Impact of Fluoride Concentrations on Natural Waters throughout Texas

Mark Stehouwer

GIS in Water Resources

12/6/2013

Executive Summary

The goal of this study was to produce a visual medium by which fluoride contamination in the state of Texas along with the impacted geographic regions and populations could better be understood. Data concerning fluoride, population, and geographic and hydrologic characteristics of the state of Texas were obtained from numerous sources such as the EPA, USGS, and U.S. Census Bureau. Data was imported into the ArcMap software and manipulated to produce thematic maps concerning the presence of fluoride in natural waters throughout Texas. Northwest Texas was determined to potentially have fluoride contamination in both ground and surface waters with fluoride concentrations greater than 2 mg/L. Features common to this region of Texas include higher elevations and the Ogallala aquifer. Other aquifers in the northwest regions were also found to have high fluoride concentrations. These aquifers include the Seymour, Trinity-Edwards, and Pecos Valley aquifers. Literature reviews and consideration of case studies confirms that these four aquifers in northwest Texas have histories of high fluoride levels. Watersheds did not appear to influence fluoride presence in the environment; however, land usages may cause fluoride contamination in surface and ground waters. The number of Texans potentially impacted by fluoride contamination that occurs in northwest Texas is approximately 6%.

Mapping results from this project hold potential for mapping additional contaminants and their presence in the environment. Communities, water systems, consulting firms, and researchers can benefit from the thematic maps created. Recommendations for future work include gathering more widespread measurements for fluoride data and incorporating other contaminants in the mapping process. This would improve interpolation results by decreasing uncertainty in predicted values. In addition, contaminated regions due to other pollutants could also be identified, allowing for awareness and directing treatment efforts.

Table of Contents

1.0 Introduction

1.1 Project Background

Fluoride is a naturally occurring inorganic anion which can be found in many natural waters across the United States. These natural waters are often used as drinking water sources for both small and large communities. In the past, fluoride was not considered a significant water contaminant; it has traditionally been understood as a beneficial background constituent or additive in water supplies. This is because at low concentrations (<1.5mg/L) fluoride aids in tooth development and helps prevent dental caries (Arnold 1956; Carton 2006; Fawell 2006). For this reason many communities have favored having fluoride in their drinking water.

The Environmental Protection Agency (EPA) initially established a maximum contaminant level (MCL) of 4 mg/L for fluoride in drinking water in 1986 before any health impacts related to fluoride were known to occur. In later years, a secondary MCL for fluoride was established at 2mg/L to serve as a precautionary measure against any potential detrimental health impacts (EPA 2013). Recent health research and studies, however, have indentified health risks such as pitting of teeth and skeletal fluorosis associated with prolonged exposure to high concentrations (>2mg/L) of fluoride (Figure 1) (Heller et al 1997; Ayoob and Gupta 2006; Carton 2006; Fawell 2006; Kakumanu and Sudhaker 2013). Drinking water was indicated as one of the primary sources of exposure to fluoride because it is ingested daily by individuals whereas other fluoride sources such as food depend heavily on diet (Levy 2003).

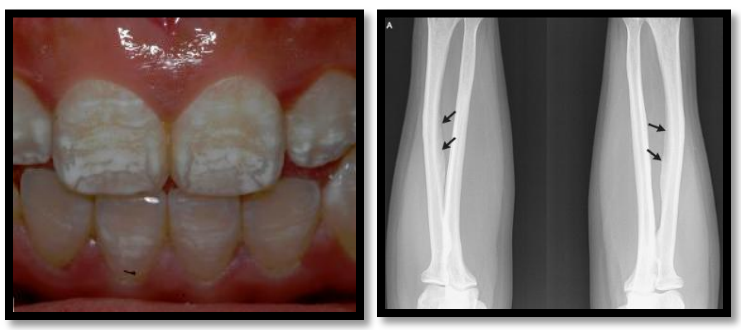

Figure 1. Health detriments due to prolonged exposure to fluoride. Left image shows pitting of teeth (McGrady et al. 2012). Right image shows skeletal flourosis due to excessive tea drinking (Kakumanu and Sudhaker 2013).

The EPA has begun to review its fluoride regulations because of these new health concerns associated with prolonged exposure to fluoride in drinking water. The World Health Organization recommends an MCL of 1.5 mg/L and it is reasonable to anticipate the EPA lowering their MCL to a similar level in the near future (2006). Many public water systems in the United States that currently struggle to meet the existing MCL for fluoride will have an even greater challenge in the future if the existing MCL is lowered by EPA. Moreover, additional water districts may need to address fluoride removal when the standard is lowered. It is essential that these water systems, along with private wells and household water supplies, be identified so that appropriate treatment and help can be provided to ensure safe drinking water in the future.

1.2 Texas Water Supplies

Within the state of Texas there are 6,973 active public water supplies serving small communities, household developments, businesses, and major cities (TCEQ 2013). Table 1 provides a breakdown of Texas water supplies by their water sources. Numbers in this figure however do not include the large number of private wells and water supplies that are often used by individual households or businesses found in rural areas which are not required to report their annual water quality. High fluoride concentrations are often found in groundwaters. This fact suggests that a major of Texas water systems and private households may experience fluoride contamination depending on their geographic location. Surface waters can also have high concentrations of fluoride, but this is not as common. These waters should still be considered because cases do occur and fluoride concentrations can impact the efficacy of some conventional water treatment processes such as coagulation. A medium to identify potential fluoride impacted regions is needed to focus efforts for new water treatment strategies and bring awareness to those communities that may be affected.

Table 1. Distribution of Public Waters Systems in Texas by Water Source

Water Source	**Public Water Systems**
Ground Water	5267
Ground Water Purchased	254
Ground Water Under the Influence of Surface Water	32
Surface Water	332
Surface Water Purchased	1076
Other Water	12

1.3 Research Goal

Many communities in Texas have naturally occurring fluoride in their water, especially rural communities that rely predominately on groundwater as their water source. This project aims to better understand geography, population, and fluoride contamination in the state of Texas. Mapping efforts from this project will identify and raise awareness for geographic regions that may potentially have high fluoride concentrations in their ground and surface waters. In addition, population density mapping integrated with the fluoride analysis of Texas would allow for estimates revealing the current number of Texans likely impacted by waters with high fluoride content. Information from this project will also be useful to municipalities and consulting firms looking for projects in the future or advances in their treatment should EPA regulations change. Concerned residents who are water conscious or those moving to new rural locations in Texas as the state develops may also find information and maps from this project useful as they transition to a new community.

2.0 Methods and Approach

Successful completion of this research is described by the following three phases and is represented by the flow chart shown in Figure 2.

1. Acquisition of data concerning fluoride in natural water of Texas and county-level population information. This data will provide the means for creating a visual medium by which to better identify which regions and populations in the state of Texas may be impacted by fluoride contamination. Processing of the data will allow for it to be used within the ArcMap software for visualization and manipulation. Additional datasets concerning population, geography, geology, and hydrology of Texas will be obtained.

2. Mapping will be performed using the ArcMap software concerning fluoride concentrations in natural waters within the state of Texas. Additional construction and visualization of geographic regions, and impacted populations will be completed in tandem.

3. Interpretation, analysis, and discussion of mapping results will be conducted to understand the project deliverables and outcomes. Conclusions will be made concerning the study and its results, including consideration of the research project's applications, limitations, and recommendations for improvement.

