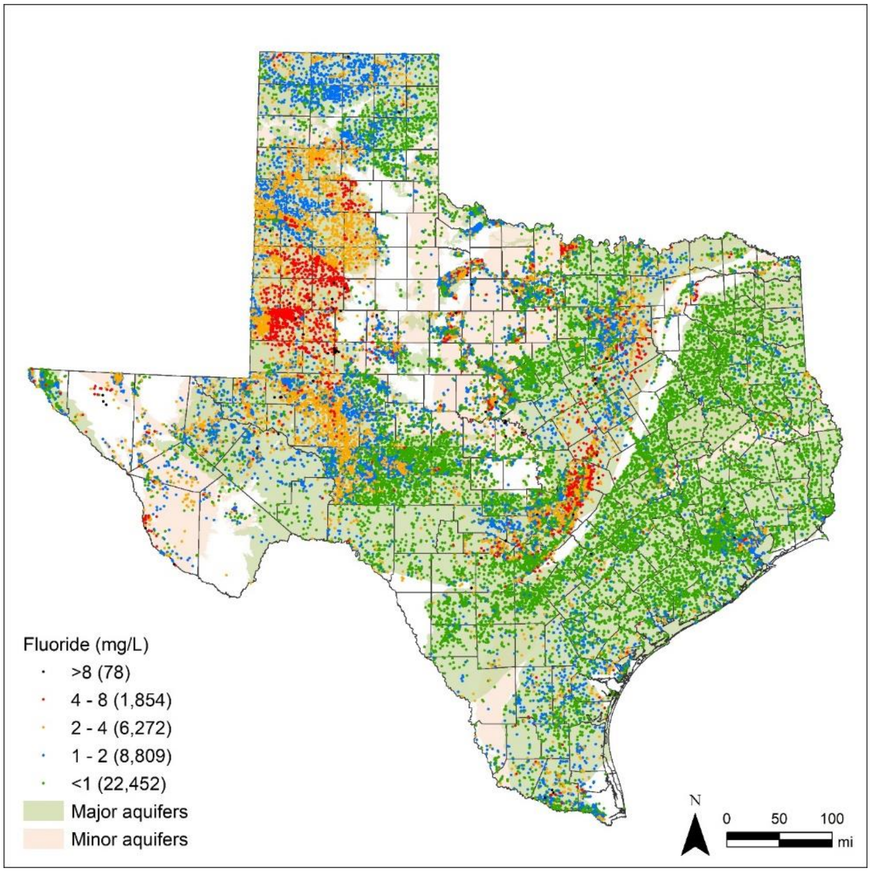
Assessment of Fluoride in Groundwater and Public Water Supply Systems in Texas



by

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Table of Contents

List of Figures

List of Tables

Executive Summary

Understanding the spatial distribution of elevated groundwater fluoride levels is an important issue because of adverse health effects of fluoride. Many previous studies indicate that elevated fluoride concentrations in groundwater primarily originate from natural geologic sources. The objective of this study was to quantify the distribution of groundwater fluoride in the major and minor aquifers in Texas and assess linkages to populations using this water. Groundwater fluoride data were compiled from 39,466 wells sampled from 1929 through 2019**.** The spatial distribution of elevated fluoride concentrations was mapped for the state and by aquifer using indicator kriging based on two threshold concentrations: 2 mg/L representing the EPA secondary Maximum Contaminant Level (MCL) and 4 mg/L representing the EPA primary MCL. The current number of non-compliant Public Water Supply (PWS) systems and associated populations were obtained from EPA listings and the estimated populations with non-compliant non-PWS system water (domestic/self-supplied systems) were obtained from the U.S. Geological Survey water use data.

Results show that a total of 1,798 samples exceeded the fluoride primary MCL of 4 µg/L, representing ~5% of all fluoride analyses. A total of 85% of the MCL exceedances were from major aquifers, primarily the Ogallala aquifer (63%) with much lower percentages from other major aquifers. Median fluoride concentration was also highest in the Ogallala Aquifer (2.1 mg/L) with the 95th percentile of 5.3 mg/L. Concentrations at 95th percentile generally exceeded 2 mg/L for all major aquifers. A much larger percentage (19%) of samples (7,610 samples) exceeded the secondary MCL of 2 mg/L fluoride, indicating that if the primary MCL was reduced to 2 mg/L, the percentage of systems exceeding the MCL would increase by about four times. Of samples >2 mg/L, about 84% are from major aquifers and 16% from minor aquifers, similar to the distribution of MCL exceedances.

The majority of the population has access to PWS systems (28.5 million in 2020; 95% of the estimated total 2020 population of 29.9 million) with a much lower number of people relying on domestic or non-PWS systems (1.4 million, 5% of total population). A total of 44 PWS exceeded the fluoride MCL, mostly (41) in major aquifers and only 3 in minor aquifers. The population impacted by fluoride MCL exceedances is predominantly from PWS systems, totaling ~ 206,000 people (~0.7% of the 2020 population) whereas non-PWS systems accounted for 78,000 people (0.26% of the 2020 population). These percentages are much higher for the secondary MCL of 2 mg/L (PWS, 3.6% of 2020 population, non-PWS, 1.0%), indicating that reduction of the primary MCL to 2 mg/L would greatly increase the number of violations and population served. Major aquifers accounted for the majority of population impacted by primary and secondary MCL violations for PWS systems in terms of population served (99% and 92%, respectively) whereas the percentages from population served from major aquifers were lower for non-PWS systems (~73% for both primary and secondary MCL).

While the State has been making considerable progress towards bringing PWS systems into compliance, there are still a number of non-compliant PWS. There are a variety of approaches for managing fluoride contamination in small PWS systems.

Introduction

Groundwater fluoride levels in drinking water are of great interest because the optimal range of fluoride, from a health perspective, is narrow, from a minimum of ~0.5 mg/L in order to reduce dental caries (NRC, 2006), to a maximum level, the definition of which ranges from 1.5 mg/L (World Health Organization guidance level, WHO, 2011, European Union standard set in 1998) to 4 mg/L (primary MCL in the United States, set by EPA in 1986 for health purposes). The EPA also established a secondary MCL (SMCL) of 2 mg/L for dental purposes that is not Federally enforceable except in California (U.S. EPA, 2020). In 2000, ~60% of the U.S. population had artificially fluoridated water (0.7 – 1.2 mg/L) (NRC, 2006). This percentage with access to fluoridated water increased to 73% of the population in 2018 (~ 207 million people) on PWS systems (community water systems) (CDC, 2020).

The upper fluoride limits have been established to minimize adverse health impacts related to fluoride toxicity, including dental and skeletal fluorosis, bone fractures, and cognitive and behavioral effects (NRC, 2006). A National Academy of Sciences panel concluded that the EPA MCL of 4 mg/L should be lowered to prevent dental fluorosis and reduce risk of clinical stage II skeletal fluorosis and bone fractures (NRC, 2006). States with highest levels of exposure to fluoride >4 mg/L from public water supply systems included South Carolina (~105,000 people, F≤6 mg/L), Texas (37,000 people, F≤9 mg/L), Oklahoma (19,000 people, F≤12 mg/L) and Virginia (19,000 people, F≤6 mg/L) (NRC, 2006).

The EPA regulations only apply to public water supply systems and not to private domestic-supply wells. A recent study shows that ~85% of fluoride concentrations in untreated groundwater in the U.S. were below 0.7 mg/L, the proposed optimal level for oral health (McMahon et al., 2020; U.S. Public Health Service, 2015). This study estimated that ~ 28 million people are potentially served by domestic wells with fluoride levels below the optimal 0.7 mg/L. The narrow range in optimal fluoride concentrations and controversy over recommended upper limits underscore the importance of understanding the sources and mobilization mechanisms impacting fluoride levels in groundwater.

An important source of fluoride is the mineral fluorite (CaF_2) which is found in hydrothermal deposits and rarely in sedimentary deposits (Edmunds and Smedley, 2005). Fluoride is also found adsorbed onto marine clays and is concentrated in phosphates from biogeochemical processes (Edmunds and Smedley, 2005). Anthropogenic inputs include phosphatic fertilizers and contamination from aluminum smelters (Amini et al., 2008). Higher concentrations of fluoride are thought to be controlled primarily by fluorite solubility, as shown by the following reaction: $Ca + 2F = CaF_2$. Based on this reaction, fluoride should be inversely related to Ca as is found in many regions, such as alkaline volcanic rocks with low-Ca groundwater (Edmunds and Smedley, 2005).

Elevated fluoride is also associated with semiarid climates with low flow rates and limited flushing. Probability maps of global groundwater fluoride levels have been developed based on geology, climate (evapotranspiration/precipitation ratio), water type ($NaHCO_3$), and soil pH conditions (Amini et al., 2008). The global distribution of elevated fluoride was summarized according to geologic settings (geothermal springs [e.g. East Africa, western United States], crystalline basement rocks [West Africa, India, Sri Lanka], volcanic rocks [East Africa], and sedimentary basins [China, Argentina, India, United Kingdom, West Africa, United States]) (Edmunds and Smedley, 2005).

Many studies evaluated different mechanisms for mobilizing fluoride in groundwater. High correlations between fluoride and arsenic in oxidizing systems suggest that both may be mobilized by similar mechanisms (Currell et al., 2011; Smedley et al., 2002). Both arsenic and fluoride may be sorbed onto hydrous metal (Al/Fe/Mn) oxides in oxidizing systems; therefore, ions that compete for the same sorption sites can mobilize both elements, such as PO_4, SO_4, HCO_3, SiO_2, and VO_4. A previous study of arsenic in the southern High Plains aquifer in Texas indicated that the most plausible explanation for arsenic mobilization was changing water chemistry from Ca- to Na-dominant water (owing to the counter-ion effect) by upward movement of saline water from the underlying Dockum aquifer (Scanlon et al., 2009).

A similar mechanism was invoked for mobilizing arsenic and fluoride in the Yuncheng Basin in China (Currell et al., 2011). The counter-ion effect results from the reduced sorption of hydrous metal oxides with replacement of divalent Ca by monovalent Na, resulting in mobilization of arsenic and fluoride. Fluorite is also considered a primary control on elevated fluoride concentrations; therefore, any mechanism reducing Ca should increase fluoride mobility, such as cation exchange of Ca for Na with increasing residence time of groundwater as shown in some sedimentary basins (Edmunds and Walton, 1983; Currell et al., 2011). Increasing pH in these basins should also mobilize both fluoride and arsenic.

Assessing treatment technologies for mitigation of high fluoride can also provide insights into mobilization mechanisms. Basic approaches for mitigating fluoride include techniques based on precipitation, adsorption, ion exchange, membrane filtration, and distillation (Feenstra et al., 2007). Precipitation involves addition of alum (aluminum sulfate), lime, alum and lime together (the Nalgonda process), gypsum, or $CaCl_2$. Commonly used sorbents include activated carbon or alumina, zeolites, clay pots, and bone. More expensive approaches include electrodialysis and reverse osmosis. For waters with elevated fluoride and As, the technology should be selected to treat both.

The objective of this study was to address the following questions:

- What is the spatial variability in groundwater fluoride concentrations in major and minor aquifers in Texas?
- What impact do different regulatory levels (e.g., EPA's 2 and 4 mg/L) have on the percentage of fluoride exceedances?
- What is the potential population served by domestic wells and public water supply systems with fluoride exceedances (2 and 4 mg/L)

Elevated fluoride levels represent a public health risk because groundwater is the primary source of water in many regions in Texas. The prevalence of high fluoride groundwater also represents an economic challenge for small municipal public water supply systems that are required to provide chemical treatment. Unique aspects of this study include the long historical water-quality database from the TWDB with good geographical coverage, which provides an opportunity to apply statistical and geospatial approaches to fluoride distributions.

Methods

Data Sources

Data on groundwater fluoride concentrations for this study were obtained from the Texas Water Development Board (TWDB) groundwater database. The TWDB database contains water analyses of groundwater sampled at the well head prior to any treatment processes and the results are considered representative of groundwater conditions at that location at the time of sampling.

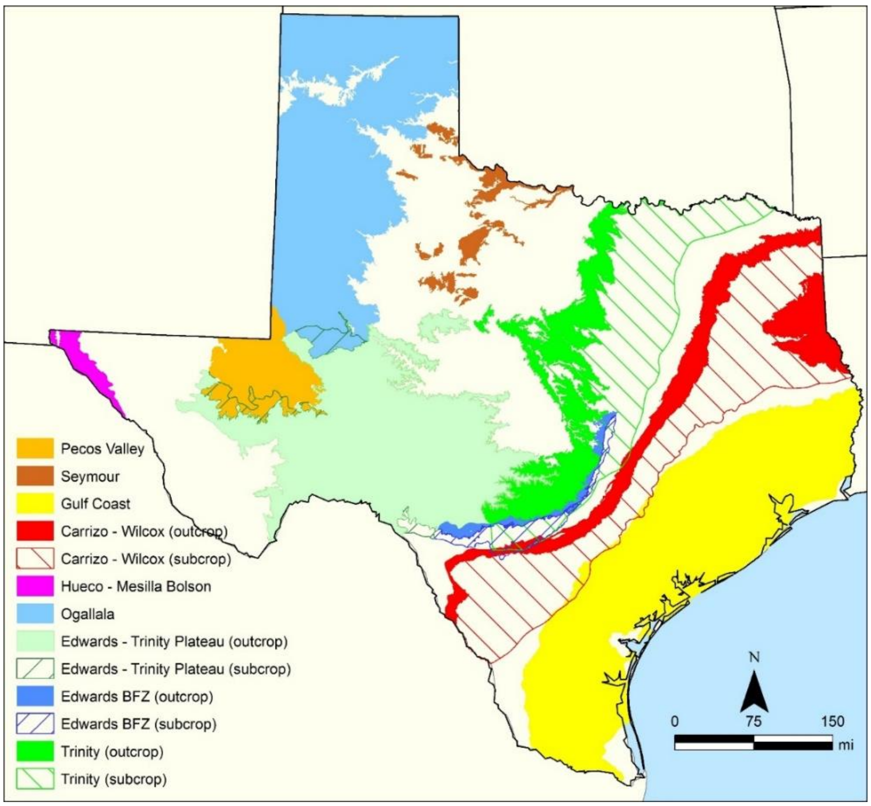


Figure 1. Major aquifers of Texas.

The source aquifer for pumped water is identified for all groundwater wells in the database. Only samples from wells that were completed in a single aquifer, which represent 88% of all fluoride samples in the database, were used in this study. The aquifers represented in this study include the nine major aquifers (Figure 1) and 21 minor aquifers (Figure 2) identified and named by the TWDB.

Samples from 39,466 groundwater wells in Texas are represented in this study (Figure 3). TWDB groundwater database samples analyzed for fluoride were collected between 1929 and 2019 (Figure 4a). The concentration distribution of the sample population collected prior to the median sample date (4/14/1976) was compared to that of samples collected after the median sample date (Figure 4b). The distributions are virtually identical, with only a slight difference in concentrations below 0.5 mg/L. This indicates that there is no significant bias in the analytical precision of fluoride over the sampled time period and that "older" data can be reliably incorporated. As this study is primarily focused on fluoride concentration threshold values of either 2 mg/L or 4 mg/L, the slight difference in distributions below 0.5 mg/L should be inconsequential. The database includes the most recent analysis from each well. Analyses with fluoride concentrations less than the various method detection limits were excluded from the database, totaling 898 samples representing 2.2% of all samples.

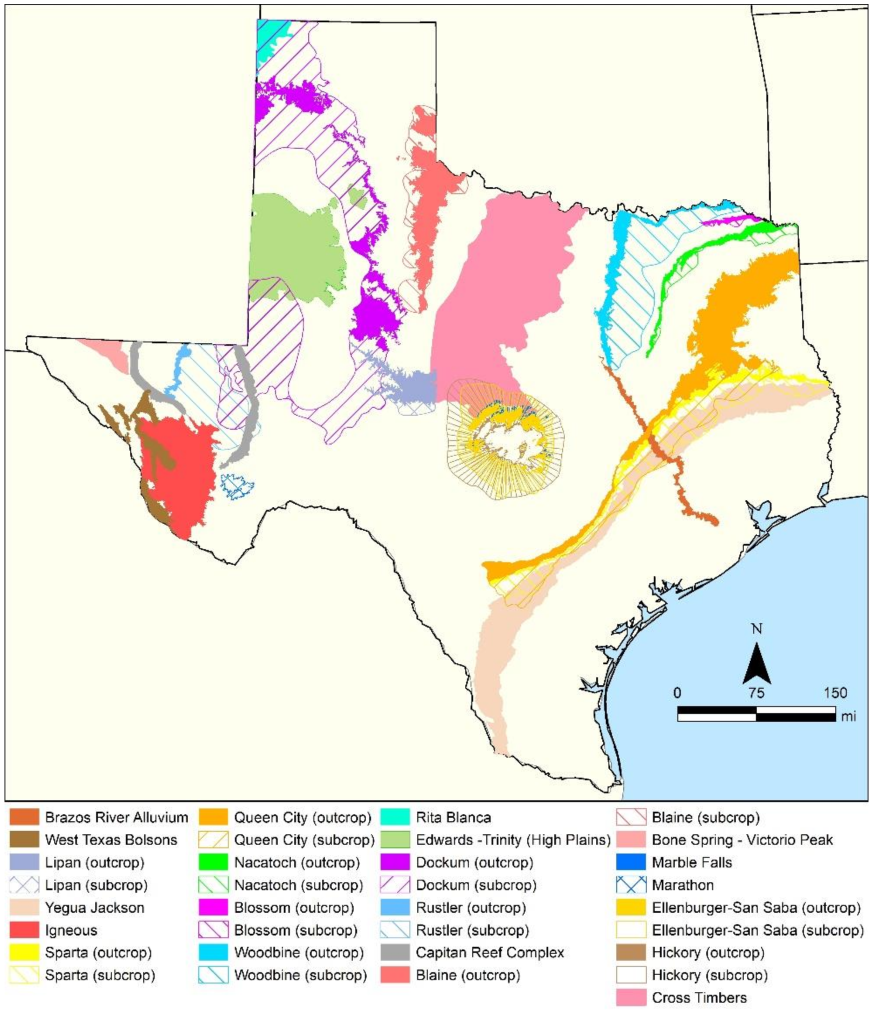


Figure 2. Minor aquifers of Texas.

Analytical detection limits for fluoride varied based on the laboratory and method used. Analytical results for samples with undetectable fluoride concentrations are deemed “non-detects” and results are characterized with the “<” symbol followed by the method detection limit. The highest non-detect fluoride concentration level included in this study is 0.5 mg/L, substantially below the US Environmental Protection Agency (EPA) drinking water Maximum Contamination Level (MCL) of 4 mg/L and also below the 2 mg/L secondary MCL value. A total of 6 samples with detection limits above 0.5 mg/L were omitted from the data set. Finally, one outlier with a concentration of 350 mg/L (10x greater than the next highest concentration sample) was rejected. The non-detect samples have a median detection limit of 0.1 mg/L and range from 0.01 mg/L to 0.5 mg/L (mean 0.15 mg/L).

