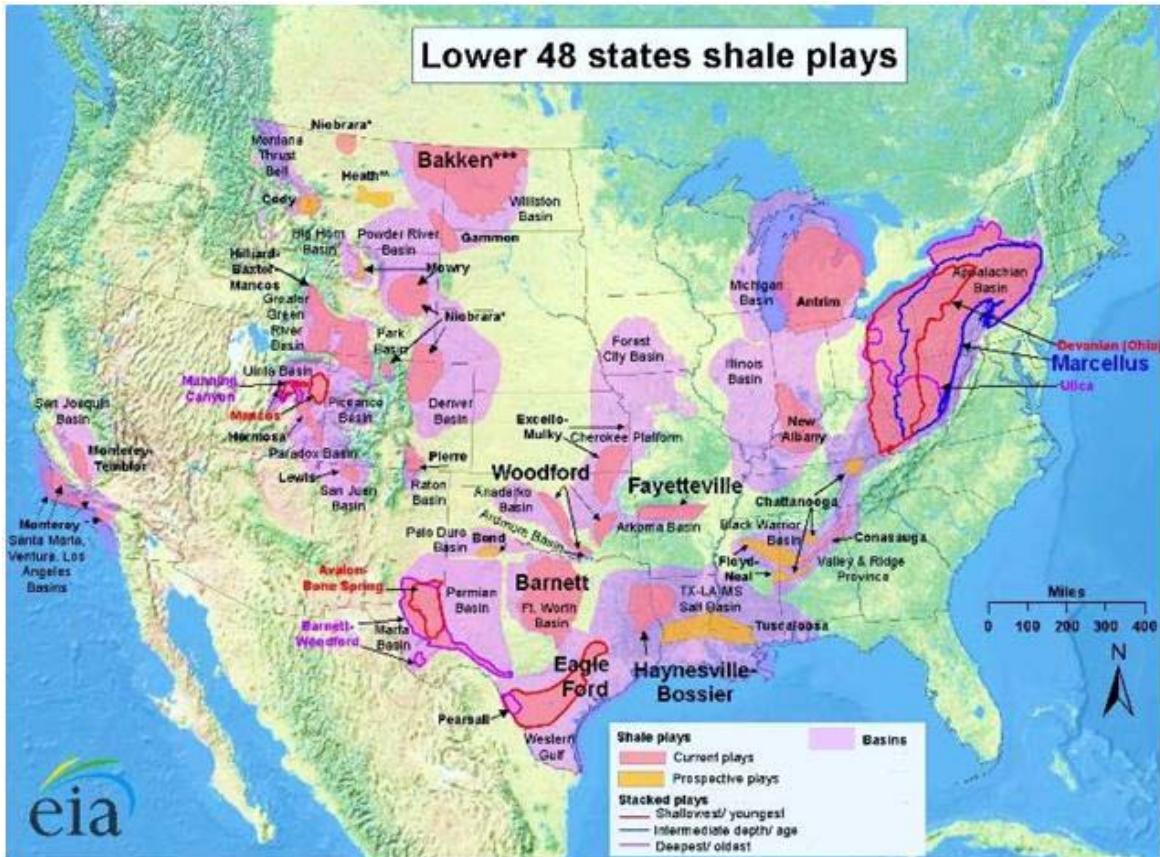


Figure 2: U.S. Natural Gas and Oil Shales Map: Cooley and Donnelly 2012

While in recent years the use of these methods have exploded, (in the U.S. especially) fracking is not such a “new” technology. In fact it was first attempted in Texas back in the 1940s. Since then, fracking technology experienced improvements in the 1970s and 1990s, however, it was not until the 2000s when vast improvements were made in horizontal drilling technologies which made these unconventional horizontal shales more economically viable for drilling; this is what has caused fracking operations to skyrocket in recent years (Ridley 2011). The U.S. EIA (Energy Information Administration) estimates that natural gas production is projected to increase by nearly 30 percent over the next 25 years from 22 trillion cubic feet in 2010 to 28 trillion cubic feet in 2035 (Cooley and Donnelly 2012).

