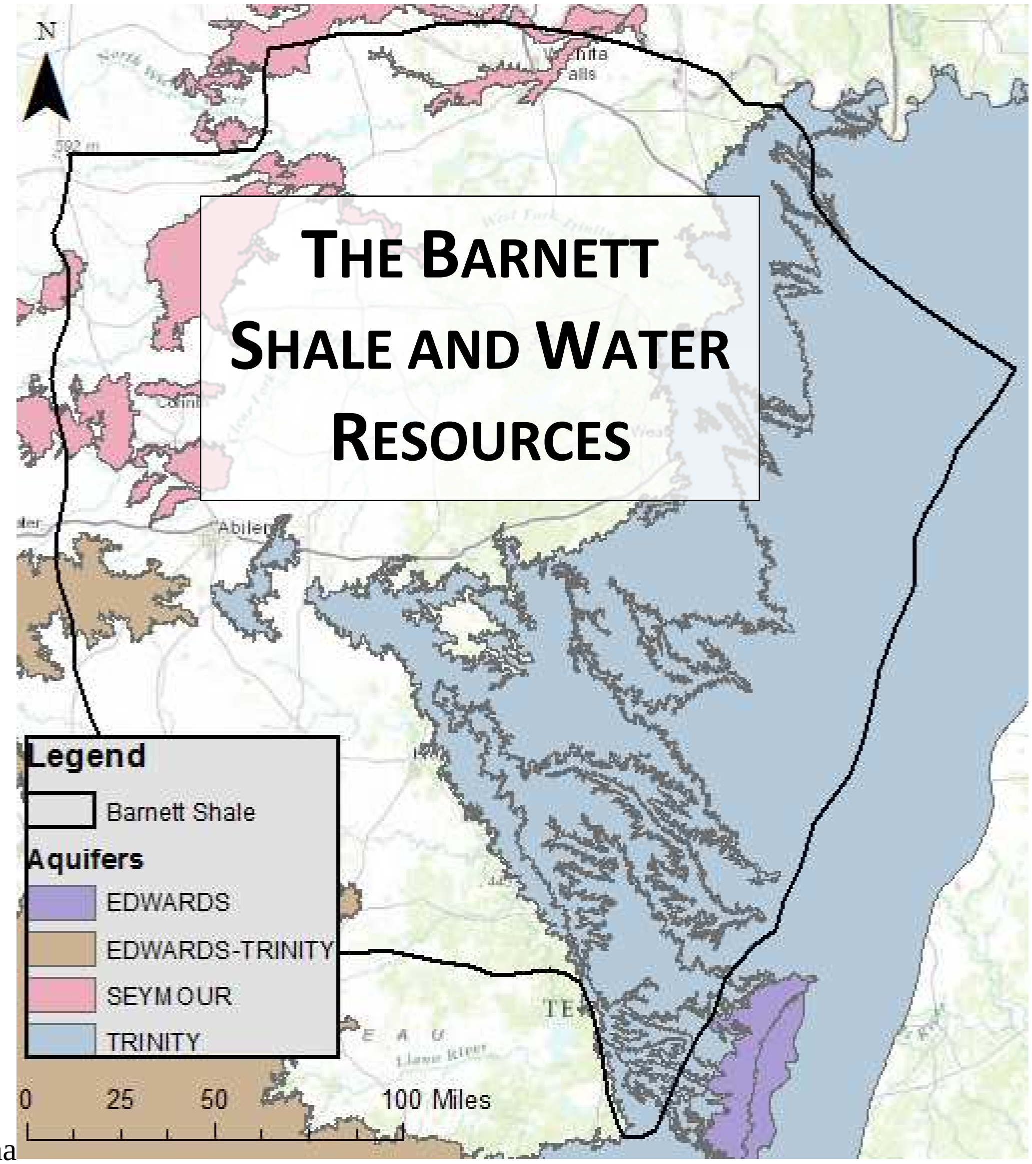

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Fracking and Texas Water Resources: A Case Study in the Barnett Shale

Prepared by Dana Lazarus for GIS and Water Resources in Fall 2013

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1. Introduction

This report describes an analysis of the impacts of hydraulic fracturing (“fracking”) on groundwater resources in the Barnett shale basin, located near Dallas-Fort Worth, Texas. The analysis uses groundwater monitoring data from the Texas Water Development Board to interpolate average annual groundwater levels for Tarrant County, Texas for the years 1993-2012. These results are then incorporated into a regression model with natural gas production, population, economic, and weather data to analyze the various factors affecting groundwater levels in the area of study. The results confirm that there is a relationship between population, business activity, and natural gas production on groundwater levels in Tarrant County, but the specific relationship between these factors requires further study.

This report begins with an overview of hydraulic fracturing and its impacts on Texas water resources, particularly in the Barnett shale (Section 2). Then, Section 3 describes the data sources used to describe hydraulic fracturing activity, groundwater resources, and weather and socioeconomic conditions in the area of study. Section 4 details the methodology used to select the area of study, evaluate the available groundwater monitoring data, interpolate groundwater levels, and conduct a regression analysis. Next, Section 5 presents the results of the groundwater level interpolation and regression analysis. Finally, this document concludes with an interpretation of the results and suggestions for future avenues of study.

2. Background

Over the past few years, hydraulic fracturing of shale deposits has revolutionized the energy industry in the U.S. Hydraulic fracturing is a process by which water is injected into a drilling site at high pressure to create fractures in oil and gas-bearing deposits, providing a way to extract these resources which were previously uneconomic to develop. Hydraulic fracturing has taken off in various parts of the U.S., including Texas.

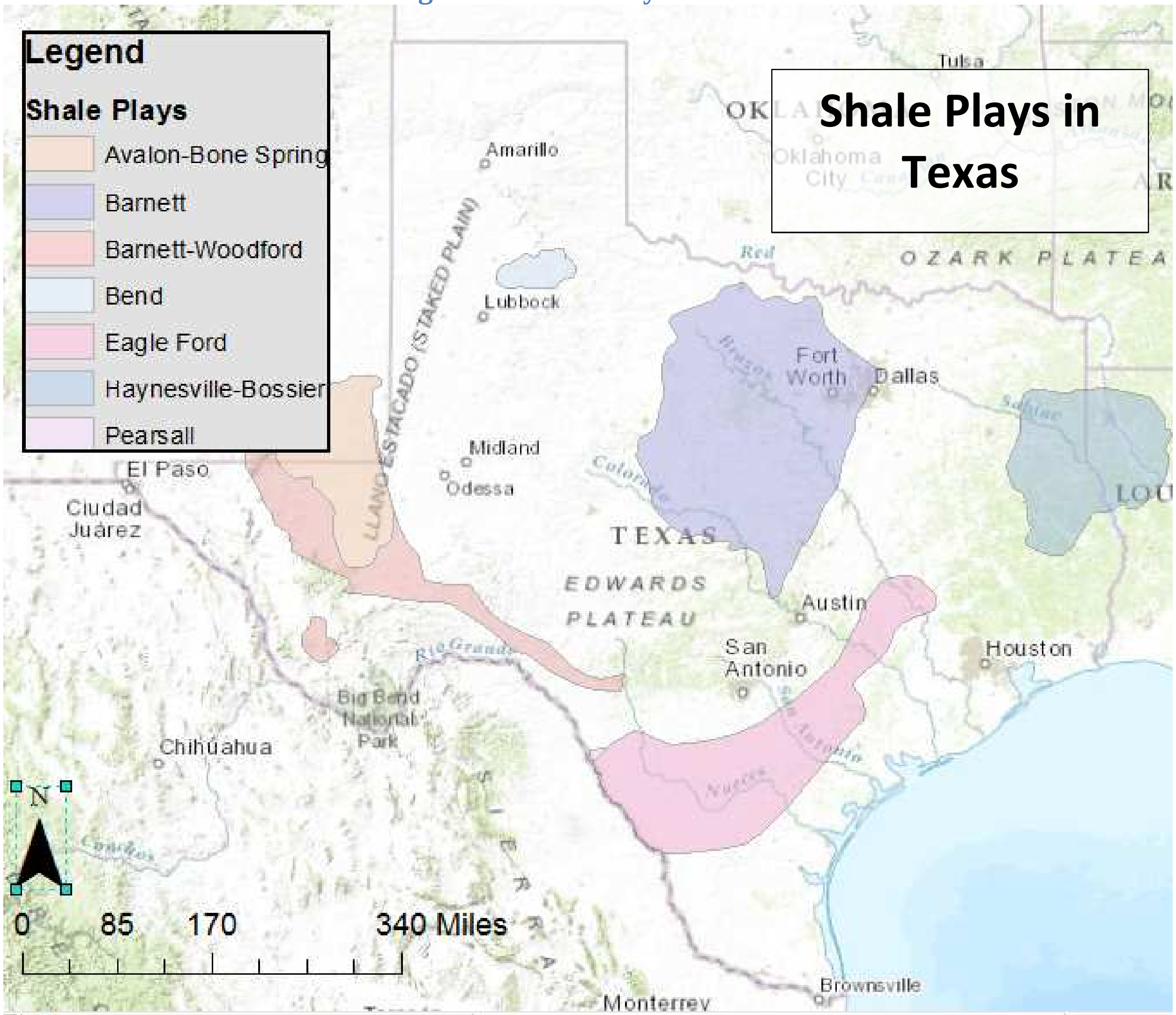
Hydraulic fracturing poses several concerns related to water resources, stemming from the large quantities of water required for the hydraulic fracturing process, the disposition of wastes from drilling sites, and potential groundwater and surface water contamination from spills, surface runoff, and migration from well casings. Of these, the most problematic impact is the large water requirements (Pacific Institute 2012). This issue is especially concerning in Texas, which in the current drought is already struggling to develop adequate water supplies for urban, industrial and agricultural needs. For this reason, changes to water supply were designated as the primary focus of this study.

This analysis uses the mapping and interpolation tools in ArcGIS to interpret how the growth of hydraulic fracturing in the Barnett Shale has impacted local water resources, and how the industry compares to other water users in the area. Due to the numerous data requirements of this study, this analysis further refined its scope to Tarrant County to make the data requirements more manageable. The reasons for selecting Tarrant County will be discussed in Section 4.1. The time period 1993-2012 was selected for this analysis because that is the period for which production data was available from the Texas Railroad Commission, and it provides a sufficient time horizon prior to the growth of hydraulic fracturing in the area. In the text that follows, Section 2.1 provides background on shale plays in Texas and the Barnett Shale, while Section 2.2 describes the groundwater resources in the Barnett shale.