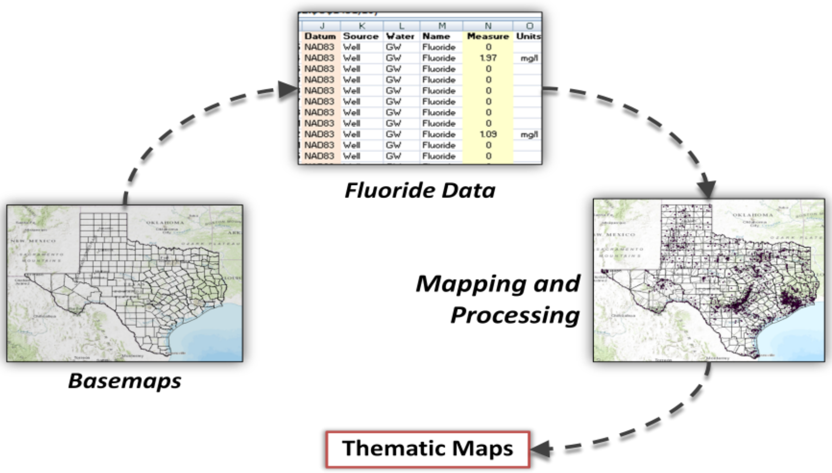

Figure 2. Flow chart showing approach to project

2.1 Data Acquisition

2.1.1 Datasets

This project aimed to better understand geography, population, and fluoride contamination. Each of these topics required its own dataset so that they that could be integrated together through data processing and mapping techniques. The necessary data sets to complete this project were obtained from state and government databases or basemap layer files provided by the USGS and Environmental Services Research Institute (ESRI).

2.1.2 EPA STORET Data

Data concerning fluoride concentrations in ground and surface waters across the state of Texas was obtained using the EPA's STORET Data Warehouse. STORET is an online repository containing water quality monitoring data. Federal, state, and local water resource management groups submit their data to the STORET database through a water exchange service which automatically formats the data and makes it publically accessible for downloads and analyses (EPA 2013). The data available contains specific results for the water quality parameter of interest along with a substantial amount of metadata such as site location, sample time, analytical method used, medium, and organization. Latitude and longitude based on the NAD1983 datum for each sampling site is also contained in the metadata which is important for the implementation of this project.

A request was submitted using the STORET website to collect fluoride data for this project. Specific parameters of the request are contained in Table 2. Two datasets were obtained from the request with a total of 9,561 values. The first dataset contained information on the sampling sites, indicating where fluoride data was available (1,451 stations). The second dataset contained measurement results for fluoride concentrations in the ground or surface water being monitored from the period of January 1, 2000 to October 1, 2013 (9,751 samples). These datasets were downloaded and then integrated together using computer programming to organize the sites by identification numbers and subsequently pair each site with measurement results for fluoride. This allowed the fluoride measurement results to be associated with a specific geographic coordinate. ArcMap was then used to project and manipulate the data. This mapping was accomplished by using the function for plotting XY coordinates and assigning symbology to the data using a graduated color scheme based on fluoride concentration magnitudes.

Table 2. Critical parameters for retrieving fluoride data from the EPA STORET data warehouse.

Search Criteria	**Selection**
State	Texas
Organization	Federal/US Government
	State/US Government
	Local/US Government
Station Type	River/Stream
	Lake
	Well
	Ocean
	Estuary
	Spring
	Reservoir
	Other-Ground Water
	Other-Surface Water
	River/Stream Ephemeral
	River/Stream Intermittent
	River/Stream Perennial
Date	Jan 2000 - Nov 2013
Activity Medium	Water
Water Parameter	Fluoride

2.1.3 Population Data

Population data for the state of Texas was obtained from both the United States Census Bureau and the Texas State Data Center. The data obtained contained county-based population information and was joined using ArcMap to the attribute table of the Texas counties shapefile. Topologically Integrated Geographic Encoding and Referencing (TIGER) line files which contain a significant amount of metadata concerning population demographics were considered for use during implementation of this project however time constraints did not allow for their inclusion. These files are recommended for any future analysis of fluoride impacted regions to determine the demographics and socioeconomic statuses of those regions.

2.1.4 Hydrologic, Geologic, Geographic, and Elevation Data

ArcMap has the capability of downloading basemaps from their online website or connecting to GIS servers. Basemaps of Texas aquifers and geology were obtained through these services. The National Elevation Dataset with 30m or 1-arcsecond resolution was projected and extracted for further manipulation to better understand the relationship of fluoride concentrations with elevation. Shapefiles containing information about the major aquifers and watersheds were downloaded as basemaps from the ESRI basemap collection. These datasets were also projected to try and determine correlations or trends concerning fluoride contamination in various regions of the state of Texas. A complete list of the basemaps obtained and used during this project is contained in Table 3. Figure 4 shows the ArcGIS online user interface for finding select basemaps.

Table 3. Basemaps for Hydrologic, Geologic, Geographic, and Elevation Data

Basemap	Data Type	Source
Texas State	State map	ArcGIS Online
Texas Counties	County map	ArcGIS Online
National Elevation Data Set	Elevation (NED30m)	USGS
Texas Major Aquifers	Hydrologic	USGS; TWDB; ArcGIS Online
Texas Major River Basins	Hydrologic	USGS; TWDB; ArcGIS Online
Texas Major Cities	Geographic	ArcGIS Online
Texas Geology	Geologic	USGS

Figure 4. ArcGIS online user interface.

3.0 Results

3.1 Fluoride in Texas

Fluoride data was processed after its retrieval from the STORET data warehouse. Stations and their locations were matched with fluoride measurement results. The sources of the water were also extracted so that surface and ground waters could be observed separately in ArcMap. After processing, the fluoride data was imported into the ArcMap software and projected onto the state of Texas. Figure 5 shows the locations of ground and surface water monitoring stations in the state of Texas.

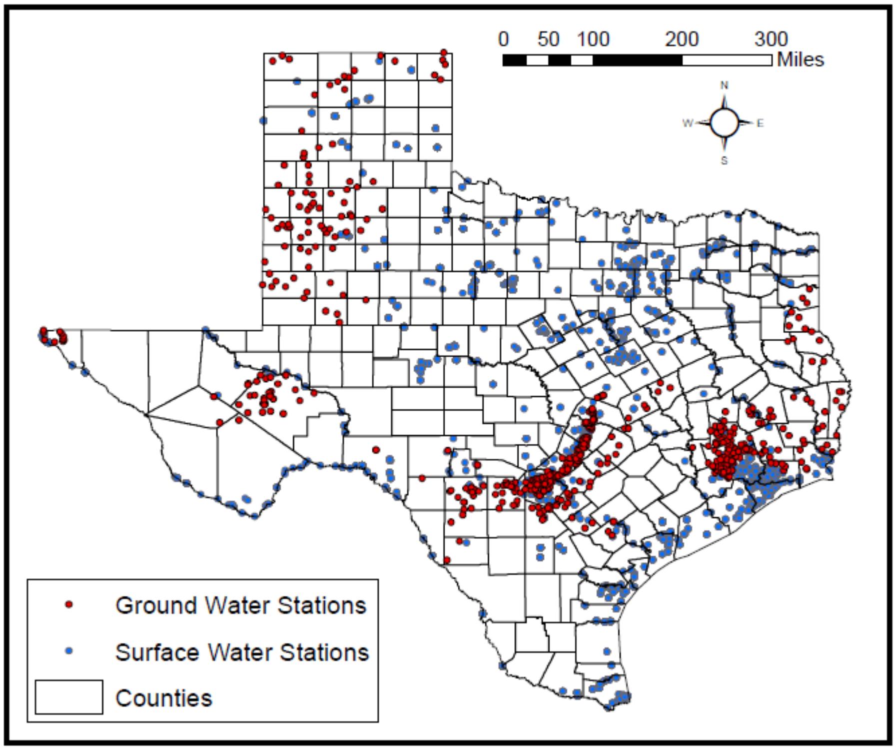

Figure 5. Locations of monitoring stations that measure fluoride concentrations in ground and surface waters within the state of Texas.

To interpolate fluoride concentrations across the state of Texas and in areas where no station values were available, kriging was performed using the geostatistical analyst toolset in ArcMap. A raster feature class for fluoride concentrations was produced and used for further analysis. The Thiessen polygon method (nearest neighbor method) was considered for interpolation, however results from using this tool gave single valued regions of fluoride concentrations instead of gradated fluoride concentrations which was desired. Figures 6 and 7 show the results from kriging interpolation and provide a more detailed visualization of fluoride and its presence in natural waters within the state of Texas. The contours lines delineate regions of similar fluoride concentrations. Regions enclosed by darker contours representing 2 mg/L are considered to likely have fluoride contamination because exposure to concentrations greater than 2 mg/L can have detrimental health effects. Figures 6 and 7 show that high fluoride in natural waters exist primarily in the northwestern portion of Texas near. Surface water contamination occurs around Amarillo while ground water contamination occurs towards Lubbock and extends slightly south and east. Eastern and southern regions of Texas have fluoride in their water, but these concentrations are under 2 mg/L which does not cause adverse health effects.