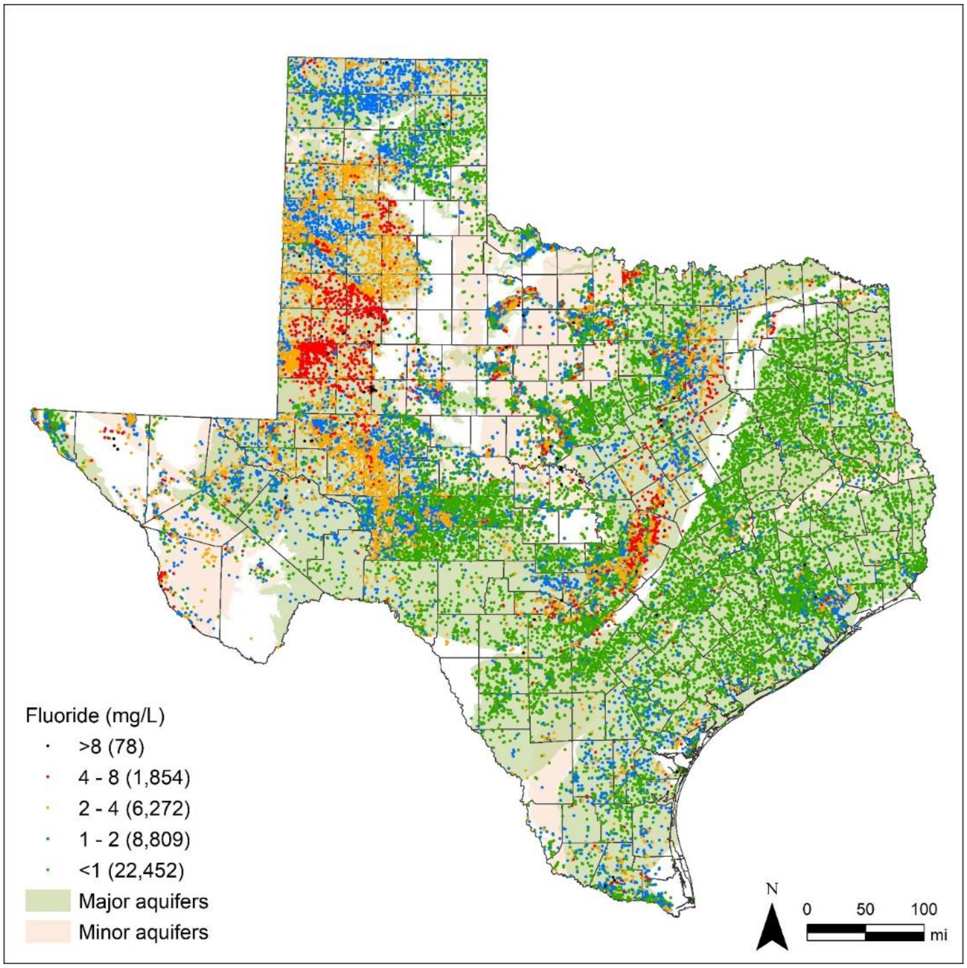
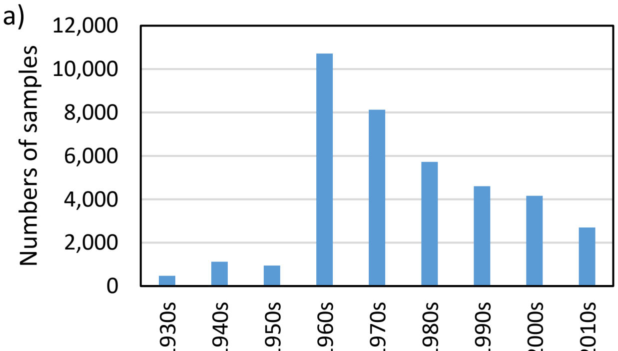


Figure 3. Spatial distribution of groundwater fluoride concentrations in Texas groundwater, including samples collected from 1929 – 2019 with detected concentrations (39,466). The numbers of samples within the stated concentration ranges are shown in parenthesis. Samples with non-detect concentrations and samples from wells that were not completed in either a single named major or minor aquifer are not included.

a)



b)

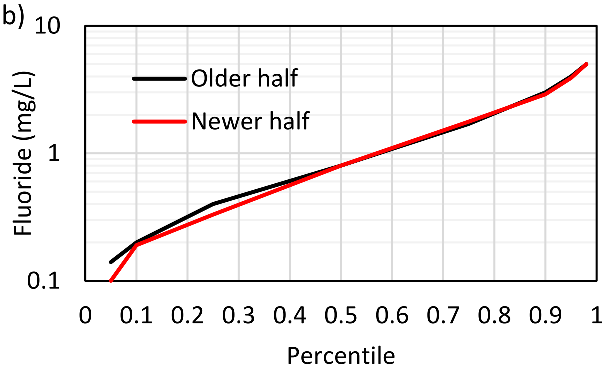


Figure 4. Distributions of a) fluoride sample collection dates and b) percentile concentrations of samples collected prior to and after the median sample date (4/14/1976).

Data Analysis

Fluoride concentrations were evaluated by aquifer using various statistical analyses. Statistical analyses include simple determinations of the numbers of samples, numbers of non-detects, the mean, minimum and maximum concentrations, and selected percentile concentrations. The Geostatistical Analyst extension in ArcMap 10.7 was used to generate maps representative of the fluoride spatial distribution in the different aquifers. Indicator kriging was used as this method can incorporate non-detect data as well as the detect data. It also has the advantage that no assumptions are made regarding normality of the underlying (and unknown) distribution of the concentration data.

Indicator kriging does not result in a concentration map. Rather, the output is a map of the estimated probability that fluoride concentrations exceed a selected threshold value. Two threshold values were used. The lower threshold of 2 mg/L represents the EPA secondary MCL for drinking water. A higher threshold value of 4 mg/L was used to identify areas where the likelihood that groundwater fluoride concentrations exceed the EPA primary MCL for drinking water.

Maps were generated for both threshold values for the entire State of Texas data set and also for each aquifer having sufficient data points to warrant application of the method. As a general rule-of-thumb, it is desirable to have 100 or more data points and 50 is considered the minimum required to obtain a statistically stable and meaningful result using kriging methods. Further consideration must also be given to the spatial distribution of data point locations within the modeled area, i.e., whether the data are overly clustered in one area and sparse or absent in others. There were more than sufficient data for all nine of the major aquifers while there were sufficient data for only 10 of the minor aquifers. The remaining 11 minor aquifers not mapped had either insufficient samples or had very low percentages of samples above 2 mg/L.

The indicator kriging procedure begins with a binary transformation of the concentration data as either 0 (zero) for all data points less than or equal to the threshold value or 1 (one) for all data points greater than the threshold value. A semi-variogram is created that represents the average variance between data locations as a function of the separation distance between the data points. The semi-variogram may include directional anisotropy components if the variance displays structure based on azimuthal direction within the data. A mathematical model is then fit to the semi-variogram points and this model is used to predict values at locations between the data points. The resulting output is a grid map of predicted probability (or likelihood) values that fluoride concentrations exceed the threshold value. In this study a uniform grid cell size of 1 km x 1 km was selected for all but the state-wide scale maps, which used a 2 km × 2 km grid.

The resulting maps depict the estimated spatial distribution of the probability or likelihood of exceeding the threshold value on an integer scale between 0% and 100%. For this study we characterized predicted probability ranges using seven descriptive categories, including none (0%), very low (<10%), low (10-25%), moderate (25-50%), elevated (50-75%), high (75-90%), and very high (>90%). The maps should be interpreted in part with consideration given to the spatial distribution of the underlying data as data may be clustered in some areas and relatively sparse elsewhere. Some artifacts are present in the maps that arise primarily in regions with little or no data and/or the results of directional anisotropy in the underlying semi-variogram structure.

All of the aquifer probability maps are reproduced as page-width size graphics in Appendix I for the reader's convenience.

At Risk Population Estimates

A separate assessment was performed to estimate the various populations at risk of exposure to fluoride concentrations above the two threshold values of 2 mg/L (SMCL) and 4 mg/L (MCL). The analysis focused on two general classes of water supply systems that were assessed separately, including 1) public water supply systems that are regulated by the TCEQ and 2) domestic or otherwise self-supplied systems that are not regulated.

Public Water Supply Systems

Public water supply (PWS) systems in Texas are regulated under the Safe Drinking Water Act with primacy transferred from EPA to TCEQ and must provide distribution system water sample analyses to monitor system performance with regard to various potential contaminants of concern, including fluoride. Sample data from the TCEQ database were assessed to estimate the at-risk PWS populations for fluoride concentrations in excess of the nominal background level (>2 mg/L) in the distribution systems. These assessments are based on whether the PWS system had at least one distribution water sample with fluoride >2 mg/L during the period from January 2017 through about July 2020.

The EPA maintains a national database of current PWS system water quality compliance with respect to the MCL status for all contaminants of concern. The database includes several system attributes of interest to this study, including estimates of the PWS populations served by the PWS systems that are out of compliance and identification of the sources of water for each system (surface water, groundwater, groundwater under the direct influence of surface water, or water purchased from a wholesaler who pumps and treats water). Following are excerpts from the EPA website documentation that define other attributes in the database that are of significance to this study:

__Public Water Supply System Type__

"The type of public water supply (PWS). A public water supply system is a system for the provision to the public of piped water for human consumption, which has at least 15 service connections or regularly serves an average of at least 25 individuals at least 60 days out of the year.

- *Community water system - A PWS that serves at least fifteen service connections used by year-round residents or regularly serves at least 25 year-round residents (e.g., homes, apartments and condominiums that are occupied year-round as primary residences).*
- *Non-community water system*
    - *Transient non-community water system - A non-community water system that does not regularly serve at least 25 of the same persons over six months per year. A typical example is a campground or a highway rest stop that has its own water source, such as a drinking water well.*
    - *Non-transient non-community water system - A non-community PWS that regularly serves at least 25 of the same persons over six months per year. A typical example of a non-transient non-community water system is a school or an office building that has its own water source, such as a drinking water well."*

__Compliance Status__

- *"Serious Violator*

- *'Yes' indicates a public water supply system with unresolved serious, multiple, and/or continuing violations that is designated as a priority candidate for formal enforcement, as directed by EPA's Drinking Water Enforcement Response Policy.*
- *EPA designates systems as serious violators so that the drinking water system and primacy agency will act quickly to resolve the most significant noncompliance. Many public water supply systems with violations, however, are not serious violators. Operators and the primacy agencies are expected to correct the violations at non-serious violators as well, but without the more strict requirements and deadlines applicable to serious violators. If the violations at a non-serious violator are left uncorrected, that system may become a serious violator. When a serious violator has received formal enforcement action or has returned to compliance, it is no longer designated a serious violator. EPA updates its serious violator list on a quarterly basis.*

- *Health-Based Violations*
  - *Violations of maximum contaminant levels (MCLs) or maximum residual disinfectant levels (MRDLs), which specify the highest concentrations of contaminants or disinfectants, respectively, allowed in drinking water; or of treatment technique (TT) rules, which specify required processes intended to reduce the amounts of contaminants in drinking water. MCLs, MRDLs, and treatment technique rules are all health-based drinking water standards."*

Compliance Points

- *"EPA uses a weighted point system that reflects the degree of noncompliance at each public water system; generally more points means more violations of a serious nature. The point system allows primacy agencies – usually states – to rank public water supply systems in order of severity of noncompliance, so that those with more serious noncompliance can receive appropriate responses, including formal enforcement action."*

Table 1. EPA guidelines for assigning violation point values to PWS systems.

Points	*Description*
10	• Acute contaminant maximum contaminant level (MCL) violation (total coliform or nitrate)
5	• MCL or treatment technique violation for regulated contaminants other than total coliform or nitrate • Nitrate monitoring and reporting violation • Total coliform repeat monitoring violation
1	• Monitoring and reporting violation not listed above • Public notice violation • Consumer Confidence Report violation • Additional point for each year a violation is unaddressed

For this study, we summarized by aquifer the Community Water System (CWS) populations that had health-based violations (as opposed to reporting or public notice violations) related to fluoride. The EPA tracks system compliance on a quarterly basis and summarizes violations for the most recent 12-quarter period plus any new violations reported since the end of the latest official quarter.

Non-Public Water Supply Systems

Domestic and self-supplied systems are not regulated by the TCEQ. These systems are generally located in rural areas or are otherwise not connected to a regulated PWS system and are referred to in this study as non-PWS systems. Estimates of the at-risk non-PWS population were made by aquifer using the kriging probability maps discussed earlier coupled with estimates of the non-PWS county populations from the United States Geological Survey (USGS, 2015, https://water.usgs.gov/watuse/). The USGS report provides total populations and populations relying on public water supply systems. This study uses the difference between those two populations to estimate the rural (non-PWS) population in each county of Texas.

The spatial mean probabilities of exceeding both the 2 mg/L and 4 mg/L fluoride MCL threshold values were estimated for each unique aquifer-county interesting area based on the GIS probability maps. The spatial probability of exceedance mean values were multiplied by the non-PWS population estimates for each county to obtain initial estimates of the at-risk populations. The initial estimates were finally adjusted to remove populations in those county areas not underlain by the given aquifers. The final county results were summed across each aquifer.

This approach assumes that the non-PWS populations are evenly distributed within each county. The county areas were not adjusted for areas served by PWS systems. Therefore, the at-risk populations may be conservatively over-estimated in areas dominated by PWS systems. Finally, multiple aquifers are present at the same locations in some areas which could lead to double-accounting of the populations in those overlapping areas. The primary areas where this situation occurs that affect relatively larger populations are where the Edwards BFZ aquifer overlies the Trinity aquifer and where the Ogallala and Pecos aquifers overlie the Edwards-Trinity Plateau aquifer. Similar secondary areas affecting smaller populations occur where minor aquifers either overlie each other or are overlain by a major aquifer. Reasoning that the shallowest aquifer in a given overlapping area is likely the primary water source for non-PWS systems, this study assigns those populations to the shallowest aquifer in a given area.

Results

PWS and Non-PWS system populations

The total population of Texas increased by a factor of about 3 between 1960 (9.6 million) and 2015 (27.5 million) and further to a present population of approximately 29.9 million in 2020 (Figure 5). The percentage of the population served by PWS systems has varied between about 80-95% during that time and is estimated at 28.5 million in 2020 (Table 2). The population served by non-PWS systems generally fluctuated between about 0.9 to 2.7 million people during that time and was estimated to be 1.4 million in 2020. As a percentage of the total population, the non-PWS population ranged from 10% to 22% between 1960 and 1980 and decreased to 5% to 10% afterwards.

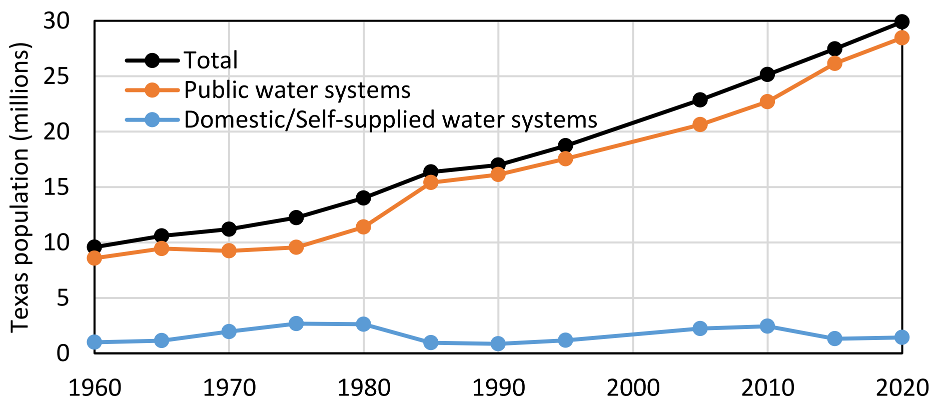


Figure 5. Historical evolution of Texas population relying on Public (PWS) vs Domestic/Self-supplied (non-PWS) water systems (USGS, https://water.usgs.gov/watuse/data/). Values for 2020 are estimated based on 2015 data.

Table 2. Historical evolution of the Texas population relying on PWS and Non-PWS systems and the relative percentages of the total population (USGS, https://water.usgs.gov/watuse/data/).

Year	*Total Population*	*PWS Population*	*Non-PWS Population*	*PWS (%)*	*Non-PWS (%)*
1960	9,580,000	8,580,000	1,000,000	89.6	10.4
1965	10,591,000	9,450,000	1,141,000	89.2	10.8
1970	11,197,000	9,240,000	1,957,000	82.5	17.5
1975	12,236,000	9,560,000	2,676,000	78.1	21.9
1980	14,013,000	11,390,000	2,623,000	81.3	18.7
1985	16,361,330	15,403,760	957,570	94.1	5.9
1990	16,986,410	16,129,900	856,510	95.0	5.0
1995	18,723,940	17,550,400	1,173,540	93.7	6.3
2005	22,859,968	20,628,993	2,230,975	90.2	9.8
2010	25,145,561	22,704,975	2,440,586	90.3	9.7
2015	27,469,114	26,154,041	1,315,073	95.2	4.8
2020*	29,900,000	28,464,800	1,435,200	95.2	4.8

*Estimated U.S. Census Bureau population for Texas. PWS and Non-PWS values based on 2015 % of total values.

General Results

A total of ~39,466 samples were analyzed for fluoride in the state between 1929 through 2019. This dataset includes all raw water samples from various sectors from the TWDB database, including those from public water supply systems. Most of the data (80%, 31,548 samples) represent the major aquifers while the rest (20%, 7,918 samples) represent the minor aquifers (Table 3). A total of 7,610 samples (19% of all groundwater fluoride data in this study) exceed the secondary MCL of 2 mg/L threshold while 1,798 samples (4.6%) had fluoride concentrations above the primary MCL of 4 mg/L.

Table 3. Summary of Fluoride analyses in the TWDB database. Values represent the latest sample for wells sampled between 1929 and 2019. Samples include all sectors (e.g. domestic, irrigation, etc) and untreated PWS samples.

Aquifer Group	*Samples*	*Detects*	*Non-detects*	*F >2 mg/L*		*F >4 mg/L*	
				Samples	*% of Total*	*Samples*	*% of Total*
Majors	31,548	30,969	579	6,360	20.2	1,535	4.9
Minors	7,918	7,599	319	1,250	15.8	263	3.3
All	39,466	38,568	898	7,610	19.3	1,798	4.6

Among the major aquifers, 1,535 samples (4.9%) had fluoride >4 mg/L and The Ogallala had by far the greatest percentage of samples exceeding the MCL (18.5%), followed by the Edwards (Balcones Fault Zone) (5.0%), Trinity (3.8%), and Pecos Valley (2.5%) aquifers. The remaining major aquifers had from 0.1% to 1.7% of samples above the MCL.

Table 4. Numbers of fluoride samples from the major aquifers in Texas. Values are based on the latest samples from the TWDB groundwater database and wells completed in multiple aquifers were excluded.

