SPATIO-TEMPORAL VARIATION OF NITRATE LEVELS IN GROUNDWATER

IN TEXAS, 1970 TO 2010

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This study looks at spatial variation of groundwater nitrate in Texas and its fluctuations at 10 year increments using data from the Texas Water Development Board. While groundwater nitrate increased in the Ogallala and Seymour aquifers across the time period, the overall rate in Texas appears to be declining as time progresses. However, the available data is limited. Findings show that a much more targeted, knowledge based strategy for sampling would not only reduce the cost of water quality analysis but also reduce the risk of error in these analyses by providing a more realistic picture of the spatial variation of problem contaminants, thereby giving decision-makers a clearer picture on how best to handle the reduction and elimination of problem contaminants.
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by

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ACKNOWLEDGEMENTS

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In 1962, Rachel Carson’s pivotal book, *Silent Spring*, focused public attention on the damage that was being wrought on ecosystem function, wildlife, and ultimately, human life. She points out how man is the only species that has “…acquired significant power to alter the nature of his world” (Carson 1962, 5) and his most alarming “assaults upon the environment is the contamination of air, earth, rivers, and sea with dangerous and even lethal materials,” (Carson 1962, 6). She is uncompromisingly direct as she asserts, “For the first time in the history of the world, every human being is now subjected to contact with dangerous chemicals from the moment of conception until death,” (Carson 1962, 15).

Ominous words and more than half a century later, humankind continues to contaminate and degrade the very environment upon which all life depends. And in spite of regulations and lawmaking inspired to combat our ongoing self destruction, the world now faces several environmental crises on a global scale, not the least of which is the depletion of drinking water resources.

United States waters receive contaminated waste-water from a multitude of sources (Scholz & Tchobanoglous 2008). Among these contaminants, and of growing concern, are nitrogen and nitrogenous compounds, namely, nitrate and nitrite, both of which are reactive forms of the element. While reactive nitrogen has an important and necessary function in the natural environment, until about the 1950s, nitrogen was
relatively scarce, and, in spite of its profound abundance in the atmosphere as N$_2$, was a limiting biological factor for growth (Galloway et al. 2003, 2004; Vitousek et al. 1997; Ward et al. 2005).

Two major factors contribute to nitrate contamination of groundwater. One is through the burning of fossil fuels; nitric oxide is produced as a wasteful byproduct. The other is fertilizer use. Due to its importance to crop yields, since the advent of fertilizer, nitrate contamination of groundwater has become especially pronounced in rural areas (De Roos et al. 2003; Galloway et al. 2004; Vitousek et al. 1997). Because of these activities, nitrate has become the most common contaminant in the world’s aquifers (Ward et al. 2005, 1607).

The U.S. Environmental Protection Agency (EPA) set a maximum contaminant level (MCL) for nitrate-N at 10 mg/L and 1 mg/L for nitrite-N, mainly in order to protect infants from developing methemoglobinemia, a condition which results in death through suffocation fairly quickly when infants are exposed to nitrate contaminated drinking water (De Roos et al. 2003; Ward et al. 2005). However, according to the 2010 State of Texas Water Quality Inventory Groundwater Assessment, exposure to nitrate concentrations $\geq$ 4 mg N/L was indicated as a contributing factor in cases of non-Hodgkin’s lymphoma in a Nebraska study. The water quality report goes on to suggest that MCL levels for nitrate will likely be reduced sometime in the future.

This study examines the geography of nitrate contamination in Texas aquifers. Using well water data, it seeks to document the spatial variations in potential human risk resulting from nitrate concentration and the challenges involved in effective assessment
of nitrate contamination levels. We begin with a brief review of the nitrogen cycle after which we describe the research methodology.

The Nitrogen Cycle

In order to understand nitrate levels in groundwater, it’s important to understand how nitrogen functions in the environment. The element, nitrogen, plays a vital role in the sustenance of life. It is necessary for the production of proteins, amino acids, and nucleic acids. Nitrogen comes in two forms, reactive nitrogen ($N_r$) and non-reactive or molecular form ($N_2$). The latter, $N_2$, is highly abundant in the atmosphere, making up about 78 percent, however, it is completely unavailable for biotic uptake in this form. A massive input of energy, such as lightning or heat intensive processes, is required to break the triple bond that holds the two nitrogen atoms together; therefore, there are only a handful of pathways in which $N_2$ can be broken down into usable forms. When $N_2$ is broken down in the atmosphere, it is deposited on the earth via precipitation where it continues to go through a series of chemical reactions through the process of biotic uptake (Galloway et al. 2003, 2004; Vitousek et al. 1997).

Other than lightning, oxidation, and human activity, only a few specialized microorganisms have the capacity to split nitrogen atoms in two (Vitousek et al. 1997). During this process (Figure 1), microorganisms that live in the soil convert organic nitrogen into inorganic forms. Mineralization converts ammonium to ammonia. Then micelle fixation takes N from ammonia and converts it to nitrite. Finally, nitrite is oxidized into nitrate which is then taken up by surrounding vegetation. Since nitrate is
very soluble, what nitrate that is not taken up by plants then leaches into aquatic pathways. There, the denitrification process converts nitrate (NO$_3^-$) back to N$_2$ and nitrous oxide (N$_2$O) which are then released back into the atmosphere (Pidwirny 2006).