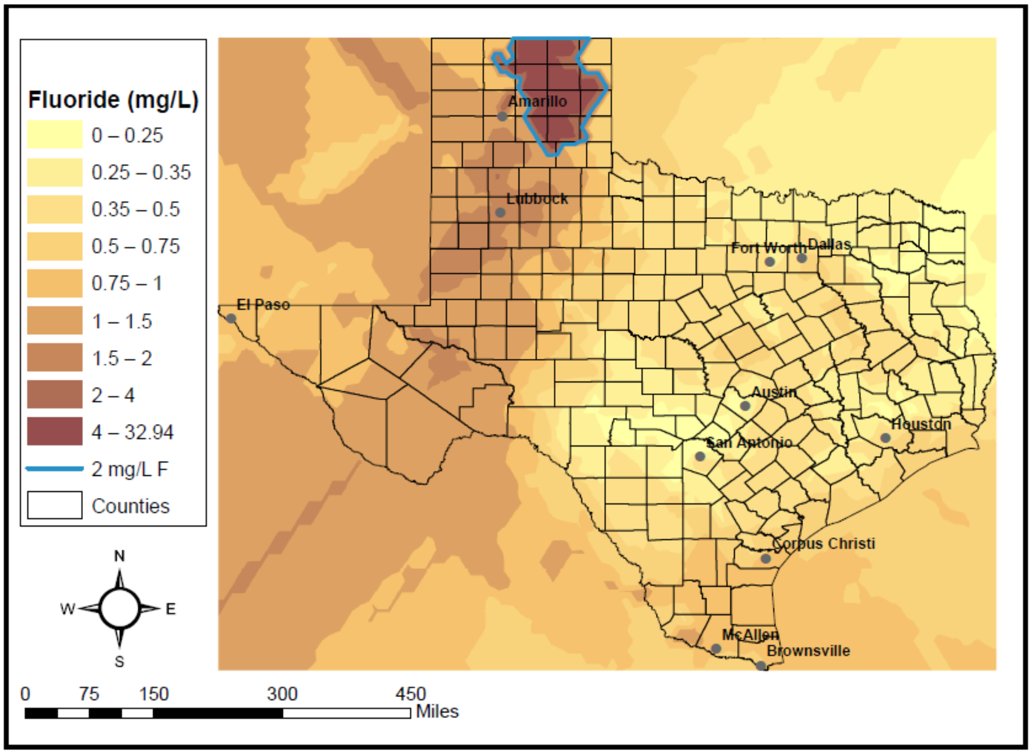

Figure 6. Fluoride concentrations and contours for surface waters within the state of Texas.

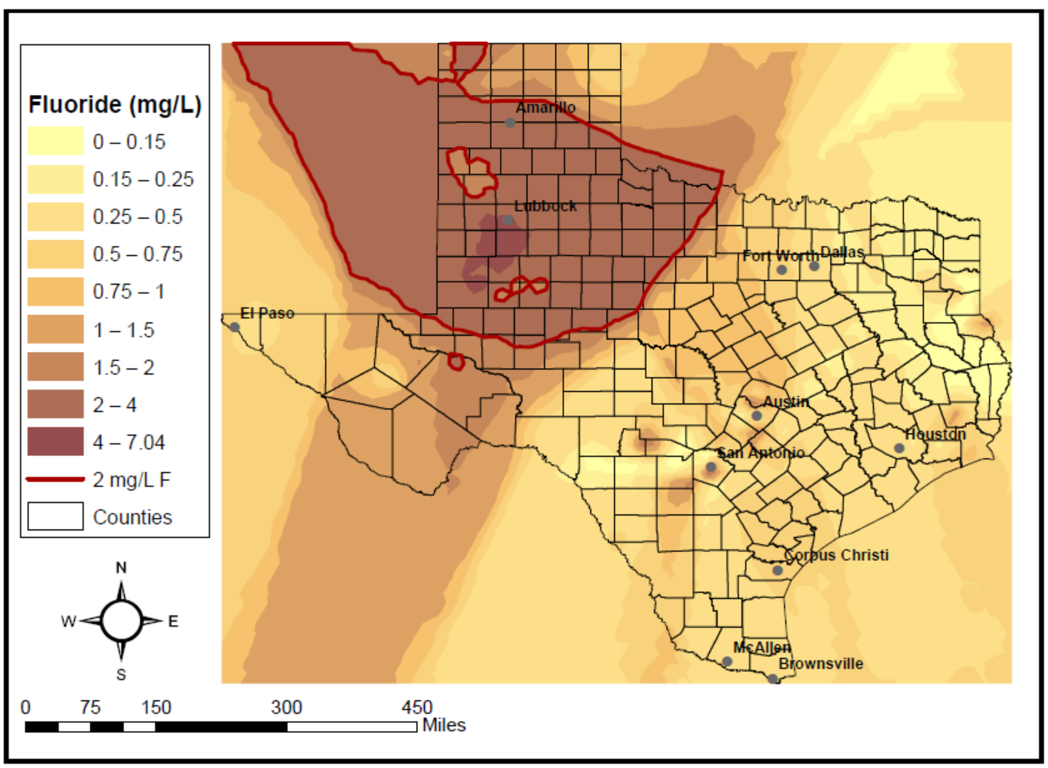

Figure 7. Fluoride concentrations and contours for ground waters within the state of Texas.

The spread of surface water stations was much greater across the state of Texas compared to the clusters of ground water stations. Because of this spread, the surface water estimates of fluoride concentrations throughout the state of Texas will be robust than those ground water estimates. Figures 8 and 9 show the uncertainty associated with fluoride interpolation associated with the different natural waters. Groundwater results have higher uncertainties because less stations and a smaller spread was available in the original data. Kriging results could be improved and uncertainty of interpolation decreased if a greater number of stations and regional spread could be obtained with fluoride data.

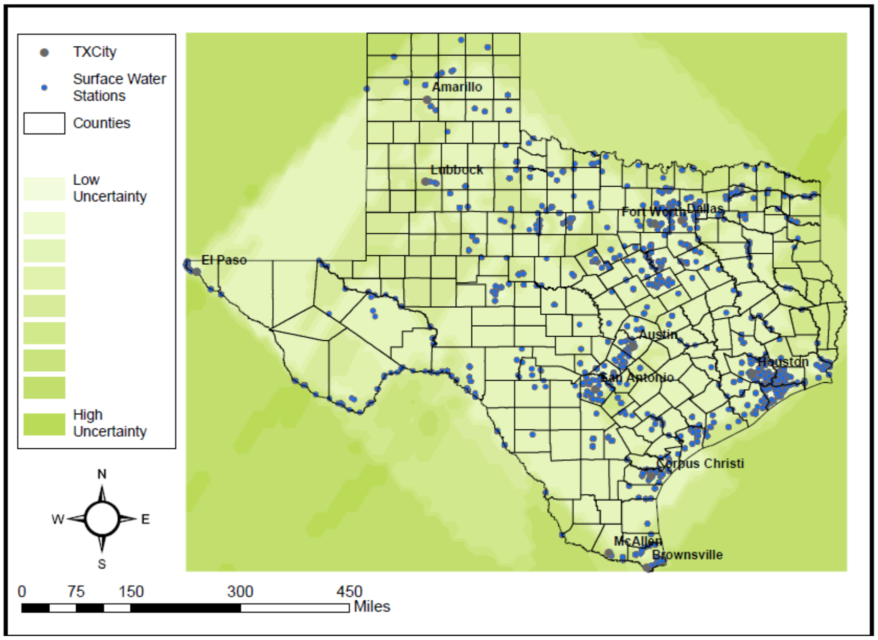

Figure 8. Magnitudes of uncertainty in fluoride concentration estimates associated with kriging interpolation for surface waters.