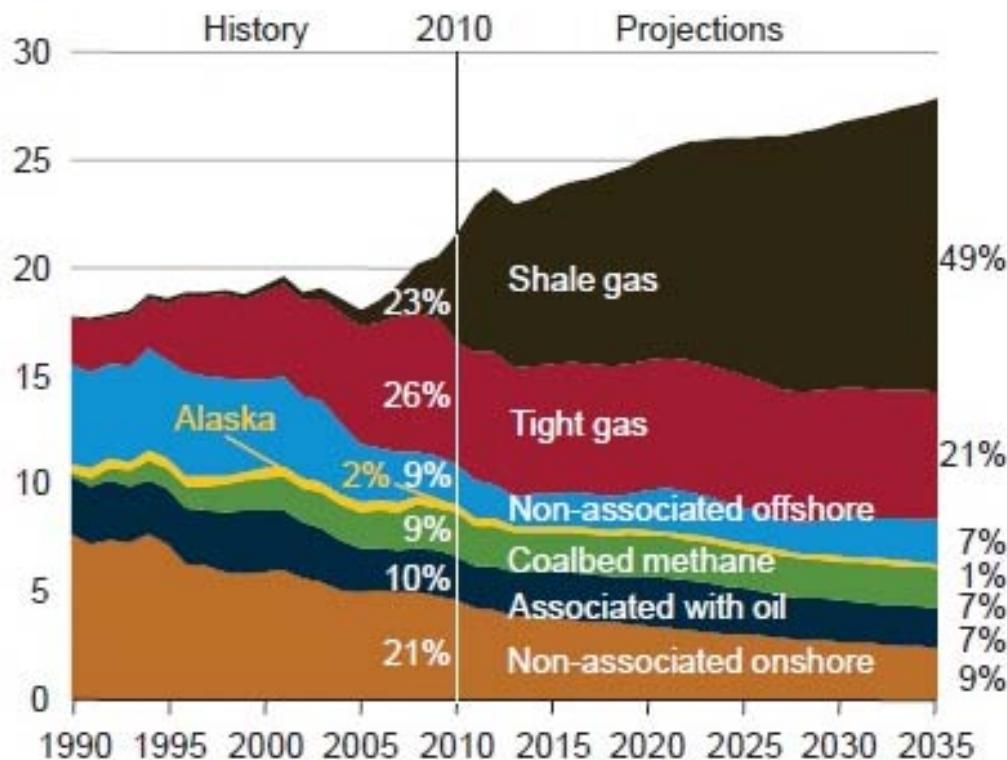


Figure 3: U.S. Natural Gas production by source 1990-2035: U.S. EIA 2012

While horizontal drilling methods are more complicated than traditional vertical operations, the fracking process is relatively simple. Most shale gas reserves are located between 6,000 and 10,000 feet below Earth's surface, and can be as thin as 50-200 feet. This thinness of the rock layers is what requires horizontal drilling. Horizontal drilling is accomplished by drilling vertically downward until the drill bit is around 900 feet from the shale formation, then a directional drill is used to create a gradual 90 degree curve, in order for the well bore to become horizontal as it reaches the shale's depth, figure four on the next page illustrates this process (Clark et al. 2012).

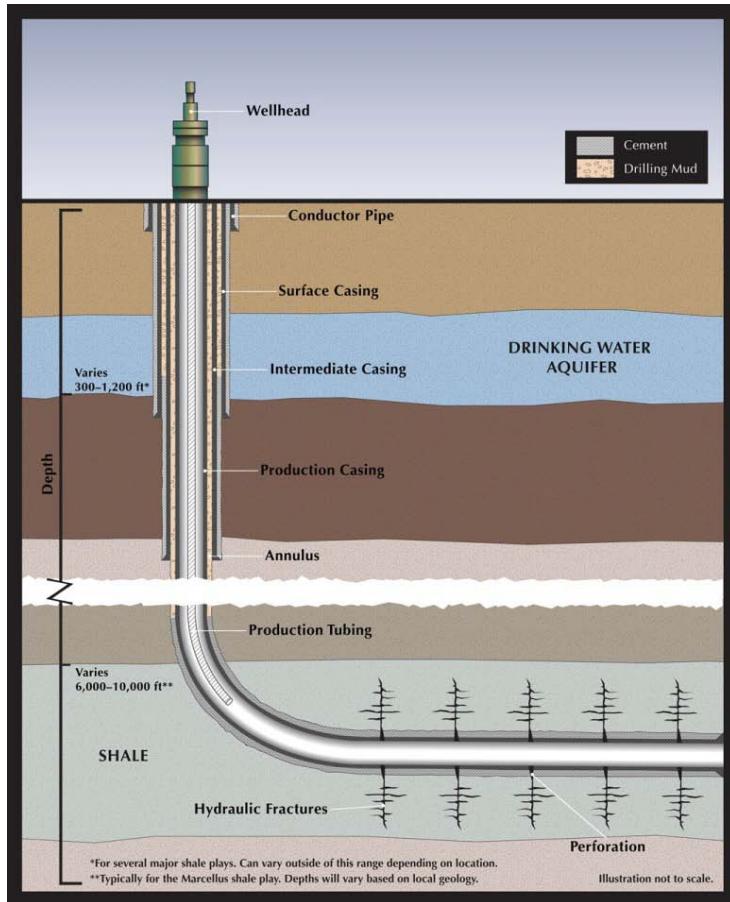


Figure 4: Visualization of the Fracking Process: Clark et al. 2012

Once this process is completed fracturing can then be done throughout the horizontal wellbore which can follow the shale formation for a mile or more; this process is usually carried out multiple times on individual drilling sites and throughout shale formations until the energy potential of each site has been maximized (Rotman 2009).

Industry experts assure that fracking is “ubiquitous, cheap, and environmentally benign”(Ridley 2011) due to various criticisms following studies that have associated water pollution with fracking operations. These criticisms vary from reasons such as a small sample size or area, to improper data collection due to not establishing a baseline for specific chemicals. To claims that methane is not used in the fracking process so the

presence of methane in groundwater where fracking operations exist could be due to natural geologic processes (Schon 2011; Davies 2011). While there is some support for the idea that fracking may be relatively harmless in both the professional as well as the academic communities; these new fracking operations are springing up at unprecedented rates, and are producing large volumes of waste products and are also consuming copious amounts of resources. This new boom in production coupled with the fact that the industry faces no federal regulations, and little to no state regulations means that fracking operations certainly have the potential to create an environmental footprint. From air pollution, due to the high trucking traffic required to transport the large volumes of water needed to support these operations. To water consumption, it is estimated that it takes up to 5.5 million gallons of fluid just to fracture one well. These are just some of the more documented impacts of fracking operations (Clark et al. 2012). Other possible environmental impacts include underground leakage which could be possible through disposal wells or improperly cased wellbores, or through improperly stored or disposed fracking fluids which also create pathways for pollution to enter water resources. Finally, methane migration could be possible from the shale resources to aquifers through natural and hydraulically fractured underground cracks and crevices, where methane can then dissolve into drinking water sources. There has even been an increase in seismic activity associated with the rise of fracking operations across the U.S. (Clark et al. 2012) . Once one has fully examined the breadth and complexity of the entire process behind fracking operations which is required to sustain this industry then it does not seem implausible that there may be some unintended environmental consequences as a result of these fracking operations particularly concerning water resources.

As previously mentioned, fracking may pose a particular concern for water pollution as the process involves the injection of fluids (primarily water by volume) into the ground in and around surface and groundwater bodies. This fracking water is combined with a mixture of chemicals that are largely unknown to the public and contain proppants which are typically sand, metal, or ceramic particles, as well as friction reducers, gelling agents, breakers, biocides, corrosion inhibitors, and scale inhibitors, many of which have previously been proven to be toxic or carcinogenic. Some of the known chemicals frequently used are potassium chloride, guar gum, potassium carbonate, sodium chloride, various acids, benzene, glutaraldehyde, petroleum distillate, isopropanol, hydrochloric acid, methanol, and ethylene glycol (Rahm 2011; Meyers 2012). Industry representatives would say that these chemicals only represent 1 percent or less of the fracking fluid used, however, if a single fracking operation were to use 5 million gallons of fluid then this could represent up to 50 thousand gallons of toxic chemicals which could contaminate water resources (Cooley and Donnelly 2012). Oil shales and sands are notoriously difficult to fracture, so the force with which this fluid is injected into the Earth is tremendous. The pressure needed to fracture a shale can be as much as 15,000 pounds per square inch, which is equivalent to a moderate explosion, and the full impacts of these processes are not entirely known.

