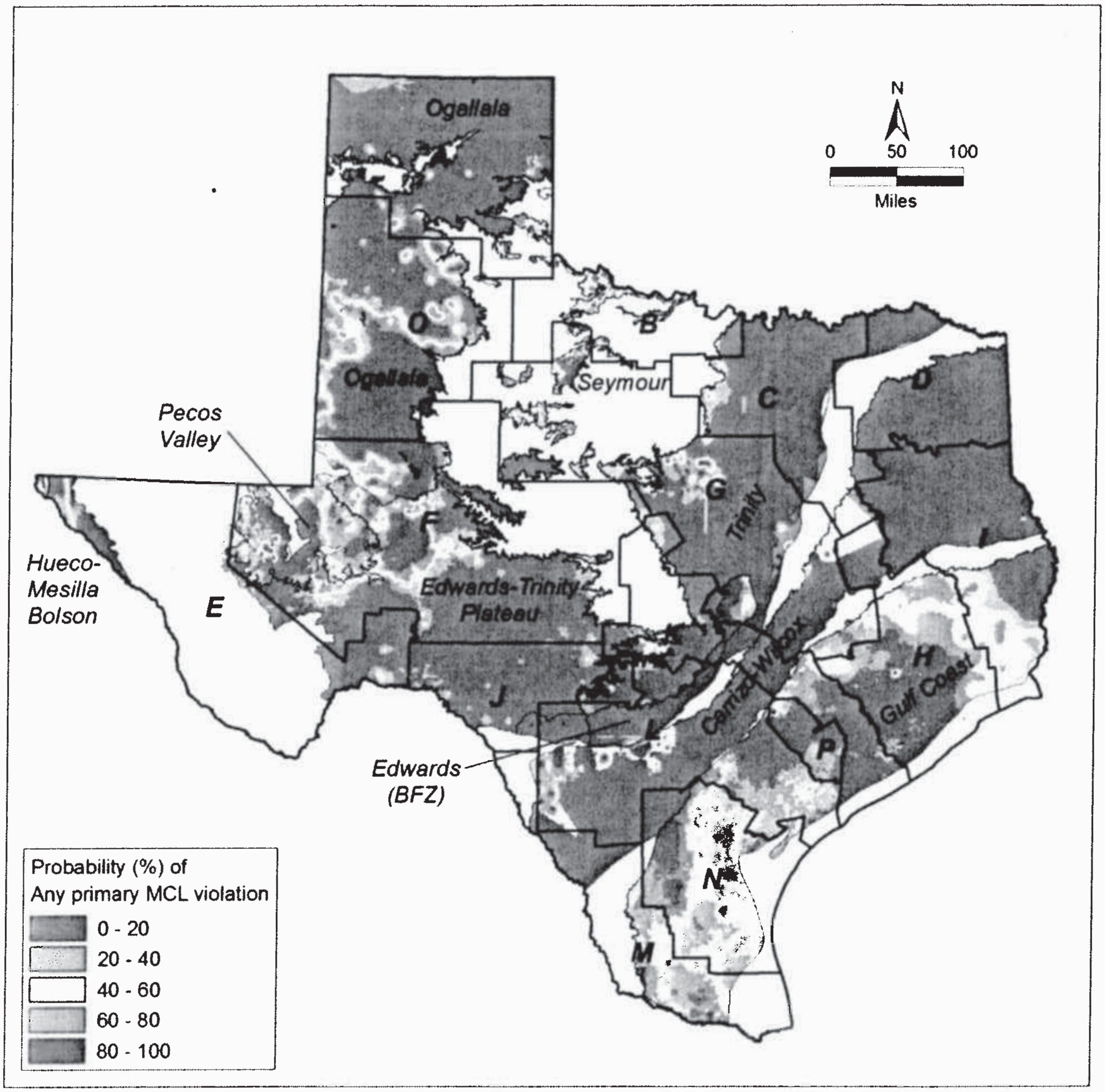
Naturally Occurring Groundwater Contamination in Texas



Final Contract Report prepared for the Texas Water Development Board
by

Robert C. Reedy, Bridget R. Scanlon, Steven Walden, and Gil Strassberg
Bureau of Economic Geology, The University of Texas at Austin

Contract Number 1004831125

1 of 2

1004831125_Final Report

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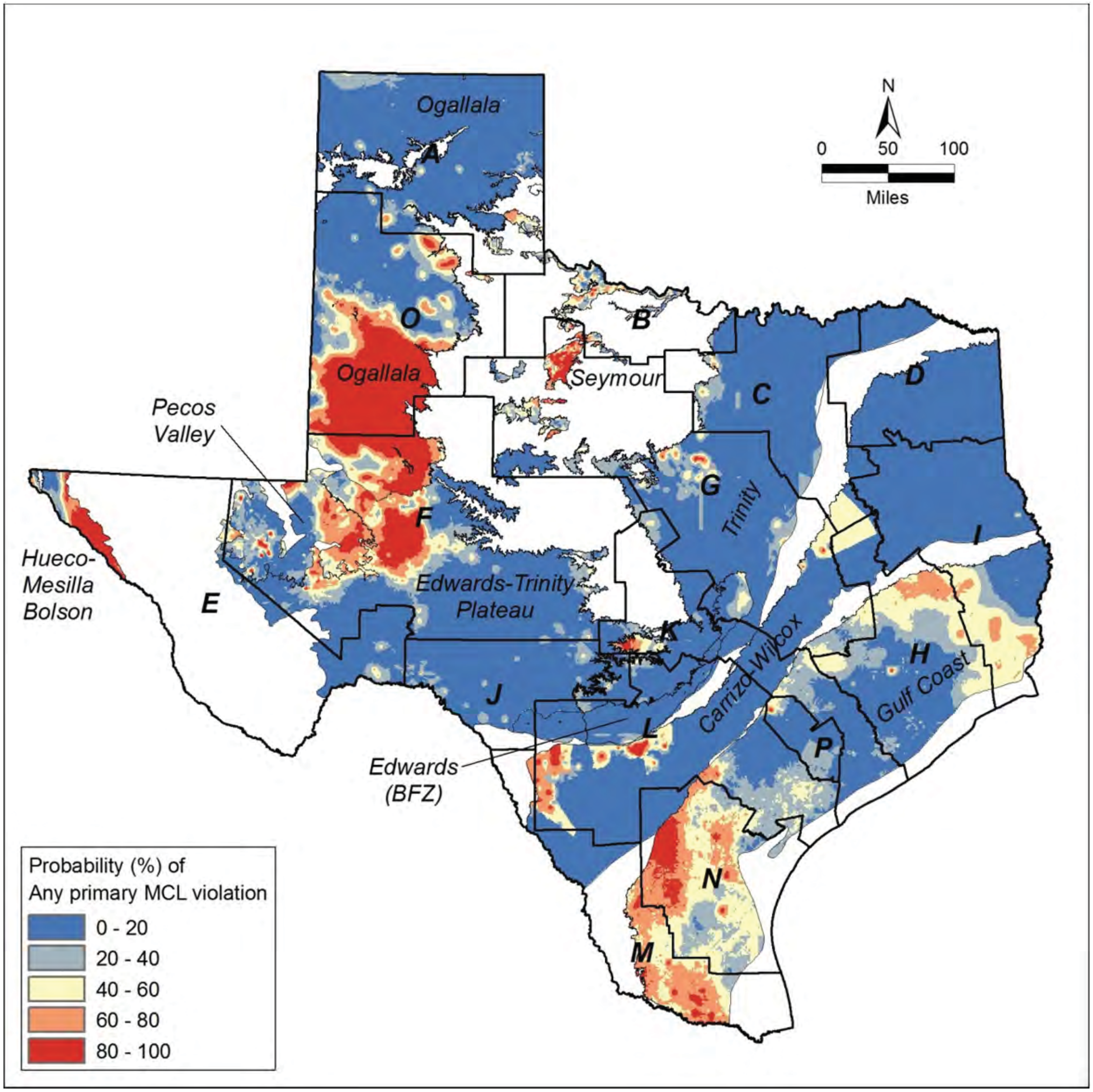

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Executive Summary

Groundwater accounts for ~60 percent of total water used in Texas. Estimates of future groundwater availability strongly depend on groundwater quality because of strong linkages and feedbacks between water quantity and quality. Groundwater quality impacts available fresh groundwater and groundwater quantity affects the ability of aquifers to dilute or assimilate contaminants. Groundwater quality in the state is greatly impacted by naturally occurring contamination derived from meteoric sources (precipitation), soils, and/or geologic sources. These naturally occurring substances contrast with anthropogenic substances that are added to the system through human activities. The objective of this study is to assess all naturally occurring and limiting chemical constituents that affect the quantity of fresh groundwater in Texas.

Impacts of naturally occurring chemical constituents on groundwater availability were evaluated by quantifying exceedances of U.S. Environmental Protection Agency (EPA) primary and secondary maximum contaminant levels (MCL) for drinking water in the state. The analysis was based on the most recent groundwater analysis from the TWDB water quality database using analyses from 1988 – 2010. The percent of wells that exceed each MCL was quantified for each of the nine major and 21 minor aquifers.

The spatial probability distribution of exceeding individual MCL concentrations was determined using indicator kriging for all major and minor aquifers in Texas for which there were sufficient data. Maps representing the probability of exceeding any primary MCL were also developed for aquifers having MCL violations of multiple constituents. The impact of water quality on groundwater quantity was evaluated by categorizing the probability of any primary MCL as having a low (0 – 40 percent), moderate (40 – 60 percent), or high (60 – 100 percent) probability of exceedance. Impacts of water quality on water volumes expressed as percentages of total volumes were estimated from the spatial probability of exceeding any primary MCL linked with aquifer saturated thickness from the Source Water Assessment Program conducted by the Texas Commission on Environmental Quality.

The high risk category of primary MCL exceedance represents 18 percent of the total aquifer area and 14 percent of the total aquifer volume in Texas. Many aquifers are affected by multiple contaminants and the aquifer areas and volumes at high risk of any MCL exceedance are greater than those for individual MCL constituents. Major aquifers with any primary MCL exceedance in the high probability category are greatest for the Hueco-Mesilla Bolson, Seymour, and Ogallala aquifers and lowest for the Edwards (BFZ) Aquifer by both aquifer area and volume. Minor aquifers with primary MCL exceedance in the high probability category are

greatest for the Hickory, Lipan, and Edwards Trinity (High Plains) aquifers and lowest for the Nacatoch, Queen City, and Sparta aquifers by both aquifer area and volume. The most widespread contaminant in the high probability category in major aquifers is arsenic, followed by fluoride, alpha radiation, nitrate-N, and combined radium. The most widespread contaminant in the high probability category in minor aquifers is combined radium, followed by arsenic, fluoride, alpha radiation, and nitrate-N by aquifer area and combined radium, followed by fluoride, arsenic, alpha, and nitrate-N by aquifer volume. The dominant secondary MCL exceedance for major and minor aquifers is total dissolved solids.

Percent of arsenic MCL exceedances increased markedly with reduction of the MCL from 50 to 10 micrograms/Liter. Arsenic contamination is highest in the Ogallala, Gulf Coast, and Edwards-Trinity (High Plains), Hueco-Mesilla Bolson, Igneous, and West Texas Bolson aquifers and is geologic in origin from volcanic ashes and from igneous rocks.

Nitrate contamination is also widespread but is highest in the Seymour and Lipan aquifers with 67 and 61 percent nitrate-N MCL exceedances, respectively. Nitrate contamination also occurs in many other major aquifers (Pecos Valley, Ogallala, Edwards-Trinity (Plateau) aquifers) and minor aquifers with up to 15 percent MCL exceedances in wells. Previous studies indicate that much of the nitrate-N in the High Plains and Seymour aquifers is derived from oxidation of soil organic nitrogen that was mobilized at the beginning of cultivation.

Radionuclide MCL exceedances are widespread in major aquifers, including Ogallala, Edwards-Trinity (Plateau), Gulf Coast, Pecos Valley, and Seymour aquifers. Gross alpha is found in all these aquifers; however, analyses for combined radium and uranium are generally more limited in many aquifers. Radionuclide exceedances are also widespread in the Dockum Aquifer attributed to uranium in the rocks and in the minor aquifers surrounding the Llano Uplift, particularly the Hickory and Ellenburger-San Saba aquifers, attributed to high levels of radionuclides in Precambrian rocks in the uplift.

Fluoride has both a primary (4 milligrams/Liter) and a secondary (2 milligrams/Liter) MCL concentration. Fluoride primary MCL percent exceedances are found mostly in the Ogallala Aquifer and some minor aquifers; however, secondary MCL percent exceedances are much more pervasive, particularly in the Ogallala and Pecos Valley aquifers and many minor aquifers in West Texas. Therefore, if the MCL for fluoride were reduced from 4 to 2 milligrams/Liter, as has been considered by the US Environmental Protection Agency, MCL exceedances (in wells) would increase from 4 to 47 percent in the Ogallala and lesser amounts in other aquifers.

Secondary MCL percent exceedances are dominated by TDS in most major aquifers, particularly the Pecos Valley aquifer, with the exception of the Edwards (BFZ) and Carrizo-Wilcox aquifers. TDS MCL exceedances are also widespread in many minor aquifers.

Because private well owners are not regulated under the Safe Drinking Water Act, we evaluated various point of entry (POE) and point of use (POU) water treatment options for these well users. The advantages and disadvantages of various treatment options are outlined. Reverse osmosis and distillation apply to most of the contaminants. An absorptive iron based media cartridge is suggested as a widely efficient scheme for arsenic removal due to high volume efficiency over a wide pH and smaller sensitivity to competing ions. Areas such as the southern Ogallala aquifer that have multiple contaminants, including arsenic, fluoride, nitrate, and selenium, should be treated with reverse osmosis. Different types of membranes can be selected to optimize treatment. The preferred and most commonly used approach for nitrate treatment is also reverse osmosis. Although a variety of techniques can be used to treat radionuclides, reverse osmosis can be used to treat radium, uranium, alpha and beta emitters. Ion exchange can also be used but may be problematic because of disposal of residual wastes. Oxidation filtration is recommended for treating iron and manganese contamination, which is widespread in the Carrizo-Wilcox aquifer. In most contaminant removal cases, POU systems are sufficient; however, POE systems would be required for iron and manganese and possibly some radionuclides.

This study represents the first time that the effects of naturally occurring contaminants on groundwater quantity have been evaluated. A conservative estimate of water quality impacts in major aquifers was made by focusing on probability of exceeding any primary MCL; however, in many systems, secondary MCL exceedances are also of concern, particularly TDS and iron and manganese. Estimation of relative percent of groundwater volumes impacted was based on total water quantity in the system and the assumption that confined aquifers would become unconfined with depletion. If storage volumes for confined aquifers are restricted to compressive storage, groundwater volumes would be much lower. In addition to assessing water quality impacts on water quantity, results of this study can be used in groundwater remediation studies to show the regional distribution of naturally occurring contaminants that can be considered as the baseline level of chemical constituents in the system. Future studies can use the approach developed in this study to estimate water quality impacts on water quantity in other aquifers, including unconfined and confined systems.

1.0 Introduction

Groundwater is a critical component of water resources in Texas, representing 59 percent of the 15.6 million acre feet (maf) of water used in 2003 (Texas State Water Plan, 2007). Groundwater availability was estimated to be 12.7 maf/yr in 2010 by the regional water planning groups; however, this estimate does not take into account water quality issues. Water quality is becoming a more important factor in water resources as fresh water and brackish water are being considered for planning purposes. Groundwater quality and quantity are strongly linked because quality affects the amount of available fresh water resources, particularly for potable use, and groundwater quantity affects the ability of aquifers to dilute or assimilate contaminants. Therefore, groundwater quality data should play an integral role in water availability estimates for planning purposes. Understanding the distribution of naturally occurring contaminants is also important for private well owners, who constitute the major group of groundwater users and are not protected by the Safe Drinking Water Act (EPA, 1974). There are no federal or state law requirements for analyzing the water chemistry of existing or newly drilled wells; therefore, many well owners may be unaware of contamination problems, particularly those derived from natural sources. Information on naturally occurring contaminants would also be invaluable for remediation programs because distinguishing anthropogenic and natural contaminants is critical for setting remediation targets.

Groundwater quality also impacts surface water quality by discharging to springs and streams. The importance of instream flows is increasingly being recognized as is evident from the National Academy of Sciences committee dedicated to review of the Texas instream flow program. While linkages between groundwater and surface water were not readily recognized until the past few decades (Winter, 1998), it is important to consider groundwater inputs to streams when evaluating surface water contamination. Slade et al. (2002) delineated gaining and losing streams in Texas, and the quality of groundwater in baseflow should be considered in gaining streams. The Total Maximum Daily Load program focuses on surface water quality and calculates the maximum amount of a pollutant that a water body can receive and still safely meet water quality standards. Groundwater is an obvious input to most of these systems and should be considered.

Various uses of groundwater have different water quality requirements. Irrigation is the primary user of groundwater in Texas, accounting for 79 percent of the total water used in 2003, predominantly in the High Plains aquifer (82 percent of groundwater for irrigation; 6.0 million acre-feet per year) (Texas State Water Plan, 2007). The main water quality issues with respect to irrigation are salinity, including total salinity and sodium salinity, expressed through the sodium adsorption ration (SAR). Groundwater is the primary source of water for ~ 7 million people in Texas and represents ~ 36 percent of municipal water supplies. Water quality standards for potable groundwater were established by EPA under the National Primary Drinking Water Regulations (NPDWRs or primary standards) within the Safe Drinking Water Act which was passed in 1974. Primary maximum contaminant levels (MCLs) were established for safety and represent the highest level of a contaminant that is allowed in drinking water. Primary MCLs of various chemical constituents are listed in Table 1. Reduction in arsenic MCL from 50 to 10 micrograms/Liter (µg/L) greatly increased the number of wells that exceeded the MCL (e.g., increase from 2 to 47 percent in the Southern High Plains; Scanlon et al., 2009a).The primary standards are legally enforceable; however, they only apply to public water systems. Drinking water for domestic well users is not protected under this program. Secondary MCLs are not legally enforceable and were established for aesthetic or nuisance purposes, including taste, odor, staining, and scaling problems (Table 1).

Texas has the most comprehensive groundwater quality database in the US. The TWDB water quality database is the primary source of water quality data for groundwater in Texas wells. The purpose of the program is to monitor changes in groundwater quality over time and to develop the baseline natural groundwater quality in major and minor aquifers in the state. Temporal variability in groundwater quality is used to evaluate trends over time. The database includes general information for ~135,000 wells in the state with water quality data for ~55,000 wells. About 30,000 of the 130,000 wells have been inventoried as domestic, and 17,000 of these wells include some type of water quality information. Until 2010, TWDB has annually sampled water from 600 to 700 sites; and cooperators, including groundwater conservation districts, have collected samples from up to 200 more sites. Most of the samples are collected from wells, but, on occasion, springs are also sampled. Through these collection efforts, all aquifers are sampled once every four to five years, while five or six major and minor aquifers are sampled each year. Historical data are available from the early 1900s. The database includes information on basic water quality parameters measured in the field, including temperature, pH, conductivity, and alkalinity. In addition, major and trace elements are measured in the laboratory. In addition, the Texas Commission on Environmental Quality (TCEQ) includes limited information on individual wells for single-source untreated public-supply wells.

The Texas Groundwater Protection Committee (TGPC) was created by the Texas Legislature's House Bill 1458 in 1989 (www.tgpc.state.tx.us). The TGPC includes nine state agencies and improves coordination among agencies involved in groundwater activities. The

TGPC addresses special issues through subcommittees. Examples of various subcommittees include: agricultural chemicals, data management, groundwater research, legislative report, nonpoint source, and public outreach and education. It produces a Joint Groundwater Monitoring and Contamination Report each year. The TGPC also provides recommendations to the legislature and reports on Priority Groundwater Management Areas and Groundwater Conservation Districts.

1.1 Background

Important factors affecting groundwater quantity and quality include climate, land use, physiography, soils, and geology. Mean annual precipitation ranges from 8.2 in/yr in the west to 62 in/yr in the east (PRISM database, 1971 – 2000). Mean annual temperature ranges from 73^{o} F in the south to 55^{o} F in the north. Precipitation and temperature contours are perpendicular to each other. Land use is also an important factor relative to water quality and may impact groundwater through changes in recharge as in the High Plains (Scanlon et al., 2007) and through irrigation (Scanlon et al., 2010b). The distribution of different land covers is described in the National Land Cover Data (Vogelman, 2001). There is a strong linkage between the geology and aquifers in the state. The geology is also important from a water quality perspective because naturally occurring contaminants mainly have a geologic origin. These geologic units will be referred to in discussing the origin of various chemical constituents. The water quality is described for the nine major and 21 minor aquifers in the state (Figure 1 and Figure 2). The unconfined and confined sections for different aquifers are also important.

1.2 Relationship between Surface Water and Groundwater

Groundwater contributes 10 – 90 percent of surface water in various river systems throughout the US (Winter, 1998). Groundwater discharges to surface water through baseflow to streams and rivers; therefore, groundwater quality affects surface water quality through this process. However, during flood conditions, surface water may recharge groundwater and affect groundwater quality. The Texas Commission on Environmental Quality (TCEQ) has adopted the Ground Water Rule (GWR) to improve drinking water quality in the state and to provide additional protection from disease-causing microorganisms, particularly groundwater sources that are susceptible to fecal contamination. The GWR applies to all public water systems that provide groundwater, except public water systems that combine all of their groundwater with surface water prior to treatment.

1.3 Natural Contamination

Natural contamination can occur from leaching of minerals in the soil zone and in aquifers. If the head gradient reverses such that deeper more saline aquifers discharge into shallower aquifers, then such discharge can impact groundwater quality of shallower aquifers.

Soils play an important role in groundwater quality by controlling rate of movement of water and surface derived chemicals to underlying aquifers. Important soil parameters include soil texture, permeability, and organic matter content. Soils can filter contaminants and provide a buffer to reduce groundwater contamination from surface sources. Coarse, permeable soils with low organic matter generally allow contaminants to move through the soil profile more readily. Rate of water movement through the soil zone will determine if chemical constituents are leached or concentrated in the soil profile. Chemicals that bind strongly to soil are not readily mobilized into underlying aquifers. Chemicals can also be degraded in soils. McMahon et al. (2006) showed that pesticides were restricted to the upper 6 ft of soils over the High Plains aquifer. Leaching potentials for chemicals vary and are controlled by water solubility, hydrolysis, adsorption, volatility, and soil degradation. The most mobile contaminants are chloride and nitrate.

Once contaminants reach the water table, they move laterally within the aquifer. The rate of movement depends on aquifer permeability, which can range from on the order of 1 ft/yr in many porous media aquifers to miles/yr in karst aquifers such as the Edwards aquifer.

Other factors that affect naturally occurring contaminants include type of aquifer, including unconfined versus confined aquifer, water table depth, geologic conditions, and climate forcing. In many cases, unconfined aquifers are more vulnerable to contamination than confined aquifers because groundwater is younger and generally circulates more rapidly through the system, whereas older water in confined aquifers may be under reducing conditions that can decrease concentrations of some contaminants. Aquifers with shallow water tables are generally more vulnerable to surface derived contaminants. While high precipitation can leach more chemicals through the system, the water can also dilute chemical concentrations.

1.4 Groundwater Quality Relative to Use

Irrigation is the primary user of groundwater in Texas and accounted for 79 percent of groundwater use in 2003. Water quality requirements for irrigation include salinity, particularly sodium salinity, and specific ion toxicities (Ayers and Westcot, 1994). Total salt concentrations affect crop yield through osmotic effects. Increasing salinity decreases the amount of plant available water and can result in physiological droughts. Sodium concentrations relative to calcium and magnesium concentrations are also very important because they can deflocculate clay particles, decreasing infiltration into soils. The sodium adsorption ratio is used to assess vulnerability to this problem. Specific ion toxicities include boron concentrations. Boron is an essential element but can be toxic at concentrations as low as 1 mg/L and crops such as wheat and barley are particularly vulnerable to boron toxicity.

Livestock is more tolerant of most chemicals than humans; therefore, water quality standards for livestock are not as stringent as those for humans. Livestock can tolerate salinity up to 5,000 – 6,000 mg/L. Excessive nitrate concentrations can be a problem for some livestock because nitrates are converted to nitrite in the rumen of cows and sheep and ntirites are toxic. Excess nitrites react with hemoglobin in the bloodstream, forming methemoglobin, which prevents oxygen being transported. This is similar to methemoglobinemia in infants.

Requirements for drinking water quality for humans are specified in the EPA Maximum Contaminant Levels established through the Safe Drinking Water Act (Table 1). Water is classified with respect to salinity as fresh (< 1,000 mg/L), slightly saline (1,000 – 3,000 mg/L), moderately saline (3,000 – 10,000 mg/L), very saline (10,000 – 35,000), and brine (> 35,000 mg/L).

1.5 Health Impacts

The health effects of different naturally occurring contaminants in groundwater have been examined in various studies. The book *Essentials of Medical Geology* (Selinus, 2005) covers many aspects of health impacts related to groundwater and other media. The health impacts of different elements are complicated by the fact that in many cases a certain level of an element is required whereas higher concentrations may be toxic, a phenomenon recognized by some scientists as early as the sixteenth century as reflected in the aphorism “the dose makes the poison,” attributed to Paracelsus (1493 – 1541). The gap between deficiency and toxicity is sometimes relatively narrow, as in the case of selenium (40 – 400 ug/L) (Fordyce, 2005).

Elevated concentrations of nitrate-N in drinking water have been associated with adverse health effects. Nitrate toxicity primarily results from its reduction to nitrite (Rivett et al.,2006). Nolan et al. (2002) outlines some of the health impacts of nitrate in groundwater. In infants up to one year of age, up to 100 percent of nitrate is converted to nitrite relative to 10 percent in children over one year and in adults. Nitrite causes a chemical reaction resulting in methemoglobinemia. Methemoglobin is the oxidized form of hemoglobin and cannot transport oxygen. Increasing methemoglobin from a normal concentration of 1 – 3 percent to exceed 5 – 10 percent reduces oxygen transport, resulting in “blue baby” syndrome that is potentially fatal

(Rivett et al., 2006). A total of eight spontaneous abortions among four women during 1991-1994 may have been related to elevated nitrate-N concentrations in wells in Indiana (19 – 29 mg/L; Grant et al., 1996). Increased cancer risk from nitrate in groundwater may be related to production of *N*-nitroso compounds in the body, which are highly carcinogenic (Weyer et al., 2001). Elevated nitrate-N concentrations (≥ 2.5 mg/L) in municipal water in Iowa may be related to increased risk of bladder (2.8 times higher) and ovarian (1.8 times higher) cancer, and nitrate-N concentrations > 4 mg/L in community wells in Nebraska increased the risk of non-Hodgkins lymphoma (Ward et al., 1996). Health effects of nitrate in Texas aquifers are described in Dozier et al. (2006).

The health impacts of arsenic vary with the form of arsenic, with inorganic forms being about 100 times more toxic than organic forms and with trivalent arsenite being about 60 times more toxic than hexavalent arsenate (Kain and Ali, 2000). Although the primary exposure pathway for humans is through food, food arsenicals are organic and have negligible toxicity (Abernathy et al., 2003). Arsenic was classified as a Group 1 human carcinogen by the International Agency for Research on Cancer, primarily related to skin cancer (arsenicosis); however, long term exposure to arsenic in groundwater is also linked to lung, bladder, kidney, and liver cancers. In addition, arsenic can also cause various noncancerous diseases such as skin lesions, hyperkeratosis of hand and feet, hypertension, and diabetes (Tseng et al., 2000). Blackfoot disease in Taiwan is related to peripheral vascular problems associated with elevated arsenic concentrations. The primary pathway for arsenic is through drinking water; however, arsenic can be taken up in the food chain (e.g. arsenic is routinely added to chicken feed to make them more robust (Rutherford et al., 2006)). Arsenic is also associated with coal burning in China. Lesikar et al. (2006a) also reviewed health effects of arsenic relative to Texas aquifers.

Chronic health effects from fluoride include dental fluorosis (mottled teeth) at concentrations of 1.5-4 mg/L; dental and skeletal fluorosis at 4-10 mg/L; and crippling fluorosis ≥10mg/L (Edmunds and Smedley, 2005). The health impacts of elevated fluoride are thought to be linked to other dietary deficiencies, particularly calcium and vitamin C. Fluoride deficiency has been related to increased incidence of dental caries. As a result, waters deficient in fluoride were fluoridated since the 1940s in the US (Maier, 1950; McDonagh, 2000). There has been considerable controversy about the benefits of fluoridation of water supply systems. More recently studies suggest that there may be adverse health effects at these levels of fluoride concentrations. While some studies suggest linkages between fluoride and cancer, particularly osteosarcoma, there is no convincing evidence that links fluoride with bone cancer. The EPA primary MCL (4 mg/L) is much higher than the guidance value set by the World Health

Organization (1.5 mg/L). A National Research Council Panel reviewed the EPA MCL values for fluoride and suggested that the levels should be lowered to reduce risk of dental fluorosis in children and bone fracturing and potential skeletal fluorosis in adults (NRC, 2006).

Radionuclides also have large scale impacts on human health because they cause ionization of nearby atoms that can affect chromosomes and cause abnormal cell reproduction (cancer). Uranium in drinking water is a health concern because radioactive decay of uranium can cause cancer and long-term exposure to uranium impacts kidney function (Rivett et al., 2006). The EPA MCL for uranium was set at 30 ug/L in 2003. Radium is also a concern. Exposure to elevated levels has been linked to bone sarcomas and carcinomas of sinuses and mastoids on the basis of data from workers painting watch dials using paint containing radium. The EPA MCL for combined radium-226 (^{226}Ra) and radium-228 (^{228}Ra) is 5 picoCuries/Liter (pCi/L). Radium decays to radon which has been linked to lung cancer. The health effects of groundwater radon are primarily related to its contribution to radon in indoor air rather than directly related to ingestion of water. The primary mode of decay for many radionuclides is emission of alpha particles, particularly uranium (U) and ^{226}Ra. Alpha particles represent the most dangerous type of radiation because although they do not penetrate far, they cause intense ionization due to the large mass and charge of the particles (Rivett et al., 2006). Alpha particles cannot penetrate the skin, butenter the body through the lungs and are associated with increased risk of lung cancer. Beta particles and photon emitters are primarily anthropogenic in origin and associated with nuclear power plants. Beta particles and photon emitters occur primarily in surface water. Lesikar et al. (2006b) reviewed the health effects of radionuclides relative to Texas aquifers.

Additional metals of health concern and their health effects as described in the EPA website are as follows: antimony decreases blood sugar and increases blood cholesterol, barium increases blood pressure, beryllium increases intestinal lesions, cadmium causes kidney damage, chromium causes allergic dermatitis, copper causes liver and kidney damage, cyanide is related to nerve damage and thyroid problems, lead causes delays in physical and mental development in children and kidney problems and high blood pressure in adults, mercury results in kidney damage, and selenium causes hair and fingernail loss and circulatory. Many of these metals are almost entirely anthropogenic in origin, such as chromate, copper, lead, and mercury.

1.6 Purpose and Scope

The objective of this study is to assess all naturally occurring and limiting chemical constituents that affect each of the major (Figure 1) and minor (Figure 2) aquifers and to assess effects on the quantity of fresh groundwater in Texas in terms of a relative percent of volume of aquifer volume. All inorganic and radiogenic chemical constituents that have established primary and secondary MCLs were considered. The emphasis of this report is on natural water quality that is largely determined by aquifer characteristics. The maps produced for this report therefore emphasize individual aquifers at the regional scale or all aquifers at a statewide scale that may help regional water planning groups make better estimates of their available groundwater. The extensive groundwater quality database developed and maintained by the TWDB provides a unique opportunity to evaluate impacts of water quality on groundwater quantity. Probability maps for exceeding any primary or secondary MCL were developed and provide valuable information on the spatial extent of groundwater contamination from primarily natural sources. Treatment options and costs were estimated for private well owners because these are not regulated under the Safe Drinking Water Act.

Table 1. List of primary and secondary MCL concentrations and their effects.

Primary	*MCL*	*Units**	*Health Effects*
Antimony	6	μg/L	Increase in blood cholesterol, decrease in blood sugar
Arsenic	10	μg/L	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer
Barium	2,000	μg/L	Increase in blood pressure
Beryllium	4	μg/L	Intestinal lesions
Cadmium	5	μg/L	Kidney damage
Chromium	100	μg/L	Allergic dermatitis
Copper	1,300	μg/L	Gastrointestinal distress, liver or kidney damage
Fluoride	2	mg/L	Bone disease, mottled teeth
Lead	15	μg/L	Detrimental to child physical/mental development, kidney damage
Mercury	2	μg/L	Kidney damage
Nitrate-N	10	mg/L	Infant methemoglobinemia (“blue-baby” syndrome)
Nitrite-N	1	mg/L	Infant methemoglobinemia (“blue-baby” syndrome)
Selenium	50	μg/L	Hair or fingernail loss, numbness in extremities, circulatory problems
Thallium	2	μg/L	Hair loss, changes in blood, kidney, intestine, or liver problems
Gross Alpha	15	pCi/L	Increased risk of cancer
Gross Beta*	50	pCi/L	Increased risk of cancer
Combined Radium	5	pCi/L	Increased risk of cancer
Uranium	30	μg/L	Increased risk of cancer, kidney toxicity
Secondary	*MCL*	*Units*	*Nuisance Effects*
Aluminum	0.2	mg/L	Colored water
Chloride	300	mg/L	Salty taste
Copper	1,000	μg/L	Metallic taste, blue-green staining
Fluoride	2	mg/L	Tooth discoloration
Iron	300	μg/L	Rusty color, Sediment, metallic taste, reddish or orange staining
Manganese	50	μg/L	Black to brown color, black staining, bitter metallic taste
pH	6.5-8.5	pH	*Low pH:* bitter taste, corrosion; *High pH:* soda taste, deposits
Silver	100	μg/L	Skin discoloration; graying of the white part of the eye
Sulfate	300	mg/L	Salty taste
TDS	1000	mg/L	Hardness, deposits, colored water, staining, salty taste
Zinc	5	mg/L	Metallic taste

∗ μg/L: micrograms/Liter, mg/L: milligrams/Liter, pCi/L = picocuries/Liter. Gross Beta MCL is formally expressed as an exposure limit of 4 millirems/year.

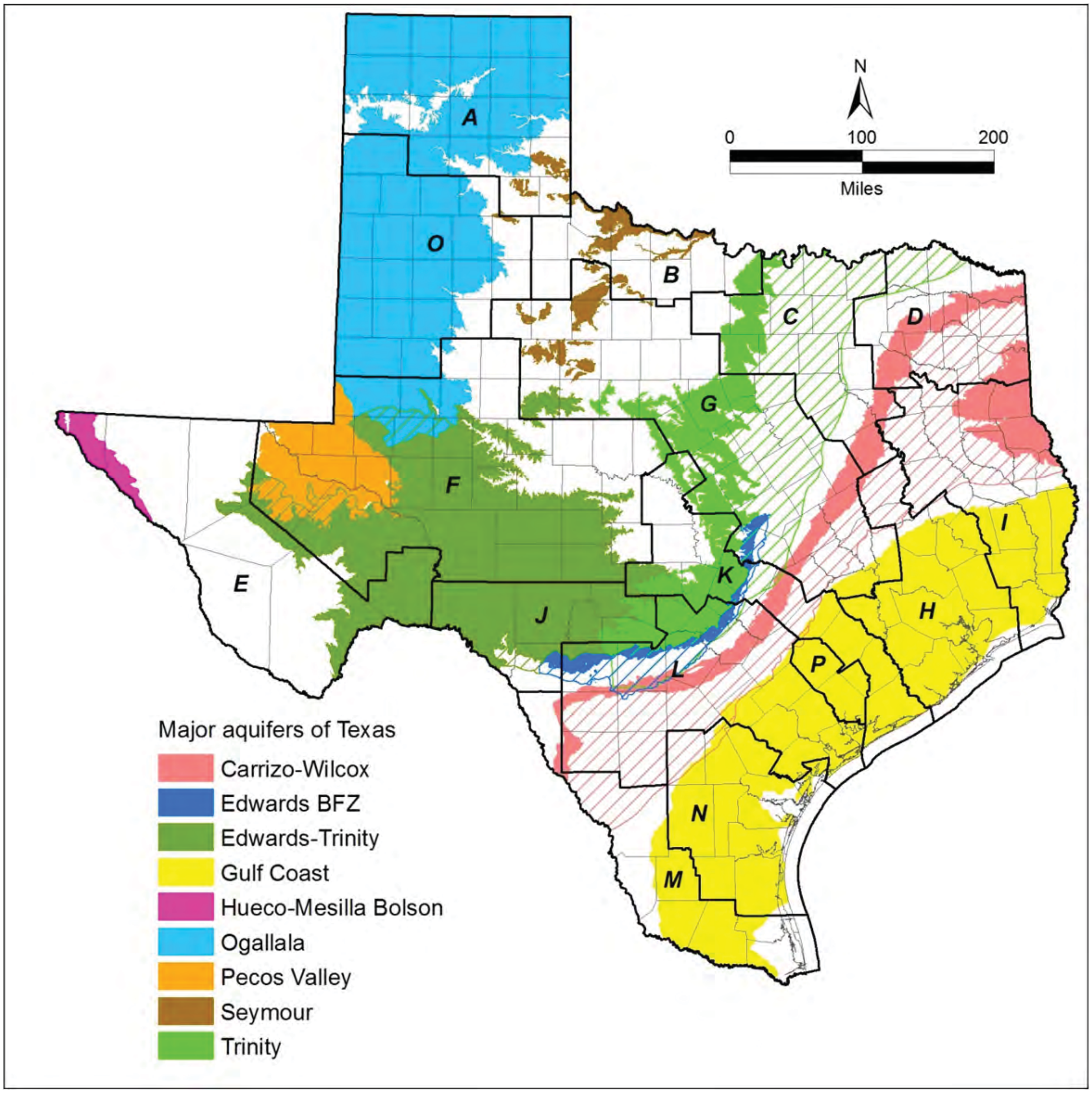

Figure 1. Major aquifers of Texas and Regional Water Planning Area (RWPA) boundaries. Aquifer outcrop (unconfined) extents are shown with solid colors. Aquifer subcrop (confined) extents are shown with cross-hatched symbols of the same color.

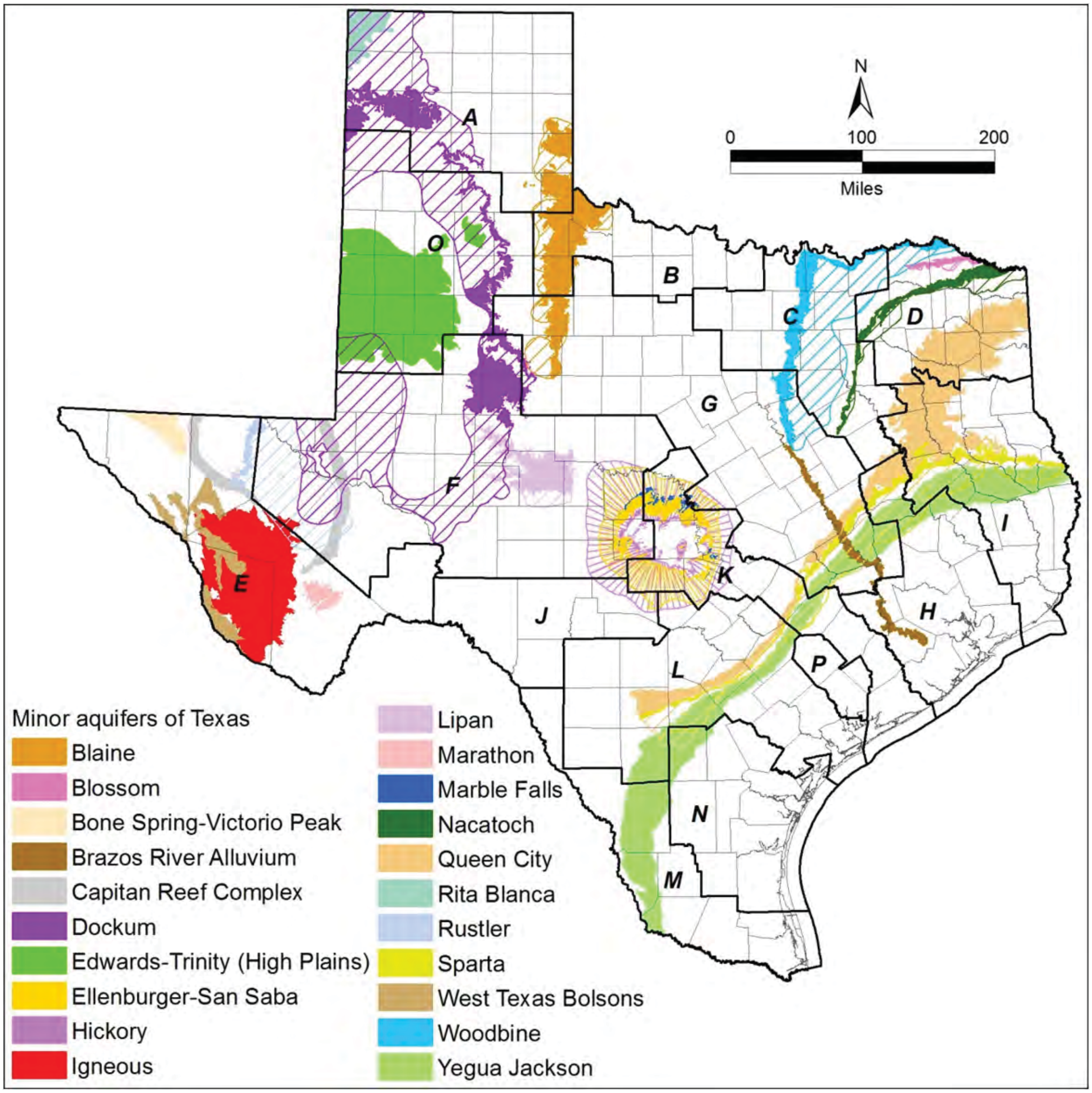

Figure 2. Minor aquifers of Texas and Regional Water Planning Area (RWPA) boundaries. Aquifer outcrop (unconfined) extents are shown with solid colors. Aquifer subcrop (confined) extents are shown with cross-hatched symbols of the same color.

2.0 Methods

2.1 Data Sources

The water quality data used for this study were derived primarily from the TWDB water quality online database. Although water quality data are available from the early 1900s, this study focused on the most recent analysis from data collected from 1988 – 2010 because these data are considered most reliable. Many of the samples during this time were collected under a rigorous quality assurance plan and the Lower Colorado River Authority's Environmental Laboratory Services was the primary laboratory for the majority of the analyses. Throughout this period, the TWDB annually sampled water from 600 to 700 wells and cooperators collected samples from up to 200 additional sites. All aquifers were sampled once every four to five years, while five or six major and minor aquifers were sampled each year (TWDB State Water Plan, 2007). A total of 11,762 wells were used in the final analysis of water quality for all aquifers in the state. Chemical data from the TCEQ Public Water System (PWS) database were also included in the analysis. These data were limited to untreated ("raw") water samples from single wells and represent an additional 519 wells.

Aquifer volumes were estimated using GIS data from the TCEQ Source Water Assessment Program (SWAP), including aquifer boundaries and saturated thicknesses. In some cases, the SWAP aquifer boundaries do not match those of the currently published TWDB aquifer extents and the analyses were restricted to the extents of the SWAP data files. Additionally, six minor aquifers had no SWAP data available: Bone Spring-Victorio Peak, Brazos River Alluvium, Capitan Reef, Marathon, Marble Falls, and Rustler, and no volumes were calculated for these aquifers.

2.2 Data Limitations

Whereas this report includes the best water quality information available to the TWDB's knowledge, inaccuracies may exist despite the use of data from the most recently and more frequently visited sites by the TWDB. Locations are quite accurate (within 10 feet) because sites monitored in the last two decades have been field located mainly through use of global positioning receivers (GPS) and verified with online GPS systems such as Google Earth. However, there are a number of wells with depth or screened interval/completion data that may be questionable or lacking, which in turn might result in potential inaccuracies relating to which aquifer the well is producing from, particularly in areas with multiple underlying aquifers. Generally, however, at least in such situations where the groundwater quality is markedly different between vertically adjacent aquifers, even possibly inaccurate depths have not led to gross inaccuracies.

Changes over time in laboratories and analytical techniques used to determine concentrations of various constituents might present a greater challenge in characterizing contamination. Advances in analytical technology have resulted in lowered concentration detection limits, which are a concern particularly for primary MCL concentrations that have been recently lowered. For example, a well sampled in the mid 1990's when the arsenic MCL was 50 μg/L might have had a concentration below the (then) detection limit of 20 mg/L for a particular lab. A more recent sample analyzed with newer technology and having a detection limit of 1 μg/L might result in 15 μg/L, which is greater than the (current) MCL of 10 μg/L. Keeping such occurrences in mind at sites with multiple samples over time, we used only the most recent analyses and discarded those with detection limits greater than the current MCL concentration.

2.3 Maps of MCL Exceedances

Statewide water quality maps representing sample concentrations for individual wells were made for each EPA primary and secondary MCL constituent to show the distribution of MCL exceedances in all major aquifers. Aquifer maps were developed using indicator kriging methods to spatially represent the probability of exceeding a given MCL concentration value. Maps were developed for each primary MCL constituent having a pervasive occurrence of violations and for which there were sufficient data available. "Pervasiveness" was determined for each aquifer on a case-by-case basis. In general, a contaminant was considered pervasive if more than 2 to 3 percent of wells had MCL violations and the overall number and spatial distribution of all wells was sufficient to produce a reasonably representative map. Aquifer maps representing the probability of exceeding the (secondary) MCL for total dissolved solids (TDS, 1,000 mg/L) were also developed to provide an indication of general water quality.

Ordinary kriging is an alternative method that is commonly used to produce maps representing the spatial distribution of concentrations. However, this method assumes that the data are either normally distributed or that the data can be otherwise transformed into a normal distributed, which is frequently not a statistically valid assumption. Additionally, ordinary kriging methods cannot incorporate non-detect or "less than" values. The concentrations of many MCL constituents in groundwater samples are below analytical detection limits and are reported in the database as non-detects. In many instances, significant proportions of the data consist of non-detect values and this information would be lost using ordinary kriging.

In contrast, indicator kriging uses cut-off transformed values to produce maps that estimate the probability of exceeding the cut-off or threshold value. The primary advantages of using indicator kriging in this application are that it requires no *a priori* assumption regarding the normality of the data distribution and that it can incorporate non-detect values that are less than or equal to the threshold concentration. Concentration values were assigned a value of “1” if greater than the MCL (threshold) concentration and a value of “0” if less than or equal to the MCL. If a particular aquifer had multiple pervasive MCL violations, a final map representing the probability of exceeding any primary MCL was generated by combining the multiple MCL maps using:

$$P(A\ or\ B) = P(A) + P(B) - P(A \times B) \qquad (1)$$

where *P* is probability and *A* and *B* represent the different MCL exceedance probabilities. Thus, due to the additive nature of probabilities, aquifer regions that have relatively low to moderate probabilities of exceeding a *single* MCL concentration will have a higher probability of exceeding *any* MCL if multiple contaminants are present. For example, an aquifer region with a 40 percent probability of exceeding the MCL for arsenic and a 40 percent probability of exceeding the MCL for fluoride will result in a probability of 58 percent of exceeding *either* MCL. Equation 1 can be applied to more than two contaminants by successive iteration (i.e., in a second calculation, the result of the first iteration becomes “*A”* and a third probability map becomes “*B”*, and so forth until all of the individual maps have been incorporated into the calculation). All of the probability maps are symbolized in 20th percentile intervals of MCL exceedance probability.

Schematic cross sections were developed for each major aquifer to depict the ground surface derived from digital elevation models (DEM) and the upper and lower surfaces of the saturated aquifer interval(s) derived from the TCEQ Source Water Assessment Program (SWAP) data set. To provide an indication of water quality changes with depth, MCL concentrations (excluding non-detect values) for each mapped constituent were plotted against well depth and a locally-weighted scatterplot smoothing (LOWESS) line was fitted to the data. LOWESS smoothing is a robust regression technique that can be used to identify trends in data having high variance. The regression uses a smoothing factor value between 0 and 1 that dictates the fractional proportion of the data to be examined in a “moving window” fashion with larger values resulting in greater smoothing. Values between 0.25 and 0.5 were used.

2.4 Impact of Water Quality on Water Quantity

The impact of water quality on quantity of fresh groundwater was determined. Probability maps of contaminants for major and minor aquifers were used to estimate the relative percent volumes of groundwater impacted by naturally occurring chemical constituents. The impacted aquifer volume, V, affected by chemical constituents was calculated as follows:

$$V = A \times St \tag{2}$$

where aquifer area, *A*, corresponds to the spatial distribution of different degrees of risk calculated from the kriged probability maps and saturated thickness, *St*, derived from the TCEQ SWAP data. The results of the indicator kriging were summarized in table form for each aquifer/MCL combination by consolidating the total areas and associated saturated thicknesses within each of three "risk" categories based on the estimated probability of exceeding a given MCL concentration, including "low" (0 – 40 percent probability), "moderate" (40 – 60 percent probability), and "high" (60 – 100 percent probability) categories. The moderate category may be considered as approximately representing the 50 percent probability of exceeding the MCL. Although specific yield/storage values may be used to estimate the amount of available or producible water, there are few measurements of these values and they generally are highly variable spatially. Producible water volumes vary greatly both between aquifers and spatially within individual aquifers and generally range from a maximum of about 20 to 25 percent to values much less than one percent of aquifer volume. Additionally, the term "producible" water incorporates economic and practical engineering factors that are beyond the scope of this study. Therefore, the volumes reported here represent estimates of *aquifer* volumes (equivalent to saturated formation volume) and do not represent actual water volumes.

2.5 Assessment of Water Treatment Options

We evaluated available treatment alternatives for the various naturally occurring chemical constituents that exceed EPA MCLs in Texas aquifers. Systems for which treatment was evaluated in this study were those that fall outside EPA regulations, i.e. non-Public Water Supply systems, such as domestic wells. Although in situ treatments can be considered, these were generally inappropriate for individual well systems. This study focused on Point-of-use (POU) and Point of Entry (POE) treatment devices. POU devices are appropriate for removing contaminants that pose an ingestion risk only, such as arsenic and fluoride, whereas POE systems treat all water coming into a household and are more appropriate for contaminants such as iron and manganese. The advantages and disadvantages of various treatment technologies were evaluated and are reported. In cases where there are multiple contaminants, appropriate technologies for treating all contaminants in one system were considered. Many treatment systems are based on the affinity of a contaminant to sorb and or exchange which can be impacted by competing ions such as silica. Therefore, we also examined the distribution of potential competing ions.

Estimating costs of treatment technologies is difficult because treatment systems are continually evolving and costs change quite rapidly. Treatment costs vary by system, volume of water treated, and, in some cases, by severity of contamination. In addition to purchasing costs of the POU treatment systems, costs of operations and management may also be important, including projected lifespan of the cartridges.

3.0 Results and Discussion

3.1 MCL Exceedances in Texas Aquifers

Groundwater contamination is widespread in Texas. Statewide maps were developed for each of the constituents that correspond to primary and secondary MCL concentrations (Figure 3 through Figure 28). These maps show the general distributions of MCL exceedances in groundwater wells and provide context for the descriptions of individual aquifers that follow. The maps depict point locations of sampled wells. Wells with sample concentrations greater than the analytical method detection limit are depicted using four concentration ranges bounded by multiples of the given MCL, including <0.5, 0.5-1, 1-2, and >2 times the MCL concentration. Wells with sample concentrations less than the analytical method detection limit (i.e., “less than” or non-detect values) are depicted using one or two detection limit concentration values. The results of the statewide analysis are summarized in Table 2. The highest EPA primary MCL percent exceedance throughout all aquifers is gross alpha radiation representing 11.6 percent of all gross alpha analyses and combined radium-226 and radium-228 (11.4 percent of all combined radium analyses). These are followed by arsenic (7.9 percent), nitrate-N (7.0 percent), fluoride (4.3 percent), uranium (3.0 percent), selenium (1.4 percent), and gross beta radiation (1.1 percent). The remaining primary MCL percent exceedances represent < 0.4 percent of analyses for those chemical constituents in the state.

Secondary MCL percent exceedances in all aquifers are dominated by total dissolved solids (21.5 percent of all TDS analyses), fluoride (19.5 percent), chloride (17.2 percent), sulfate (15.6 percent), iron (13.8 percent), manganese (10.8 percent), pH (9.8 percent), and aluminum (2.3 percent) (Table 2). Percents of zinc, silver, and copper exceedances were less than 0.1 percent of analyses. The map of TDS (Figure 27), which reflects general water quality, shows high TDS throughout much of the state with low areas in the northern part of the Gulf Coast and Carrizo-Wilcox aquifers where precipitation is high and large parts of the aquifer are confined and in the northern part of the southern and Central High Plains in Texas where the Ogallala Aquifer is thick. Chloride (Figure 22) and sulfate (Figure 26) generally follow similar trends to TDS.