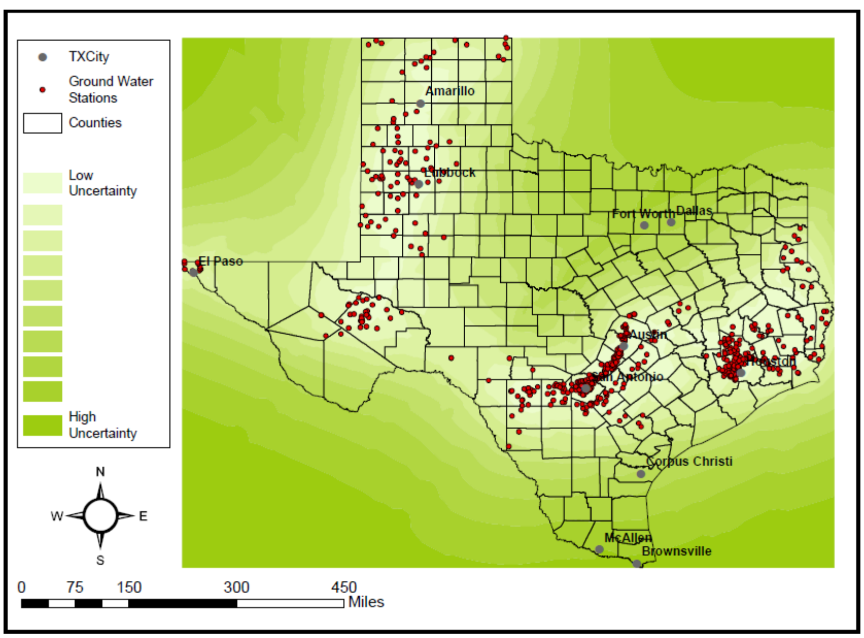

Figure 9. Magnitudes of uncertainty in fluoride concentration estimates associated with kriging interpolation for ground waters.

3.2 Elevation and Fluoride

The National Elevation Dataset at 30m resolution was clipped and extracted for the state of Texas. The hillshading tool in spatial analyst was used and adjustment of the aspect was applied to better visualize elevation changes in the state of Texas. Elevations increase with increasing distance from the Texas coastline as expected. Fluoride contours extracted as lines from prior mapping of fluoride concentrations were overlaid to identify relationships between fluoride and elevation. Reference to Figure 10 shows that as elevation increases, fluoride concentrations also tend to increase. The overlap of contour lines and darker shaded regions show this trend. Potentially these results from the state of Texas could be applied to other gulf coast states and suggest that that coastal regions do not need to be concerned with fluoride contamination, but inland areas should monitor their water as elevation increases.

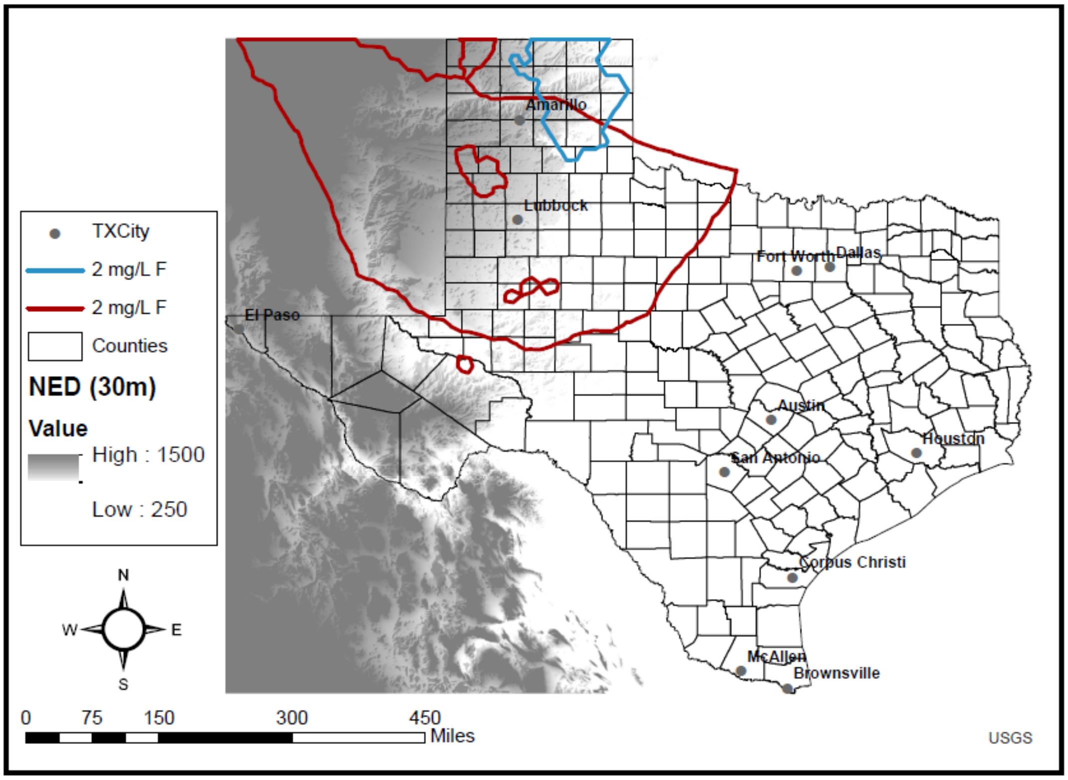

Figure 10. Impact of elevation on fluoride levels in the state of Texas.

3.3 Hydrology and Fluoride

3.3.1 Texas River Basins and Fluoride

The relationship between major Texas river basins and fluoride contamination was investigated using kriging results and a basemap containing the river basins. Clipping and intersections were used to determine which river basins had fluoride concentrations greater than 2 mg/L at any point in their basin. If there was a correlation between fluoride and a river basin, fluoride concentrations throughout the river basin would be expected to be similar or gradated. Figure 11 shows that regions of high fluoride concentrations are not enclosed by the bounds of the major river basins. Instead, regions of high fluoride seem to extend vertically through river basins in the North making any exclusive relationship between fluoride and river basins undetectable. Reasons for fluoride in surface waters are most likely to due human factors such as irrigation (fertilizers), fossil fuels (coal mines and energy plants), electronic waste (landfills) (Hudak 1999, 2009; Brindha and Elango 2011).