Major Aquifer	*Total Number of Samples*	*Number of Detects*	*Number of Non-detects*	*F >2 mg/L*		*F >4 mg/L*	
				Number	*%*	*Number*	*%*
Carrizo-Wilcox	3,943	3,675	268	59	1.5	5	0.1
Edwards BFZ	1,414	1,369	45	246	17.4	70	5.0
Edwards-Trinity Plateau	4,910	4,878	32	1,059	21.6	27	0.5
Gulf Coast	6,299	6,174	125	288	4.6	30	0.5
Hueco-Mesilla Bolson	571	567	4	35	6.1	6	1.1
Ogallala	6,151	6,123	28	3,239	52.7	1,135	18.5
Pecos Valley	556	552	4	177	31.8	14	2.5
Seymour	2,091	2,081	10	269	12.9	35	1.7
Trinity	5,613	5,550	63	988	17.6	213	3.8
All Majors	31,548	30,969	579	6,360	20.2	1,535	4.9

Among the minor aquifers, 1,250 samples (16% of all fluoride data from minor aquifers) had fluoride > 2 mg/L (SMCL) and 263 samples had fluoride levels > 4 mg/L (primary MCL, 3.3% of samples) (Table 5, Figure 6). A total of 17 of the minor aquifers had at least one sample above the MCL of 4 mg/L. The data are relatively sparse among the minor aquifers as compared to the major aquifers, with the numbers of samples mostly ranging from 33 samples (Marathon) to 837 samples (Dockum), and one with 2,256 samples (Cross Timbers). Four of the minor aquifers have fewer than 50 samples and several aquifers lack spatial representation in some area. The Edwards-Trinity High Plains had by far the greatest percentage of samples exceeding the MCL (52%), followed by the Rita Blanca (18%), the West Texas Bolson (8.9%), the Bone Spring-Victorio Peak (7.7%), and the Woodbine (6.8%) aquifers. The remaining minor aquifers had from 0% to 5.4% of samples above the MCL.

Table 5. Numbers of fluoride samples from the minor aquifers in Texas. Values are based on the latest samples from the TWDB groundwater database. Samples from wells completed in multiple aquifers are not included.

Minor Aquifer	*Kriged*	*Number of Samples*	*Number of Detects*	*Number of Non-detects*	*Detects >2 mg/L*		*Detects >4 mg/L*	
					Number	*%*	*Number*	*%*
Blaine	N	196	190	6	2	1.0	0	0.0
Blossom	N	75	63	12	8	10.7	0	0.0
Bone Spring-Victorio Peak	Y	155	155	0	62	40.0	12	7.7
Brazos River Alluvium	N	258	256	2	1	0.4	0	0.0
Capitan Reef Complex	N	63	59	4	13	20.6	1	1.6
Cross Timbers	Y	2,256	2,246	10	358	15.9	70	3.1
Dockum	Y	837	824	13	259	30.9	35	4.2
Edwards-Trinity High Plains	Y	71	71	0	62	87.3	37	52.1
Ellenburger-San Saba	Y	318	287	31	21	6.6	9	2.8
Hickory	Y	459	441	18	16	3.5	4	0.9
Igneous	Y	198	198	0	58	29.3	3	1.5
Lipan	N	158	154	4	5	3.2	1	0.6
Marathon	N	33	33	0	2	6.1	1	3.0
Marble Falls	N	41	39	2	3	7.3	0	0.0
Nacatoch	Y	203	193	10	39	19.2	11	5.4
Queen City	N	636	501	135	7	1.1	1	0.2
Rita Blanca	N	34	33	1	10	29.4	6	17.6
Rustler	N	43	42	1	19	44.2	0	0.0
Sparta	N	348	315	33	11	3.2	1	0.3
West Texas Bolson	Y	224	224	0	82	36.6	20	8.9
Woodbine	Y	723	716	7	199	27.5	49	6.8
Yegua-Jackson	N	589	559	30	13	2.2	2	0.3
All Minors	Y:10 N:12	7,918	7,599	319	1,250	15.8	263	3.3

With the large number of samples available, two statewide maps were made representing the probability of fluoride exceeding the 2 mg/L and 4 mg/L fluoride threshold concentrations. The results are generally consistent with the individual aquifer maps with the added benefit of gaining an overall impression of the fluoride distribution in Texas groundwater. The difference between the two maps shows that if the fluoride MCL was reduced from 4 to 2 mg/L, the probability of exceeding the MCL would substantially increase and the areas impacted would expand.

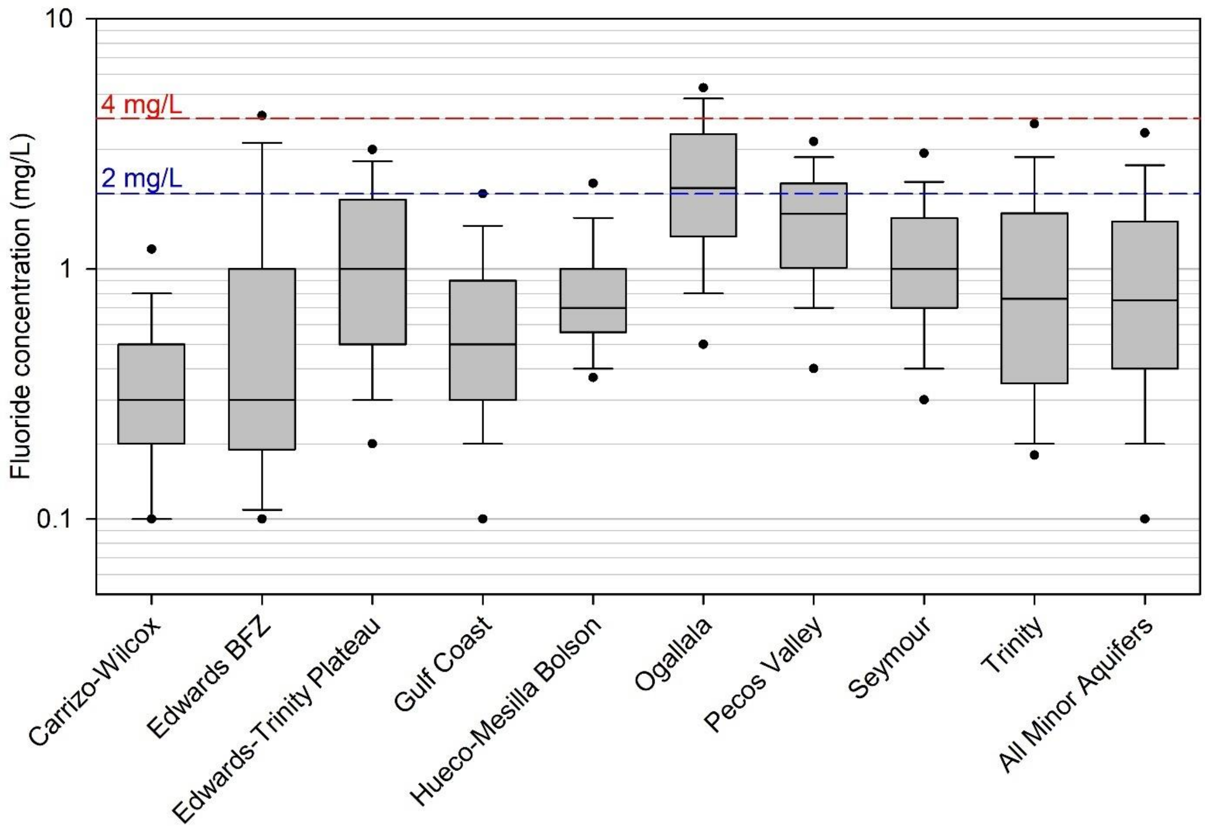


Figure 6. Distribution of detected groundwater fluoride concentrations in the individual major aquifers (31,548 samples, 80% of data, Table 4) and in the combined minor aquifers (7,918 samples, 20% of data, Table 5) of Texas. The lines inside the shaded boxes represent the 50th percentiles (medians), the shaded boxes represent the 25th to 75th percentile ranges, the upward and downward lines extending from the boxes are terminated by horizontal lines at the 10th and 90th percentiles, and the points represent the 5th and 95th percentiles. Reference lines are shown for the 2 mg/L and 4 mg/L threshold values.

Based on the EPA database, 44 PWS systems were not compliant with the MCL of 4 mg/L, 41 in major aquifers (Table 6) and 3 in minor aquifers (Table 7). Most noncompliant systems were sourced from the Ogallala aquifer (34, 76% of total). An estimated total of 205,875 people were served by 44 PWS systems that have been non-compliant with respect to the fluoride MCL (4 mg/L) in at least one of the last 14 quarters (Jan 2017 – June 2020) representing 0.7% of the 2020 Texas total population (29.9 million, Figure 8, Table 2). Most (98%, 202,563 people, Table 6) are associated with PWS systems that source their water from one of the major aquifers while the remaining (2%, 3,312 people, Table 7) are associated with minor aquifer PWS systems. The major aquifers include the Ogallala (183,183 people), Edwards BFZ (17,795 people), Trinity (877 people), and Hueco-Mesilla Bolson (708 people) (Table 6).

Minor aquifers include the Woodbine (3,312 people) (Table 7). There were no systems identified as having serious violations.

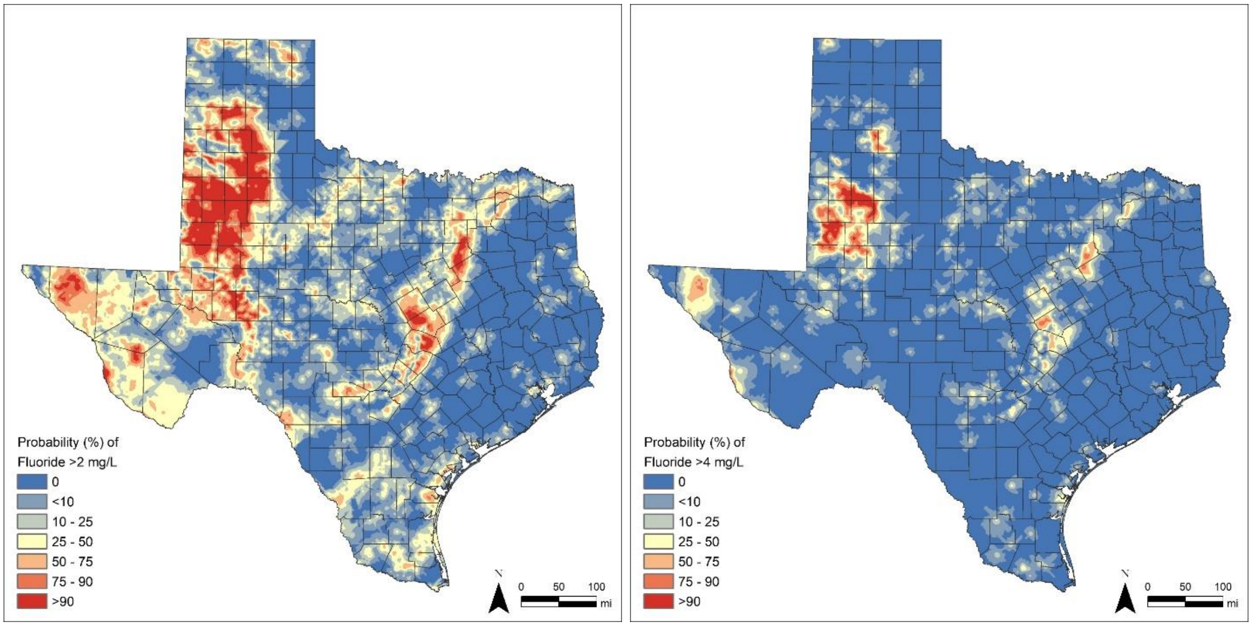


Figure 7. Statewide probability of groundwater fluoride >2 mg/L (left) and >4 mg/L (right) based on all of the data in this study, including 39,466 samples from all named major and minor aquifers.

Table 6. Numbers of major aquifer PWS systems with fluoride concentrations greater than the secondary MCL (>2 mg/L) and greater than the primary MCL (>4 mg/L). The populations shown are those associated with Community Water Systems (CWS). The numbers of non-community water systems are also shown.

Aquifer	*TCEQ Database PWS Systems Fluoride >2 mg/L*			*EPA Non-compliant PWS Systems Fluoride >4 mg/L*	
	Number of NCWS	*CWS*	*CWS At-risk Population*	*CWS*	*Population*
Carrizo-Wilcox	-	7	11,876	-	-
Edwards BFZ	4	18	207,024	2	17,795
Edwards-Trinity Plateau	11	8	11,868	-	-
Gulf Coast	10	35	160,693	-	-
Hueco-Mesilla Bolson	1	1	708	1	708
Ogallala	38	94	292,928	34	183,183
Pecos Valley	1	3	8,906	-	-
Trinity	55	78	292,068	4	877
Total Major Aquifers	120	244	986,071	41	202,563
Percent of 2020 population			3.30		0.68

Table 7. Numbers of minor aquifer PWS systems with fluoride concentrations greater than nominal background (>2 mg/L) and greater than the MCL (>4 mg/L) The populations shown are those associated with community water systems (CWS). The numbers of non-community water systems (NCWS) are also shown.

Aquifer	*TCEQ Database PWS Systems Fluoride >2 mg/L*			*EPA Non-compliant CWS Systems Fluoride >4 mg/L*	
	NCWS Systems	*CWS* Systems	*CWS At-risk Population*	*CWS* Systems	*CWS Population*
Cross Timbers	1	-	-	-	-
Dockum	3	9	17,724	-	-
Edwards	2	1	25	-	-
Hickory	-	1	3,987	-	-
Igneous	4	5	10,282	-	-
Nacatoch	-	4	3,690	-	-
West Texas Bolson	-	2	2,833	-	-
Woodbine	-	16	44,226	3	3,312
Yegua-Jackson	-	1	332	-	-
Other	12	9	3,717	-	-
Total Minor Aquifers	22	48	86,816	3	3,312

Based on the aquifer GIS analyses coupled with the USGS county water use population data for 2015, an estimated total of 77,921 people, representing about 0.26% of the estimated 2020 Texas total population (29.9 million) are served by non-PWS water systems with fluoride concentrations above the 4 mg/L MCL threshold (Table 8). As with the PWS systems, these are predominantly major aquifer non-PWS systems (73%, 57,269 people), with generally smaller populations associated with minor aquifer systems (27%, 20,652 people). Thus, the Texas population served by either PWS or non-PWS systems with fluoride concentrations above the MCL is estimated at about 286,200 people, representing about ~1% of the 2020 Texas total population.

A total of 293 PWS had fluoride levels greater than the SMCL of 2 mg/L, more than six times greater than the 44 PWS systems exceeding 4 mg/L. Most (83%) of the SMCL PWS violations (244) are sourced from major aquifers. The population served by these SMCL noncompliant PWS systems is ~ 1 million people, ~ 3.6% of the estimated 2020 population. A total of 309,000 people outside of the PWS system have water sources that exceed the SMCL of 2 mg/L, 72% sourced from major aquifers. Based on the TCEQ database and the rural supply analysis, a total of 1,384,271 people (about 4.6% of the estimated 2020 Texas total population) have water with fluoride concentrations above the secondary MCL of 2 mg/L (this includes the MCL violations). Again, most (88%) represent water sourced from one of the major aquifers while the remaining 12% are sourced from minor aquifers.

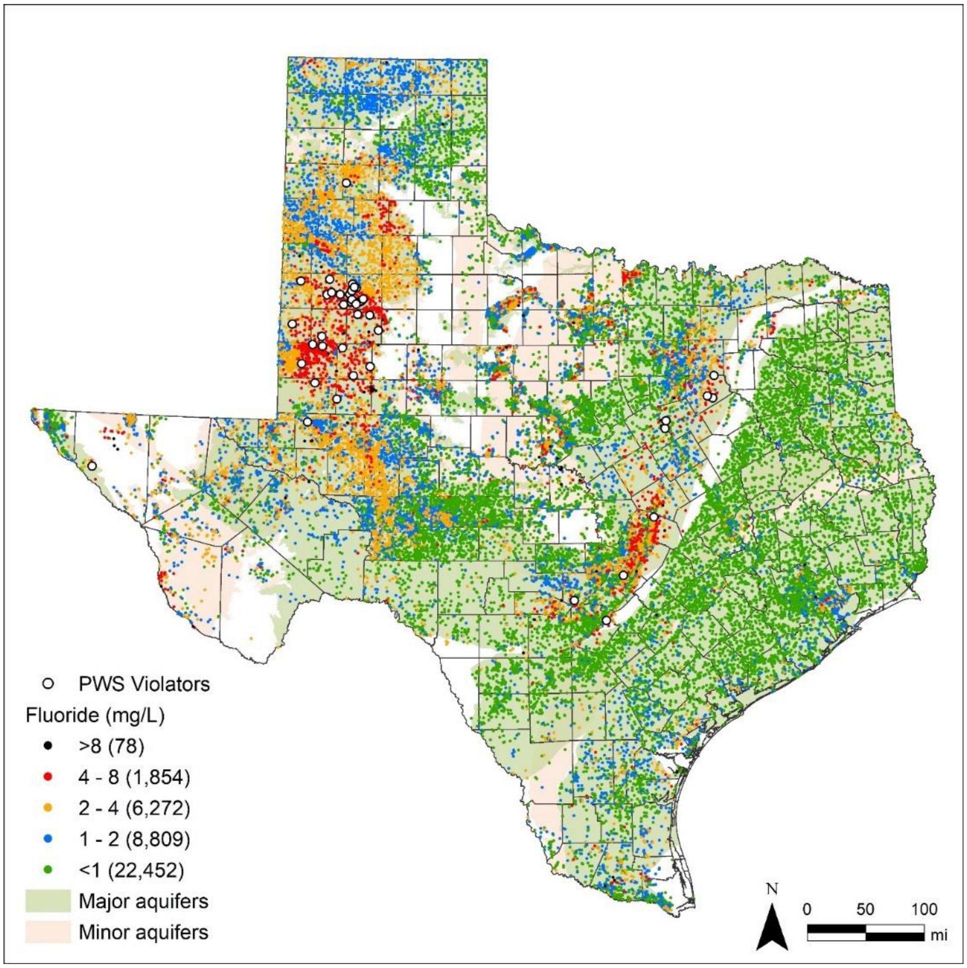


Figure 8. Locations of 44 community water supply systems that have health-related non-compliance violations for fluoride concentration in distributed water based on the EPA database (14 quarters, Jan 2017 – Jun 2020). The violating systems are located primarily in the southern Ogallala, Trinity, Edwards BFZ, and Woodbine aquifers.

Table 8. Texas populations served by PWS (community water systems) and non-PWS systems with fluoride (F) concentrations >2 mg/L and >4 mg/L MCL. The percent of the estimated 2020 population is also provided (29,900,000 people).

Water Source	*PWS population*		*Non-PWS population*		*PWS & Non-PWS population*	
	F >2 mgl/L	*F >4 mg/L*	*F >2 mgl/L*	*F >4 mg/L*	*F >2 mgl/L*	*F >4 mg/L*
All Major Aquifers	986,071	202,563	223,904	57,269	1,209,975	259,832
All Minor Aquifers	86,816	3,312	85,063	20,652	171,879	23,964
Total	1,072,887	205,875	308,967	77,921	1,381,854	283,796
% of 2020 population	3.6	0.69	1.0	0.26	4.6	0.95

Major Aquifer Results

There were sufficient data to perform indicator kriging on fluoride concentrations for all nine of the major aquifers in Texas. There were 31,548 samples in the major aquifers, representing 80% of all TWDB samples included in this study (Table 4). Of the major aquifer samples, 98% (30,969) had detectable concentrations while only 2% (579) had non-detectable concentrations (<1 mg/L or lower). A total of 20% (6,360) of the major aquifer samples exceeded the threshold fluoride concentration of 2 mg/L and 4.9% (1,535) samples exceeded the MCL of 4 mg/L. All of the major aquifers had at least five samples with fluoride >4 mg/L. Median detected fluoride concentrations ranged from 0.3 mg/L in the Carrizo-Wilcox and Edwards BFZ aquifers to 2.11 mg/L in the Ogallala aquifer (Table 9). Median detected concentrations were ≤2 mg/L in all but the Ogallala aquifer.