Table 2. State wide summary of MCL violations by constituent

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*> MCL*	*% MCL*
Primary MCL							
Antimony	6	μg/L	7,905	7,900	7,827	5	0.1
Arsenic	10	μg/L	10,119	3,489	6,630	797	7.9
Barium	2,000	μg/L	10,193	9,962	231	11	0.1
Beryllium	4	μg/L	7,954	15	7,939	6	0.1
Cadmium	5	μg/L	7,937	72	7,865	16	0.2
Chromium	100	μg/L	9,290	3,805	5,485	8	0.1
Copper	1,300	μg/L	9,968	5,285	4,683	2	0.0
Fluoride	4	mg/L	11,312	10,977	335	491	4.3
Lead	15	μg/L	8,607	1,073	7,534	29	0.3
Mercury	2	μg/L	5,738	206	5,532	5	0.1
Nitrate-N	10	mg/L	11,158	8,300	2,858	778	7.0
Nitrite-N	1	mg/L	3,862	698	3,164	1	0.0
Selenium	50	μg/L	9,843	3,255	6,588	140	1.4
Thallium	2	μg/L	7,663	68	7,595	27	0.4
Gross alpha	15	pCi/L	5,499	4,042	1,457	638	11.6
Gross beta	50	pCi/L	4,619	3.161	1,458	49	1.1
Combined Radium	5	pCi/L	2,119	686	1,433	242	11.4
Uranium	30	μg/L	2,274	1,240	1,034	68	3.0
Total			131,441	61,073	78,190	3,264	2.5
Secondary MCL							
Aluminum	50	μg/L	8,951	2,515	6,436	202	2.3
Chloride	300	mg/L	11,842	11,820	22	2037	17.2
Copper	1,000	μg/L	9,968	5,285	4,683	0	0.0
Fluoride	2	mg/L	11,312	10,977	335	2204	19.5
Iron	300	μg/L	10,621	5,555	5,066	1471	13.8
Manganese	50	μg/L	10,281	6,017	4,264	1106	10.8
Silver	100	μg/L	5,420	73	5,347	1	0.0
Sulfate	300	mg/L	11,549	11,228	321	1799	15.6
TDS	1,000	mg/L	10,892	10,892	0	2347	21.5
Zinc	5,000	μg/L	10,095	7,172	2,923	15	0.1
pH	6.5-8.5		11,645	11,645	0	1144	9.8
Total			112,576	83,179	29,397	12,326	10.9

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

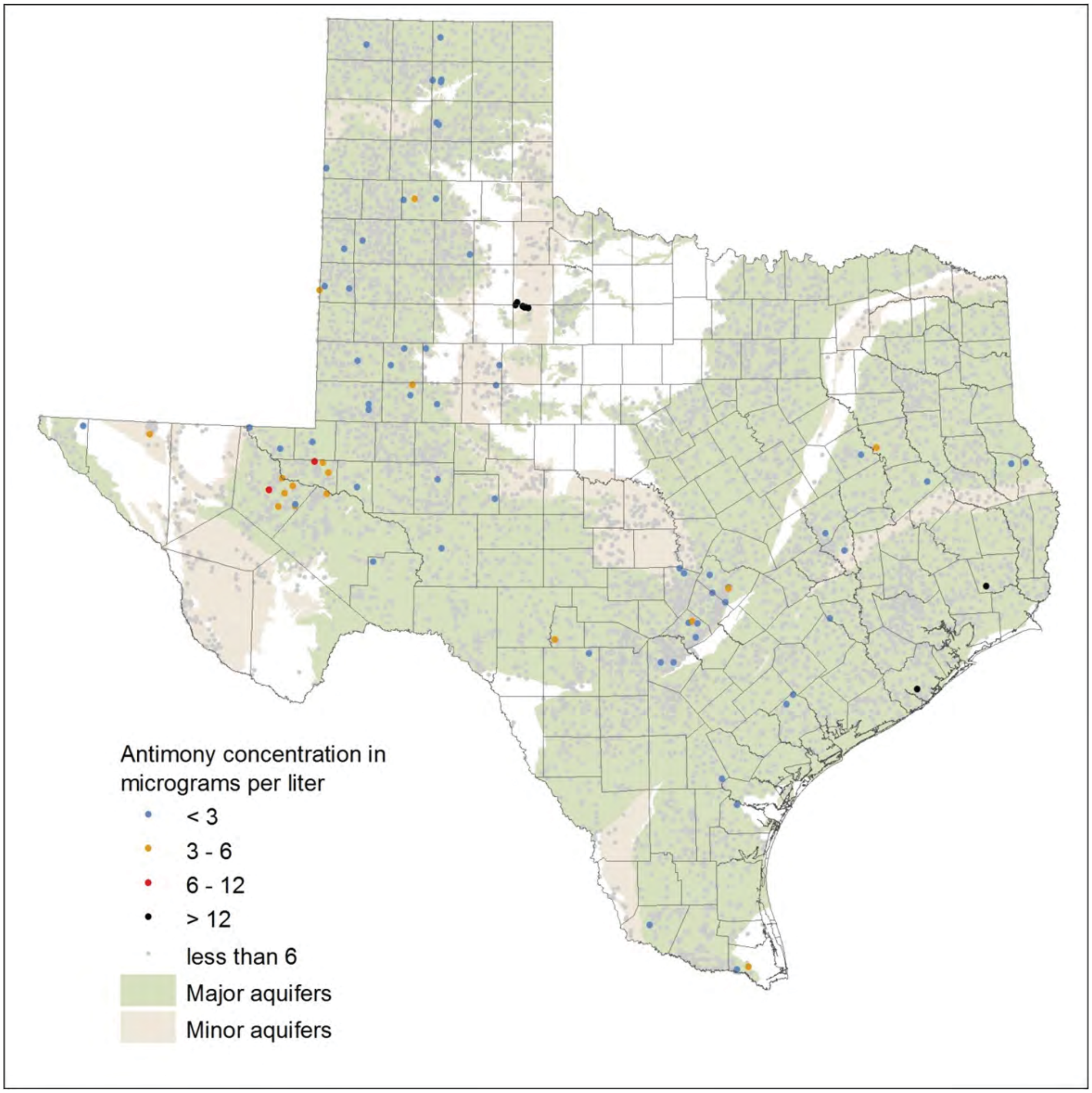

Figure 3. Antimony concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

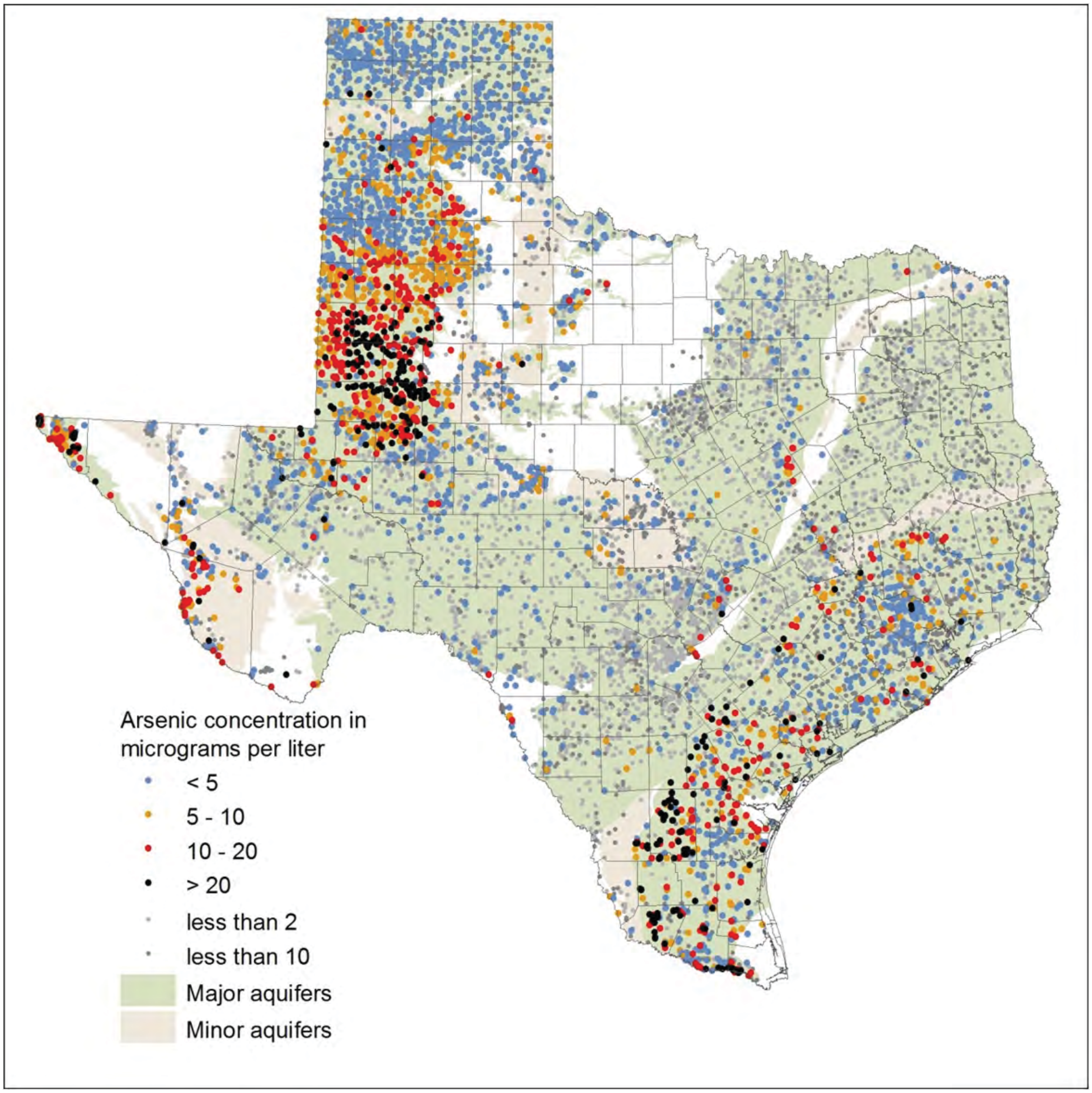

Figure 4. Arsenic concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

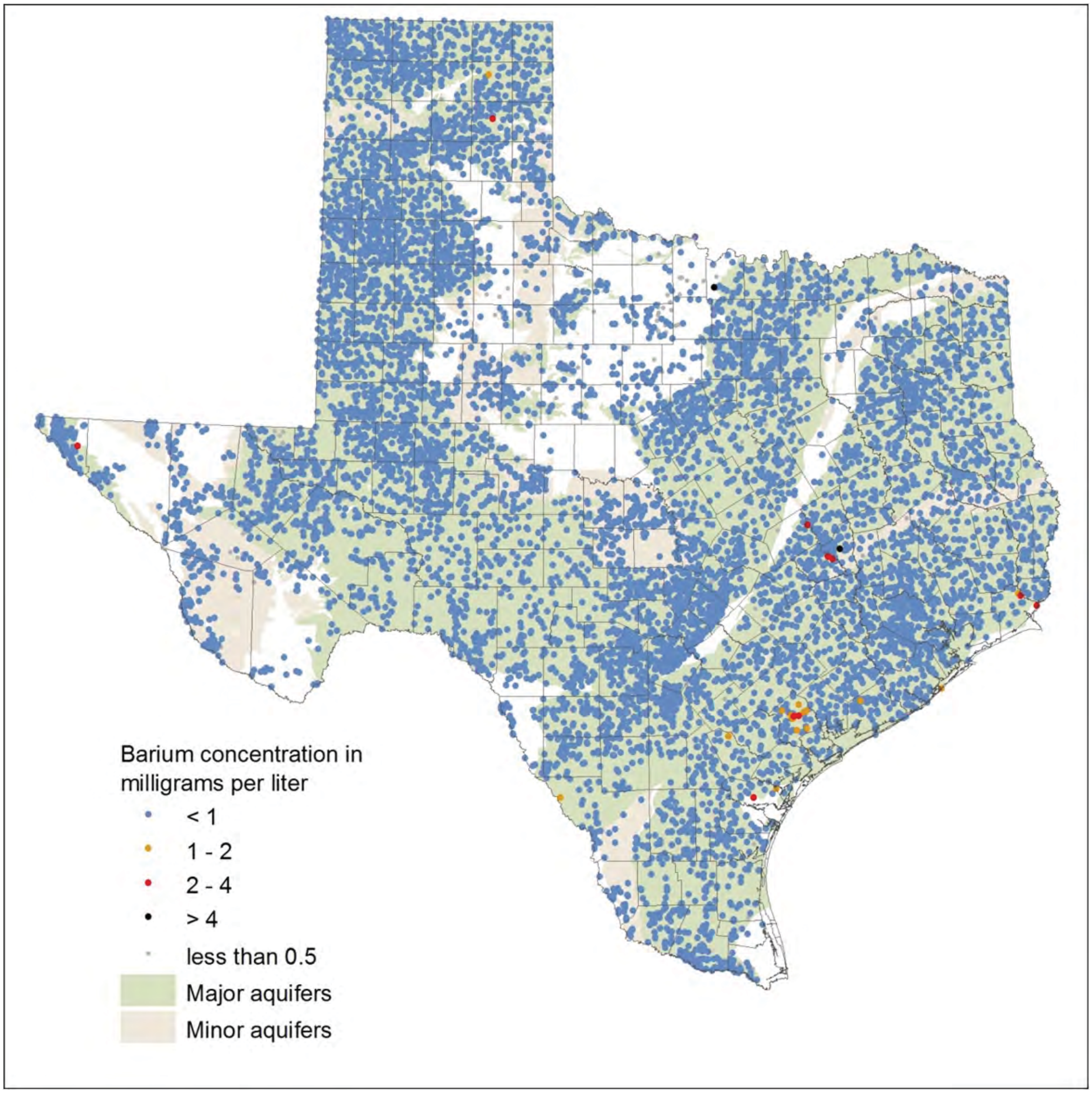

Figure 5. Barium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

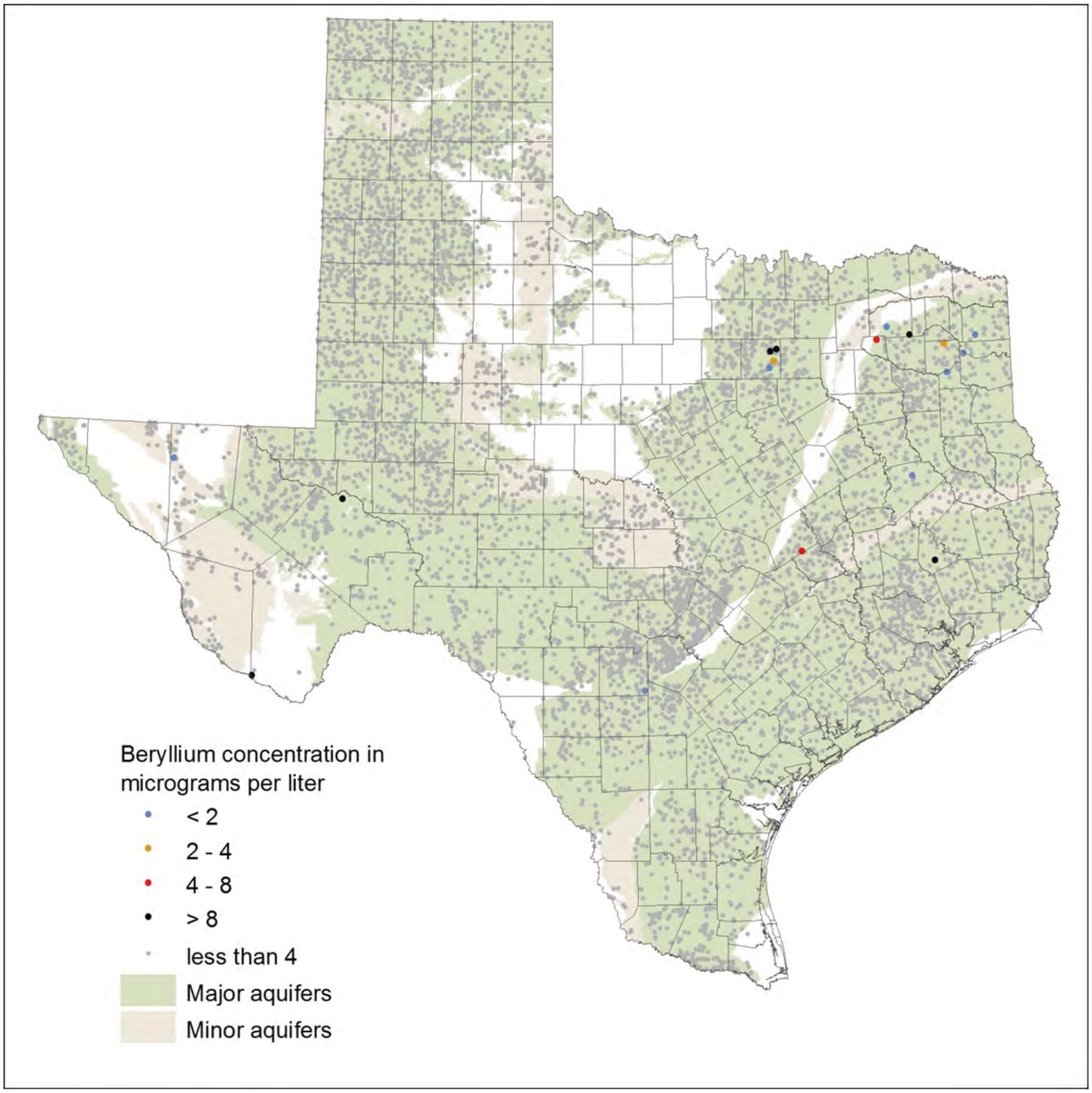

Figure 6. Beryllium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

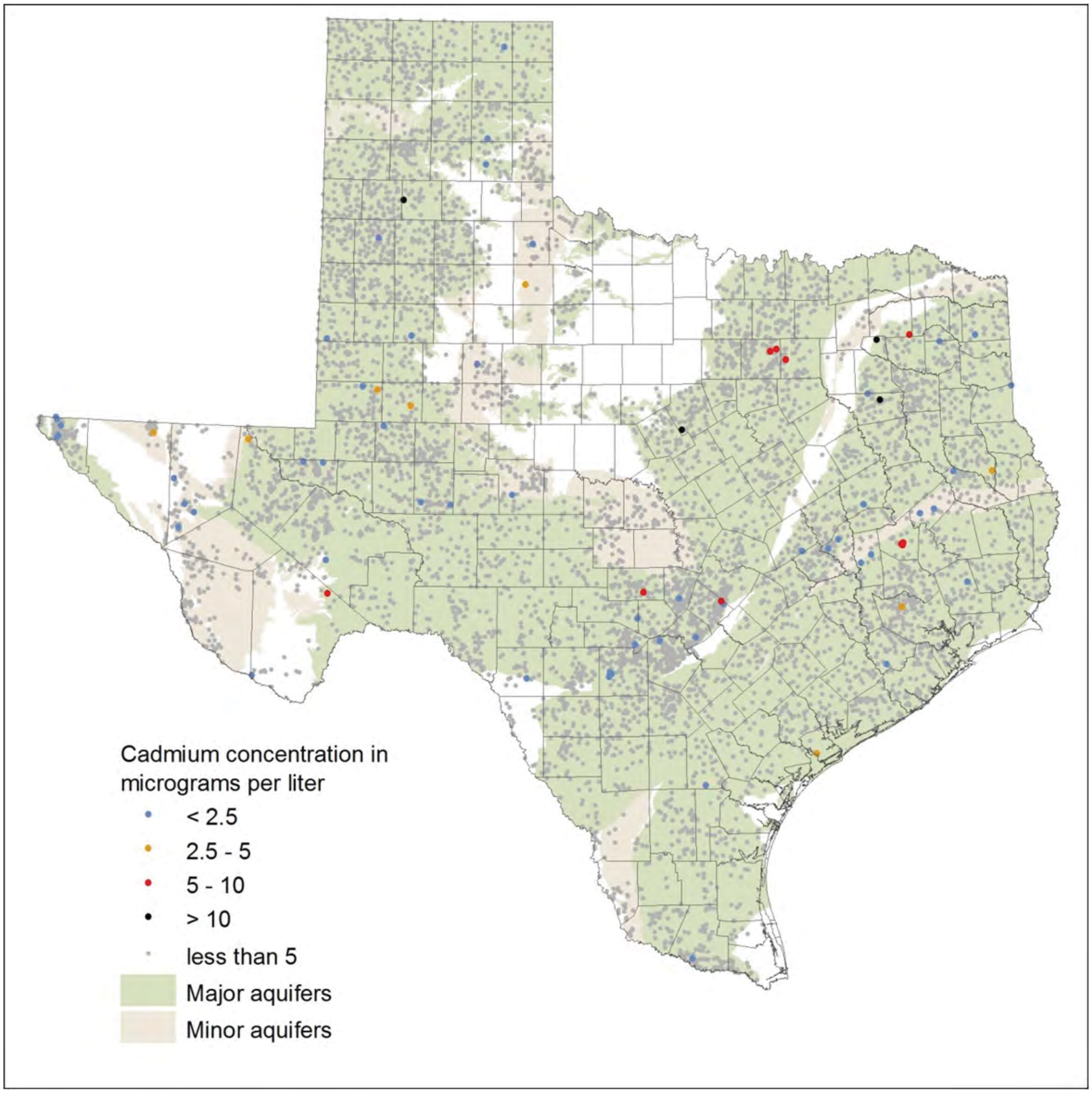

Figure 7. Cadmium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

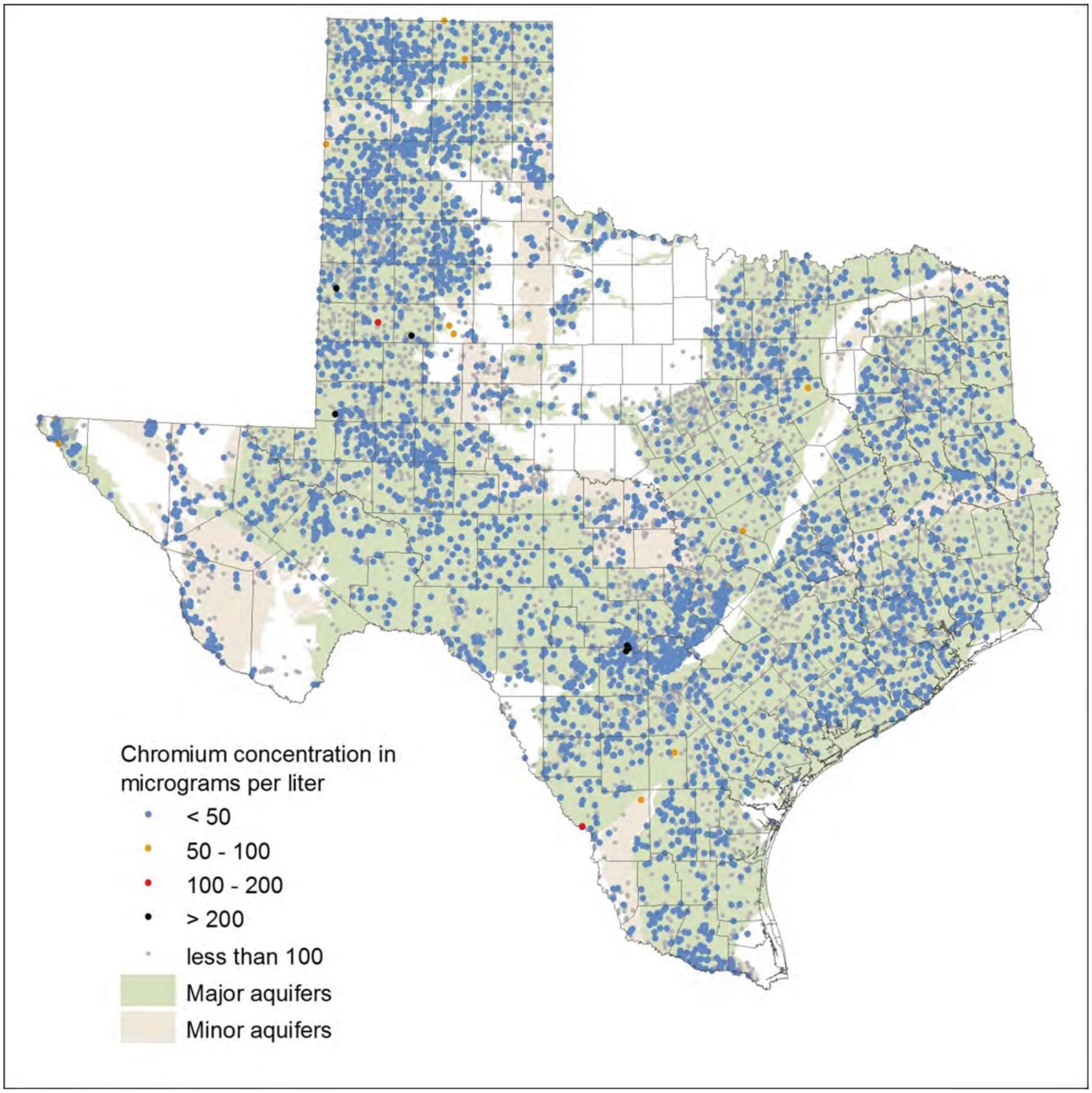

Figure 8. Chromium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

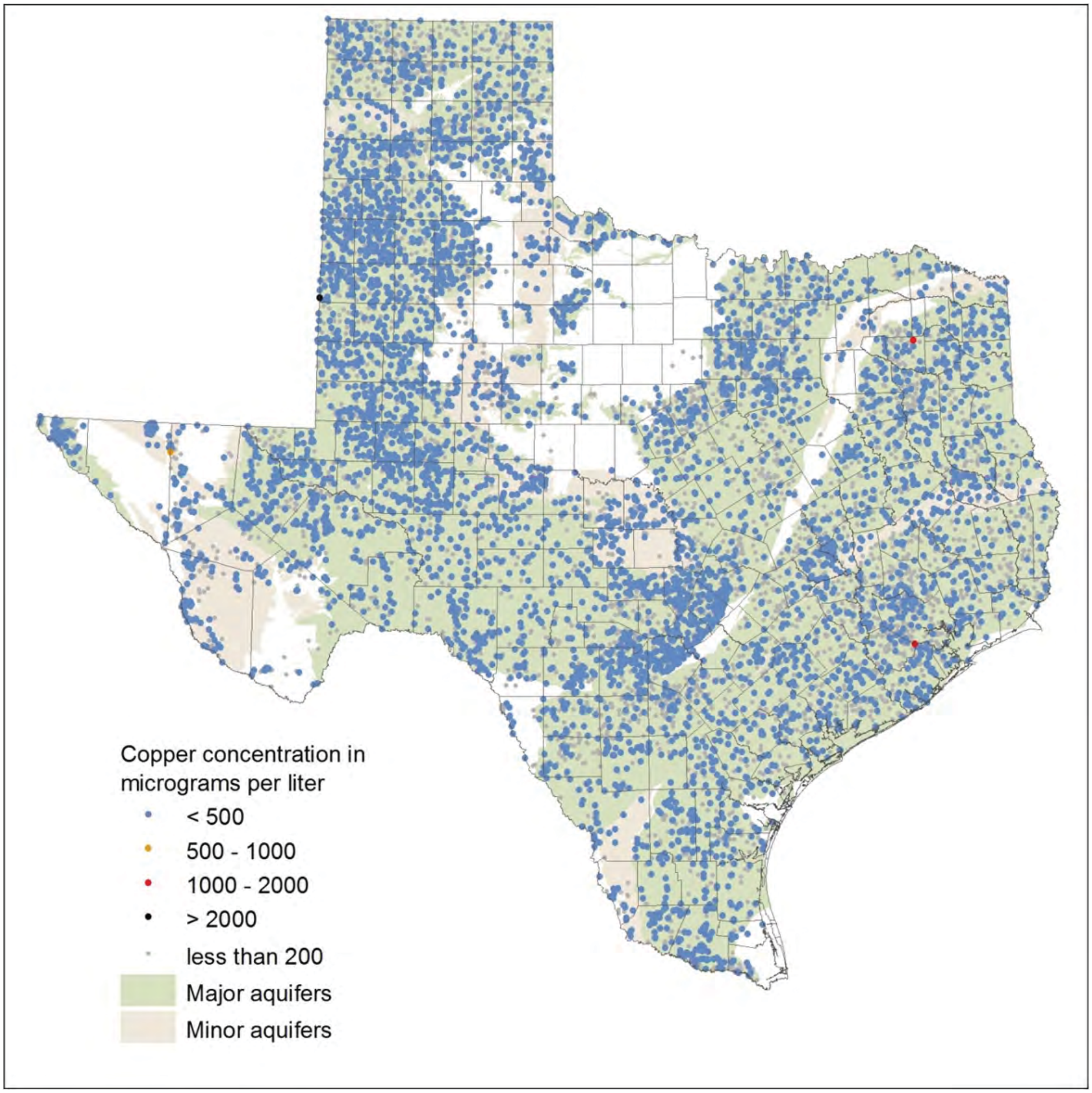

Figure 9. Copper concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

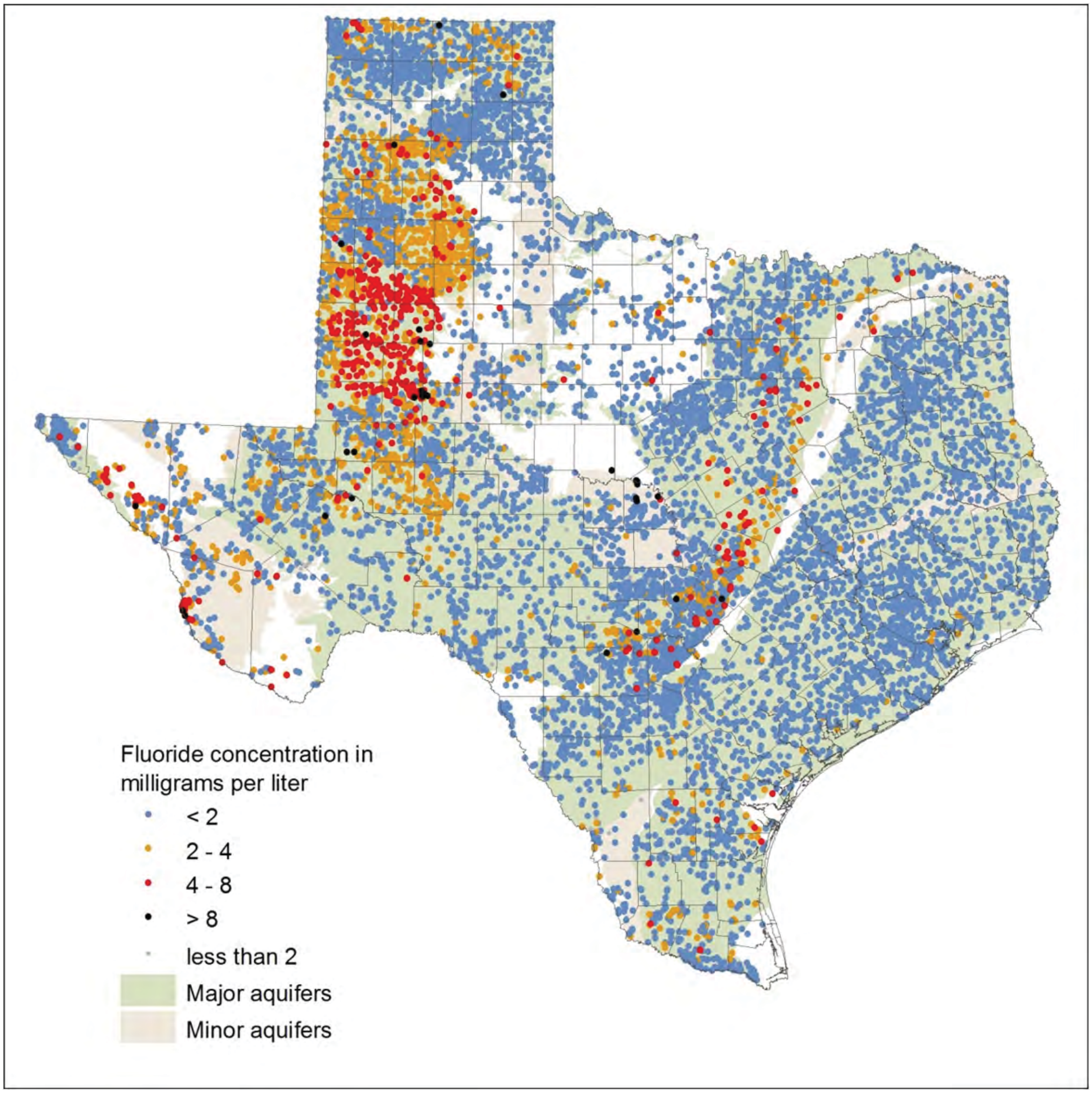

Figure 10. Fluoride concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

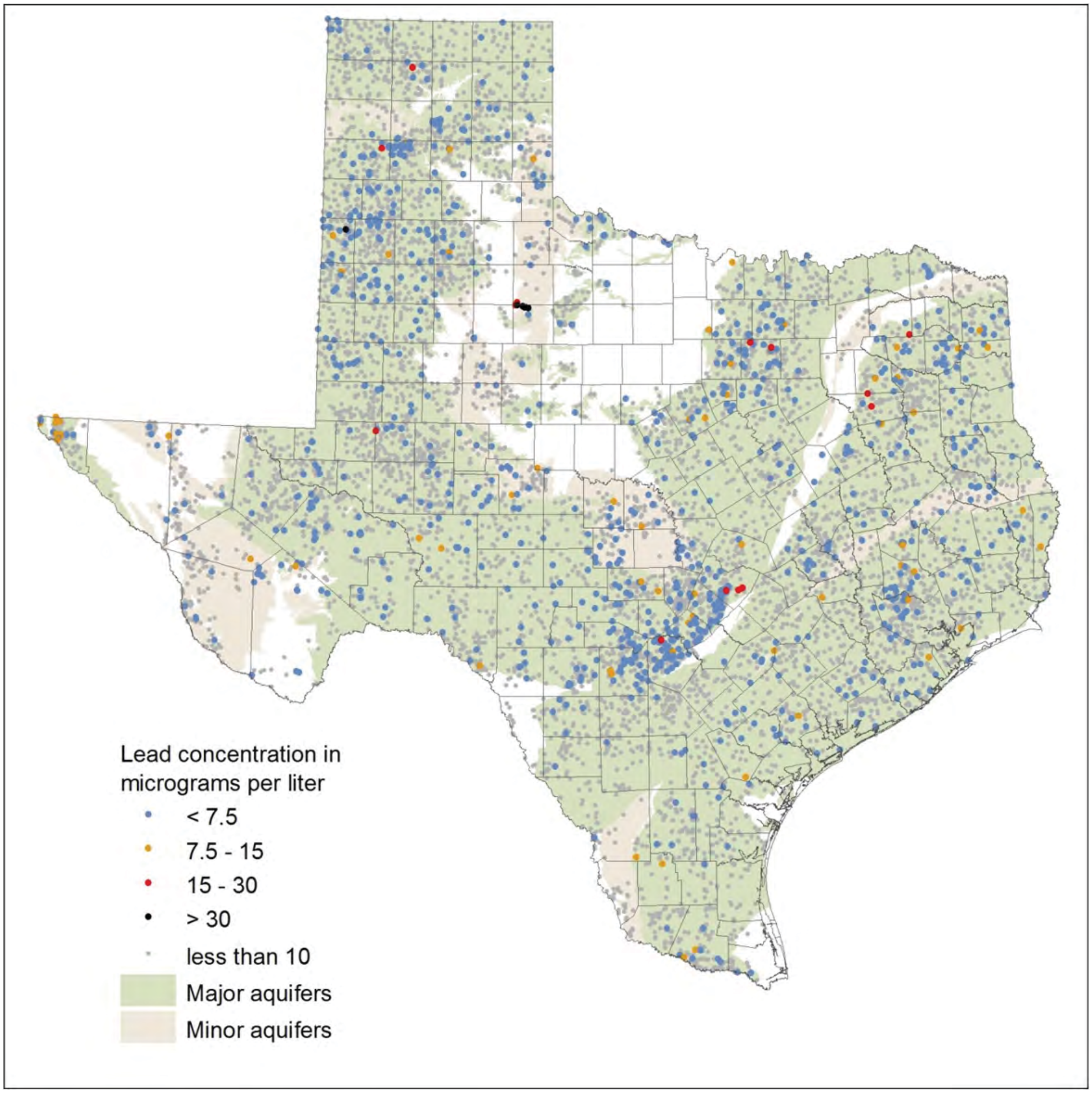

Figure 11. Lead concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

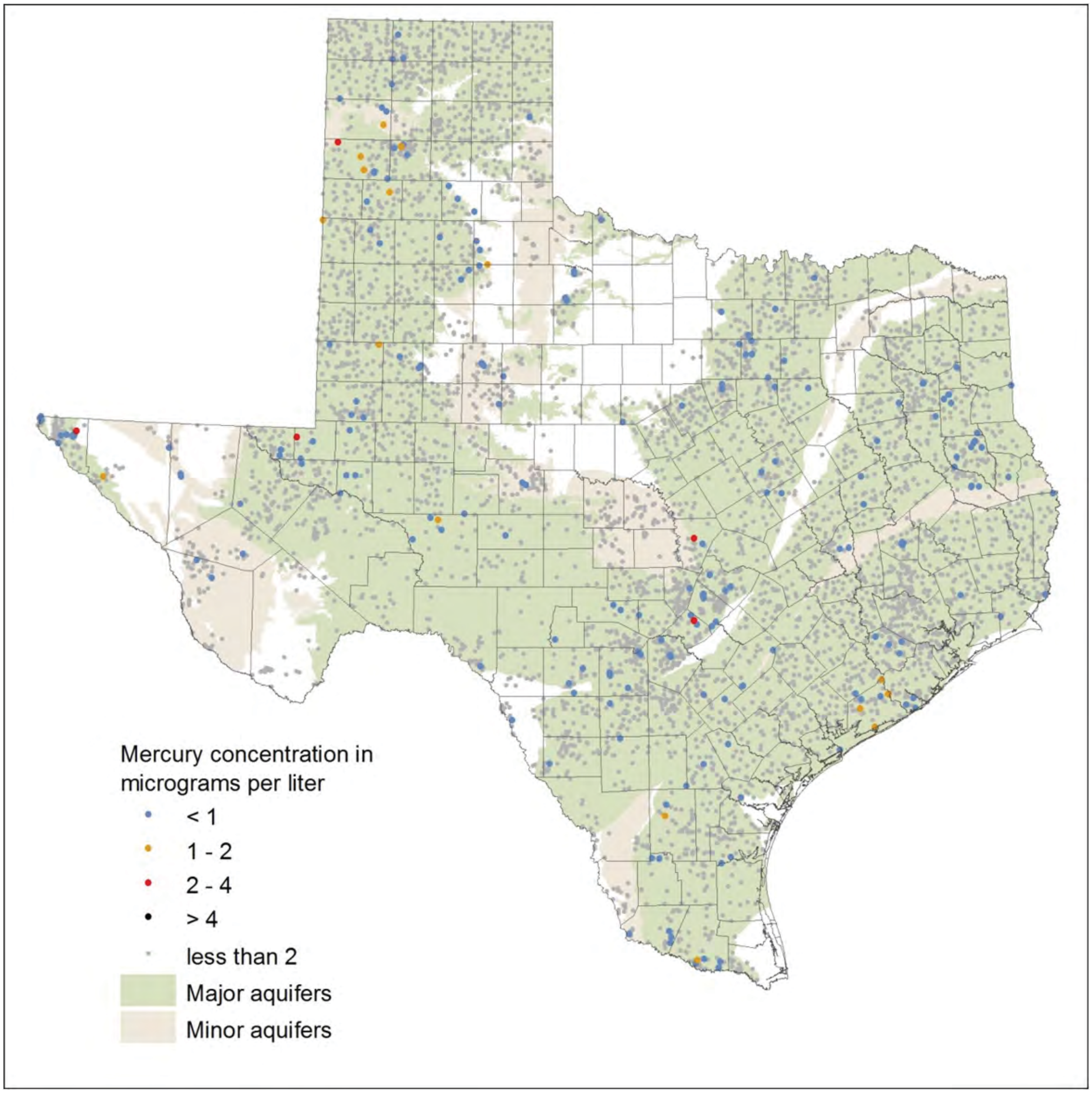

Figure 12. Mercury concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

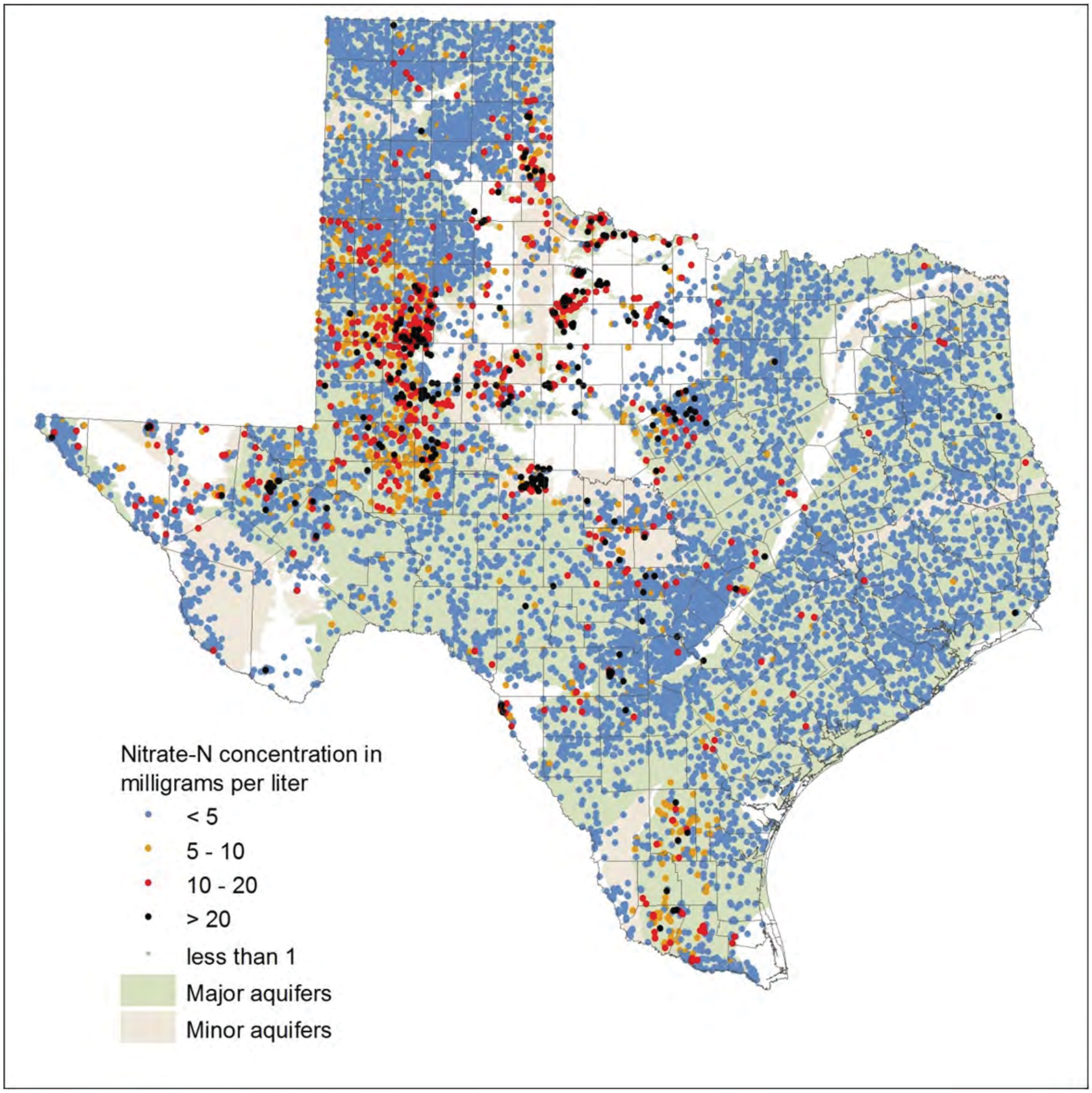

Figure 13. Nitrate-N concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

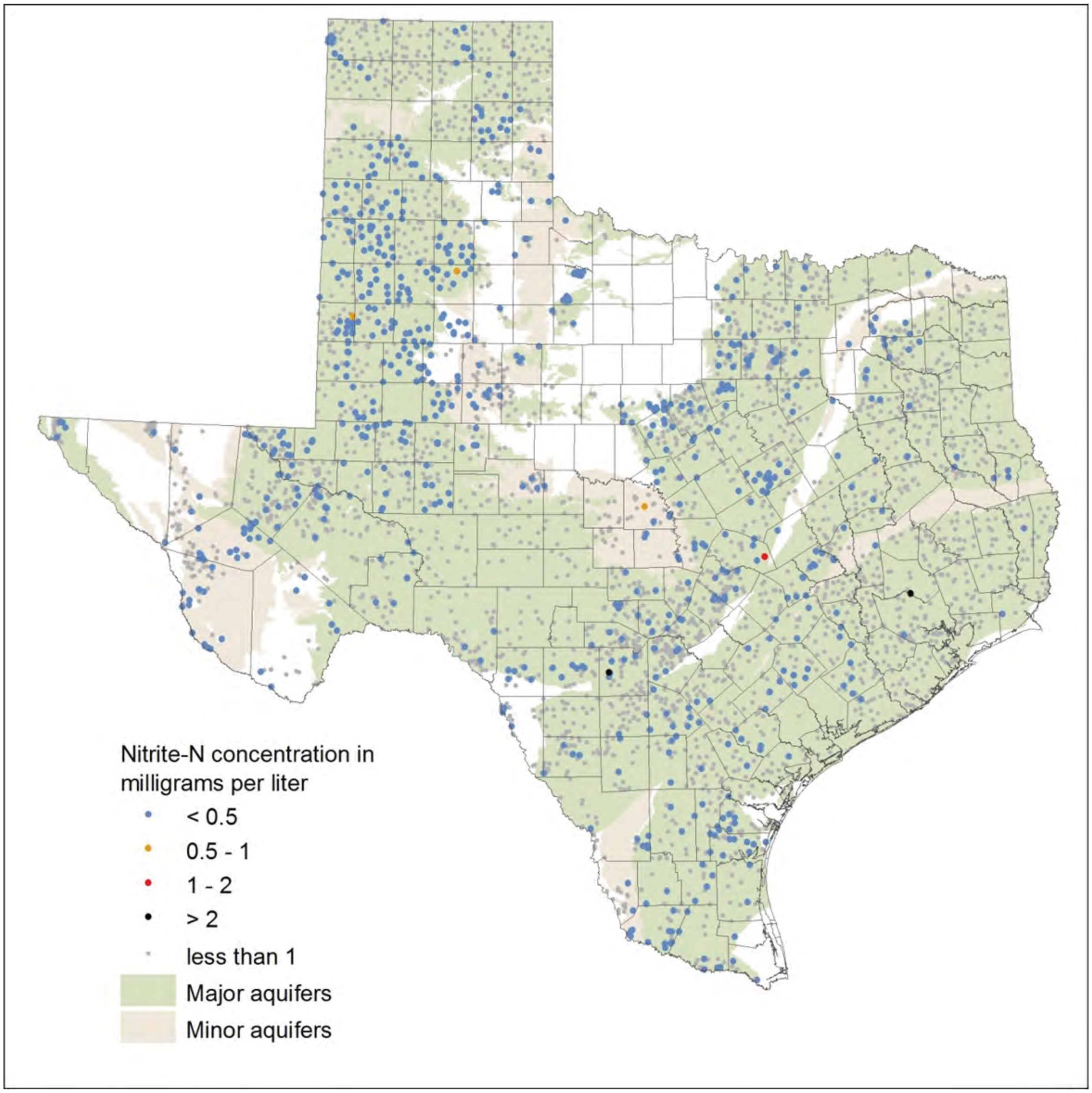

Figure 14. Nitrite-N concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

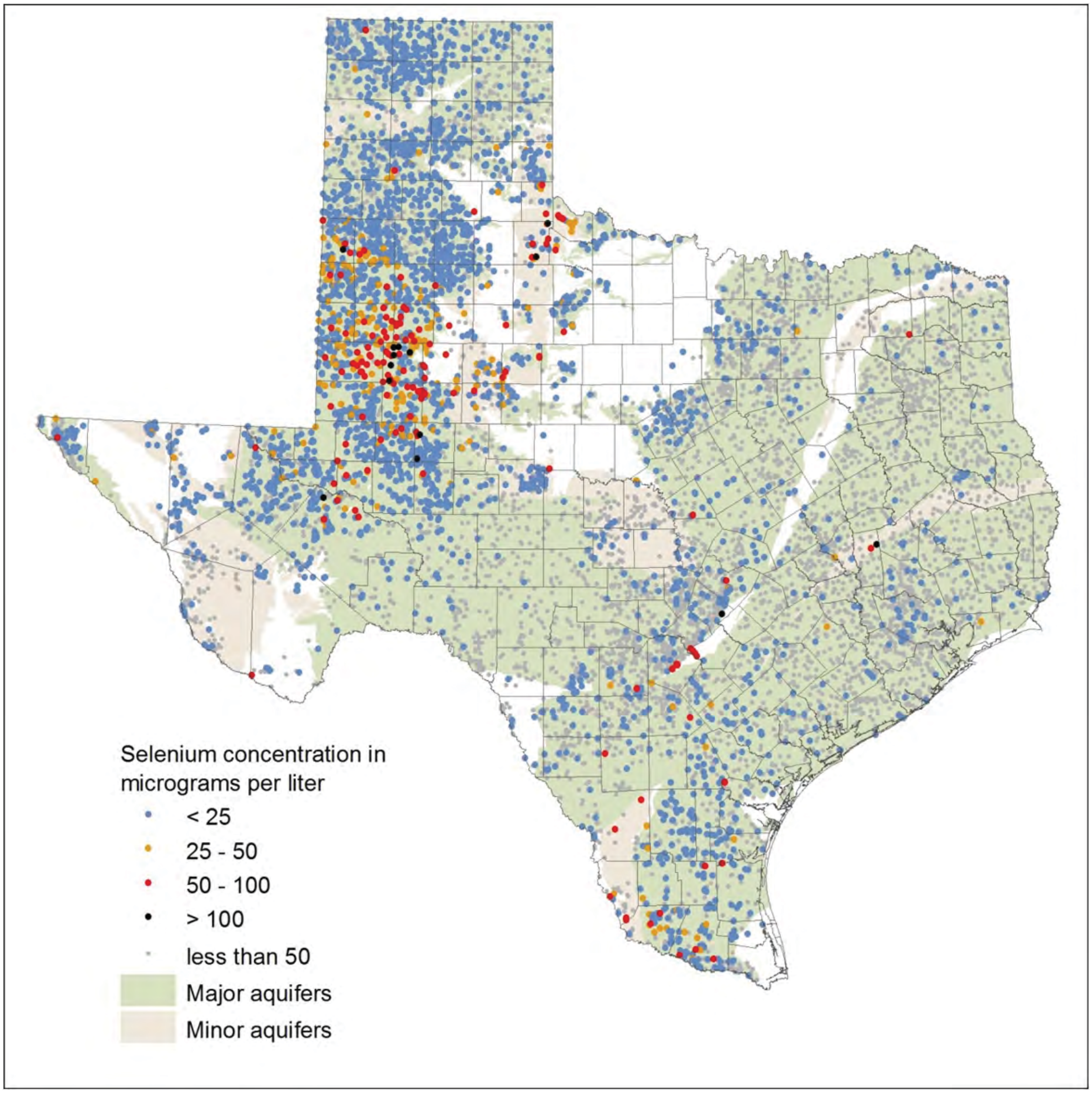

Figure 15. Selenium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

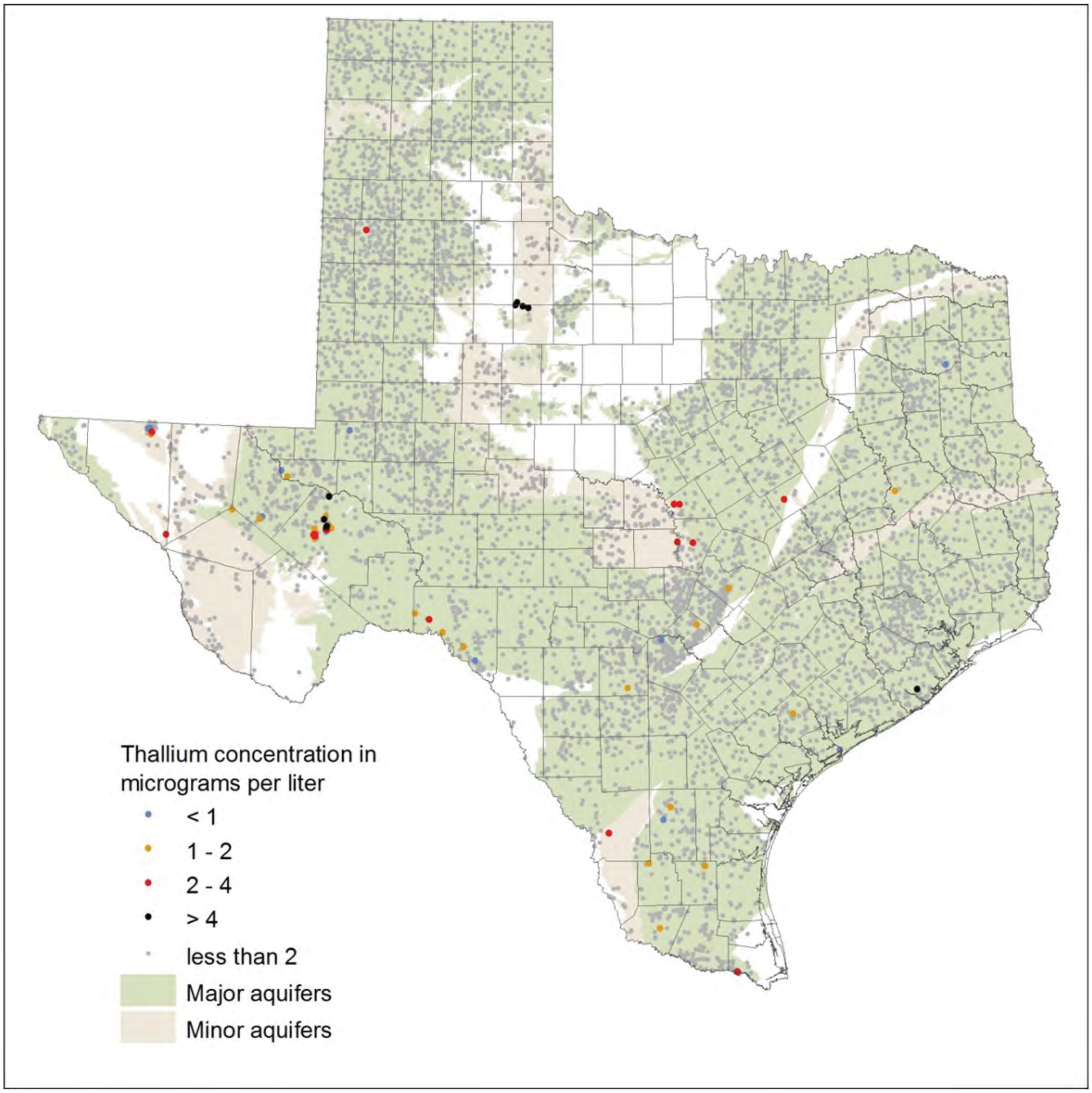

Figure 16. Thallium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

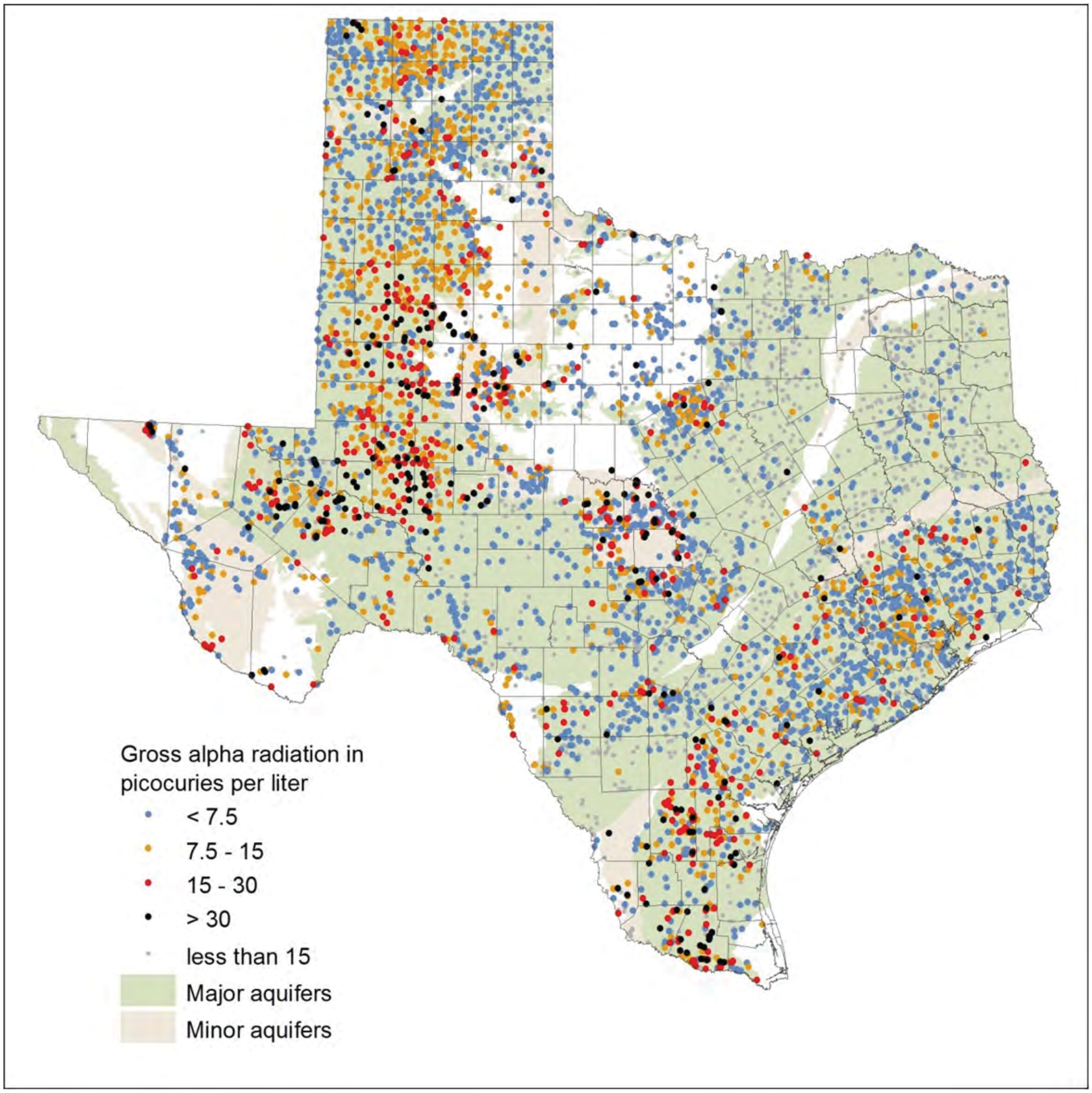

Figure 17. Gross alpha radiation activity in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