Oil and natural gas shales are typically located beneath aquifers and should not then cause the transfer of pollutants back up through the ground and into aquifers or surface waters (Cooley and Donnelly 2012). However, fracking can create pathways with up to 9.2 million square meters of surface area in the shale of a horizontal well, some argue these pathways may then become inter-connected with natural fractures potentially

leading to water resources (King et al. 2012). Concurrently, up to eight wells may be drilled from each pad at a single time, which must be done to fully exploit the potential of the shale. This creates even more pathways for pollution to move throughout the Earth's crust (Myers 2012). Reports of water contamination in areas of high fracking, while they have not been definitively proven to be caused directly by hydraulic drilling processes, include red, orange, gray, brown, yellow, or flammable tap water and some chemicals that have been detected in well waters in areas with a large fracking presence include methane gas, ammonia, arsenic, chloromethane, iron, manganese, t-butyl alcohol, and toluene (Brasch 2012).

Some pathways through which toxins may be entering surface or groundwater systems are through ruptured or improperly placed casings, disposal wells, or accidental spills and seepages surrounding the process of fracking fluid disposal. During the creation of a horizontal well, when the preliminary vertical drilling occurs, a cement or metal frame-work is fitted around the well in order to protect the aquifers that are adjacent to the upper sections of the well from cross contamination as the fracking fluid is pumped through the vertical portion of the well. However, due to a lack of regulations it is not known precisely how well these casings hold up over time. This could be one possible pathway for the contamination of water sources (Northrup 2010). Yet another possible pathway for contamination of water sources as a result of fracking may be through disposal wells. Oftentimes after a site has been fracked a large portion of the fracking fluid used is collected at the surface. Sometimes this fluid is treated and reused, other times it is stored off site until it can be disposed of at a later point in time. However much of the time (particularly in Texas) the waste fluid is injected back into the ground

either into a depleted horizontal well, or into an old conventional vertical well which is no longer in use. These disposal wells present a concern as it is not fully understood what impacts they may or may not be having on the environment. Finally it is possible that fracking fluids may be entering the environment through unintended seepages and spillages which can occur accidentally due to human error through the processes surrounding the storing, transporting, and disposing of fracking wastewater.

While every shale play with fracking operations is subject to scrutiny as to what pollution from fracking may or may not be occurring, the number of documented incidents of water pollution (of groundwater sources in particular) seems to be on the rise. In the small town of Pavilion, Wyoming, 11 of 39 wells tested by the U.S. EPA (Environmental Protection Agency) detected unsafe levels of methane gas, hydrocarbons, lead, and copper. This was the first time the EPA investigated water quality in response to residents' complaints of contamination in drilling areas (Lustgarten 2009). In another study conducted by Duke University in 2011 there was documented evidence of methane contamination of drinking water associated with shale gas extraction in the Marcellus shale play in Pennsylvania and New York. They found methane concentrations in drinking water that were almost 20 times the levels that were found in similar wells with no nearby gas extraction sites (Osborn et al. 2011). Finally, on New Year's day in 2009 in Dimock, Pennsylvania there was an explosion in a residential drinking water well due to methane build-up, and the Pennsylvania Department of Environmental Protection conducted an investigation and determined Cabot Oil & Gas was responsible for polluting 18 wells, stating that Cabot Oil & Gas failed to prevent natural gas from entering groundwater sources, and has since been ordered to cease drilling and has also

been completely banned from fracking new or existing wells in Pennsylvania. However, as of 2012 many homes in the area are still reporting contaminated water supplies (Cooley 2012).

There are seemingly numerous pathways through which water contamination could be occurring around hydraulic fracturing operations. Whether these pathways are through above ground sources such as improperly stored wastewater, through accidental spills or seepages, or through underground sources such as fractures connecting with natural fissures which could lead to water sources. Pollution may also be entering the environment through ruptured and or improperly cased wells, or through disposal wells which may run adjacent to aquifers, water wells, or surface waters which could lead to contamination. It certainly seems as though there is a possibility of water contamination surrounding fracking operations throughout the U.S. including the Barnett shale region of Texas. These aforementioned factors, along with the fact that the Barnett shale region is such a highly populated area are why research should be conducted in order to determine whether or not there has been a decline in surface water quality in the Barnett shale. Through examining Ph levels in surface waters throughout the Barnett shale of Texas it may be possible to see a decline in surface water quality which coincides with the rise of the fracking industry in the area. The literature review section will detail more of the evidence across the U.S. and in Texas to support the idea that fracking may not be quite as safe as industry representatives have indicated, as well as the policy or lack thereof at both the state and federal levels which has led to the current state of the industry today.

CHAPTER III

LITERATURE REVIEW

While the full impacts of the fracking process are still somewhat in question, the blame cannot be placed on the drilling industries for utilizing this technology to fill the world's, and nation's unquenchable need for oil and natural gas resources. The explosive nature seen in the rise of fracking operations in recent years can be partially attributed to the lack of regulations by the federal government at the beginning of the fracking boom, and subsequently the lack of regulations thereafter in certain states (Texas being a prime example).