Table 9. Distributions of fluoride concentrations above detection limits for the major aquifer samples in Texas. Values are based on the latest samples from the TWDB groundwater database and samples from wells completed in multiple aquifers were excluded.

Major Aquifer	*Samples*	*Mean (mg/L)*	*Percentile (mg/L)*								
			Min	*0.05*	*0.1*	*0.25*	*0.50*	*0.75*	*0.90*	*0.95*	*Max*
Carrizo-Wilcox	3,675	0.41	0.01	0.10	0.10	0.20	0.30	0.50	0.80	1.20	9.60
Edwards BFZ	1,369	0.97	0.02	0.10	0.11	0.19	0.30	1.00	3.20	4.10	11.20
Edwards-Trinity Plateau	4,878	1.26	0.01	0.20	0.30	0.50	1.00	1.90	2.69	3.00	9.63
Gulf Coast	6,174	0.78	0.01	0.10	0.20	0.30	0.50	0.90	1.49	2.00	10.00
Hueco-Mesilla Bolson	567	0.92	0.01	0.38	0.40	0.57	0.70	1.00	1.60	2.18	6.10
Ogallala	6,123	2.52	0.01	0.50	0.80	1.35	2.11	3.47	4.80	5.30	16.00
Pecos Valley	552	1.80	0.08	0.40	0.70	1.02	1.66	2.20	2.80	3.20	38.70
Seymour	2,081	1.25	0.02	0.30	0.40	0.70	1.00	1.60	2.22	2.90	9.80
Trinity	5,550	1.20	0.01	0.18	0.20	0.35	0.76	1.67	2.80	3.80	12.70
Total	30,969										

The TCEQ database lists 7,065 active PWS systems in Texas, including 4,657 community water systems and 1,533 non-community water systems. During the period Jan 2017 – Jun 2017, a total of 363 systems (5.1%) with distribution water derived at least in part from one of the major aquifers had fluoride >2 mg/L. This includes 244 community water systems and 120 non-community water systems with an associated population of about 1 million people (Table 6).

Based on the EPA database, 41 community water systems had non-compliant water samples with fluoride >4 mg/L in major aquifers, with a total associated population of about 200,000 people (Table 6). The most affected populations are located in the Southern High Plains area (Ogallala aquifer, 34 CWS systems with 183,183 people), and in parts of Williamson and Bell counties (Edwards BFZ aquifer, 2 systems with 17,795 people).

Table 10. Estimated non-PWS system populations at risk of groundwater fluoride concentrations >2 mg/L and >4 mg/L US EPA MCL in the Major Aquifers. The populations shown are estimated from the GIS map mean county-by-county probability multiplied by the estimated non-PWS system population.

Aquifer	*Total Non-PWS Population*	*At-risk Population >2 mg/L*	*At-risk Population >2 mg/L % of Total*	*At-risk Population >4 mg/L*	*At-risk Population >4 mg/L % of Total*
Carrizo-Wilcox	332,651	5,585	1.68	217	0.07
Edwards	188,446	4,992	2.65	1,445	0.77
Edwards-Trinity Plateau	152,877	17,456	11.42	586	0.38
Gulf Coast	449,786	9,219	2.05	1,249	0.28
Hueco-Mesilla Bolson	16,413	1,846	11.25	171	1.04
Ogallala	154,377	82,880	53.69	32,837	21.27
Pecos Valley	36,571	4,901	13.40	466	1.27
Seymour	19,727	800	4.05	146	0.74
Trinity	486,408	96,225	19.78	20,152	4.14
Total Major Aquifers	1,837,256	223,904	12.19	57,269	3.12
Percent of 2020 population	6.14	0.75		0.19	

Carrizo-Wilcox Aquifer

The Carrizo-Wilcox aquifer covers 36,800 mi^2 in Texas extending from the international border with Mexico in south central Texas to the Arkansas/Louisiana border in northeast Texas (Figure 1, Figure 9). The aquifer underlies all or parts of 65 counties in Texas. It is composed of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group. The aquifer is up to 3,000 ft in thick locally and the total thickness of sands saturated with fresh water is about 670 ft.

There were 3,985 samples analyzed for fluoride with only 310 samples (7.8%) having non-detectable concentrations. The probability of fluoride exceeding 2 mg/L is zero over most (72%) of the aquifer area with only (18%) of the aquifer area primarily in south and south-central Texas down-dip reaches having a generally low to moderate probability of fluoride >2 mg/L with the highest probability region in the extreme south end of the aquifer. The median concentration of samples with detectable concentrations is 0.3 mg/L and the 5th-95th percentile range is 0.1–1.2 mg/L. Only four samples exceeded the MCL with a concentration of 4 mg/L.

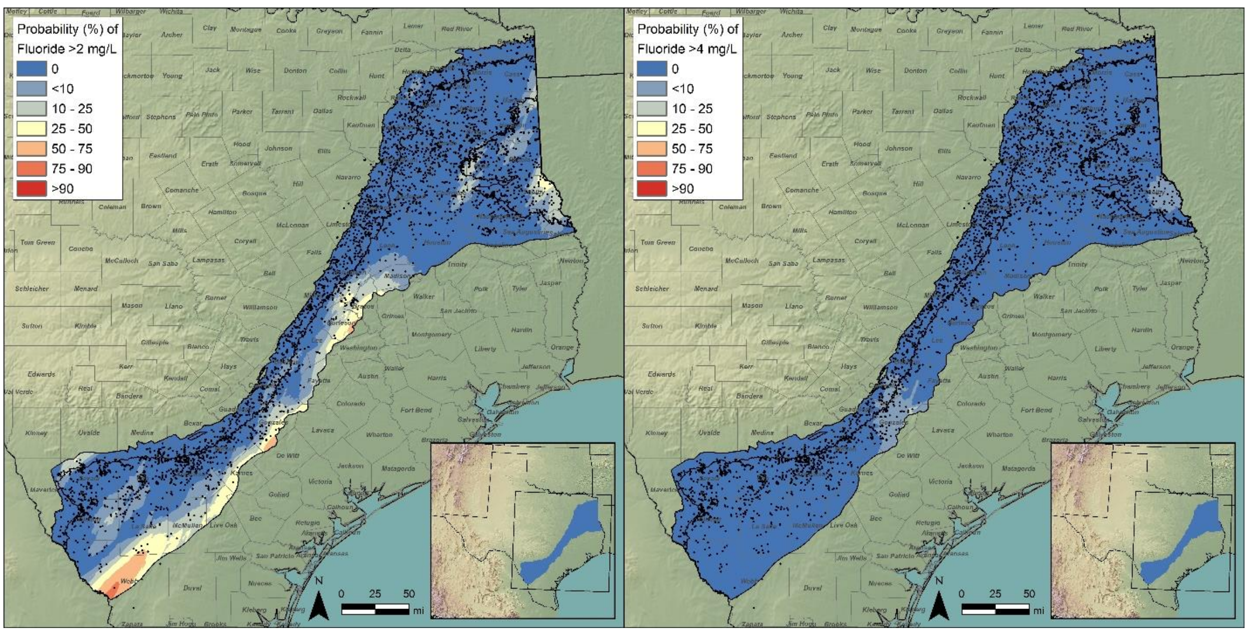


Figure 9. Carrizo-Wilcox aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 7 PWS systems had fluoride concentrations >2 mg/L, all of which are community water systems, with a population of 11,876 people. Based on the EPA PWS database, there were no community water systems that were non-compliant for fluoride. The non-PWS system at-risk population of > 4 mg/L fluoride is very low at 217, located in southern Maverick County along the international border with Mexico and along the extreme down-dip extents.

Edwards (Balcones Fault Zone) Aquifer

The Edwards BFZ aquifer covers 4,300 mi^2 in Texas skirting the eastern and southern boundaries of the Llano Uplift in south central Texas (Figure 1, Figure 10). The aquifer underlies parts of 13 counties in Texas. It composed of the Edwards Limestone and is highly permeable due to dissolution of the unit.

There were 1,418 samples analyzed for fluoride during the study period with only 49 samples (3.5%) having non-detectable concentrations. Most (82%) of the aquifer area has no probability of fluoride >2 mg/L with 14% of the area having low to moderate and 2% having elevated probabilities in the down-dip edges in confined regions of the aquifer. The median concentration of samples with detectable concentrations is 0.3 mg/L and the 5th-9th percentile range is 0.1–4.1 µg/L. A total of 70 samples (4.9%) exceeded the MCL with a range of concentrations from 4.1 to 11.2 mg/L, mostly in the far down-dip regions in the north.

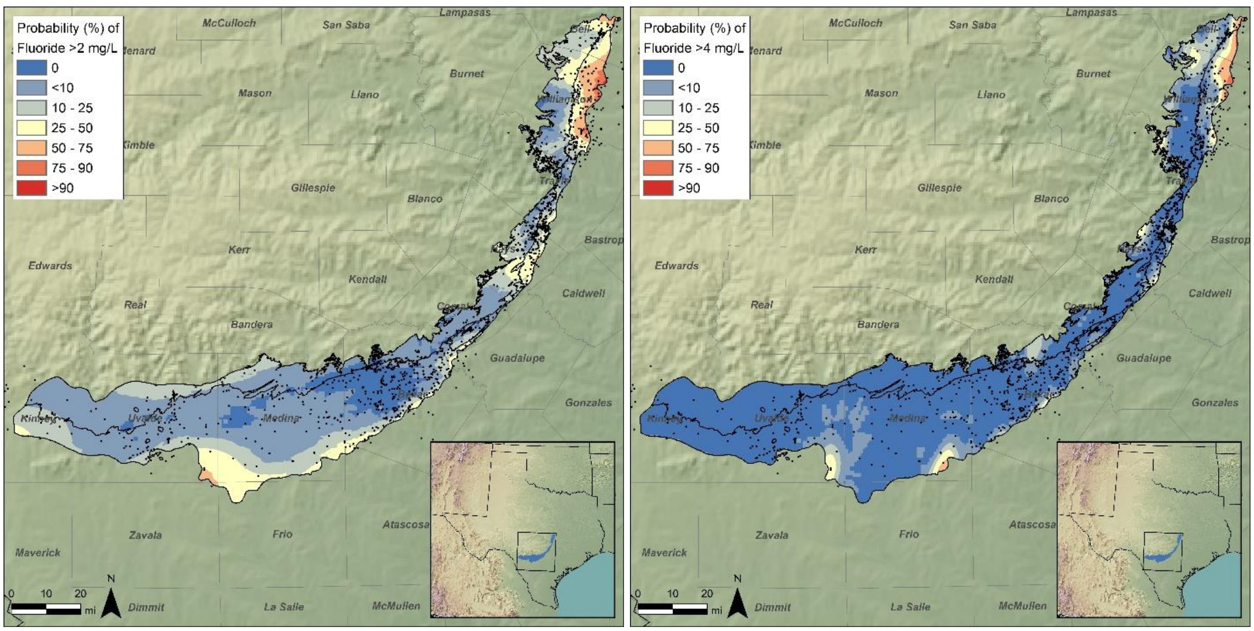


Figure 10. Edwards (BFZ) aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Table 11. Edwards (BFZ) aquifer PWS systems with violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Population Served*
0150115	JBSA – Randolph	Comm	GW	2	3-2017	10,949
2460157	Sonterra MUD	Comm	GW	4	4-2019	6,846

Based on the TCEQ PWS database, a total of 22 PWS systems are impacted by fluoride concentrations >2 mg/L, including 18 community water systems and 4 non-community water systems. The community water systems are associated with an estimated population of 207,024 people. Based on the EPA PWS database, there are 2 community water systems that are non-compliant for fluoride (Table 11). The non-PWS system at-risk population of fluoride >4 mg/L is 1,445 people located primarily in the furthest down-dip areas of the aquifer in Williamson, Bell, and Medina counties.

Edwards-Trinity Plateau Aquifer

The Edwards-Trinity Plateau aquifer covers 35,400 mi^2 in Texas including the southern area of the Llano Uplift in south central Texas west to the Pecos River and south to the international border with Mexico (Figure 1, Figure 11). The aquifer underlies all or parts of 40 counties in Texas. Most of the aquifer area (32,400 mi, 92%) is unconfined. Two areas underlie other major aquifers including 1,500 mi^2 (4%) beneath the Pecos Valley Alluvium aquifer and 1,140 mi^2 (3%) beneath the Ogallala aquifer. The aquifer is composed of limestones and dolomites of the Edwards Group and sands in the underlying Trinity Group. Saturated thickness averages 430 ft and is locally greater than 800 ft.

There were 4,913 samples analyzed for fluoride with 35 samples (0.7%) having non-detectable concentrations. About 73% of the aquifer area has no to moderate probability of fluoride >2 mg/L. About 22% of the area has elevated to high probability and 5% has high to very high probability, primarily located in a north-south trending band through the middle of the aquifer. The median concentration of samples with detectable concentrations is 1.0 mg/L and the 5^{th}-9^{th} percentile range is 0.2–3.0 mg/L. A total of 27 samples (0.5%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 9.6 mg/L that are located in generally isolated areas.

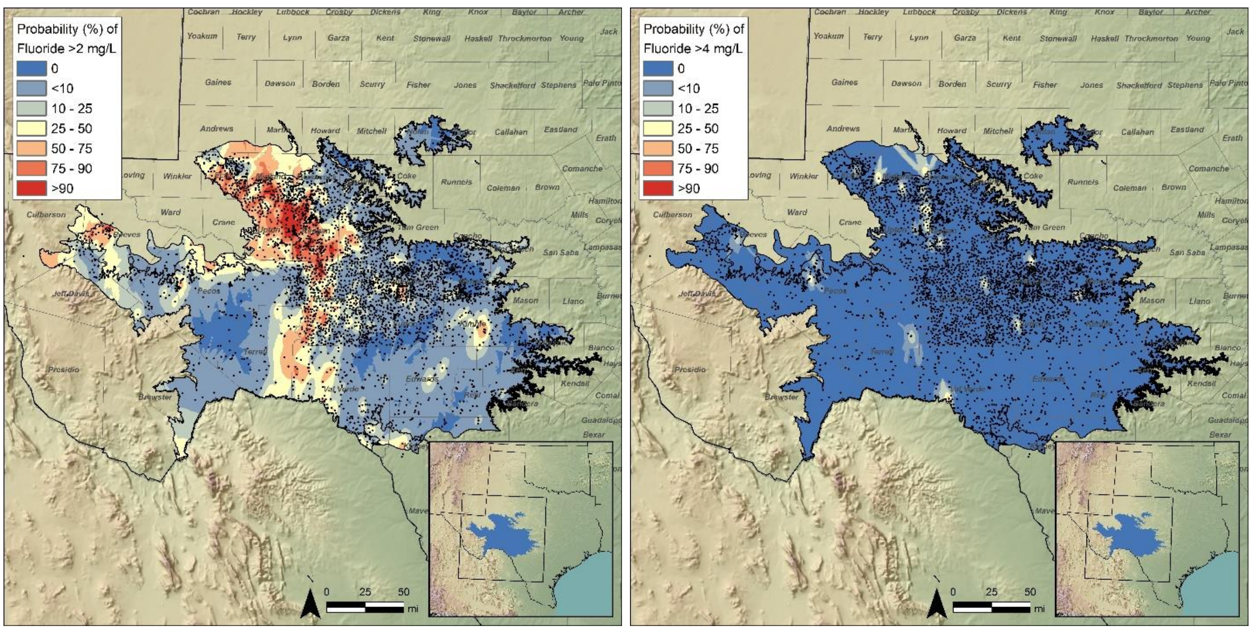


Figure 11. Edwards-Trinity Plateau aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 19 PWS water supply systems are impacted by fluoride concentrations >2 mg/L, including 11 non-community water systems and 8 community water systems with a population of 11,868 people. Based on the EPA PWS database, there no community PWS systems impacted by fluoride concentrations >4 mg/L. The estimated non-PWS system at-risk population of fluoride >4 mg/L is 586 people.

Gulf Coast Aquifer System

The Gulf Coast aquifer is a complex system that covers 40,500 mi^2 in Texas extending in a 100-120 mile-wide arc along the entire Texas Gulf Coast from the international border with Mexico to Louisiana (Figure 1, Figure 12). The aquifer underlies all or parts of 56 counties in Texas. The Gulf Coast aquifer is composed of three primary subunits, including from oldest to youngest the Jasper, Evangeline, and Chicot aquifers which outcrop in the most inland areas toward the coast, respectively. Conditions in the aquifer range from unconfined to semi-confined to confined in different areas and depths. Fresh water saturated thickness averages about 1,000 ft.

There were 6,371 samples analyzed for fluoride during the study period with 197 samples (3.1%) having non-detectable concentrations. Fluoride occurrence in the Gulf Coast aquifer is generally located in the south and near the coast, with isolated inland areas in the north. About 81% of the aquifer area has no to very low probability of fluoride >2 mg/L and a further 18% with low to moderate probability. Only about 1% of the aquifer has probabilities that exceed 50%. The median of samples with detectable concentrations is 0.5 mg/L and the 5^{th}-9^{th} percentile range is 0.1–2.0 mg/L. A total of 30 samples (0.5%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 30 mg/L.

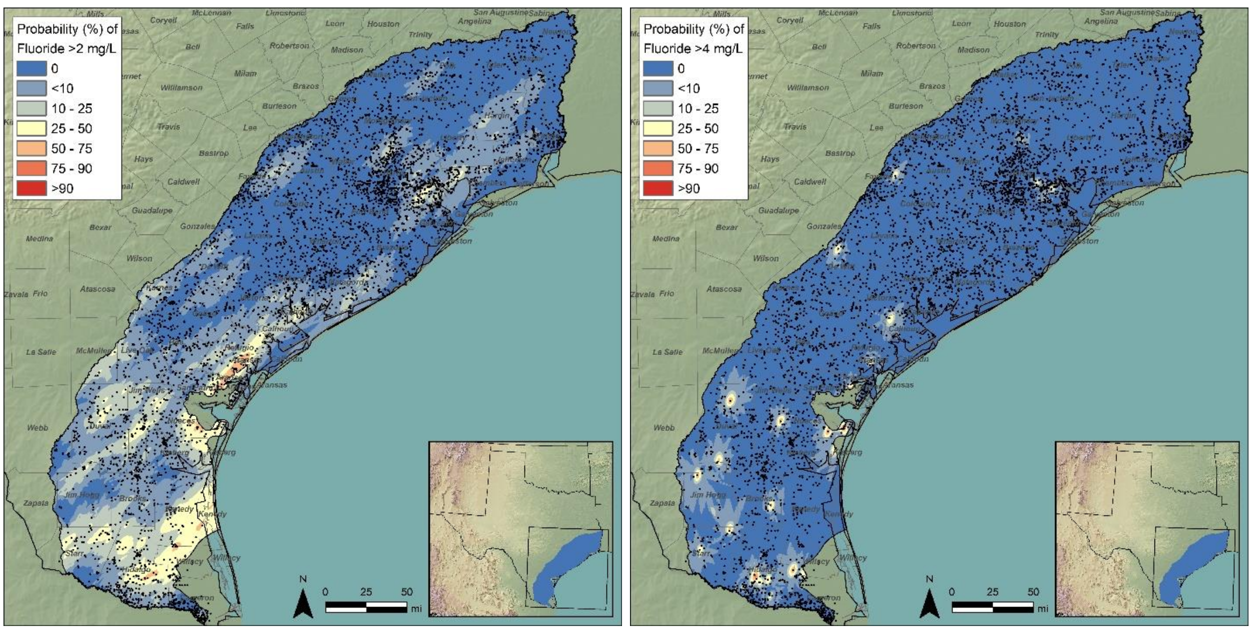


Figure 12. Gulf Coast aquifer system probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 44 PWS systems are impacted by fluoride concentrations >2 mg/L, including 10 non-community water systems and 35 community water systems with a population of 160,693 people. Based on the US EPA database, there are no PWS systems that are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >4 mg/L is 1,249 located primarily in isolated areas of the southern part of the aquifer.