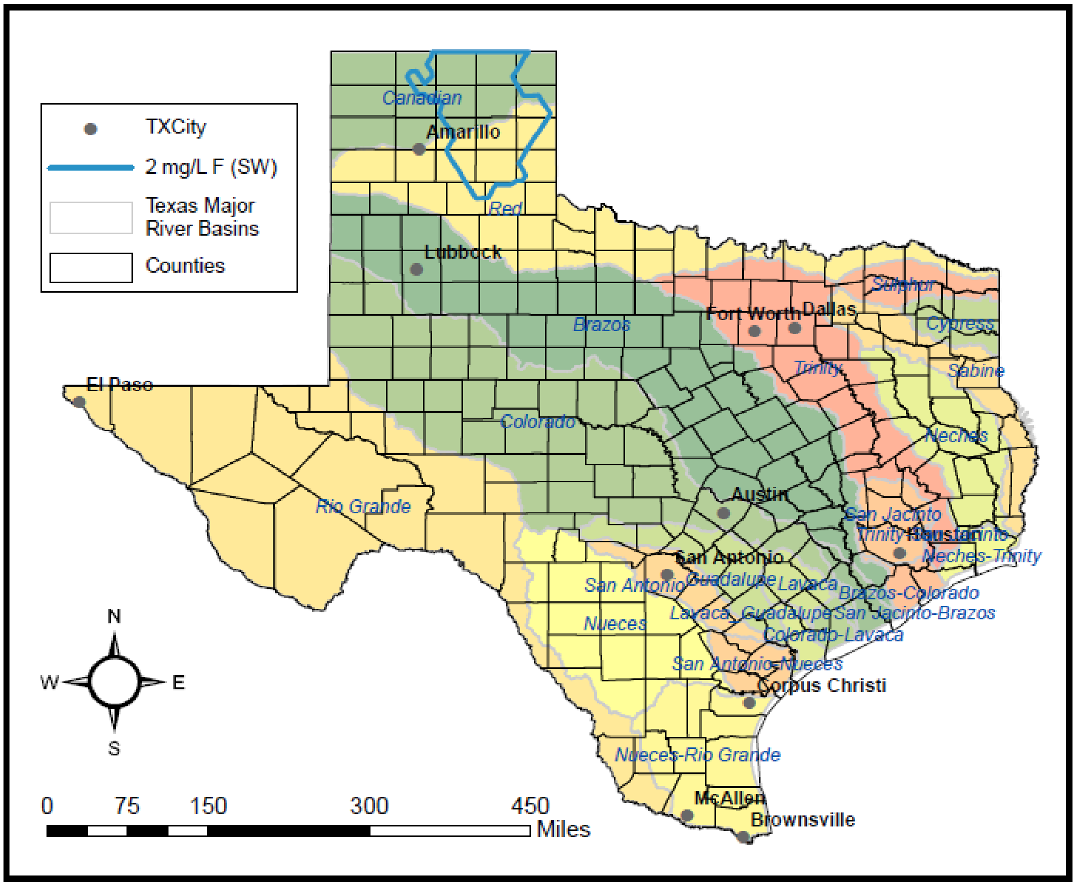

Figure 11. Location of fluoride contamination in Texas river basins.

3.3.2 Texas Aquifers and Fluoride

A layer containing the major aquifers of Texas was obtained from ArcGIS online and extracted so that it could be overlaid with fluoride contours associated with ground waters. A relationship between fluoride in ground waters and Texas aquifers was expected. Monitoring stations sampling water from the same aquifer should have similar concentrations of fluoride because ground water is contained in each aquifer and travels directionally throughout them. This means that if fluoride is present at high locations in one area of the aquifer it would most likely migrate or spread throughout the rest of the aquifer. Also, rock layers and geologic formations enclosing aquifers most likely are similar in mineral content, instilling common properties to the water contained in the aquifer.

Results of mapping fluoride and Texas aquifers are shown in Figure 12. Analysis of fluoride contours and their intersection with aquifers reveals that the Ogallala, Seymour, Edwards-Trinity, and Pecos Valley aquifers contain high fluoride concentrations. The Ogallala aquifer covers the most area in the high fluoridated region of northwestern Texas. Because some of these aquifers such as the Ogallala and Pecos Valley extend into other states (New Mexico, Colorado, Oklahoma, Kansas, Nebraska, and Wyoming, and South Dakota) identification of fluoride contamination in the these aquifers within the state of Texas indicates that contamination could be occurring in other states as well.

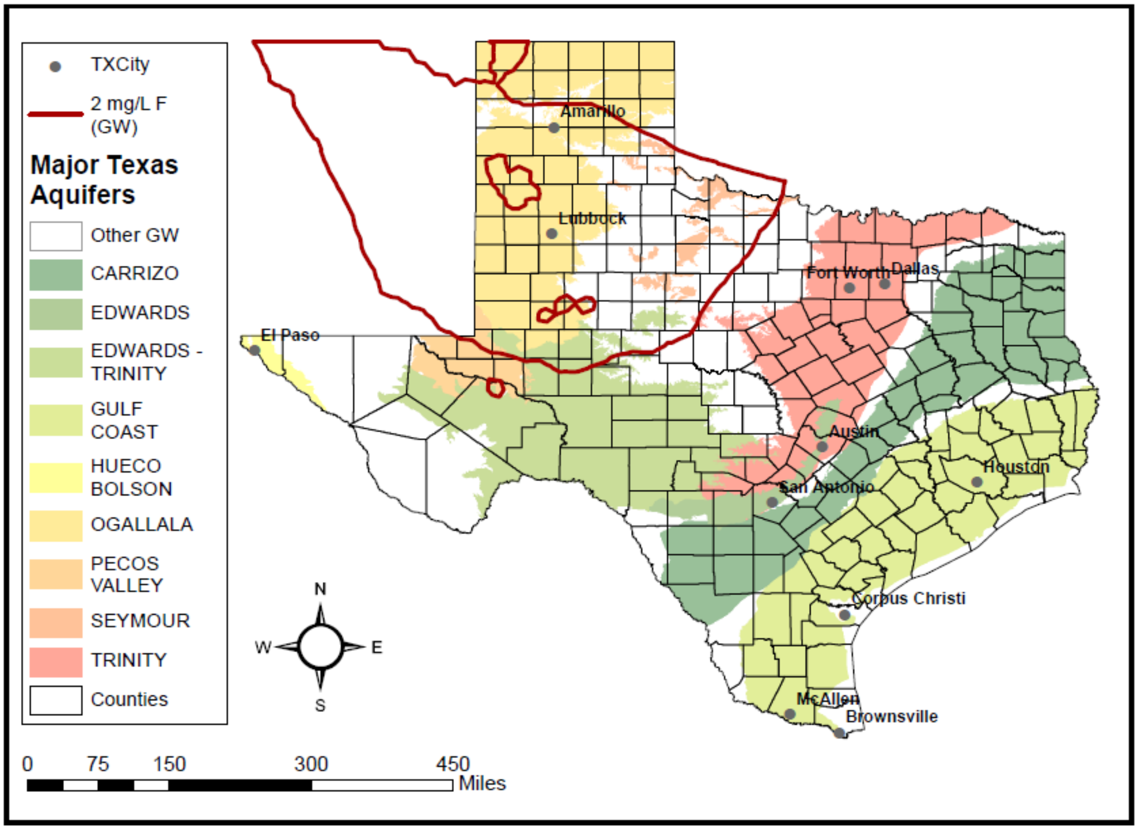

Figure 12. Location of fluoride contamination in major Texas aquifers.

3.3.3 Geology and Fluoride

The Texas Water and Development Board found that fluoride was third most common contaminant in a recent 2011 study conducted on groundwater contamination in the state of Texas. The geology of the state of Texas influences the water quality of its groundwaters. Fluoride is present in groundwaters because it leaches from minerals and goes into solution under favorable conditions. Studies by Hem, Hudakand Sanmanee, and Brindha and Elango found that fluoride usually originates in water by dissolution from minerals such as fluorite, apatite, silicates, hornblende, and volcanic ashes (1985, 2003; 2011). For this reason, groundwaters in the northwestern regions of Texas likely have higher concentrations of fluoride; there are a greater number of minerals with high fluoride compositions in those areas which influences the fluoride concentrations in those groundwaters. The Texas Almanac reports that the mineral fluorite occurs in both central and west Texas (2013). Figure 13 shows the geologic layers of the state of Texas by their age. Specific aquifers and their surrounding formations were investigated through literature reviews.