2.1 Shale Resources in Texas and the Barnett Shale

Shale resources are typically referred to as basin or plays. A shale basin is the deposit of shale under the surface, whereas a shale play is an area where exploration and production activity is actually taking place. Therefore, the shale plays are the more heavily impacted areas. As can be seen from Figure 1 below, there are seven shale plays in Texas: Avalon-Bone Spring, Barnett, Barnett-Woodford, Bend, Eagle Ford, Haynesville-Bossier, and Pearsall.

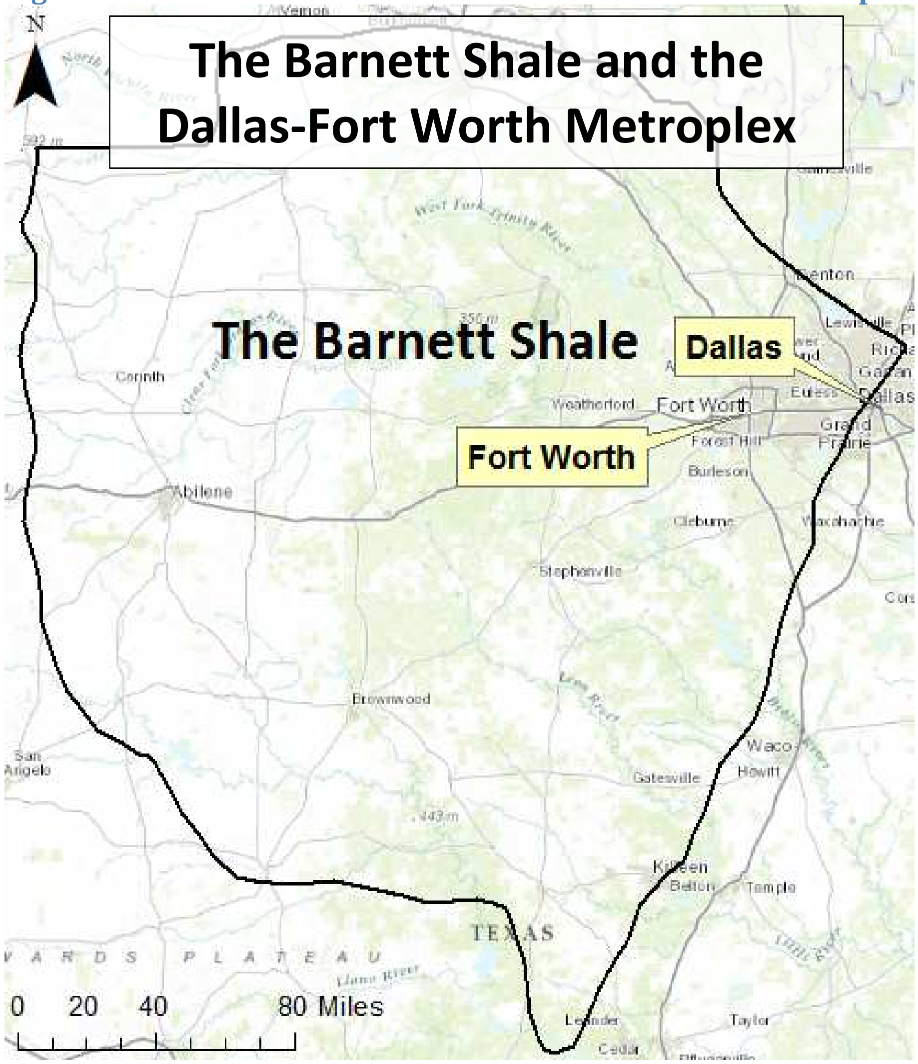
Figure 1: Shale Plays in Texas



Source: EIA 2011

As noted above, this analysis focuses on the Barnett Shale in Texas. The Barnett Shale was selected as the area of study because it is the most productive shale play to date in the U.S., and because it has the distinctive feature of being located adjacent to the Dallas-Fort Worth metroplex (as can be seen in Figure 2 below), presenting a unique interaction of energy production and urban management issues.

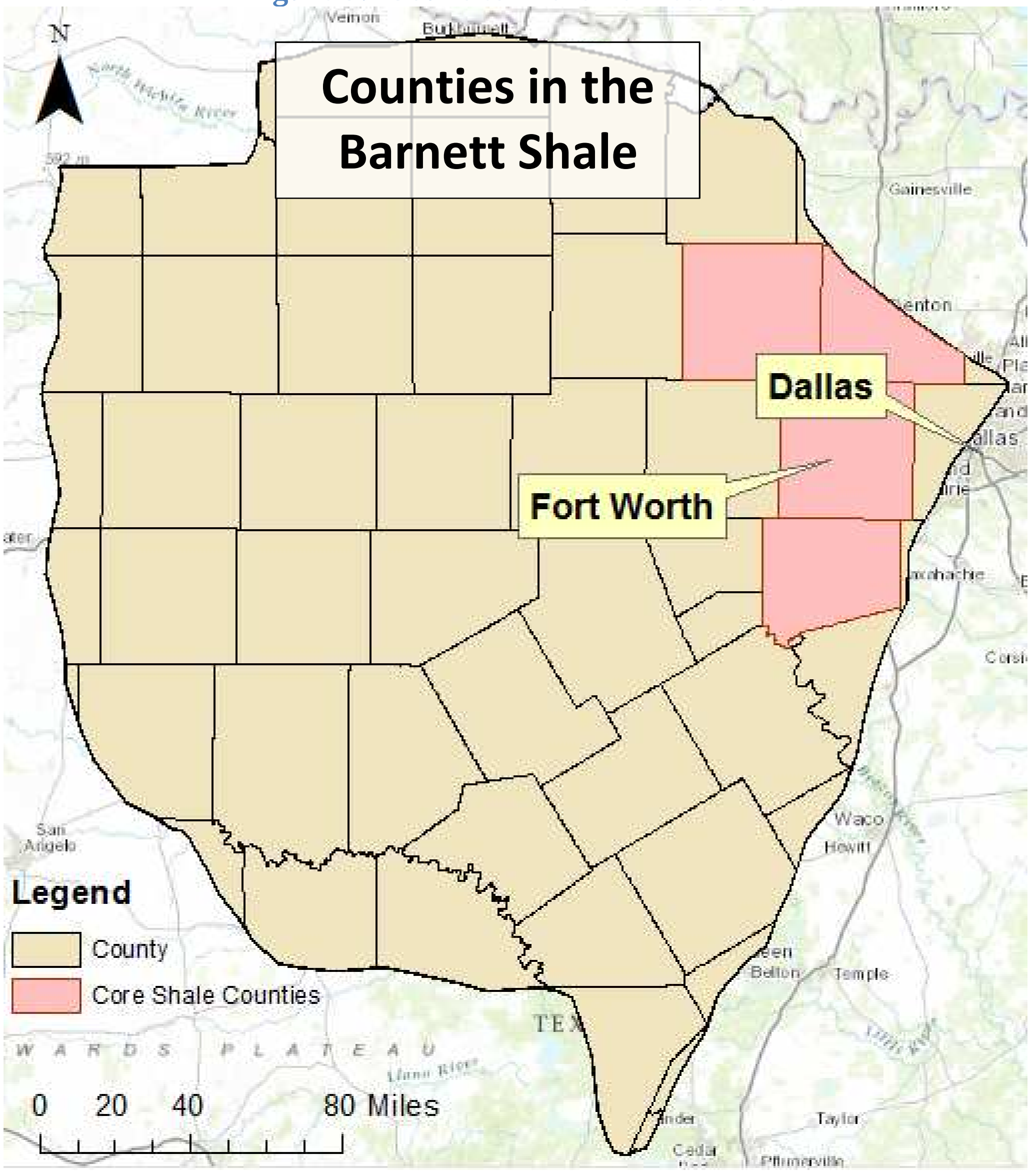
Figure 2: The Barnett Shale and the Dallas-Fort Worth Metroplex



Source: EIA 2011

The Texas Railroad Commission, responsible for well permitting in the state, designates "core" and "non-core" areas of the Barnett Shale (Texas Railroad Commission 2013a). According to the Texas Railroad Commission, the "core" production counties in the Barnett Shale are Denton, Johnson, Tarrant, and Wise County. As can be seen from Figure 3 below, Fort Worth and Dallas are located within or in close proximity to the most productive shale counties.