Before technological interference, $N_r$ production from N$_2$ was basically through two different means, lightning and biological nitrogen fixation (BNF). There was no accumulation of reactive N since its production did not exceed denitrification processes (Galloway et al. 2003).

**Figure 1** *Diagram of nitrification.*
While determining background nitrogen levels is difficult at best, Vitousek et al. (1997) estimated that microbial activity would most likely fix about 90 to 140 Tg of nitrogen annually, nitrogen fixation in marine environments have been found to range from less than 30 to more than 300 Tg/yr, and lightning fixes less than 10 Tg/yr, approximating background nitrogen fixation at 129 to 440 Tg/yr. However, Galloway et al. (2004) suggest a terrestrial N-fixation background rate of 100 to 290 Tg/yr, noting that numbers from most studies on BNF were inflated and did not reflect true global fixing rates since they had been carried out in areas where disproportionately large communities of nitrogen fixing organisms reside. Either way, using Vitousek’s calculation of anthropogenic activity adds approximately 210 Tg/yr through direct nitrogen fixation (≈140 Tg/yr) and mobilization (≈70 Tg/yr), making a grand total of ≈339 to 650 million metric tons of nitrogen released to the environment per year on a global scale. According to Vitousek et al. (1997, 737) human alterations of the nitrogen cycle have:

1. Nitrogen input rate has almost doubled and continues to rise
2. Concentrations of N2O and other nitrogenous oxides have increased in the atmosphere causing photochemical smog over large areas of the Earth
3. Decreased soil fertility through the loss of essential nutrients
4. Caused substantial acidification of soils, lakes and streams
5. Drastically increased nitrogen input into estuaries and oceans
6. Increased organic carbon storage in ecosystems
7. Accelerated loss of biological diversity, both foliar and animal
8. Altered composition and function of estuarine ecosystems
9. Have played a role in fishery decline
Nitrogen Pollution

Humans have altered the nitrogen cycle dramatically over the last half-century, and as a result, nitrate is steadily accumulating in our water resources (Ward et al. 2005). Prior to 1950, human activity produced a relatively small fraction of N₂ compared to that produced through biological and environmental processes. However, over the last half century, the advent of technology and the sharp incline in population growth have caused greater and more abundant mechanisms for nitrogen release into the biosphere. As a result, anthropogenic caused nitrogen fixation has climbed steadily and now exceeds that produced by the forces of nature (Galloway et al. 2003; Vitousek et al. 1997; Ward et al. 2005).

Due to fossil fuel consumption, agriculture, and industrial releases to the air and water, nitrogen deposition rates are above critical loads in many industrially developed countries (Bowman et al, 2008). As a result, nitrogen pollution has contributed to soil acidification and inhibited natural nitrogen sinks through decreased biodiversity. This reduction in foliar biodiversity is critical to groundwater recharge. Decreased natural ground cover increases storm runoff, causes compaction of the soil above aquifers which, in turn, decreases percolation and groundwater recharge (Bowman et al. 2008; Foster & Chilton 2003).

In rural areas where intensive agriculture dominates land use, extensive use of fertilizers contributes to nitrate contamination of groundwater. When nitrogen rich materials, such as fertilizer or manure, are used on crops, what is not taken up by plants then leaches into the underlying water table. According to Chae et al. (2009, 1819-1820),
“…nitrate is biogeochemically stable and usually poorly adsorbed in oxygenated sandy soils. Therefore, it is easily leached during groundwater recharge, resulting in nitrate contamination of groundwater and adjacent river water.”

Health Effects of Nitrate Contamination

The health effects of nitrate contamination are many and varied. Nitrate contaminated drinking water has been linked with non-Hodgkin’s lymphoma and methemoglobinemia. It has also been linked with gastric cancer in several studies. When nitrate is ingested, it is then reduced to nitrite which in turn reacts with amines and amides to form N-nitroso compounds within the digestive tract in a process known as endogenous nitrosation (De Roos et al. 2003; Sandor et al. 2001; Morales-Suarez-Varela et al. 1995).

Morales-Suarez-Varela et al. (1995) found individuals who were exposed for long periods of time to increased levels of nitrates in drinking water had increased risk for stomach, bladder, and prostate cancers. Grinsven et al. (2010) point out that, while regardless of source, chronic exposure to nitrates can bring about carcinogenesis, and while intake of nitrate increases nitric oxide levels which are beneficial to “…vascular endothelial function and the defense against infections. Nitric oxide and NO-synthase are also known to be involved in cancer-related events (angiogenesis, apoptosis, cell cycle, invasion, and metastasis) and are linked to increased oxidative stress and DNA damage,” (5).

Ward et al. (2005, 1608) give a detailed explanation of the processes which
occur during endogenous nitrosation. Nitrosation, the process by which nitrate and nitrite react with amines and amides in the human body, begins in the mouth. When consumed, nitrate is absorbed orally, 25 percent is secreted as saliva and 20 percent is converted to nitrite by bacteria. Nitrite then reacts with acids in the stomach to form nitrous acid (HNO₂). HNO₂ is then converted to three other nitrogenous compounds, dinitrogen trioxide (N₂O₃), nitric oxide (NO), and nitrogen dioxide (NO₂). While, as mentioned before, NO may have some physiological benefits, N₂O₃ contributes in the production of N-nitrosamines while HNO₂ undergoes a chain of reactions leading to N-nitrosamides, both of these compounds are potential carcinogens. Ward et al. (2005, 1609) state that drinking water with nitrate levels that exceed 10 mg/L increases human capacity to nitrosate proline, noting studies that showed that “populations with high rates of esophageal and gastric cancer excrete high levels of N-nitrosoproline.”