Hueco-Mesilla Bolson Aquifer

The Hueco-Mesilla Bolson aquifer covers 1,400 mi^2 in Texas adjacent to the international border with Mexico in El Paso and Hudspeth counties (Figure 1, Figure 13). The aquifer is composed of basin fill deposits derived from surrounding uplifted areas including the Franklin Mountains in two bolsons, including the Hueco Bolson with a thickness up to 9,000 ft and the Mesilla Bolson with a thickness up to 2,000 ft.

There were 580 samples analyzed for fluoride during the study period with 13 samples (2.2%) having non-detectable concentrations. The Hueco-Mesilla Bolson aquifer is poorly sampled in its southern reaches in Hudspeth County, but available samples indicate that fluoride concentrations tend to increase toward the south. Only about 34% of the area has no to very low probability of fluoride >2 mg/L. About 38% of the total aquifer area has elevated to very high probabilities of fluoride >2 mg/L. The median concentration of samples with detectable concentrations is 0.7 mg/L and the 5th-9th percentile range is 0.38–2.18 µg/L. A total of 6 samples (1%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 6.1 mg/L.

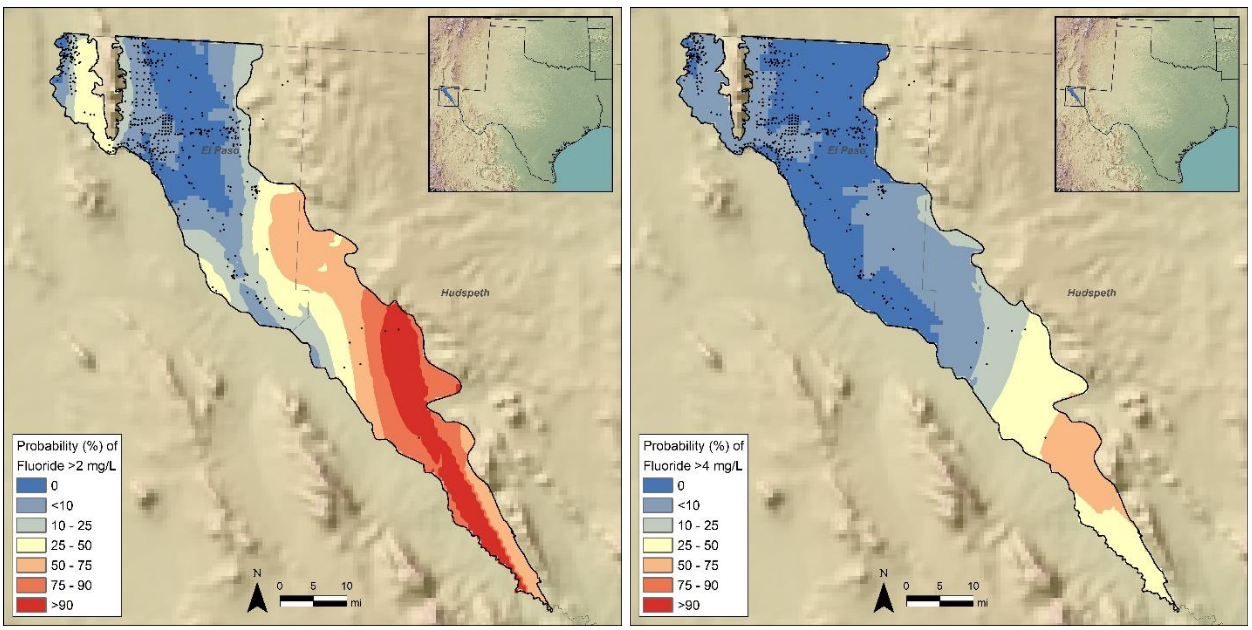


Figure 13. Hueco-Mesilla Bolson aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 2 PWS water supply systems are impacted by fluoride concentrations >2 mg/L, including 1 non-community water system and 1 community water system with a population of 708 people. Based on the EPA PWS database, there is 1 community system impacted by fluoride concentrations >4 mg/L (Table 12). The non-PWS system at-risk population of fluoride >4 mg/L is low at 171 people located primarily in Hudspeth County.

Table 12. Hueco-Mesilla Bolson aquifer PWS systems with violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Population Served*
1150010	Esperanza Water Service	Comm.	GW	13	2-2020	708

Ogallala Aquifer

The Ogallala aquifer covers 36,300 mi^2 in Texas extending across most of the panhandle and southward to Midland. The aquifer underlies all or parts of 49 counties in Texas (Figure 1, Figure 14). The Ogallala in Texas is part of the High Plains Aquifer System, the largest in the United States. It consists primarily of unconsolidated sediments ranging from clay to gravel and has a thickness up to about 800 ft. Thickness varies by region and the thickness is much less (150-300 ft) in the southern areas. The Ogallala is in hydraulic contact with the Pecos Valley aquifer to the southwest and also with the underlying Edwards-Trinity (High Plains), Dockum, and Rita Blanca aquifers.

There were 6,163 samples analyzed for fluoride during the study period with 40 samples (0.6%) having non-detectable concentrations. Fluoride occurrence is widespread in the Ogallala aquifer and concentrations are notably higher in the southern areas. About 17% of the area has no to very low probability of fluoride >2 mg/L and a further 31% has low to moderate probability. About 20% of the total aquifer area has elevated to high probabilities and fully 28% of the aquifer area has a very high probability. The median concentration of samples with detectable concentrations is 2.11 mg/L and the 5^{th}-9^{th} percentile range is 0.5–5.3 mg/L. A total of 1,134 samples (18.4%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 16 mg/L.

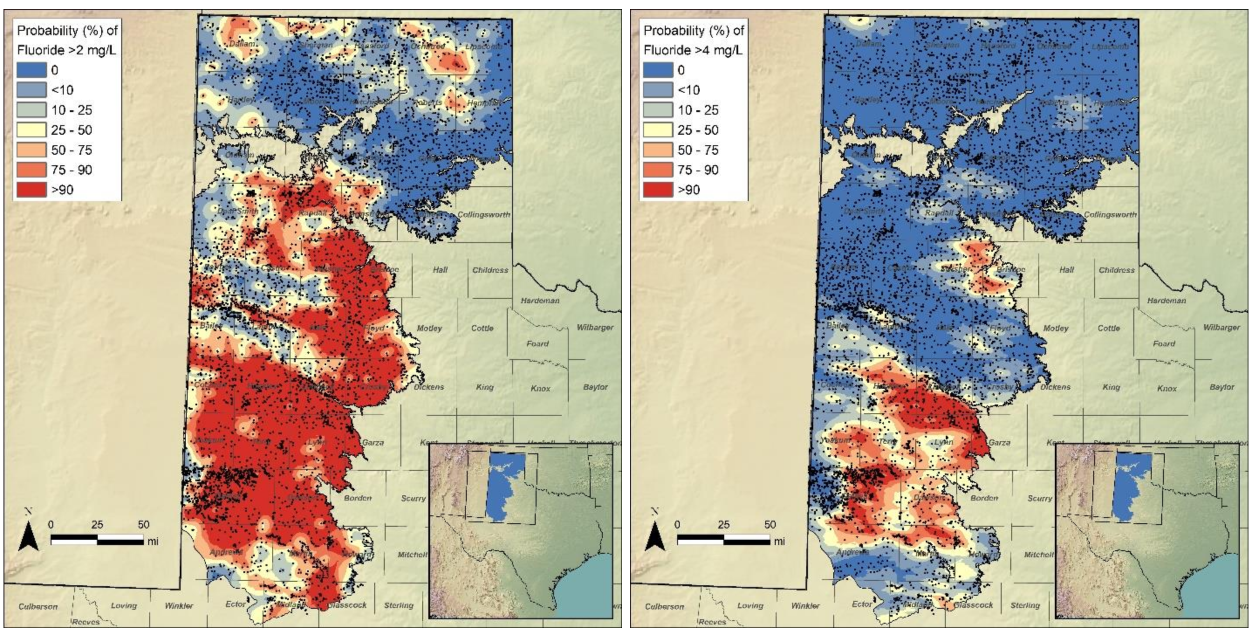


Figure 14. Ogallala aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 132 PWS water supply systems are impacted by fluoride concentrations >2 mg/L, including 38 non-community water systems and 94 community water systems with a population of 292,928 people. Based on the EPA PWS database, there are a total of 34 community systems that are impacted by fluoride concentrations >4 mg/L with a total population of 183,183 people (Table 13). The non-PWS system at-risk population of fluoride >4 mg/L is the highest in the state at 32,837 located primarily in the areas of the aquifer south of Lubbock.

Table 13a. Ogallala aquifer PWS systems with MCL violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Pop. Served*
0020001	City of Andrews	Comm.	GW	3	1-2019	11,088
0170010	Borden County WS	Comm.	GW	13	2-2020	300
0400001	City of Morton	Comm.	GW	5	4-2019	2,025
0580013	Welch WSC	Comm.	GW	1	1-2019	315
0580025	Klondike ISD	Comm.	GW	8	4-2018	264
0680012	City of Goldsmith	Comm.	GWP	1	1-2018	257
0830001	City of Seagraves	Comm.	GW	13	2-2020	2,417
0830011	Loop WSC	Comm.	GW	5	2-2020	300
0830012	City of Seminole	Comm.	GW	2	1-2020	8,917
1100002	City of Levelland	Comm.	SWP	1	4-2019	14,278
1100004	City of Ropesville	Comm.	GW	14	2-2020	428
1100010	City of Smyer	Comm.	GW	14	2-2020	474
1100011	Whitharrel WSC	Comm.	GW	5	3-2018	200
1100030	City of Opdyke West	Comm.	GW	10	4-2019	273
1520005	City of Wolfforth	Comm.	GW	2	3-2017	3,600
1520039	Lubbock MH Community	Comm.	GW	12	4-2019	81
1520062	Plott Acres	Comm.	GW	4	2-2020	204
1520064	Fort Jackson Mobile Estates	Comm.	GW	2	2-2020	72
1520067	114th St Mobile Home Park	Comm.	GW	13	1-2020	125
1520094	Town North Village WS	Comm.	GW	2	2-2020	360
1520106	Cox Addition WS	Comm.	GW	9	2-2020	114
1520149	Stormlight Mobile Home Park	Comm.	GW	0	2-2020	54
1520152	Town North Estates	Comm.	GW	11	2-2020	216
1520188	Seven Estates	Comm.	GW	0	1-2020	261
1520192	Terrells Mobile Home Park	Comm.	GW	14	2-2020	60
1520199	Wolfforth Place	Comm.	GW	14	2-2020	400
1520217	Southwest Garden Water	Comm.	GW	13	2-2020	375
1530003	City of Wilson	Comm.	GW	1	1-2020	489
1530004	City of New Home	Comm.	GW	8	1-2020	345
1530005	Grassland WSC	Comm.	GW	13	2-2020	55
1650001	City of Midland WPP	Comm.	GW	3	4-2017	132,950
1910024	Umbarger Community WS	Comm.	GW	3	4-2019	180
2230003	City of Wellman	Comm.	GW	14	2-2020	225
2510002	City of Plains	Comm.	GW	9	2-2020	1,481

System Type: Community water system (Comm.) or Non-Transient non-community (Non)
Primary Source: Groundwater (GW), Groundwater purchased (GWP), surface water purchased (SWP)
Quarters: number of quarters with violations in the 14-quarter period from Jan 2017 to Jun 2020.

Table 13b. Ogallala aquifer PWS systems with MCL violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*
0830019	Gaines County GC	TNC	GW	1	1-2018
0850002	Southland ISD	NTNC	GW	14	2-2020
1100040	Worley Welding Works	NTNC	GW	4	4-2018
1400013	Plant X Power Plant	NTNC	GW	1	3-2019
1520104	Lubbock KOA Campground	TNC	GW	1	1-2019
1520147	Short Road WS	NTNC	GW	14	2-2020
1520179	Stripes 121	TNC	GW	1	1-2018
1520184	Tech Cafe	TNC	GW	1	1-2019
1520189	Dave’s Roofing, Siding, & Metal	TNC	GW	1	1-2019
1520208	Bernard’s Liquor Store	TNC	GW	1	1-2019
1520212	Shallowater Truck Stop	TNC	GW	1	1-2019
1520244	Fast Stop 15	TNC	GW	1	1-2018
1520250	Scott Manufacturing	NTNC	GW	12	2-2020
1520263	Jaguars Gold Club Lubbock	NTNC	GW	2	2-2020
1520265	Cash Register Services	NTNC	GW	14	2-2020
1520274	Profab	NTNC	GW	6	1-2019
1520279	1585 & Frankford Discount RV Storage	NTNC	GW	14	2-2020
1520299	High Point Village	NTNC	GW	5	3-2018
1520307	Llano Estacado Winery	TNC	GW	1	4-2018
1910157	Canyon Country Club	TNC	GW	1	3-2018
2510023	Wasson CO2 Recovery Plant	NTNC	GW	9	2-2019

System Type: Transient Non-Community water system (TNC) or Non-Transient non-community (NTNC)
Primary Source: Groundwater (GW)
Quarters: number of quarters with violations in the 14-quarter period from Jan 2017 to Jun 2020.

Pecos Valley Aquifer

The Pecos Valley aquifer covers 6,800 mi^2 extending across parts of 12 counties in west Texas (Figure 1, Figure 15). The Pecos Valley consists of alluvial and aeolian deposits that locally reach up to 1,500 thick with an average saturated thickness of about 250 ft.

There were 556 samples analyzed for fluoride during the study period with 4 samples (0.7%) having non-detectable concentrations. Elevated fluoride concentrations are wide spread in the eastern half of the Pecos Valley Aquifer. About 19% of the area has no or very low probability of fluoride >2 mg/L and a further 47% has low to moderate probability. About 32% of the total aquifer area has elevated to high probabilities and 2% very high probabilities. The spatial pattern of probabilities displays artifacts of limited data density in some areas. The median concentration of samples with detectable concentrations is 1.66 mg/L and the 5^{th}-9^{th} percentile range is 0.4–3.2 µg/L. A total of 14 samples (2.5%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 38 mg/L.

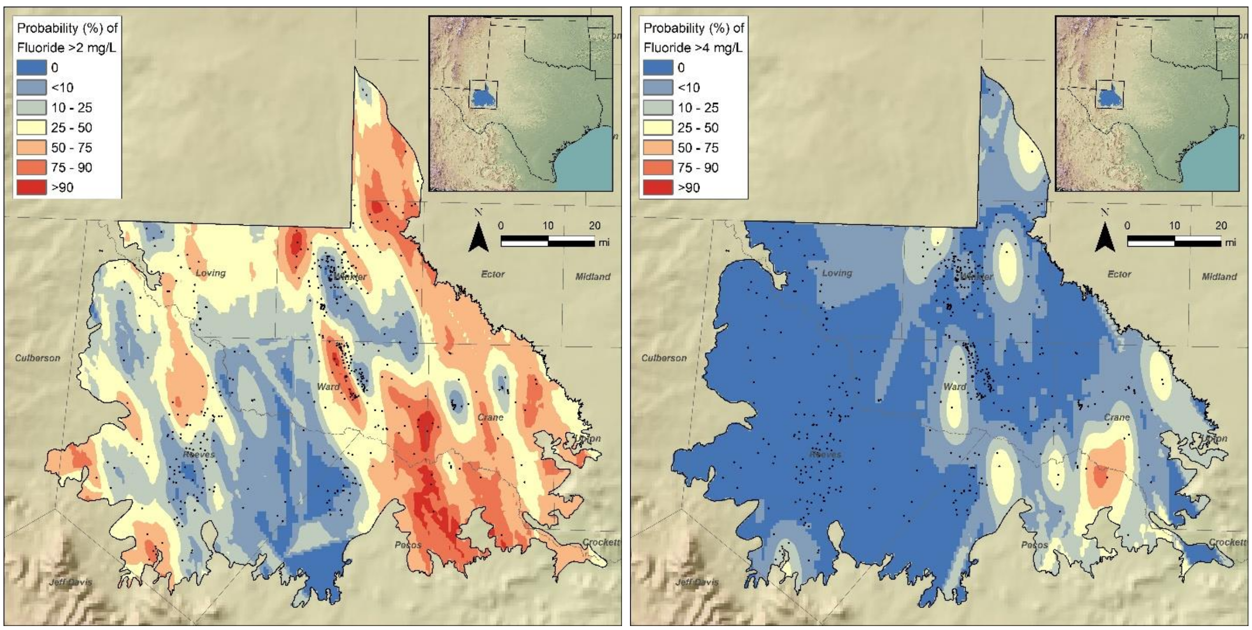


Figure 15. Pecos Valley aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 4 public supply systems are impacted by fluoride concentrations >2 mg/L, including 1 non-community water system and 3 community water systems with a population of 8,906 people. Based on the EPA PWS database, there are no PWS systems impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >4 mg/L is low at 466 located primarily in the eastern half of the aquifer.

Seymour Aquifer

The Seymour aquifer covers 3,400 mi^2 and is present as a series of isolated pods that extending across parts of 23 counties in north central Texas (Figure 1, Figure 16). The aquifer consists of conglomerate, gravel, sands, and silty sands ranging up to 360 ft thick. Most of the aquifer is affected by high nitrate-N concentrations.

There were 2,091 samples analyzed for fluoride with 10 samples (0.5%) having non-detectable concentrations. About 63% of the area has no or very low probability of fluoride >2 mg/L and a further 33% has low to moderate probability of. Only about 4% of the total aquifer area has elevated to high probabilities of fluoride >2 mg/L. The spatial pattern of probabilities displays artifacts of limited data density, particularly in some areas with the higher concentrations in the south in the Fisher-Jones county area. The median concentration of samples with detectable concentrations is 1.0 mg/L and the 5^{th}-9^{th} percentile range is 0.3–2.9 mg/L. A total of 35 samples (1.7%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 9.8 mg/L.