Figure 3: Counties in the Barnett Shale

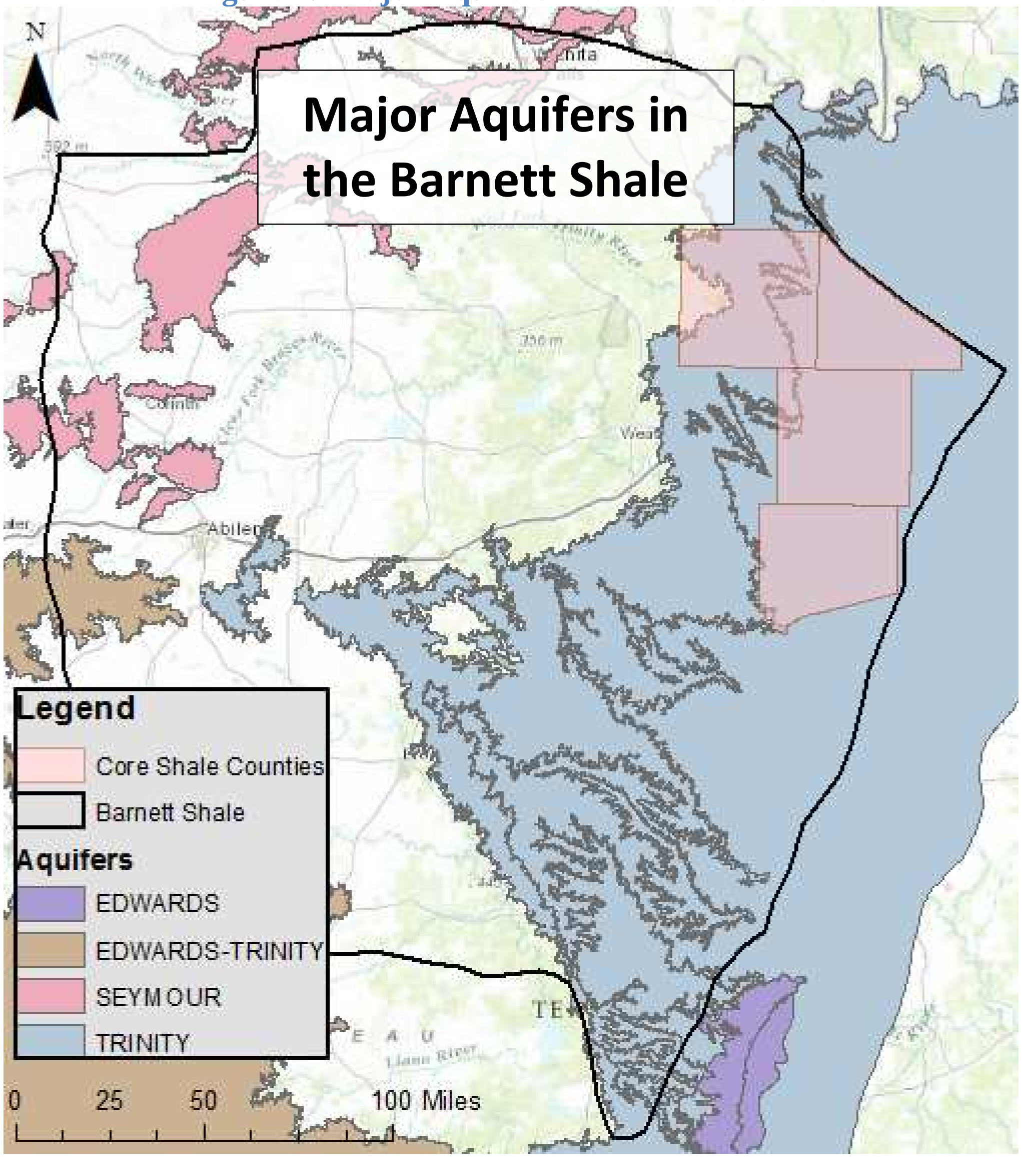


Source: EIA 2011; Texas Railroad Commission 2013a; TxSDC 2013

2.2 Groundwater Resources in the Barnett Shale

Water supply comes primarily from the Trinity aquifer in this region. For this reason, groundwater resources (rather than surface water resources) were the focus of this study. As Figure 4 below shows, the Barnett shale overlays several major aquifers, but the Trinity aquifer is the most impacted. It is located directly beneath the "core" productive areas of the Barnett shale, and serves as a water source for both the hydraulic fracturing industry and the municipal water utility (Nicot 2009; Nicot et al. 2012). In addition to the Trinity aquifer, the Seymour and Edwards-Trinity aquifers also underlay portions of the Barnett shale; however these areas are not located in the "core" of shale development activity. The Edwards aquifer is also located adjacent to the southeastern edge of the Barnett shale.

Figure 4: Major Aquifers in the Barnett Shale



Source: EIA 2011; Texas Railroad Commission 2013a; TWDB 2013a, TxSDC 2013

In addition to hydraulic fracturing, there are several important factors that could affect the local water supply. The largest water consumer is municipal utilities, especially with the growing population (and associated water demands) in the area. There are also other industries that impose heavy water requirements, such as electricity generation, agriculture, and electronics manufacturing. Finally, precipitation (and subsequent migration into aquifers) will also affect groundwater levels. This analysis considers all of these factors and their individual and cumulative demands on the Trinity aquifer in Tarrant County.

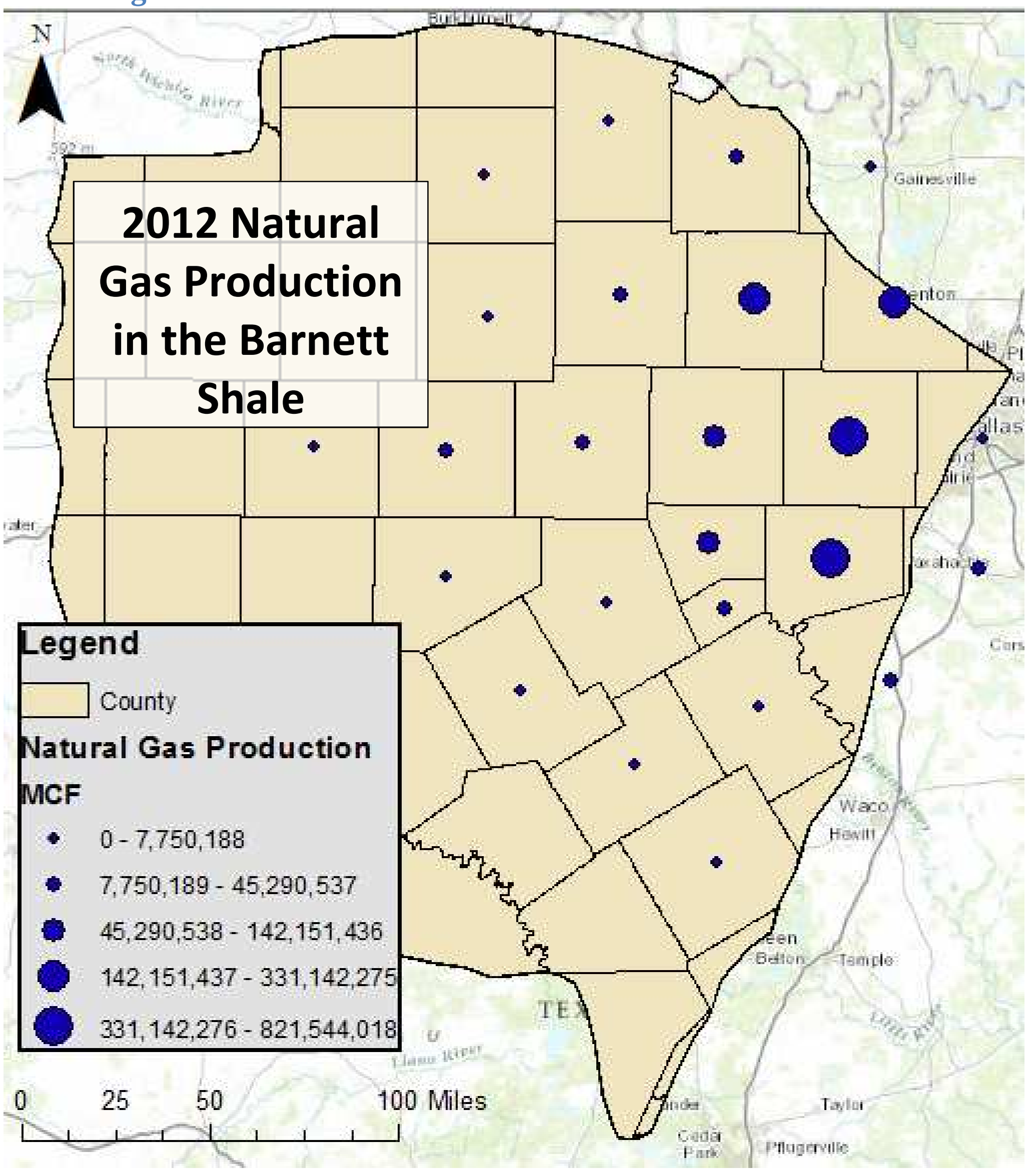
3. Data Sources

This section describes the data sources used in this analysis to describe natural gas production (Section 3.1), groundwater resources (Section 3.2), precipitation (Section 3.3), population (Section 3.4), and economic activity (Section 3.5).

3.1 Natural Gas Production Data

The Texas Railroad Commission provides oil and natural production data by county in its Oil and Gas Data Query Tool (Texas Railroad Commission 2013b). This data was downloaded for all counties (core and non-core) in the Barnett Shale for 1993-2013 (all the years of available data). However, this analysis excluded the 2013 data because it does not represent a full year's worth of information. Figure 5 below displays production for 2012, for those counties labeled as "core" and "non-core" by the Texas Railroad Commission. Those counties located within the shale basin but not designated as an affected county by the Texas Railroad Commission are not included in this analysis. Tarrant County had the highest amount of production in 2012, with 821,544,018 MCF of natural gas produced.

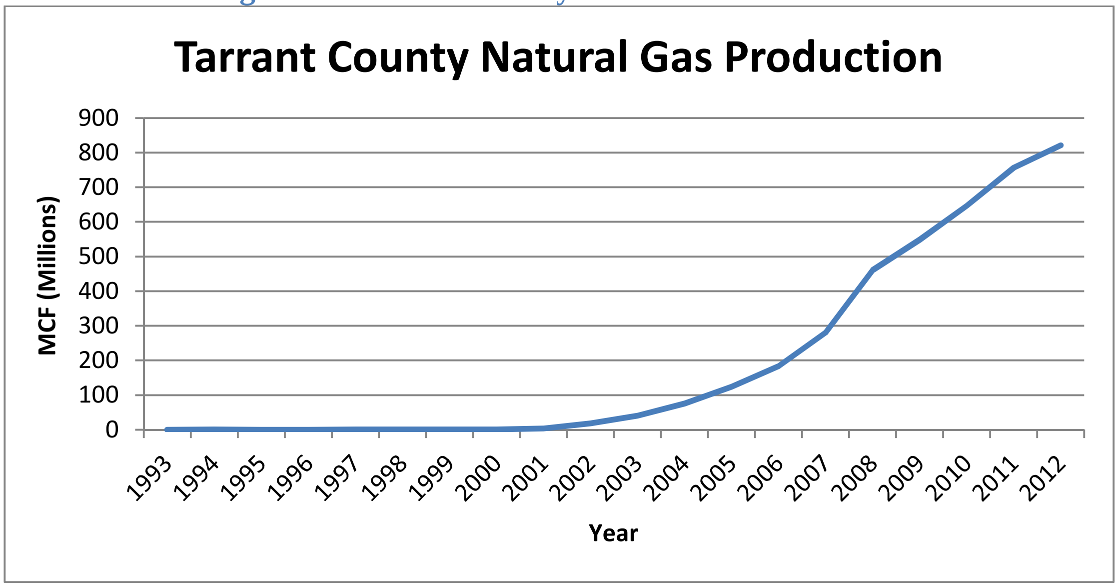
Figure 5: 2012 Natural Gas Production in the Barnett Shale



Source: EIA 2011; Texas Railroad Commission 2013b; TxSDC 2013

Figure 6 below shows the trend for natural gas production in Tarrant County. As can be seen from the chart, natural gas production began to increase around 2002-2003 due to the introduction of hydraulic fracturing.