Esophageal cancer affects the lining and tissues of the esophagus. There are two types of esophageal cancer, squamous cell carcinoma and adenocarcinoma. Squamous cell carcinoma originates in the flat cells lining the esophagus. Adenocarcinoma originates in cells that produce mucus and other bodily fluids. The National Cancer Institute estimates that there will be 16,640 new cases in 2010 and 14,500 deaths. Zhang et al. (2003) found a significantly positive correlation between the level of nitrogenous compounds in well water and mortality from esophageal cancer in Cixian County, an area in China with a very high mortality rate from this disease.

Gastric cancer affects the lining and tissues of the stomach. The National Cancer Institute reported 21,000 new cases of gastric cancer and 10,570 deaths for the U.S. for
2010. Sandor et al. (2001, 443) state that, “The biological model for the relationship between N-nitroso compounds and the occurrence of gastric cancer was established several years ago. It has been demonstrated that nitrate itself is a precursor of these carcinogens.” Clearly, tracking nitrate levels in groundwater is important for both human and environmental health. While there is a clear geography to nitrate contamination, this has not been studied for Texas. Moreover, it is unclear how nitrate contamination in Texas is changing through time. This study fills this gap by examining the geographic distribution of nitrate contamination in Texas and how that has changed over time.
CHAPTER 2
THE SOUTHERN HIGH PLAINS AND SEYMOUR AQUIFERS

The Southern High Plains and Seymour Aquifers are unconfined aquifers which lie in the Texas Panhandle and just east of the base of the panhandle (Figure 2 and Figure 3). However, some parts of the Seymour Aquifer are confined in clay beds (Ryder 1996). Unconfined aquifers, or water-table aquifers, can be close to the land surface with layers of permeable material which extend from the geological surface to the base of the aquifer while confined or artesian aquifers lie beneath a confining surface (Fetter 2001).

Historically, this area has been subject to heavy agriculture with the advent of irrigation in the early 1900s (Ryder 1996). The Texas Panhandle is a largely rural area dominated by irrigated cropland and livestock production. Therefore, the surrounding land use activities increase the vulnerability of the aquifer to nitrate contamination. Enwright and Hudak (2009) found that the southern portion of the High Plains Aquifer had higher nitrate contamination than the northern portion and attributed this phenomenon to a shallower water table. Hudak (1999) found that nitrate concentrations had an inverse relationship with well depth in the Seymour Aquifer indicating land use as the contributing factor for nitrate contamination.

The Southern High Plains Aquifer underlies about 174,000 square miles and extends from the southern part of South Dakota into the Texas Panhandle, reaching across eight states, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, Texas and Wyoming (Figure 4).
Figure 2 Ogallala Aquifer formation in the Texas Panhandle.
Figure 3  Seymour Aquifer, Texas.
Figure 4 Ogallala formation.
The Texas portion of the aquifer spans approximately 55,923 square miles, extending about 300 miles from the Oklahoma border, and consists mainly of treeless plateaus. Elevations range from 2,000 to 4,000 feet above sea level. The region is semi-arid with an average annual precipitation ranging from about 12 inches in the southwest to about 24 inches in the northeast (Enwright & Hudak 2009; Howard et al. 2003; Ryder 1996; Stewart 2008).

The Seymour Aquifer (Figure 3) lies mainly in the Central Lowland Physiographic Province with the most western portion lying in the Great Plains Province. A cluster of about 14 eroded remnants of the Seymour Formation of the Pleistocene Era lies in 22 alluvial areas scattered non-continuously across 20 Texas counties and has been referred to as the "north- central Texas alluvial aquifers". Areas of the alluvial patches range from 20 square miles to about 430 square miles in the largest continuous patch that runs across Haskell and Knox counties. Saturated thickness ranges from 20 to 60 ft. deep and up to as much as 100 feet in some areas. Median well depth is approximately 49 ft., with the average being around 48 ft. deep. Elevation ranges from approximately 891 ft. to 2,440 ft. above sea level. Precipitation averages from 19 to 26 inches, annually. Precipitation is the main source of recharge for this aquifer. Water in the aquifer ranges from fresh to slightly saline with about 90 percent of its use geared towards agricultural purposes such as irrigation; the rest serves to meet municipal water supply requirements (Hillin & Hudak 2003; Ryder 1996).
CHAPTER 3

METHODS AND MATERIALS

Water quality data from the Groundwater Database (GWDB) provided by the Texas Water Development Board (TWDB) was used in conjunction with ESRI’s ArcGIS™ mapping software to ascertain the mean nitrate levels for each county of the state of Texas from 1970 to 2010 at 10 year increments. Since number of wells tested annually have gradually decreased since 1970, and this being an observation of changes in nitrate concentrations over time, all observations were included.

The groundwater database supplied by the Texas Water Development Board contains one main table and 40 relational tables. Two tables were used for this study, the main table for general well data and the table for water quality analyses. The main table has 135,604 records with 44 attribute fields describing location, ownership, depth, aquifer, and other types of well specifics. For the purpose of this study, only fields containing locational and use (domestic, public, etc.) data were used.