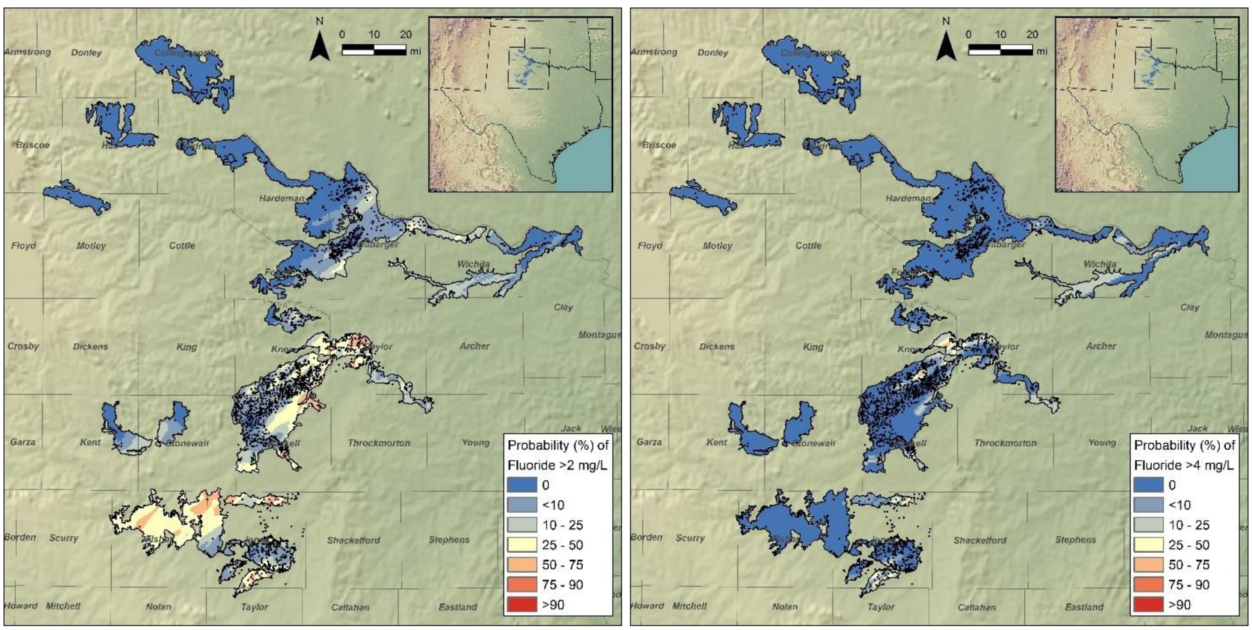


Figure 16. Seymour aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, no public supply distribution systems are impacted by fluoride concentrations >2 mg/L. Based on the EPA PWS database, there are no PWS water supply systems that are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of >4 mg/L is very low at 146 located primarily in the southern aquifer pods. However, samples are sparse in most of the highest probability areas and the results may not be reliable.

Trinity Aquifer

The Trinity aquifer covers 32,100 mi^2 and extends across parts of 60 counties from north central to south central Texas (Figure 1, Figure 17). The aquifer includes several units of the Early Cretaceous Trinity Group, including permeable units in the Antlers, Glen Rose, Paluxy, Twin Mountain/Travis Peak, Hensell, and Hosston formations. Total fresh water thickness ranges from 600 ft in North Texas to about 1,900 ft in Central Texas.

There were 5,624 samples analyzed for fluoride during the study period with 74 samples (1.3%) having non-detectable concentrations. About 35% of the area has no to very low probability of fluoride >2 mg/L and a further 48% has low to moderate probability. Only about 18% of the total aquifer area has elevated to high probabilities and 1% with very high probability. The spatial pattern of probabilities displays artifacts of limited data density in the down-dip confined areas of both the far north and south areas. The median concentration of samples with detectable concentrations is 0.76 mg/L and the 5th-9th percentile range is 0.18–3.8 mg/L. A total of 213 samples (3.8%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 12.7 mg/L.

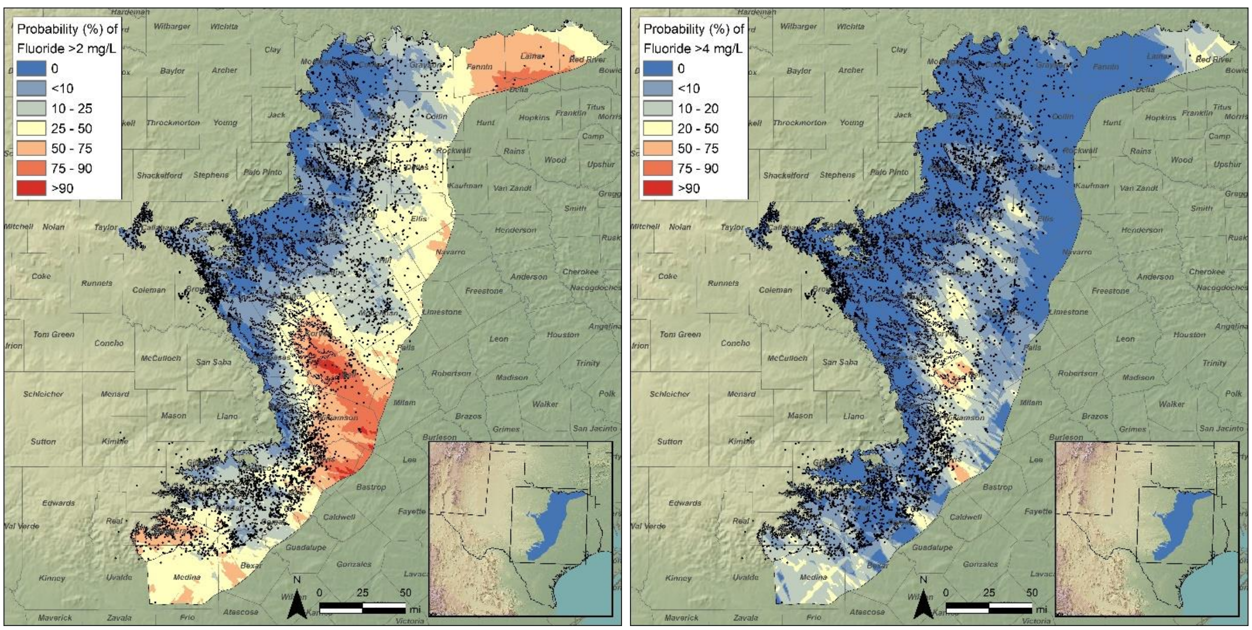


Figure 17. Trinity aquifer probability distribution of fluoride >2 mg/L (left) and >4 µg/L (right).

Based on the TCEQ PWS database, a total of 133 public supply systems are impacted by fluoride concentrations >2 mg/L, including 55 non-community water systems and 78 community water systems with a population of 292,068 people. Based on the EPA PWS database, there are 4 community water supply systems that are impacted by fluoride concentrations >4 mg/L with a population of 877 people (Table 14). The non-PWS system at-risk population of fluoride >4 m/L is the second highest in the state at 20,152 located primarily in Bell, Coryell, and Travis counties.

Table 14. Trinity aquifer PWS systems with violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Pop. Served*
1090045	Beachview Acres Water Assoc.	CWS	GW	13	2-2020	2,417
0180041	Shuler Point	CWS	GW	1	4-2019	56
1050131	La Ventana WSS	CWS	GW	6	1-2020	33
1300008	Foothills MH Ranch	CWS	GW	2	2-2020	606
0100097	Patios del Lago Felipes Restaurant	TNC	GW	1	1-2017	-
0150564	Schott's Taxidermy Meat Market	TNC	GW	1	1-2017	-
0100066	Pomarosa RV Park	TNC	GW	1	2-2017	-
0100048	Oasis for Warriors	TNC	GW	1	4-2018	-
0460267	Cliff View Condominium Commun.	TNC	GW	1	4-2018	-

System Type: Community water system (CWS.) or Transient Non-community (TNC)
Primary Source: Groundwater (GW)
Quarters: number of quarters with violations in the 14-quarter period from Jan 2017 to Jun 2020.

Minor Aquifer Results

Indicator kriging of fluoride concentrations was performed for ten of the minor aquifers in Texas. Maps were not generated for the remaining ten minor aquifers because they had either <50 data points, very low percentages of samples exceeding the threshold values, or very poor spatial coverage (Table 5). Data for the minor aquifers represent 7,918 samples, representing 20% of all samples included in this study. Of all the minor aquifer samples, 96% (7,599) had detectable concentrations while only 4% (319) had non-detectable concentrations (). A total of 16% (1,250) of all the minor aquifer samples exceeded the 2 mg/L threshold and 3.3% (263) of samples exceeded the MCL of 4 mg/L. Seventeen of the minor aquifers had at least one sample with fluoride >4 mg/L, though six of these had only 1 or 2 such samples. Median detected fluoride concentrations ranged from 0.2 mg/L in the Queen City aquifer to 4.1 mg/L in the Edwards-Trinity High Plains aquifer (Table 15).

Table 15. Distributions of detected fluoride concentrations for the minor aquifer samples in Texas. Values are based on the latest samples from the TWDB groundwater database. Samples from wells completed in multiple aquifers are not included.

Minor Aquifer	*Detect Samples*	*Mean (mg/L)*	*Percentile (mg/L)*								
			Min	*0.05*	*0.1*	*0.25*	*0.50*	*0.75*	*0.90*	*0.95*	*Max*
Blaine	190	0.71	0.05	0.21	0.30	0.46	0.66	0.82	1.20	1.60	2.75
Blossom	63	0.81	0.10	0.10	0.20	0.30	0.60	0.90	2.10	2.60	3.10
Bone Spring - Victorio Peak	155	2.27	0.50	1.12	1.26	1.60	1.90	2.40	3.00	5.28	9.00
Brazos River Alluvium	256	0.37	0.05	0.18	0.20	0.27	0.30	0.40	0.50	0.61	3.00
Capitan Reef Complex	59	1.35	0.10	0.19	0.30	0.78	1.10	1.93	2.51	2.94	4.12
Cross Timbers	2,246	1.18	0.10	0.20	0.30	0.40	0.80	1.50	2.70	3.60	22.00
Dockum	824	1.77	0.10	0.40	0.59	0.98	1.50	2.30	3.09	3.78	10.00
Edwards-Trinity HP	71	4.05	1.00	1.83	2.00	2.58	4.10	5.10	6.00	6.75	10.00
Ellenburger - San Saba	287	0.80	0.04	0.10	0.10	0.20	0.45	0.78	1.67	2.40	11.10
Hickory	441	0.84	0.05	0.25	0.30	0.43	0.62	1.00	1.50	2.00	9.20
Igneous	198	1.58	0.10	0.37	0.50	0.81	1.40	2.20	2.92	3.31	4.90
Lipan	154	0.86	0.10	0.32	0.40	0.53	0.80	1.02	1.35	1.64	4.20
Marathon	33	1.16	0.40	0.44	0.49	0.80	1.00	1.29	1.93	2.08	4.20
Marble Falls	39	0.71	0.12	0.20	0.20	0.29	0.40	0.89	1.29	2.50	3.90
Nacatoch	193	1.28	0.01	0.17	0.20	0.40	0.78	1.80	3.20	4.28	5.80
Queen City	501	0.34	0.01	0.03	0.05	0.10	0.20	0.40	0.70	1.00	4.96
Rita Blanca	33	2.14	0.79	0.89	0.93	1.19	1.60	2.50	4.36	5.04	6.02
Rustler	42	1.84	0.08	0.40	0.81	1.34	2.00	2.42	2.70	2.80	2.87
Sparta	315	0.51	0.01	0.06	0.10	0.11	0.30	0.60	1.09	1.71	4.30
West Texas Bolson	224	2.04	0.29	0.57	0.71	1.20	1.72	2.25	3.84	5.05	10.00
Woodbine	716	1.58	0.06	0.24	0.30	0.60	1.20	2.20	3.50	4.40	6.10
Yegua-Jackson	559	0.51	0.02	0.10	0.10	0.20	0.40	0.60	1.00	1.40	5.00

Table 16. Estimated non-PWS system at-risk populations with groundwater fluoride concentrations >2 mg/L and >4 mg/L in the Minor Aquifers. The populations shown are estimated from the GIS map mean county-by-county probability multiplied by the estimated non-PWS system population.

Aquifer	*Total Population*	*At-risk Population >2 mg/L*	*At-risk Population >2 mg/L % of Total*	*At-risk Population >4 mg/L*	*At-risk Population >4 mg/L % of Total*
Bone Spring-Victorio Peak	155	12	7.90	2	1.44
Cross Timbers	110,253	4,690	4.25	547	0.50
Dockum*	121,810	40,402	33.17	12,340	10.13
Ellenburger-San Saba	64,279	1,224	1.90	439	0.68
Edwards-Trinity High Plains	65,240	29,237	44.81	7,010	10.75
Hickory	140,540	6,629	4.72	3,552	2.53
Igneous	10,722	316	2.95	13	0.12
Nacatoch	35,547	2,299	6.47	1,078	3.03
West Texas Bolsons	1,580	58	3.66	10	0.64
Woodbine	115,783	40,598	35.06	8,001	6.91
Minor Aquifers**	544,099	85,063	15.63	20,652	3.80
Percent of 2020 population	1.82	0.28		0.07	

* The Dockum mostly underlies the Ogallala in the study area and it is unlikely that domestic wells utilize the aquifer.

** Excludes Dockum values

Bone Spring – Victorio Peak

The Bone Spring - Victorio aquifer covers 710 mi^2 located in northern Hudspeth County (Figure 2, Figure 18). The aquifer consists of limestones of Permian age. Water quality is generally fair to poor with concentrations generally between 1,000 and 10,000 mg/L TDS.

There were 155 samples analyzed for fluoride with no samples having non-detectable fluoride concentrations. There were 62 samples (40%) with fluoride >2 mg/L and there were 12 samples (7.7%) that exceed the MCL. Most of the samples are clustered around the City of Dell Valley.

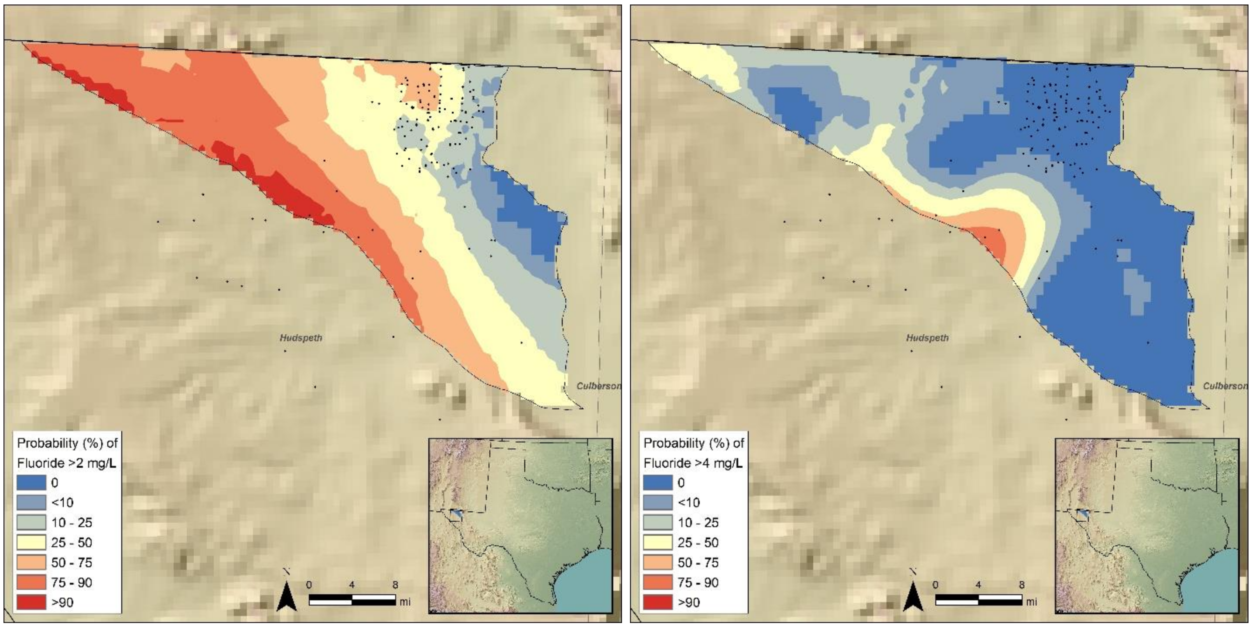


Figure 18. Bone Spring – Victorio Peak aquifer probability distributions of fluoride >2 mg/L (left) and of fluoride >4 mg/L (right).

There are no PWS systems impacted by fluoride concentrations >2 ml/L and therefore no PWS water supply systems are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >2 mg/L very small at 12, representing about 12% of the rural population.

Cross Timbers

The Cross Timbers aquifer covers 17,800 mi^2 located in north-central Texas (Figure 2, Figure 19). The aquifer consists of Paleozoic age limestone, shale, and sandstone units of the Strawn, Canyon, Cisco, and Wichita groups. Water quality is generally fair to poor with concentrations generally between 1,000 and 10,000 mg/L TDS.

There were 2,256 samples analyzed for fluoride with 2,246 samples (99.6%) having detectable concentrations and only 10 samples (0.4%) with non-detectable concentrations. About 48% of the area has no to very low probability of fluoride >2 mg/L and a further 50% has low to moderate probability. Only about 2% of the total aquifer area has elevated to high probabilities of fluoride >2 mg/L. The spatial pattern of probabilities displays artifacts limited data density in some regions while most of the samples form clusters throughout the aquifer. The occurrence of fluoride in the clustered areas might indicate a similar pattern in other areas of the aquifer that are less densely sampled. The median concentration of samples with detectable concentrations is 0.8 mg/L and the 5th-9th percentile range is 0.2–3.6 mg/L. A total of 70 samples (3.1%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 22 mg/L.

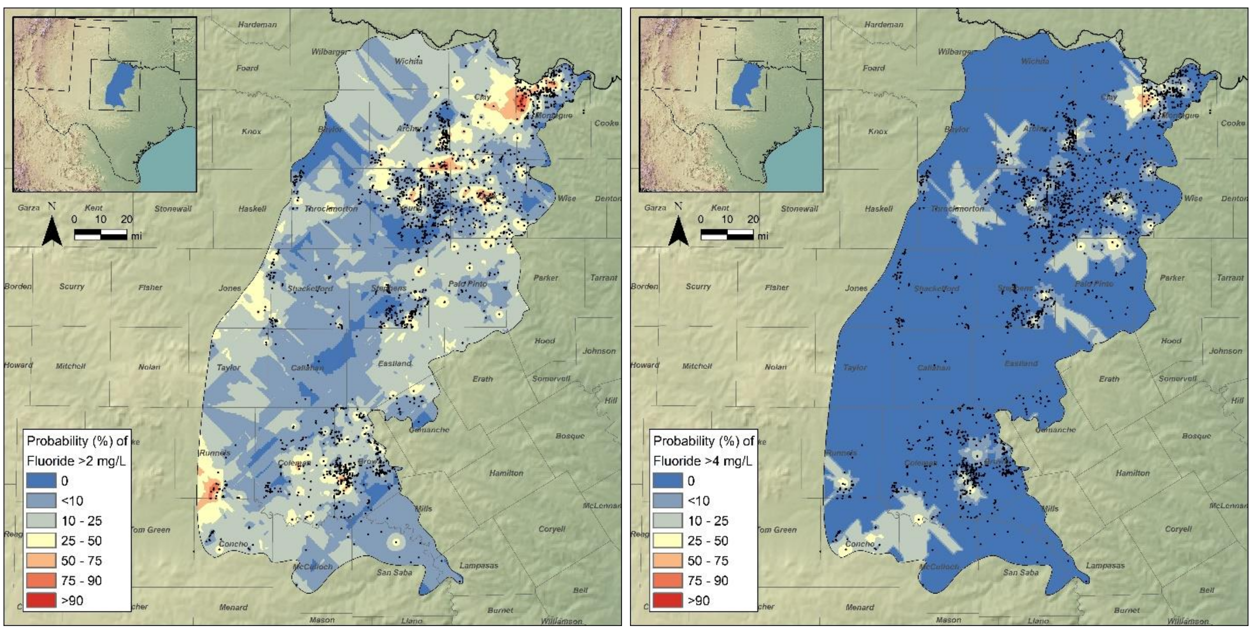


Figure 19. Cross Timbers aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, one public water supply system is impacted by fluoride concentrations >2 mg/L, represented by a non-community water system. There are no PWS systems impacted by fluoride concentrations >4 ml/L. The non-PWS system at-risk population of fluoride >2 mg/L is moderate at 4,690, representing about 4% of the rural population.