In 1974 Congress passed the Safe Drinking Water Act (SDWA), which directed the Environmental Protection Agency (EPA) to regulate underground injections of fluids in order to protect our nations underground water sources. Section 1421 of the SDWA states that the EPA regulations: "contain minimum requirements for programs to prevent underground injection that endangers drinking water sources" (Tiemann and Vann 2012). However, Section 1421(b)(2) specifies:

"[the EPA] may not prescribe requirements for state underground injection control programs which interfere with or impede- A) the underground injection of brine or other fluids which are brought to the surface in connection with oil or natural gas production or natural gas storage operations, or B) any underground injection for the secondary or tertiary recovery of oil or natural gas, unless such requirements are essential to assure that underground sources of drinking water will not be endangered by such injection"

While it would seem the ordinary citizen that requirements should always be essential to assure that sources of drinking water are being protected, apparently the federal government disagrees. In 2005 Section 1421D was amended so that “the term “underground injection” as defined by the SDWA means the subsurface emplacement of fluids by well injection, but specifically excludes the underground injection of fluids or propping agents associated with hydraulic fracturing operations related to oil, gas, or geothermal production activities”. Section 1422 of the SWDA “delegate[s] primary enforcement authority for underground injection control programs to the states” (Tiemann and Vann 2012). Clearly the federal government is taking a hands off approach to the issues surrounding fracking which leaves it up to the states to regulate their own fracking operations.

While fracking regulations vary across the country, some states have began to take steps towards heavily regulating the fracking industry. States like Vermont, New York, and Maryland have banned fracking altogether until its environmental impacts are more fully understood, and the proper regulations can be put in place to protect people and the environment. Pennsylvania has strict zoning rules regulating the location of new wells, and has placed strict construction, casing, maximum fracking pressure limits, routine inspections, and other regulations on horizontal drilling operations. Meanwhile, more conservative states such as Wyoming and Colorado simply require that hydraulic fracturing operations disclose the chemicals which make up their fracking fluids (Clark et al. 2012; Rahm 2011). However, while some states have taken more proactive steps to mitigate the environmental impacts of fracking operations, Texas has taken a more laissez faire approach.

Historically the oil and natural gas industries have been huge drivers of the Texas economy, and this continues to be the case today. As previously mentioned Texas produces 30 percent of the natural gas in the U.S., and in Texas the oil and natural gas industries employ over 200,000 people and contributes over \$200 billion to the Texas economy (Texas PetroFacts 2011). Such a prosperous and well entrenched industry coupled with a generally conservative attitude along with the somewhat fragmented nature of Texas' regulatory bureaucracy creates an environment where hydraulic fracturing can thrive (Rahm 2011).

While Texas remains one of the more conservative states in terms of regulating the fracking industry, there have been several regulations set forth by the Railroad Commission in order to police the industry. In 2012 a law was passed which requires water volumes, and chemical additives used in fracking operations in Texas to be disclosed to the public through FracFocus.org (Clark et al. 2012). Other regulations in Texas are that you must obtain a permit to drill new or to re-drill old wells, and fracking operations are required to comply with proper casing and cementing construction requirements which include placing several layers of steel and or cement casings to protect ground waters from cross contamination of fracturing fluids. Railroad Commission rules also require gauges to monitor these casings at the surface so a down hole problem can be identified. Fracking operations are also required to use approved methods of waste disposal for fracking fluids. However, there are no other additional laws or regulations regarding environmental assessments of fracking operations' impacts or any of the industry's other environmental or wildlife related impacts. It is left up to the oil and natural gas companies to police themselves on the proper "safe" implementation

of fracking technology in Texas (Mazzone, Mendoza, and Kulander 2010; Davis 2012; RRC 2014).

Texas does not have a centralized regulatory bureaucracy, the environmental management and regulation of Texas' environmental quality and resource management is divided between multiple authorities. Environmental quality and pollution issues usually fall under the jurisdiction of the TCEQ; the Texas Commission on Environmental Quality is charged with protecting the state's air and water quality, as well as implementing federal clean air and water laws. However, the Railroad Commission of Texas (RRC) is responsible for regulating virtually all safety and environmental impacts of the oil and natural gas industry, and thus any of the impacts which may result from fracking operations. The RRC is also charged to "promote enhanced development and economic vitality" (Rahm 2011). This seems to create a bit of a conflict of interest, as promoting the development of industries may contribute to negative effects on the environmental quality of Texas. This conflict seems further exacerbated by the fact that the Railroad Commission has the right to give access to as much groundwater as it needs to complete a given job, as well as eminent domain over land rights for the construction of new pipelines (Davis 2012). Between the generally conservative attitudes among Texas' residents, Texas' vast supplies of oil and natural gas resources, and the freedom with which the Railroad Commission is allowed to operate and promote the oil and natural gas industries, Texas is the perfect state for hydraulic fracturing to prosper (Rahm 2011).

While government entities like the RCC and industry experts continue to assure the public that fracking operations are following proper regulations and are having negligible impacts on the environment and our water sources, growing evidence from the scientific

and academic communities suggest that there could be many unintended consequences as a result of fracking operations. Some of the most well documented impacts of the fracking industry include a decline of air quality, and changes to land cover in areas with a high fracking presence. Fracking operations require a tremendous amount of equipment and materials transport all of which requires the use of large diesel trucks. The New York State Department of Environmental Conservation estimated that fracking operations could require as many as 3,950 truck trips per day during early development of a new shale. This is two to three times more than would be required for conventional vertical wells (Cooley and Donnelly 2012; NYSDEC 2011). Evidence of this was documented in a Colorado School of Health study which found that areas within half a mile from fracking wells were at higher risks for various health issues. Air pollutants originating from fracking sites in this study included xylenes, benzene, and alkanes which cause eye, nose, throat, and lung irritation (Coimbra 2013; Mckenzie 2012). Evidence on impacts of air quality have even been seen in Texas; in the town of Dish an independent study conducted in 2009 found the “presence in high concentrations of carcinogenic and neurotoxin compounds in ambient air near and or on residential properties” (Michaels et al. 2010). These compounds included benzene, zylene, carbon disulfide, naphthalene, dimethyl disulphide, methyl ethyl disulphide, and pyridine metabolites (Michaels et al. 2010). Another study conducted out of Southern Methodist University in Ft. Worth found that levels of benzene in and around the city exceeded the safe limits, and that “pollutant emissions from natural gas drilling activities per day surpassed those produced by all of the vehicle traffic in the Dallas-Fort Worth region” (Al Armendariz 2009). Changes in surface cover as a result of the construction of well pads, and new roads as well as the

degradation of those roads as a result of high trucking traffic required to maintain fracking operations are certainly a consequence of the boom seen in the oil and gas industries across the country (Ridley 2011; Cooley and Donnelly 2012). While negative impacts on surface and groundwater quality remain contentious and difficult to implicate directly as a result of horizontal drilling processes, to say that there are no environmental impacts from the fracking industry is inaccurate.