The water quality table has 50 fields covering various water quality attributes, including sample dates, times, collecting facility, contaminants, and minerals. The only fields used from this table were the key field, sample year, and the field for nitrate. The water quality table consisted of 108,935 records. The records were then culled by the sample year for each year in the time period. In some instances, data was culled for specific aquifers using aquifer codes.
According to the 2010 State of Texas Water Quality Inventory Groundwater Assessment, nitrate concentrations ≥16 mg/L in public water supply well systems were found to be related to non-Hodgkin’s lymphoma. In addition, nitrate can have synergistic effects when combined with other compounds and, thus, have an even greater negative impact on public health (TCEQ 2010). Consequently, TCEQ suggests that the MCL set forth by the EPA may be reduced sometime in the future. For this study, the health risk level (HRL) for nitrate was set at 10 mg/L. This is approximately halfway between natural levels of nitrate (~2mg/L) and the 16 mg/L mentioned for non-Hodgkin’s lymphoma.

Smoothed maps were created in order to show a more realistic picture of the spatial variation of nitrate across the state and to account for variable testing patterns, while choropleth maps were created to show mean county levels. Furthermore, smoothed and choropleth maps were created to show areas that were beneath, at, or exceeded the 10 mg/L health risk level. Areas where nitrate concentrations exceeded 11 mg/L were shaded red, areas over 9 mg/L up to 11 mg/L were shaded yellow, and those areas which were 9 mg/L and under were shaded green. The same types of maps were created to show areas or counties that met, exceeded, or were beneath the state average of that particular year. One smoothed map was created to depict the mean concentration of nitrate in groundwater in Texas for all 40 years. For the last two maps, however, since annual water quality analyses had decreased considerably, data for 2003 to 2006 and 2007 to 2010 were aggregated into maps for each data set in order to show the spatial variation for that time period.
Finally, correlations were run between county mean nitrate levels for the 2007 to 2010 time period and race/ethnicity, and income to determine if any particular populations had increased risk of nitrate contamination.
From 1970 to 2010, the highest levels of groundwater nitrate were concentrated in the Texas Panhandle. Nitrate levels dissipate gradually over large sections of land moving towards the Gulf Coast (see Figure 6); however, the average levels may be severely underestimated due to the declining number of wells that were tested each successive year. In 1970, out of 135,604 wells in Texas, 3,970 wells were tested for water quality. In 1980, 2,018 wells were tested. In 1990 and 2000, 1,644 and 1,183, respectively, were tested. Lastly, only 636 wells were tested for water quality in 2010 (Figure 5). Out of all possible tests for all years, only about 1.11 percent of all possible observations were made. In all, only about 30 percent of all wells have been tested.

**Figure 5** Annual water quality analyses in the State of Texas, 1970-2010.
Figure 6 Nitrate levels in Texas, 1970-2010.
The Texas Panhandle has historically been a site of extensive agriculture (Ryder 1996). The Ogallala and the Seymour Aquifers both lie in this region. Both aquifers have persistently high levels of nitrate contamination (Table 1) with a majority of wells tested for water quality exceeding 10 mg/L, and a mean nitrate concentration has increased consistently over the past four decades.

**Table 1 Well statistics for Ogallala Aquifer**

<table>
<thead>
<tr>
<th>Year</th>
<th>Tested</th>
<th>Mean</th>
<th>Max</th>
<th>No. Wells &gt; HRL</th>
<th>% Over HRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>304</td>
<td>12.78</td>
<td>1845</td>
<td>53</td>
<td>17.43</td>
</tr>
<tr>
<td>1980</td>
<td>597</td>
<td>13.22</td>
<td>306.4</td>
<td>212</td>
<td>35.51</td>
</tr>
<tr>
<td>1990</td>
<td>500</td>
<td>19.65</td>
<td>334.64</td>
<td>215</td>
<td>43</td>
</tr>
<tr>
<td>2000</td>
<td>649</td>
<td>21</td>
<td>418.79</td>
<td>371</td>
<td>57.17</td>
</tr>
<tr>
<td>2008</td>
<td>485</td>
<td>21</td>
<td>313.99</td>
<td>264</td>
<td>54.43</td>
</tr>
</tbody>
</table>

Source: Texas Water Development Board Groundwater Database.

Currently, 3,071 of the 21,571 wells in the Ogallala Aquifer have been deemed fit for human use. In 1970 (Table 1), 304 wells were tested. The highest level of nitrate concentration was 1,845 mg/L and 53 of the wells that were tested exceeded 10 mg/L. The mean concentration was 12.78 mg/L. In 1980, 597 wells were tested. The highest concentration was 306.4 mg/L and the mean was 13.22 mg/L. Two hundred twelve wells exceeded 10 mg/L. Five hundred wells were tested for water quality in 1990 and the average nitrate level had increased again with a new mean of 19.65 mg/L. The highest concentration was 334.64 mg/L. Two hundred fifteen wells exceeded the HRL set for this study. In 2000, 649 wells were tested, the max was 418.79 mg/L and 371 wells exceeded 10 mg/L. The average had increased again to 21 mg/L. No water quality testing was done in either 2010 or 2009 for the Ogallala; however, in 2008, 485 wells were tested. Two hundred sixty-four wells exceeded the designated amount. The highest
concentration was 313.99 mg/L while the average remained about the same as in 2000 (Figure 7).
The Seymour Aquifer (Figure 3), located just east of the base of the panhandle consistently exhibited mean nitrate levels exceeding the set concentration by a minimum of 30 mg/L throughout the study period. There are 4,837 wells in the Seymour aquifer, 1,110 of which are deemed fit for human use.