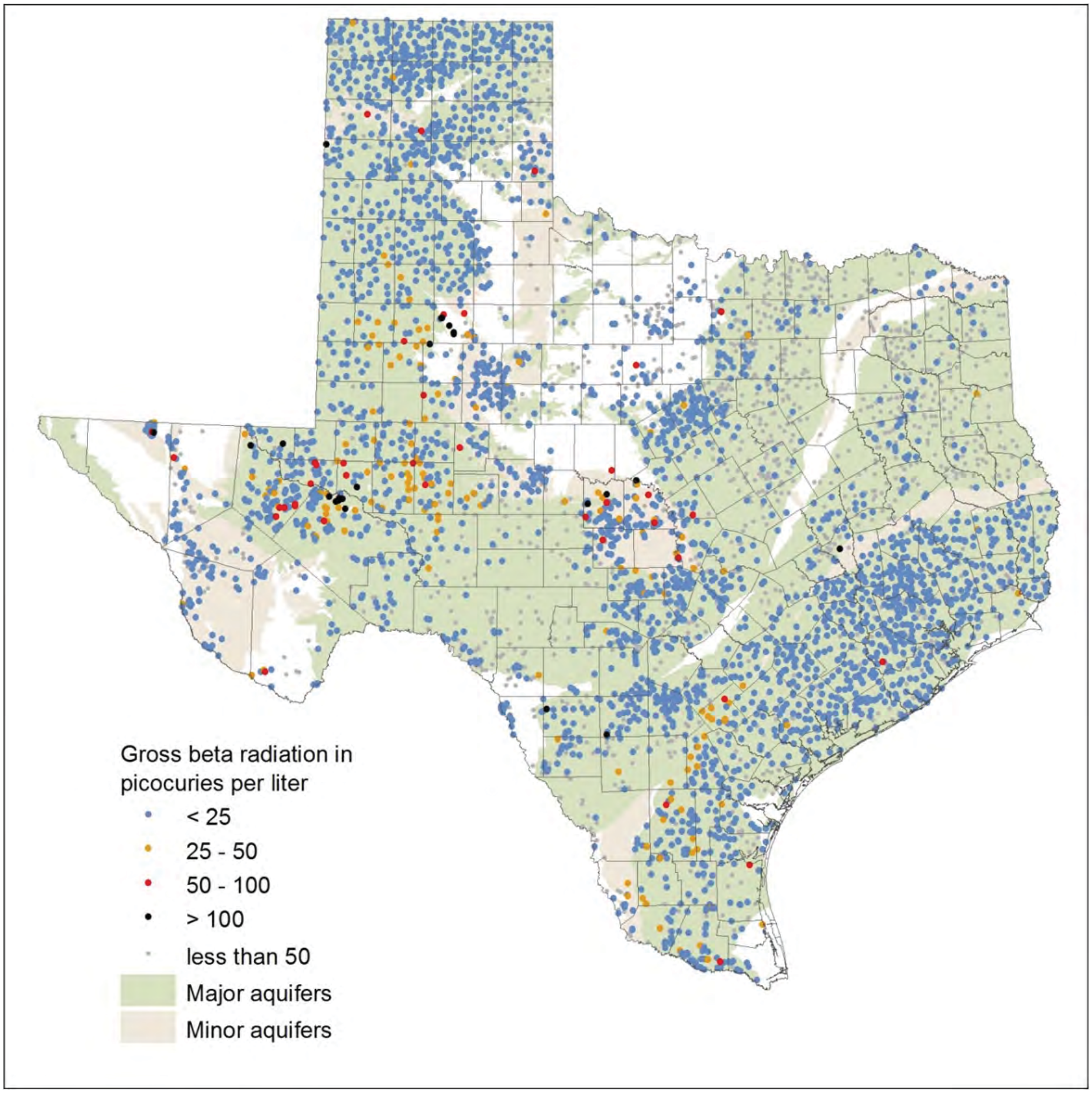

Figure 18. Gross beta radiation activity in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

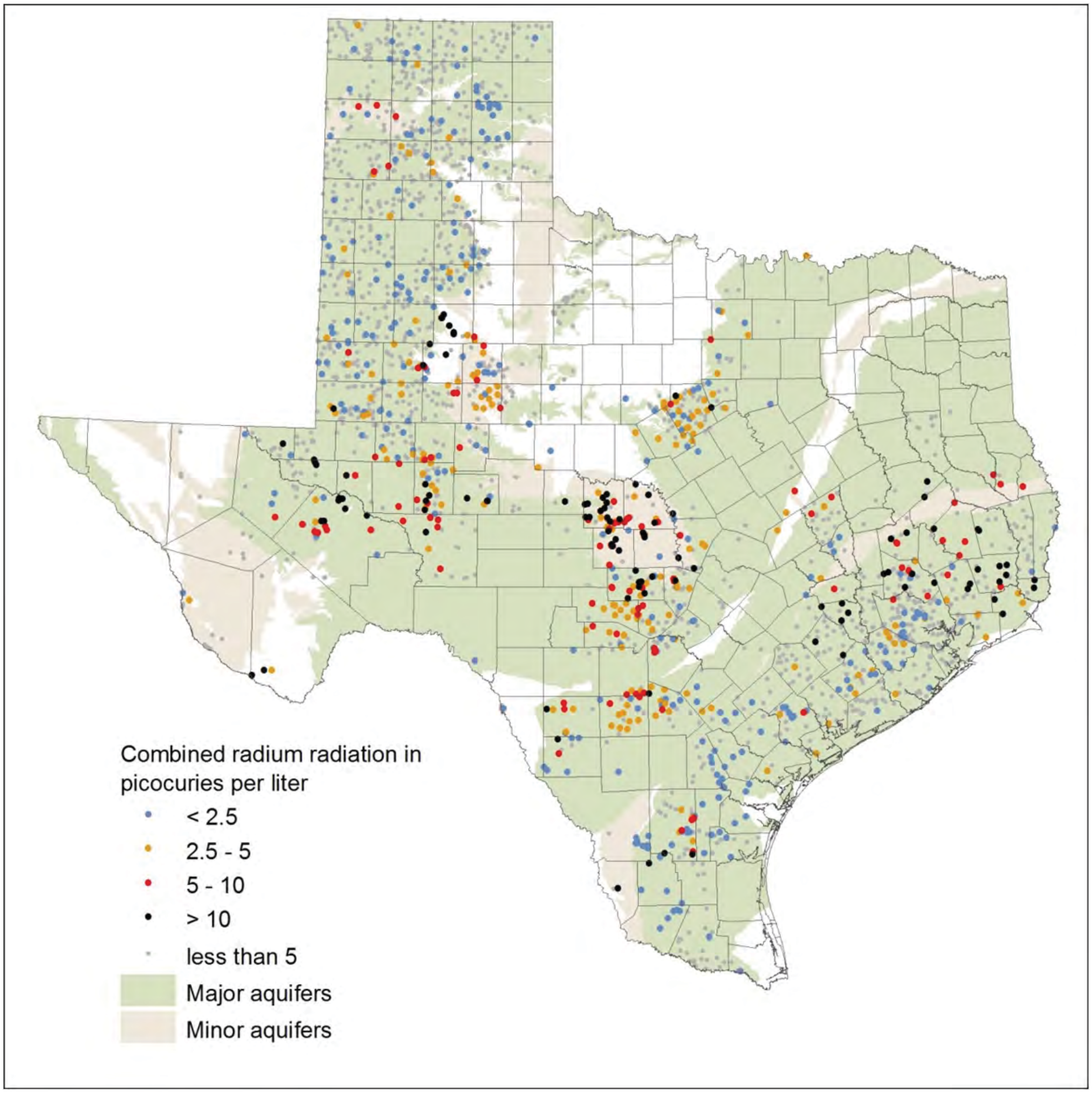

Figure 19. Combined radium radiation activity in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

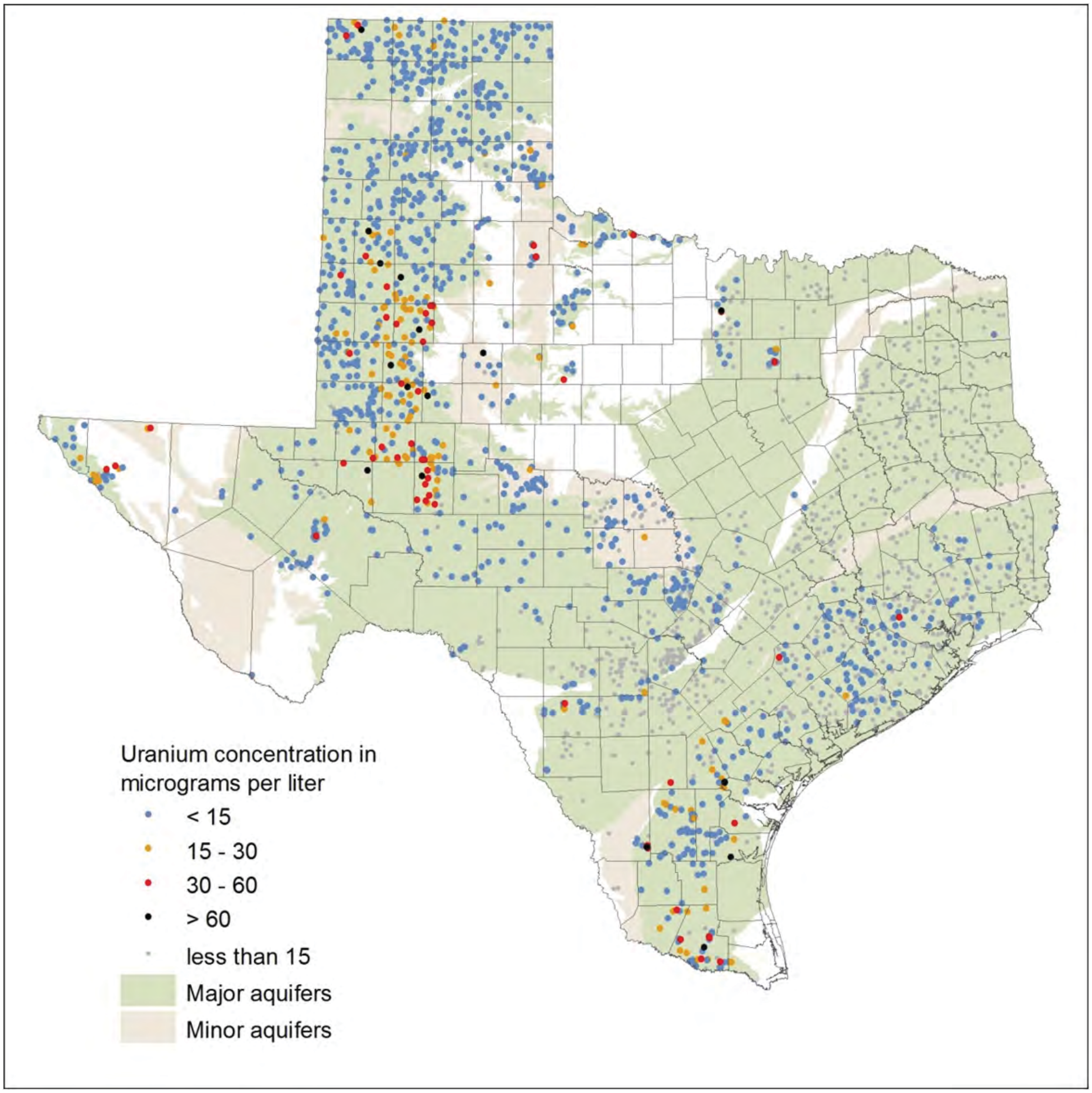

Figure 20. Uranium concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

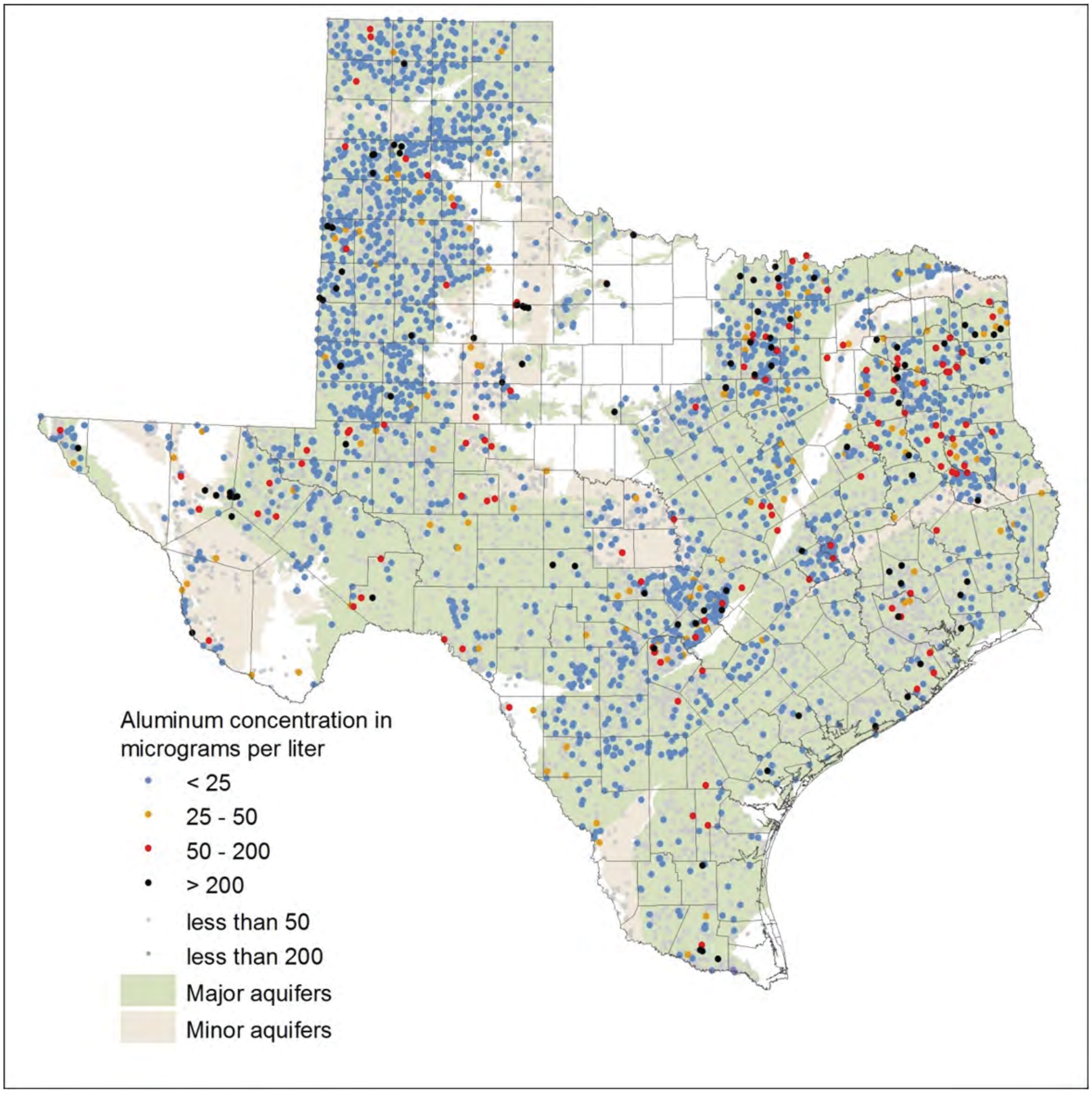

Figure 21. Aluminum concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

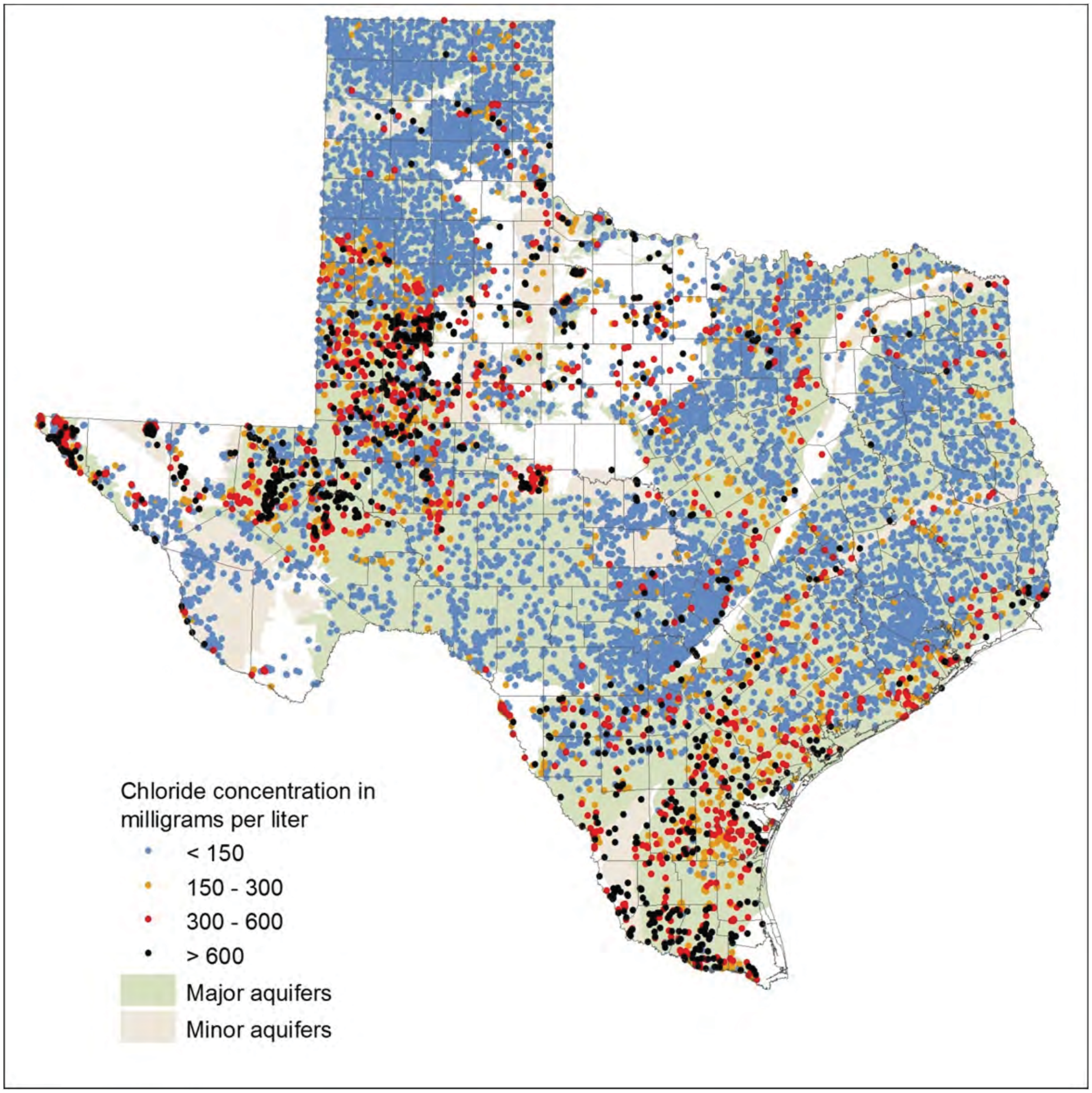

Figure 22. Chloride concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

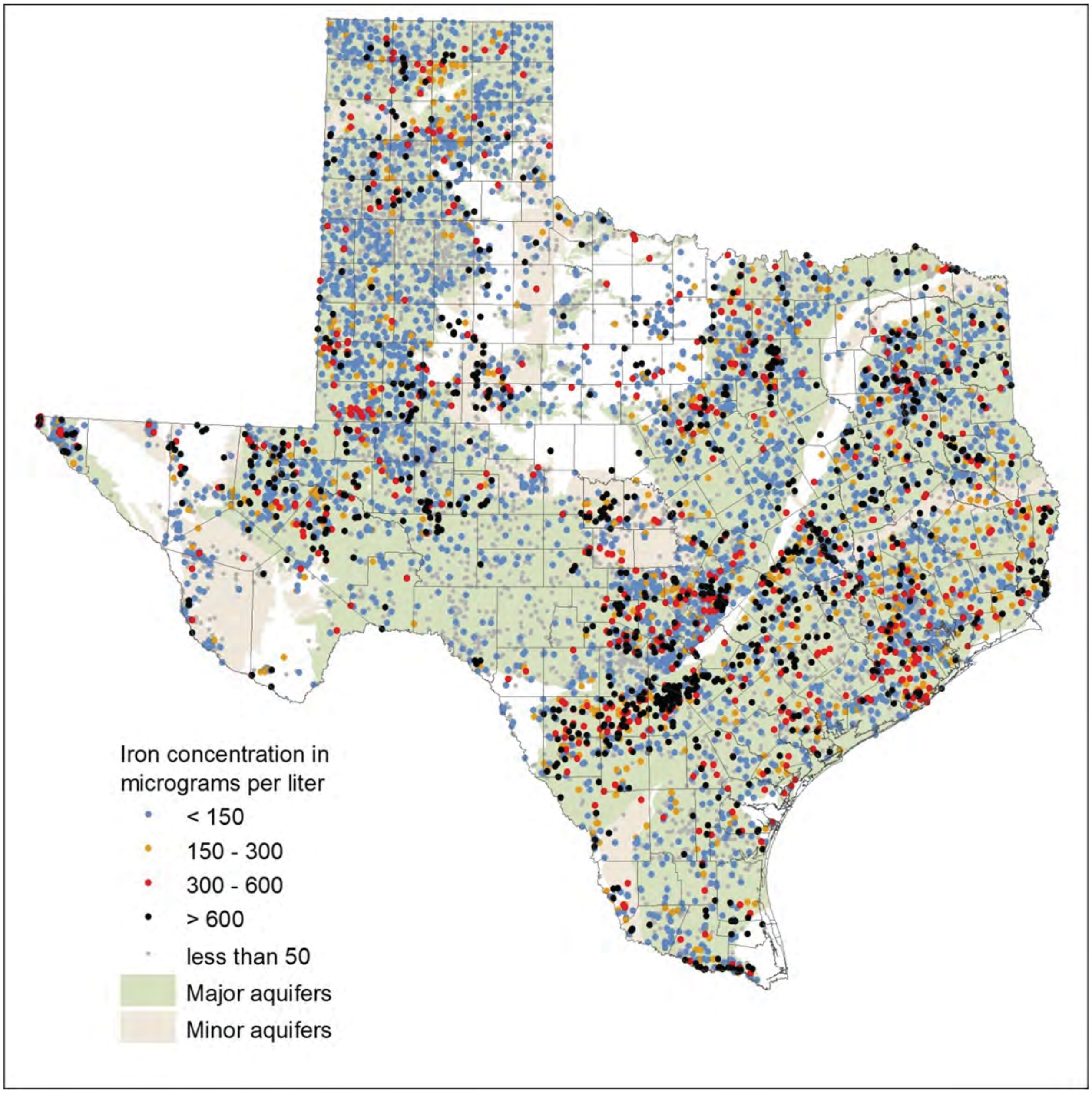

Figure 23. Iron concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

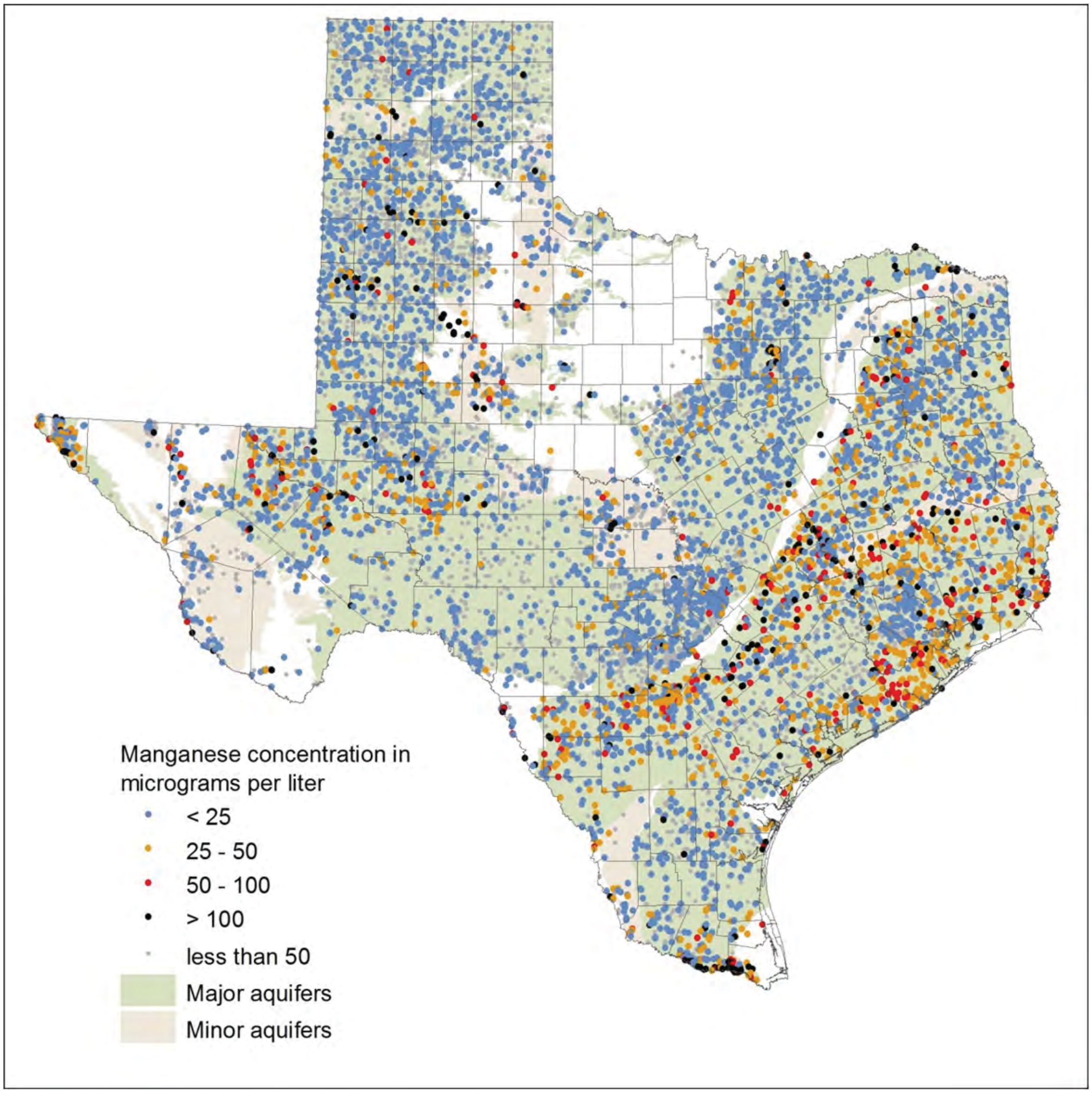

Figure 24. Manganese concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

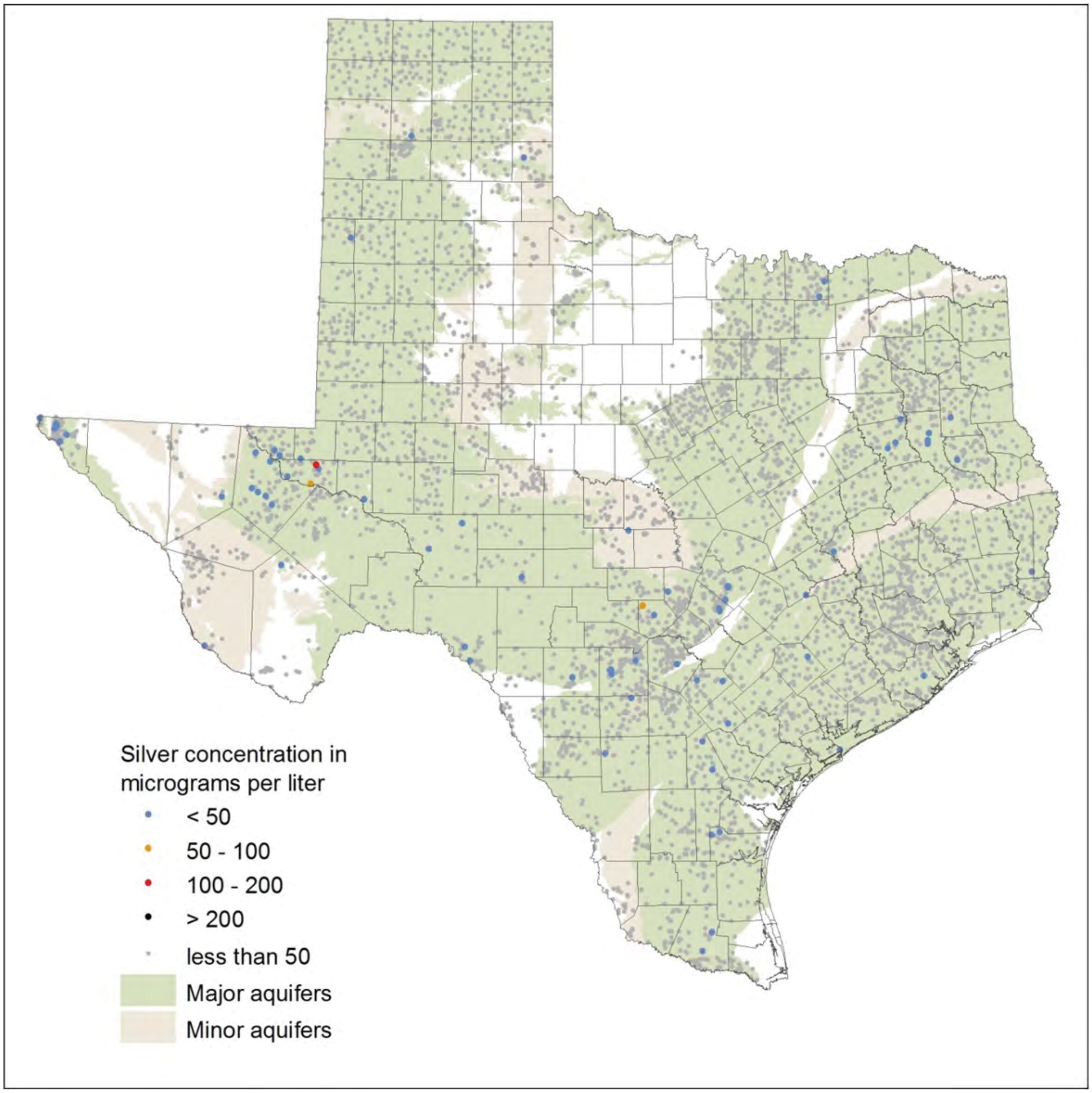

Figure 25. Silver concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Smaller gray symbols and associated less than values indicate non-detects below the indicated detection limit concentration. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

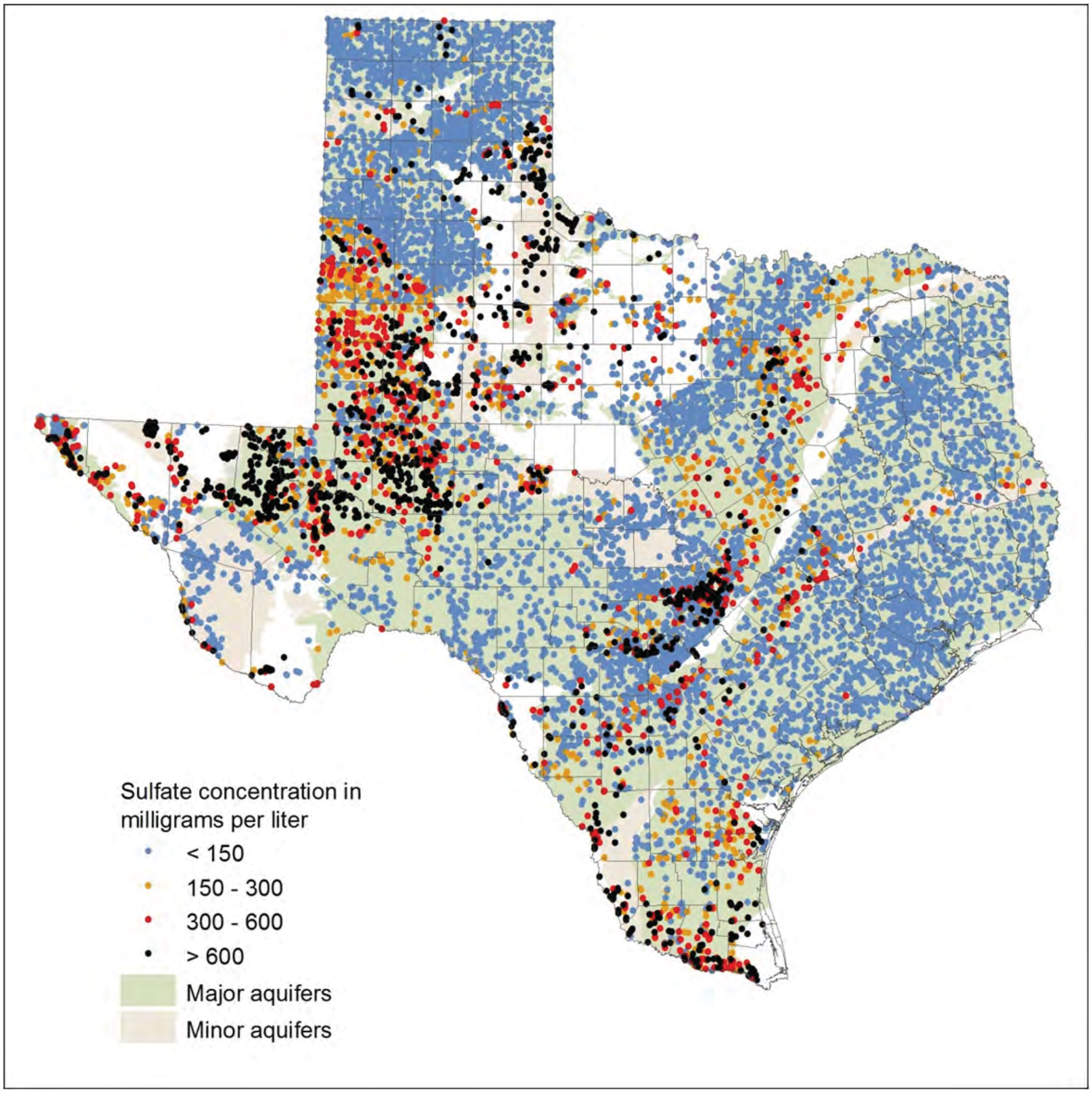

Figure 26. Sulfate concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

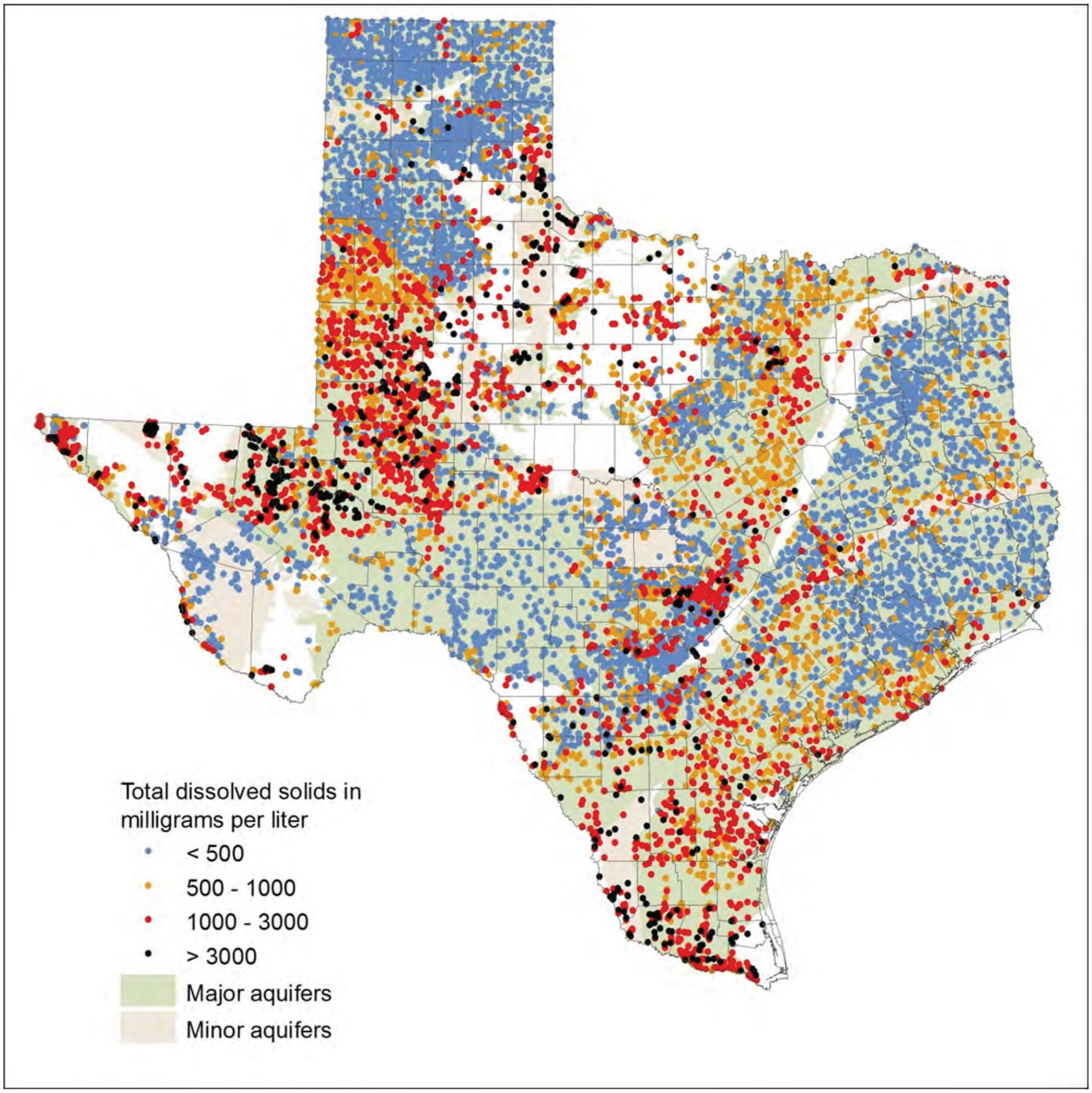

Figure 27. Total dissolved solids concentrations in Texas groundwater. Colored symbols indicate detected concentrations within indicated ranges. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

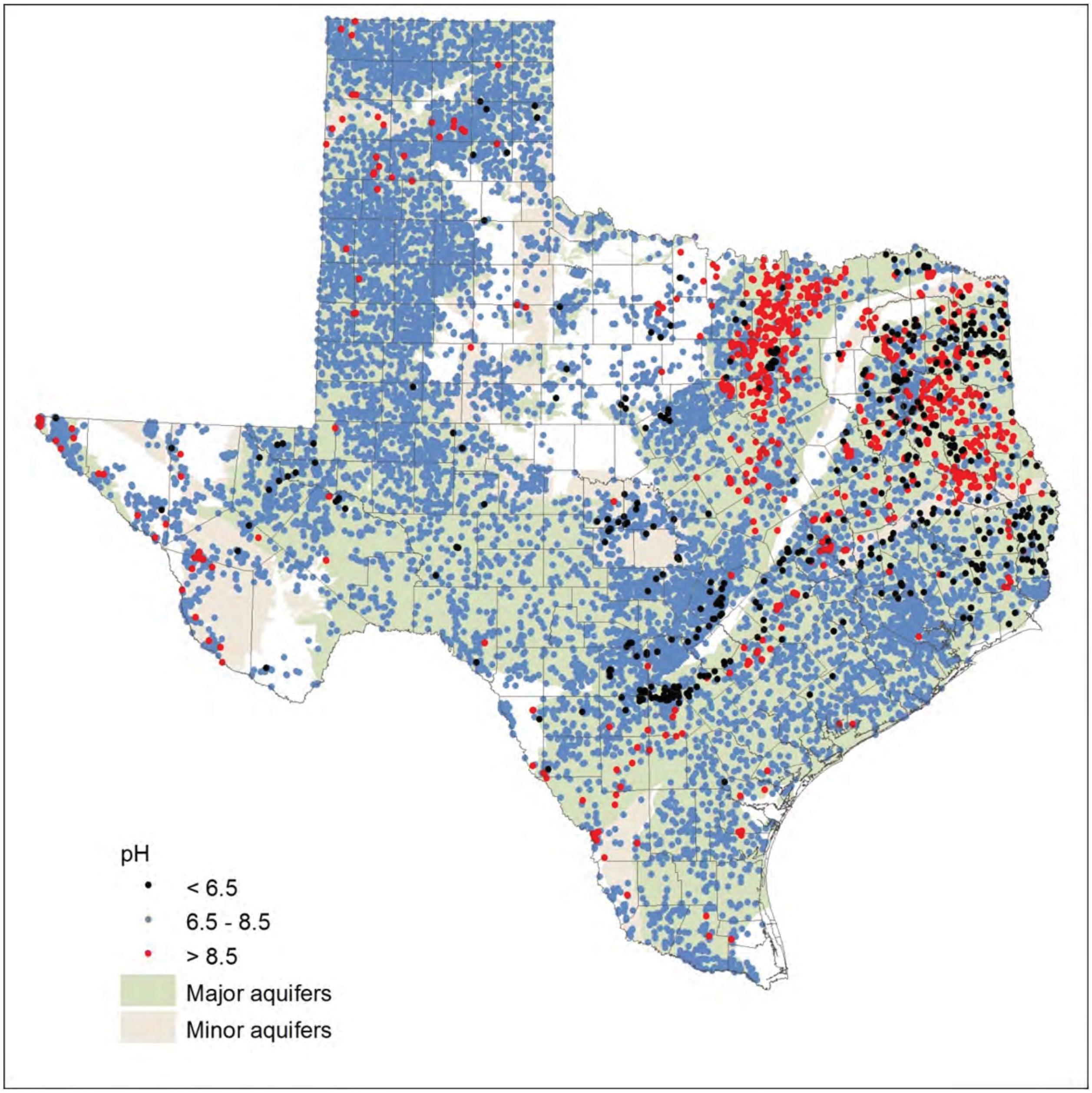

Figure 28. pH values in Texas groundwater. Colored symbols indicate detected values within indicated ranges. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

3.1a Summary Results for Major and Minor Aquifers

The probability or risk of exceeding any primary MCL is summarized for all major and minor aquifers and is subdivided into low (0 – 40 percent), moderate (40 – 60 percent) and high (60 – 100 percent) risk categories by both aquifer area and aquifer volume (Table 3). Maps of all major aquifers (Figure 29) and minor aquifers (Figure 30) depict the area results. Percent exceedances by aquifer area and by aquifer volume differ because of spatial variations in aquifer thickness. For example, 27 percent of the Ogallala aquifer area is in the high risk category whereas only 14 percent of the aquifer volume is in this category because most of the contamination is in the southern region where the aquifer is thinner.

Area percent probabilities of exceeding any primary MCL for all major aquifers combined are 14 percent in the high, 14 percent in the moderate, and 72 percent in the low risk categories. Aquifers with the greatest percentage of high risk areas are the Hueco-Mesilla Bolson (62 percent), followed by the Seymour (29 percent), Ogallala (27 percent), and Pecos Valley (26 percent) aquifers and lowest in the Edwards (BFZ) (0 percent), Trinity (2 percent), and Carrizo-Wilcox (3 percent) aquifers.

Volume percent exceedances of any primary MCL for all major aquifers combined are 8 percent in the high, 14 percent in the moderate, and 78 percent in the low risk categories. Aquifers with the greatest percentage of high risk volumes are the Hueco-Mesilla Bolson (47 percent), Seymour (26 percent), Ogallala (14 percent), and Pecos Valley Alluvium (14 percent) aquifers and lowest in the Edwards (BFZ) (0 percent), Trinity (2 percent), Carrizo-Wilcox (2 percent), and Edwards-Trinity Plateau (6 percent) aquifers.

Area percent exceedances of any primary MCL for all minor aquifers combined are 25 percent in the high, 19 percent in the moderate, and 56 percent in the low risk categories. Aquifers with the greatest percentage of high risk areas are the Hickory (73 percent), Lipan (70 precent), and Edwards-Trinity (High Plains) (68 percent) aquifers and lowest in the Blossom, Nacatoch, Queen City, and Sparta aquifers (0 percent).

Volume percent exceedances of any primary MCL for all minor aquifers combined are 15 percent in the high, 16 percent in the moderate, and 69 percent in the low risk categories. Aquifers with the greatest percentage of high risk volumes are the Hickory (77 percent), Lipan (71 percent), Edwards-Trinity (High Plains) (69 percent) aquifers and lowest in the Blossom, Nacatoch, Queen City, and Sparta aquifers (0 percent).

Table 3. Probability of exceeding any primary MCL by aquifer. Aquifer areas overlap. Aquifer volumes do not represent water storage volumes. Exceedance probability values are expressed as percentages and those for "All" aquifers represent weighted total values. Aquifers without area percentages have insufficient data for analysis and aquifers without volume values and percentages do not have SWAP saturated thickness information.

	Aquifer area				*Aquifer volume*			
	mi^2	*Low %*	*Mod %*	*High %*	mi^3	*Low %*	*Mod %*	*High %*
Major Aquifers								
Ogallala	36,000	67	6	27	650	83	3	14
Gulf Coast	40,900	57	27	16	4,920	67	23	10
Carrizo-Wilcox	35,800	90	7	3	4,020	94	4	2
Trinity	32,100	92	6	2	2,140	94	4	2
Edwards-Trinity Plateau	34,200	65	19	16	2,810	75	19	6
Seymour	3,300	40	31	29	17	43	31	26
Hueco-Mesilla Bolson	1,360	30	8	62	700	44	9	47
Pecos Valley Alluvium	5,780	59	15	26	269	75	11	14
Edwards BFZ	4,250	61	39	0	336	55	45	0
All major aquifers	194,000	72	14	14	15,900	78	14	8
Minor Aquifers								
Blaine	3,610	62	22	16	93	54	28	18
Blossom	278	100	0	0	1.3	100	0	0
Dockum	25,600	32	27	41	2,570	26	26	48
Edwards-Trinity (High Plains)	7,740	21	11	68	185	21	10	69
Ellenburger-San Saba	5,220	78	8	14	653	76	7	17
Hickory	8,610	9	18	73	576	8	15	77
Igneous	5,620	67	27	6	1,960	72	24	4
Lipan	670	16	14	70	67	15	14	71
Nacatoch	1,610	100	0	0	16	100	0	0
Queen City	14,600	99	1	0	393	100	0	0
Rita Blanca	392	65	11	24	14	60	13	27
Sparta	7,850	100	0	0	172	100	0	0
West Texas Bolsons	1,870	62	29	9	205	30	50	20
Woodbine	7,640	92	4	4	237	90	5	5
Yegua-Jackson	13,400	42	49	9	261	55	37	8
Bone Spring-Victorio Peak	716	(?)	(?)	(?)	N/A	(?)	(?)	(?)
Brazos River Alluvium	1,060	81	8	11	N/A	-	-	-
Capitan Reef	1,850	62	29	9	N/A	(?)	(?)	(?)
Marathon	39	-	-	-	N/A	-	-	-
Marble Falls	215	-	-	-	N/A	-	-	-
Rustler	1,300	(?)	(?)	(?)	N/A	(?)	(?)	(?)
All minor aquifers	111,000	56	19	25	7,400	50	51	29
Summary								
All aquifers	305,000	66	16	18	23,300	69	16	15

Area: total aquifer area, *Volume*: total aquifer volume calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Mod*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

"N/A" not available, "-" pervasive MCL exceedances are not present, "(?)" pervasive MCL exceedances are present but there are insufficient data for analysis.

The total area of all aquifers in Texas is approximately 305,000 mi^2, which includes overlapping regions of spatially-coincident aquifers, and the total volume is approximately 23,300 mi^3. The probability of exceeding MCL concentrations was summarized for the highest risk category (60 – 100 percent) for the five most commonly pervasive contaminants across all aquifers by both affected aquifer area (Table 4) and affected aquifer volume (Table 5). Areas at high risk of MCL violation by these contaminants individually represent more than 1% of the total aquifer area in Texas and include arsenic (4.0 percent), fluoride (2.7 percent), nitrate-N (1.0 percent), gross alpha (1.7 percent), and combined radium (2.4 percent). Areas at high risk of MCL violation by less widespread contaminants, including selenium and uranium, together affect approximately 0.5 percent of total aquifer area in Texas.

Because many aquifers are affected by multiple contaminants, the total aquifer area at high risk of any MCL is greater. The total aquifer area at high risk of any primary MCL exceedance is approximately 53,300 mi^2 which represents 18 percent of the total aquifer area in Texas (Table 4). Among the five most pervasive individual contaminants, arsenic is the most widespread with 12,200 mi^2 at high risk with the Ogallala, Gulf Coast, and Edwards-Trinity (High Plains) aquifers accounting for most of that area (10,800 mi^2). The second-most pervasive contaminant is fluoride, with 8,050 mi^2 at high risk, primarily in the Ogallala and Edwards-Trinity (High Plains) aquifers (6,630 mi^2). Combined radium affects the next largest area (7,140 mi^2), primarily in the Dockum and Hickory aquifers (6,290 mi^2), though this may reflect under-sampling of these aquifers, particularly in their deepest regions. Gross alpha affects 5,190 mi^2 and nitrate-N affects 2,780 mi^2.

The total aquifer volume at high risk of any primary MCL exceedance is approximately 3,360 mi^3 which represents 14 percent of the total aquifer volume in Texas (Table 5). Among the five most pervasive individual contaminants, arsenic affects the greatest volume (738 mi^3), primarily in the Hueco-Mesilla Bolson, Edwards-Trinity (High Plains) and Igneous aquifers (482 mi^3 combined). Radium affects the next largest volume (519 mi^3), primarily in the Hickory and Dockum aquifers (411 mi^3 combined), though again this may reflect under-sampling of these aquifers. Fluoride affects 323 mi^3, primarily in the Ogallala, Dockum, Edwards-Trinity (High Plains), and Ellenburger-San Saba aquifers (297 mi^3 combined). Gross alpha affects 322 mi^3, primarily in the Gulf Coast, Edwards-Trinity Plateau, and Dockum aquifers (232 mi^3 combined). Nitrate-N affects 53 mi^3, primarily in the Pecos Valley, Ogallala, Seymour, Edwards-Trinity (High Plains) and Lipan aquifers (49 mi^3 combined).

Table 4. Aquifer areas (mi^2) within high probability (60 – 100 percent) MCL exceedance categories by contaminant.