Negative impacts on water quality in regions experiencing a fracking boom remain to be highly debated among the public, the fracking industry, and the academic and scientific communities. Industry experts continue to assure that fracking practices are environmentally sound, however there are clearly numerous pathways through which contamination or pollutants could enter the environment. These pathways could range from illicit or accidental activities such as illegal discharges, surface spills, improper wastewater treatment or containment, and illegal wells or permit violations; to unintended consequences like chemical, brine, or gas migration from hydraulic fractures extending into natural pathways which could contaminate surface or ground water sources (Osborn et al. 2011; Revesz et al. 2012; Michaels et al. 2010).

The most highly debated of the possible pathways for fracking's impact on water resources is fluid or gas migration from hydraulic fractures which have become interconnected with natural geologic formations and have in turn led to surface or ground water contamination. While there is some evidence that this is indeed occurring, industry experts argue that these migrations are occurring through natural geologic processes. Studies in Pennsylvania have found numerous instances of elevated levels of methane, other hydrocarbons, and other pollutants in water wells and in tap waters near fracking

areas (Osborn et al. 2011; Revesz et al. 2012). Along with these studies there are multiple recorded events of both gas and water well explosions, as well as explosions occurring in residential homes in Pennsylvania, West Virginia, and Wyoming in areas with a high fracking presence (Michaels et al. 2010). While it seems there is scientific as well as anecdotal evidence to support the claims of gas migration into natural fissures which lead to surface or ground waters, there is also evidence to support the contrary. A study conducted by the Society of Petroleum Engineers in 2011 which examined the fracture height growth of hydraulic fractures found that “under normal circumstances, where hydraulic fractures are conducted at depth, there is no method by which a fracture is going to propagate through the various rock layers and reach the surface”, and that “hydraulic fracture heights are relatively well contained”(Fisher and Warpinski 2011). Studies like this make proving gas or fluid migration into drinking water sources difficult to prove definitively, and make it seem somewhat unlikely particularly in Texas which has deeper shales than are found in the Marcellus shale in the northeastern states (Cooley and Donnelly 2012). However, there are other various pathways which have yet to be fully studied and researched which seem to be more likely sources for water resource contamination.

The most likely sources of water contamination from fracking operations also happen to be the least studied and least regulated of the industry, particularly in Texas. These are surface spills or seepages due to improper waste water treatment or containment, various permit violations, illegal wells, and injection or disposal wells. These sources are particularly difficult to study due to the lack of regulations mentioned

earlier which do not require the monitoring or the reporting of such events leaving little to study.

While instances of water contamination are particularly well documented in states such as Pennsylvania, West Virginia, Wyoming, and Colorado (Michaels et al. 2010; Osborn 2011; Revesz 2012) . There is in fact some evidence of water contamination occurring in Texas in areas with a high fracking concentration. In an incident in Dish, Texas a homeowner complained about gray tap water following the instillation of fracking operations near his home in 2009. The RRC tested this water and found elevated amounts of hydrocarbons, arsenic, butanone, carbon disulfide, acetone, lead, chromium, and strontium up to 21 times above safe levels (Michaels et al. 2010). A second piece of evidence in Texas is from a study conducted out of the University of Texas at Arlington in 2013 which evaluated water quality in 100 private drinking wells in the Barnett Shale Formation. This study found that some private water wells located within 3 kilometers of natural gas wells had elevated levels of arsenic, selenium, strontium and total dissolved solids which exceeded the maximum contaminant limit. This study also found that private wells outside of 3 kilometers from natural gas wells had lower levels of arsenic, selenium, strontium, and barium. Methanol and ethanol were also detected in 29 percent of the samples. The study also revealed that samples which exceeded the maximum contaminant limit were randomly distributed within areas of active natural gas extraction, and the exact cause of these findings could not be explicitly determined (Fontenot et al. 2013).

This evidence indicates that there could be some correlation between compromised water quality and the boom seen in horizontally drilled oil and natural gas wells. Whether

these findings are a direct result of the horizontal drilling and hydraulic fracturing process themselves, or whether these instances of impaired water quality are a symptom of another part of the fracking industry has yet to be determined. However through examining the evidence clearly there has been some effect on water quality in areas with horizontal drilling operations; this is why through conducting an analysis on surface water quality in the 4 core counties of the Barnett shale using pH as an indicator it may be determined that there is a correlation between a decline in pH levels in surface waters and the rise of the fracking industry in the four core counties of Barnett shale region.

CHAPTER IV

DATA AND METHODOLOGY

As mentioned previously the true reasons behind water quality degradation in areas with a fracking presence remain unproven, although numerous possible pathways for contamination and pollution have been identified throughout the various processes which surround the fracking industry. In Texas it seems unlikely that contamination is occurring through underground fluid or gas migration due to the depths at which Texas' shales are found; thus it seems more likely that pollution could be entering the environment in Texas through one of the unintended or illicit activities sometimes associated with fracking operations (i.e. surface spills, improper waste water treatment or containment, various permit violations, illegal wells, and injection or disposal wells). Unfortunately in Texas the data concerning the majority of these incidents is not available due to a lack of regulations requiring such events to be monitored and reported for documentation. However, through examining pH levels of the surface waters in the four core counties (Denton, Johnson, Tarrant, and Wise) of the Barnett shale it may be possible to see a correlation between the boom of the fracking industry and a drop in surface water pH levels in the area due to the acidic nature of fracking fluids. Using water quality monitoring station data obtained by the Texas Stream Team (and one station from the USGS), an examination of pH levels could be a good indicator of any contamination of surface waters which may be occurring through fracking operations. I will focus my attention on surface water quality as the study from 2013 by Fontenot et. al. previously mentioned already found a correlation between fracking wells and diminished well water quality in the Barnett shale. By comparing current levels of pH in the core counties of the

Barnett shale with the pH levels of that found in the same counties before the fracking boom, as well as current pH levels found in surface waters in relatively similar geographic areas in Texas which are not near areas associated with fracking; it may be possible to observe a drop in pH levels in the Barnett Shale associated with the rise of the fracking industry in the area.