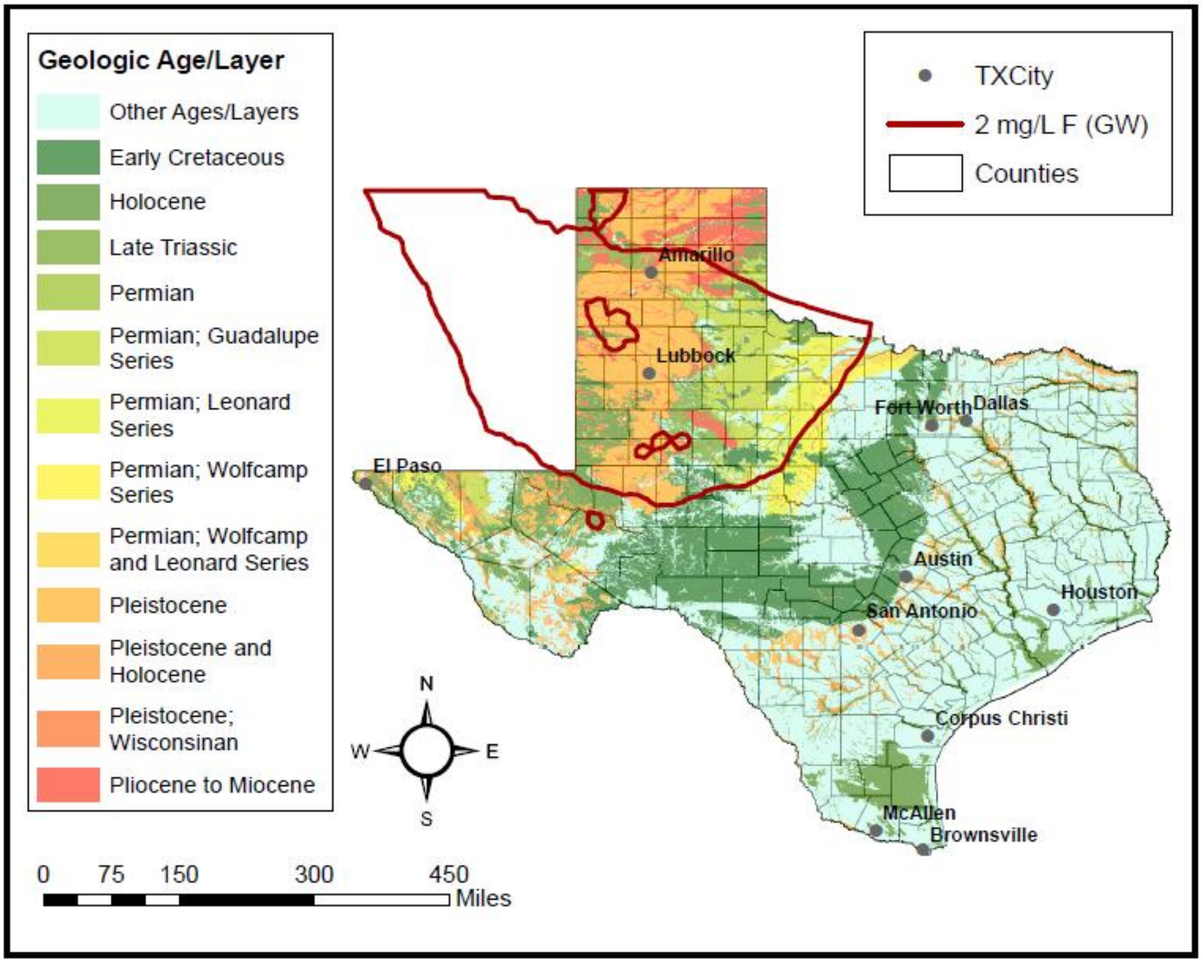

Figure 13. Fluoride contamination and geology in the state of Texas

3.3.3.1 Geology and Hydrology – Ogallala Aquifer

The Ogallala aquifer is also known as the High Plains aquifer. The surrounding formations of this aquifer are comprised of sand, clay, gravel and silt (Ashworth and Hopkins 1995). Hudak studied the concentrations of fluoride and selenium throughout the Ogallala aquifer and analyzed samples from 634 water wells (2009). He found that approximately 19% of the groundwater samples exceeded the fluoride MCL for drinking water. The Texas Water and Development Board also reported high fluoride levels in the Ogallala aquifer (2011).Most likely underlying sedimentary bedrock causes poor water quality in the aquifer and serves as the source of fluoride (Hudak 2009). Intermittent layers of volcanic ash in the area may also contribute to high fluoride concentrations in the aquifer (Gutentag et al 1984). A map produced by Hudak showing fluoride concentrations in northwest Texas is compared to results obtained from this project in Figure 14. Similar fluoride concentrations can be observed between the two maps.

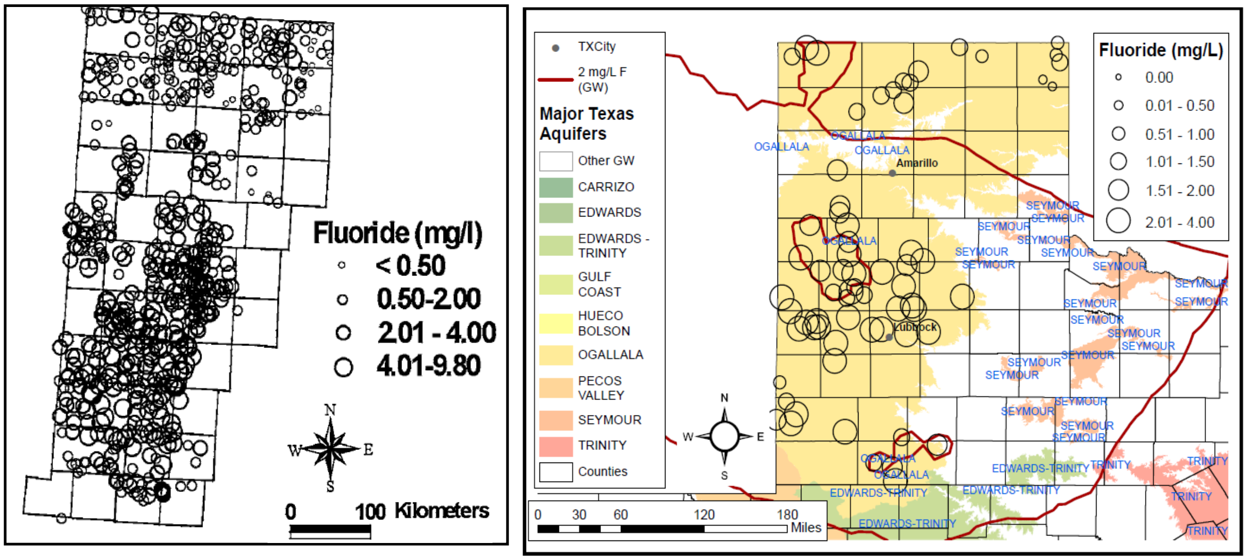

Figure 14. Fluoride contamination in northwest Texas. Left image taken from a study by Hudak in 2009. Right image is a map generated from efforts in this current study.

Ashworth and Hopkins also investigated the reason for high fluoride levels in the Ogallala aquifer because they found that fluoride concentrations in forty-six northwestern Texas counties often exceeded the MCL. They found that groundwater moves through the aquifer towards the south east edge of the High Plains region of Texas. As water travels southeast, it accumulates higher concentrations of dissolved solids including fluoride and produces alkaline water favorable to fluoride dissolution. This understanding of flow direction and retention time in the aquifer may help explain the high concentrations of fluoride observed by Ashworth and Hopkins (1995), Hudak (1999, 2009), and results from this study.

3.3.3.2 Geology and Hydrology – Trinity-Edwards Aquifer

The Trinity-Edwards aquifer is located in central Texas. It surrounding formations consist primarily of limestones and dolomites. Ashworth and Hopkins found that the salinity of the water in the Trinity-Edwards aquifer increased as one moved to the west (1995). In these regions they found some areas with “unacceptable levels of fluoride.” The Texas Water and Development Board also reports high fluoride levels in the Trinity-Edwards aquifer which agrees with mapping results from this current study (2011, 2013). Fluoride contamination in this aquifer may potentially be the effect of natural erosion of minerals in the aquifers surrounding geologic formations. Otherwise, water recharging the aquifer may pick up fluoride from fertilizers that are used for irrigation. Contaminated recharge water may be a source of fluoride in the aquifer because the Texas Water Development Board reports that over two-thirds of the water drawn from this aquifer is used for irrigation (2013).

3.3.3.3 Geology and Hydrology – Seymour Aquifer

The Seymour aquifer occurs scattered over northwest Texas. However, it is more centrally located than the Ogallala aquifer. Harden and Associates compiled a report on the water quality of the Seymour aquifer in Knox and Haskell counties (1978). They determined that the aquifer was primarily surrounded by sand and gravel formations and that the lower levels of the aquifer were around sixty feet below ground. Because the Seymour aquifer is such a shallow aquifer, Harden and Associates concluded that it was susceptible to contamination from surface waters which recharged the aquifer. Agriculture does occur in this region of Texas and fluoride contamination from those fertilizers may increase the natural fluoride concentrations in the aquifer. Figures 15 and 16 show a comparison between fluoride concentrations measured in the Seymour aquifer by Harden and Associates in 1978 and those interpolated values obtained from kriging in this study for Knox and Haskell counties. Results from this project show high concentrations of fluoride for the Seymour aquifer, but not at the levels reported by Harden and Associates.