Aquifer	*Total*	*Any*	*As*	*F*	*NO_3-N*	*Alpha*	*Ra*	*TDS*
Major Aquifer								
Ogallala	36,000	9,790	5,540	3,690	637	6.2	-	4,360
Gulf Coast	40,900	6,700	1,370	-	-	549	223	7,220
Carrizo-Wilcox	35,800	1,100	-	-	-	17	431	1,450
Trinity	32,100	611	-	165	-	29	150	5,630
Edwards-Trinity Plateau	34,200	5,540	-	-	12	1,500	49	4,260
Seymour	3,600	968	-	-	736	3.5	-	739
Hueco-Mesilla Bolson	1,360	839	839	-	-	-	-	484
Pecos Valley	5,780	1,520	164	-	127	128	-	3,550
Edwards (BFZ)	4,250	1.9	-	0.4	-	1.5	-	5.8
All major aquifers	194,000	27,100	7,900	3,860	1,510	2,230	853	27,700
Minor Aquifer								
Blaine	3,610	573	-	-	-	-	-	3,610
Blossom	276	-	-	-	-	-	-	3.5
Dockum	25,600	10,500	45	581	48	2,050	2,050	8,710
Edwards-Trinity (High Plains)	7,740	5,230	3,850	2,940	640	-	-	1,890
Ellenburger-San Saba	5,220	725	-	303	1.5	316	-	204
Hickory	8,610	6,310	-	-	2.3	431	4,240	-
Igneous	5,620	349	225	-	-	2.3	-	-
Lipan	670	471	-	-	471	-	-	503
Nacatoch	1,610	-	-	-	-	-	-	334
Queen City	14,600	4.6	-	-	-	4.6	-	1,210
Rita Blanca	392	92	-	-	-	-	-	28
Sparta	7,850	-	-	-	-	-	-	1,180
West Texas Bolsons	1,870	155	42	32	-	-	-	74
Woodbine	7,640	330	-	330	-	-	-	2,070
Yegua-Jackson	13,400	1,220	153	-	-	-	-	6,580
Bone Spring-Victorio Peak	716	(?)	-	-	(?)	(?)	-	(?)
Brazos River Alluvium	1,060	119	-	-	109	-	-	48
Capitan Reef	1,850	159	-	-	-	159	(?)	1,330
Marathon	39	(?)	-	-	(?)	-	-	-
Marble Falls	215	-	-	-	-	-	-	-
Rustler	1,300	(?)	-	-	-	(?)	(?)	(?)
All minor aquifers	111,000	26,200	4,310	4,190	1,270	2,960	6,290	27,800
All Aquifers	305,000	53,300	12,200	8,050	2,780	5,190	7,140	55,500

Total: total aquifer area, aquifer areas in high probability (60 – 100%) category of exceeding the MCL for *Any*: any constituent, *As*: arsenic, *F*: fluoride, *NO_3-N*: nitrate-N, *Alpha*: gross alpha, *Ra*: radium, *TDS*: total dissolved solids.

“N/A” not available, “-“ pervasive MCL exceedances are not present, “(?)” pervasive MCL exceedances are present but there are insufficient data for analysis.

Table 5. Aquifer volumes (mi^3) within high probability (60 – 100 percent) MCL exceedance categories by contaminant.

Aquifer	*Total*	*Any*	*As*	*F*	*NO_3-N*	*Alpha*	*Ra*	*TDS*
Major Aquifer								
Ogallala	650	90	53	33	5.1	0.04	-	42
Gulf Coast	4,920	510	71	-	-	63	34	746
Carrizo-Wilcox	4,020	78	-	-	-	1.5	40	135
Trinity	2,140	40	-	2.2	-	1.0	21	357
Edwards-Trinity Plateau	2,810	170	-	-	0.3	55	2.6	196
Seymour	17	4.6	-	-	3.4	0.01	-	2.9
Hueco-Mesilla Bolson	698	327	327	-	-	-	-	227
Pecos Valley	269	36	3.9	-	16	11	-	197
Edwards (BFZ)	336	0.2	0.02	-	-	0.2	-	0.3
All major aquifers	15,900	1,260	460	35	25	132	98	1,900
Minor Aquifer								
Blaine	93	17	-	-	0.01	-	-	93
Blossom	1.3	-	-	-	-	-	-	-
Dockum	2,570	1,230	8.7	139	0.6	114	99	1,290
Edwards-Trinity (High Plains)	185	128	95	76	15	-	-	47
Ellenburger-San Saba	653	108	-	49	0.01	46	-	47
Hickory	576	446	-	-	0.2	29	322	-
Igneous	1,960	88	60	0.04	-	0.8	-	-
Lipan	67	12	-	-	12	-	-	13
Nacatoch	16	-	-	-	-	-	-	3.3
Queen City	393	0.1	-	-	-	0.1	-	54
Rita Blanca	14	3.7	-	-	-	0.5	-	1.0
Sparta	172	-	-	-	-	-	-	24
West Texas Bolsons	205	40	6.6	12	-	-	-	3.0
Woodbine	237	12	-	12	-	-	-	72
Yegua-Jackson	261	20	7.8	-	-	-	-	106
Bone Spring-Victorio Peak	N/A	(?)	-	-	(?)	(?)	-	(?)
Brazos River Alluvium	N/A	(?)	-	-	(?)	-	-	(?)
Capitan Reef	N/A	(?)	-	-	-	(?)	(?)	(?)
Marathon	N/A	-	-	-	-	-	-	-
Marble Falls	N/A	-	-	-	-	-	-	-
Rustler	N/A	(?)	-	-	-	(?)	(?)	(?)
All minor aquifers	7,400	2,100	278	288	28	190	421	1,750
All Aquifers	23,300	3,360	738	323	53	322	519	3,650

Total: total aquifer volume, aquifer volumes in high probability (60 – 100%) category of exceeding the MCL for *Any*: any constituent, *As*: arsenic, *F*: fluoride, *NO_3-N*: nitrate-N, *Alpha*: gross alpha, *Ra*: radium, *TDS*: total dissolved solids.

"N/A" not available, "-" pervasive MCL exceedances are not present, "(?)" pervasive MCL exceedances are present but there are insufficient data for analysis.

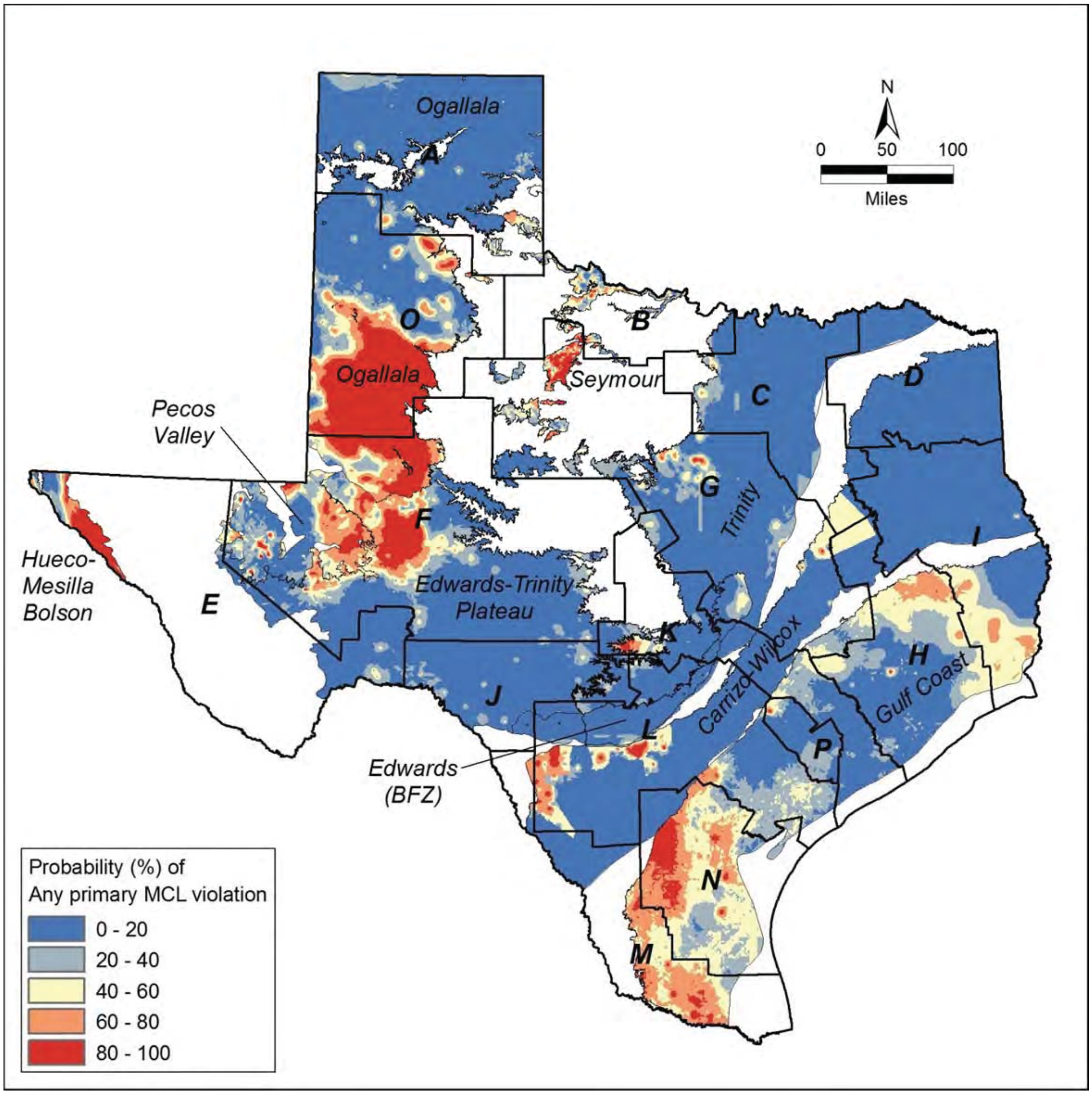

Figure 29. Probability of exceeding any primary MCL in major aquifers. Regional Water Planning Area (RWPA) boundaries and designations are also shown.

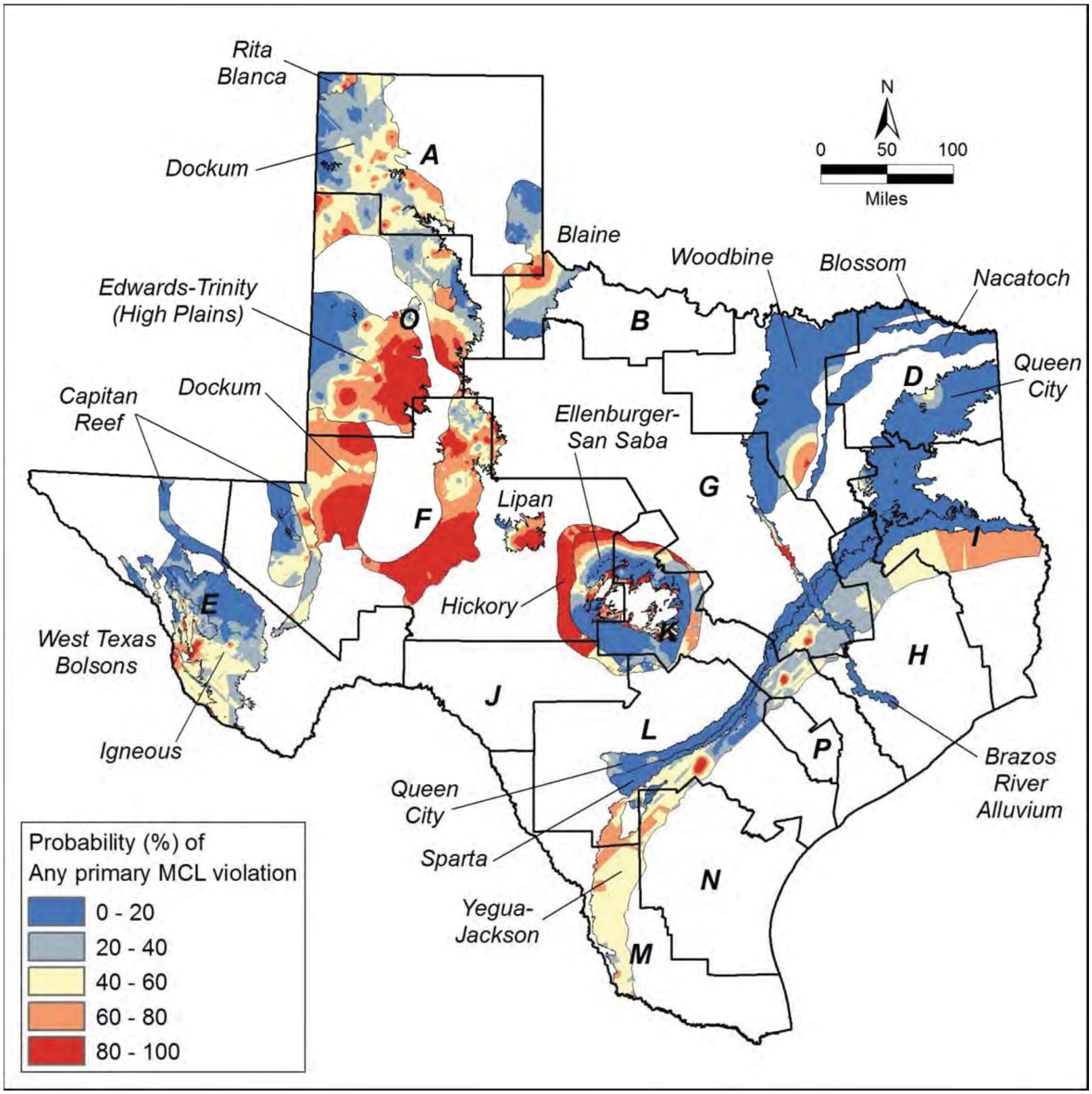

Figure 30. Probability of exceeding any MCL in minor aquifers. Regional Water Planning Area (RWPA) boundaries and designations are also shown.

3.1b Major Aquifers

Ogallala

The Ogallala Aquifer shows high percentages of primary MCL exceedances for arsenic, followed by fluoride, nitrate-N, gross alpha, uranium, and selenium (Table 6 and Table 7). The highest probabilities of any primary MCL exceedance are focused in the southern part of the southern Ogallala Aquifer (Figure 31). High levels of primary MCL exceedances in this region may be related to the fact that the aquifer is thin—the median thickness 16 meters (m)--relative to the northern part of the southern Ogallala in Texas (median thickness 45 m), and these contaminants are not as readily diluted (Scanlon et al., 2009). Other factors may also contribute to MCL exceedances in this region, such as hydrochemistry and upward flow from the underlying Dockum Aquifer. The high risk category of exceeding any primary MCL represents 27 percent of the area and 14 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 12 percent of the area and 6 percent of the volume. Concentrations of most constituents of concern tend to increase with increasing well depth (Appendix 1). However, this may primarily reflect a regional difference in depth to water and saturated thickness, both of which are less in the southern part of the Ogallala relative to the northern part. Secondary MCL percent exceedances are dominated by fluoride, followed by TDS (Figure 32), chloride, and sulfate. Most of the secondary MCL exceedances also occur in the southern part of the Ogallala Aquifer. The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 1.

Arsenic contamination was originally attributed to application of arsenical pesticides to defoliate cotton in the southern Ogallala Aquifer (Nativ, 1988); however, unsaturated zone profiling showed that arsenic from this source is likely adsorbed in the shallow soil zone (upper 6 ft) and is highly correlated with phosphate concentrations (Reedy et al., 2007). Previous studies showed that arsenic contamination is related to volcanic ashes in the Ogallala Aquifer; however, leaching of ashes generally occurs shortly after deposition; therefore, arsenic released from volcanic ashes is most likely sorbed onto iron oxides. Mobilization of arsenic in the southern High Plains was attributed to the counter-ion effect, related to change in groundwater chemistry from calcium to sodium type water (Scanlon et al., 2009). Fluoride contamination is also high in the southern Ogallala Aquifer. A recent National Academy Panel suggested reducing the fluoride MCL; however, if the primary fluoride MCL were reduced to 2 mg/L, similar to the World Health Organization (WHO) guidance value of 1.5 mg/L, percentage of fluoride exceedances would increase from 14 to 47 percent throughout the Texas Ogallala Aquifer, as seen in the differences in primary and secondary fluoride MCL percent exceedances (Table

7Table 6). Previous studies found that arsenic, fluoride, and selenium concentrations are highly correlated, which was attributed to a common source in volcanic ashes. High nitrate contamination is related to cropland. Unsaturated zone profiles show that much of the high nitrate could be attributed to conversion of soil organic nitrogen under rangeland vegetation to nitrate with oxidation during initial cultivation (Scanlon et al., 2008). In addition to mineralization of soil organic nitrogen, fertilizer application also results in groundwater nitrate contamination because nitrate is readily leached through the soil profile. Nitrate-N exceedances are likely to continue to increase on the basis of mobilization of large nitrate inventories measured in unsaturated zone profiles. Finer grained soils in the northern part of the southern High Plains and the Central High Plains (Pullman clay loam and equivalent soils) also restrict water movement from the land surface and minimize nitrate loading to the underlying aquifer in these regions.

Table 6. Ogallala Aquifer percent area and volume within MCL exceedance probability categories. Ogallala Aquifer area is 36,000 mi^2 and volume is 650 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	67	6	27	83	3	14
Arsenic	78	6	15	88	4	8
Fluoride	83	7	10	91	4	5
Nitrate-N	92	6	2	96	3	1
Selenium	98	2	0	99	1	0
Gross alpha	92	8	0	96	4	0
Uranium	98	2	0	99	1	0
TDS	79	9	12	90	7	6

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 7. Summary of MCL violations in Ogallala Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	1,502	25	1,477	NA	0.9	4.58	0	0
Arsenic	10	µg/L	2,041	1,528	513	4.11	1	164	383	**19**
Barium	2,000	µg/L	2,025	2,010	15	71.2	43	3,470	1	0
Beryllium	4	µg/L	1,505	0	1,505	NA	NA	NA	0	0
Cadmium	5	µg/L	1,338	11	1,327	NA	0.2	11	1	0
Chromium	100	µg/L	1,724	832	892	1.37	1	1,200	3	0
Copper	1,300	µg/L	1,945	1,129	816	1.59	1	72,700	1	0
Fluoride	4	µg/L	2,577	2,531	46	1.9	0.01	16	348	**14**
Lead	15	µg/L	1,614	240	1,374	2	1	378	4	0
Mercury	2	µg/L	1,083	17	1,066	NA	0.2	2	0	0
Nitrate-N	10	mg/L	2,720	2,694	26	2.2	0.005	96	295	**11**
Nitrite-N	1	mg/L	634	197	437	4	1	0.56	0	0
Selenium	50	µg/L	2,010	1,412	598	5	1	494	73	**4**
Thallium	2	µg/L	1,503	1	1,502	NA	3.4	3.4	1	0
Gross alpha	15	pCi/L	999	952	47	7.26	1.17	525	92	**9**
Gross beta	50	pCi/L	650	575	75	8.3	2.9	104	3	0
Combined Radium	5	pCi/L	612	101	511	NA	0.99	14.1	6	1
Uranium	30	µg/L	515	512	3	7.42	1.1	322	19	**4**
Secondary MCL										
Aluminum	50	µg/L	1,850	735	1,115	2.5	0.7	24,500	24	1
Chloride	300	mg/L	2,732	2,731	1	31.3	1	13,898	384	14
Copper	1,000	µg/L	1,945	1,129	816	1.59	1	72,700	0	0
Fluoride	2	mg/L	2,577	2,531	46	1.9	0.01	16	1,201	47
Iron	300	µg/L	2,079	939	1,140	11	1	69,600	103	5
Manganese	50	µg/L	1,987	891	1,096	6.2	1	880	65	3
Silver	100	µg/L	678	5	673	NA	0.1	0.31	0	0
Sulfate	300	mg/L	2,604	2,602	2	47	1	4,760	327	13
TDS	1,000	mg/L	2,547	2,547	0	403	69	22,675	409	16
Zinc	5,000	µg/L	1,974	1,444	530	9.95	1	23,000	11	1
pH	6.5-8.5		2,573	2,573	0	7.41	5.11	8.99	19	1

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

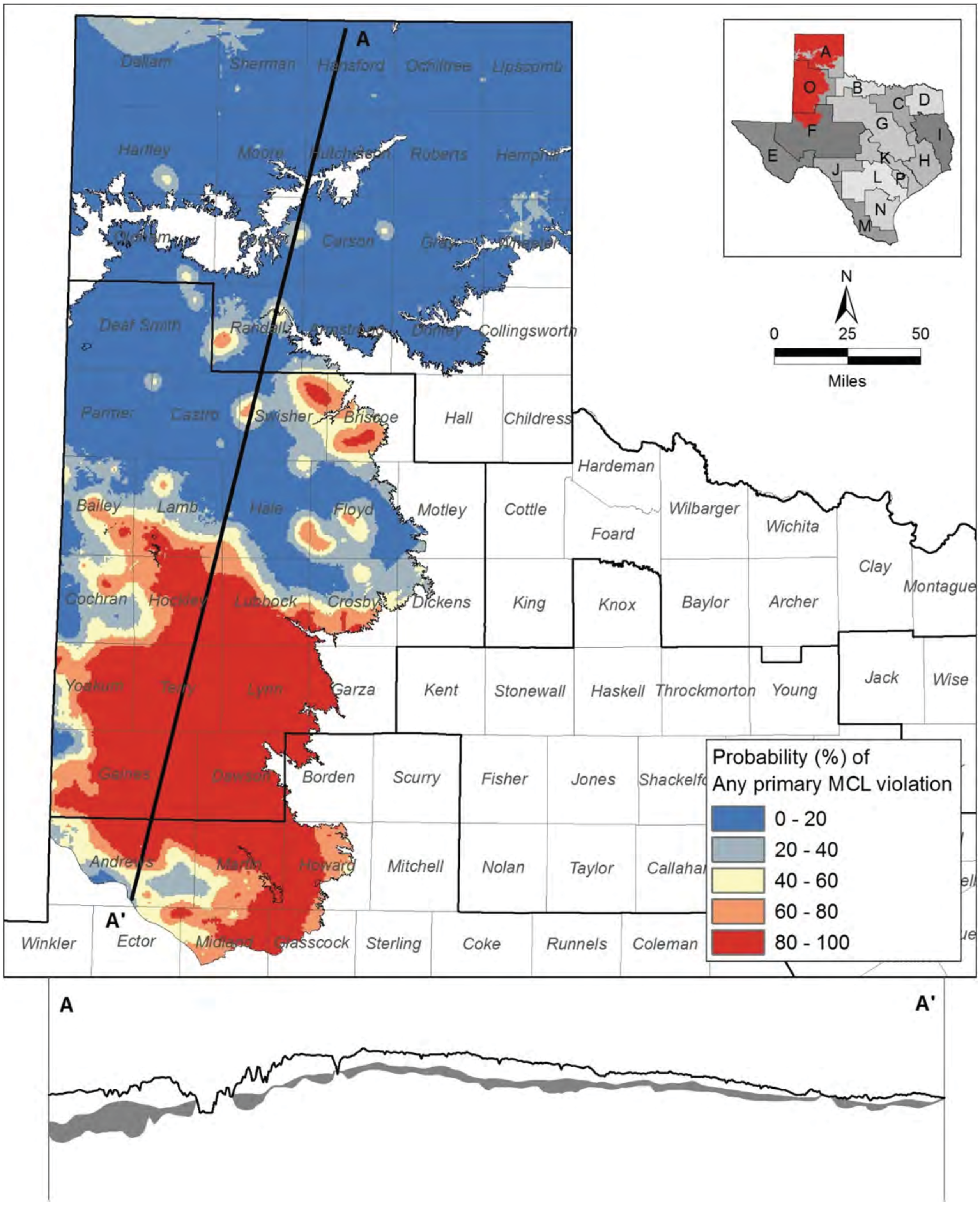

Figure 31. Ogallala Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

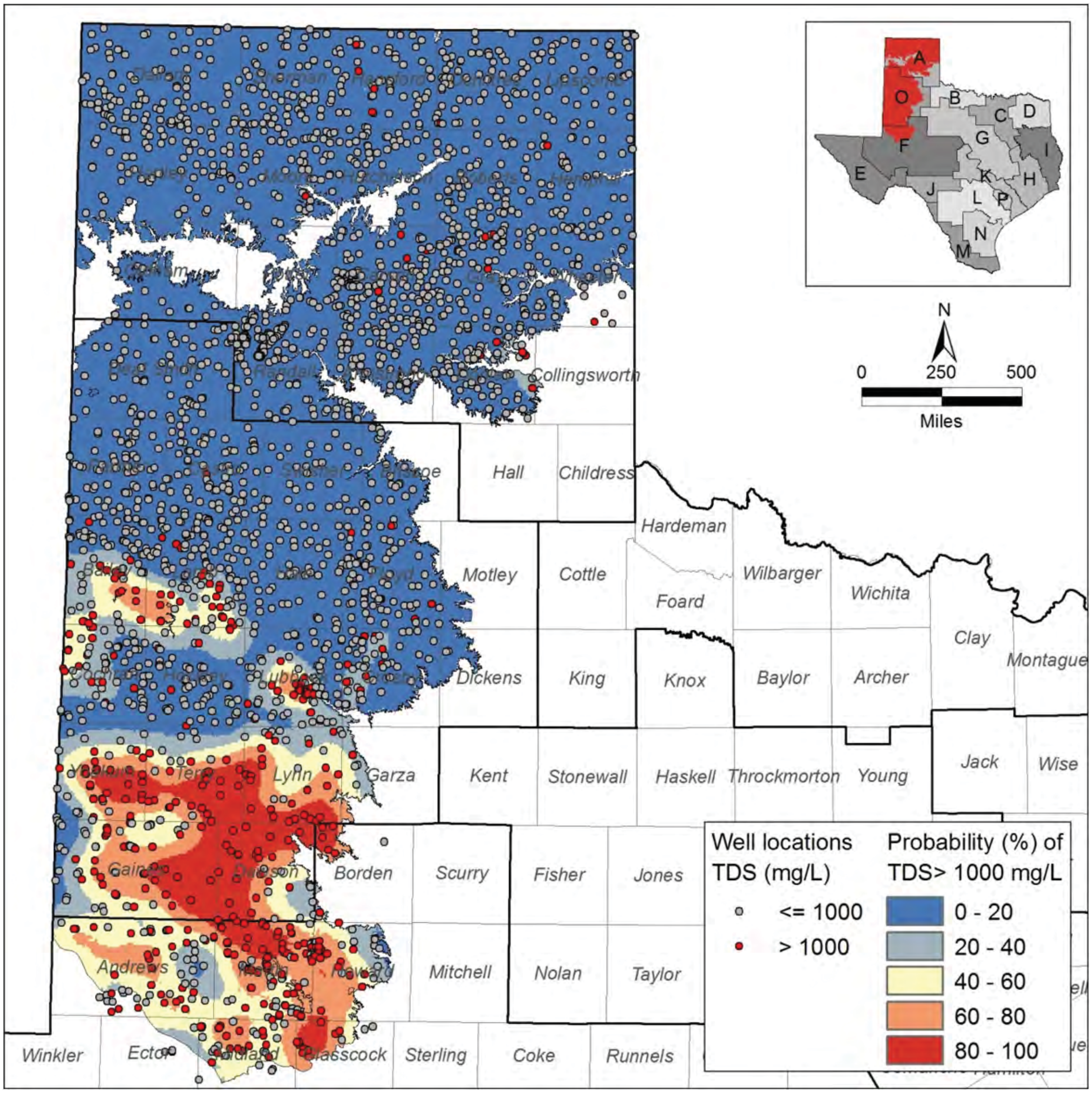

Figure 32. Ogallala Aquifer probability of total dissolved solids (TDS) secondary MCL violation.

Gulf Coast

The Gulf Coast Aquifer is characterized by high levels of any primary MCL exceedance (Table 8 and Table 9). Concentrations of the constituents of concern do not generally show any trends with increasing well depth (Appendix 2), although this may reflect under-sampling of deeper horizons nearer the coast line. The high risk category of exceeding any primary MCL represents 16 percent of the area and 10 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 12 percent of the area and 6 percent of the volume. The highest levels of primary MCL exceedances occur in the southern part of the aquifer and in a zone in the northern part of the aquifer (Figure 33). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 2. The only constituent with high primary MCL percent exceedance in the north is combined radium; all other primary MCL exceedances are focused in the south. However, the radium results may be biased by under-sampling because radium analyses are frequently performed only when indicated by elevated gross alpha activities. The primary MCL with the highest percent exceedance is arsenic, followed by gross alpha and combined radium (Table 9). Volcanic ashes, typified by the Catahoula Formation., are the most likely source of arsenic (Scanlon et al., 2005; Glenn and Lester, 2010; Gates et al., 2011). Arsenic MCL percent exceedances are highest in the Jasper Aquifer of the Gulf Coast Aquifer which is immediately adjacent to the Catahoula Formation and decrease in aquifers that are more distant from the Catahoula Formation (e.g. Evangeline and Chicot aquifers). Gates et al. (2011) conducted a detailed transect of arsenic and other ions in the outcrop zones of the Jasper, Evangeline, and Chicot aquifers in Karnes and Goliad counties and attributed elevated arsenic concentrations to the volcanic ashes in the Catahoula Formation followed by sorption onto iron oxides and competitive desorption from iron oxides by silica.

High levels of gross alpha radiation are found throughout the Gulf Coast aquifers. Combined radium-226 and radium-228 are high near uranium bearing volcanic ashes, such as those found in the Catahoula Formation and adjacent to salt domes and leaky faults. Combined radium concentrations are highest in the northern Gulf Coast and the distribution is similar to that of radon-222 in public water wells because radon-222 is derived from radium-226 through radioactive decay. Cech et al. (1988) noted that high radon concentrations are found in proximity to salt domes, leaky faults, and uranium bearing volcanic ashes rather than being related to the bulk mineralogy in the host rock of the aquifer. Cech et al. (1988) noted high radon concentrations in Harris County near Houston related to salt domes. The percentage of uranium MCL exceedances in the Gulf Coast Aquifer (3 percent) is much lower than that of gross alpha radiation or combined radium, and uranium exceedances are mostly restricted to the southern Gulf Coast. Nicot et al. (2010) describe the origin and distribution of uranium in the South Texas Uranium province and show that uranium VI, leached from volcanic ashes in the Catahoula Formation, is transported downdip with oxidizing fresh groundwater; it precipitates when it reaches reducing conditions related to lignite deposits or hydrogen sulfide or methanogenic fluids associated with upward movement along faults. Mineralization results in the typical roll front deposits. Uranium is related to other oxyanions such as arsenic, vanadium, and selenium. Restriction of elevated uranium concentrations in the southern Gulf Coast is attributed to the drier climate since Eocene times and concentration of uranium, whereas gaining streams in the more humid northern portion would mobilize uranium and discharge it to the ocean without encountering reducing conditions on land.

Groundwater is also contaminated with nitrate (2 percent of wells in the Gulf Coast Aquifer). Most nitrate contamination is restricted to the southern Gulf Coast Aquifer and nitrate-N concentrations decrease with depth, suggesting a source near the land surface (Glenn and Lester, 2010). Groundwater in the Gulf Coast is also characterized by high TDS, mostly related to elevated chloride concentrations and generally restricted to the southern Gulf Coast where precipitation is much lower (Figure 34). Elevated iron and manganese concentrations are mostly found in the northern Gulf Coast and may be related to more pervasive reducing conditions in this part of the aquifer.

Table 8. Gulf Coast Aquifer percent area and volume within MCL exceedance probability categories. Gulf Coast Aquifer area is 40,900 mi^2 and volume is 4,920 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	57	27	16	67	23	10
Arsenic	90	7	3	94	4	1
Gross alpha	93	6	1	95	4	1
Combined radium	90	9	1	92	8	1
Uranium	99	0	0	99	0	0
TDS	67	15	18	74	11	15

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 9. Summary of MCL violations in Gulf Coast Aquifer groundwater wells

	MCL	units	Analyses	Detects	Non-detects	Median	Min	Max	> MCL	% MCL
Primary MCL										
Antimony	6	μg/L	1,409	9	1,400	NA	1.02	39	2	0
Arsenic	10	μg/L	1,814	793	1,021	2	0.5	569	251	**14**
Barium	2,000	μg/L	1,817	1,800	17	128	4	3,720	5	0
Beryllium	4	μg/L	1,412	1	1,411	NA	33	33	1	0
Cadmium	5	μg/L	1,212	13	1,199	NA	0.2	10	5	0
Chromium	100	μg/L	1,655	643	1,012	1.48	1	30.1	0	0
Copper	1,300	μg/L	1,814	820	994	1.63	0	1,410	1	0
Fluoride	4	μg/L	1,774	1,741	33	0.5	0.01	350	9	1
Lead	15	μg/L	1,423	144	1,279	NA	1	34	4	0
Mercury	2	μg/L	1,293	44	1,249	0.1	0.1	2	0	0
Nitrate-N	10	mg/L	1,692	893	799	0.018	0	85	42	2
Nitrite-N	1	mg/L	681	85	596	NA	0.01	14.9	1	0
Selenium	50	μg/L	1,806	366	1,440	0.6	0.6	82	9	0
Thallium	2	μg/L	1,370	11	1,359	NA	0.43	59	2	0
Gross alpha	15	pCi/L	1,400	1,117	283	4.5	-1.2	537	176	**13**
Gross beta	50	pCi/L	1,182	938	244	6.2	0	80	4	0
Comb. radium	5	pCi/L	604	190	414	0	-2.5	26.6	65	**11**
Uranium	30	μg/L	585	266	319	0.6	0.003	211	20	**3**
Secondary MCL										
Aluminum	50	μg/L	1,518	178	1,340	NA	1	65,000	29	2
Chloride	300	mg/L	1,943	1,942	1	108	2	6,840	543	28
Copper	1,000	μg/L	1,814	820	994	1.63	0	1,410	0	0
Fluoride	2	mg/L	1,774	1,741	33	0.5	0.01	350	92	5
Iron	300	μg/L	1,854	1,055	799	43	0	139,000	300	16
Manganese	50	μg/L	1,834	1,250	584	10.4	0	3,300	398	22
Silver	100	μg/L	1,297	11	1,286	NA	1.06	10	0	0
Sulfate	300	mg/L	1,787	1,623	164	17	0.03	5,110	146	8
TDS	1,000	mg/L	1,660	1,660	0	580	22	12,900	407	25
Zinc	5,000	μg/L	1,816	1,165	651	9.2	1	3,790	0	0
pH	6.5-8.5		1,960	1,960	0	7.38	4.57	11.4	110	6

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

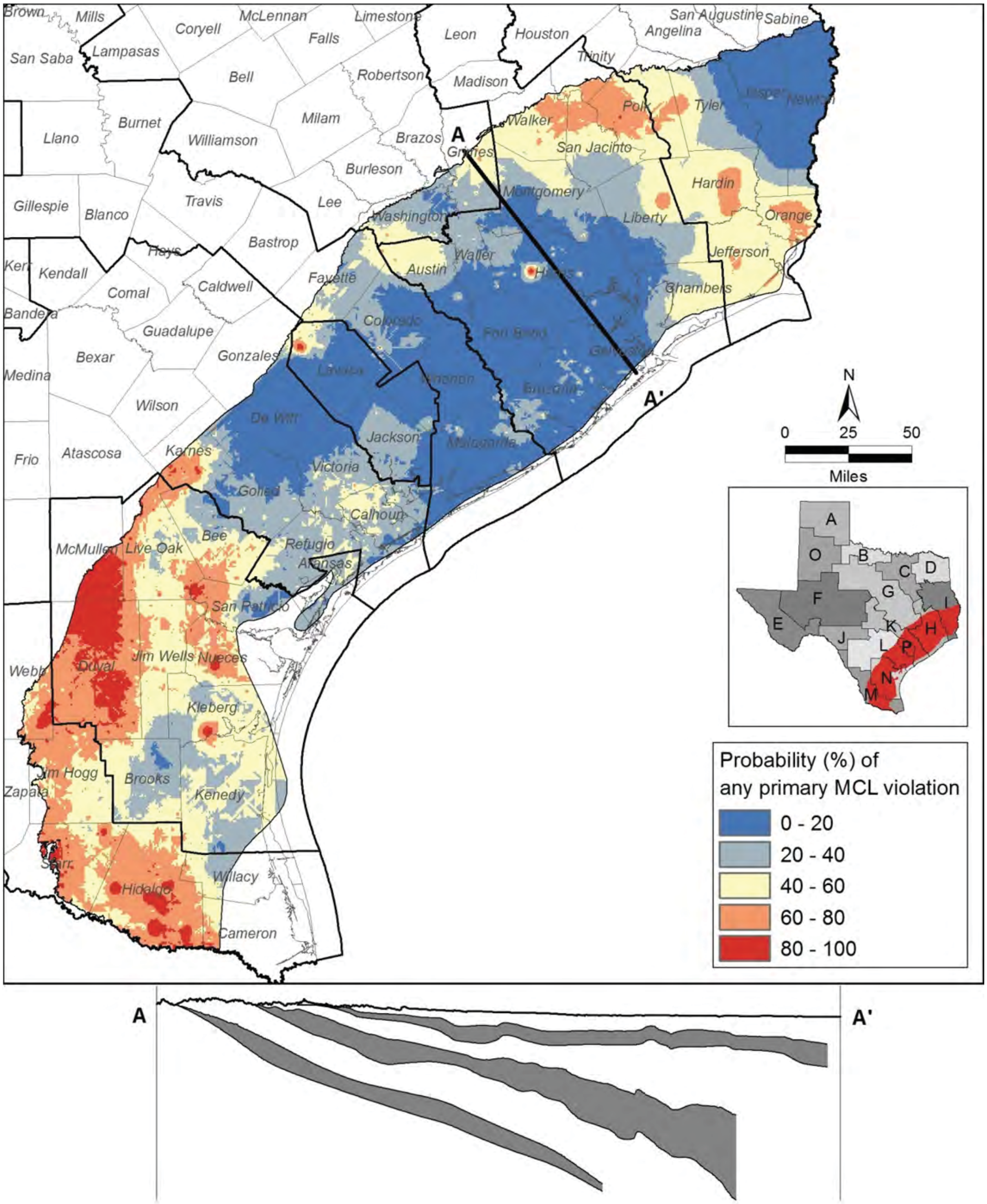

Figure 33. Gulf Coast Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

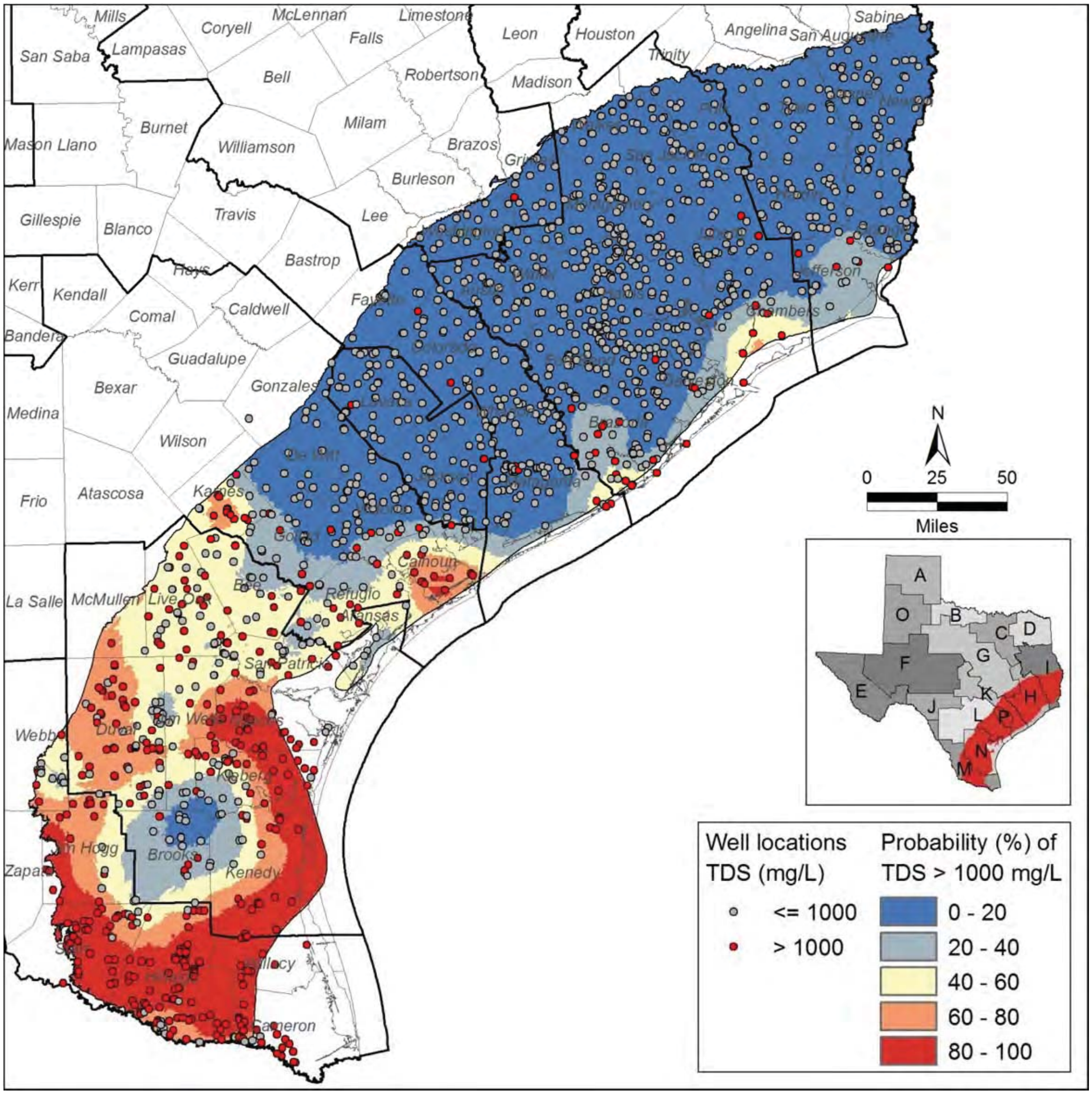

Figure 34. Gulf Coast Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Carrizo-Wilcox

Groundwater in the Carrizo-Wilcox Aquifer is generally of high quality with very low occurrences of primary MCL violations (Table 10 and Table 11). Concentrations of the primary MCL constituents of concern typically exhibit a decreasing trend with increasing well depth while TDS shows an increase with increasing well depth (Appendix 3). The high risk category of exceeding any primary MCL represents 3 percent of the area and 2 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 4 percent of the area and 3 percent of the volume. Primary MCL violations are mainly restricted to radionuclides within limited areas in the south and central outcrop regions (Figure 36). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 3. TDS are generally low throughout the aquifer, with the exception of a zone of high TDS downdip in the southern part of the aquifer Figure 36). Although the aquifer extent is defined to be within the 3,000 mg/L TDS region, there are a very few wells beyond the downdip limit of the aquifer. There are no wells with MCL exceedances for arsenic or fluoride and very low MCL percent exceedances of selenium, uranium, and combined radium. Combined radium MCL percent exceedances are generally restricted to the southern Carrizo-Wilcox Aquifer. Lignite has also been shown to contain uranium and its radiogenic derivatives (Preusse, 1982). Secondary MCL percent exceedances are dominated by iron and manganese which are generally found throughout the aquifer. Boghici (2009) evaluated chemical analyses of 331 groundwater samples collected by TWDB between 2005 and 2006 and noted that groundwater quality was generally good, although there were some MCL exceedances for nitrate-N, lead, fluoride, chloride, sulfate, iron, manganese, and TDS. Groundwater salinity generally did not change over time in the northern and central Carrizo-Wilcox Aquifer but increased slightly (mostly by ≤100 mg/L) in the southern zone, with the exception of Zavala, Dimmit, and Frio counties, where larger changes were found. Groundwater ages increased progressively along flow paths from recharge areas to downdip areas, and most groundwater originated from precipitation sources.

Table 10. Carrizo-Wilcox Aquifer percent area and volume within MCL exceedance probability categories. Carrizo-Wilcox Aquifer area is 35,800 mi^2 and volume is 4,020 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	90	7	3	94	4	2
Gross alpha	99	1	0	99	1	0
Combined radium	91	8	1	94	5	1
TDS	91	5	4	92	4	3

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 11. Summary of MCL violations in Carrizo-Wilcox Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	880	5	875	NA	1.0	4.6	0	0
Arsenic	10	μg/L	1,118	34	1,084	NA	1.0	6.7	0	0
Barium	2,000	μg/L	1,117	1,092	25	58.3	2.0	34,100	1	0
Beryllium	4	μg/L	896	4	892	NA	0.08	10.5	2	0
Cadmium	5	μg/L	970	7	963	NA	1.0	15.4	2	0
Chromium	100	μg/L	1,110	430	680	1.1	1.0	155	1	0
Copper	1,300	μg/L	1,121	433	688	0.73	1.0	229	0	0
Fluoride	4	mg/L	1,189	1,140	52	0.25	0.01	3.9	0	0
Lead	15	μg/L	948	80	868	NA	1.0	54	7	1
Mercury	2	μg/L	759	18	741	NA	0.14	0.8	0	0
Nitrate-N	10	mg/L	1,138	356	782	NA	0.002	70.7	8	1
Nitrite-N	1	mg/L	437	30	407	NA	0.005	0.1	0	0
Selenium	50	μg/L	1,111	100	1,011	NA	1.0	105	4	0
Thallium	2	μg/L	850	1	849	NA	0.653	0.65	0	0
Gross alpha	15	pCi/L	474	199	275	1.7	-0.8	1,120	19	**4**
Gross beta	50	pCi/L	438	177	261	7.9	0.9	590	2	0
Comb. radium	5	pCi/L	100	55	45	1.8	0.2	462	16	**16**
Uranium	30	μg/L	324	25	299	NA	1.1	43	1	0
Secondary MCL										
Aluminum	50	μg/L	1,004	373	631	2.0	0.2	62,100	26	3
Chloride	300	mg/L	1,237	1,230	4	33.8	1.14	9,600	86	7
Copper	1,000	μg/L	1,121	433	688	0.73	0.1	229	0	0
Fluoride	2	mg/L	1,189	1,140	52	0.25	0.01	3.9	15	1
Iron	300	μg/L	1,224	838	386	60	0.5	20,200	322	26
Manganese	50	μg/L	1,197	991	206	11.1	1.0	2,570	222	19
Silver	100	μg/L	787	12	775	NA	1.2	6.6	0	0
Sulfate	300	mg/L	1,235	1,130	108	26.6	0.3	3,100	40	3
TDS	1,000	mg/L	1,150	1,150	0	373	16	17,600	91	8
Zinc	5,000	μg/L	1,124	614	510	5.13	0.3	3,500	0	0
pH	6.5-8.5		1,191	1,190	0	7.9	4.0	9.13	381	32

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

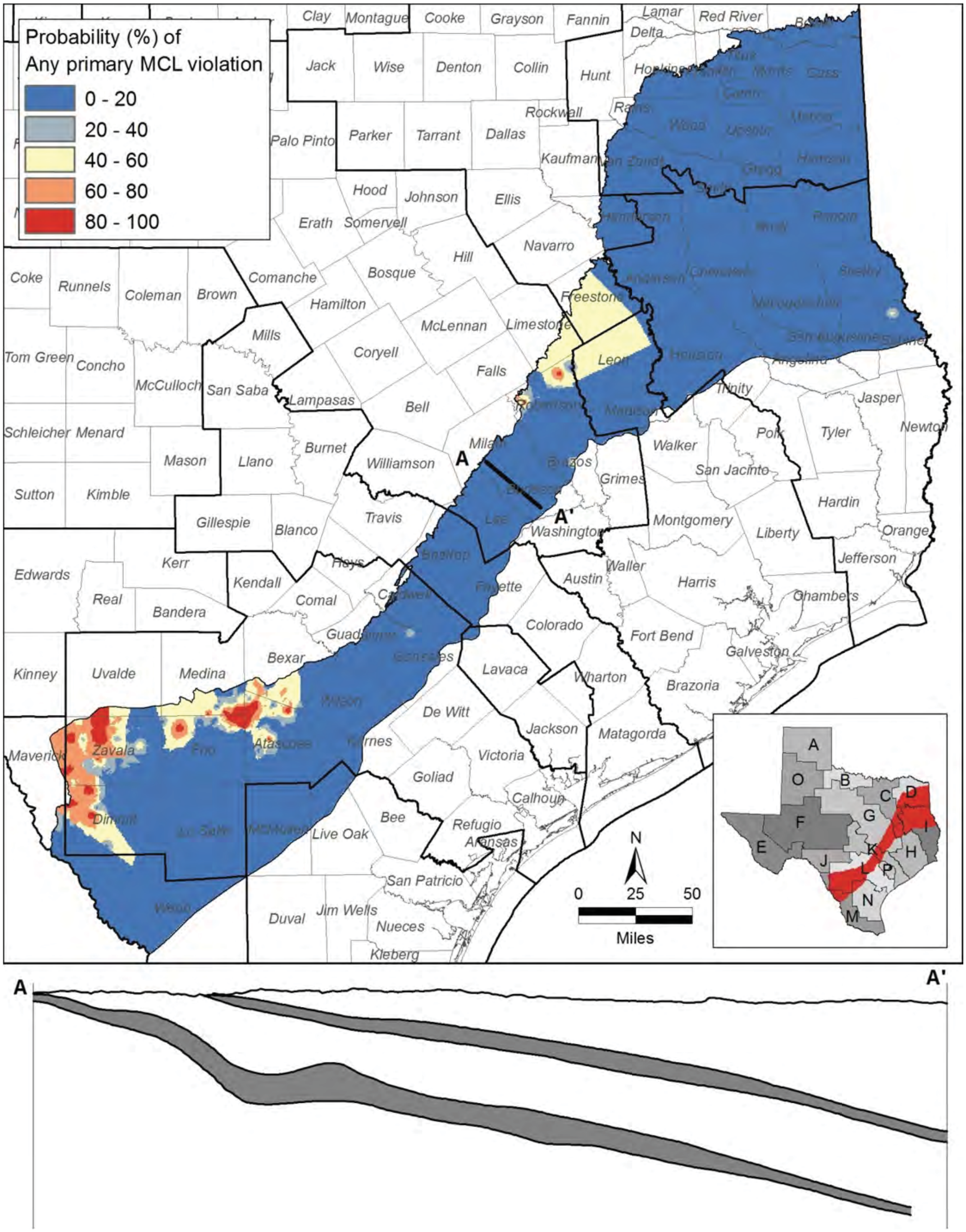

Figure 35. Carrizo-Wilcox Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

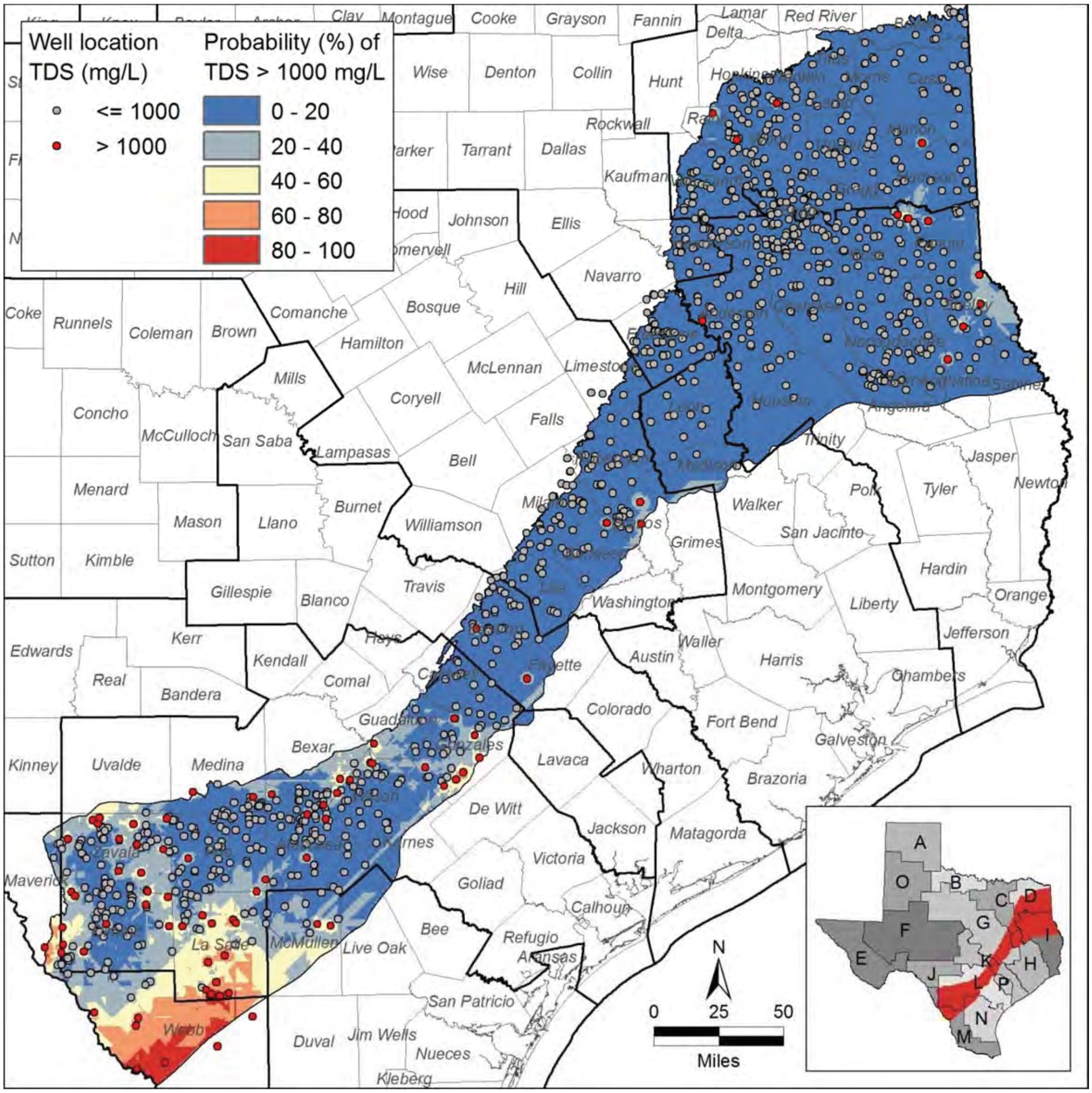

Figure 36. Carrizo-Wilcox Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Trinity

Groundwater in the Trinity Aquifer is generally of high quality with low percentages of any primary MCL violation (Table 12 and Table 13). Concentrations of the constituents of concern exhibit trends with well depth (Appendix 4). The high risk category of exceeding any primary MCL represents 2 percent of the area and 2 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 18 percent of the area and 17 percent of the volume. Nitrate-N concentrations tend to decrease while fluoride concentrations tend to increase with increasing well depth. The probability of exceeding any primary MCL is generally restricted to limited regions near the outcrop in the south and central parts of the aquifer and to downdip regions in the central and northern regions (Figure 37). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 4. The highest primary MCL percent exceedances are for fluoride and combined radium. However, secondary MCL percent exceedances are higher with moderately high TDS percent exceedances that are mostly related to high sulfate concentrations, and probabilities of exceeding the MCL generally increase downdip (Figure 38). High sulfate concentrations in the Upper Trinity Aquifer are attributed to dissolution of evaporite beds in the upper unit of the Glen Rose Formation and in the Middle Trinity Aquifer to gypsum and evaporite beds in the Cow Creek Member. of the Travis Peak Formation. There are moderately high fluoride and iron secondary MCL percent exceedances.