In 1970, 350 wells were tested, the mean concentration was 41.58 mg/L and the maximum was 273 mg/L. Two hundred eighty-five wells exceeded the MCL. In 1980, only two wells were tested. Both wells exceeded 10 mg/L with the minimum at 27.2 mg/L and the maximum at 58.83 mg/L. The average concentration was 70.18 mg/L in 1990 with a maximum at 172.03 mg/L. Out of 47 wells that were tested, 46 wells exceeded the rate set for this study. Zero wells were tested in 2000; however, 53 wells were tested in 2001, only 10 of which were at or below the HRL (Table 2).

Table 2 Well statistics for Seymour Aquifer

<table>
<thead>
<tr>
<th>Seymour</th>
<th>Tested</th>
<th>Mean</th>
<th>Max</th>
<th>No. Wells &gt; HRL</th>
<th>% Over HRL</th>
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<tbody>
<tr>
<td>1970</td>
<td>350</td>
<td>41.58</td>
<td>273</td>
<td>285</td>
<td>81.43</td>
</tr>
<tr>
<td>1980</td>
<td>2</td>
<td>43.015</td>
<td>58.83</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>1990</td>
<td>47</td>
<td>70.18</td>
<td>172.03</td>
<td>46</td>
<td>97.87</td>
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<tr>
<td>2001</td>
<td>53</td>
<td>60.98</td>
<td>280.23</td>
<td>43</td>
<td>81.13</td>
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<tr>
<td>2010</td>
<td>39</td>
<td>70.66</td>
<td>196.55</td>
<td>37</td>
<td>94.87</td>
</tr>
</tbody>
</table>

Source: Texas Water Development Board Groundwater Database.

The highest concentration was 280.23 mg/L and the average was 60.98 mg/L. Finally, in 2010, out of 39 wells which were tested, 37 wells exceeded the HRL. The average concentration for nitrate was at 70.66 mg/L and the highest concentration was 169.55 mg/L.

Meanwhile, the lowest levels of nitrate were found in the Gulf Coast Aquifer (Table 3). As of 2010, there were 24,292 documented wells in this region; 6,790 were
designated for domestic use and 3,551 wells were listed as public water supply.

**Table 3 Well statistics for Gulf Coast Aquifer**

<table>
<thead>
<tr>
<th>Gulf Coast</th>
<th>Tested</th>
<th>Mean</th>
<th>Max</th>
<th>No. Wells &gt; HRL</th>
<th>% Over HRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>451</td>
<td>3.24</td>
<td>133</td>
<td>39</td>
<td>8.65</td>
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<tr>
<td>1980</td>
<td>285</td>
<td>3.74</td>
<td>141.4</td>
<td>31</td>
<td>10.88</td>
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<td>1990</td>
<td>147</td>
<td>4.91</td>
<td>376.3</td>
<td>15</td>
<td>10.20</td>
</tr>
<tr>
<td>2000</td>
<td>11</td>
<td>16.18</td>
<td>85</td>
<td>3</td>
<td>27.27</td>
</tr>
<tr>
<td>2010</td>
<td>26</td>
<td>0.02</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Texas Water Development Board Groundwater Database.

In 1970, 451 wells were tested. The mean nitrate level was 3.24 ppm, maximum was 133 ppm; 39 wells exceeded the set limit. Two hundred eighty-five wells were tested in 1980. About 11 percent of the tested wells exceeded levels of 10 mg/L.

Similarly, 10 percent of the 147 wells tested in 1990 exceeded the 10mg/L level. The mean was 4.91 mg/L and the max was 376.3 mg/L. Only 11 wells were tested in 2000. The average level for nitrate was 16.18 mg/L and the maximum was 85 mg/L. Three of the 11 wells exceeded 10 mg/L. Finally, in 2010, 26 wells were tested. Every single observation was recorded at 0.02 ppm.

For the state of Texas, it is immediately evident in the maps from 1970 that nitrate concentrations were highest directly in and around the Seymour Aquifer and prevail through the center of the state and towards the west while a few patches were scattered across the northeast. Concentrations exceeding 11mg/L made up about 28 percent of the total. Areas that were between 9 and 11 mg/L comprised about 2.8 percent of the total and were mainly found directly next to areas of higher concentrations, with the exception of a few small patches along the Texas/Mexico border. The majority of wells (~69 percent) were below 9 mg/L.
The county level representation shows that there were 37 counties with mean nitrate levels above 11 mg/L. Six Texas counties had levels ranging from 9 to 11 mg/L. One hundred twenty-two counties were below 9 mg/L. There was no data for 89 counties. The counties with the highest levels occurred around the Seymour and Ogallala Aquifers and in rural areas where land use is primarily agricultural. Levels appeared to be considerably lower in more urban or more densely populated areas (Figure 8).

Overall, there were a total of 114,793 wells in the state of Texas in 1970 (Table 4). Out of this, 24,877 wells were designated for domestic use and 5,746 wells were listed as public water supply. Altogether, about 42.7 percent (1,613 individual wells) of the 3,780 observations made that year were designated for human use. Yet, approximately 20 percent of those wells deemed fit for human consumption exceeded 10 mg/L for nitrate. The state average was about 26.46 and the max was 2,162 mg/L. Out of all observations made in 1970 across the state, 1,127 exceeded 10 mg/L for nitrate (Figure 8).