Dockum Aquifer

The Dockum aquifer covers 25,300 mi^2 and extends across parts of 46 counties from the Oklahoma border in the northwestern Panhandle to south to the general area of Midland, Texas (Figure 2, Figure 20). The aquifer is Late Triassic age and includes the stratigraphic components of the Dockum Group, including the Santa Rosa, Tecovas, Trujillo, and Copper Canyon formations. Water quality is generally poor with fresh water present primarily in the outcrop areas in the north and southeast. The Dockum underlies the Ogallala, Pecos Valley, Edwards-Trinity Plateau, and Edwards-Trinity High Plains aquifers.

There were 837 samples analyzed for fluoride with 3 samples (1.6%) having non-detectable concentrations. About 18% of the area has no or very low probability of fluoride > 2 mg/L and a further 49% has low to moderate probability. Only about 31% of the total aquifer area has elevated to high probability of fluoride >2 mg/L and 2% has very high probability. The median concentration of samples with detectable concentrations is 1.5 mg/L and the 5th-9th percentile range is 0.4–3.78 µg/L. A total of 35 samples (4.2%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 10 mg/L.

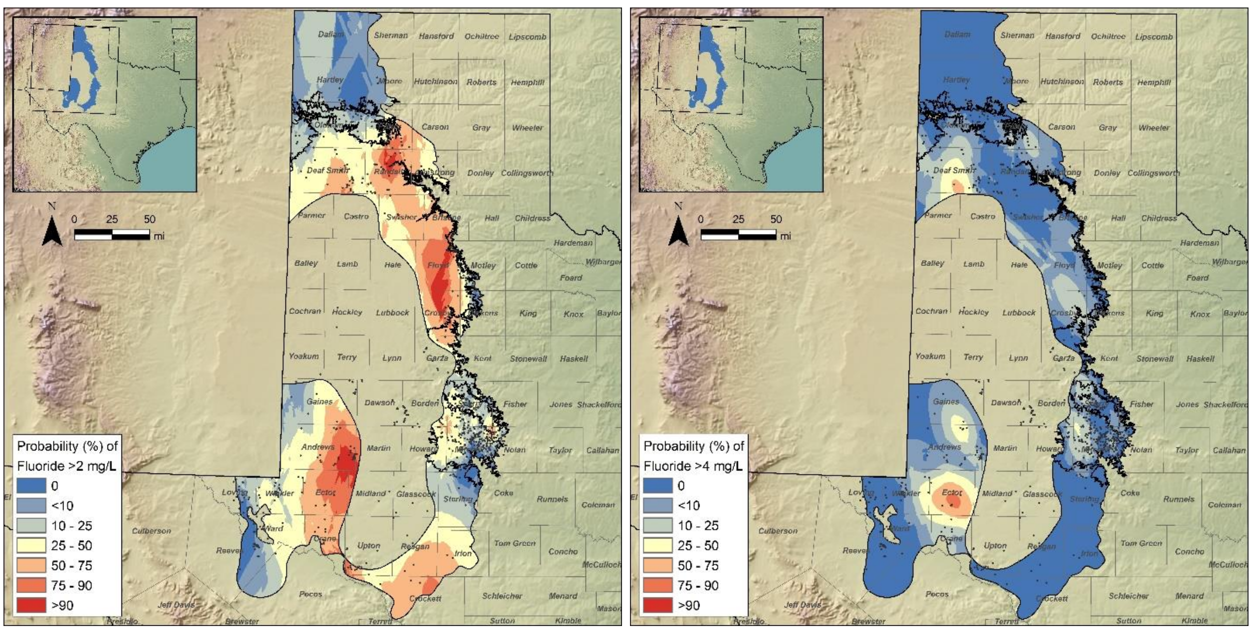


Figure 20. Dockum aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right). While the Dockum is continuous and present in the central "empty" region of the figure, the TWDB limits the extents of the defined aquifer to regions that have water with total dissolved solids (TDS) <3000 mg/L.

Based on the TCEQ PWS database, a total of 12 PWS systems are impacted by fluoride concentrations >2 mg/L, including 3 non-community water systems and 9 community water systems with a population of 17,724 people. Based on the EPA PWS database, there are no PWS water supply systems that are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >2 µg/L is high at 40,402 people, representing about 33% of the rural population. However, these areas also lie within the limits of the Ogallala aquifer and the numbers of domestic wells in the Dockum is likely very small. Accordingly, the estimated non-PWS at-risk population is estimated at zero.

Edwards-Trinity High Plains

The Edwards-Trinity aquifer covers 9,000 mi^2 and extends across parts of 13 counties in the Southern High Plains of Texas and lies just beneath the Ogallala aquifer and above the Dockum (Figure 2, Figure 21). The aquifer is composed of a limestones and sandstones of the Comanche Peak, Edwards, and Antlers formations of the Trinity Group and the freshwater saturated thickness averages about 125 ft. Water quality is generally more saline than the overlying Ogallala aquifer, with TDS generally ranging from 1,000 up to 3,000 mg/L.

There were 71 samples analyzed for fluoride, all with detectable concentrations. Only about 9% of the area has no to very low probability of fluoride >2 mg/L and a further 45% has low to moderate probability. About 31% of the total aquifer area has elevated to high probabilities of fluoride >4 mg/L and 14% has very high probability. The kriging results display artifacts limited data in large areas of the aquifer. The median concentration of samples with detectable concentrations in 4.10 m/L and the 5th-9th percentile range is 1.83–6.75 µg/L. There 37 samples (52%) that exceed the 4 mg/L MCL, almost all of them located in a cluster in eastern Gaines County.

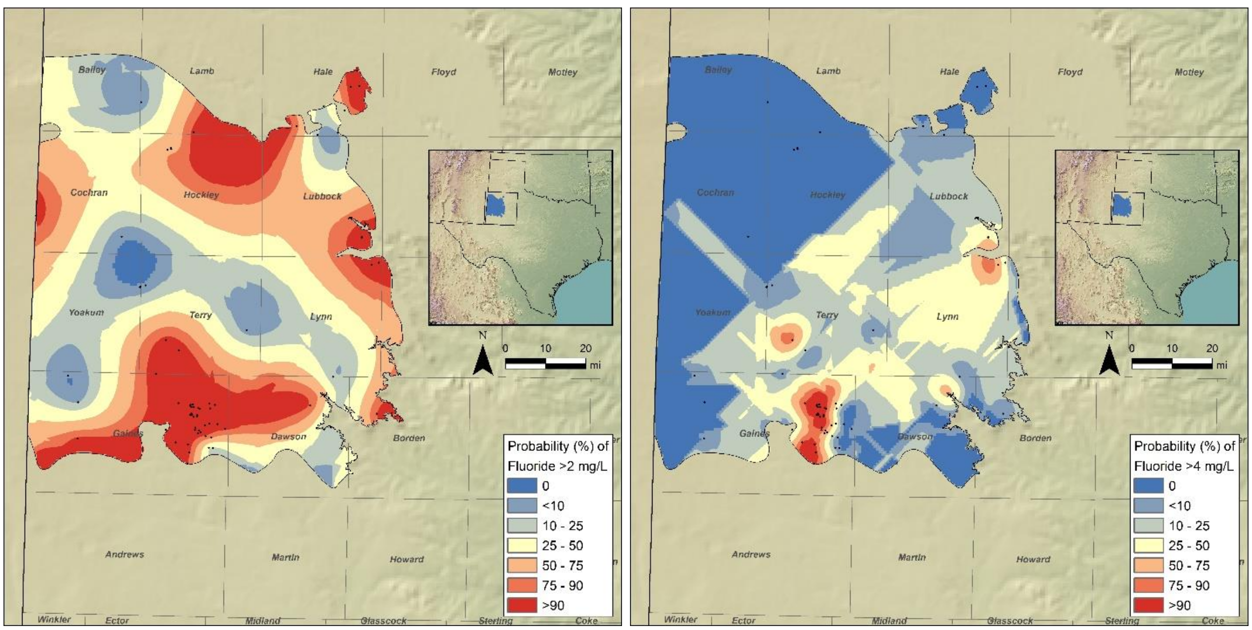


Figure 21. Edwards-Trinity High Plains aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, there are no PWS systems are impacted by fluoride concentrations >2 mg/L, and therefore no PWS water supply systems are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >2 µg/L is high at 29,237 people, representing about 45% of the rural population. This aquifer immediately underlies the Ogallala aquifer and wells are frequently completed in both aquifers, therefore no adjustment has been made as with the Dockum aquifer.

Ellenburger-San Saba Aquifer

The Ellenburger-San Saba aquifer covers 5,400 mi^2 and extends across parts of 16 counties surrounding the Llano Uplift in central Texas (Figure 2, Figure 22). The aquifer is composed of a limestones and dolomites of the Tanyard, Gorman, and Honeycut formations of the Ellenburger Group and the San Saba limestone of the Wilberns Formation and total thickness ranges up to 2,700 ft thick. The confined areas of the aquifer dip away from the uplift to depths of 3,000 ft and are compartmentalized by regional block faulting.

There were 318 samples analyzed for fluoride with 31 samples (9.7%) having non-detectable concentrations. About 70% of the area has no or very low probability of fluoride >2 mg/L and a further 21% has low to moderate probability. Only about 9% of the total aquifer area has elevated to high probabilities of fluoride >2mg/L and 1% with very high probability. The high probability areas are located in the far down-dip northern reaches of the aquifer. The median concentration of samples with detectable concentrations is 0.45 mg/L and the 5th-9th percentile range is 0.1–2.4 µg/L. There were 9 samples (2.8%) with fluoride concentrations greater than the MCL.

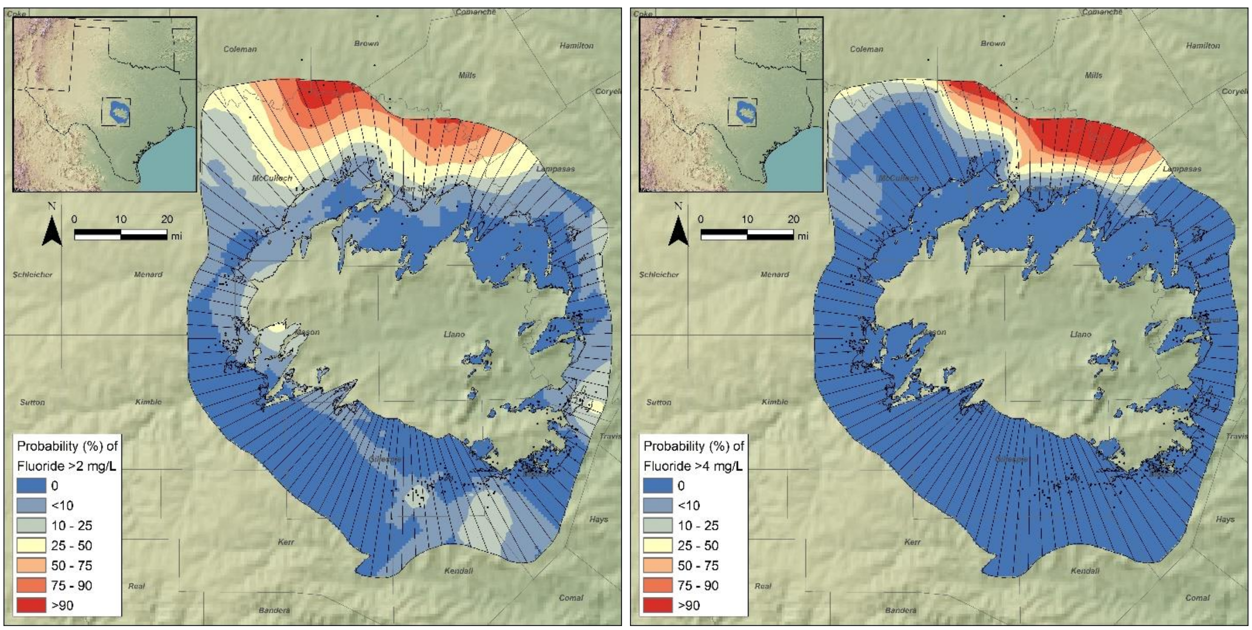


Figure 22. Ellenburger-San Saba aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

There are no PWS systems impacted by fluoride concentrations >2 mg/L and therefore no PWS water supply systems are impacted by fluoride concentrations >4 mg/L. The non-PWS system at-risk population of fluoride >2 mg/L is low at 1,224, representing 1.9% of the rural population.

Hickory Aquifer

The Hickory aquifer covers 8,600 mi^2 and extends across parts of X counties surrounding the Llano Uplift in central Texas (Figure 2, Figure 23). The aquifer is composed of parts of the Hickory Sandstone Member of the Riley Formation with a total thickness ranging up to 480 ft thick. While water quality is generally good in the Hickory aquifer with TDS < 1,000 mg/L, the primary contaminants of concern are radium and associated radon and gross alpha radiation.

There were 459 samples analyzed for fluoride with only 18 samples (3.9%) having non-detectable concentrations. The kriging results display artifacts resulting from limited data in many areas of the aquifer as most of the samples are located in the central outcrop areas. As with the adjacent Ellenburger-San Saba aquifer, the high probability areas are located in the far down-dip northern reaches of the aquifer. About 61% of the Hickory area has no to very low probability of fluoride >2 mg/L and a further 35% has low to moderate probability of fluoride >4 mg/L. About 5% of the area has elevated probability. The median concentration of samples with detectable concentrations is 0.62 mg/L and the 5^{th}-9^{th} percentile range is 0.25–2.0 mg/L. Only 4 samples (0.9%) exceed the 4 mg/L MCL.

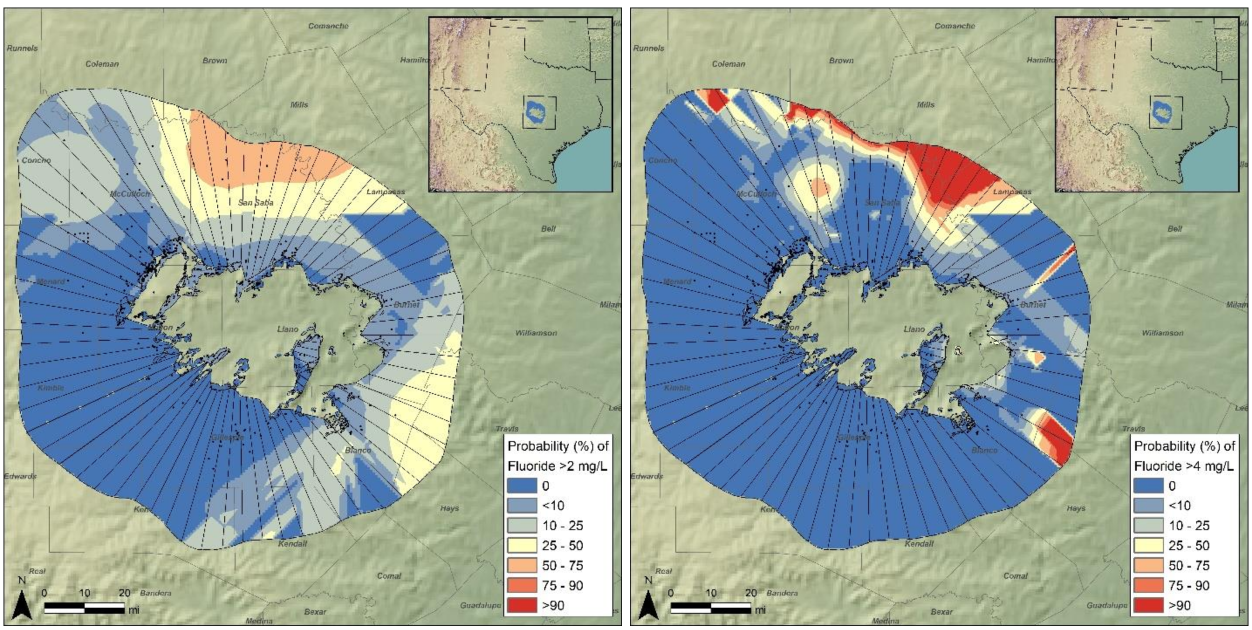


Figure 23. Hickory aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, a single public supply system is impacted by fluoride concentrations >2 mg/L, represented by a PWS community water system serving 3,987 people. There are no PWS systems impacted by fluoride concentrations >4 ml/L. The non-PWS system at-risk population of fluoride >2 mg/L is moderate at 6,629, representing about 5% of the rural population.

Igneous Aquifer

The Igneous aquifer covers 6,100 mi^2 and extends across parts of 6 counties in western Texas primarily in Presidio, Jeff Davis, and Brewster counties with minor areas in Culberson, Reeves, and Pecos counties (Figure 2, Figure 24). The aquifer is composed of a complex series of pyroclastic and volcanoclastic sediments up to 6,000 ft thick. The Igneous underlies parts of the West Texas Bolson aquifer.

There were 198 samples analyzed for fluoride, all having detectable concentrations. About 22 % of the area has no or very low probability of fluoride >2 mg/L and a further 56% has low to moderate probability. About 20% of the total aquifer area has elevated to high probability of fluoride >2 mg/L and 2% has very high probability. The highest concentrations are generally located in the central area of the aquifer. The median concentration of samples with detectable concentrations is 1.4 mg/L and the 5th-9th percentile range is 0.37–3.31 mg/L. Only 3 samples (1.5%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 4.9 mg/L.

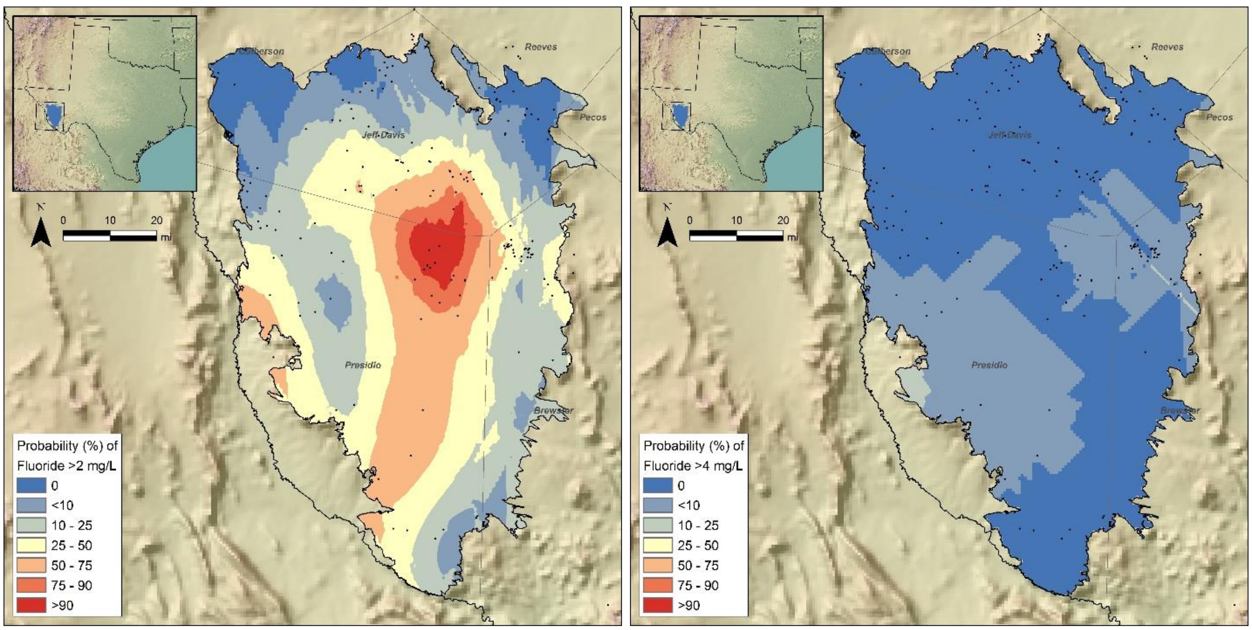


Figure 24. Igneous aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, a total of 9 PWS systems are impacted by fluoride concentrations >2 mg/L, including 4 non-community water systems and 5 community water systems with a total population of 10,282 people. Based on the EPA PWS database, there are no PWS water supply distribution systems impacted by fluoride concentrations >4 mg/L. The estimated non-PWS system at-risk population of fluoride >2 mg/L is small at 316, representing about 3% of the rural population. The estimated non-PWS system at-risk population of fluoride >4 mg/L is very small at 13, representing about 0.1% of the rural population.