Table 12. Trinity Aquifer percent area and volume within MCL exceedance probability categories. Trinity Aquifer area is 32,100 mi^2 and volume is 2,140 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	92	6	2	94	4	2
Fluoride	97	3	1	99	1	0
Nitrate-N	100	0	0	100	0	0
Gross alpha	99	1	0	99	1	0
Combined radium	99	1	0	97	2	1
TDS	72	10	18	74	9	17

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 13. Summary of MCL violations in Trinity Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	1,123	5	1,118	NA	2.6	3.4	0	0
Arsenic	10	μg/L	1,379	138	1,241	NA	1.0	18	10	1
Barium	2,000	μg/L	1,357	1,330	27	45	1.0	990	0	0
Beryllium	4	μg/L	1,151	0	1,151	NA	NA	NA	0	0
Cadmium	5	μg/L	1,157	7	1,150	NA	0.5	70	3	0
Chromium	100	μg/L	1,315	358	957	NA	1.0	320	3	0
Copper	1,300	μg/L	1,352	577	775	1.63	1.0	290	0	0
Fluoride	4	μg/L	1,524	1,495	29	0.7	0.01	12.7	43	**3**
Lead	15	μg/L	1,154	192	962	NA	1.0	63.3	4	0
Mercury	2	μg/L	841	36	805	NA	0.13	3.0	2	0
Nitrate-N	10	mg/L	1,412	840	572	0.041	0.002	213	43	**3**
Nitrite-N	1	mg/L	658	118	540	NA	0.01	0.23	0	0
Selenium	50	μg/L	1,303	193	1,110	NA	1.0	54	1	0
Thallium	2	μg/L	1,064	7	1,057	NA	0.42	2.6	4	0
Gross alpha	15	pCi/L	689	335	354	2.6	0.2	504	25	**4**
Gross beta	50	pCi/L	685	341	344	NA	1.2	45.8	0	0
Comb. radium	5	pCi/L	202	102	100	1.8	0.02	23.4	23	**11**
Uranium	30	μg/L	115	39	76	NA	1.0	99	1	1
Secondary MCL										
Aluminum	50	μg/L	1,240	427	813	3.0	0.02	3,370	37	3
Chloride	300	mg/L	1,602	1,596	6	31	2.0	4,580	110	7
Copper	1,000	μg/L	1,352	577	775	1.63	1.0	290	0	0
Fluoride	2	mg/L	1,524	1,495	29	0.7	0.01	12.7	259	17
Iron	300	μg/L	1,461	795	666	25.3	1.0	12,200	205	14
Manganese	50	μg/L	1,406	810	596	2.0	1.0	405	42	3
Silver	100	μg/L	894	4	890	NA	3.0	67	0	0
Sulfate	300	mg/L	1,602	1,601	1	76.2	0.89	4,620	209	13
TDS	1,000	mg/L	1,420	1,420	0	564	150	10,400	247	17
Zinc	5,000	μg/L	1,365	973	392	12	1.0	11,700	2	0
pH	6.5-8.5		1,560	1,560	0	7.4	5.49	9.86	258	17

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

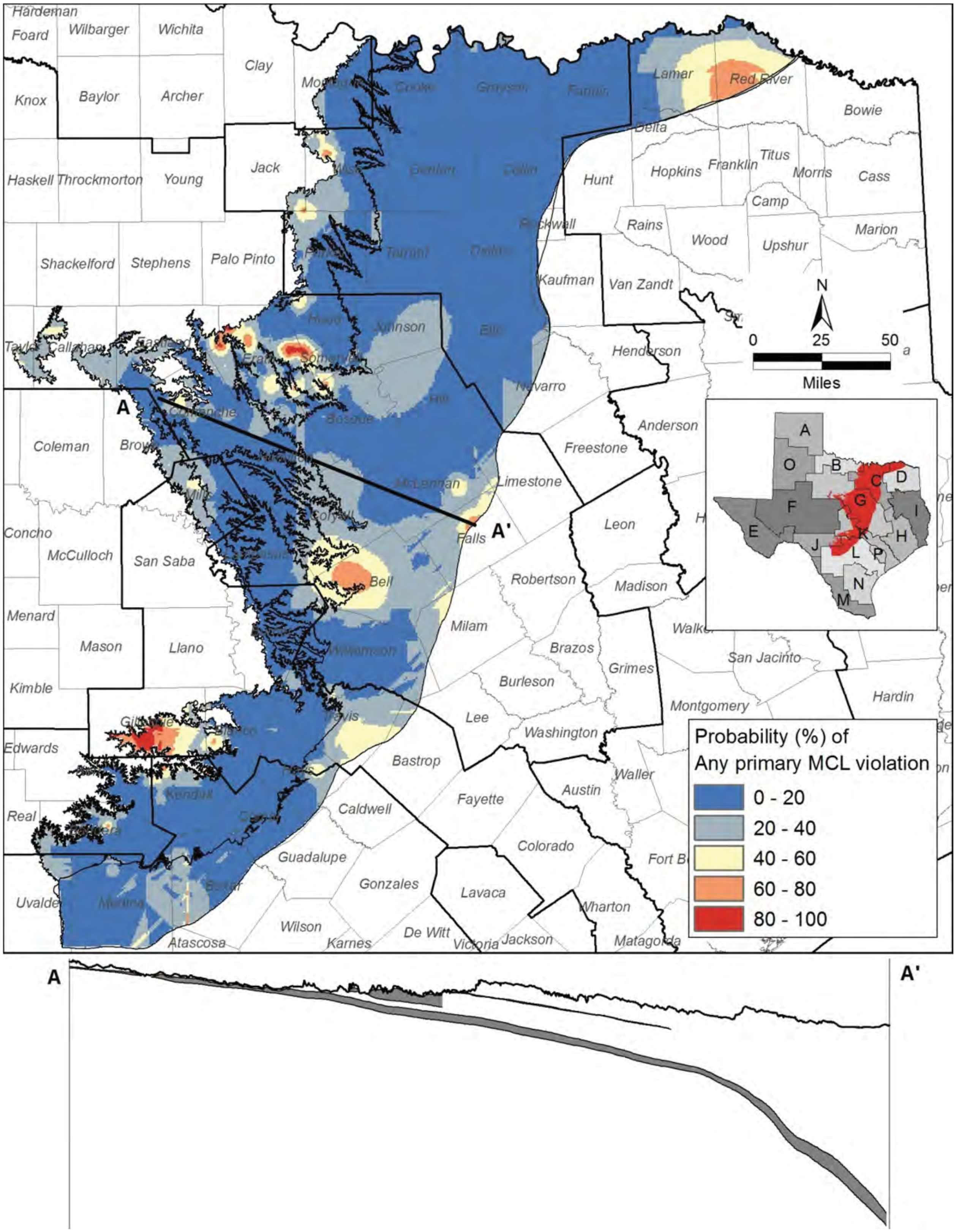

Figure 37. Trinity Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

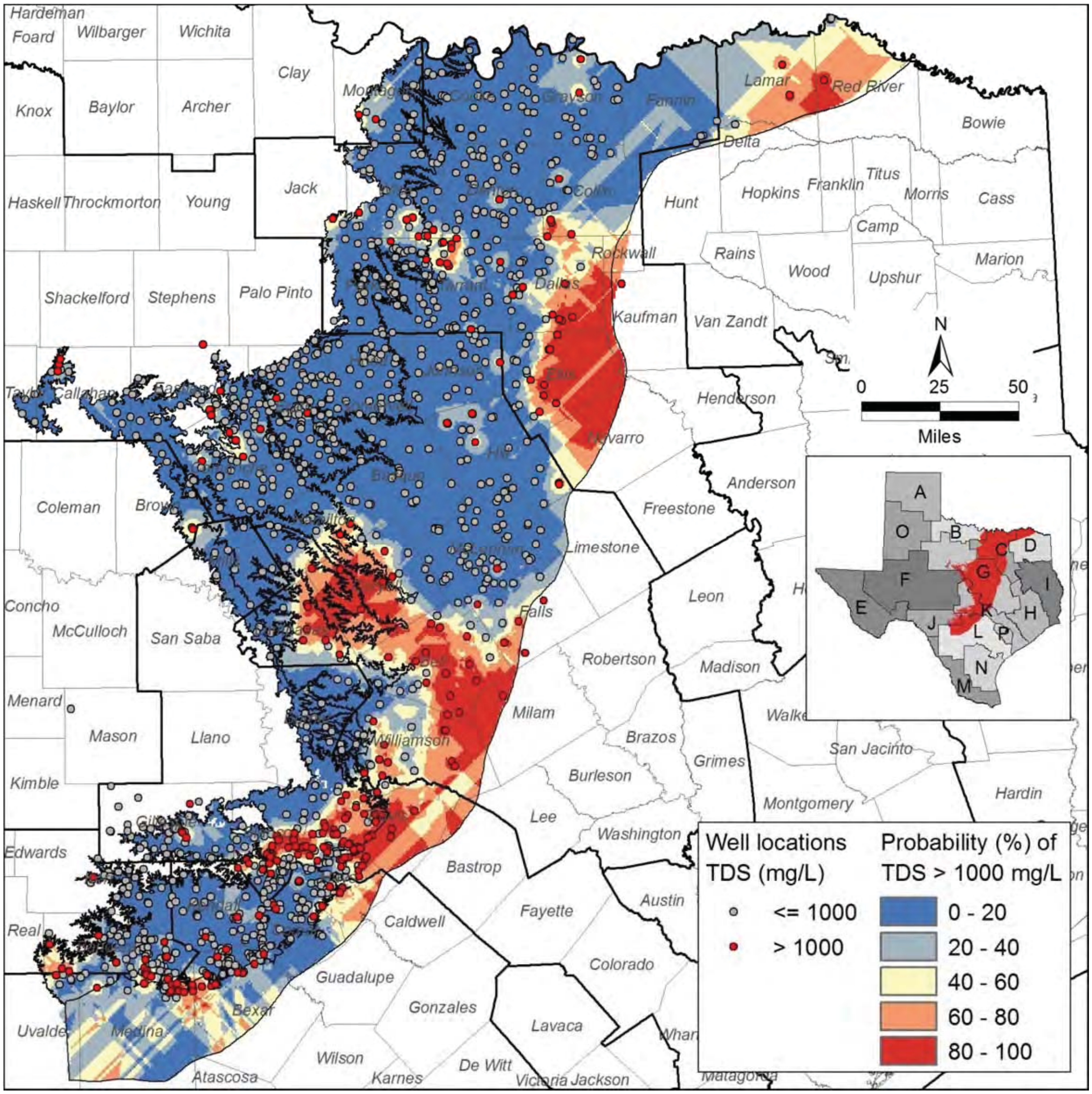

Figure 38. Trinity Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Edwards-Trinity Plateau

The probability of exceeding any primary MCL in the Edwards-Trinity (Plateau) Aquifer is focused on the northwestern region of the aquifer and is related to exceedances of gross alpha, combined radium, and uranium (Table 14 and Table 15). There are generally no significant concentration trends with well depth (Appendix 5). The high risk category of exceeding any primary MCL represents 16 percent of the area and 6 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 12 percent of the area and 7 percent of the volume. MCL exceedance percentages are the highest of all the major aquifers (Figure 39). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 5. There is a limited amount of nitrate-N contamination also in the northwest. Secondary MCL percent exceedances are characterized by high TDS, related to high sulfate and to a lesser extent high chloride concentrations (Figure 40). Secondary fluoride MCL percent exceedances are also high and indicate that reducing the fluoride primary MCL from 4 to 2 mg/L would increase the percent of wells exceeding the fluoride MCL from 0.6 percent to 18 percent.

Table 14. Edwards-Trinity Plateau Aquifer percent area and volume within MCL exceedance probability categories. Edwards-Trinity Plateau Aquifer area is 34,200 mi^2 and volume is 2,810 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	65	19	16	75	19	6
Nitrate-N	98	2	0	100	0	0
Thallium	100	0	0	100	0	0
Gross alpha	90	6	4	95	3	2
Combined radium	86	14	0	92	8	0
Uranium	96	2	2	98	1	1
TDS	80	8	12	90	3	7

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 15. Summary of MCL violations in Edwards-Trinity Plateau Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	792	5	787	NA	1.0	3.1	0	0
Arsenic	10	μg/L	966	201	765	NA	0.99	53.9	17	2
Barium	2,000	μg/L	965	959	6	50	1.74	473	0	0
Beryllium	4	μg/L	799	0	799	NA	NA	NA	0	0
Cadmium	5	μg/L	847	4	843	NA	1.1	8.9	1	0
Chromium	100	μg/L	860	462	398	1.3	1.0	62.5	0	0
Copper	1,300	μg/L	953	678	275	2.6	1.0	313	0	0
Fluoride	4	μg/L	999	985	14	1.0	0.01	9.63	6	1
Lead	15	μg/L	950	98	852	NA	1.0	10.1	0	0
Mercury	2	μg/L	293	8	285	NA	0.14	1.0	0	0
Nitrate-N	10	mg/L	1,042	975	67	2.11	0.01	67.4	66	**6**
Nitrite-N	1	mg/L	381	59	322	NA	0.01	0.28	0	0
Selenium	50	μg/L	869	319	550	2.0	1.0	131	2	0
Thallium	2	μg/L	794	30	764	NA	1.0	16	11	1
Gross alpha	15	pCi/L	481	384	97	6.0	1.0	80.4	95	**20**
Gross beta	50	pCi/L	360	228	132	10	2.6	63	2	1
Comb. radium	5	pCi/L	114	45	69	NA	1.25	43.4	24	**21**
Uranium	30	μg/L	156	136	20	4.2	0.9	91.2	15	**10**
Secondary MCL										
Aluminum	50	μg/L	856	150	706	NA	1.0	1,200	19	2
Chloride	300	mg/L	1,039	1,038	1	44.9	2.0	16,300	178	17
Copper	1,000	μg/L	953	678	275	2.6	1.0	313	0	0
Fluoride	2	mg/L	999	985	14	1.0	0.01	9.63	179	18
Iron	300	μg/L	993	373	620	15	1.0	14,100	79	8
Manganese	50	μg/L	966	459	507	0.58	0.17	761	43	4
Silver	100	μg/L	290	8	282	NA	1.1	12	0	0
Sulfate	300	mg/L	1,035	1,032	3	74.2	1.0	4,950	292	28
TDS	1,000	mg/L	989	989	0	463	147	27,800	277	28
Zinc	5,000	μg/L	957	894	63	29	1.0	4,050	0	0
pH	6.5-8.5		1,031	1,031	0	7.2	5.93	8.7	10	1

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

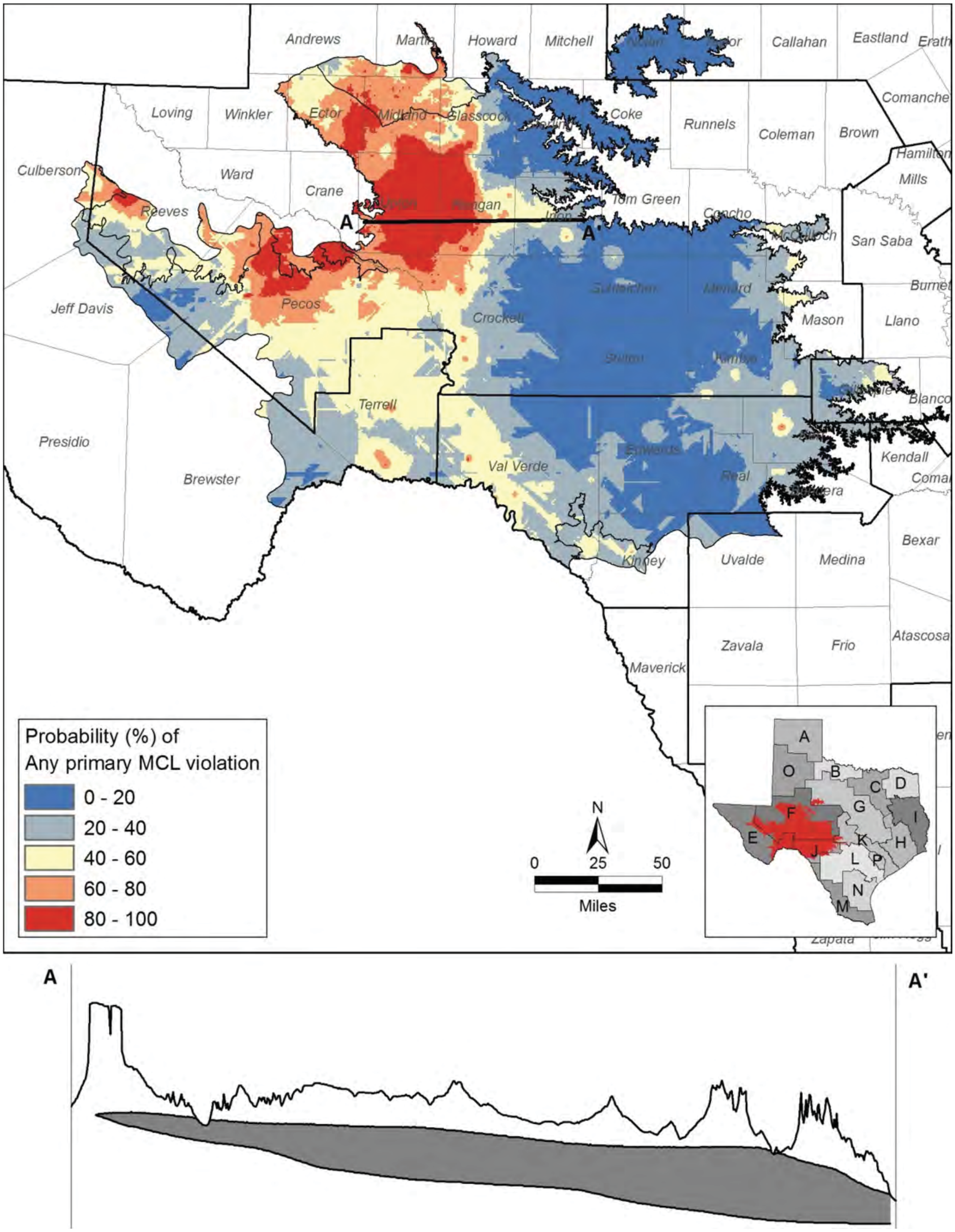

Figure 39. Edwards-Trinity Plateau Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

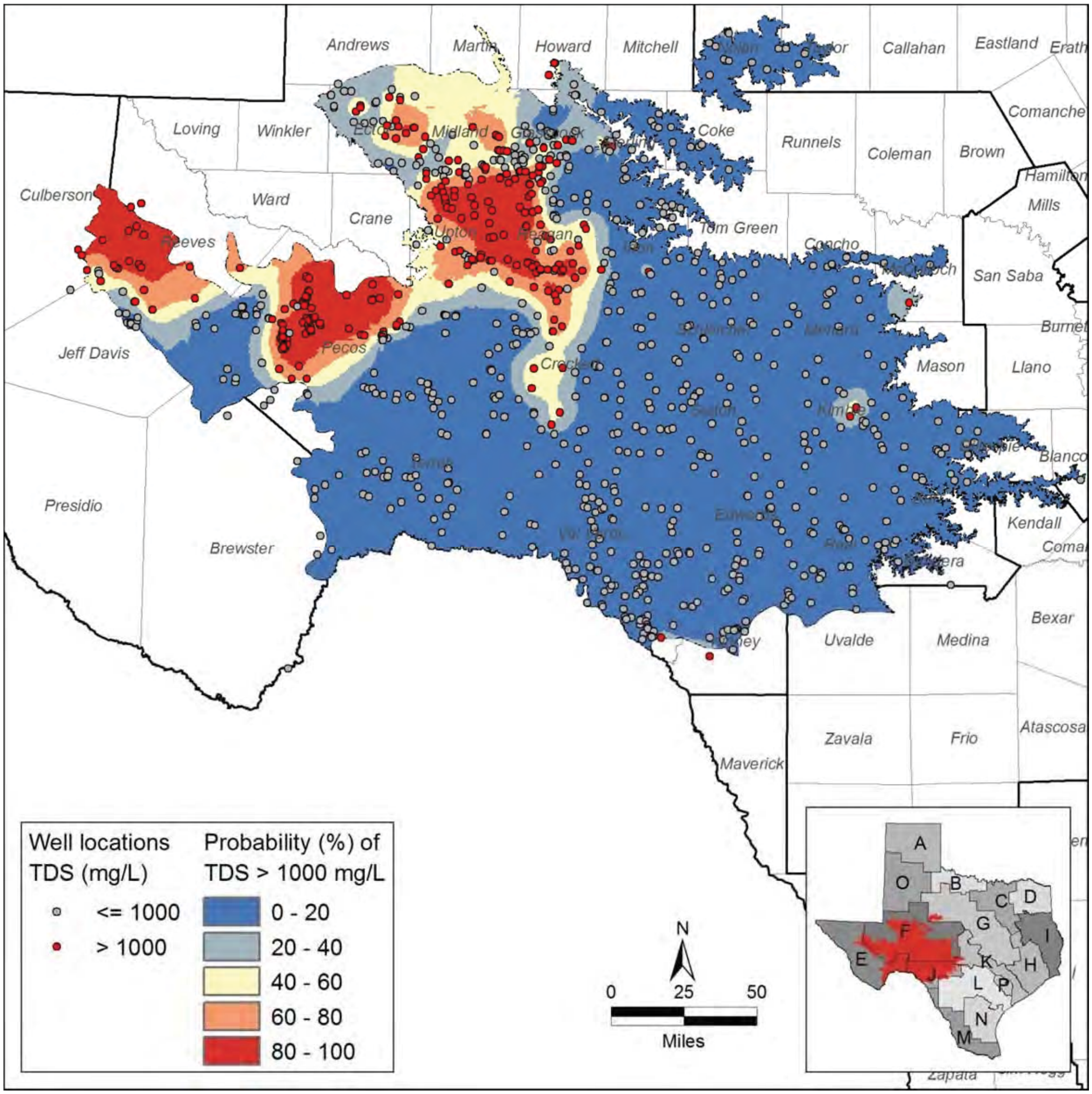

Figure 40. Edwards-Trinity Plateau Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Seymour

Groundwater in the Seymour Aquifer is dominated by nitrate-N MCL percent exceedances, attributed to oxidation of soil organic nitrogen during initial cultivation followed by leaching of fertilizers (Table 16 and Table 17) (Olyphant, 2009). The aquifer generally has a small saturated thickness and there are no significant concentration trends with will depth (Appendix 6). The high risk category of exceeding any primary MCL represents 29 percent of the area and 26 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 22 percent of the area and 17 percent of the volume. Probabilities of exceeding any primary MCL are uniformly highest in the Haskell-Knox counties pod of the aquifer Figure 41). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 6. Gross alpha MCL exceedances are also high; however, they are not linked to high combined radium or uranium exceedances. Secondary MCL percent exceedances are dominated by TDS, related to elevated chloride and sulfate, and moderately low fluoride exceedances which tend to increase towards the south and west (Figure 42).

Table 16. Seymour Aquifer percent area and volume within MCL exceedance probability categories. Seymour Aquifer area is 3,300 mi^2 and volume is 17 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	40	31	29	43	31	26
Nitrate-N	52	26	22	54	27	20
Gross alpha	98	2	0	99	1	0
TDS	61	47	22	50	33	17

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 17. Summary of MCL violations in Seymour Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	144	1	143	NA	148	148	1	1
Arsenic	10	µg/L	204	95	109	2.15	1.0	11	3	1
Barium	2,000	µg/L	221	216	5	63.2	4.7	624	0	0
Beryllium	4	µg/L	143	0	143	NA	NA	NA	0	0
Cadmium	5	µg/L	136	0	136	NA	NA	NA	0	0
Chromium	100	µg/L	182	81	101	1.99	1.0	25.7	0	0
Copper	1,300	µg/L	207	143	64	4.0	1.0	146	0	0
Fluoride	4	µg/L	234	226	8	0.75	0.02	4.07	1	0
Lead	15	µg/L	157	27	130	NA	1.0	243	1	1
Mercury	2	µg/L	123	5	118	NA	0.1	0.3	0	0
Nitrate-N	10	mg/L	223	223	0	13.6	0.08	335	149	**67**
Nitrite-N	1	mg/L	99	28	71	NA	0.01	0.49	0	0
Selenium	50	µg/L	205	142	63	4.58	1.0	62.1	3	1
Thallium	2	µg/L	144	1	143	NA	251	251	1	1
Gross alpha	15	pCi/L	111	80	31	5.1	1.1	65	15	**14**
Gross beta	50	pCi/L	69	27	42	NA	2.5	24.9	0	0
Comb. radium	5	pCi/L	51	1	50	NA	1.3	1.3	0	0
Uranium	30	µg/L	62	62	0	6.2	1.2	34.5	1	2
Secondary MCL										
Aluminum	50	µg/L	185	24	161	NA	1.0	266	5	3
Chloride	300	mg/L	234	231	3	118	3.0	2,970	60	26
Copper	1,000	µg/L	207	143	64	4.0	1.0	146	0	0
Fluoride	2	mg/L	234	226	8	0.75	0.02	4.07	17	7
Iron	300	µg/L	222	52	170	7.4	7.4	1,050	7	3
Manganese	50	µg/L	205	52	153	NA	1.0	252	4	2
Silver	100	µg/L	122	0	122	NA	NA	NA	0	0
Sulfate	300	mg/L	234	231	3	113	9.1	2,500	50	21
TDS	1,000	mg/L	217	217	0	804	215	7,960	79	36
Zinc	5,000	µg/L	205	154	51	10.2	1.7	607	0	0
pH	6.5-8.5		227	227	0	7.16	6.25	7.95	3	1

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

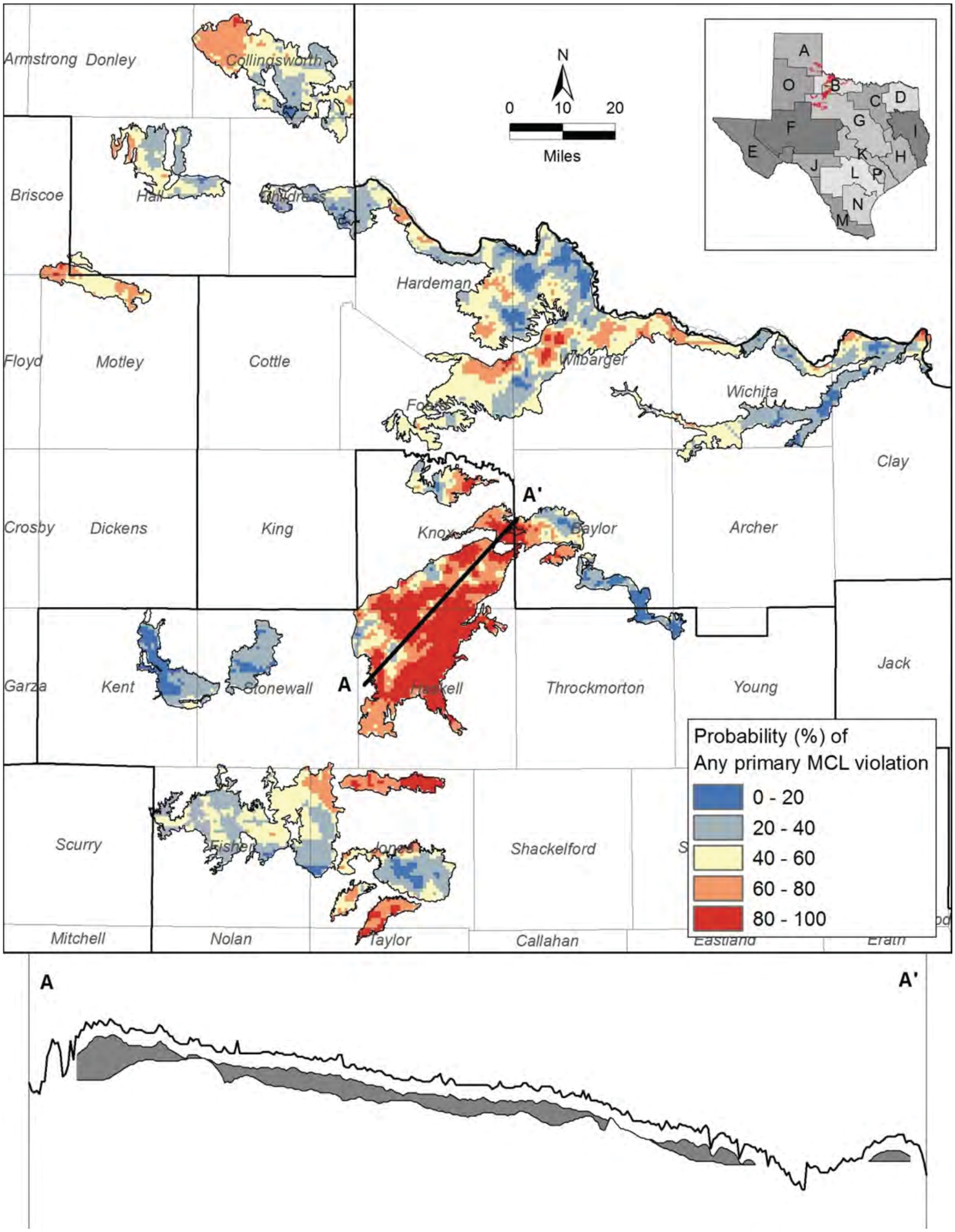

Figure 41. Seymour Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

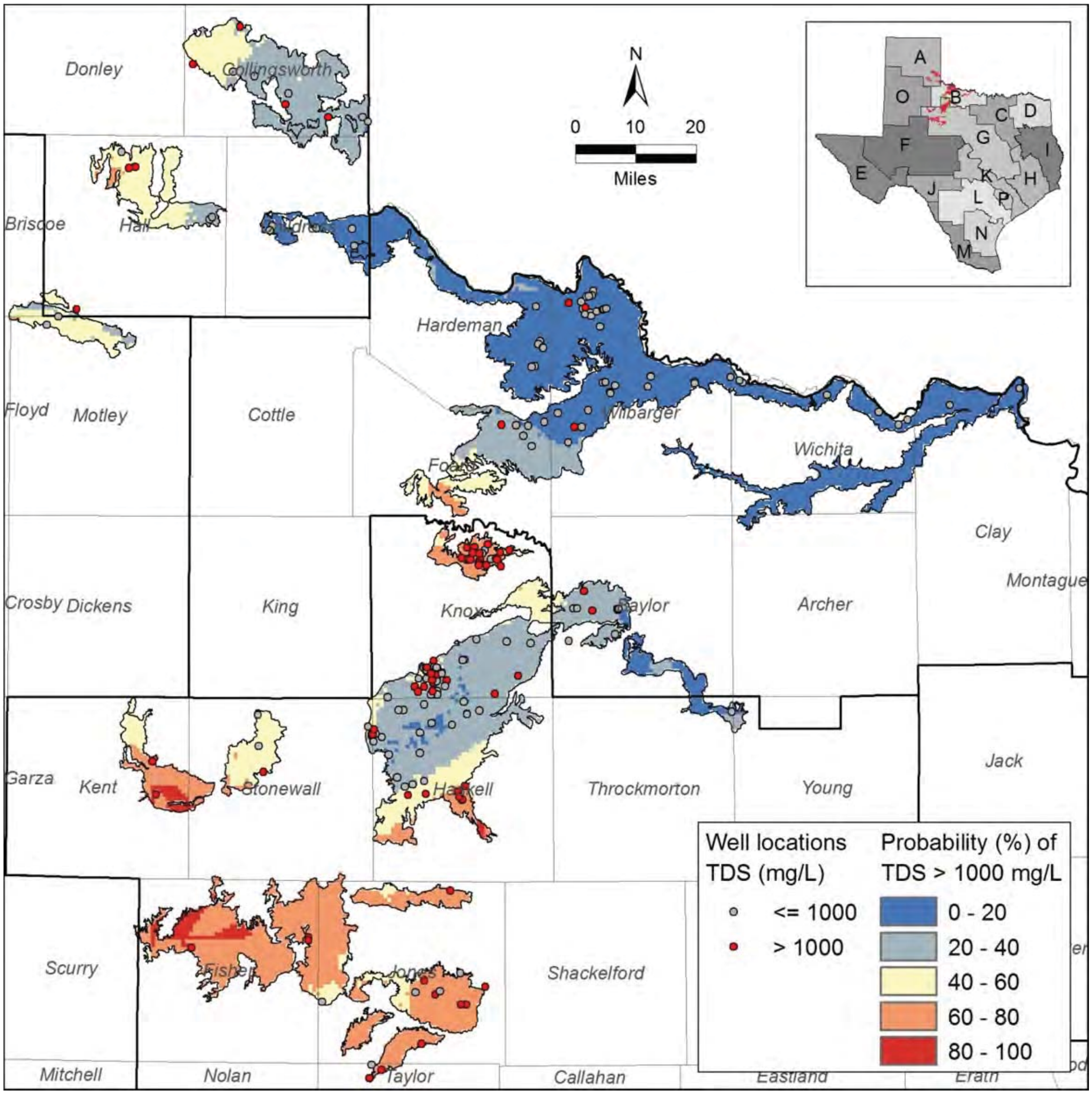

Figure 42. Seymour Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Hueco-Mesilla Bolson

Probability of exceeding any primary MCL in the Hueco-Mesilla Bolson Aquifer is dominated by arsenic exceedances (Table 18 and Table 19). Arsenic concentrations do not display a significant trend with well depth (Appendix 7). The high risk category of exceeding any primary MCL represents 62 percent of the area and 47 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 35 percent of the area and 33 percent of the volume. However, the number of analyses is very limited in the central and southern parts of the aquifer (Figure 43). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 7. There are insufficient data to evaluate gross alpha, combined radium, and uranium exceedances. Secondary MCL percent exceedances are dominated by high TDS, related primarily to high chloride and to a lesser extent high sulfate and moderate levels of iron and manganese percent exceedances (Figure 44). Salinity is attributed to intrusion of brackish water caused by lowering of water levels in areas of fresh groundwater (Hutchison, 2006).

Table 18. Hueco-Mesilla Bolson Aquifer percent area and volume within MCL exceedance probability categories. Hueco-Mesilla Bolson Aquifer area is 1,360 mi^2 and volume is 700 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (arsenic)	30	8	62	44	9	47
TDS	36	29	35	42	25	33

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 19. Summary of MCL violations in Hueco-Mesilla Bolson Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	34	1	33	NA	1.11	1.11	0	0
Arsenic	10	μg/L	173	139	34	8.4	1.55	60.1	59	**34**
Barium	2,000	μg/L	215	206	9	76	11.1	3,600	1	0
Beryllium	4	μg/L	43	0	43	NA	NA	NA	0	0
Cadmium	5	μg/L	136	6	130	NA	0.5	2.0	0	0
Chromium	100	μg/L	142	32	110	0.2	0.2	72	0	0
Copper	1,300	μg/L	153	55	98	1.95	1.0	225	0	0
Fluoride	4	μg/L	305	294	11	0.7	0.1	6.1	4	1
Lead	15	μg/L	123	11	112	NA	2.02	21.8	2	2
Mercury	2	μg/L	123	12	111	NA	0.2	2.2	1	1
Nitrate-N	10	mg/L	298	265	33	1.19	0.01	16.2	4	1
Nitrite-N	1	mg/L	28	5	23	NA	0.01	0.06	0	0
Selenium	50	μg/L	136	39	97	1.8	1.0	68	1	1
Thallium	2	μg/L	32	0	32	NA	NA	NA	0	0
Gross alpha	15	pCi/L	1	0	1	NA	NA	NA	0	0
Gross beta	50	pCi/L	2	0	2	NA	NA	NA	0	0
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	15	11	4	2.5	1.06	21.5	0	0
Secondary MCL										
Aluminum	50	μg/L	52	17	35	3.14	1.83	520	2	4
Chloride	300	mg/L	310	310	0	190	5.39	5,500	120	39
Copper	1,000	μg/L	153	55	98	1.95	1.0	225	0	0
Fluoride	2	mg/L	305	294	11	0.7	0.1	6.1	15	5
Iron	300	μg/L	200	135	65	30	3.0	5,200	20	10
Manganese	50	μg/L	186	114	72	10	0.29	690	26	14
Silver	100	μg/L	132	6	126	NA	0.7	5.9	0	0
Sulfate	300	mg/L	310	309	1	93	18.6	2,660	42	14
TDS	1,000	mg/L	303	303	0	647	234	9,220	71	23
Zinc	5,000	μg/L	190	112	78	11	1.0	521	0	0
pH	6.5-8.5		305	305	0	8	6.5	9.35	26	9

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

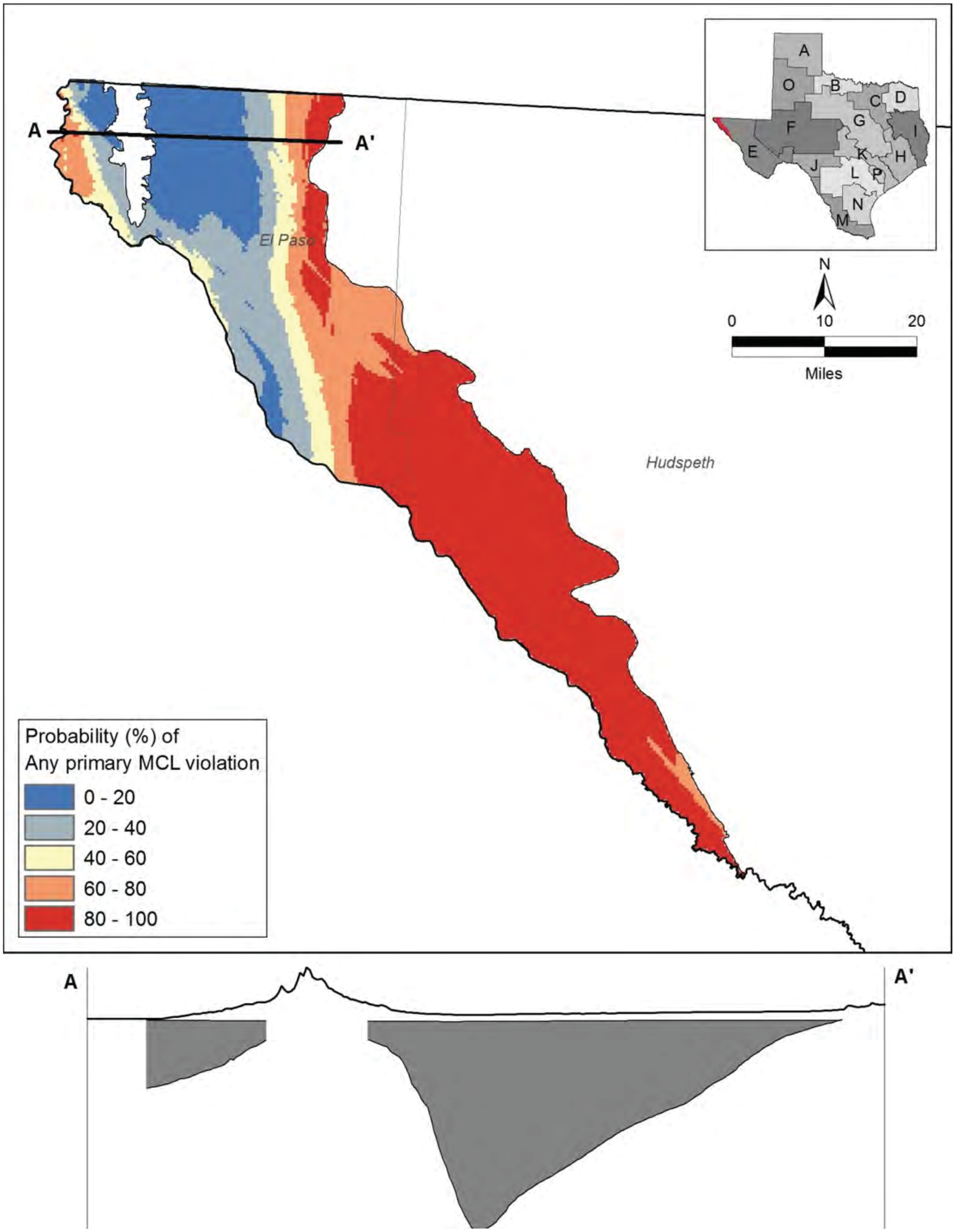

Figure 43. Hueco-Mesilla Bolsin Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

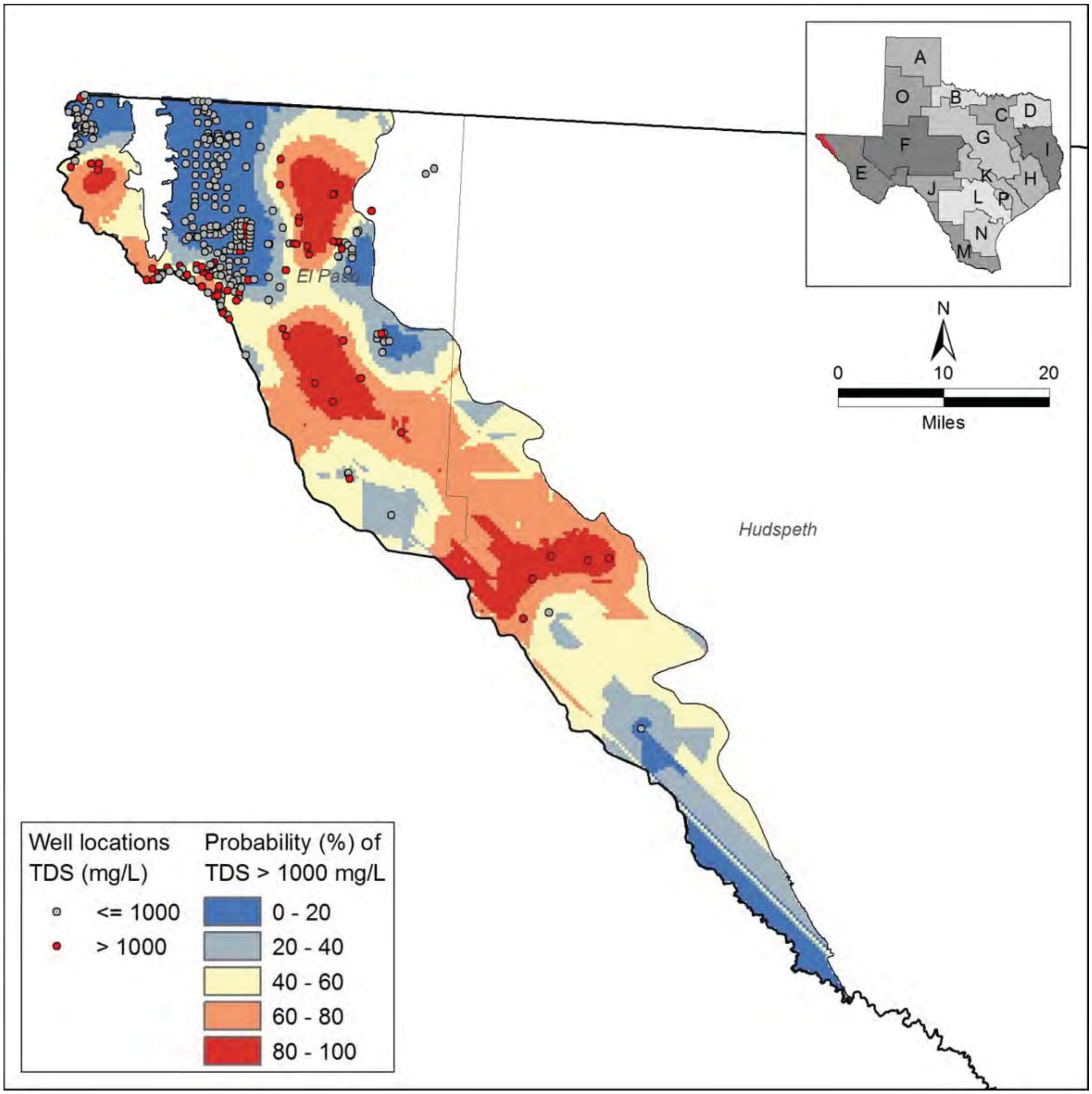

Figure 44. Hueco-Mesilla Bolson Aquifer probability of total dissolved solids (TDS) secondary MCL violation.

Pecos Valley

The Pecos Valley Aquifer is divided into two troughs formed by subsidence caused by evaporite dissolution: Monument Draw trough to the east and Pecos Valley trough to the west. Primary MCL exceedances are dominated by arsenic, fluoride, nitrate-N, and gross alpha (Table 20 and Table 21). Arsenic and fluoride concentrations tend to decrease with increasing well depth whereas there are no consistent trends among the remaining constituents (Appendix 8). The high risk category of exceeding any primary MCL represents 26 percent of the area and 14 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 61 percent of the area and 73 percent of the volume. The probability of exceeding any primary MCL is highest in the eastern part of the Monument Draw trough and is related to gross alpha, arsenic, nitrate-N, and fluoride MCLs (Figure 45). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 8. However, the number of analyses is generally limited. There are insufficient data to evaluate combined radium and uranium MCL exceedances. Secondary MCL percent exceedances are characterized by very high levels of TDS in the eastern portion of the Monument Draw trough and throughout most of the Pecos Valley trough (Figure 46). High TDS is related to high chloride and sulfate concentrations. Secondary fluoride MCL percent exceedances are also fairly high, and iron and manganese exceedances are moderately high. High chloride and sulfate levels are attributed to halite and evaporite dissolution in underlying Permian aquifers and cross formational flow of these waters into the Pecos Valley Aquifer (Jones, 2004). Increasing salinity may be related to declining water levels from irrigation, resulting in increased cross formational flow, particularly in Reeves County to the west. Irrigation return flow, groundwater evaporation where the water table is shallow near the Pecos River, and flow from the Pecos River where it is losing can also contribute salinity to the aquifer.

Table 20. Pecos Valley Aquifer percent area and volume within MCL exceedance probability categories. Pecos Valley Aquifer area is 5,780 mi^2 and volume is 269 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	59	15	26	75	11	14
Arsenic	90	7	3	97	2	1
Fluoride	96	4	0	98	2	0
Nitrate-N	77	20	2	79	15	6
Gross alpha	86	12	2	90	6	4
TDS	24	15	61	20	7	73

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 21. Summary of MCL violations in Pecos Valley Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	173	6	167	NA	2.8	6.5	1	1
Arsenic	10	µg/L	200	85	115	1.0	1.0	51	11	**6**
Barium	2,000	µg/L	207	186	21	18.7	3.0	482	0	0
Beryllium	4	µg/L	164	0	164	NA	NA	NA	0	0
Cadmium	5	µg/L	172	3	169	NA	1.42	3.0	0	0
Chromium	100	µg/L	191	60	131	NA	1.0	285	1	1
Copper	1,300	µg/L	192	103	89	2.0	1.0	32.2	0	0
Fluoride	4	µg/L	192	188	4	1.51	0.15	38.7	7	**4**
Lead	15	µg/L	177	14	163	NA	1.0	6.51	0	0
Mercury	2	µg/L	100	0	100	NA	NA	NA	0	0
Nitrate-N	10	mg/L	195	179	16	1.77	0.002	175	27	**14**
Nitrite-N	1	mg/L	92	12	80	NA	0.01	0.12	0	0
Selenium	50	µg/L	206	122	84	4	1.0	117	5	2
Thallium	2	µg/L	168	4	164	NA	0.736	2.0	0	0
Gross alpha	15	pCi/L	84	58	26	4.8	1.6	275	14	**17**
Gross beta	50	pCi/L	88	71	17	12	4.1	251	3	3
Comb. radium	5	pCi/L	12	4	8	NA	2.3	3.45	0	0
Uranium	30	µg/L	5	4	1	11.8	6.23	89.4	2	40
Secondary MCL										
Aluminum	50	µg/L	191	37	154	NA	1.0	8,120	4	2
Chloride	300	mg/L	196	196	0	361	5.0	6,290	114	58
Copper	1,000	µg/L	192	103	89	2.0	1.0	32.2	0	0
Fluoride	2	mg/L	192	188	4	1.51	0.15	38.7	55	29
Iron	300	µg/L	209	124	85	32	1.0	19,700	31	15
Manganese	50	µg/L	208	133	75	4.0	0.94	2,560	31	15
Silver	100	µg/L	96	9	87	NA	7.0	30	0	0
Sulfate	300	mg/L	196	196	0	808	18	4,208	137	70
TDS	1,000	mg/L	191	191	0	2,480	216	13,800	136	71
Zinc	5,000	µg/L	192	165	27	16	1.0	873	0	0
pH	6.5-8.5		215	215	0	7.2	6.2	8.33	4	2

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

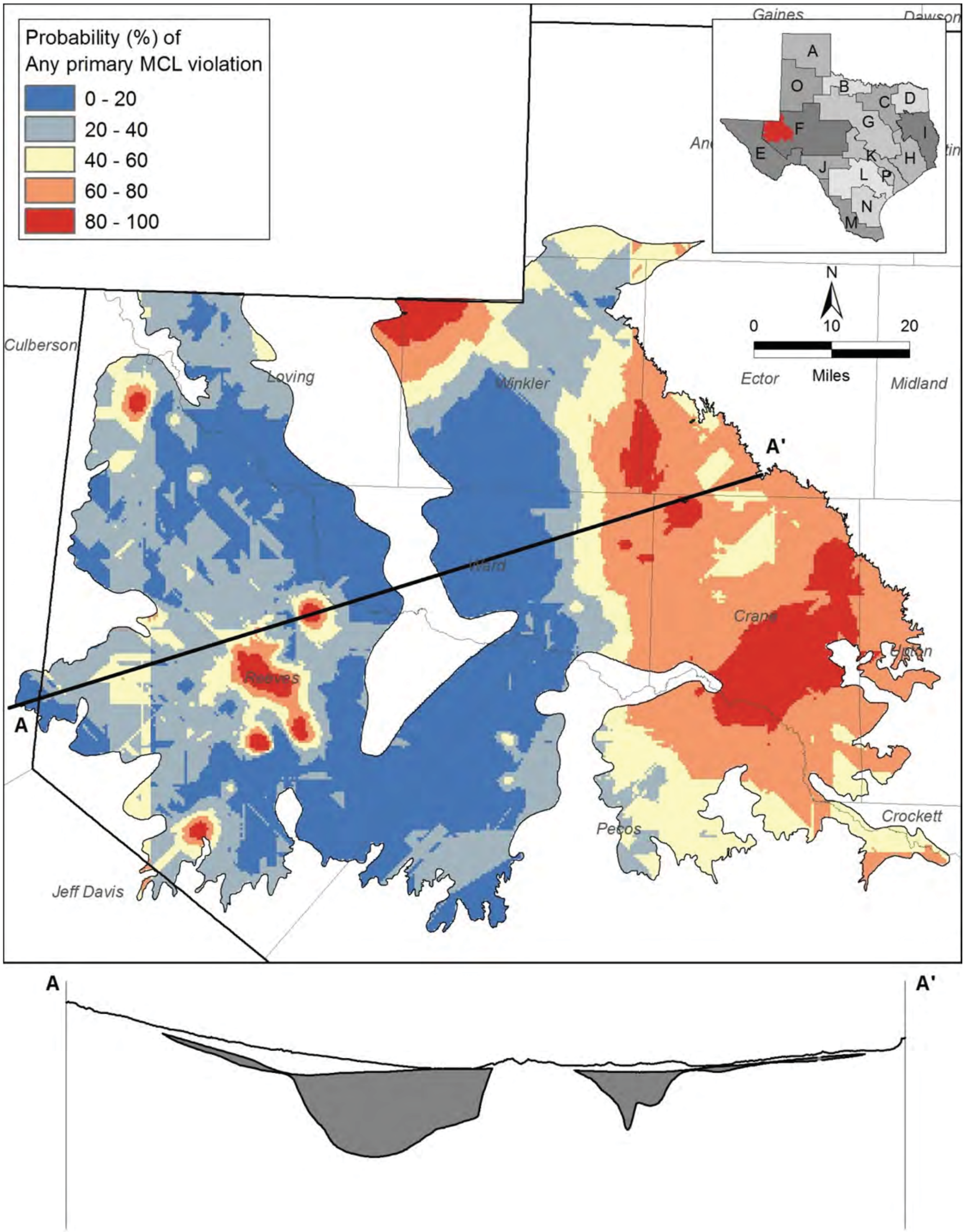

Figure 45. Pecos Valley Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

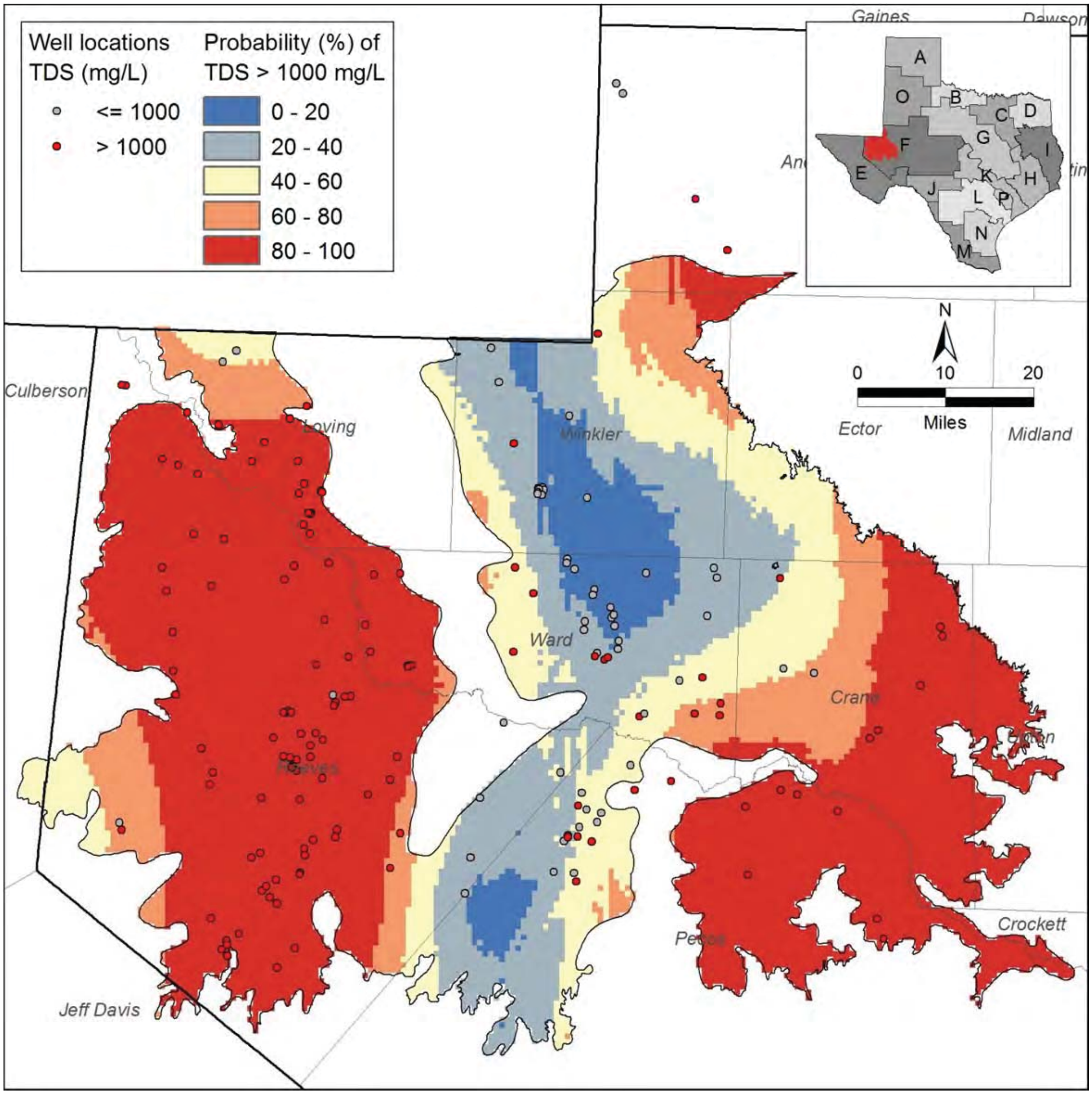

Figure 46. Pecos Valley Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Edwards (BFZ)

The Edwards Aquifer is characterized by very high quality groundwater (Table 22 and Table 23) with limited occurrences of fluoride and gross alpha exceedance, both of which display increasing concentrations with increased well depth (Appendix 9). There are no areas in the high risk category for exceeding any primary MCL or the secondary MCL for TDS. Exceedances are limited to regions of elevated fluoride in the northern Barton Springs segment and gross alpha in the southern San Antonio segment (Figure 47). The component maps used to calculate the probability of any primary MCL violation map are shown in Appendix 9. Secondary MCL percent exceedances are dominated by fluoride, with the remaining constituents less than 5 percent exceedance and TDS exceedances limited to downdip regions (Figure 48).