Figure 6: Tarrant County Natural Gas Production

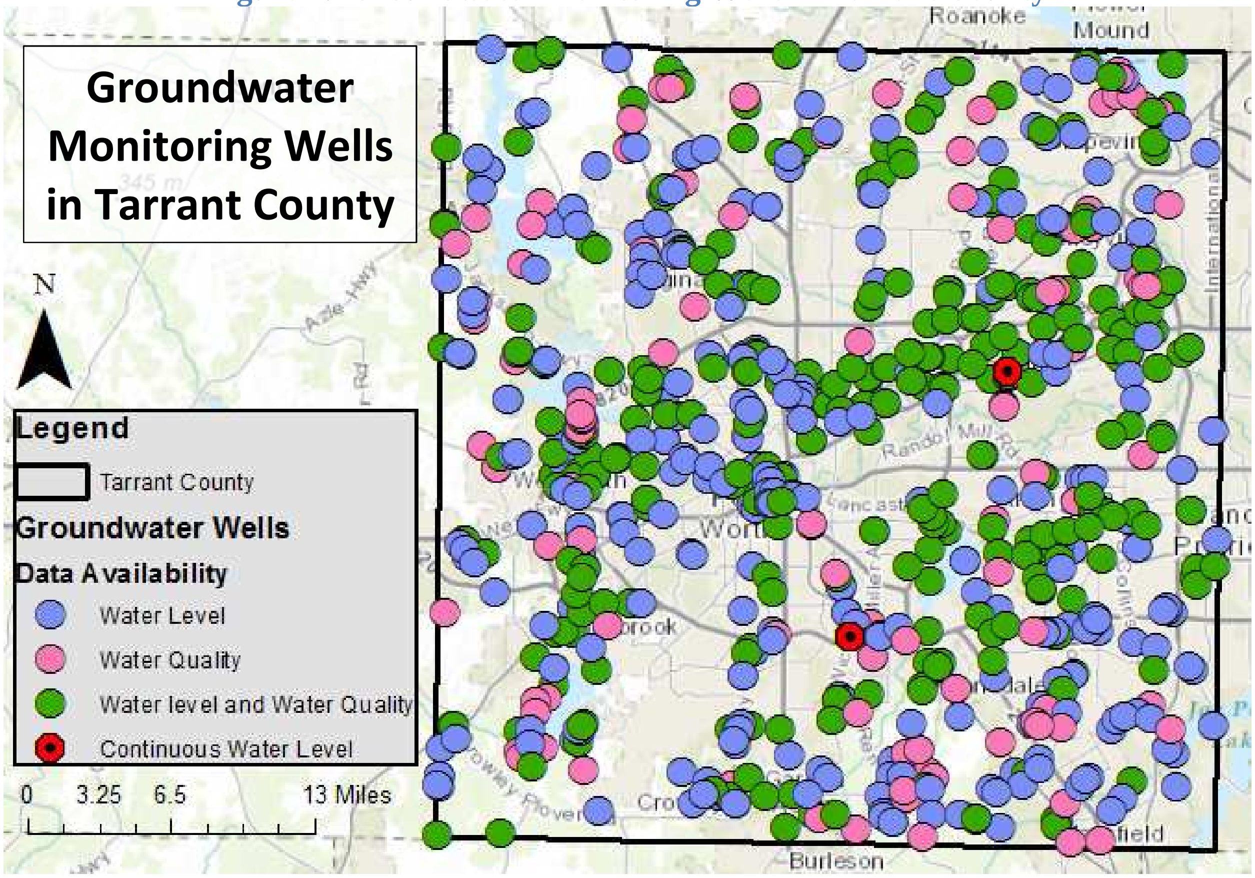


Source: Texas Railroad Commission 2013b

3.2 Groundwater Monitoring Data

The Texas Water Development Board publishes a Groundwater Database (GWDB) on its website (TWDB 2013b). The database contains well locations and monitoring measurements for groundwater wells in Texas. The data includes both water level and water quality measurements. However, most of these measurements are not taken regularly, but intermittently over the past century. The GWDB does include reports on five-day water level measurements taken continuously over certain time periods, but the number of wells monitored in this way is limited. Figure 7 below shows the monitoring wells in Tarrant County. The suitability of this data for the analysis will be discussed further in Section 3.2.

Figure 7: Groundwater Monitoring Wells in Tarrant County

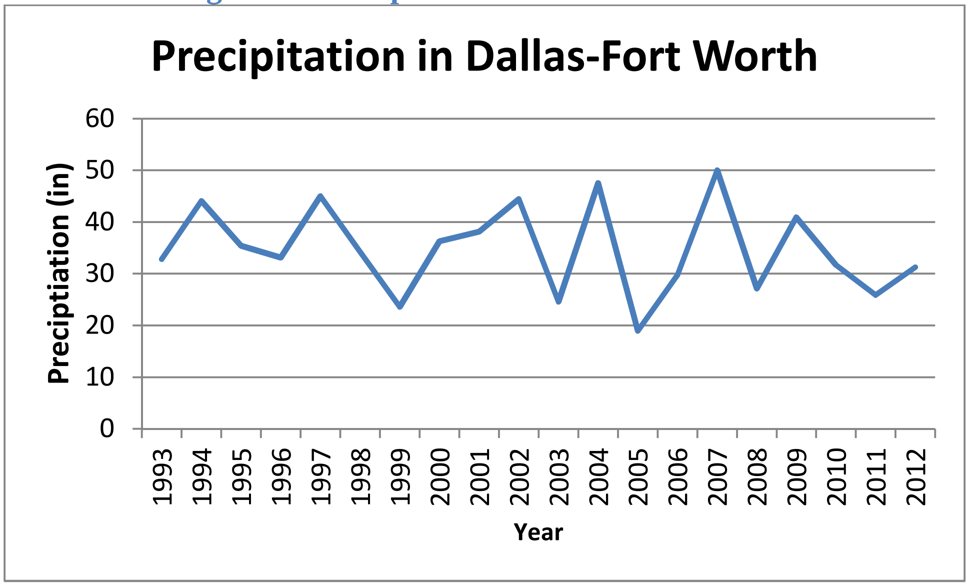


Source: TWDB 2013b; TxSDC 2013

3.3 Precipitation Data

Annual and monthly precipitation data for 1993-2012 was obtained from the National Weather Service Forecast Office (National Weather Service 2013). Information was obtained for the Dallas-Fort Worth area, and used as a proxy for precipitation in Tarrant County. Because the relationship between precipitation and groundwater is not as direct as the relationship between precipitation and surface water, an order of magnitude estimate was deemed sufficient for the purposes of this analysis. Figure 8 below shows the annual precipitation for Dallas-Fort Worth over this time period.

Figure 8: Precipitation in Dallas-Fort Worth

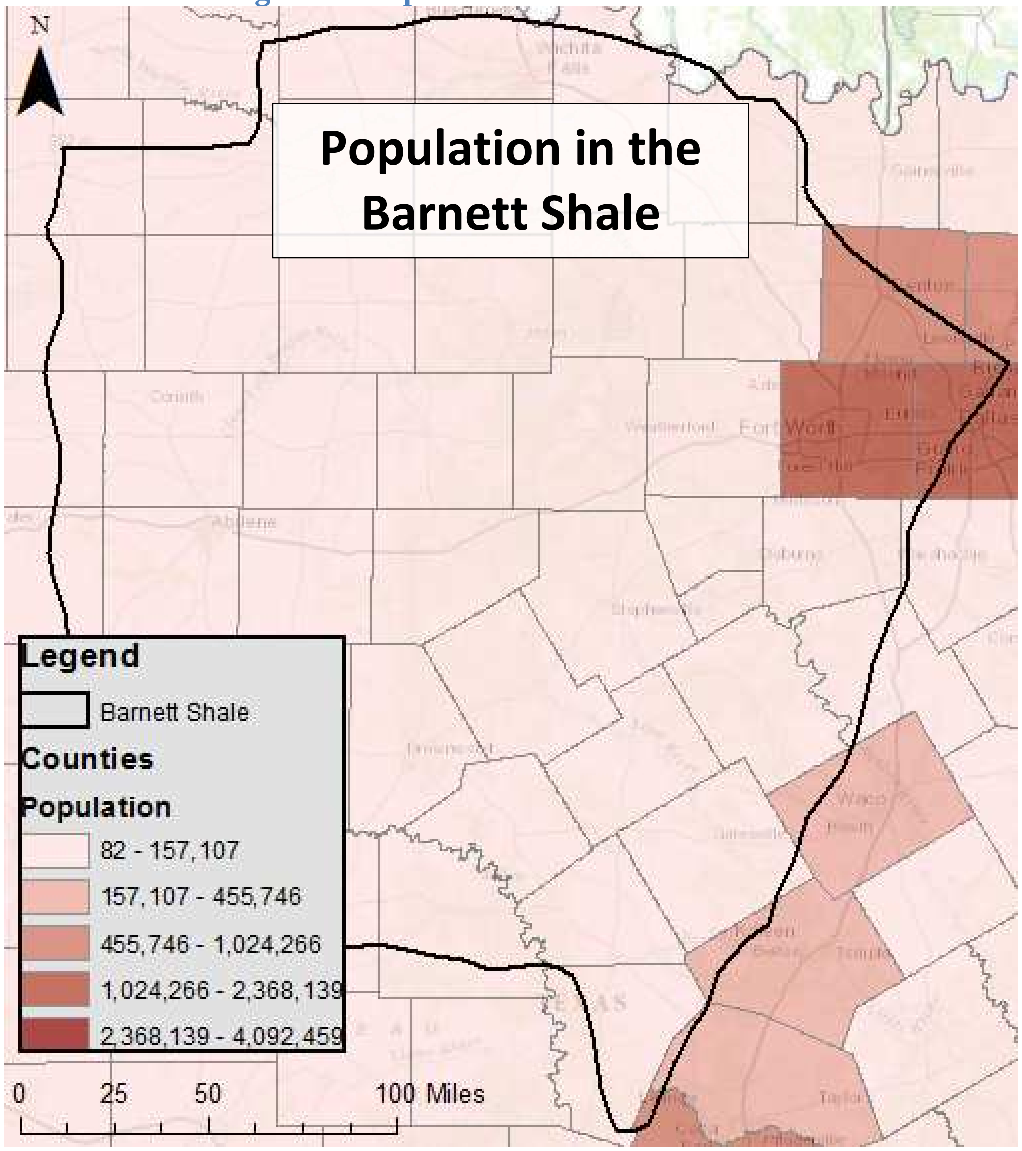


Source: National Weather Service 2013

3.4 Population Data

The Dallas-Fort Worth Metropolitan Statistical Area is the 4th largest urban area in the country, and Fort Worth alone is the 16th largest city in the U.S. (U.S. Census Bureau 2013a; 2013d). The colocation of a shale play with a large population center poses unique environmental, social, and economic issues. Figure 9 below displays the population by county of the areas in close proximity to the Barnett Shale.