**Table 4 Well statistics for the state of Texas**

<table>
<thead>
<tr>
<th>Year</th>
<th>Wells tested</th>
<th>Mean</th>
<th>Max</th>
<th>Wells over 10 mg/L</th>
<th>Total wells</th>
<th>Domestic</th>
<th>Public</th>
<th>Human Use</th>
<th>% tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>3,780</td>
<td>26.46</td>
<td>2,162</td>
<td>1,127</td>
<td>114,793</td>
<td>24,877</td>
<td>5,746</td>
<td>30,623</td>
<td>3.29</td>
</tr>
<tr>
<td>1980</td>
<td>1,904</td>
<td>7.88</td>
<td>306</td>
<td>381</td>
<td>125,247</td>
<td>27,182</td>
<td>7,930</td>
<td>35,112</td>
<td>1.52</td>
</tr>
<tr>
<td>1990</td>
<td>1,385</td>
<td>15.42</td>
<td>1,244</td>
<td>399</td>
<td>131,299</td>
<td>28,415</td>
<td>10,396</td>
<td>38,811</td>
<td>1.06</td>
</tr>
<tr>
<td>2000</td>
<td>1,142</td>
<td>16.45</td>
<td>419</td>
<td>485</td>
<td>134,022</td>
<td>28,889</td>
<td>11,633</td>
<td>40,522</td>
<td>0.85</td>
</tr>
<tr>
<td>2010</td>
<td>620</td>
<td>13.63</td>
<td>282</td>
<td>156</td>
<td>135,604</td>
<td>29,203</td>
<td>12,271</td>
<td>41,474</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Source: Texas Water Development Board Groundwater Database.
Figure 8 Wells tested and mean nitrate levels above, at, and below the set health risk level, state and county level, Texas 1970.
Although the state average for nitrate in 1980 dropped to 7.88 mg/L (about 70 percent), it is important to note that considerably fewer wells were tested this year. Out of the 125,247 wells which were in existence that year, only 1,904 were tested for water quality (i.e. 65.6 percent fewer observations made than in 1970). In spite of the drastic reduction in the state rate, however, the year 1980 exhibited a noticeable expansion in the spatial variation of the same areas where nitrate levels exceeded 11 mg/L across the western half of the state and crept up around the border of the panhandle (Figure 9). The areas which had levels between 9 and 11 ppm also expanded further and outward from where they had been in 1970. Areas which were less than 9 mg/L continued to remain in the eastern part of the state and amid more populated regions.

County level data showed a significant decrease in the number of counties with wells tested for water quality. Pecos county nitrate levels decreased from an average of 17.77 mg/L in 1970 to 9.02 mg/L in 1980. Reeves County, which lies just north of Pecos, also decreased from 11.26 mg/L in 1970 to 0.15 mg/L in 1980. Two counties in the westernmost tip of the state, Brewster (0.4 ppm) and Hudspeth (2.3 ppm), had previously been below 10 mg/L in 1970, but in 1980, they had risen to 17.13 ppm and 29.25 ppm, respectively.

In both the smoothed map and the choropleth map, elevated nitrate levels expanded in a western direction. There was no data for counties in the southernmost tip in 1970; then in 1980, high nitrate levels appear to be moving northwards from the Texas/Mexico border. While the number of counties with excessive nitrate levels (>11 ppm) decreased from 37 to 34 counties, the number of counties where wells were
analyzed for water quality only made up about 25 percent of the 254 counties in this state. In 1970, six counties had levels between 9 mg/L and 11 mg/L, and 122 counties had rates less than or equal to 9 mg/L. In 1980, seven counties lay between 9 and 11 mg/L, and 96 counties had average levels less than 9 mg/L. There were 117 counties with no data.

By 1980, the number of wells in the state had increased by about 9 percent from 114,793 wells to 125,247 wells (Table 4). There were 27,182 domestic use wells and 7,930 public water supply wells. Three hundred fifty-two and 507 of the 1,904 analyses performed were on wells designated for domestic and public water supply use, respectively. Three hundred eighty-one (20 percent) wells exceeded 10 mg/L with a maximum at 306.4 mg/L (Figure 9). In 1990, excessive nitrate levels appeared to have decreased in the Panhandle and occurred more centrally beneath the Ogallala and directly over the Seymour Aquifers (Figure 10). The entire westernmost wing of the state had fallen back below 9 mg/L. The eastern part of the state and well into Central Texas also remained below the 9 mg/L mark. Excessive nitrate contamination tended to remain constant in the southern tail of the state.

The number of wells across the state rose about 4.8 percent from 125,247 in 1980 to 131,299 in 1990. The number of domestic (28,415) and municipal (10,396) wells increased by about 10.5 percent; despite the new wells, however, the number of observations for water quality (1,385) in 1990 continued to decline (Table 4). In 1980, water quality analyses were performed in 137 of the 254 Texas counties. In 1990, water quality analyses were performed in 115 counties.
Figure 9 Wells tested and mean nitrate levels above, at, and below the set health risk level, state and county level, Texas, 1980.
Figure 10 Wells tested and mean nitrate levels above, at, and below the set health risk level, state and county level, Texas, 1990.
In the western tip, the counties that had had the highest nitrate levels had no data for the year 1990. Hudspeth, Culberson, and Brewster counties, which had been high in 1980, now had no reported water quality analyses for 1990. However, counties with reported data showed declines in the mean levels of nitrate. For instance, El Paso County showed about a 50 percent decrease from 8.6 mg/L in 1980 to 4.9 mg/L in 1990. Presidio County showed a drastic decrease from 17.6 mg/L in 1980 to a natural level of 2.4 ppm. Counties in and around the Seymour and Ogallala Aquifers continued to exceed 11 mg/L.