Table 22. Edwards (BFZ) Aquifer percent area and volume within MCL exceedance probability categories. Edwards (BFZ) Aquifer area is 4,250 mi^2 and volume is 336 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	61	39	0	55	45	0
Fluoride	85	15	0	90	10	0
Gross alpha	75	25	0	63	37	0
TDS	84	16	0	83	17	0

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 23. Summary of MCL violations in Edwards (BFZ) Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	472	6	466	NA	1.22	6.0	0	0
Arsenic	10	μg/L	512	28	484	0.38	0.38	79.6	5	1
Barium	2,000	μg/L	521	520	1	42.7	3.07	304	0	0
Beryllium	4	μg/L	478	0	478	NA	NA	NA	0	0
Cadmium	5	μg/L	502	3	499	NA	1.0	10	1	0
Chromium	100	μg/L	512	275	237	1.2	1.0	60	0	0
Copper	1,300	μg/L	519	322	197	1.9	1.0	351	0	0
Fluoride	4	μg/L	638	614	24	0.2	0.04	9.74	18	**3**
Lead	15	μg/L	509	95	414	NA	0.9	107	2	0
Mercury	2	μg/L	212	10	202	NA	0.1	0.8	0	0
Nitrate-N	10	mg/L	594	540	54	1.5	0.01	17	3	1
Nitrite-N	1	mg/L	168	23	145	NA	0.01	0.06	0	0
Selenium	50	μg/L	504	58	446	NA	1.0	243	9	2
Thallium	2	μg/L	430	2	428	NA	1.4	2.0	0	0
Gross alpha	15	pCi/L	87	67	20	2.3	0.1	22	3	**3**
Gross beta	50	pCi/L	65	43	23	3.1	1.0	33.9	0	0
Comb. radium	5	pCi/L	10	0	10	NA	NA	NA	0	0
Uranium	30	μg/L	150	15	135	NA	0.6	2.26	0	0
Secondary MCL										
Aluminum	50	μg/L	480	102	378	2.0	1.0	980	6	1
Chloride	300	mg/L	643	643	0	17	2.0	7,900	24	4
Copper	1,000	μg/L	519	322	197	1.9	1.0	351	0	0
Fluoride	2	mg/L	638	614	24	0.2	0.04	9.74	76	12
Iron	300	μg/L	563	216	347	11.4	1.0	7,660	39	7
Manganese	50	μg/L	530	132	398	0.68	0.56	429	12	2
Silver	100	μg/L	243	7	236	NA	1.0	10	0	0
Sulfate	300	mg/L	642	640	2	24.1	1.0	2,860	31	5
TDS	1,000	mg/L	584	584	0	319	215	17,100	26	4
Zinc	5,000	μg/L	522	343	179	6.27	0.97	2,300	0	0
pH	6.5-8.5		684	684	0	7.1	5.98	8.84	16	2

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

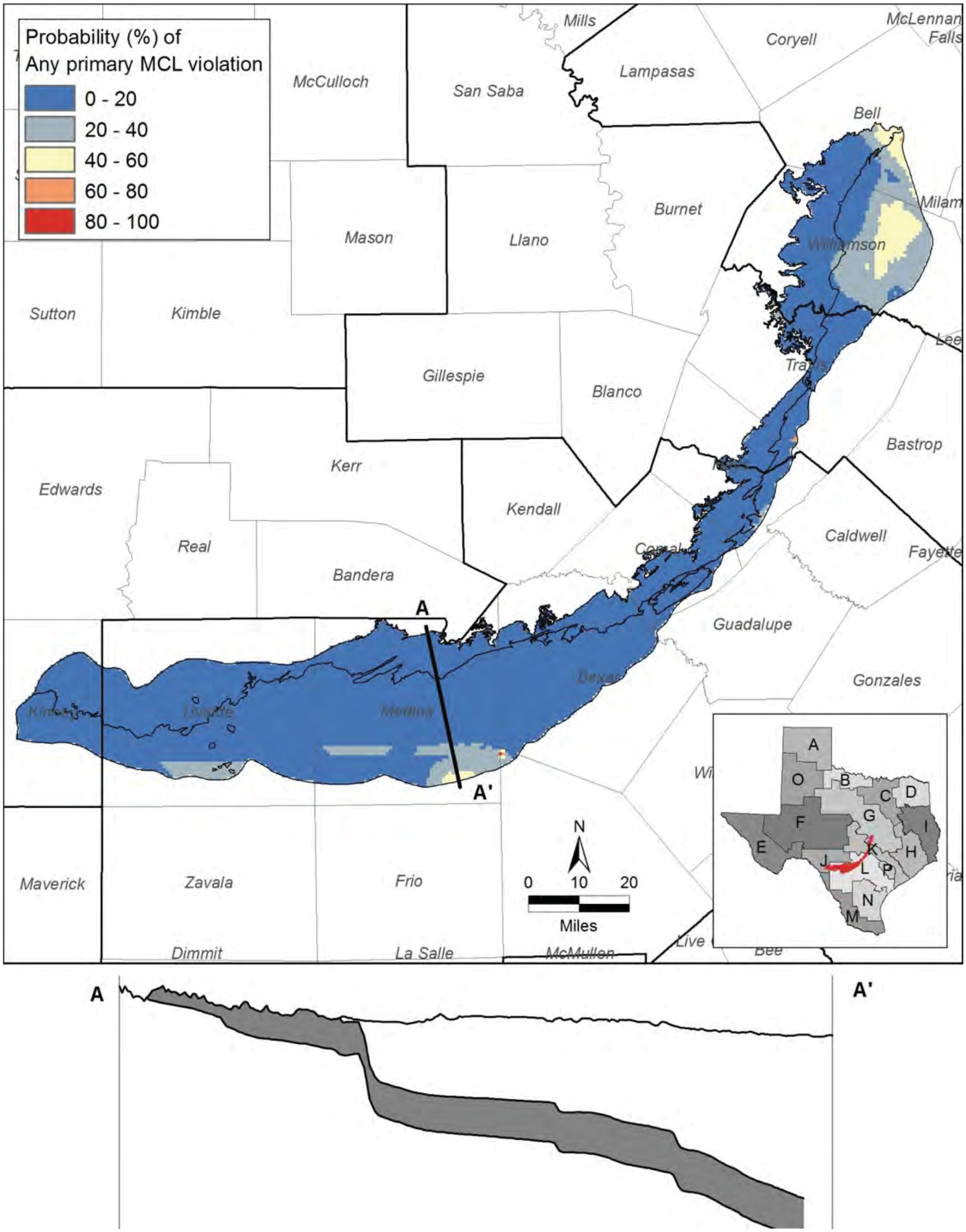

Figure 47. Edwards (BFZ) Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation and cross section schematically illustrating total saturated thickness of the aquifer and depth from land surface.

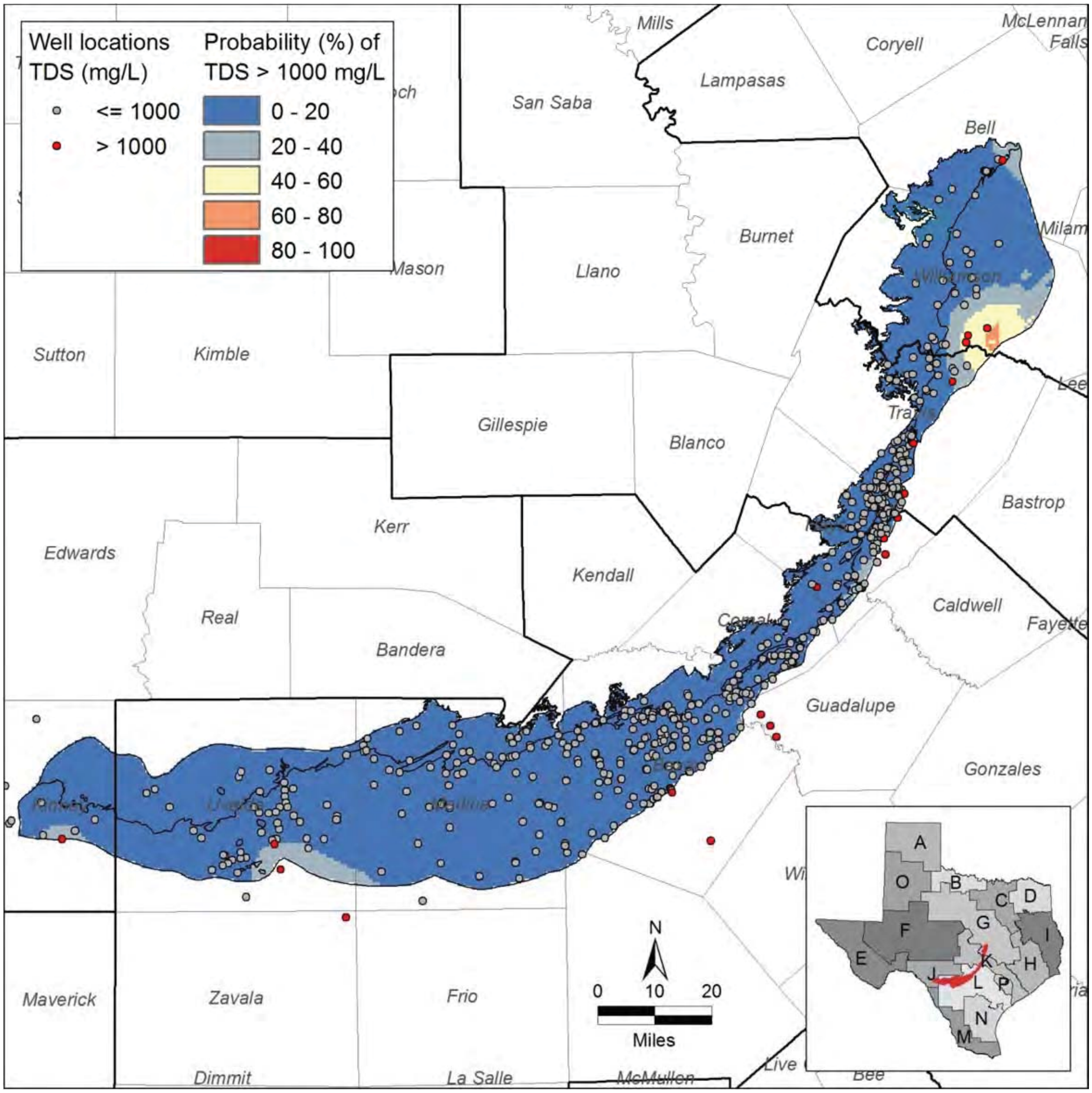

Figure 48. Edwards (BFZ) Aquifer probability of total dissolved solids (TDS) secondary MCL violation

3.1c Minor Aquifers

Blaine

Primary exceedances in the Blaine Aquifer are dominated by selenium and nitrate-N (Table 24 and Table 25, Figure 49) and do not exhibit consistent concentration trends with well depth (Appendix 10). The high risk category of exceeding any primary MCL represents 16 percent of the area and 18 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 100 percent of the area and 100 percent of the volume. The Blaine Aquifer is adjacent to the Seymour Aquifer and is of Permian age. Water moving through the aquifer dissolves anhydrite and halite, resulting in very high TDS secondary MCL exceedances related to high chloride and sulfate exceedances. High TDS is found throughout the aquifer (Figure 50). Concentrations of TDS increase with well depth (Appendix 10). Groundwater in the Blaine Aquifer is also characterized by moderate gross alpha MCL exceedances, although there are a limited number of analyses. The volume of groundwater expected to be impacted by TDS is very likely to be 100 percent.

Table 24. Blaine Aquifer percent area and volume within MCL exceedance probability categories. Blaine Aquifer area is 3,610 mi^2 and volume is 93 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	62	22	16	54	28	18
Nitrate-N	97	3	0	96	4	0
Selenium	80	13	7	79	14	7
TDS	0	0	100	0	0	100

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 25. Summary of MCL violations in Blaine Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	64	0	64	NA	NA	NA	0	0
Arsenic	10	μg/L	66	19	47	NA	2.05	5.4	0	0
Barium	2,000	μg/L	73	68	5	10.9	4.8	62.8	0	0
Beryllium	4	μg/L	63	0	63	NA	NA	NA	0	0
Cadmium	5	μg/L	58	2	56	NA	1.1	4.46	0	0
Chromium	100	μg/L	60	31	29	1.22	1.0	6.3	0	0
Copper	1,300	μg/L	69	62	7	4.34	1.11	49.4	0	0
Fluoride	4	mg/L	93	90	3	0.73	0.05	2.75	0	0
Lead	15	μg/L	67	8	59	NA	1.07	12.2	0	0
Mercury	2	μg/L	33	0	33	NA	NA	NA	0	0
Nitrate-N	10	mg/L	92	90	2	4.42	0.04	27.2	13	14
Nitrite-N	1	mg/L	6	3	3	NA	0.01	0.01	0	0
Selenium	50	μg/L	68	60	8	18.1	2.0	310	14	21
Thallium	2	μg/L	63	0	63	NA	NA	NA	1	2
Gross alpha	15	pCi/L	29	26	3	6.5	2.4	45	4	14
Gross beta	50	pCi/L	27	12	15	NA	0.1	28	0	0
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	26	26	0	6.9	3.22	46.1	2	8
Secondary MCL										
Aluminum	50	μg/L	67	5	62	NA	3.9	24.6	0	0
Chloride	300	mg/L	94	93	1	279	8.83	5,660	54	57
Copper	1,000	μg/L	69	62	7	4.34	1.11	49.4	0	0
Fluoride	2	mg/L	93	90	3	0.73	0.05	2.75	1	1
Iron	300	μg/L	73	30	43	30	19.1	2,970	6	8
Manganese	50	μg/L	69	45	24	3.1	1.1	100	3	4
Silver	100	μg/L	33	1	32	NA	2.4	2.4	0	0
Sulfate	300	mg/L	94	94	0	1,810	59.9	4,020	93	99
TDS	1,000	mg/L	94	94	0	3,230	385	12,800	93	99
Zinc	5,000	μg/L	69	67	2	28.3	4.96	4,320	0	0
pH	6.5-8.5		92	92	0	6.85	6.51	7.68	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

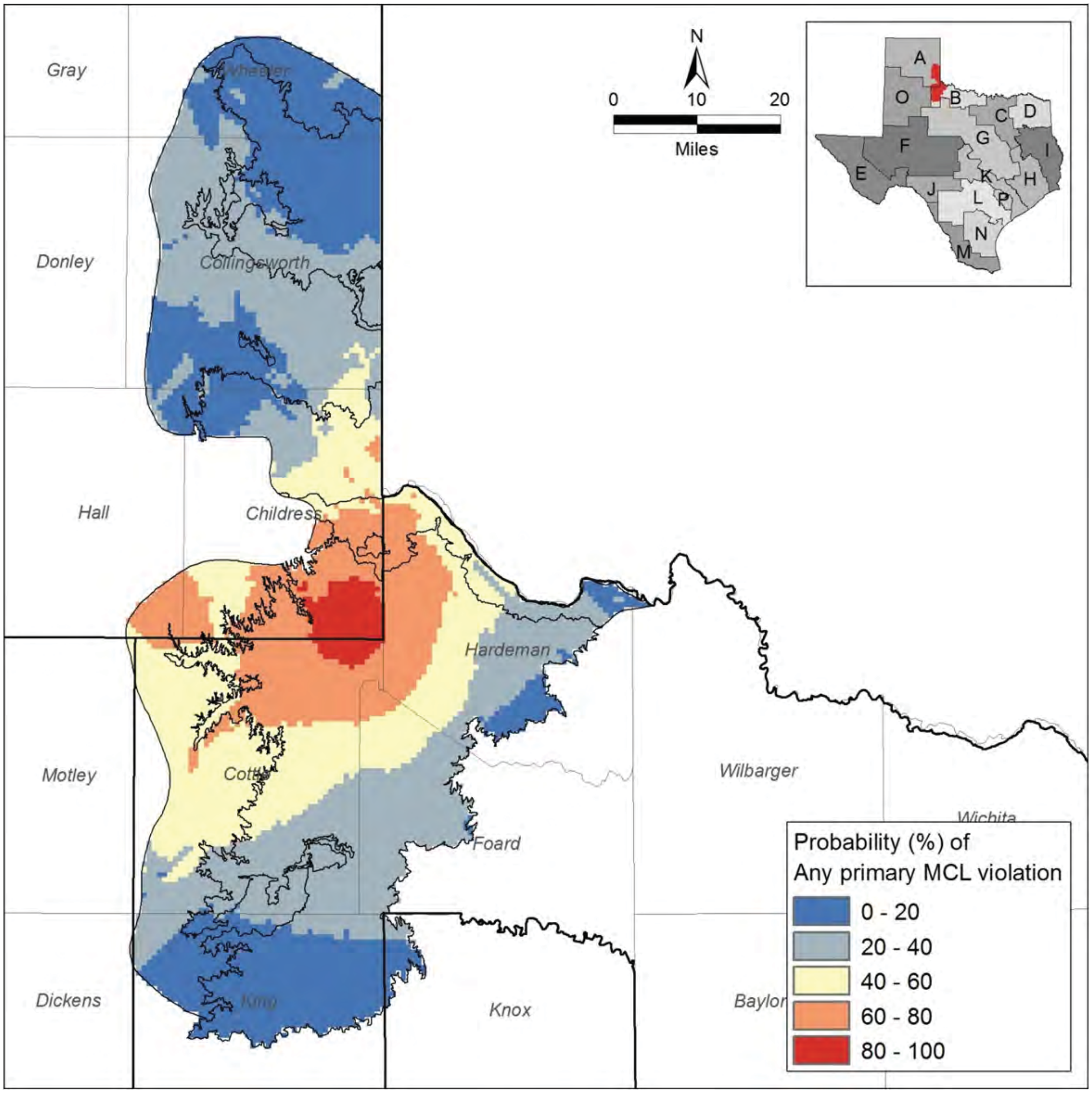

Figure 49. Blaine Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

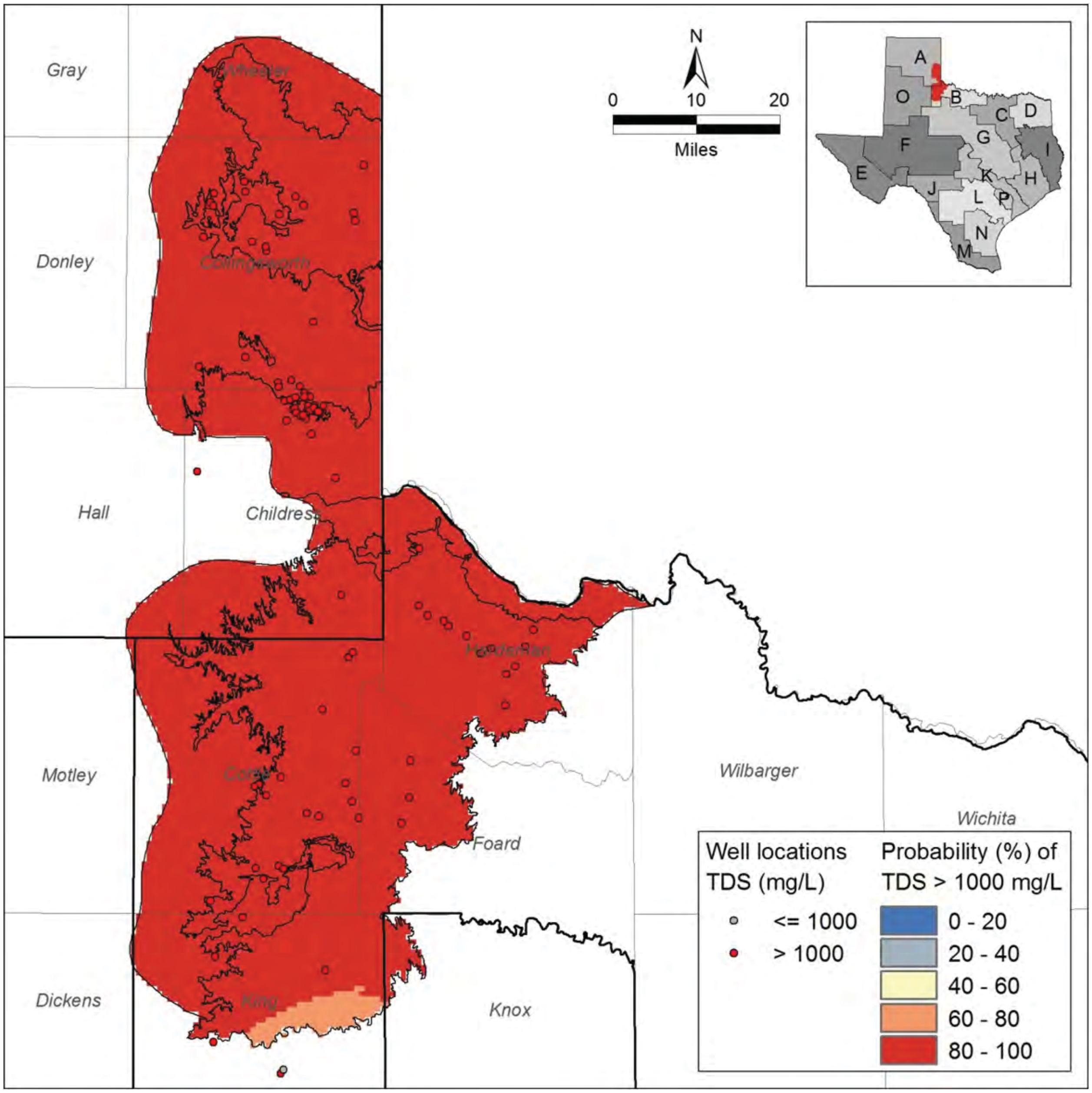

Figure 50. Blaine Aquifer probability of to tal dissolved solids (TDS) secondary MCL violation

Blossom

The Blossom Aquifer consists of the Blossom Sand Formation of Cretaceous age with alternating sequences of sand and clay (Ashworth and Hopkins, 1995). The probable volume of groundwater impacted by any primary MCL exceedance is negligible; however, groundwater could be impacted by TDS in a very small percent of the volume of the aquifer (Table 26 and Figure 51). TDS is generally highest in deeper wells in the downdip regions of the aquifer (Appendix 11). There are no areas in the high risk category for exceeding any primary MCL while the high risk category of exceeding the secondary MCL for TDS represents 1 percent of the area and 4 percent of the volume. The number of chemical analyses in the Blossom Aquifer is limited (20), therefore, it is difficult to comment on the water quality. There are some arsenic and nitrate-N primary MCL exceedances (Table 27Table 27), and higher levels of TDS exceedances related to chloride and sulfate exceedances. Limited iron and manganese exceedances are also found in the data.

Table 26. Blossom Aquifer percent area and volume within MCL exceedance probability categories. Blossom Aquifer area is 278 mi^2 and volume is 1.3 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (none)	100	0	0	100	0	0
TDS	91	8	1	80	17	4

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 27. Summary of MCL violations in Blossom Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	20	0	20	NA	NA	NA	0	0
Arsenic	10	μg/L	20	3	17	NA	2.0	14.7	1	5
Barium	2,000	μg/L	20	20	0	15	4.9	520	0	0
Beryllium	4	μg/L	20	0	20	NA	NA	NA	0	0
Cadmium	5	μg/L	19	0	19	NA	NA	NA	0	0
Chromium	100	μg/L	19	10	9	1.0	1.0	5.29	0	0
Copper	1,300	μg/L	20	11	9	1.0	1.0	290	0	0
Fluoride	4	mg/L	20	18	2	0.5	0.1	2.69	0	0
Lead	15	μg/L	20	4	16	NA	1.0	2	0	0
Mercury	2	μg/L	4	0	4	NA	NA	NA	0	0
Nitrate-N	10	mg/L	20	7	13	0.06	0.06	11.3	1	5
Nitrite-N	1	mg/L	4	1	3	NA	0.01	0.01	0	0
Selenium	50	μg/L	20	11	9	1.0	1.0	5.41	0	0
Thallium	2	μg/L	20	0	20	NA	NA	NA	0	0
Gross alpha	15	pCi/L	5	3	2	0.4	0.4	3.6	0	0
Gross beta	50	pCi/L	5	3	2	NA	0.8	2	0	0
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	0	NA	NA	NA	NA	NA	NA	NA
Secondary MCL										
Aluminum	50	μg/L	20	18	2	3.0	1.0	34.6	0	0
Chloride	300	mg/L	20	20	0	103	4.0	463	2	10
Copper	1,000	μg/L	20	11	9	1.0	1.0	290	0	0
Fluoride	2	mg/L	20	18	2	0.5	0.1	2.69	1	5
Iron	300	μg/L	20	6	14	NA	37	20,800	3	15
Manganese	50	μg/L	20	19	1	7.0	1.0	2,640	3	15
Silver	100	μg/L	4	0	4	NA	NA	NA	0	0
Sulfate	300	mg/L	20	20	0	95	8.0	458	3	15
TDS	1,000	mg/L	20	20	0	901	101	1,410	7	35
Zinc	5,000	μg/L	20	16	4	7.0	1.0	225	0	0
pH	6.5-8.5		20	20	0	8.27	5.12	8.87	14	70

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

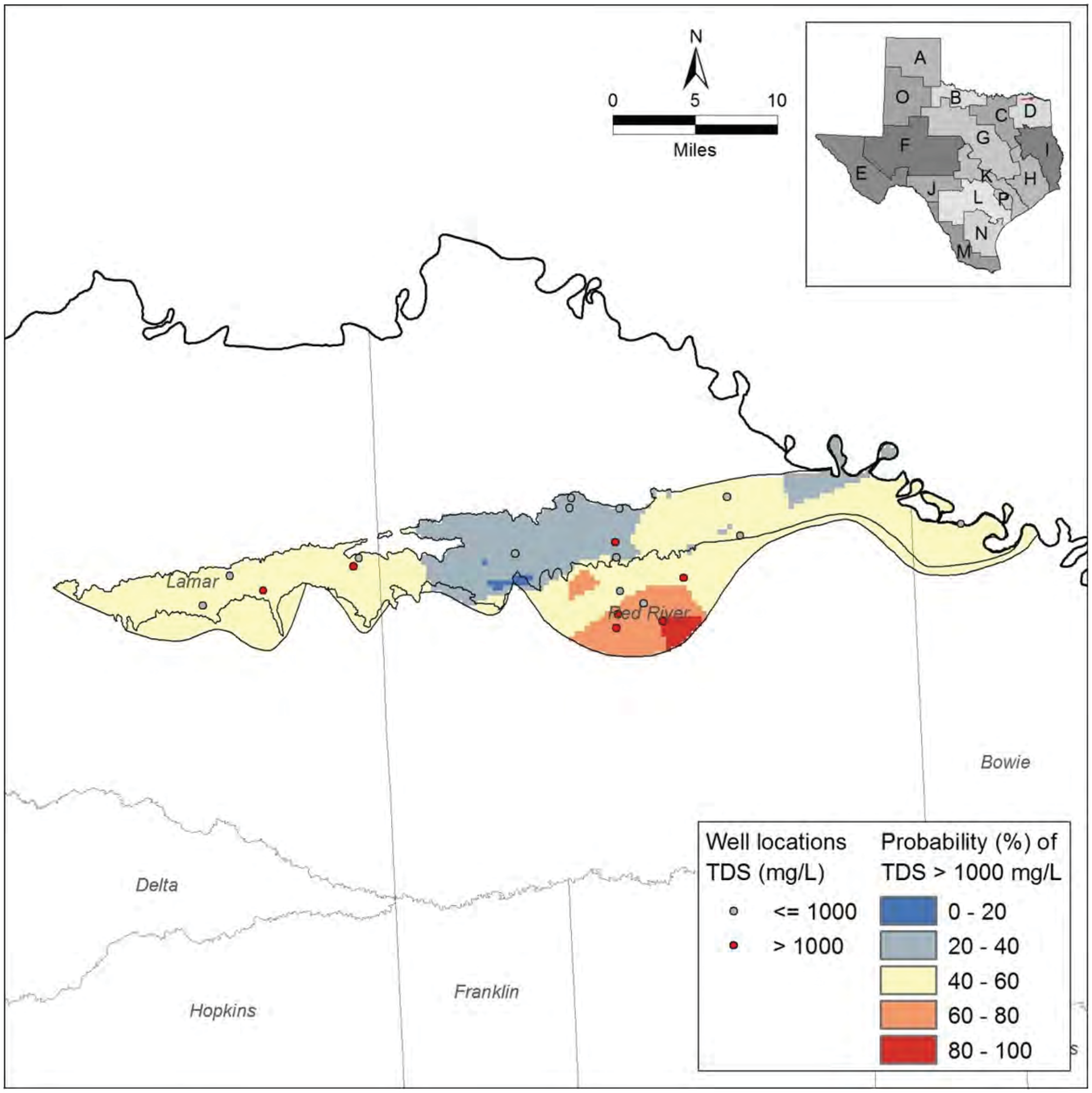

Figure 51. Blossom Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Dockum

The Dockum Aquifer has numerous primary MCL percent exceedances throughout most of the aquifer. Up to half the volume of groundwater may be impacted by any primary MCL and TDS (secondary) exceedances (Table 28 and Table 29). With the exception of nitrate-N, which shows decreasing concentrations with increased well depth, concentrations do not exhibit consistent trends with well depth (Appendix 12). The high risk category of exceeding any primary MCL represents 41 percent of the area and 48 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 34 percent of the area and 50 percent of the volume. Primary MCL exceedances are more widespread in the southern and eastern regions of the aquifer (Figure 52).

Primary exceedances are dominated by gross alpha and combined radium which are attributed to high levels of uranium in the rocks (≤ 400 ppm) with potential sources in granitic rocks in Oklahoma, Triassic volcanics in Texas and New Mexico, and volcanic ashes in the Ogallala Aquifer (McGowan, 1977; Cech et al., 1988; Bradley and Kalaswad, 2003; Dutton and Simpkins, 1986; Ewing et al., 2008). Nitrate-N MCL exceedances are moderately high, mostly in the central eastern part of the aquifer where it outcrops, and nitrate is attributed to cultivation. TDS exceedances are greatest in the south and southwest parts of the aquifer and increase toward the basin center (Figure 53); however, the aquifer as defined does not extend into the basin center. High TDS is related to high chloride and sulfate concentrations. Fluoride secondary MCL percent exceedances are also high and may be related to fluoride derived from volcanic ashes in the Ogallala Aquifer. Iron and manganese secondary MCL percent exceedances are moderately high.

Table 28. Dockum Aquifer percent area and volume within MCL exceedance probability categories. Dockum Aquifer area is 25,600 mi^2 and volume is 2,570 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	32	27	41	26	26	48
Arsenic	97	3	0	92	8	0
Fluoride	94	4	2	87	8	5
Nitrate-N	99	1	0	100	0	0
Selenium	100	0	0	100	0	0
Gross alpha	74	18	8	82	13	5
Combined Radium	81	11	8	83	13	4
TDS	50	16	34	37	13	50

Low: 0 – 40% probability, Moderate: 40 – 60% probability, High: 60 – 100% probability that a constituent MCL will be exceeded.

Table 29. Summary of MCL violations in Dockum Aquifer groundwater wells

	MCL	*units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	258	5	253	NA	0.88	3.7	0	0
Arsenic	10	μg/L	313	146	167	2.33	0.75	45.1	14	**4**
Barium	2,000	μg/L	322	298	24	37.5	1.2	486	0	0
Beryllium	4	μg/L	264	0	264	NA	NA	NA	0	0
Cadmium	5	μg/L	258	1	257	NA	1.0	1	0	0
Chromium	100	μg/L	317	141	176	1.78	1.2	76.2	0	0
Copper	1,300	μg/L	318	187	131	2.8	0.99	268	0	0
Fluoride	4	mg/L	364	352	12	1.38	0.1	9.31	10	**3**
Lead	15	μg/L	259	15	244	NA	0.89	7.2	0	0
Mercury	2	μg/L	232	29	203	NA	0.2	2.8	2	1
Nitrate-N	10	mg/L	359	294	65	1.01	0.01	54.3	39	**11**
Nitrite-N	1	mg/L	134	36	98	NA	0.01	0.29	0	0
Selenium	50	μg/L	314	185	129	4.55	1.05	241	12	**4**
Thallium	2	μg/L	251	0	251	NA	NA	NA	0	0
Gross alpha	15	pCi/L	312	290	22	8.4	1.6	519	86	**28**
Gross beta	50	pCi/L	304	264	40	8.75	1.0	288	11	4
Comb. radium	5	pCi/L	236	86	150	1.1	1.06	148	42	**18**
Uranium	30	μg/L	44	37	7	5.67	1.31	91.9	1	2
Secondary MCL										
Aluminum	50	μg/L	335	105	230	1.6	0.71	5,120	6	2
Chloride	300	mg/L	365	363	2	79.1	1.0	26,900	106	29
Copper	1,000	μg/L	318	187	131	2.8	0.99	267	0	0
Fluoride	2	mg/L	364	352	12	1.38	0.1	9.31	101	28
Iron	300	μg/L	350	230	120	54.8	1.0	5,830	98	28
Manganese	50	μg/L	341	214	127	5.0	0.18	762	51	15
Silver	100	μg/L	223	3	220	NA	2.0	10	0	0
Sulfate	300	mg/L	365	365	0	176	6.0	5,370	132	36
TDS	1,000	mg/L	341	341	0	762	195	46,700	136	40
Zinc	5,000	μg/L	341	262	79	16.8	1.01	3,050	0	0
pH	6.5-8.5		358	358	0	7.35	6.14	8.97	16	4

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

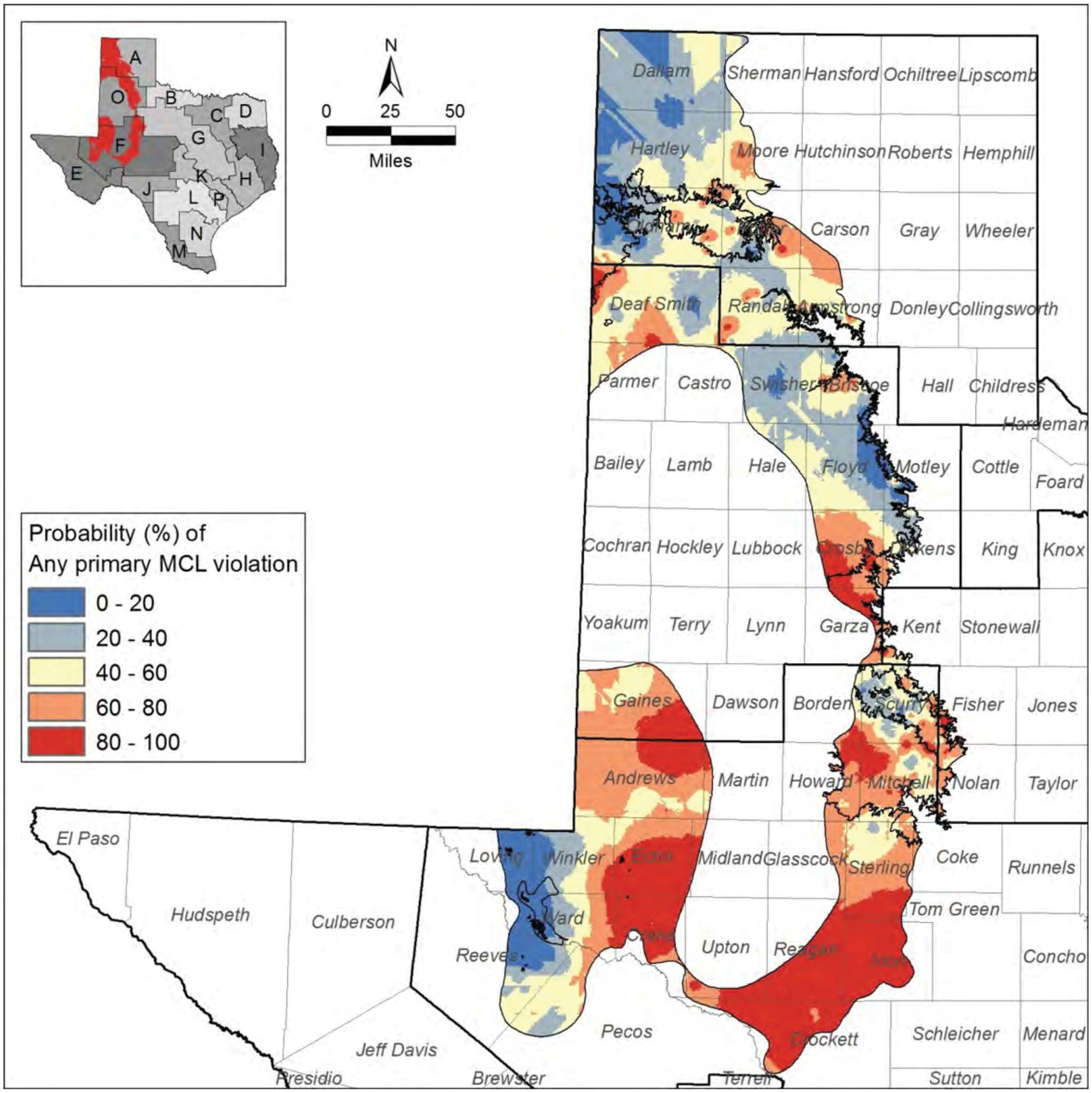

Figure 52. Dockum Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

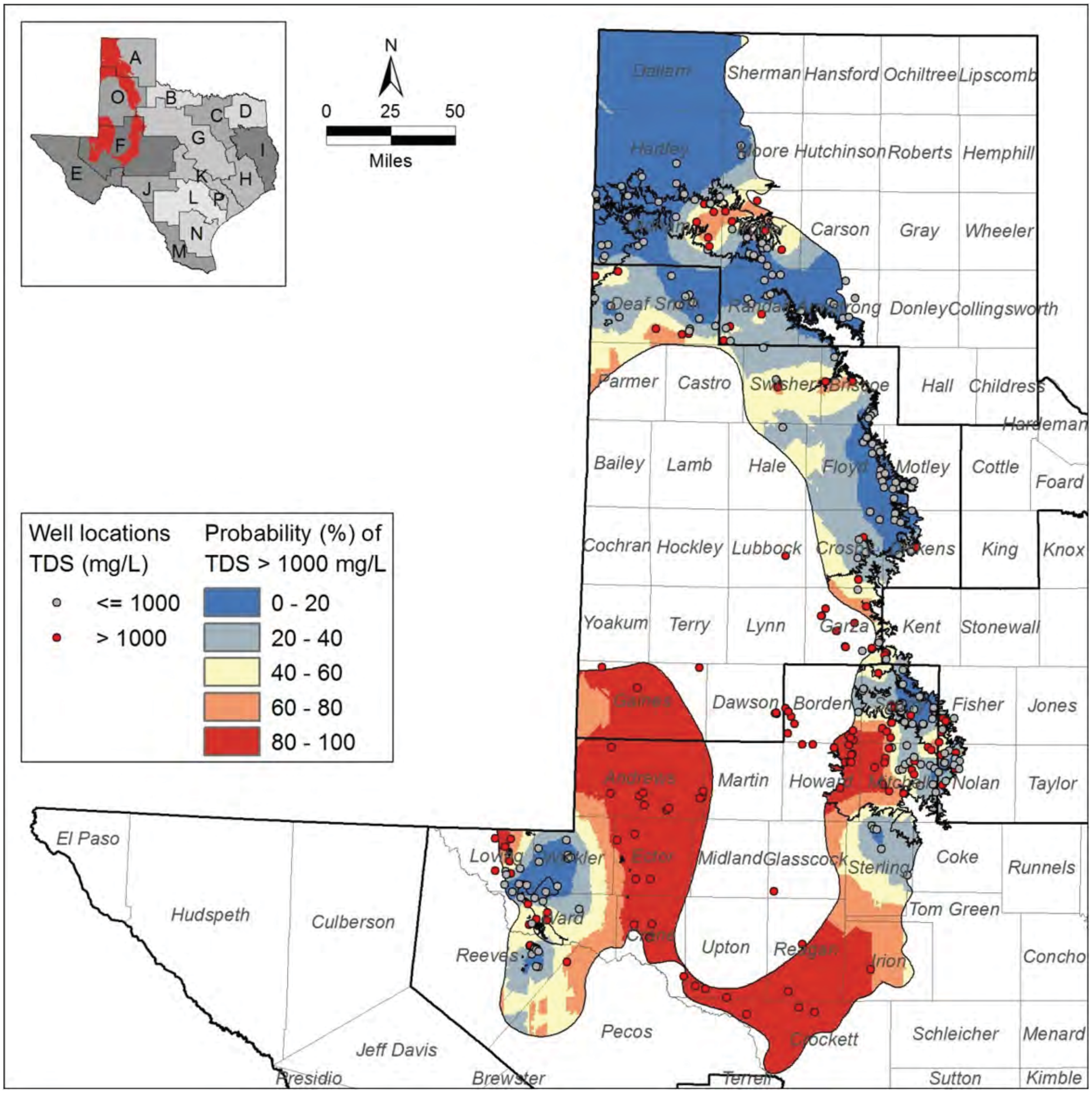

Figure 53. Dockum Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Edwards-Trinity (High Plains)

The Edwards-Trinity (High Plains) has relatively numerous primary MCL exceedances for arsenic, fluoride, nitrate-N, and selenium, similar to the overlying Ogallala Aquifer and attributed to hydraulic connections between the two aquifers (Nativ, 1988). There are only 19 wells in the TWDB database that are completed solely in the Edwards-Trinity (High Plains) Aquifer. Due to the similarity in water chemistry with the overlying Ogallala Aquifer, an additional 50 wells that are completed in both the Edwards-Trinity (High Plains) Aquifer and in the Ogallala Aquifer were included in this analysis. Up to 70 percent of the aquifer volume could be potentially impacted by any primary MCL exceedance (Table 30 and Table 31). The high risk category of exceeding any primary MCL represents 68 percent of the area and 69 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 24 percent of the area and 25 percent of the volume. The region of primary MCL exceedance is located in the eastern two-thirds of the aquifer (Figure 54, Appendix 13) while TDS exceedances are primarily located in the south-central region of the aquifer (Figure 55). There are insufficient data to evaluate problems with gross alpha radiation, uranium and combined radium exceedances.

Table 30. Edwards-Trinity (High Plains) Aquifer percent area and volume within MCL exceedance probability categories. Edwards-Trinity (High Plains) Aquifer area is 7,740 mi^2 and volume is 185 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	21	11	68	21	10	69
Arsenic	38	12	50	36	13	51
Fluoride	44	18	36	41	18	41
Nitrate-N	72	20	8	71	21	8
Selenium	83	10	7	82	9	9
TDS	48	28	24	45	30	25

Low: 0 – 40% probability, Moderate: 40 – 60% probability, High: 60 – 100% probability that a constituent MCL will be exceeded.

Table 31. Summary of MCL violations in Edwards-Trinity (High Plains) Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	60	1	59	NA	NA	NA	0	0
Arsenic	10	μg/L	67	64	3	11.9	1	59.1	42	**63**
Barium	2,000	μg/L	67	67	0	47.7	7.23	318	0	0
Beryllium	4	μg/L	60	0	60	NA	NA	NA	0	0
Cadmium	5	μg/L	51	0	51	NA	NA	NA	0	0
Chromium	100	μg/L	47	22	25	1.5	1.2	5.1	0	0
Copper	1,300	μg/L	67	48	19	2.75	0.91	22	0	0
Fluoride	4	μg/L	69	69	0	3.76	0.71	7.54	30	**43**
Lead	15	μg/L	60	7	53	NA	1.1	3.6	0	0
Mercury	2	μg/L	33	0	33	NA	NA	NA	0	0
Nitrate-N	10	mg/L	69	65	4	3.55	0.01	70.9	13	**19**
Nitrite-N	1	mg/L	11	3	8	NA	0.006	0.01	0	0
Selenium	50	μg/L	67	59	8	15.2	0.99	340	13	**19**
Thallium	2	μg/L	60	0	60	NA	NA	NA	0	0
Gross alpha	15	pCi/L	27	26	1	9.4	2.82	43.9	11	41
Gross beta	50	pCi/L	3	3	0	5.6	5.4	8.3	0	0
Comb. radium	5	pCi/L	19	4	23	NA	2.2	2.8	0	0
Uranium	30	μg/L	20	20	0	7.47	1.2	38.2	1	5
Secondary MCL										
Aluminum	50	μg/L	66	34	32	4.08	0.7	1,840	0	0
Chloride	300	mg/L	69	69	0	175	25.6	1,590	23	33
Copper	1,000	μg/L	67	48	19	2.75	0.90	22	0	0
Fluoride	2	mg/L	69	69	0	3.76	0.71	7.54	57	83
Iron	300	μg/L	68	39	29	47.5	0.74	1,830	6	9
Manganese	50	μg/L	68	32	36	1.21	0.14	861	1	1
Silver	100	μg/L	16	0	16	NA	NA	NA	0	0
Sulfate	300	mg/L	69	69	0	224	23.2	1,630	24	35
TDS	1,000	mg/L	66	66	0	925	350	4,570	28	42
Zinc	5,000	μg/L	67	58	9	10.6	0.72	459	0	0
pH	6.5-8.5		65	65	0	7.29	6.82	8.63	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

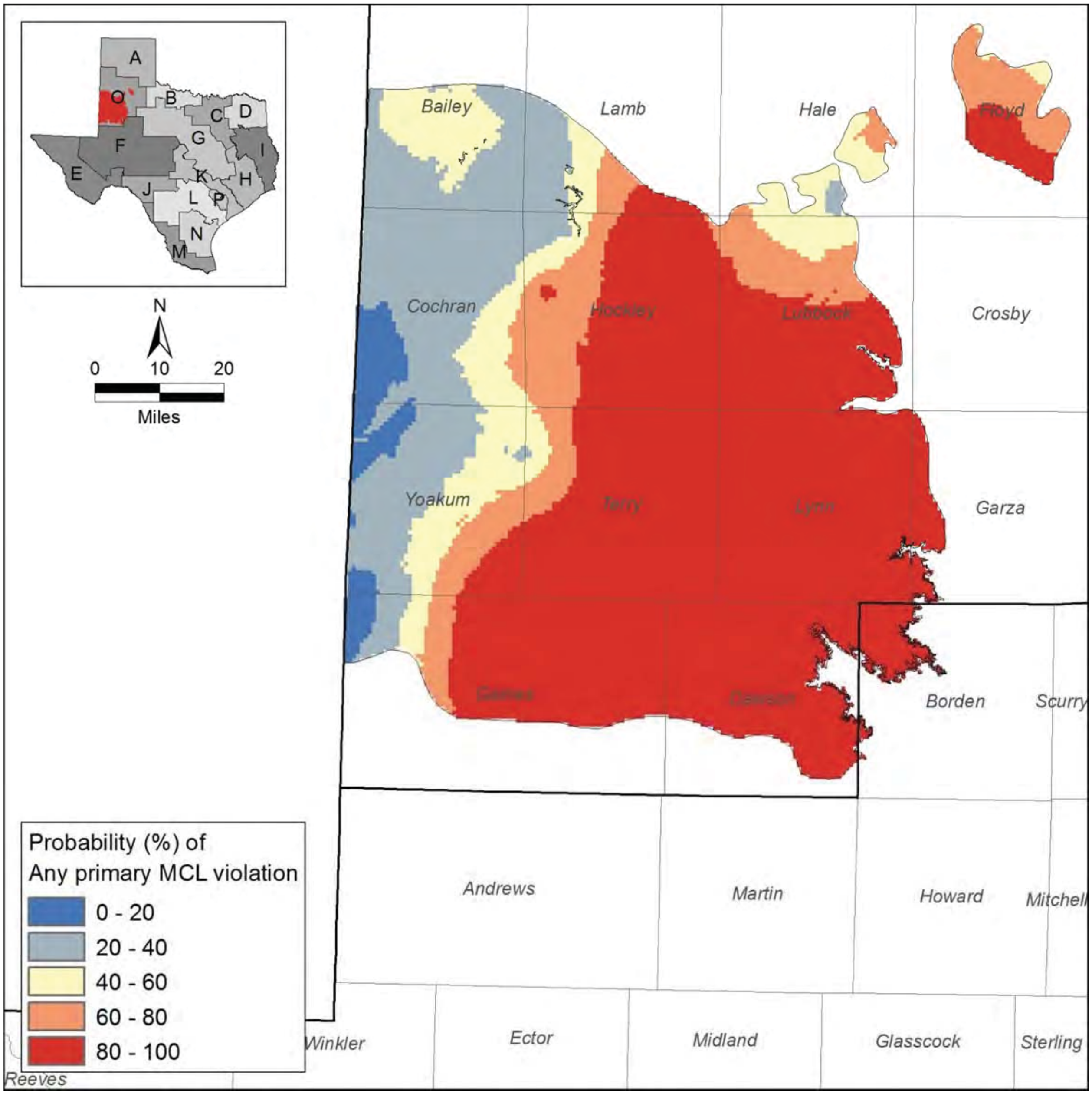

Figure 54. Edwards-Trinity (High Plains) Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

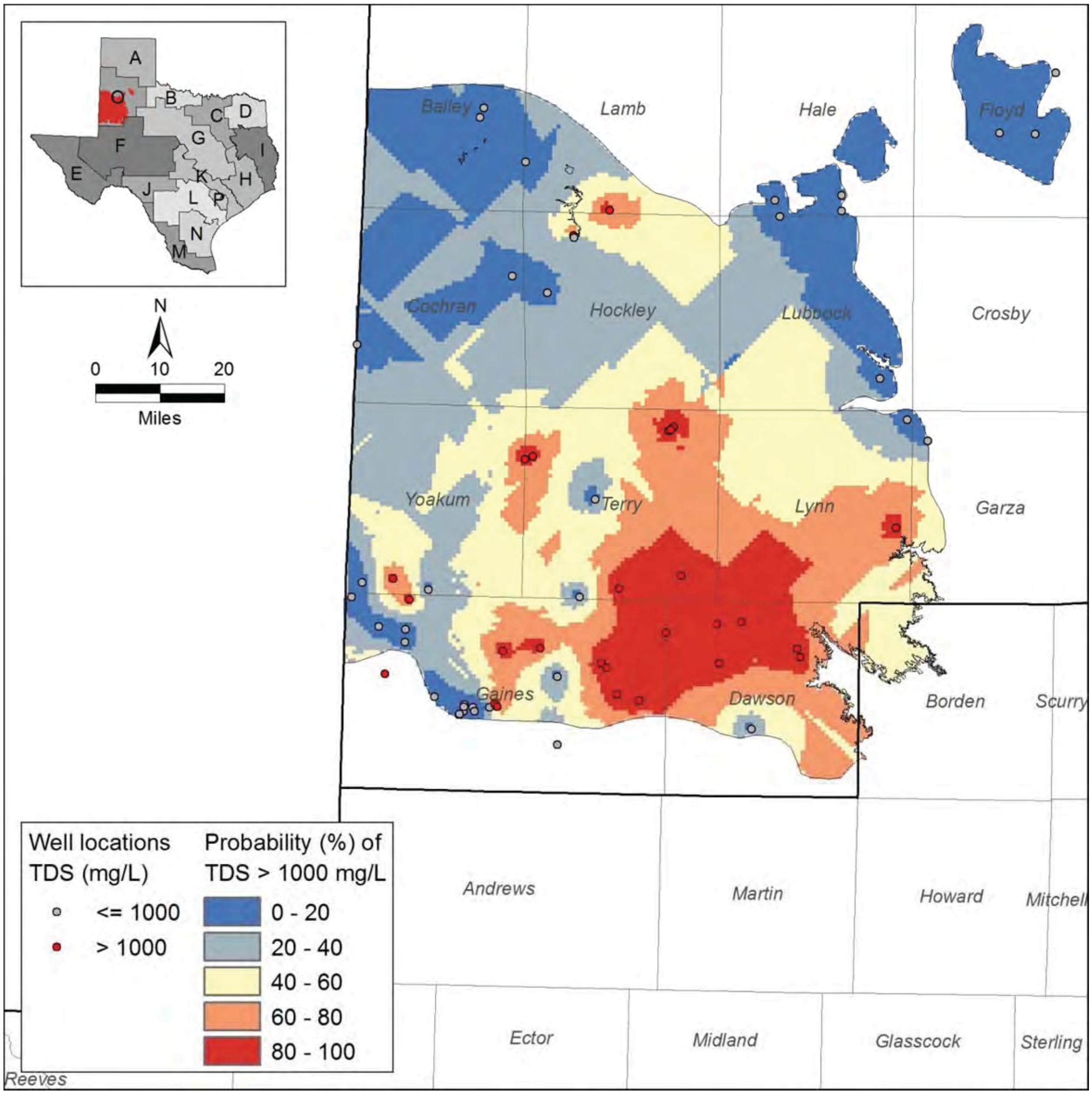

Figure 55. Edwards-Trinity (High Plains) Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Ellenburger-San Saba

The Ellenburger-San Saba Aquifer is located in the area of the Llano Uplift and is mostly impacted by radionuclide exceedances, including gross alpha, beta, and combined radium. Moderate volumes of groundwater could be impacted by any primary MCL exceedance related primarily to gross alpha radiation and fluoride (Table 32 and Table 33). Fluoride concentrations tend to increase with well depth whereas nitrate-N decreases (Appendix 14). The high risk category of exceeding any primary MCL represents 14 percent of the area and 17 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 4 percent of the area and 7 percent of the volume. Most of the primary MCL exceedances are in the northern part of the aquifer near the primary source of the radionuclides in the uplifted Precambrian igneous and metamorphic rocks of the Llano Uplift (Figure 56). Secondary MCL exceedances are low to moderate (Figure 57).