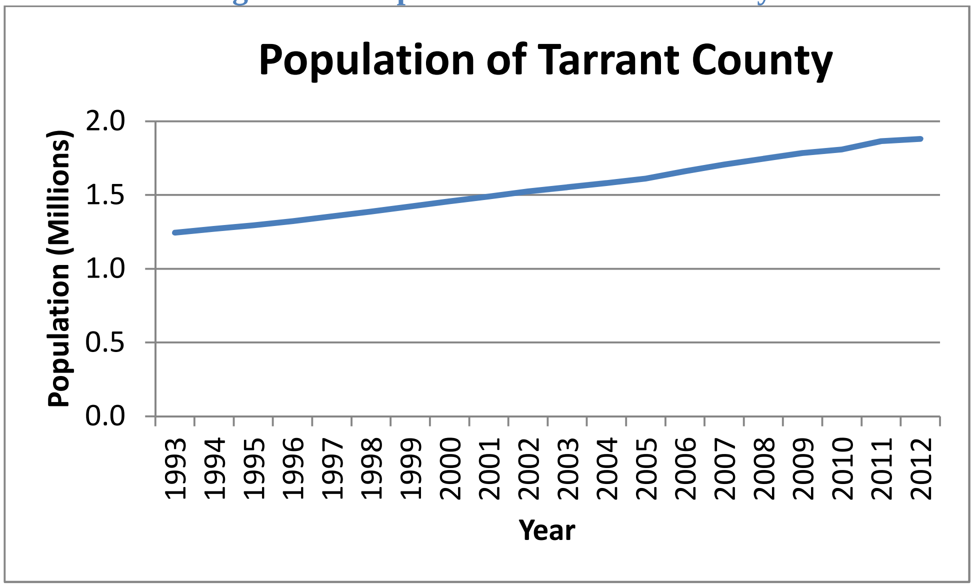
Figure 9: Population in the Barnett Shale



Source: EIA 2011; TxSDC 2013

Population data was used to approximate municipal water supply needs. In addition to its decennial census, the U.S. Census Bureau estimates population for the intervening years. This analysis uses the U.S. Census Bureau population estimates for Tarrant County for 1993-2010 (U.S. Census Bureau 2013c). However, the estimates for 2011 and 2012 were not yet available from this source at the time of this report. Instead, the 2011 population was obtained from an Annual Demographic Profile (North Central Texas Workforce Board 2012), and the 2012 population was obtained the Census Bureau's QuickFacts (U.S. Census Bureau 2013e). As can be seen in Figure 10 below, the population of Tarrant County has been growing steadily over the time period of this analysis.

Figure 10: Population of Tarrant County



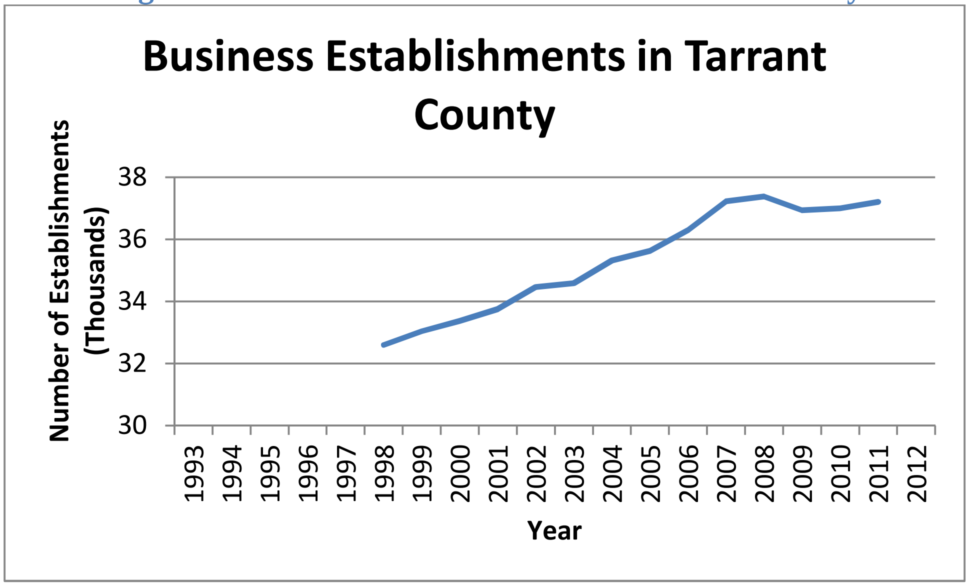
Source: North Central Texas Workforce Board 2012; U.S. Census Bureau 2013c, 2013e

3.5 Economic Data

Information on the number of business establishments in Tarrant County for 1993-2012 was obtained from the U.S. Census Bureau's County Business Patterns (U.S. Census Bureau 2013b). This data set is published annually and provides information on business establishments, employment, and payroll at the county, state, and national level. However, information was only readily available for 1998-2011 for these parameters.

This analysis used data on the total number of establishments across all industry sectors, in order to approximate the level of economic activity in the area. Figure 11 below displays the trend in business establishments for Tarrant County. Interestingly, the trend is almost linear until 2007, and the effects of the recession can be seen in the dip in the data for 2007-2009.

Figure 11: Business Establishments in Tarrant County



Source: U.S. Census Bureau 2013b

Because the data is almost linear, a formula for the line was derived using excel, and the slope of the line was used to estimate the missing values (1993-1997 and 2012) so that the data could be used for the full term of the analysis.

Note, however, that the U.S. Census Bureau does not collect economic information on agricultural sectors. The U.S. Department of Agriculture does publish a Census of Agriculture, but this information is only available every five years, which is not sufficient for this analysis. For this reason, it was not possible to incorporate agricultural activity into this analysis. Because Tarrant County is primarily urban, it is likely that the population and business activity would account for most of the water use.

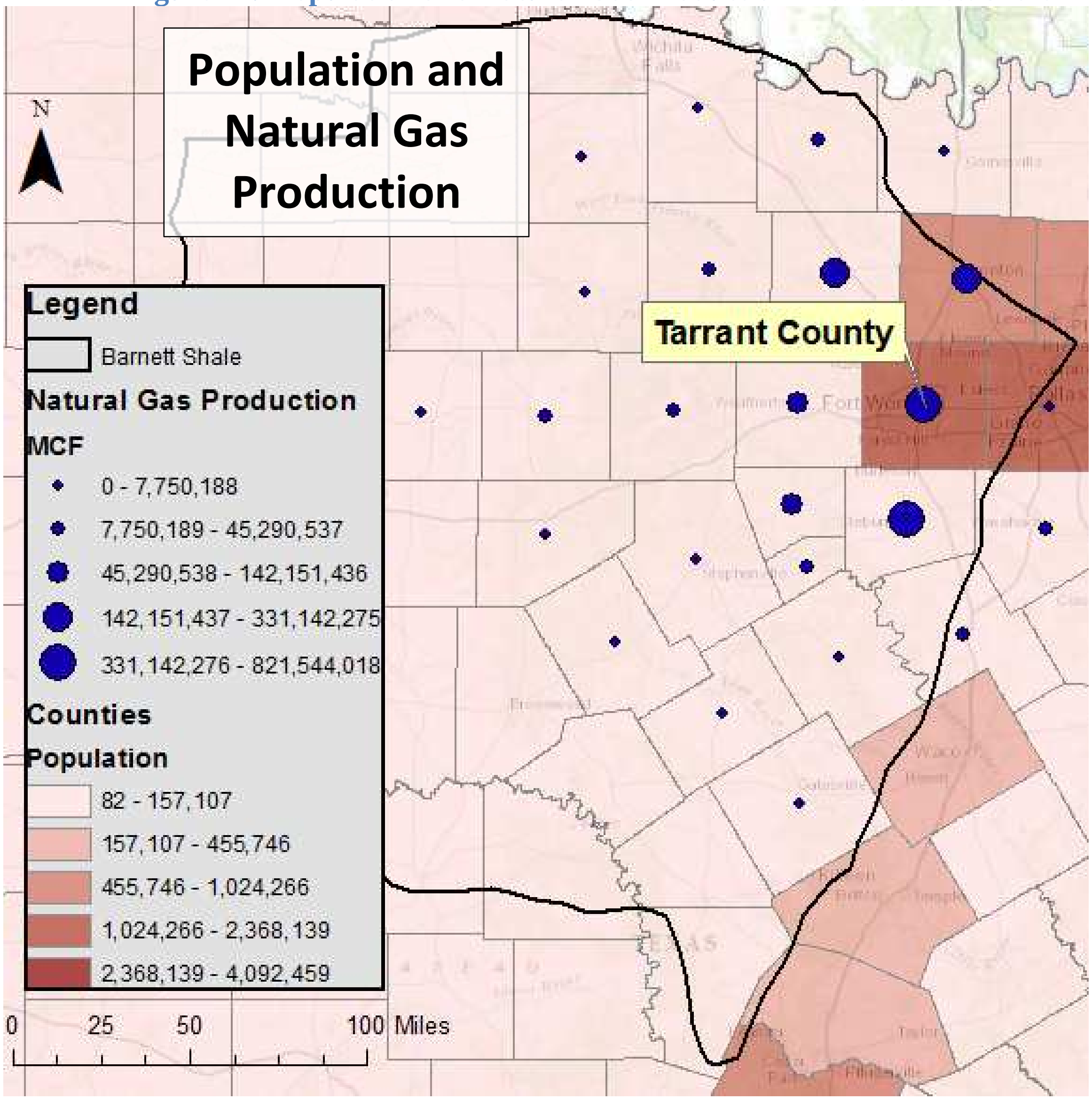
4. Methodology

This section describes the methodology used to select the area of focus for this study (Section 4.1), evaluate the available groundwater monitoring data (Section 4.2), interpolate groundwater levels based on intermittent monitoring data (Section 4.3), and perform a regression analysis of water levels and socioeconomic parameters (Section 4.4).