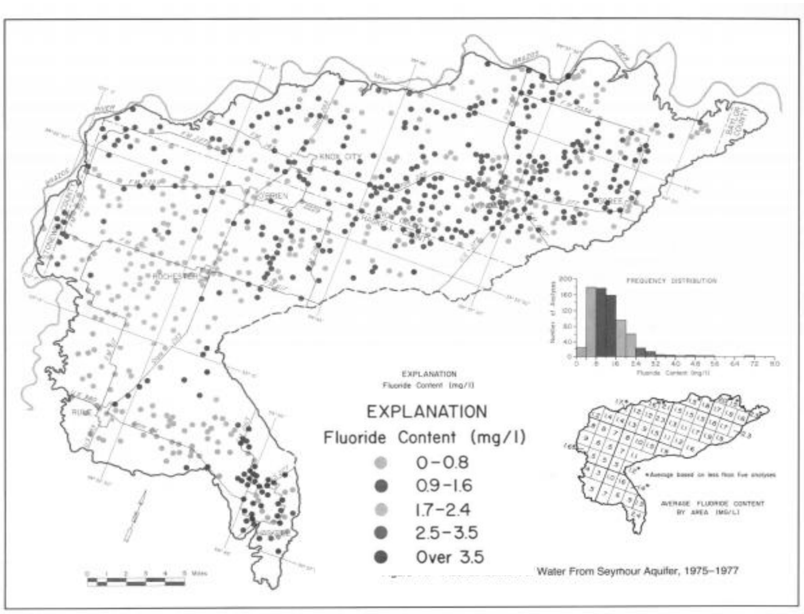

Figure 15. Fluoride concentrations in the Seymour aquifer in Knox and Haskell Counties (Figure from 1978 study conducted by Harden and Associates).

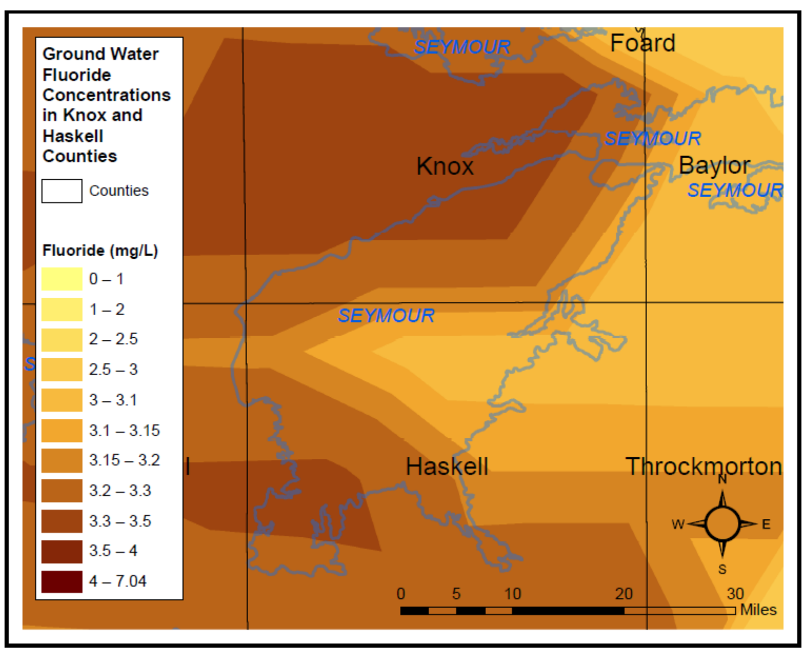

Figure 16. Fluoride concentrations in the Seymour aquifer in Knox and Haskell Counties (interpolated fluoride concentrations from kriging).

3.3.3.4 Geology and Hydrology – Pecos Valley Aquifer

The Pecos Valley aquifer is located in west Texas and extends partially into the southeast corner of the state of New Mexico. Its formation consists of alluvial and windblown deposits saturated with brackish and hard groundwater. The Texas Water and Development Board reports high fluoride levels in the Pecos Valley Aquifer with fluoride concentrations increasing with increasing well depth which concur with mapping results from this study (2011, 2013).

3.4 Population and Fluoride

Population data from the 2010 census was obtained from the United States Census Bureau. This data was incorporated into the attribute table of the Texas counties shapefile. Field calculations were performed to determine population density in each county. Contours delineating regions of high fluoride concentrations greater than 2 mg/L for both surface and ground water was overlaid with the population density layer in ArcM ap (Figure 17).

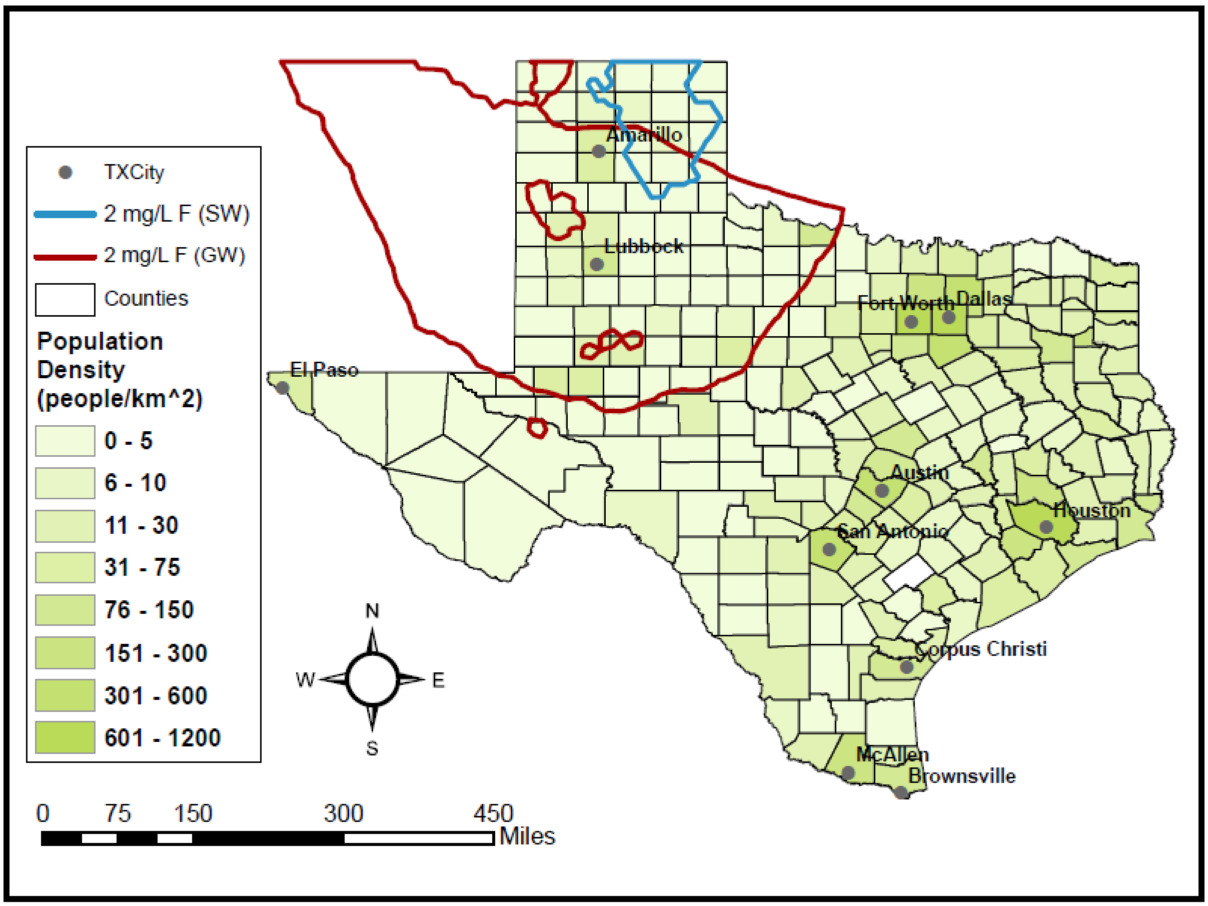

Figure 17. Population density of Texas counties in relation to regions potentially contaminated by fluoride.