Table 32. Ellenburger-San Saba Aquifer percent area and volume within MCL exceedance probability categories. Ellenburger-San Saba Aquifer area is 5,220 mi^2 and volume is 653 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	78	8	14	76	7	17
Fluoride	89	5	6	85	7	8
Nitrate-N	99	1	0	100	0	0
Gross alpha	89	5	6	87	6	7
TDS	84	12	4	73	20	7

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 33. Summary of MCL violations in Ellenburger-San Saba Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	86	2	84	NA	1.06	1.87	0	0
Arsenic	10	μg/L	104	10	94	NA	0.75	7.7	0	0
Barium	2,000	μg/L	106	106	0	65.2	7.4	656	0	0
Beryllium	4	μg/L	86	0	86	NA	NA	NA	0	0
Cadmium	5	μg/L	81	0	81	NA	NA	NA	0	0
Chromium	100	μg/L	87	40	47	1.41	1.18	20	0	0
Copper	1,300	μg/L	98	67	31	2.95	1.35	27	0	0
Fluoride	4	μg/L	117	102	15	0.42	0.04	11.1	5	**4**
Lead	15	μg/L	91	13	78	NA	1.1	26.6	1	1
Mercury	2	μg/L	56	0	56	NA	NA	NA	0	0
Nitrate-N	10	mg/L	115	103	12	1.18	0.01	15.2	5	**4**
Nitrite-N	1	mg/L	15	4	11	NA	0.01	0.2	0	0
Selenium	50	μg/L	98	18	80	1.04	1.0	52.6	1	1
Thallium	2	μg/L	86	0	86	NA	NA	NA	0	0
Gross alpha	15	pCi/L	94	72	22	3.1	1.5	605	9	**10**
Gross beta	50	pCi/L	67	57	10	4.6	1.0	92	2	3
Comb. radium	5	pCi/L	27	8	19	NA	1.88	28.1	3	11
Uranium	30	μg/L	39	16	23	NA	1.05	3.85	0	0
Secondary MCL										
Aluminum	50	μg/L	100	27	73	2.1	0.77	231	1	1
Chloride	300	mg/L	121	121	0	35	1.0	3,330	7	6
Copper	1,000	μg/L	98	67	31	2.95	1.35	27	0	0
Fluoride	2	mg/L	117	102	15	0.42	0.04	11.1	9	8
Iron	300	μg/L	117	51	66	20	1.0	1,700	18	15
Manganese	50	μg/L	106	45	61	0.73	0.22	79.1	1	1
Silver	100	μg/L	43	1	42	NA	1.9	1.9	0	0
Sulfate	300	mg/L	121	118	3	26.7	5.13	2,480	5	4
TDS	1,000	mg/L	119	119	0	469	292	5,820	11	9
Zinc	5,000	μg/L	106	76	30	10	1.25	2,210	0	0
pH	6.5-8.5		125	125	0	6.96	5.5	8.4	4	3

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

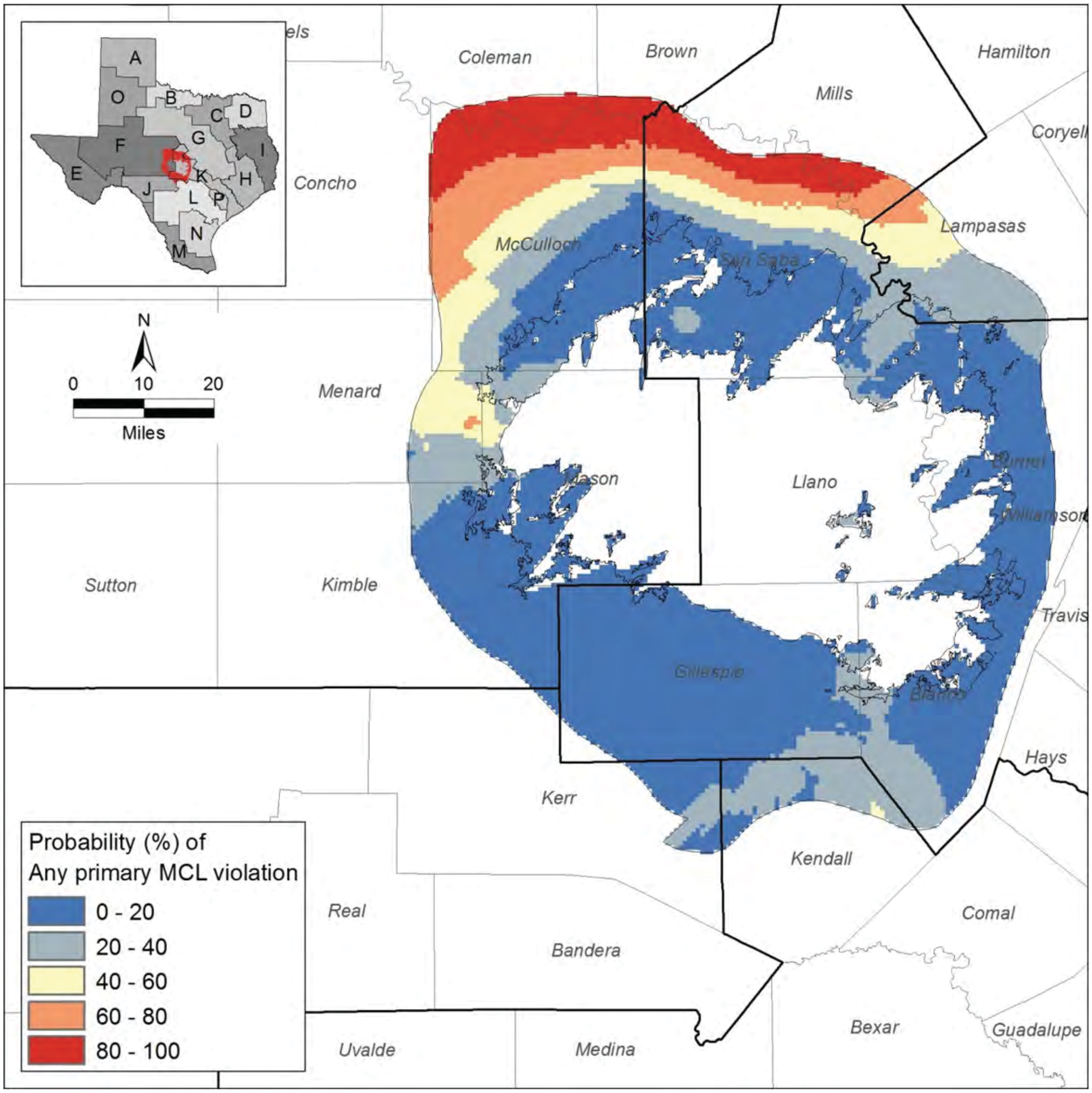

Figure 56. Ellenburger-San Saba Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

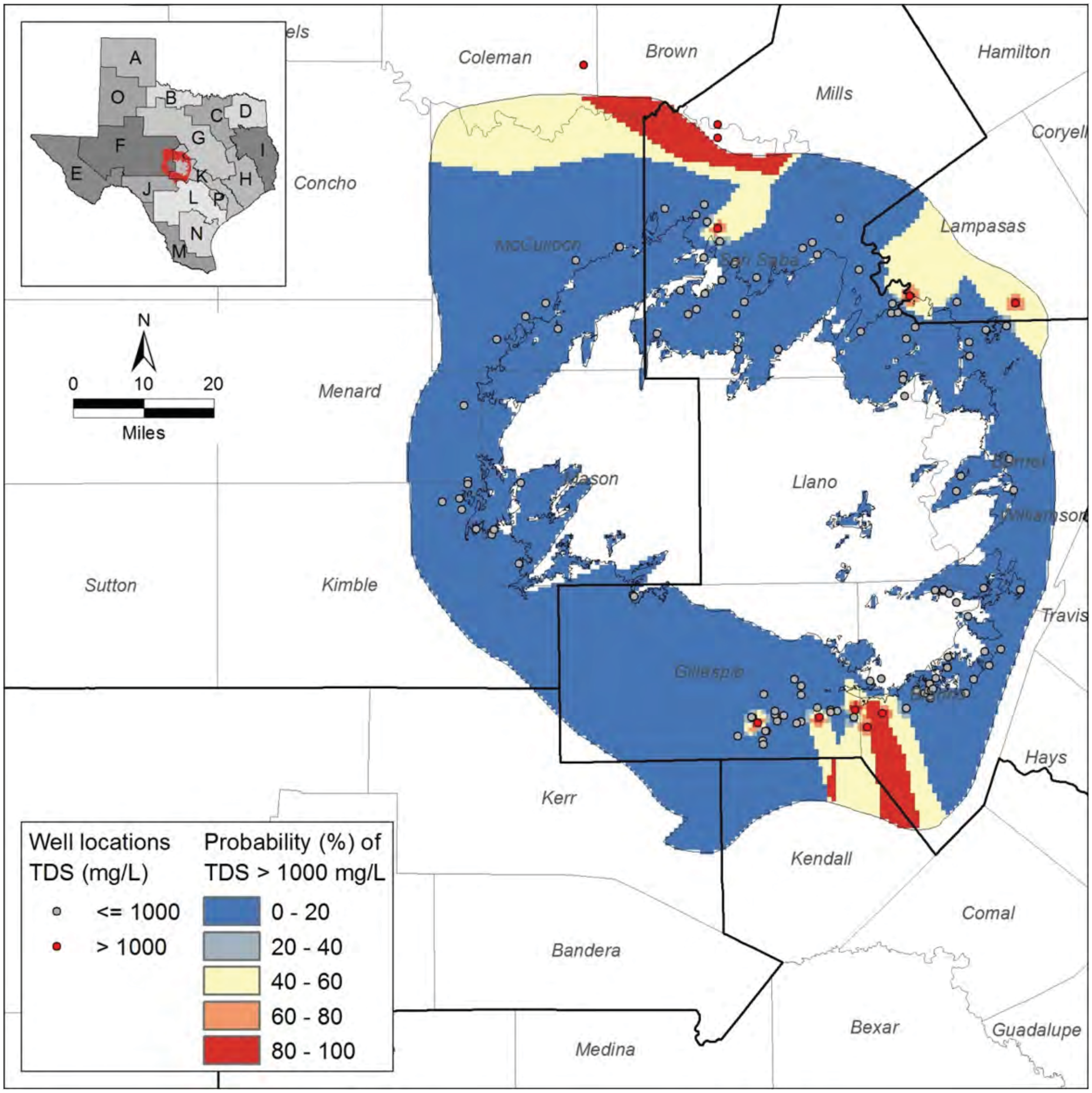

Figure 57. Ellenburger-San Saba Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Hickory

The Hickory Aquifer is adjacent to the Llano Uplift. The aquifer is characterized by high levels of gross alpha and combined radium primary MCL percent exceedances and probably about 75 percent of the volume has a high probability of any MCL exceedance (Table 34 and Table 35). High concentrations of both gross alpha and combined radium are found across all well depths (Appendix 15). The high risk category of exceeding any primary MCL represents 73 percent of the area and 77 percent of the volume while there are no areas at high risk of exceeding the secondary MCL for TDS. The highest probabilities of exceedance are located in the northwest (Figure 58). The sources of high levels of gross alpha and combined radium in groundwater in the Cambrian Hickory Sandstones are attributed to high levels of uranium typical of igneous rocks in the uplifted Precambrian igneous and metamorphic rocks of the Llano Uplift. TDS probabilities of exceedance are generally very low in this aquifer (Figure 59).

Table 34. Hickory Aquifer percent area and volume within MCL exceedance probability categories. Hickory Aquifer area is 8,610 mi^2 and volume is 576 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	9	18	73	8	15	77
Nitrate-N	100	0	0	100	0	0
Gross alpha	66	29	5	65	30	5
Radium	11	40	49	9	35	56
TDS	99	1	0	99	1	0

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 35. Summary of MCL violations in Hickory Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	111	0	111	NA	NA	NA	0	0
Arsenic	10	μg/L	130	24	106	NA	0.73	10	0	0
Barium	2,000	μg/L	131	129	2	79.9	6.7	460	0	0
Beryllium	4	μg/L	111	0	111	NA	NA	NA	0	0
Cadmium	5	μg/L	106	0	106	NA	NA	NA	0	0
Chromium	100	μg/L	116	27	89	NA	1.0	4.61	0	0
Copper	1,300	μg/L	129	78	51	2.3	0.96	24.7	0	0
Fluoride	4	μg/L	141	122	19	0.53	0.08	8.9	2	1
Lead	15	μg/L	121	22	99	NA	0.88	14.3	0	0
Mercury	2	μg/L	78	0	78	NA	NA	NA	0	0
Nitrate-N	10	mg/L	141	108	33	0.68	0.01	42.5	15	**11**
Nitrite-N	1	mg/L	27	3	24	NA	0.01	0.04	0	0
Selenium	50	μg/L	130	23	107	NA	1.0	9	0	0
Thallium	2	μg/L	111	2	109	NA	1.08	2.01	1	1
Gross alpha	15	pCi/L	148	140	8	9.4	1.3	104	44	**30**
Gross beta	50	pCi/L	105	99	6	14.9	2.7	131	7	7
Comb. radium	5	pCi/L	71	66	5	8.04	1.60	67.7	47	**66**
Uranium	30	μg/L	50	27	23	1.0	0.8	15.2	0	0
Secondary MCL										
Aluminum	50	μg/L	120	33	87	1.42	0.89	132	1	1
Chloride	300	mg/L	141	141	0	38	6.01	649	7	5
Copper	1,000	μg/L	129	78	51	2.3	0.96	24.7	0	0
Fluoride	2	mg/L	141	122	19	0.53	0.08	8.9	6	4
Iron	300	μg/L	140	73	67	20	0.01	10,600	22	16
Manganese	50	μg/L	131	82	49	1.77	0.15	3,180	10	8
Silver	100	μg/L	47	1	46	NA	1.48	1.48	0	0
Sulfate	300	mg/L	140	139	1	28.2	3.0	202	0	0
TDS	1,000	mg/L	134	134	0	413	150	1,590	4	3
Zinc	5,000	μg/L	131	89	42	9.14	2.0	1,260	0	0
pH	6.5-8.5		162	162	0	7.04	6.1	8.85	11	7

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

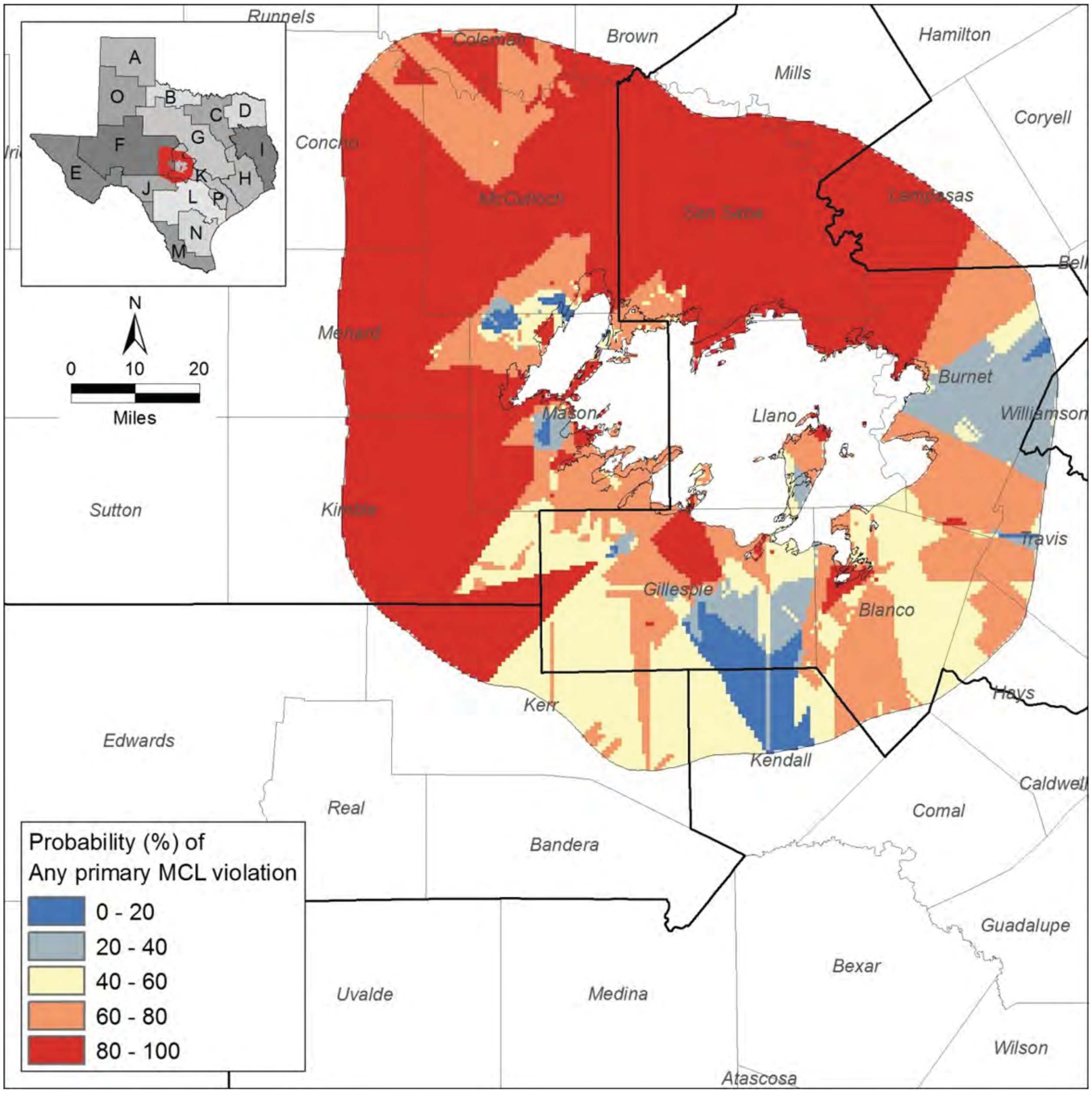

Figure 58. Hickory Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

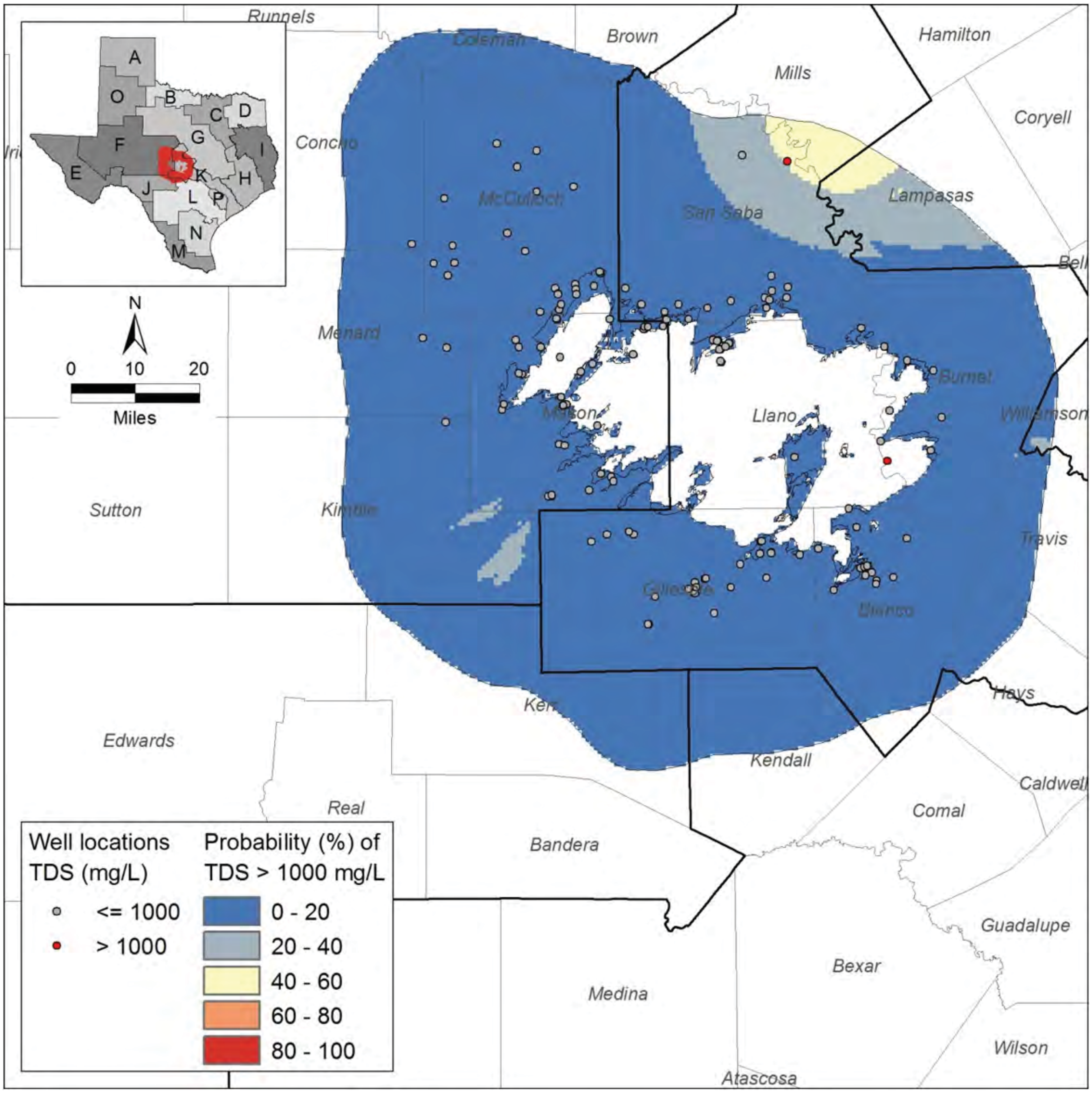

Figure 59. Hickory Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Igneous

Groundwater in the Igneous Aquifer is dominated by arsenic exceedances, followed by fluoride and gross alpha exceedances, related to the igneous source rocks (Table 36 and Table 37). There are no prominent trends in water quality with well depth (Appendix 16). The high risk category of exceeding any primary MCL represents 6 percent of the area and 4 percent of the volume while there are no areas at high risk of exceeding the secondary MCL for TDS. Percentages of affected aquifer volumes are expected to be low (below 10 percent) for primary MCL violations in sampled wells (Figure 60). Secondary MCL exceedances are dominated by fluoride whereas TDS is generally low (Figure 61).

Table 36. Igneous Aquifer percent area and volume within MCL exceedance probability categories. Igneous Aquifer area is 5,620 mi^2 and volume is 1,960 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	67	27	6	72	24	4
Arsenic	85	11	4	86	11	3
Fluoride	100	0	0	100	0	0
Gross alpha	100	0	0	100	0	0
TDS	100	0	0	100	0	0

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 37. Summary of MCL violations in Igneous Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	36	0	36	NA	NA	NA	0	0
Arsenic	10	μg/L	64	32	32	1.5	1.0	33.1	11	**17**
Barium	2,000	μg/L	66	55	11	15.7	1.04	77	0	0
Beryllium	4	μg/L	36	0	36	NA	NA	NA	0	0
Cadmium	5	μg/L	56	0	56	NA	NA	NA	0	0
Chromium	100	μg/L	64	13	51	NA	1.3	28.5	0	0
Copper	1,300	μg/L	64	28	36	1.29	1.0	51	0	0
Fluoride	4	μg/L	83	83	0	1.54	0.2	4.9	3	**4**
Lead	15	μg/L	56	6	50	NA	1.0	11.8	0	0
Mercury	2	μg/L	39	2	37	NA	0.15	0.3	0	0
Nitrate-N	10	mg/L	76	75	1	0.94	0.01	5.26	0	0
Nitrite-N	1	mg/L	36	11	25	NA	0.01	0.02	0	0
Selenium	50	μg/L	66	10	56	1.0	1.0	19.9	0	0
Thallium	2	μg/L	36	0	36	NA	NA	NA	0	0
Gross alpha	15	pCi/L	48	47	1	6.1	0.8	27	4	**8**
Gross beta	50	pCi/L	47	31	16	6.3	1.1	19	0	0
Comb. radium	5	pCi/L	8	0	8	NA	NA	NA	0	0
Uranium	30	μg/L	1	1	0	NA	2.7	2.7	0	0
Secondary MCL										
Aluminum	50	μg/L	64	5	59	NA	4.88	208	1	2
Chloride	300	mg/L	84	84	0	11.2	2.88	570	1	1
Copper	1,000	μg/L	64	28	36	1.29	1.0	51	0	0
Fluoride	2	mg/L	83	83	0	1.54	0.2	4.9	31	37
Iron	300	μg/L	67	15	52	5.8	5.8	1,000	3	4
Manganese	50	μg/L	66	19	47	NA	1.1	291	2	3
Silver	100	μg/L	41	0	41	NA	NA	NA	0	0
Sulfate	300	mg/L	83	83	0	17	4.97	561	2	2
TDS	1,000	mg/L	81	81	0	287	97	1,910	1	1
Zinc	5,000	μg/L	64	53	11	24.3	5.0	1,230	0	0
pH	6.5-8.5		79	79	0	7.45	6.5	8.62	1	1

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

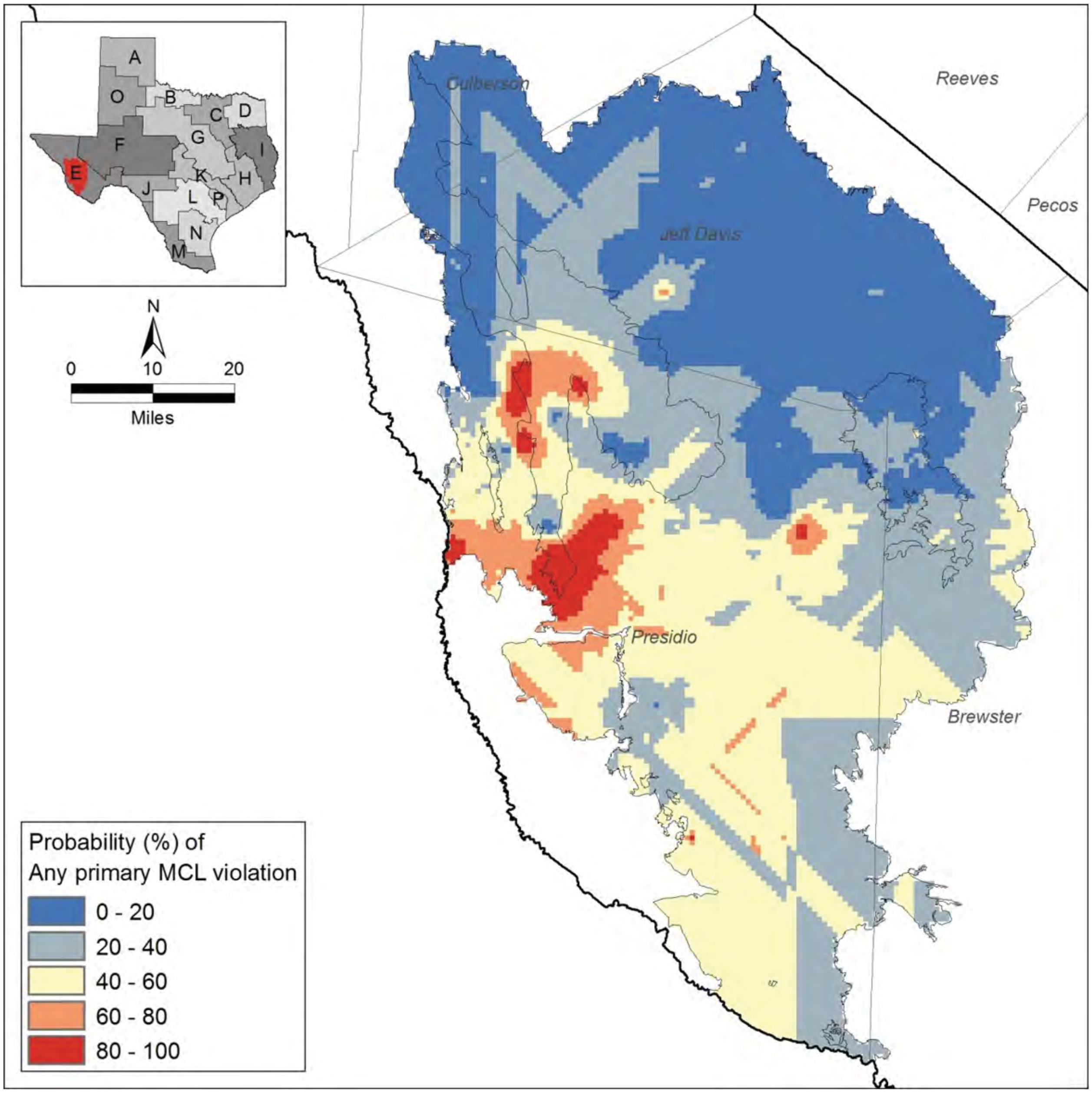

Figure 60. Igneous Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

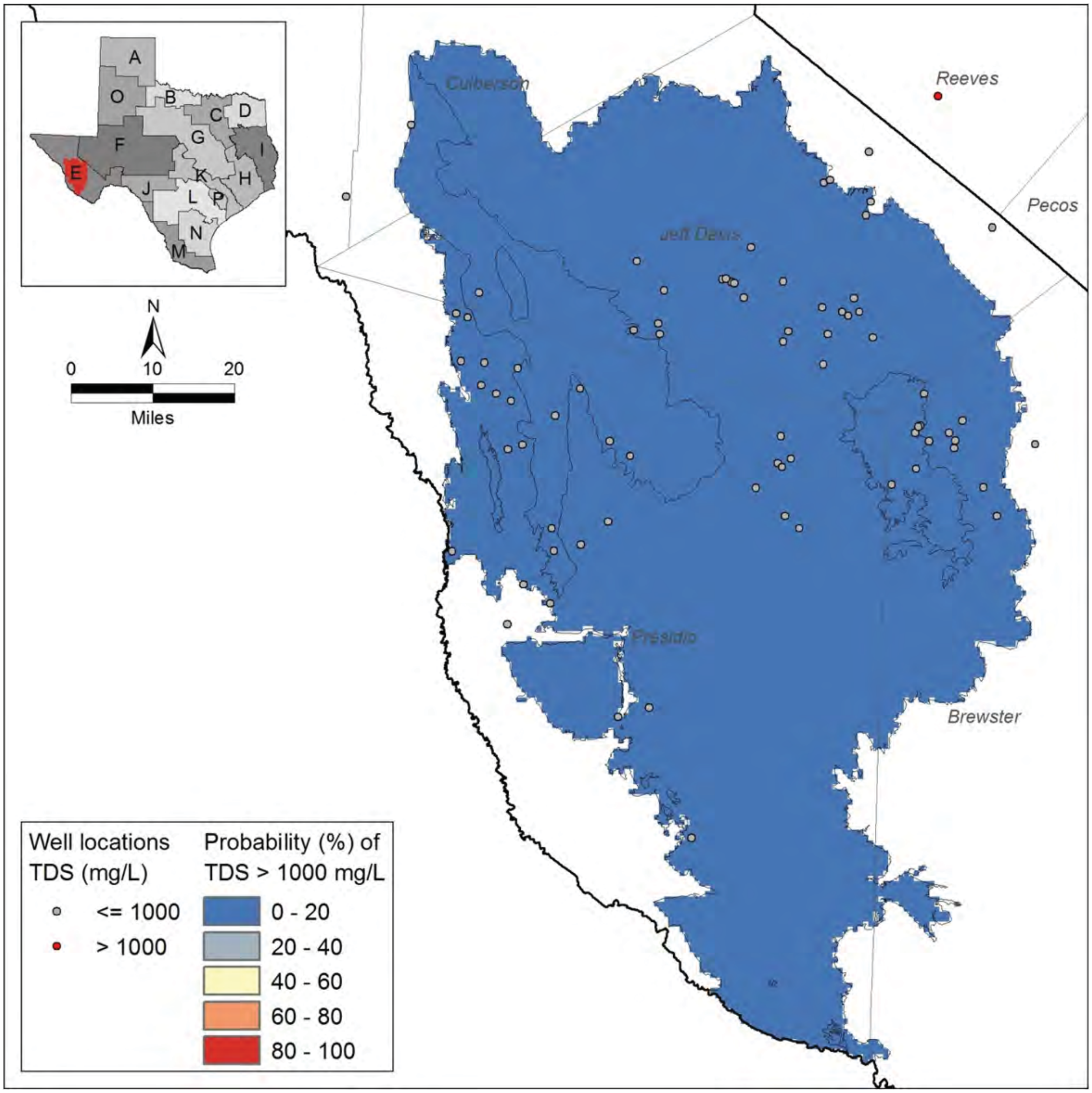

Figure 61. Igneous Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Lipan

Groundwater quality in the Lipan Aquifer is dominated by nitrate-N MCL percent exceedances. Approximately 70 percent of the aquifer volume is expected to be contaminated by excessive nitrate-N and 80 percent by excessive TDS (Table 38 and Table 39). The saturated thickness of the Lipan is small and there are no consistent trends with well depth (Appendix 17). The high risk category of exceeding any primary MCL (nitrate-N) represents 70 percent of the area and 71 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 75 percent of the area and 78 percent of the volume. The highest probabilities of primary MCL exceedance are located in the eastern regions of the aquifer (Figure 62) while secondary MCL exceedance is focused in the central regions of the aquifer (Figure 63).

Table 38. Lipan Aquifer percent area and volume within MCL exceedance probability categories. Lipan Aquifer area is 670 mi^2 and volume is 67 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (nitrate-N)	16	14	70	15	14	71
TDS	6	19	75	7	15	78

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 39. Summary of MCL violations in Lipan Aquifer groundwater wells

	MCL	Units	Analyses	Detects	Non-detects	Median	Min	Max	> MCL	% MCL
Primary MCL										
Antimony	6	µg/L	46	0	46	NA	NA	NA	0	0
Arsenic	10	µg/L	59	46	13	3.0	2.02	6.9	0	0
Barium	2,000	µg/L	59	58	1	68.7	10.2	264	0	0
Beryllium	4	µg/L	47	0	47	NA	NA	NA	0	0
Cadmium	5	µg/L	56	0	56	NA	NA	NA	0	0
Chromium	100	µg/L	57	22	35	NA	2.6	23.6	0	0
Copper	1,300	µg/L	59	47	12	3.9	1.3	31.3	0	0
Fluoride	4	µg/L	62	59	3	0.61	0.1	1.93	0	0
Lead	15	µg/L	57	9	48	NA	1.1	7.0	0	0
Mercury	2	µg/L	40	2	38	0.12	0.12	0.44	0	0
Nitrate-N	10	mg/L	61	60	1	18.6	0.05	85.3	37	61
Nitrite-N	1	mg/L	19	4	15	NA	0.01	0.01	0	0
Selenium	50	µg/L	58	41	17	7.8	2.0	92.5	1	2
Thallium	2	µg/L	46	0	46	NA	NA	NA	0	0
Gross alpha	15	pCi/L	39	35	4	3.7	1.2	17.2	1	3
Gross beta	50	pCi/L	39	31	8	5.8	2.9	19	0	0
Comb. radium	5	pCi/L	1	0	1	NA	NA	NA	0	0
Uranium	30	µg/L	26	26	0	4.0	1.6	20.3	0	0
Secondary MCL										
Aluminum	50	µg/L	47	3	44	NA	5.1	27.1	0	0
Chloride	300	mg/L	62	62	0	372	27.4	1,670	38	61
Copper	1,000	µg/L	59	47	12	3.9	1.3	31.3	0	0
Fluoride	2	mg/L	62	59	3	0.61	0.1	1.93	0	0
Iron	300	µg/L	59	15	44	9.8	8.3	125	0	0
Manganese	50	µg/L	59	15	44	NA	1.0	18.9	0	0
Silver	100	µg/L	42	0	42	NA	NA	NA	0	0
Sulfate	300	mg/L	62	62	0	171	18.7	1,850	19	31
TDS	1,000	mg/L	61	61	0	1,320	354	4,220	41	67
Zinc	5,000	µg/L	59	48	11	10	4.02	485	0	0
pH	6.5-8.5		62	62	0	7.05	6.59	7.78	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

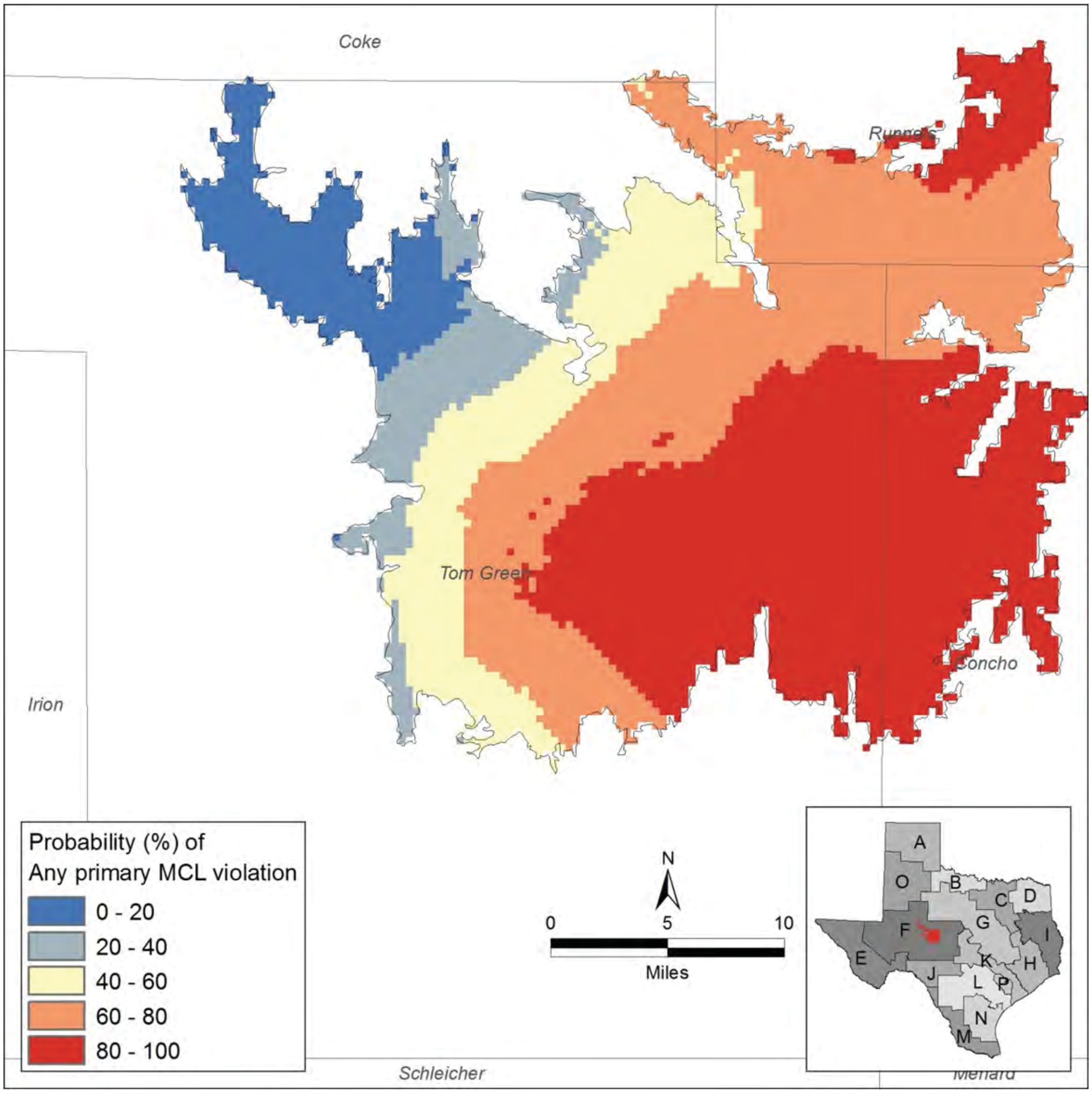

Figure 62. Lipan Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

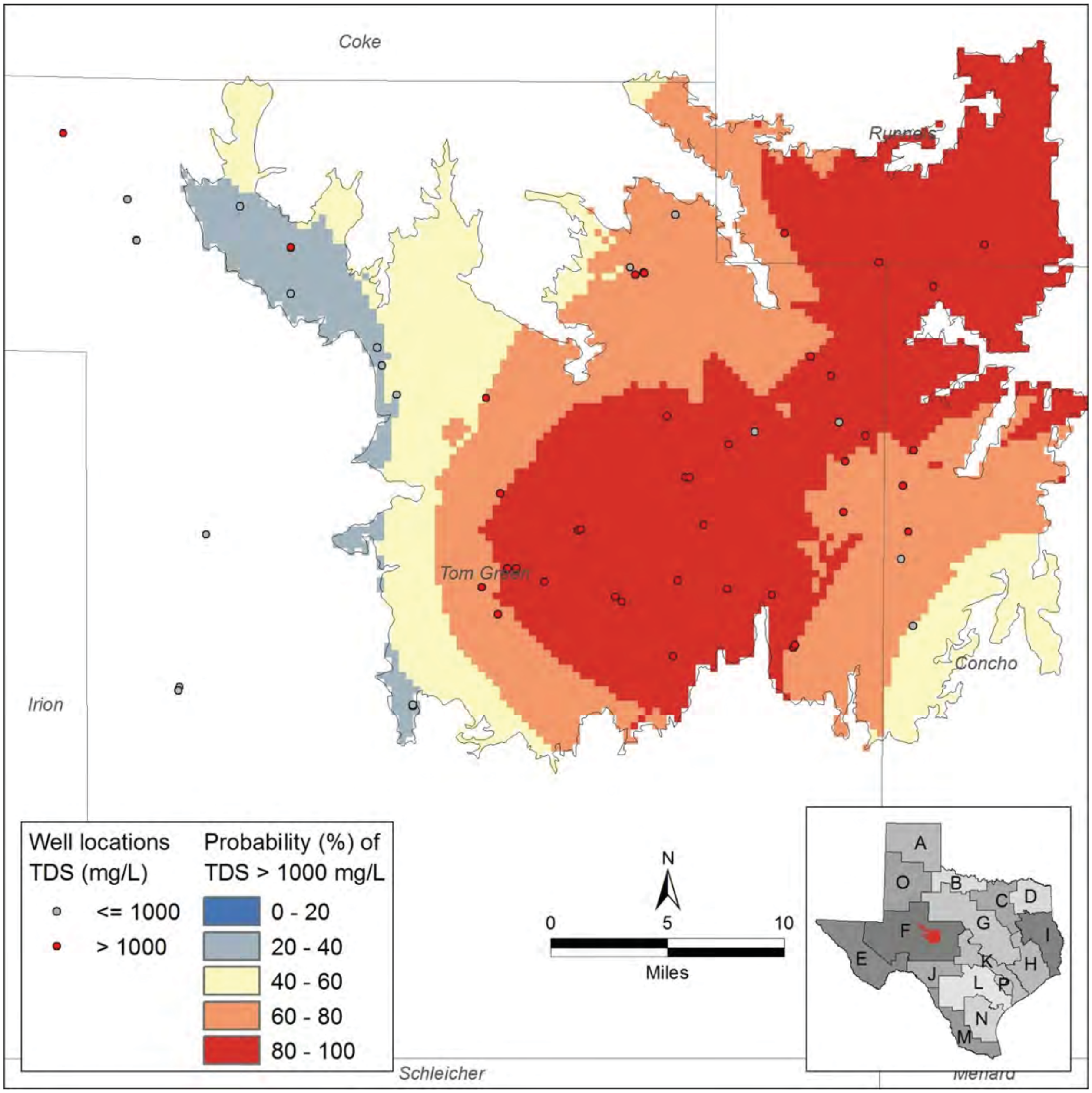

Figure 63. Lipan Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Nacatoch

Groundwater sampling in the Nacatoch Aquifer is limited, making it difficult to assess groundwater quality in the aquifer. There are no significant primary MCL violations and groundwater is likely to be impacted by TDS in a percent volume approaching the percent exceedances of TDS (Table 40 and Table 41). There are no expected volumes of groundwater to be impacted by any primary MCL exceedance. Elevated TDS concentrations are found mostly in deeper wells in the northeastern and downdip extent of the aquifer (Figure 64 and Appendix 18).

Table 40. Nacatoch Aquifer percent area and volume within MCL exceedance probability categories. Nacatoch Aquifer area is 1,610 mi^2 and volume is 16 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (none)	100	0	0	100	0	0
TDS	71	8	21	72	7	21

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 41. Summary of MCL violations in Nacatoch Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	28	0	28	NA	NA	NA	0	0
Arsenic	10	μg/L	36	6	30	NA	2.0	7.0	0	0
Barium	2,000	μg/L	36	33	3	18.2	3.7	297	0	0
Beryllium	4	μg/L	28	0	28	NA	NA	NA	0	0
Cadmium	5	μg/L	31	0	31	NA	NA	NA	0	0
Chromium	100	μg/L	36	13	23	1.0	1.0	49.4	0	0
Copper	1,300	μg/L	36	19	17	2.4	1.0	27.9	0	0
Fluoride	4	μg/L	36	33	3	0.52	0.04	4.27	1	3
Lead	15	μg/L	31	1	30	NA	1.21	1.21	0	0
Mercury	2	μg/L	27	0	27	NA	NA	NA	0	0
Nitrate-N	10	mg/L	37	12	25	NA	0.01	2.22	0	0
Nitrite-N	1	mg/L	20	5	15	NA	0.01	0.09	0	0
Selenium	50	μg/L	36	6	30	NA	2.0	22	0	0
Thallium	2	μg/L	28	0	28	NA	NA	NA	0	0
Gross alpha	15	pCi/L	25	10	15	1.5	0.9	6.5	0	0
Gross beta	50	pCi/L	25	8	17	NA	0.2	5.5	0	0
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	3	0	3	NA	NA	NA	0	0
Secondary MCL										
Aluminum	50	μg/L	32	14	18	2.0	1.8	120	1	3
Chloride	300	mg/L	38	38	0	138	10.9	1,710	9	24
Copper	1,000	μg/L	36	19	17	2.4	1.0	27.9	0	0
Fluoride	2	mg/L	36	33	3	0.52	0.04	4.27	8	22
Iron	300	μg/L	37	14	23	10.4	5.8	9,660	3	8
Manganese	50	μg/L	36	21	15	2.1	1.0	203	2	6
Silver	100	μg/L	27	0	27	NA	NA	NA	0	0
Sulfate	300	mg/L	38	34	4	21	1.0	446	4	11
TDS	1,000	mg/L	36	36	0	799	348	2,990	9	25
Zinc	5,000	μg/L	36	16	20	4.03	4.03	94.2	0	0
pH	6.5-8.5		38	38	0	8.67	6.2	9.31	25	66

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

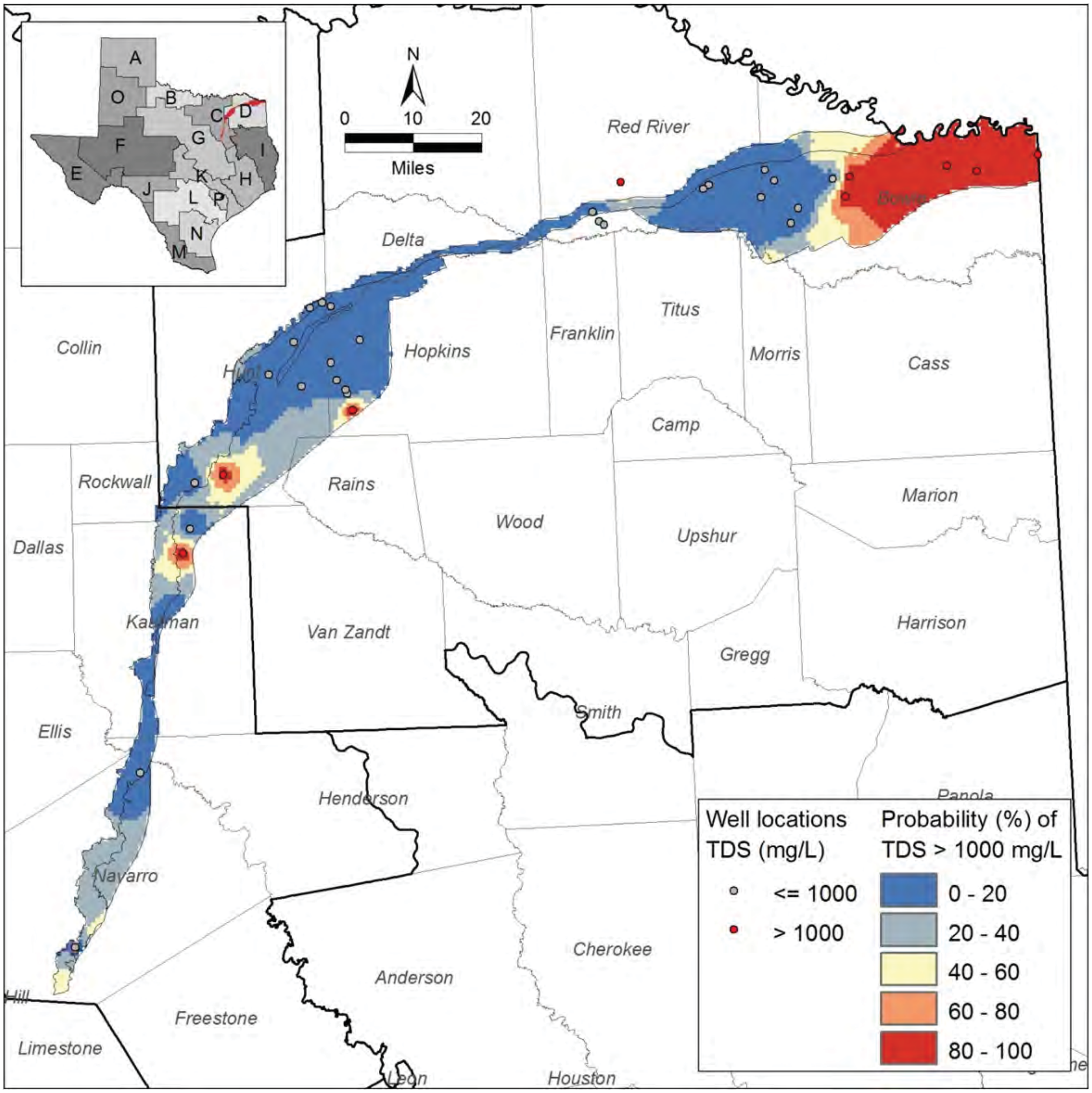

Figure 64. Nacatoch Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Queen City

Groundwater in the Queen City Aquifer has very low percentages of any primary MCL exceedances (Table 42 and Table 43), and aquifer volumes impacted by any primary MCL exceedance are suspected to be quite low and limited to the far southern region of the aquifer (Figure 65). High TDS is mostly found in the southern part of the aquifer (Figure 66); however, other secondary MCL exceedances are higher and are dominated by iron and manganese in more than half of the wells sampled. TDS tends to increase with well depth while nitrate-N deceases (Appendix 19).