Nacatoch Aquifer

The Nacatoch aquifer covers 1,800 mi^2 in a narrow band that extends across parts of 15 counties in northeast Texas (Figure 2, Figure 25). The aquifer is composed of sandstones with an average of about 50 ft of saturated thickness. General water quality ranges from 350 mg/L to 3,000 mg/L TDS. The primary water quality issue of concern in the aquifer is high alkalinity due to high concentrations of sodium bicarbonate.

There were 203 samples analyzed for fluoride with 10 samples (4.9%) having non-detectable concentrations. About 54% of the area has no or very low probability of fluoride >2 mg/L and a further 27% has low to moderate probability. About 15% of the total aquifer area has elevated to high probability of fluoride >2 mg/L and 4% has very high probability. The highest concentrations are generally located in the down dip regions of the central and far north extents of the aquifer. The median concentration of samples with detectable concentrations is 0.78 mg/L and the 5th-9th percentile range is 1.7–4.28 mg/L. There are no samples that exceeded the 10 µg/L MCL.

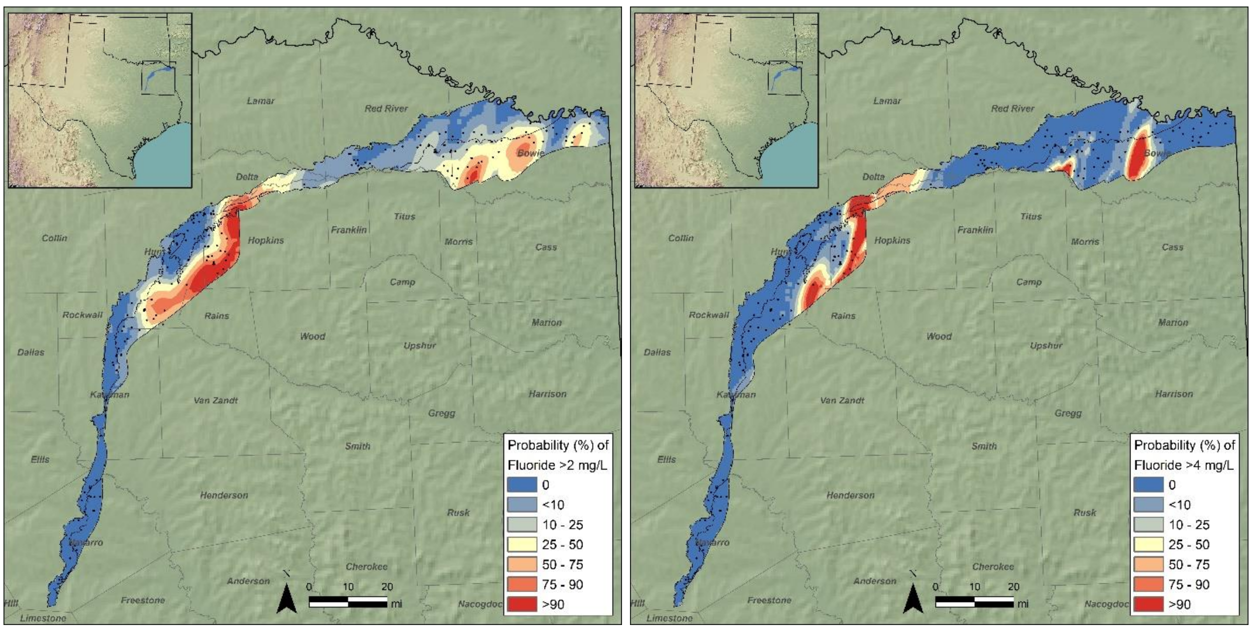


Figure 25. Nacatoch aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, a total of 4 PWS community systems are impacted by fluoride concentrations >2 mg/L with a total population of 3,690 people. Based on the EPA PWS database, there are no PWS water supply distribution systems impacted by fluoride concentrations >4 mg/L. The estimated non-PWS system at-risk population of fluoride >2 mg/L is moderate at 2,299, representing about 6.5% of the rural population. The estimated non-PWS system at-risk population of fluoride >4 mg/L is also moderate at 1,078, representing about 3% of the rural population.

West Texas Bolsons Aquifer

The West Texas Bolsons aquifer covers 1,200 mi^2 and extends across parts of 5 counties in west Texas along the international border with Mexico (Figure 2, Figure 26). The aquifer is composed of a series of basin-fill deposits ranging up to 3,000 ft thick with an average freshwater saturated thickness of 580 ft. Water quality is locally <1,000 mg/L TDS but ranges up to 4,000 mg/L TDS.

There were 224 samples analyzed for fluoride, all having detectable concentrations. Only about 11% of the area has no to very low probability of fluoride >2 mg/L with a further 54% having low to moderate probability. About 28% of the total aquifer area has elevated to high probability of fluoride >2 mg/L and 8% has very high probability. The highest concentrations are located in the southern-most basin adjacent to the Rio Grande River. The median concentration of samples with detectable concentrations is 1.72 mg/L and the 5^{th}-9^{th} percentile range is 0.57–5.05 mg/L. A total of 20 samples (8.9%) exceeded the MCL with a range of concentrations from 4.1 mg/L to 10 mg/L.

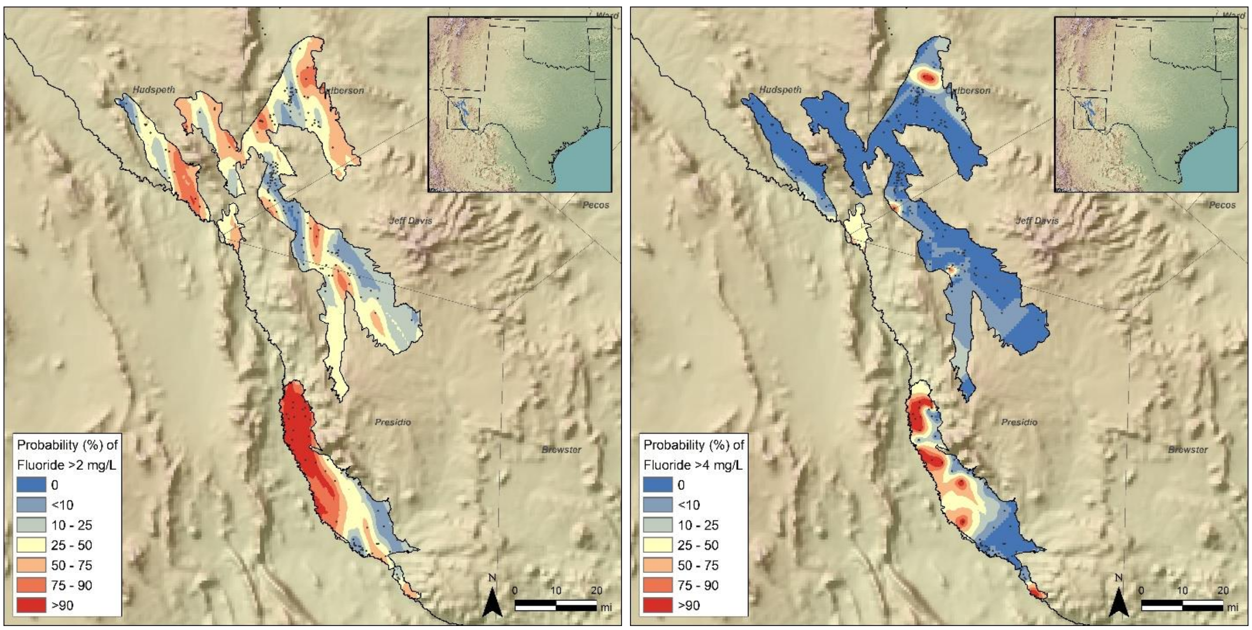


Figure 26. West Texas Bolsons aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, a total of 2 PWS community systems are impacted by fluoride concentrations >2 mg/L with a total population of 2,833 people. Based on the EPA PWS database, there are no PWS water supply distribution systems impacted by fluoride concentrations >4 mg/L. The estimated non-PWS system at-risk population of fluoride >2 mg/L is small at 58, representing about 3.7% of the rural population. The estimated non-PWS system at-risk population of fluoride >4 mg/L is very small at 10, representing about 0.6% of the rural population.

Woodbine Aquifer

The Woodbine aquifer covers 7,300 mi^2 and extends across parts of 17 counties in north central Texas (Figure 2, Figure 27). The aquifer is composed of interbedded sandstones, shales, and clays up to 600 ft thick with an average freshwater saturated thickness of 160 ft. Water quality tends to decrease with increasing depth with <1,000 mg/L TDS shallower than about 1,500 ft ranging up to 4,000 mg/L TDS at greater depths.

There were 723 samples analyzed for fluoride with only 7 samples (1.0%) having non-detectable concentrations. About 39% of the area has no to very low probability of fluoride >2 mg/L with a further 34% having low to moderate probability. About 18% of the total aquifer area has elevated to high probability of fluoride >2 mg/L and 9% has very high probability. The median concentration of samples with detectable concentrations is 1.20 mg/L and the 5th-9th percentile range is 0.24–4.4 mg/L. There are 49 samples (6.8%) that exceed the 4 mg/L MCL.

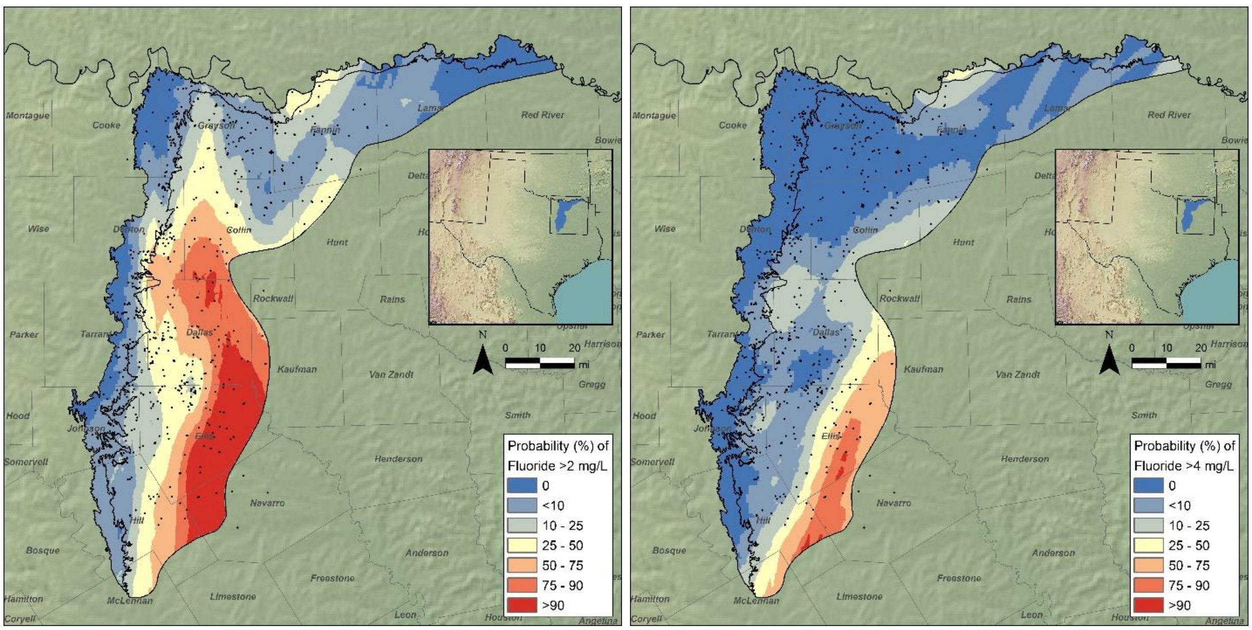


Figure 27. Woodbine aquifer probability distribution of fluoride >2 mg/L (left) and >4 mg/L (right).

Based on the TCEQ PWS database, a total of 16 PWS community systems are impacted by fluoride concentrations >2 mg/L with a total population of 44,226 people. Based on the EPA PWS database, there are 3 PWS community water supply systems impacted by fluoride concentrations >4 mg/L with a total population of 3,312 (Table 17). The estimated non-PWS system at-risk population of fluoride >2 mg/L is very high at 40,598, representing about 35% of the rural population. The estimated non-PWS system at-risk population of fluoride >4 mg/L is moderate at 8,001, representing about 7% of the rural population.

Table 17. Woodbine aquifer PWS systems with violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Pop. Served*
0700020	City of Bardwell	Comm.	GWP	3	3-2017	600
0700002	City of Ferris	Comm.	SWP	4	3-2017	2,622
0700054	Howard Water Coop	Comm.	GW	2	1-2020	90

Other Aquifers

For completeness, there were 3 non-community water systems that were impacted by fluoride concentrations >4 mg/L that use unmapped aquifers as their source.

Table 18. Other aquifer PWS systems with violations for fluoride concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Quarters w/ Violations*	*Latest Violation Qtr-Yr*	*Pop. Served*
0680229	Oasis North RV Park	TNC	GW	1	1-2018	-
1520302	A Plus Super Storage	TNC	GW	1	1-2019	-
1520301	Tega Kids Superplex	NTNC	GW	14	1-2020	-

Summary

Quantifying the spatial distribution of groundwater fluoride concentrations in aquifers in Texas is important for managing groundwater resources in the state. Previous studies show that the fluoride hotspot in the southern High Plains aquifer originates from geologic sources. This study evaluated the probability of groundwater fluoride levels exceeding the primary MCL of 4 mg/L and secondary MCL of 2 mg/L using ~39,500 analyses from 1929 through 2019. Results of the study indicate that 4.6% of samples exceed the primary MCL of 4 mg/L, mostly (3.9%) from major aquifers. The majority (34, 77%) of noncompliant systems are located in the southern High Plains, reflecting the Ogallala Aquifer. The percentage of samples exceeding the secondary MCL of 2 mg/L was much higher, totaling 19% of the samples, divided between major (16%) and minor (3%) aquifers. A total of 44 PWS exceeded the primary MCL, 41 systems sourced by major aquifers. In contrast 293 PWS exceeded the secondary MCL of 2 mg/L, 83% sourced from major aquifers.

Most of the Texas population is served with water from PWS systems, totaling 28.5 million in 2020 (95% of population of 29.9 million) whereas the number of people relying on domestic water supplies totaled 1.4 million in 2020 (5% of population). Almost 1,800 samples from the entire database exceeded the primary MCL of 4 mg/L, accounting for 4.6% of all fluoride analyses. The majority of these exceedances (85%) were sourced from major aquifers, predominantly the Ogallala aquifer (63%). A total of 44 PWS exceeded the primary MCL of 4 mg/L (2017 – mid 2020), 41 sourced by major aquifers. Study results suggest that an estimated 286,200 people may have been exposed to fluoride concentrations exceeding the primary MCL of 4 mg/L, with 73% (~208,300 people) from PWS systems and the remaining 27% (~ 78,000) from non-PWS systems.

The number of samples that exceeded the secondary MCL of 2 mg/L was much higher, totaling 7,610 samples, representing 19% of the total number of samples. This percentage is ~ 4 x higher than that for the primary MCL. The primary aquifer contributing to these exceedances was the Ogallala aquifer. The number of PWS systems that exceeded the secondary MCL totaled 293, ~ 6 x greater than those exceeding the primary MCL (44 PWS systems). The population impacted by the secondary MCL is estimated to be 1.38 million, 4.6% of the estimated 2020 population. The majority of the impacted population is served by PWS systems (78%, ~ 1 million people).

TCEQ is working with PWS systems to bring them into compliance with the fluoride regulations using either nontreatment or treatment options. Domestic supply systems are not regulated and home owners need to assess their vulnerability, particularly in the southern High Plains fluoride hotspot.

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References

Amini, M., K. Mueller, K. C. Abbaspour, T. Rosenberg, M. Afyuni, K. N. Moller, M. Sarr, and C. A. Johnson (2008), Statistical modeling of global geogenic fluoride contamination in groundwaters, *Environmental Science & Technology*, *42*(10), 3662-3668.

Currell, M., I. Cartwright, M. Raveggi, and D. M. Han (2011), Controls on elevated fluoride and arsenic concentrations in groundwater from the Yuncheng Basin, China, *Applied Geochemistry*, *26*(4), 540-552.

Edmunds, W. M., and N. R. G. Walton (1983), The Lincolnshire Limestone - Hydrogeochemical evolution over a 10-year period *Journal of Hydrology*, *61*(1-3), 201-211.

Edmunds, M., and P. L. Smedley (2005), Fluoride in natural waters, in *Essentials of Medical Geology*, edited by O. Selinus, B. Alloway, J. A. Centeno, R. B. Finkelman, R. Fuge, U. Lindh and P. L. Smedley, pp. 310-329, Elsevier, Amsterdam.

Feenstra, L., L. Vasak, and J. Griffion (2007), Fluoride in groundwater: Overview and evaluation of removal mthods, *Intl. Groundwater Resources Assessment Center, Rept. No. SP 2007-1, 21 p.*

McMahon, P. B., C. J. Brown, T. D. Johnson, K. Belitz, and B. D. Lindsey (2020), Fluoride occurrence in United States groundwater, *Science of the Total Environment*, *732*.

NRC (2006), *Fluoride in Drinking Water: A Scientific Review of EPA's Standards*, 508 pp., National Academy Press, Washington, DC.

WHO (2011), Guidelines for Drinking-Water Quality Fourth Edition, a United Nations, World Health Organization publication. [ISBN: 978 92 4 154815 1] 541 pages

Scanlon, B. R., J. P. Nicot, R. C. Reedy, D. Kurtzman, A. Mukherjee, and D. K. Nordstrom (2009), Elevated naturally occurring arsenic in a semiarid oxidizing system, Southern High Plains aquifer, Texas, USA, *Applied Geochemistry*, *24*(11), 2061-2071.

Smedley, P. L., and D. G. Kinniburgh (2002), A review of the source, behaviour and distribution of arsenic in natural waters, *Appl. Geochem.*, *17*(5), 517-568.

U.S. EPA (2020), Regulated drinking water contaminants. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations, Environmental Protection Agency, Accessed date: 15 July 2020.

U.S. Public Health Service (2015), U.S. Public Health Service recommendation for fluoride concentration in drinking water for the prevention of dental caries, *Public Health Rep. 130(4), 318-331*.