4.1 Selecting the Area of Focus

As noted above, to make the data requirements of this project manageable, it was necessary to further refine the area of focus to a single county. To select the county of interest, natural gas production and population was compared across the Barnett Shale. Figure 12 below displays this information, and highlights Tarrant County, the area selected for this analysis.

Figure 12: Population and Natural Gas Production in the Barnett Shale



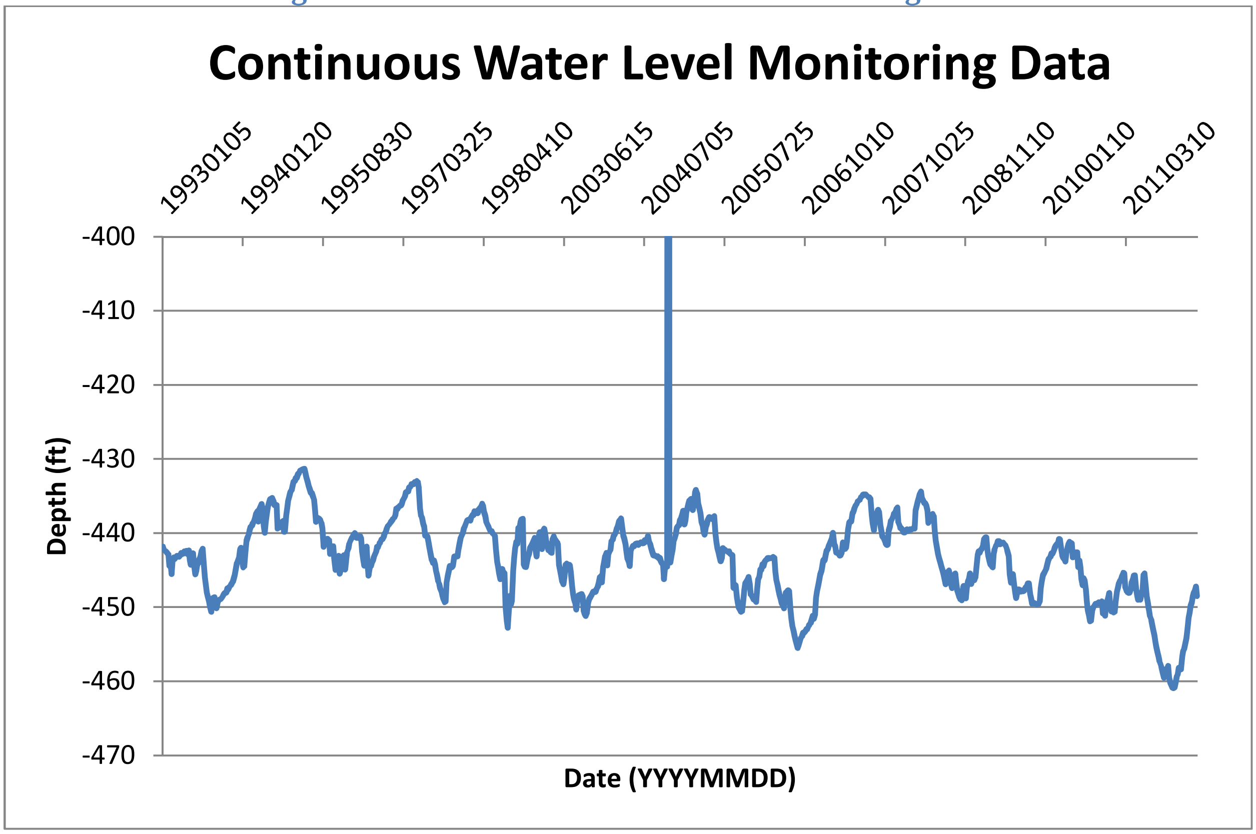
Source: EIA 2011; TxSDC 2013; Texas Railroad Commission 2013b

Tarrant County was selected for this analysis for two reasons. First, Tarrant County had the highest natural gas production in the Barnett Shale in 2012, at over 800 million MCF (Texas Railroad Commission 2013b). Second, Fort Worth and Arlington are located in Tarrant County, which had a population of over 1.8 million in 2012 (U.S. Census Bureau 2013e). With the largest natural gas production occurring in the county with the largest population in the Barnett Shale, this area seemed the most likely to have observable water impacts.

4.2 Evaluation of Groundwater Monitoring Data

As noted in Section 3.2, most of the groundwater wells in the GWDB are monitored intermittently. However, there was one well in Tarrant County that had continuous (five-day) water measurements for the time period of interest. This information was considered first to get a preliminary look at the trends in water quality in Tarrant County. As can be seen in Figure 13 below, there does seem to be a declining trend in water levels since the middle of 2006 for this well. However, data from a single well is not sufficient to draw conclusions about the impacts of hydraulic fracturing on water levels.

Figure 13: Continuous Water Level Monitoring Data



Source: TWDB 2013b

Although most wells are monitored intermittently, in any given year there were on average 46 wells with monitoring data for Tarrant County. This data was deemed sufficient to for the interpolation of average annual water levels in the Trinity aquifer underlying Tarrant County. The process for interpolating groundwater levels using this data will be described in Section 4.3.

Finally, this analysis also considered using the water quality measurements to see if it is possible to detect groundwater contamination from hydraulic fracturing in the area. However, there were too few groundwater quality measurements to conduct a rigorous analysis. Because water supply impacts are the primary focus of this study, it was decided to focus exclusively on the available water level data.

4.3 Interpolation of Groundwater Levels

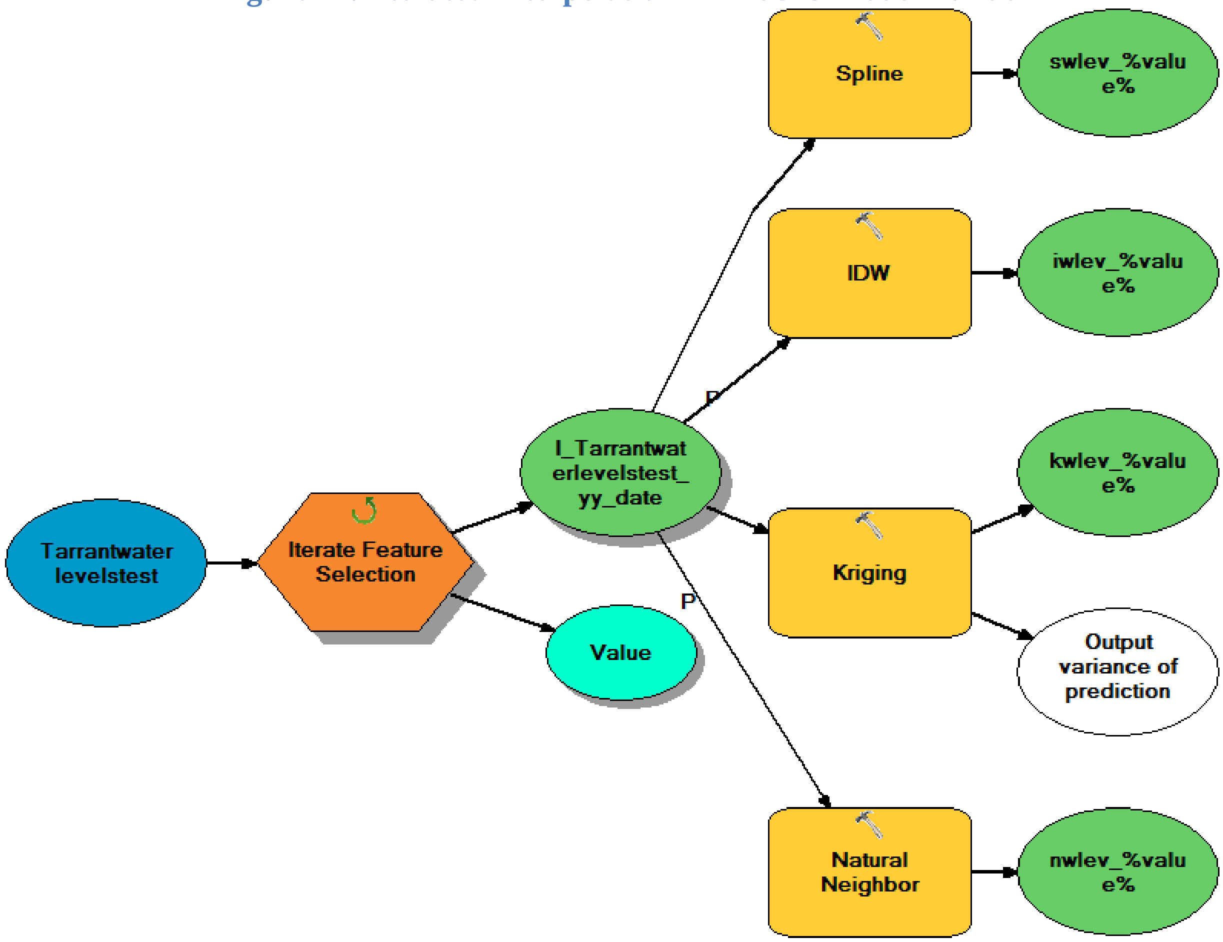
Due to the intermittent water level records, this analysis sought to interpolate annual average water levels by using all of the data points available for a particular year. This analysis was conducted using Model Builder and the interpolation tools in ArcGIS. To do so, the following steps were taken:

1. Map groundwater wells with water level observations during the time period 1993-2012.

2. Set layer properties to allow for time, with one year as the time interval.
3. Use the iterator function in ArcGIS Model Builder to interpolate the average water level for every year 1993-2012, using the inverse distance weighting, nearest neighbor, splines, and kriging tools.
4. From the results, obtain the mean value for each year and interpolation method, and construct four time series datasets.
5. Compare results across the interpolation methods and select the most appropriate results for further analysis.