In order to determine whether or not there has been some decline in surface water quality and pH levels in the surface waters of the core counties in the Barnett shale we must first identify what the typical healthy pH levels are for Texas, and the Barnett shale region. Throughout the study areas which are located in central and north Texas' Grand Prairie and Cross Timbers regions the underlying bedrock types are consistently calcareous sandy limestones and dolomites (University of Texas Bureau of Economic Geology 1996), this is important to note as a region's bedrock and soil have an important impact on water pH levels. In much of Texas, this impact is demonstrated by the fact that limestones, dolomites, and calcareous soils are all primarily composed of calcium carbonate (Long 2011), which when dissolved in water effectively increase pH levels causing waters to become more alkaline, or less acidic (Cravotta and Trahan 1999; Schreiber 1988; Huang, Fisher, Horner, and Argo 2010). Thus, if healthy, the pH levels in surface waters in the core counties of the Barnett shale region which resides mainly in the Trinity watershed, and partially in the Brazos water shed in the Grand Prairie and Cross Timber regions should all contain relatively basic pH levels, and should typically range from a pH of 7.1 to 8.5 (Jiann, Santschi, and Presley 2013). However, if some or many of the stream segments throughout the core counties of the Barnett shale are found to have acidic pH levels coinciding with the rise of the fracking industry, then this may

be attributable to the increased fracking presence as the major chemical additives utilized in fracking fluids are primarily acidic in nature (Rahm 2011; Cooley and Donnelly 2012).

By examining the current pH levels found throughout the core counties of the Barnett shale, and comparing these levels with pH levels found in similar areas in Texas which are not currently in close proximity to fracking operations, as well as through comparing the pH levels found in the core counties of the Barnett shale before the boom seen in the fracking industry it may be possible to observe a decline in the pH levels of surface waters in the core counties of the Barnett Shale with the rise of the fracking industry in the area.

CHAPTER V

ANALYSIS AND RESULTS

Once data collection for the surface water pH levels was completed there were 20 different water quality monitoring stations found throughout Denton, John, Tarrant, and Wise counties with data available from the post fracking boom (2010 to the present), and for the conditions from the 1990's before the fracking boom seen in the area there were 24 different water quality monitoring stations in the core counties of the Barnett shale maintained by the Texas Stream Team. For the comparative data from counties currently not in proximity to fracking the only data available in a similar region in Texas was from three counties (Bell, Coryell, and McLennan) which are located directly south of the Barnett shale (approximately 100 miles from the four core counties), and there were only 10 water quality monitoring stations with available data from the Texas Stream Team for this area for data from 2010 to the present.

The pH levels found throughout the 20 stations most recently monitored in the core counties of the study area were found to be relatively neutral overall with a weighted average pH of 7.6. Average pH values across this area from the individual monitoring stations ranged from 7.8 to 6.8, and the overall range across this period was from pH 9.2 to 6.0 (see Table 1). This is compared to the current average pH levels found in the three counties just south of the Barnett shale which also had a basically neutral weighted average pH across the study area (see Table 3). The average values ranged from 7.86 to 6.87 with a weighted average of 7.31 and a total range of 9.5-6.1, and this is also compared to pH levels in the core counties of the Barnett shale from the 1990's which were found to be the most basic (or least acidic) overall, but also had the greatest range.

In the core counties surface water pH levels from the 1990's were found to have average values ranging from 8.75 to 6.47 with a weighted average of 7.92, but this data set had a total range of 9.3 to 5.9 (see Table 2).

The implications of this data are that there has been no significant decline in pH levels in the core counties of the Barnett shale coinciding with the rise of the fracking industry in the area. Although the weighted average was the least alkaline (or most acidic) in the Barnett shale core county's most recent data set, the average and total ranges in pH for the core counties was almost exactly equal to the average and total range for the area directly south of the Barnett Shale. This is compared to the data from the core counties before the fracking boom which had the most alkaline (least acidic) overall average, but had the largest average and total ranges. It should be noted that all three study areas had basically the same total ranges, all pH levels collected from each study area were somewhere in the range of pH 9.5 to 5.9 which is a typical pH range for these regions of Texas.(Jiann, Santschi, and Presley 2013) It is also important to note that every measurement of current pH conditions in the core counties of the Barnett shale fell right within this range (pH 9.2 to 6.0) indicating no real change in surface water pH values coinciding with the boom seen in the region's fracking industry. If the weighted average for the current conditions in the core counties of the Barnett Shale had been found to be significantly more acidic than the other areas, or if the overall range for the Barnett shale was found to have statistical outliers ranging more acidic then it could have been possible that these anomalies were a result of incidents of pollution from the increased fracking presence in the region due to the acidic nature of fracking fluids. However, this data suggests that there has been no significant change in surface water pH

levels after the rise of the fracking industry in the four core counties of the Barnett shale as the data was highly uniform across all three study areas. While the findings of the data suggest there has been little to no impact on surface water pH levels in the core counties of the Barnett Shale coinciding with the boom in the fracking industry this could perhaps be attributable to some of the limitations with the data.

Tables 1, 2, and 3 on the following pages display the compilation of the data for the three study areas acquired from the Texas Stream Team and USGS, and show the mean, high, and low pH measurements for each individual station, as well as the weighted mean ph, and weighted mean high and low pH values for each entire study area. Weighted averages for each study area were calculated using the formula:

$\sum \frac{n_i}{N} (pH_i)$ where n_i represents the number of measurements recorded at each station, N is the total number of measurements taken for each study area, and pH_i is the pH value for a given water quality monitoring station.