In the southernmost tip of the state, while Jim Hogg County had the highest mean nitrate level; the eastern part of the state continued to remain relatively low compared to the rest of the state (Figure 10).

Only 1.1 percent of the state’s groundwater resources were tested for water quality in 1990. Of the 1.1 percent of wells that were tested, 380 were domestic wells; 450 were municipal supply. The state average for nitrate in Texas groundwater rose from 7.88 mg/L in 1980 to 15.42 mg/L in 1990; the max was 1,244.2 mg/L. Three hundred ninety-nine observations exceeded 10 mg/L.

For the years 2000 (Figure 11) and 2010 (Figure 12), so much of the state was missing data at county level that it was necessary to combine data by 4 year intervals for 2003-2006 and 2007-2010, since by this time, the Texas Water Development Board was doing water quality analyses in different areas of the state every four years. By combining the 4 year intervals, a much better spatial coverage was obtained. However, the question still remains, what does the spatial variation of nitrate look like on a yearly basis?
Figure 11 Mean nitrate levels above, at, and below the set health risk level (10 mg/L) at state and county level, Texas, 2003-2006.
Figure 12 Mean nitrate levels above, at, and below the set health risk level (10 mg/L) at state and county level, Texas, 2007-2010.
There was approximately a 2 percent increase in the number of wells from 1990 (131,299) to 2000 (134,022). Wells designated for municipal (11,633 wells) and domestic (28,889 wells) use increased by 4 percent of the total (40,522 wells) over the decade. There were 1,142 observations made for water quality in 2000. The statewide average was 16.45 mg/L; the max was 418.79 mg/L. Of the 1,142 observations made, 42.5 percent were found to exceed 10 mg/L (Table 5).

For time periods 2003-2006 (Figure 11) and 2007-2010 (Figure 12), there was very little change in the spatial variation of nitrate levels. Fewer wells (~21.5 percent) were tested in the 2007-2010 (2,517) time period than in the 2003-2006 (3,205). The highest levels of nitrate continued to occur in the Panhandle, the western wing and the southernmost tip of the state, mainly rural areas. Lowest levels remained in more densely populated areas.

For years 2007-2010, only 840 out of 5,265 census tracts had reported water quality analyses. The mean nitrate level was calculated for each census tract and linear and non-parametric correlations were run with income and population data from the U.S. Census Bureau. Percentage of total population was taken for the different races and ethnicities. Parametric correlations showed positive relationships significant to the 0.01 level between mean nitrate levels and the percent population that is Hispanic, percent population that is Hispanic and White, percent population that is institutionalized, and percent population of institutionalized males. Mean nitrate levels had significant negative correlations ($\rho \leq 0.01$) with median income, percent Black, percent non-Hispanic, and percent non-Hispanic Black populations (Table 6).
Table 5  Parametric correlations

<table>
<thead>
<tr>
<th>Positive correlations</th>
<th>Mean Nitrate</th>
<th>% Hispanic</th>
<th>% Hispanic White</th>
<th>% Institution</th>
<th>% Institution Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Nitrate Pearson</td>
<td>1</td>
<td>.104**</td>
<td>.106**</td>
<td>.126**</td>
<td>.134**</td>
</tr>
<tr>
<td>Correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Census tracts</td>
<td>840</td>
<td>840</td>
<td>840</td>
<td>807</td>
<td>807</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Negative correlations</th>
<th>Mean Nitrate</th>
<th>Median Income</th>
<th>% Black</th>
<th>% non-Hispanic</th>
<th>% non-Hispanic Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Nitrate Pearson</td>
<td>1</td>
<td>-.103**</td>
<td>-.105**</td>
<td>-.092**</td>
<td>-.108**</td>
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<tr>
<td>Correlation</td>
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<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Census tracts</td>
<td>840</td>
<td>838</td>
<td>840</td>
<td>840</td>
<td>840</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).

However, non-parametric correlations showed a much stronger relationship between Hispanic ethnicity and mean nitrate levels ($p \leq 0.01$), while non-Hispanic races were polarized with negative relationships at the 0.01 level (Table 6).