Contaminated regions were overlaid, clipped, and extracted along with population information so that the number of Texans potentially impacted by fluoride contamination could be determined. Results from calculations are shown below in Table 4. Approximately 6% of the Texas population is impacted by high fluoride concentrations over 2 mg/L.

Table 4. Number of Texans potentially impacted by fluoride contamination (>2mg/L).

Water Source	Population Impacted	% Texas Population
Surface Water	80,005	0.32%
Ground Water	1,466,737	5.84%
Ground and Surface Water	1,546,742	6.16%

4.0 Conclusion

The intent of this study was to produce a visual medium by which fluoride contamination in the state of Texas along with the impacted geographic regions and populations could better be understood. Data concerning fluoride, population, and geographic and hydrologic characteristics of the state of Texas were obtained from numerous sources such as the EPA, USGS, and U.S. Census Bureau. Data was imported into the ArcMap software and manipulated to produce thematic maps concerning the presence of fluoride in natural waters throughout Texas. Northwest Texas was determined to potentially have fluoride contamination in both ground and surface waters with fluoride concentrations greater than 2 mg/L. Features common to this region of Texas include higher elevations and the Ogallala aquifer. Other aquifers in the northwest regions were also found to have high fluoride concentrations. These aquifers include the Seymour, Trinity-Edwards, and Pecos Valley aquifers. Literature reviews and consideration of case studies confirms that these four aquifers in northwest Texas have histories of high fluoride levels. The number of Texans potentially impacted by fluoride contamination that occurs in northwest Texas is approximately 6%.

Potential fluoride contamination was investigated with respect to four regional attributes: elevation, watersheds, aquifers, and geology. Within the state of Texas, it appears that higher elevations coincide with higher fluoride concentrations in both ground and surface waters. Thus, the coastal regions along the Gulf of Mexico do not have naturally high concentrations of fluoride and inland regions experience increasing levels and have a greater likelihood of contamination. Watersheds do not appear to influence or perpetuate fluoride contamination downstream. This is because mapping results from this project showed fluoride contamination crossing watershed boundaries. Fluoride contamination of surface can occur due to a variety of reasons including groundwater and anthropogenic influences. Mining, energy production by fossil fuels, and fertilizers from agriculture are all associated with elevated levels of fluoride in the surrounding environment. Agriculture and mining are major activities in the northwest of Texas and therefore leaching of fluoride from fertilizers and mine debris may be the reason for contamination of surface water Additional analysis of these areas may reveal that land management is similar across watersheds which would explain why fluoride contamination is not confined to a single watershed.

Major aquifers in the state of Texas along with their geologic layers and properties were investigated through mapping and review of case studies. A correlation between geology and fluoride contamination in ground waters was found to exist because mineral content in the geologic formations surrounding an aquifer influence its water quality which includes fluoride levels. The Ogallala, Seymour, Trinity Edwards, and Pecos Valley aquifers were found to potentially have fluoride contamination. Because these aquifers may have experience fluoride contamination in the state of Texas, it is likely that their extensions into other states may be contaminated as well. Additional studies should look at fluoride contamination in the other portions of these aquifers when they extend beyond the state of Texas boundaries.

The mapping techniques applied in this project hold great benefit for identifying contaminated regions associated with other water contaminants. This is because the ArcMap software provides a user interface by which contaminant presence in the natural environment can be understood visually through thematic maps. Potentially contaminated fluoride regions were identified based on the station data available. Improvements for interpolation could include obtaining a larger dataset of fluoride measurements with greater spread across the state of Texas. Overall benefits from this project and future similar projects include transparency concerning environmental and water quality conditions, awareness of impacted communities, identification of future treatment projects, and improved understanding of regional characteristics on contaminant levels.

References

2010 Census Data. Texas State Data Center, 2013. Web. 1 Dec. 2013. <http://txsdc.utsa.edu/Data/Tiger/2010/Index.aspx>.

2013 TIGER/Line Shapefiles. United States Census Bureau, 2013. Web. 1 Dec. 2013. <http://www.census.gov/geo/maps-data/data/tiger-line.html>.

Arnold, F., Dean, H., Jay, P., and Knutson, J. "Effect of fluoridated public water supplies on dental caries prevalence: tenth year of the Grand Rapids-Muskegon study." Public health reports 71.7 (1956): 652.

Ashworth, John B., and Janie Hopkins. Aquifers of Texas. Texas Water Development Board, 1995.

Ayoob, S., and A. K. Gupta. "Fluoride in drinking water: a review on the status and stress effects." Critical Reviews in Environmental Science and Technology 36.6 (2006): 433-487.

Basic Information about Fluoride in Drinking Water. Environmental Protection Agency, July 2013. Web. 29 Nov. 2013. <http://water.epa.gov/drink/contaminants/basicinformation/fluoride.cfm>.

Brindha, K., and L. Elango. "Fluoride in Groundwater-causes, implications and mitigation measures." Fluoride Properties, applications and environmental management. Nova Science, New York. pp111–136 (2011).

Carton, Robert J. "Review of the 2006 United States National Research Council report: fluoride in drinking water." Fluoride 39.3 (2006): 163-172.

George, Peter G., Mace, Robert E., and Rima Petrossian. Aquifers of Texas. Texas Water Development Board, 2011.

Fawell, John Kirtley. Fluoride in drinking water. World Health Organization, 2006.

Ground Water - Aquifers. Texas Water Development Board, 2013. Web. 1 Dec. 2013. <http://www.twdb.state.tx.us/groundwater/aquifer/index.asp>.

Gutentag, Edwin D. "Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: High Plains RASA Project [Western States (USA); South Central States (USA)]." Geological Survey professional paper (1984).

Heller, Keith E., Stephen A. Eklund, and Brian A. Burt. "Dental caries and dental fluorosis at varying water fluoride concentrations." Journal of Public Health Dentistry 57.3 (1997): 136-143.

Hem, John David. Study and interpretation of the chemical characteristics of natural water. Vol. 2254. Department of the Interior, US Geological Survey, 1985.

Hudak, Paul F., and Sirichai Sanmanee. "Spatial patterns of nitrate, chloride, sulfate, and fluoride concentrations in the woodbine aquifer of north-central Texas." Environmental monitoring and assessment 82.3 (2003): 311-320.

Hudak, Paul F. "Elevated fluoride and selenium in west Texas groundwater." Bulletin of environmental contamination and toxicology 82.1 (2009): 39-42.

Hudak, Paul F. "Fluoride levels in Texas groundwater." Journal of Environmental Science & Health Part A 34.8 (1999): 1659-1676.

Kakumanu, Naveen, and Sudhaker D. Rao. "Skeletal Fluorosis Due to Excessive Tea Drinking." New England Journal of Medicine 368.12 (2013): 1140-1140.

Levy, Steven M. "An update on fluorides and fluorosis." Journal (Canadian Dental Association) 69.5 (2003): 286.

McGrady, Michael G., et al. "Evaluating the use of fluorescent imaging for the quantification of dental fluorosis." BMC oral health 12.1 (2012): 47.

Reedy, Robert C., Scanlon, Bridget., Walden, Steven, and Gil Strassberg. Naturally Occurring Groundwater Contamination in Texas. Texas Water Development Board, 2011.

Texas Almanac - Nonpetroleum Minerals. Texas State Historical Association, 2013. Web. 1 Dec. 2013. <http://www.texasalmanac.com/topics/business/nonpetroleum-minerals>.

Texas Drinking Water Watch. Texas Commission on Environmental Quality, 2013. Web. 29 Nov. 2013. <http://dww.tceq.state.tx.us/DWW/>.

STORET/WQX: STORET Data Warehouses. Environmental Protection Agency, Apr. 2012. Web. 29 Nov. 2013. <http://www.epa.gov/storet/>.