Table 1: Barnett Shale Core Counties Most Current pH levels 2010-2014

Stream Segment I.D.	Data Source	County	Measurement Date	Number of Cases	Mean PH	High PH	Low PH
Bakers Branch @ Twilight	Stream Team	Denton	01/2013- 03/2014	13	7.8	9	7.5
Cooper Creek @ Burningtree	Stream Team	Denton	01/2010-11/2012	24	7.3	7.8	7
Elm Fork Trinity River @ Hebron Parkway	Stream Team	Denton	08/2013-01/2014	6	7.1	7.4	7
Elm ForkTrinity River @ U.S. hwy 380	Stream Team	Denton	01/2010- 11/2012	27	7.5	7.5	7
Grapevine Creek (Unnamed Tributary)	Stream Team	Denton	10/2012-07/2013	10	7.5	8	7
Grapevine Lake	Stream Team	Denton	07/2012-11/2013	8	7	7.5	7
Hickory Creek @ Jackson St.	Stream Team	Denton	03/2010-02/2013	23	7.4	7.5	7
Little Elm Creek	USGS- Daily	Denton	04-09/2013 / 11/2013-04/2014	228	8	9.2	7.1
Pecan Creek @ Woodrow St.	Stream Team	Denton	01/2010-11/2012	28	7.2	7.8	7
Pecan Creek @ Gay St.	Stream Team	Denton	01/2010-11/2012	23	7.2	7.5	6
Brazos River	Stream Team	Johnson	09/2011-12/2011	7	7.7	7.9	7.4
Buffalo Creek @ CR 1112	Stream Team	Johnson	03/2012-03/2014	23	6.8	7	6.5
Farmers Branch @ limestone waterfall	Stream Team	Tarrant	09/2010- 09/2013	30	7	7	7
Johnson Creek	Stream Team	Tarrant	02/2010-12/2013	62	7.6	8.2	7
Lake Worth Greer Island Peninsula	Stream Team	Tarrant	09/2012-08/2013	13	7.8	8.5	7.2
Lake Worth @ Todd Island Crossing	Stream Team	Tarrant	09/2012-08/2013	13	7.6	8	7
Lynn Creek @ HWY 360	Stream Team	Tarrant	04/2007- 12/2008	13	7.3	7.5	6.8
West Fork Trinity River Collins St. canoe launch	Stream Team	Tarrant	03/2013 - 03/2014	18	7	7	6.9
West Fork Trinity River @ 10 Mile Bridge Rd.	Stream Team	Tarrant	09/2012-08/2013	13	7.7	8.3	7
Bear Creek	Stream Team	Wise	03/2012-07/2012	5	7.5	7.6	7.4
			Weighted averages		7.6	8.3	6.99

Table 2: Barnett Shale Core County pH levels 1992-1999

Stream Segment I.D.	Data Source	County	Measurement Date	Number of Cases	Mean PH	High PH	Low PH	
Elm Fork Trinity River @ Lewisville Lake	Texas Stream Team	Denton	10/1993 - 11/1999	66	7.79	8.9	5.9	
Elm Fork Trinity River @ SH 121	Texas Stream Team	Denton	10/1993 - 12/1999	72	7.9	8.9	7.5	
Hickory Creek @ FM 1830	Texas Stream Team	Denton	10/1993 - 12/1999	72	7.85	8.3	7.5	
Nolan River @ SH 4 NW of Celburne	Texas Stream Team	Johnson	09/1997 - 06/1998	9	8.45	9.2	7.7	
Robinson Branch of Nolan River btwn US 67 and CR 1116	Texas Stream Team	Johnson	09/1997 - 06/1998	7	8.16	8.7	7.6	
West Fork of Nolan River @ CR 1227	Texas Stream Team	Johnson	09/1997 - 06/1998	9	8.2	8.9	7.6	
West Nolan River A FM 2331	Texas Stream Team	Johnson	09/1997 - 08/1998	11	8.27	8.4	8	
Big Fossil Creek 30 meters upstream of St. Louis SW RR	Texas Stream Team	Tarrant	05/1993 - 06/1997	48	7.9	8.9	7.5	
Big Fossil Creek in City Park	Texas Stream Team	Tarrant	05/1993 - 12/1996	40	7.86	8	7.5	
Calloway Branch @ Glenview Drive	Texas Stream Team	Tarrant	05/1993 - 07/1994	15	8.05	9	7	
Calloway Branch @ High Tower Drive	Texas Stream Team	Tarrant	05/1993 - 10/1995	27	7.95	8.3	7.5	
Clear Fork near Hulen Street	Texas Stream Team	Tarrant	11/1995 - 03/1997	18	7.93	8.5	7.8	
Eagle Mountain Lake @ Shady Grove Park	Texas Stream Team	Tarrant	09/1994 - 05/1998	33	8.15	9.3	6	
Eagle Mountain Lake @ Westbay	Texas Stream Team	Tarrant	04/1994 - 01/1998	42	8.75	9	7.8	
Eagle Mountain Lake in Little Dosier Slough	Texas Stream Team	Tarrant	11/1997 - 08/1999	17	8.26	8.5	8	
Fossil Creek @ Broadway Street in North Richland Hills	Texas Stream Team	Tarrant	07/1993 - 06/1997	46	7.72	8	7.4	
Kee Branch Creek @ Bardin Road	Texas Stream Team	Tarrant	11/1992 - 10/1994	22	7.41	7.9	6.7	
Lake Bedford Boys Ranch	Texas Stream Team	Tarrant	08/1994 - 09/1997	34	8.01	8.9	6.9	
Sycamore Creek @ Seminary Drive East of IH 35	Texas Stream Team	Tarrant	02/1995 - 08/1998	47	8.42	9	8.3	
Village Creek Across from SE Landfill in Forest Hill	Texas Stream Team	Tarrant	05/1993 - 01/1995	15	8.12	8.4	7.5	
Village Creek @ Kennedale Road	Texas Stream Team	Tarrant	05/1993 - 09/1995	29	8.73	8.2	7.7	
Walker Branch Headwaters	Texas Stream Team	Tarrant	05/1993 - 06/1997	49	6.47	8	6	
Eagle Mountain Reservoir @ Marshall Drive	Texas Stream Team	Wise	07/1997 - 11/1998	16	8.34	8.8	7.8	
Oliver Creek	Texas Stream Team	Wise	02/1996 - 12/1999	40	7.65	8.3	7.6	
					Weighted averages:	7.92	8.58	7.22