Figure 14 below shows the model built in ArcGIS to run the iterated interpolations. The resulting interpolated water levels are presented in Section 5.1.

Figure 14: Iterated Interpolation in ArcGIS Model Builder



4.4 Regression Analysis

To consider the impacts of hydraulic fracturing, municipal water use, industrial water use, and weather patterns on groundwater levels, this analysis conducted a regression analysis. The analyses were conducted using ordinary least squares regression in STATA. The interpolated water levels were set as the dependent (y) variable, and several regressions were run. First, each of the interpolation results was regressed with natural gas production as independent (x) variable, to compare the robustness of each of the models. Then, one interpolation was selected for further regression with the natural gas production, weather, and socioeconomic variables. The results of the regression analysis are discussed in Section 5.2.

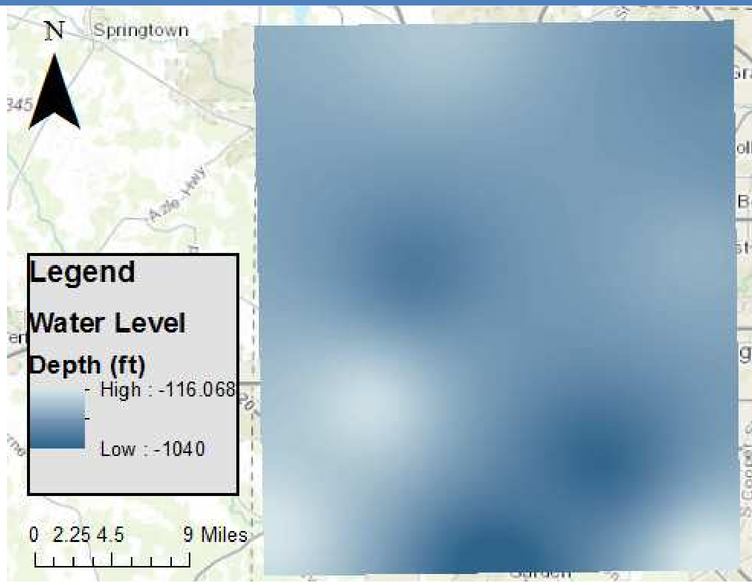
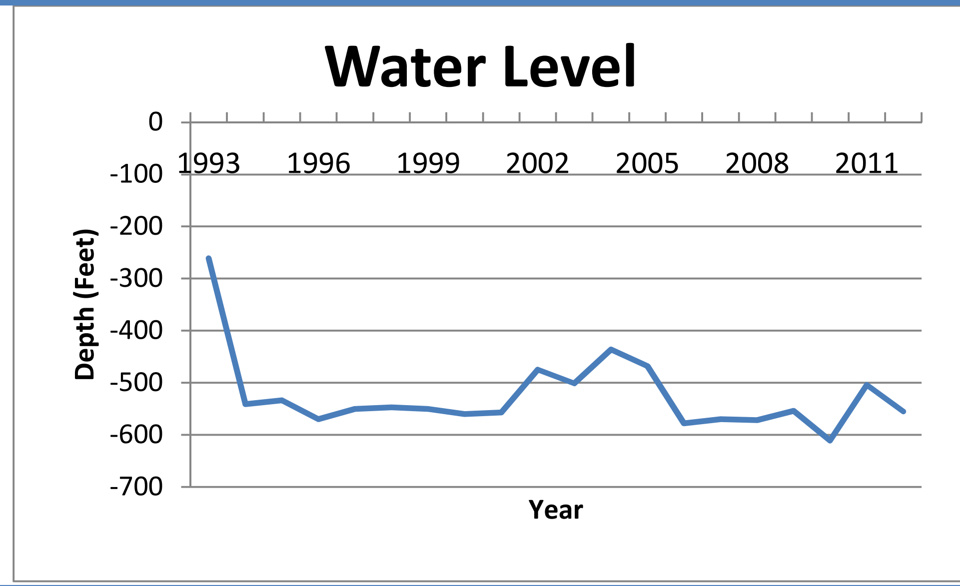
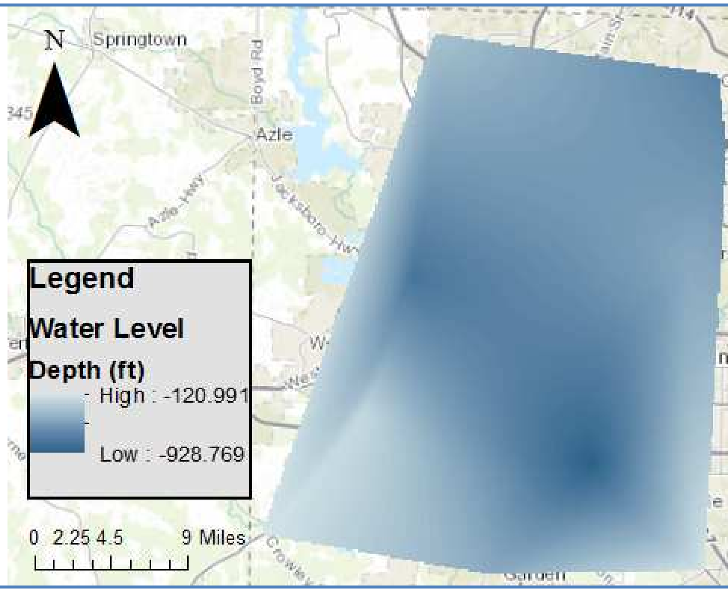
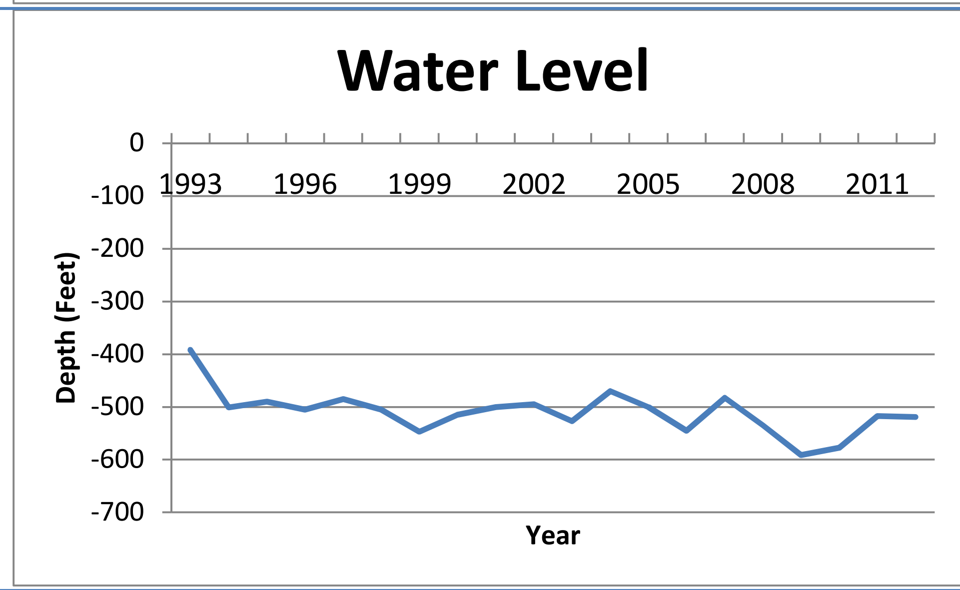
5. Results

This section presents the results of the groundwater level interpolations (Section 5.1) and regression analysis (Section 5.2).

5.1 Interpolated Water Level Results

The interpolations produced results for 1993-2012 using the four interpolation methods. Table 1 below shows an image of the interpolated surface for 2012, and a chart of the average water level for 1993-2012. Note that the water level is reported as depth below land surface, a negative value, and the darker values indicate deeper water levels (and more strain on the aquifer).

Table 1: Groundwater Level Interpolation Results

<table>
<tr><th>Method</th><th>Raster Surface for 2012</th><th>Average Water Level 1993-2012</th></tr>
<tr><td>Inverse Distance Weighting</td><td>
</td><td>
</td></tr>
<tr><td>Nearest Neighbor</td><td>
</td><td>
</td></tr>
</table>