Table 6  Kendall’s tau b correlations

<table>
<thead>
<tr>
<th>Kendall's tau b</th>
<th>Mean Nitrate</th>
<th>% Female</th>
<th>% non-Hispanic</th>
<th>% non-Hispanic White</th>
<th>% non-Hispanic Black</th>
<th>% Hispanic American Indian</th>
<th>% Hispanic Other Race</th>
<th>% Hispanic Biracial or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive correlations</td>
<td>Correlation Coefficient</td>
<td>1</td>
<td>.190**</td>
<td>.217**</td>
<td>.074**</td>
<td>.088**</td>
<td>.101**</td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0.002</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Census tracts</td>
<td>840</td>
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<td>840</td>
<td>840</td>
<td>840</td>
<td>840</td>
<td>840</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Negative correlations</th>
<th>Mean Nitrate</th>
<th>% Female</th>
<th>% non-Hispanic</th>
<th>% non-Hispanic White</th>
<th>% non-Hispanic Black</th>
<th>% Hispanic American Indian</th>
<th>% Hispanic Other Race</th>
<th>% Hispanic Biracial or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Nitrate</td>
<td>Correlation Coefficient</td>
<td>1</td>
<td>-.099**</td>
<td>-.167**</td>
<td>-.072**</td>
<td>-.237**</td>
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<td>-.070**</td>
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<tr>
<td>Sig. (2-tailed)</td>
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<td></td>
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<td>0</td>
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<td>0.006</td>
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<tr>
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<td>840</td>
<td>840</td>
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</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Groundwater constitutes a vital source of drinking water for Texans. Although the GWDB of the Texas Water Development Board provides a valuable resource, the number and frequency of observations, specifically number of wells tested, has declined considerably since 1970 for annual analyses. In a state the size of Texas, water quality analyses can become a huge financial burden, but providing regular, accurate and comprehensive groundwater testing and quality analysis is imperative. Currently, the Texas Water Development Board does monitoring in different parts of the state on a 4 year increment. However, they continue annual monitoring in aquifers with a history for high nitrate contamination, i.e. Seymour and Ogallala aquifers.

Maps and correlations both show that rural populations are more likely to have increased nitrate levels. This is not surprising since the most intensive agricultural activities occur in rural areas. There were consistently strong positive correlations between nitrate levels and populations of Hispanic ethnicity, regardless of race; while, conversely, there were significantly strong negative associations between nitrate levels and populations of non-Hispanic ethnicity. There was also a significant negative relationship between nitrate levels and median income. This confirms that the more urban, richer parts of the state have little nitrate contamination, whereas the more rural and poorer agricultural areas have higher levels.
In order to address the problem of nitrate contaminated groundwater, sources of nitrate contamination should be studied very closely. Sources cited for nitrate pollution are natural sources, deposition through precipitation, fertilizer use in both agricultural and non-agricultural regions, concentrated animal feeding operations, malfunctioning sewer systems and septic tanks, and fossil fuel consumption (TCEQ 2010). Natural sources of nitrate contamination have been cited as being a major component of pollution in some areas; however, natural sources cannot be the problem (Galloway et al. 2003). In and of themselves, there would be no excessive accumulation.

Local communities and water district authorities have worked diligently to find solutions to the high nitrate concentrations in the Seymour and Ogallala Aquifers. A brochure of best management practices provided by the Texas Water Development Board advocates practices which limit fertilizer use and irrigation strategies designed to deliver water and nutrients directly to crop plants. The TWDB strongly recommends crop residue management and conservation tillage. These are two separate practices but together, they work well to prevent soil erosion, soil disruption, alleviate need for excessive fertilizer use, reduce runoff, and conserve precipitation. Limiting fertilizer use not only decreases the incidence of contaminants being released into the environment, but also saves in total production costs.

Assessment of how nitrate pollution is changing each year is impossible because the state only does water quality analyses on a 4 year incremental basis. It could be looked at through 4 year increments, but then it’s impossible to know what populations are vulnerable. Are areas with high nitrate concerns being remediated? How have best
management practices alleviated nitrate contamination? There have been studies done in immediate areas, but what does the big picture look like? In order to answer these questions, better geographic coverage of testing is required.

Better and more systematic well testing is needed to provide a clearer picture of nitrate contamination across Texas. Currently, there are 12,984 public water supply well systems (PWS) in Texas. If all PWS were required to submit a water quality analysis every other year, with half submitting on odd number years, the other half submitting on even number years, then every year, the state would have 6,492 water quality analyses across the state. Furthermore, the burden of cost could be placed on the PWS, this would transfer to increased cost of water to the public; however, the cost of such an analysis is around $150, $35 just for nitrate, according to Bethany Sapp, sales associate of A & B Labs in Houston, Texas. The increased cost to consumers would be minimal.

Returning to the strong implications that nitrate levels tend to reside in rural areas of low population, it should be taken into consideration that urban populations are also subject to extensive fertilizer application. It’s used on lawns, golf courses, landscaping, etc. Meanwhile, there’s much greater traffic on roads and highways in these areas. However, urban areas tend to have low mean nitrate levels. This could be due to high percentage of impervious land surface. Impervious land surfaces also cause greater runoff and decrease percolation of waters into groundwater resources. Is it possible that lower nitrate levels in urban environments are due to a higher percentage of impervious ground cover?
This study showed the spatio-temporal variation of nitrate in Texas counties from 1970-2010. Data examination revealed excessive nitrate contamination in rural areas with intensive agricultural activity while low nitrate levels existed in wealthy, urban areas. Mean and maximum levels have been increasing even though the number of annual water quality analyses have decreased over time. More effective and systematic well testing is required to provide a clearer picture of the changing levels of nitrate contamination across Texas. Perhaps legislation requiring public water supply systems to perform water quality analyses for inorganic contaminants on alternating years would give a more thorough examination of what the spatio-temporal variation of nitrate is in groundwater and help to better identify at risk populations, identify ways of bringing nitrate as a constituent of drinking water resources closer to natural levels and monitoring such progress.
REFERENCES