Table 3: Most Current pH Levels non-fracking Counties 2010-2014

Stream Segment I.D.	Data Source	County	Measurement Date	Number of Cases	Mean PH	High PH	Low PH
Nolan Creek tributary	Texas Stream Team	Bell	10/2012 - 04/2014	12	7.33	8	7
Saldado Creek @ Armstrong crossing	Texas Stream Team	Bell	01/2013 - 04/2014	16	7.24	8	6.4
Saldado Creek NE of IH 35 stagecoach dam	Texas Stream Team	Bell	12/2012 - 04/2014	18	6.87	7.3	6.1
South Nolan Creek at S Young Drive	Texas Stream Team	Bell	07/2011 - 04/2014	31	7.24	7.5	6.6
Leon River at Mother Neff State Park	Texas Stream Team	Coryell	11/2012 - 08/2014	12	7.23	8	6.9
Bosque River @ McLennanCC Boat Ramp	Texas Stream Team	McLennan	11/2010 - 06/2011	7	7.86	9.5	7.5
Brazos River @ Platform in Cameron Park	Texas Stream Team	McLennan	07/2011 - 03/2012	6	7.58	7.8	7.4
Lake Waco @ Midway Parl Board Ramp	Texas Stream Team	McLennan	11/2010 - 12/2011	14	7.6	7.8	7.5
Lake Waco Wetlands Inflow area	Texas Stream Team	McLennan	12/2010 - 02/2014	21	7.4	8	7
Lake Waco Wetlands Outflow area	Texas Stream Team	McLennan	12/2010 - 04/2011	7	7.43	7.5	7.2
				Weighted averages	7.31	7.83	6.83

The first limitation of the study was the lack of detailed water quality data available; of all the water bodies found in the four core counties of the Barnett shale, many of them had no water quality monitoring stations, and the largest stream segments only had one or two monitoring stations which is not truly indicative of the water quality of these largest water bodies (such as the Trinity, or the Brazos rivers). A second limitation concerning the quality of the data used was that there was only data available for much of Texas' surface waters concerning pH, discharge, and dissolved O₂, had there been data available concerning variables such as turbidity, salinity, or levels of metals such as lead and arsenic, or even other gasses such as methane, the results of this study may have been more telling. A third limitation centered around the data quality was the frequency with which the measurements were taken, and the number of measurements taken for some of the stream segments. For all but one of the segments in the study (Little Elm Creek) the measurements were only recorded once a month, and the number of measurements for each station varied from 5 to 62, and these measurements were not over the exact same time period.; the time periods of the measurements taken ranged from as early as 2010 to as recent as 2014. Had the measurements at the monitoring stations been taken once or twice daily (or more) over the entire study area for the exact same time periods the results for this study could have been more conclusive. It should also be noted that the monitoring stations used for the core counties from both time periods (the 1990's and the present) were not the exact same monitoring stations; ideally the stations would have been identical across both time periods. A final limitation of this study was the relatively small area that it covered, while it examined the four core counties of the Barnett Shale as identified by the RRC, the Barnett Shale in its entirety

takes up some part of 25 counties in northern Texas, and had this study extended across the entire Barnett Shale then perhaps the findings would have been different. Overall while this study may not have implicated any pollution of surface waters in the core counties of the Barnett Shale as a result of fracking operations in the area, the study is not without its limitations and further study into this matter and other forms of water resource contamination surrounding fracking should be conducted not only in the Barnett Shale or in Texas, but across the country wherever fracking is highly prevalent. Had the quality of the data across the study area been more through, and the amount of water quality data had been more robust then the results of this study could have very well been different.

CHAPTER VI

CONCLUSIONS

While the exact impacts of the fracking industry are still highly debated, particularly in terms of the industry's pollution of water resources, there have been numerous pathways identified through which fracking could have negative impacts on the environment. Whether these impacts be on air quality due to increased truck traffic, or changes in land cover as a result of drill pad construction, or on water quality as a direct result of hydraulic fracturing processes, or as an indirect result from secondary activities needed to sustain these drilling processes. The precise impacts on the fracking industry are still unknown and further study should be conducted into the full environmental impacts surrounding the industry.

Although the actual sources of water pollution as a result of fracking remain definitively unproven, by examining the evidence from cases around the country it is fairly clear that there is some correlation between negative effects on water quality and areas with a high fracking presence. Whether these sources are from the processes of hydraulically fracturing its self through connecting manmade and natural fissures and natural geologic formations, or because of improperly cased well bores, or through secondary activities which are required to sustain these activities. Improper waste water containment, accidental seepages, surface spills, or disposal wells, are all possible pathways for pollution when and where fracking occurs. Until the various activities surrounding fracking operations are fully studied and understood the true impacts of the fracking industry will remain unknown.

As the fracking industry continues to grow and prosper moving into the future hopefully the fracking industry will adhere to more rigorous regulations through legislation as more people and legislatures realize the potential for harm to both citizens and the environment as a result of the fracking industry's boom. Changes in regulation, particularly in Texas could include a comprehensive program for assessing the air, surface, and ground water quality around fracking areas, as well as more rigorous system for monitoring the full environmental and ecological impacts of individual fracking operations. Establishing a system for tracking waste water disposal amounts and methods particularly surrounding accidental seepages and spills as well as known illegal discharges, wells, and other illicit drilling activity could also be useful to understanding the full impacts of the industry. If more data was available concerning these areas, then perhaps fracking's impacts on water quality could be more completely understood. Hopefully as the fracking industry continues to be studied and the data surrounding the fracking processes continues to grow, the true causes of the degradation of water quality in certain areas around fracking operations will be more fully understood. As the base of knowledge surrounding the fracking industry and its impacts continues to expand, the true causes of water pollution surrounding these operations should be identified, and once this is accomplished surely legislators can begin to work with industry experts to make hydraulic fracturing both profitable for the drilling companies and the oil and natural gas industries, as well as safe for the citizens which occupy the areas that surround these operations.

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