<table>
<tr><th>Method</th><th>Raster Surface for 2012</th><th>Average Water Level 1993-2012</th></tr>
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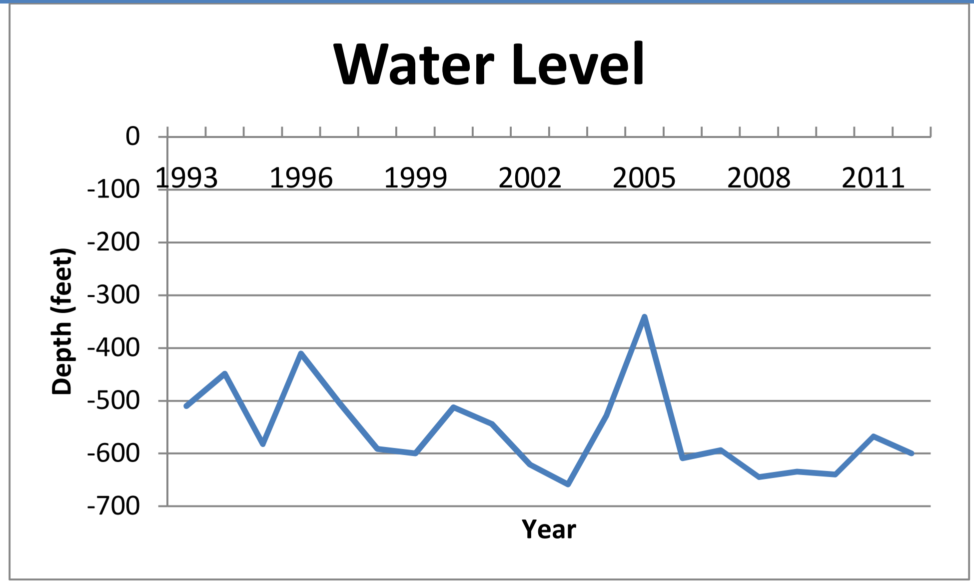
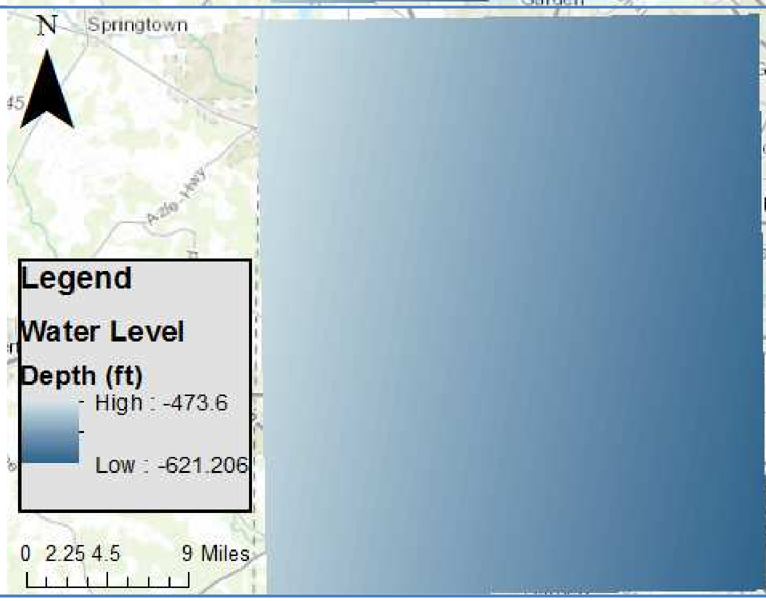
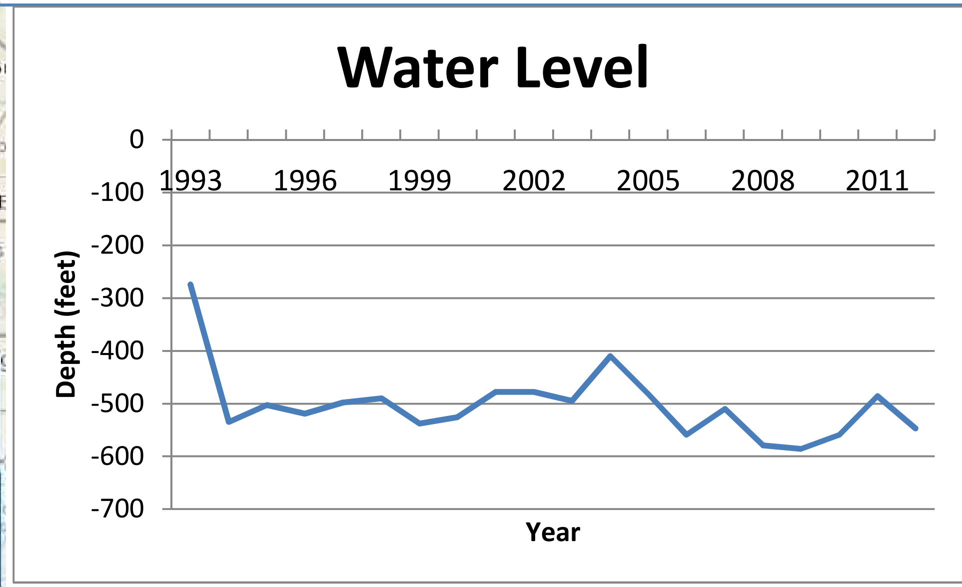
</td><td>
</td></tr>
<tr><td>Kriging</td><td>
</td><td>
</td></tr>
</table>

Of the interpolation methods, nearest neighbor seems to be the best fit for the data because it provides the smoothest line, and the results are within the range of observed values. Both the splines and kriging method produced surfaces that included values beyond the observed range (i.e., positive values indicating groundwater above the land surface) for certain years. For this reason, the results of these interpolations were not considered reliable for further analysis. Conversely, the inverse distance method produced values within the observable range, but the water levels were tied too closely to the closest well observation, resulting in a more localized rather than smoothed surface. Therefore, the results from the nearest neighbor interpolation were included in the regression analysis.

5.2 Regression Analysis Results

As noted in Section 4.4, a series of regressions were run using STATA to assess the influence of different factors on groundwater levels in the Trinity aquifer underlying Tarrant County. First, each of the interpolation results was regressed with natural gas production as the independent variable to compare the results with the different interpolation methods. The results are shown in Table 2 below.

Table 2: Regression Results for Interpolation Methods

Run #	Dependent Variable	Independent Variable	F-statistic	prob > F	R^2	Coefficient	t-statistic	prob > | t |
1	Water level (ft) (inverse distance weighting)	Natural Gas Production (million MCF)	1.44	0.03	0.23	-0.07	-1.20	0.03
2	Water level (ft) (nearest neighbor)	Natural Gas Production (million MCF)	5.40	0.09	0.15	-0.09	-2.32	0.09
3	Water level (ft) (splines)	Natural Gas Production (million MCF)	3.21	0.15	0.15	-0.11	-1.79	0.09
4	Water level (ft) (kriging)	Natural Gas Production (million MCF)	3.28	0.07	0.07	-0.07	-1.81	0.25

The F-statistic provides an indication of whether the model as a whole is statistically significant. At a 95% confidence level, only the regression model using the nearest neighbor interpolation was significant. This confirms the observations discussed in Section 4.3, that the nearest neighbor interpolation method was the most successful at estimating average annual groundwater levels. The R^2 value, a measure of goodness of fit, for this model is 0.23, indicating that the model explains 23% of the variation in the data, and suggests that there is a relationship between natural gas production and groundwater levels. This is a reasonably good fit for the model, given that natural gas production is the only independent variable included. The coefficient for the natural gas production variable is statistically significant at a 95% confidence level, as indicated by the t-statistic, and the sign (negative) is consistent with the expectation that hydraulic fracturing activities would increase demands on the aquifer and lower water levels. The coefficient can be interpreted as for a one million MCF increase in natural gas production, the water level will decrease by 0.09 feet (1.08 inches). Since 2002, natural gas production in Tarrant County has increased by an average of 74 MCF per year, which would correspond to a decrease in groundwater levels of 6.66 feet per year according to this model (not taking other factors into effect).

Next, the water level was regressed with natural gas production, population, precipitation, year, and number of business establishments. The results are shown in Table 3 below, with the results for natural gas production repeated from Table 2 above.

Table 3: Regression Results with Weather and Socioeconomic Variables

Run #	Dependent Variable	Independent Variable	F-statistic	prob > F	R^2	Coefficient	t-statistic	prob > | t |
1	Water level (ft) (nearest neighbor)	Natural Gas Production (million MCF)	5.40	0.03	0.23	-0.07	-2.32	0.03
2	Water level (ft) (nearest neighbor)	Population (1000)	8.41	0.01	0.32	-0.11	-2.90	0.01
3	Water level (ft) (nearest neighbor)	Precipitation (in)	1.39	0.25	0.07	1.29	1.18	0.25
4	Water level (ft) (nearest neighbor)	# Business Establishments (100)	7.36	0.01	0.29	-0.96	-2.71	0.01
5	Water level (ft) (nearest neighbor)	Year	8.71	0.01	0.33	-3.99	-2.95	0.01

All of the regression models (and associated coefficients) were significant except for precipitation. However, since rainwater does not directly enter groundwater aquifers, but rather infiltrates into groundwater through gaps in soil and rock, it makes sense that the relationship between precipitation and groundwater levels may not be a direct one. Therefore, it is not entirely surprising that these results are not statistically significant.

The model that includes population explains 32% of the variation in the data, and the coefficient sign is consistent with the expectation that more water would be withdrawn by municipalities as population grows. The coefficient can be interpreted as follows: for a 1,000 increase in population, the water level decreases by 0.11 feet (1.32 in). This model explains more of the variation in the data compared to natural gas production, indicating that population plays an important role in determining groundwater levels.

The model for business establishments explains 29% of the variation in the data, and the coefficient sign is consistent with the expectation that economic activity would increase water demands on local groundwater resources. The coefficient can be interpreted as follows: for 100 additional business establishments in Tarrant County, the water level would decrease by 0.96 feet (11.52 in). This model also explains more of the variation in the data compared to natural gas production (but less than population), indicating that economic activity is also an important factor in groundwater supply.

Finally, the model with the variable for year explains 33% of the variation in the data, the most of all the models. The results indicate that water levels are declining over time, and captures some of the impacts of year-to-year changes in aquifer levels. Ideally, the model could be further refined, perhaps using lagged variables, to better explain this variation systematically.

After the model was run with these individual variables, it was also run different combinations of the variables and all of the variables together. However, the regression results for any combination of the variables were not significant. The most likely explanation for this is that there are too few degrees of freedom in the model to achieve statistically significant results (i.e., the number of observations is too small). Including additional observations (e.g., expanding the scope to include additional counties) would likely address this problem and result in significant regression models.

6. Conclusion

This analysis used the ArcGIS software and tools to combine spatial and time series data to establish relationships between groundwater levels and key variables of interest. The project demonstrates the ability to utilize TWDB groundwater monitoring data to interpolate groundwater levels over time, despite the temporal limitations of the data. The analysis results indicate that, in the area of Tarrant County, natural gas production in the Barnett shale is correlated to decreases in groundwater levels in the Trinity aquifer. However, the growing population of Dallas-Fort Worth and economic activity are also correlated to changes in groundwater levels. These competing water demands will be important in the future, as more strain is placed on local water resources.

Future work could refine the methods used in this analysis to expand the scope of analysis and establish more formal relationships between the variables of interest. Specifically subsequent analyses could consider additional counties in the Barnett shale to increase the number of observations available for regression analysis and improve the reliability of the results. Alternatively, using the full extent of the Trinity aquifer would also increase the number of observations, as well as allow for a complete analysis of the aquifer. Another avenue for expansion could be the further refinement of the socioeconomic indicators included in the regression analysis. The number of business establishments could be replaced with variables corresponding to specific industries that are known to be water intensive, such as electricity generation, semiconductor manufacturing, and agriculture. Lagged variables to could also be used to investigate potentially delayed impacts of the variables of interest. There are numerous other options for expanding on this analysis and further investigating the relationship between hydraulic fracturing and groundwater levels.

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