Table 42. Queen City Aquifer percent area and volume within MCL exceedance probability categories. Queen City Aquifer area is 14,600 mi^2 and volume is 393 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	99	1	0	100	0	0
Nitrate-N	99	1	0	100	0	0
Gross alpha	100	0	0	100	0	0
TDS	88	4	8	79	7	14

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 43. Summary of MCL violations in Queen City Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	167	0	167	NA	NA	NA	0	0
Arsenic	10	µg/L	219	14	205	NA	1.1	4.3	0	0
Barium	2,000	µg/L	221	220	1	51.9	3.0	580	0	0
Beryllium	4	µg/L	168	5	163	NA	1.0	4.6	1	1
Cadmium	5	µg/L	183	4	179	NA	1.1	19.8	1	1
Chromium	100	µg/L	190	71	119	NA	1.02	40.1	0	0
Copper	1,300	µg/L	221	133	88	2.2	1.13	1,070	0	0
Fluoride	4	µg/L	218	188	30	0.1	0.01	3.2	0	0
Lead	15	µg/L	214	33	181	NA	1.0	22	2	1
Mercury	2	µg/L	84	1	83	NA	0.14	0.14	0	0
Nitrate-N	10	mg/L	219	124	95	0.03	0.01	33.5	4	**2**
Nitrite-N	1	mg/L	115	8	107	NA	0.01	0.03	0	0
Selenium	50	µg/L	189	9	180	NA	2.0	43	0	0
Thallium	2	µg/L	164	0	164	NA	NA	NA	0	0
Gross alpha	15	pCi/L	117	25	92	0.7	0.7	302	2	**2**
Gross beta	50	pCi/L	114	45	69	NA	4.1	129	1	1
Comb. radium	5	pCi/L	4	3	1	2.0	2.0	3.3	0	0
Uranium	30	µg/L	29	1	28	NA	1.0	1.0	0	0
Secondary MCL										
Aluminum	50	µg/L	183	77	106	2.0	2.0	6,200	24	13
Chloride	300	mg/L	223	221	2	20.6	1.46	4,460	19	9
Copper	1,000	µg/L	221	133	88	2.2	1.13	1,070	0	0
Fluoride	2	mg/L	218	188	30	0.1	0.01	3.2	4	2
Iron	300	µg/L	224	155	69	60	5.4	76,700	59	26
Manganese	50	µg/L	223	207	16	13.3	0.7	3,890	46	21
Silver	100	µg/L	84	1	83	NA	2.4	2.4	0	0
Sulfate	300	mg/L	223	213	10	29.5	1.0	1,880	19	9
TDS	1,000	mg/L	215	215	0	278	45	7,950	28	13
Zinc	5,000	µg/L	221	187	34	30	2.0	12,000	2	1
pH	6.5-8.5		220	220	0	7.17	3.46	9.1	100	45

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

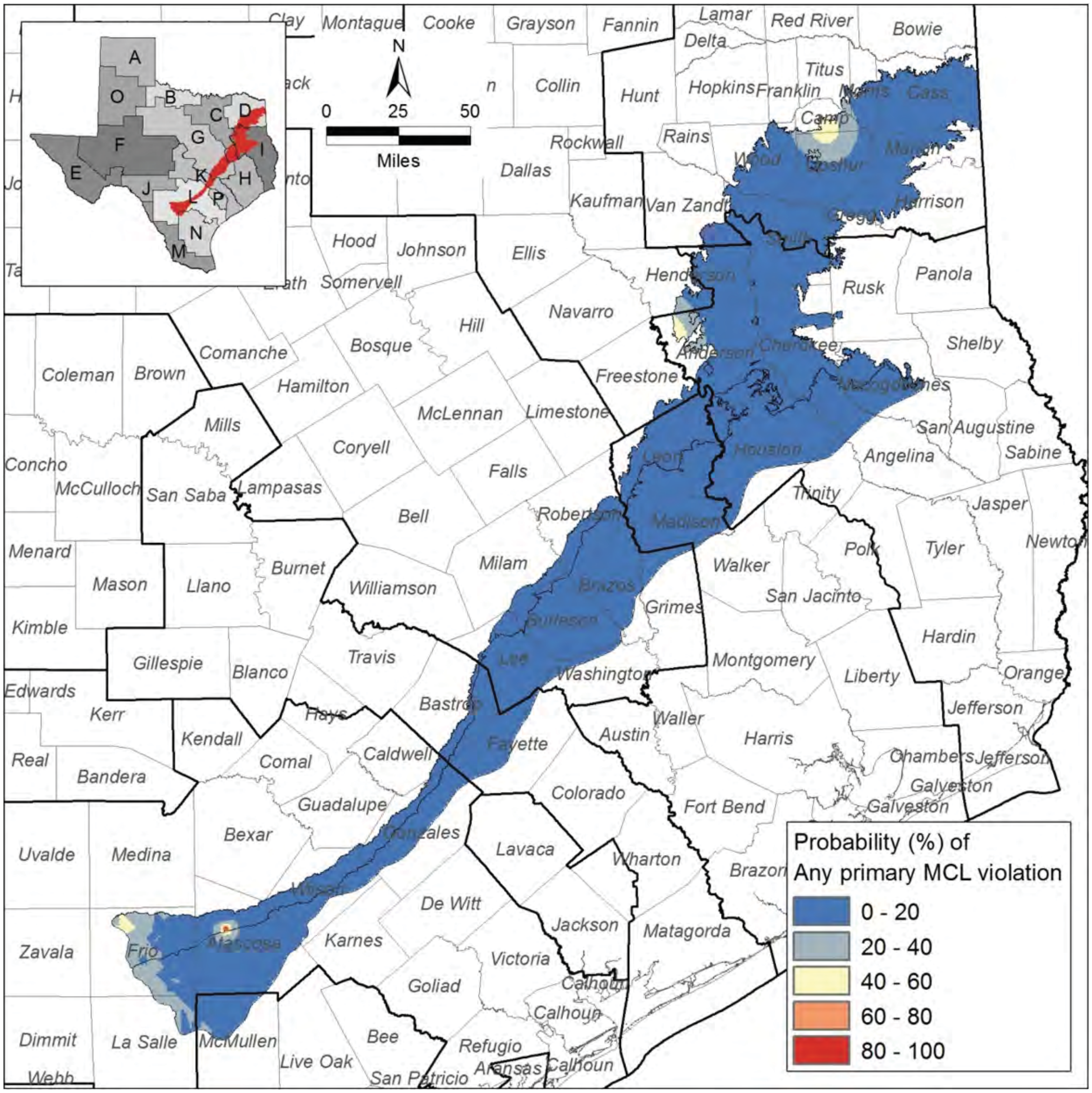

Figure 65. Queen City Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

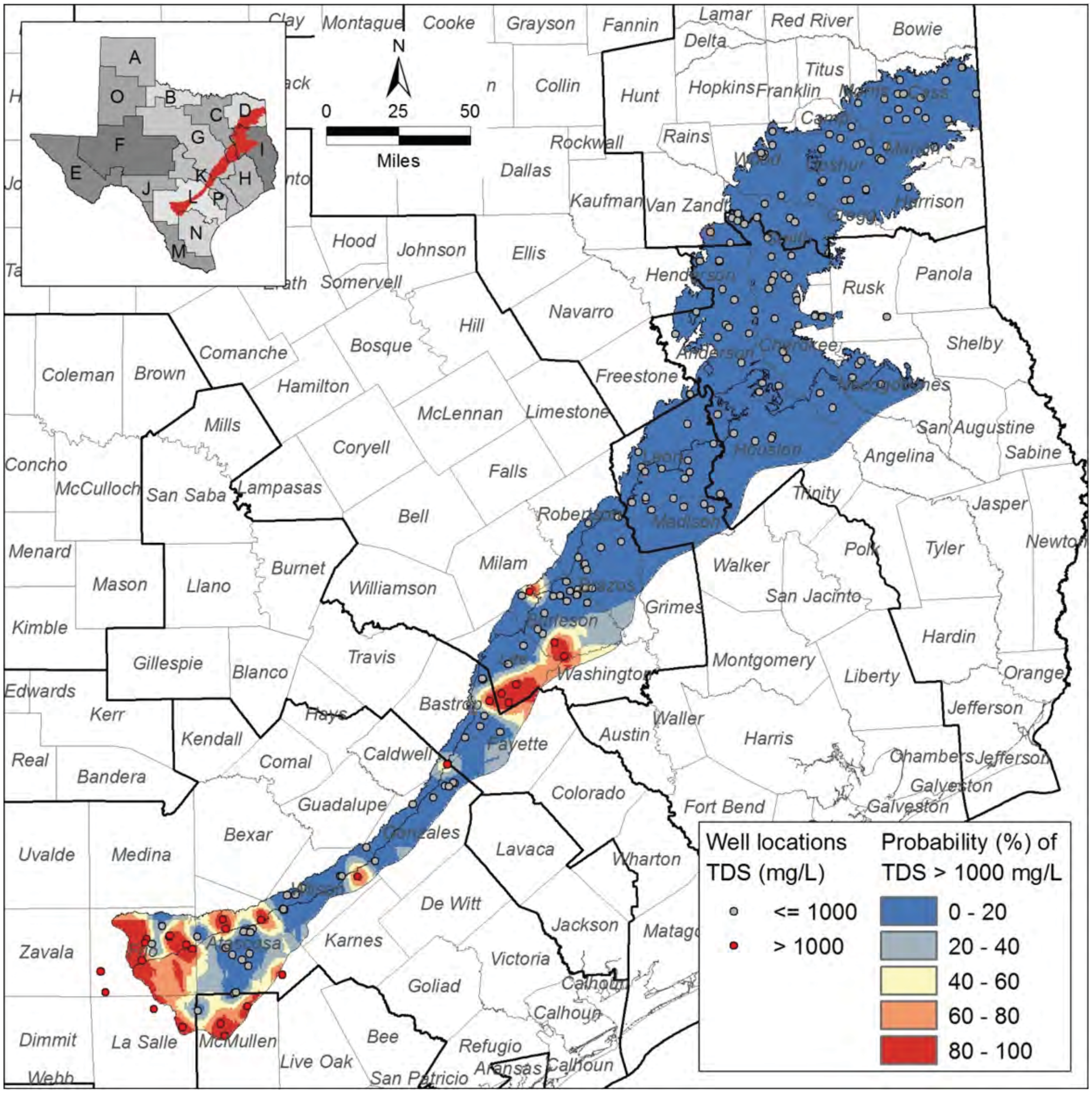

Figure 66. Queen City Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Rita Blanca

The Rita Blanca Aquifer underlies the Ogallala Formation in Dallam and Hartley counties, and groundwater quality is similar to that of the Ogallala Aquifer in that region. Primary MCL exceedances are limited and are dominated by gross alpha radiation, arsenic, and fluoride (Table 44 and Table 45), and concentrations show no clear trends with well depth (Appendix 20). The high risk category of exceeding any primary MCL represents 24 percent of the area and 27 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 7 percent of the area and 7 percent of the volume. Secondary MCL exceedances are dominated by fluoride, followed by TDS which is controlled mostly by sulfate exceedances. Most of the poor quality groundwater is in the eastern downdip section of the aquifer (Figure 67 and Figure 68). Aquifer volumes impacted by any primary MCL are expected to be about 27 percent whereas volumes impacted by TDS exceedances are believed to be much less than 10 percent.

Table 44. Rita Blanca Aquifer percent area and volume within MCL exceedance probability categories. Rita Blanca Aquifer area is 392 mi^2 and volume is 14 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	65	11	24	60	13	27
Arsenic	100	0	0	100	0	0
Fluoride	89	11	0	88	12	0
Gross alpha	83	17	0	82	18	0
TDS	85	8	7	85	8	7

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 45. Summary of MCL violations in Rita Blanca Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	14	0	14	NA	NA	NA	0	0
Arsenic	10	μg/L	18	10	8	1.6	0.99	10.2	1	**6**
Barium	2,000	μg/L	15	15	0	38.3	9.08	89.5	0	0
Beryllium	4	μg/L	14	0	14	NA	NA	NA	0	0
Cadmium	5	μg/L	11	0	11	NA	NA	NA	0	0
Chromium	100	μg/L	14	2	12	NA	1.93	2.1	0	0
Copper	1,300	μg/L	15	8	7	1.2	1.2	11.2	0	0
Fluoride	4	μg/L	18	17	1	1.4	0.79	6.23	3	**17**
Lead	15	μg/L	14	1	13	NA	1.61	1.61	0	0
Mercury	2	μg/L	10	0	10	NA	NA	NA	0	0
Nitrate-N	10	mg/L	18	18	0	0.65	0.03	2.77	0	0
Nitrite-N	1	mg/L	7	0	7	NA	NA	NA	0	0
Selenium	50	μg/L	18	8	10	1.56	1.56	17.5	0	0
Thallium	2	μg/L	14	0	14	NA	NA	NA	0	0
Gross alpha	15	pCi/L	13	12	1	6.6	1.8	57.8	3	**23**
Gross beta	50	pCi/L	10	10	0	5.8	2.9	14	0	0
Comb. radium	5	pCi/L	7	1	6	NA	3.77	3.77	0	0
Uranium	30	μg/L	7	6	1	7.26	1.6	66.9	3	43
Secondary MCL										
Aluminum	50	μg/L	15	6	9	2.5	2.5	11.7	0	0
Chloride	300	mg/L	18	18	0	17.6	5.4	262	1	6
Copper	1,000	μg/L	15	8	7	1.2	1.2	11.2	0	0
Fluoride	2	mg/L	18	17	1	1.4	0.79	6.23	4	22
Iron	300	μg/L	18	11	7	36	7.0	252	0	0
Manganese	50	μg/L	15	8	7	0.47	0.47	17.2	0	0
Silver	100	μg/L	3	0	3	NA	NA	NA	0	0
Sulfate	300	mg/L	18	18	0	64.7	23.4	954	2	11
TDS	1,000	mg/L	18	18	0	419	259	1,960	3	17
Zinc	5,000	μg/L	15	11	4	13.4	4.07	163	0	0
pH	6.5-8.5		16	16	0	7.69	7.0	9.29	3	19

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Nondetects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

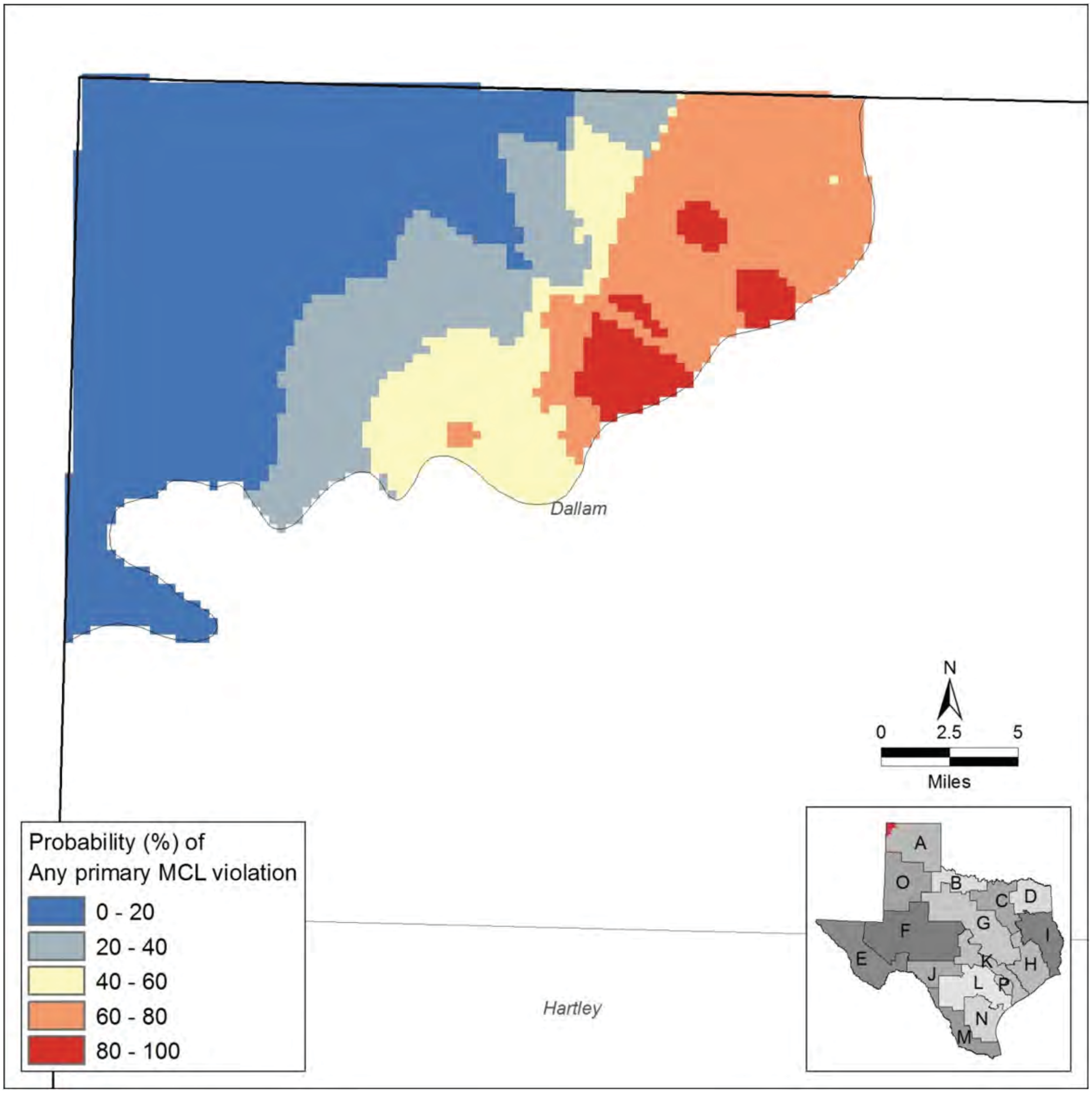

Figure 67. Rita Blanca Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

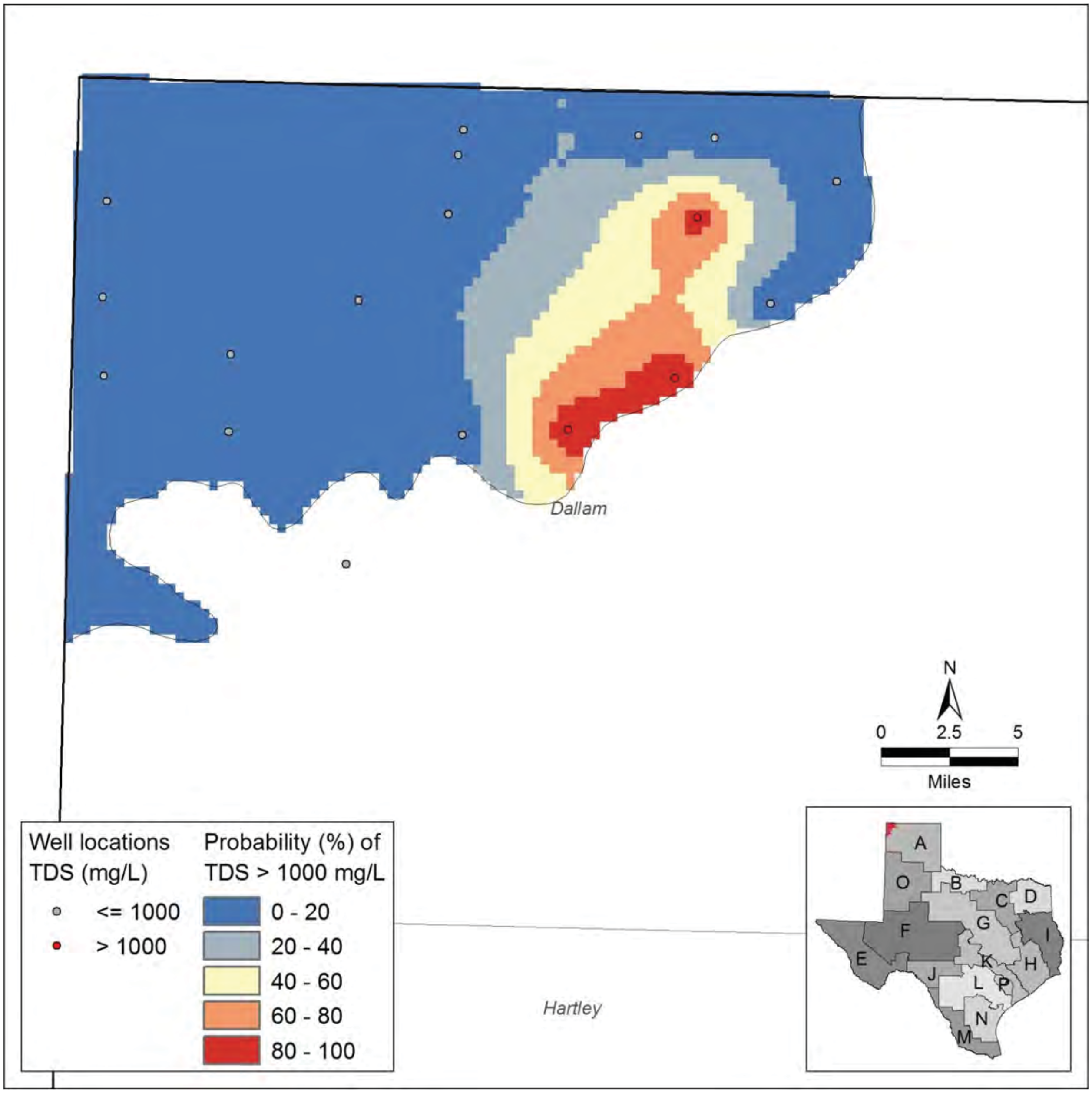

Figure 68. Rita Blanca Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Sparta

Groundwater in the Sparta Aquifer is generally of high quality, similar to the adjacent Queen City and Carrizo-Wilcox aquifers, with generally low percentages of exceedances of any primary MCL, with the exception of a very limited number of combined radium analyses (40 percent exceedance) (Table 46 and Table 47). TDS concentrations do not exhibit any trend with well depth (Appendix 21) and high risk of MCL exceedance represents 15 of the area dn 14 percent of the volume. Secondary MCL exceedances are much higher and are dominated by iron, followed by TDS, chloride, sulfate, and manganese. High TDS water is generally restricted to the southern part of the aquifer (Figure 69).

Table 46. Sparta Aquifer percent area and volume within MCL exceedance probability categories. Sparta Aquifer area is 7,850 mi^2 and volume is 172 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (none)	100	0	0	100	0	0
TDS	79	6	15	82	4	14

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 47. Summary of MCL violations in Sparta Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	78	1	77	NA	1.3	1.3	0	0
Arsenic	10	μg/L	103	3	100	NA	1.4	10.6	1	1
Barium	2,000	μg/L	105	99	6	28.2	1.5	263	0	0
Beryllium	4	μg/L	76	1	75	NA	1.3	1.3	0	0
Cadmium	5	μg/L	105	1	104	NA	2.2	2.2	0	0
Chromium	100	μg/L	105	36	69	NA	1.11	17.1	0	0
Copper	1,300	μg/L	105	44	61	1.38	1.06	36.1	0	0
Fluoride	4	μg/L	106	101	5	0.19	0.01	3.2	0	0
Lead	15	μg/L	102	8	94	NA	1.04	5.9	0	0
Mercury	2	μg/L	67	6	61	NA	0.13	0.71	0	0
Nitrate-N	10	mg/L	107	55	52	0.01	0.01	11.2	1	1
Nitrite-N	1	mg/L	58	21	37	NA	0.01	0.17	0	0
Selenium	50	μg/L	105	8	97	NA	2.0	29.1	0	0
Thallium	2	μg/L	76	1	75	NA	1.97	1.97	0	0
Gross alpha	15	pCi/L	62	9	53	1.7	1.5	6.4	0	0
Gross beta	50	pCi/L	71	35	36	NA	4.1	27	0	0
Comb. radium	5	pCi/L	5	2	3	NA	8.46	13.9	2	40
Uranium	30	μg/L	11	0	11	NA	NA	NA	0	0
Secondary MCL										
Aluminum	50	μg/L	86	22	64	NA	1.0	304	3	3
Chloride	300	mg/L	108	108	0	45	5.75	3,590	20	19
Copper	1,000	μg/L	105	44	61	1.38	1.06	36.1	0	0
Fluoride	2	mg/L	106	101	5	0.19	0.01	3.2	2	2
Iron	300	μg/L	106	83	23	81	9.4	24,000	27	25
Manganese	50	μg/L	106	90	16	11.4	1.2	431	17	16
Silver	100	μg/L	52	0	52	NA	NA	NA	0	0
Sulfate	300	mg/L	108	102	6	123	1.29	1,480	18	17
TDS	1,000	mg/L	105	105	0	560	65	6,780	24	23
Zinc	5,000	μg/L	105	76	29	14	1.0	986	0	0
pH	6.5-8.5		102	102	0	7.8	5.05	8.91	23	23

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

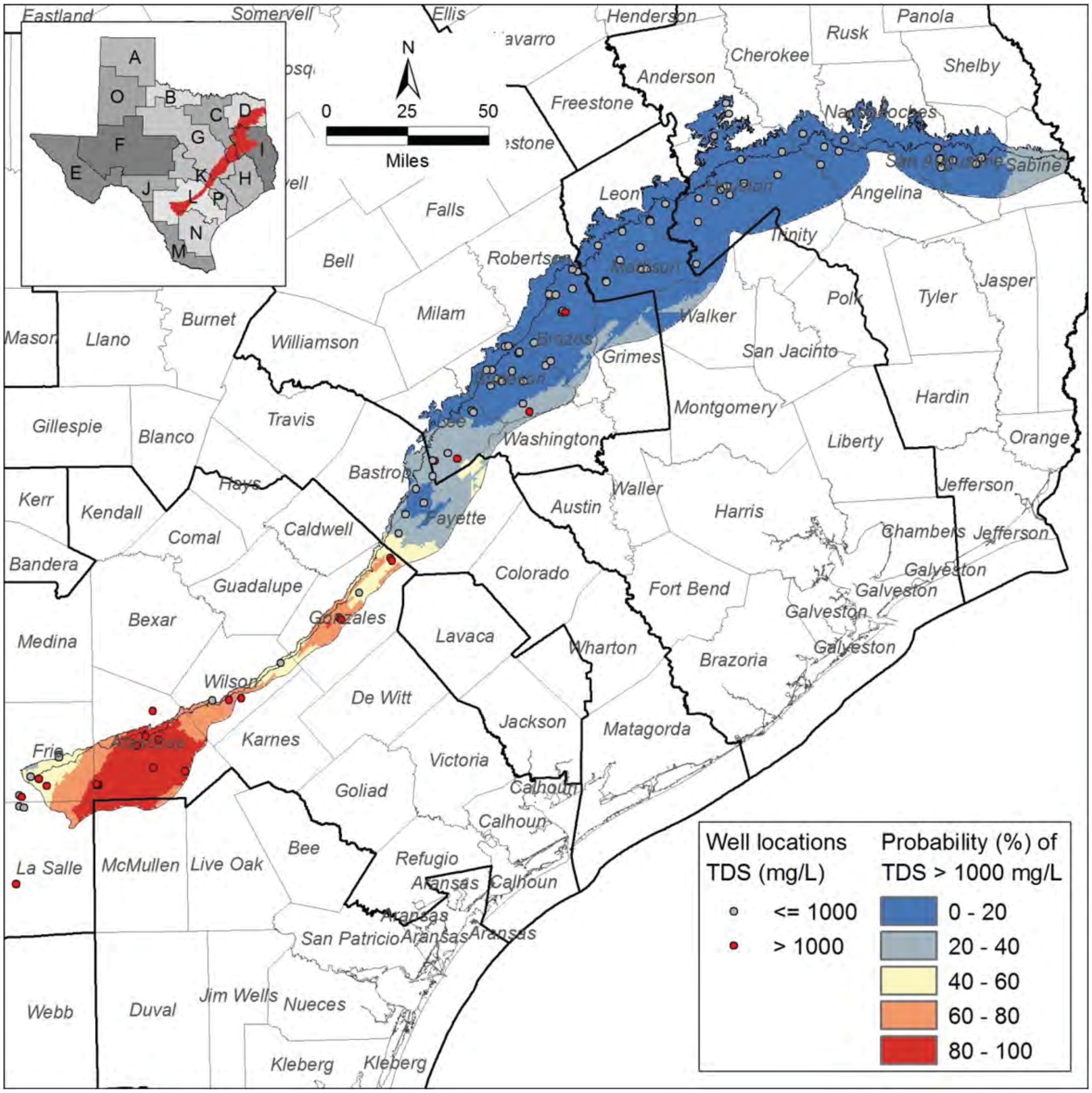

Figure 69. Aquifer probability of total dissolved solids (TDS) secondary MCL violation

West Texas Bolsons

Groundwater in the West Texas Bolsons Aquifer contains exceedances of arsenic, followed by fluoride, gross alpha, and nitrate-N primary MCLs (Table 48 and Table 49). Groundwater volumes will be impacted to some degree by primary MCL exceedances dominated by fluoride and arsenic. Groundwater volumes will likely be simlarly impacted by excessive TDS as suggested by exceedances in sampled wells. The primary MCL constituents of concern show no consistent concentration trends with well depth (Appendix 22). The high risk category of exceeding any primary MCL represents 9 percent of the area and 20 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 5 percent of the area and 1 percent of the volume. Primary MCL exceedances are generally located in the central and southern regions while TDS exceedances are located in the north (Figure 70). Secondary MCL exceedances are also dominated by fluoride, followed by TDS and related to sulfate and chloride exceedances (Figure 71). There are limited percentages of iron and manganese exceedances. The source of the contaminants is most likely volcanics eroded from the adjacent uplands.

Table 48. West Texas Bolsons Aquifer percent area and volume within MCL exceedance probability categories. West Texas Bolsons Aquifer area is 1,870 mi^2 and volume is 205 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	62	29	9	30	50	20
Arsenic	92	6	2	91	5	3
Fluoride	94	4	2	80	14	6
Nitrate-N	99	1	0	99	1	0
Gross alpha	97	3	0	95	5	0
TDS	91	4	5	96	3	1

Low: 0 – 40% probability, Moderate: 40 – 60% probability, High: 60 – 100% probability that a constituent MCL will be exceeded.

Table 49. Summary of MCL violations in West Texas Bolsons Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	68	0	68	NA	NA	NA	0	0
Arsenic	10	μg/L	93	62	31	4.58	1.0	46.7	17	**18**
Barium	2,000	μg/L	100	97	3	22	1.1	177	0	0
Beryllium	4	μg/L	66	0	66	NA	NA	NA	0	0
Cadmium	5	μg/L	85	4	81	NA	1.0	1.4	0	0
Chromium	100	μg/L	95	54	41	2.99	1.02	25.6	0	0
Copper	1,300	μg/L	93	58	35	2.2	1.0	945	0	0
Fluoride	4	μg/L	118	118	0	1.73	0.29	9.24	14	**12**
Lead	15	μg/L	85	11	74	NA	1.0	3.69	0	0
Mercury	2	μg/L	34	1	33	NA	0.13	0.13	0	0
Nitrate-N	10	mg/L	112	106	6	1.42	0.02	18.2	6	**5**
Nitrite-N	1	mg/L	45	13	32	NA	0.01	0.07	0	0
Selenium	50	μg/L	100	32	68	2.0	1.0	18.3	0	0
Thallium	2	μg/L	67	1	66	NA	2.94	2.94	1	1
Gross alpha	15	pCi/L	55	54	1	5.9	1.4	38	5	**9**
Gross beta	50	pCi/L	54	43	11	7.9	1.4	49	0	0
Comb. radium	5	pCi/L	11	1	10	NA	3.6	3.6	0	0
Uranium	30	μg/L	1	1	0	NA	7.7	7.7	0	0
Secondary MCL										
Aluminum	50	μg/L	91	14	77	NA	1.0	186	2	2
Chloride	300	mg/L	119	119	0	24.9	2.0	982	12	10
Copper	1,000	μg/L	93	58	35	2.2	1.0	945	0	0
Fluoride	2	mg/L	118	118	0	1.73	0.29	9.24	52	44
Iron	300	μg/L	102	43	59	13.4	1.0	6,960	7	7
Manganese	50	μg/L	100	43	57	0.9	0.9	190	4	4
Silver	100	μg/L	40	1	39	NA	14	14	0	0
Sulfate	300	mg/L	119	119	0	63	7.31	1,480	19	16
TDS	1,000	mg/L	117	117	0	443	159	3,360	20	17
Zinc	5,000	μg/L	93	77	16	20	2.1	726	0	0
pH	6.5-8.5		116	116	0	7.75	6.85	9.15	12	10

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

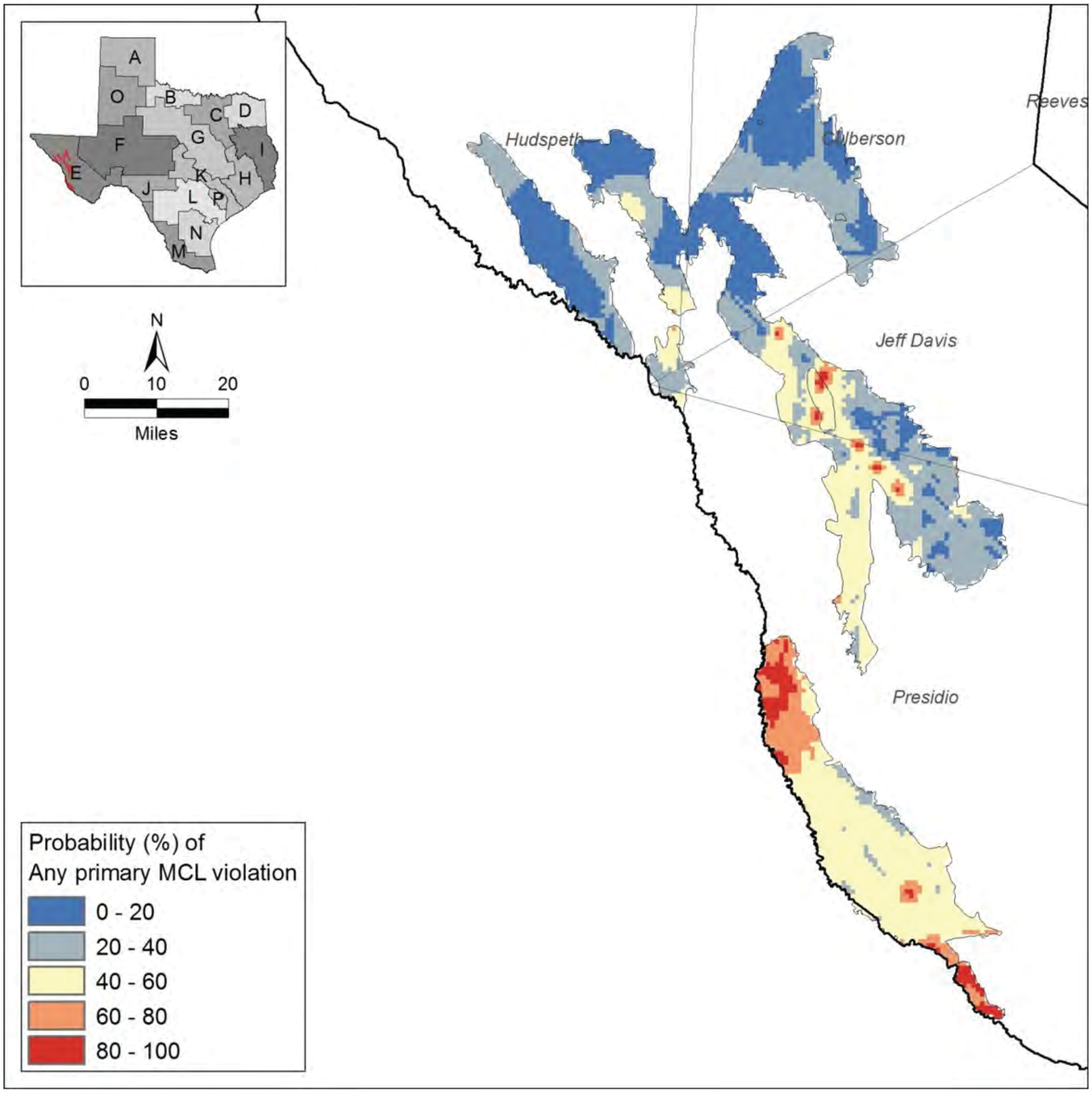

Figure 70. West Texas Bolsons Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

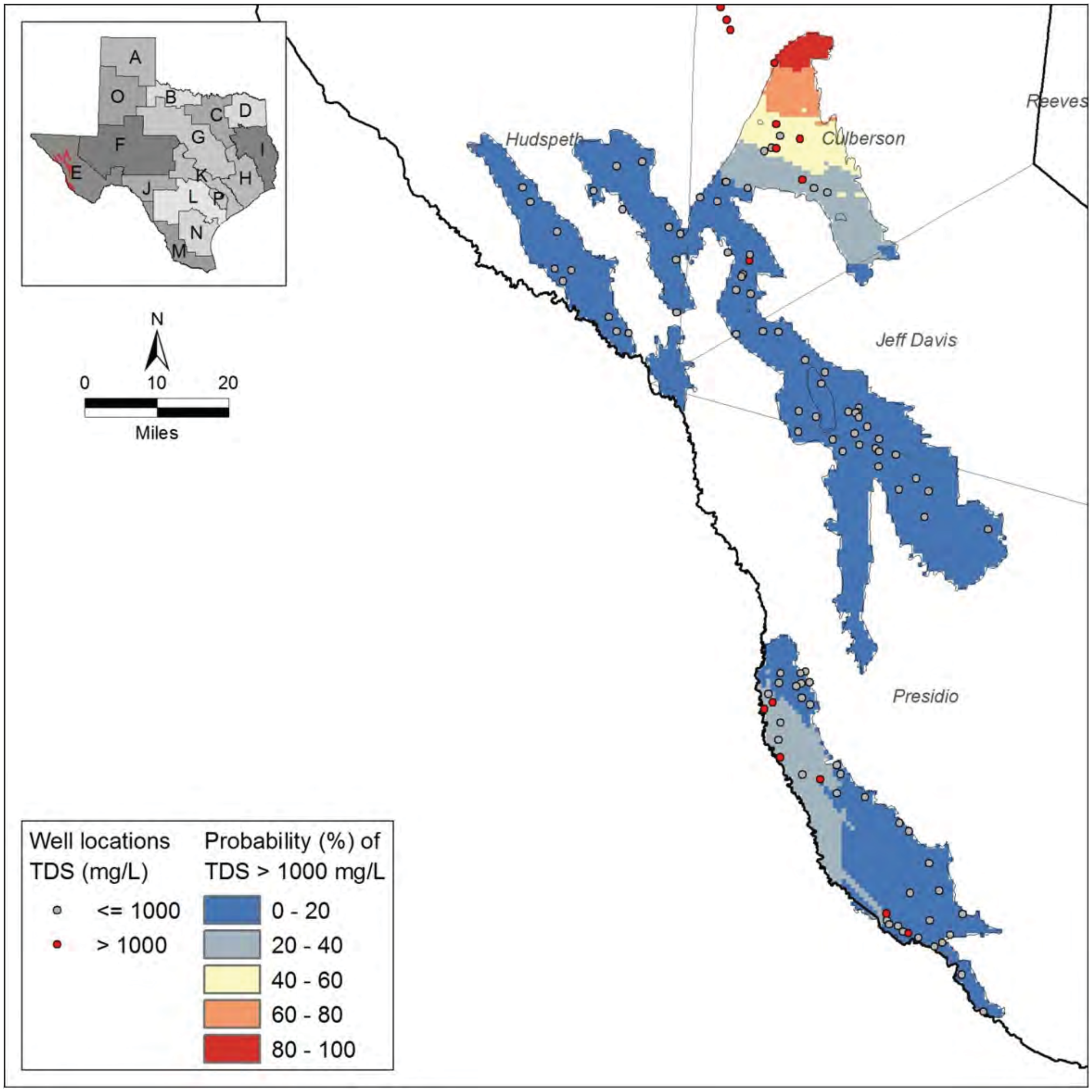

Figure 71. West Texas Bolsons Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Woodbine

Groundwater volumes in the Woodbine Aquifer may be slightly impacted by primary fluoride MCL exceedances (possibly 5 percent), corresponding to percent of sampled wells with excessive fluoride (Table 50 and Table 51), although a quarter to one third of groundwater volume will likely be impacted by TDS secondary MCL exceedances. Fluoride concentrations generally increase with increasing well depth while TDS concentrations do not exhibit a consistent trend (Appendix 23). The high risk category of exceeding any primary MCL (fluoride) represents 4 percent of the area and 5 percent of the volume while the high risk category of exceeding the secondary MCL for TDS represents 27 percent of the area and 30 percent of the volume. Groundwater quality problems are located in the southern downdip region of the aquifer (Figure 72 and Figure 73). The Woodbine aquifer has low percentages of primary MCL exceedances and relatively moderate levels of TDS secondary MCL percent exceedances primarily due to sulfate exceedance, and moderate levels of secondary fluoride, iron, and manganese exceedances.

Table 50. Woodbine Aquifer percent area and volume within MCL exceedance probability categories. Woodbine Aquifer area is 7,640 mi^2 and volume is 237 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary (fluoride)	92	4	4	90	5	5
TDS	57	16	27	57	13	30

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 51. Summary of MCL violations in Woodbine Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	131	0	131	NA	NA	NA	0	0
Arsenic	10	μg/L	167	10	157	NA	1.0	8.0	0	0
Barium	2,000	μg/L	168	151	17	7.11	1.0	355	0	0
Beryllium	4	μg/L	131	4	127	NA	2.0	18	2	2
Cadmium	5	μg/L	155	2	153	NA	6.0	8.0	2	1
Chromium	100	μg/L	167	56	111	NA	1.0	54.9	0	0
Copper	1,300	μg/L	168	99	69	2.0	1.0	58.4	0	0
Fluoride	4	μg/L	179	174	5	1.0	0.1	6.1	10	**6**
Lead	15	μg/L	153	13	140	NA	1.0	39.9	1	1
Mercury	2	μg/L	98	3	95	NA	0.28	0.42	0	0
Nitrate-N	10	mg/L	160	65	95	0.01	0.01	23.0	1	1
Nitrite-N	1	mg/L	98	12	86	NA	0.01	0.27	0	0
Selenium	50	μg/L	168	7	161	NA	1.0	14	0	0
Thallium	2	μg/L	94	0	94	NA	NA	NA	0	0
Gross alpha	15	pCi/L	72	19	53	1.2	0.4	12	0	0
Gross beta	50	pCi/L	72	14	58	NA	0.7	14	0	0
Comb. radium	5	pCi/L	1	1	0	NA	1.8	1.8	0	0
Uranium	30	μg/L	66	12	54	NA	1.0	35	1	2
Secondary MCL										
Aluminum	50	μg/L	142	70	72	3.9	1.0	462	5	4
Chloride	300	mg/L	179	179	0	49.4	4.05	3,100	16	9
Copper	1,000	μg/L	168	99	69	2.0	1.0	58.4	0	0
Fluoride	2	mg/L	179	174	5	1.0	0.1	6.1	27	15
Iron	300	μg/L	175	118	57	52	3.0	91,000	43	25
Manganese	50	μg/L	162	141	21	7.0	1.8	7,600	39	24
Silver	100	μg/L	139	0	139	NA	NA	NA	0	0
Sulfate	300	mg/L	179	179	0	166	1.86	3,300	56	31
TDS	1,000	mg/L	168	168	0	731	76	8,150	56	33
Zinc	5,000	μg/L	168	95	73	4.5	1.0	1,500	0	0
pH	6.5-8.5		177	177	0	8.26	3.7	9.27	66	37

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

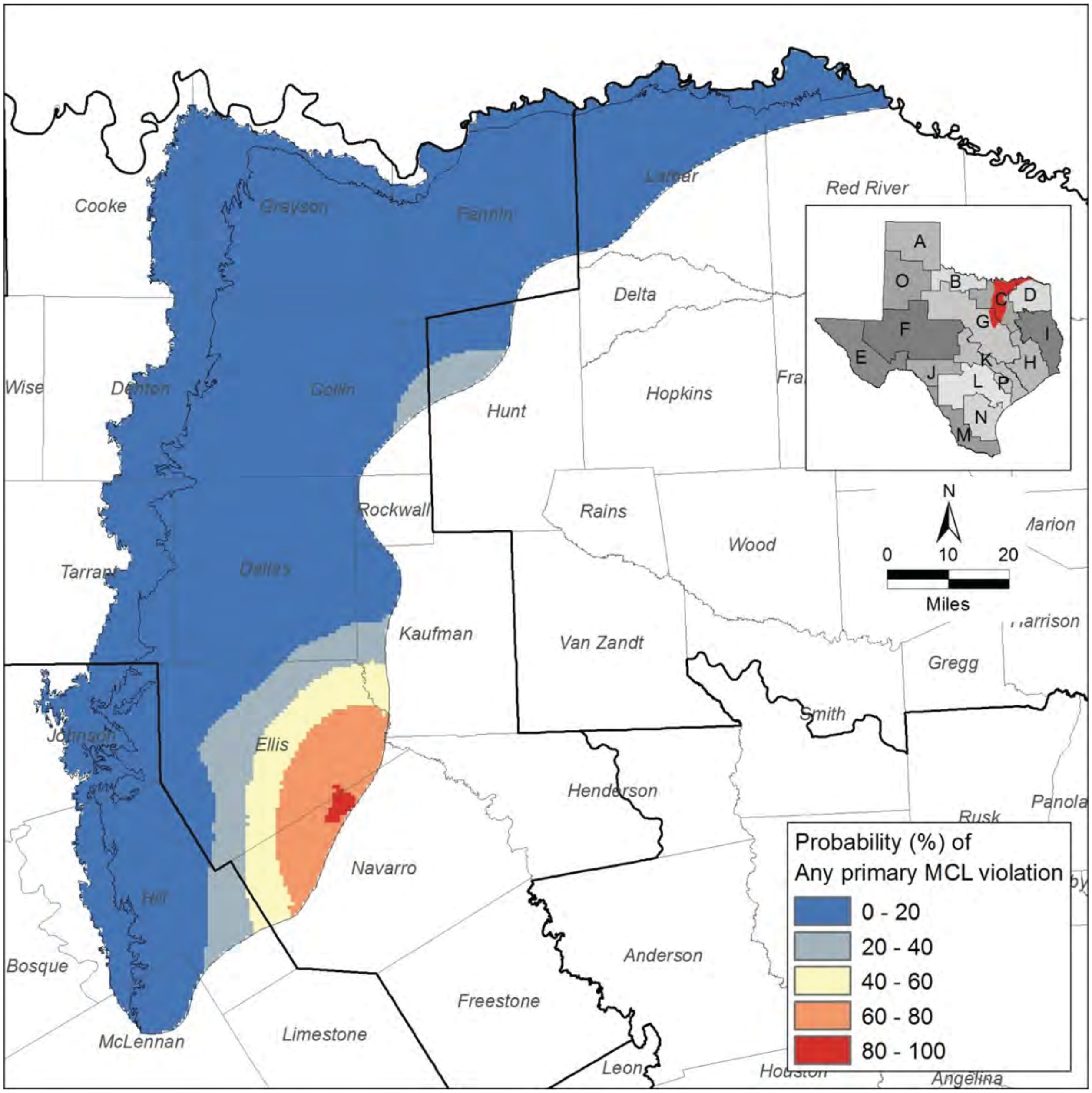

Figure 72. Woodbine Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

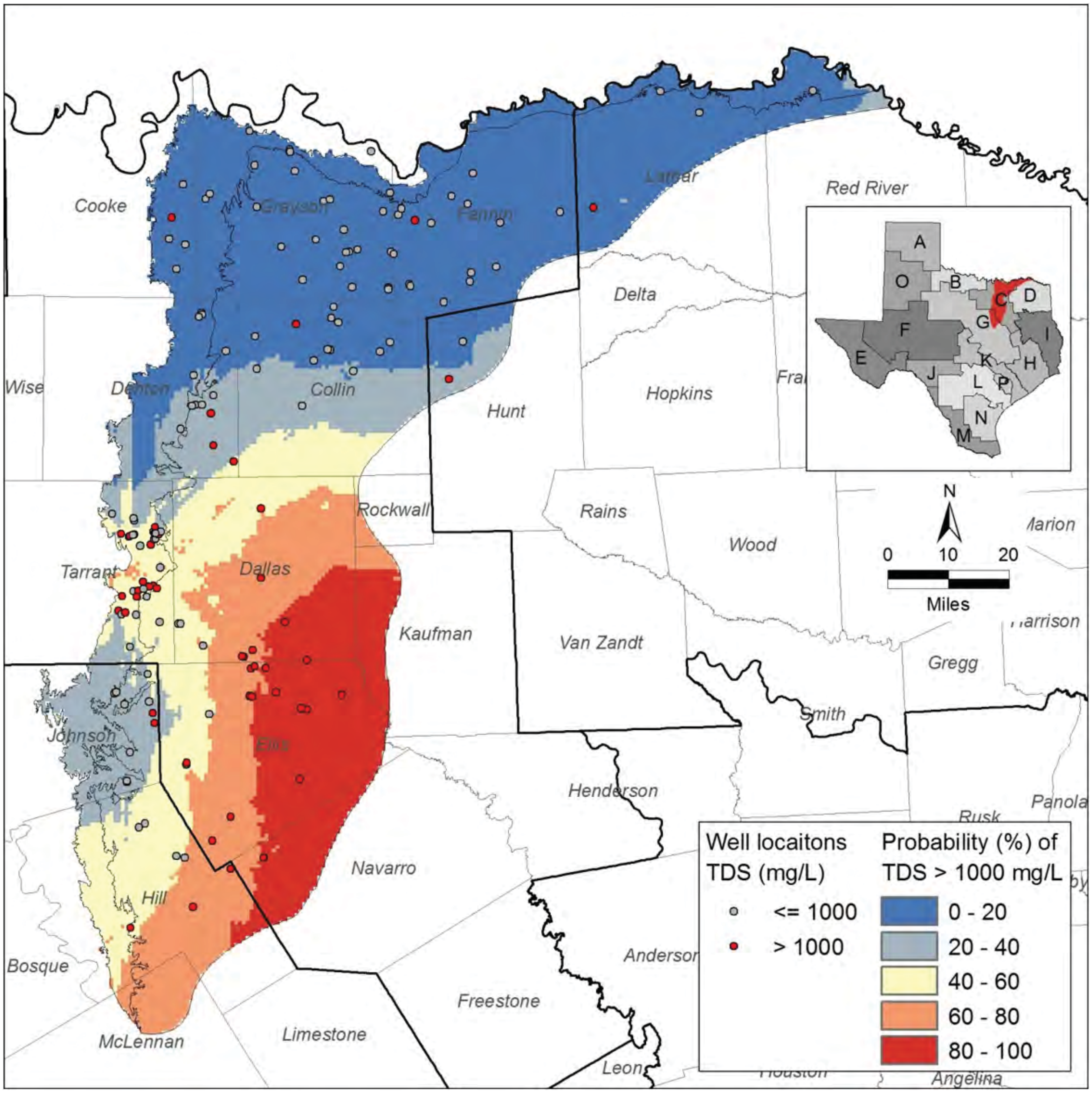

Figure 73. Woodbine Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Yegua-Jackson

The Yegua-Jackson Aquifer underlies the Carrizo-Wilcox Aquifer and exhibits similar chemistry with low levels of any primary MCL exceedances except for combined radium (Table 52 and Table 53). No more than about 8 percent of the aquifer volume is expected to be affected by primary exceedances (Figure 74). However, moderate levels of TDS exceedances occur, mostly in the southern half of the aquifer related to chloride and sulfate, as well as moderate levels of iron and manganese exceedances (Figure 75). There are no clear trends in concentrations with well depth (Appendix 24). As much as half of the groundwater volume may be affected by secondary MCL exceedances.

Table 52. Yegua-Jackson Aquifer percent area and volume within MCL exceedance probability categories. Yegua-Jackson Aquifer area is 13,400 mi^2 and volume is 261 mi^3.

	Percent of area			*Percent of volume*		
MCL	*Low*	*Moderate*	*High*	*Low*	*Moderate*	*High*
Any primary	42	49	9	55	37	8
Arsenic	98	1	1	95	2	3
Selenium	100	0	0	100	0	0
Gross alpha	96	4	0	98	2	0
Combined radium	83	17	0	92	8	0
TDS	42	9	949	48	12	40

Low: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability that a constituent MCL will be exceeded.

Table 53. Summary of MCL violations in Yegua-Jackson Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	121	1	120	NA	1.49	1.49	0	0
Arsenic	10	µg/L	138	18	120	NA	2.24	47	4	**3**
Barium	2,000	µg/L	138	132	6	19.3	1.93	646	0	0
Beryllium	4	µg/L	114	0	114	NA	NA	NA	0	0
Cadmium	5	µg/L	127	3	124	NA	1.03	1.1	0	0
Chromium	100	µg/L	138	66	72	1.69	1.04	11.7	0	0
Copper	1,300	µg/L	140	99	41	2.15	1.05	20	0	0
Fluoride	4	µg/L	144	137	7	0.3	0.02	3.39	0	0
Lead	15	µg/L	127	10	117	NA	1.07	6.71	0	0
Mercury	2	µg/L	48	9	39	NA	0.13	1.0	0	0
Nitrate-N	10	mg/L	139	69	70	0.01	0.01	14.3	1	1
Nitrite-N	1	mg/L	20	7	13	NA	0.01	0.03	0	0
Selenium	50	µg/L	140	13	127	NA	5.48	2.39	3	**2**
Thallium	2	µg/L	109	2	107	NA	1.16	2.22	1	1
Gross alpha	15	pCi/L	48	28	20	2.5	0.3	56	5	**10**
Gross beta	50	pCi/L	40	33	7	NA	1.3	57.7	1	3
Comb. radium	5	pCi/L	19	10	9	2.63	2.34	21	6	**32**
Uranium	30	µg/L	16	1	15	NA	1.28	1.28	0	0
Secondary MCL										
Aluminum	50	µg/L	125	31	94	NA	4.02	348	2	2
Chloride	300	mg/L	144	144	0	128	14.7	2,980	51	35
Copper	1,000	µg/L	140	99	41	2.15	1.05	20	0	0
Fluoride	2	mg/L	144	137	7	0.3	0.02	3.39	5	3
Iron	300	µg/L	142	84	58	58.1	24	49,000	35	25
Manganese	50	µg/L	142	132	10	24.6	1.41	2,210	50	35
Silver	100	µg/L	47	1	46	NA	1.11	1.11	0	0
Sulfate	300	mg/L	144	132	12	93.5	1.04	2,410	42	29
TDS	1,000	mg/L	139	139	0	819	83	5,880	60	43
Zinc	5,000	µg/L	140	103	37	11.4	4.0	977	0	0
pH	6.5-8.5		143	143	0	7.69	5.33	9.12	36	25

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

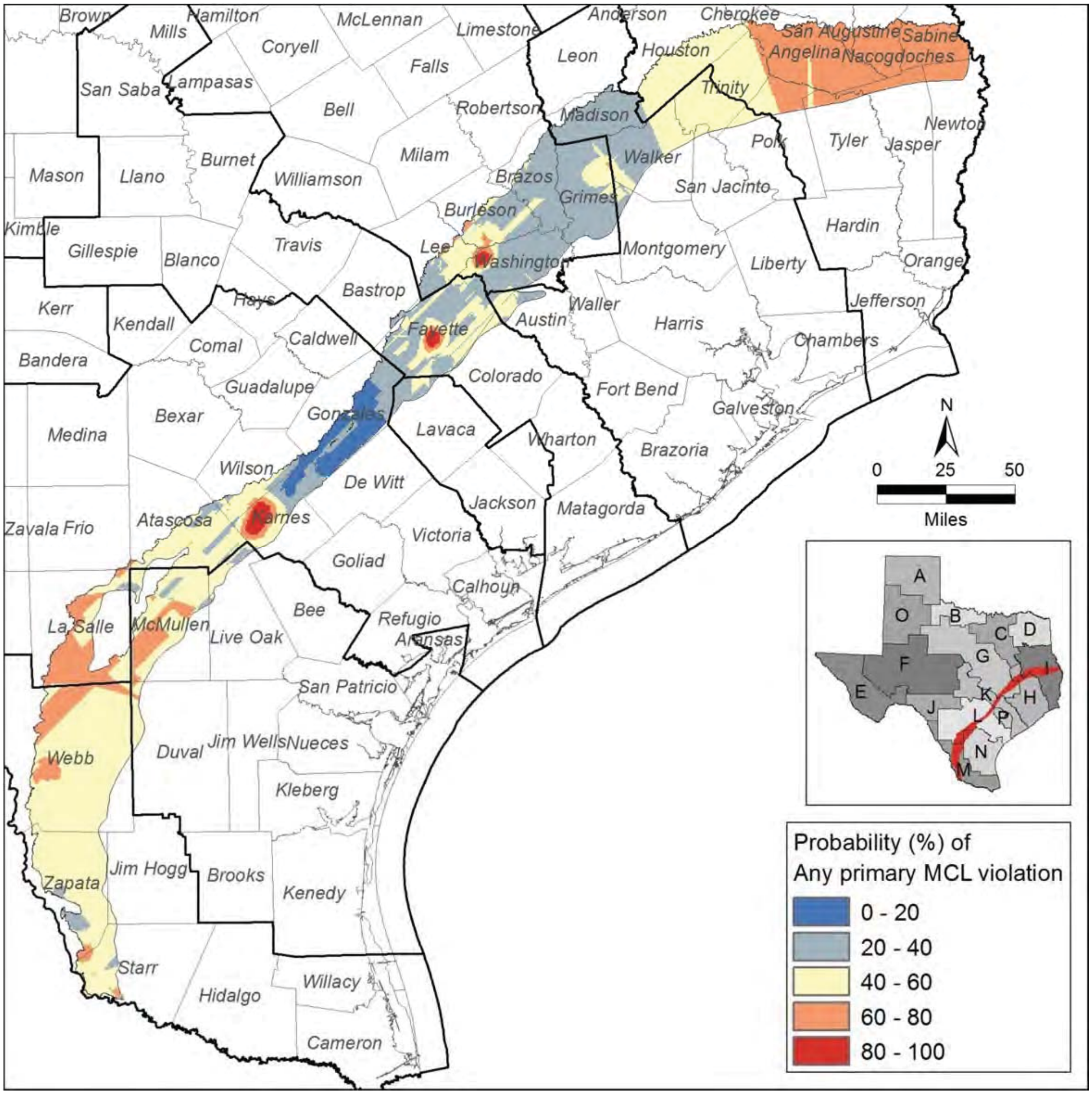

Figure 74. Yegua-Jackson Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

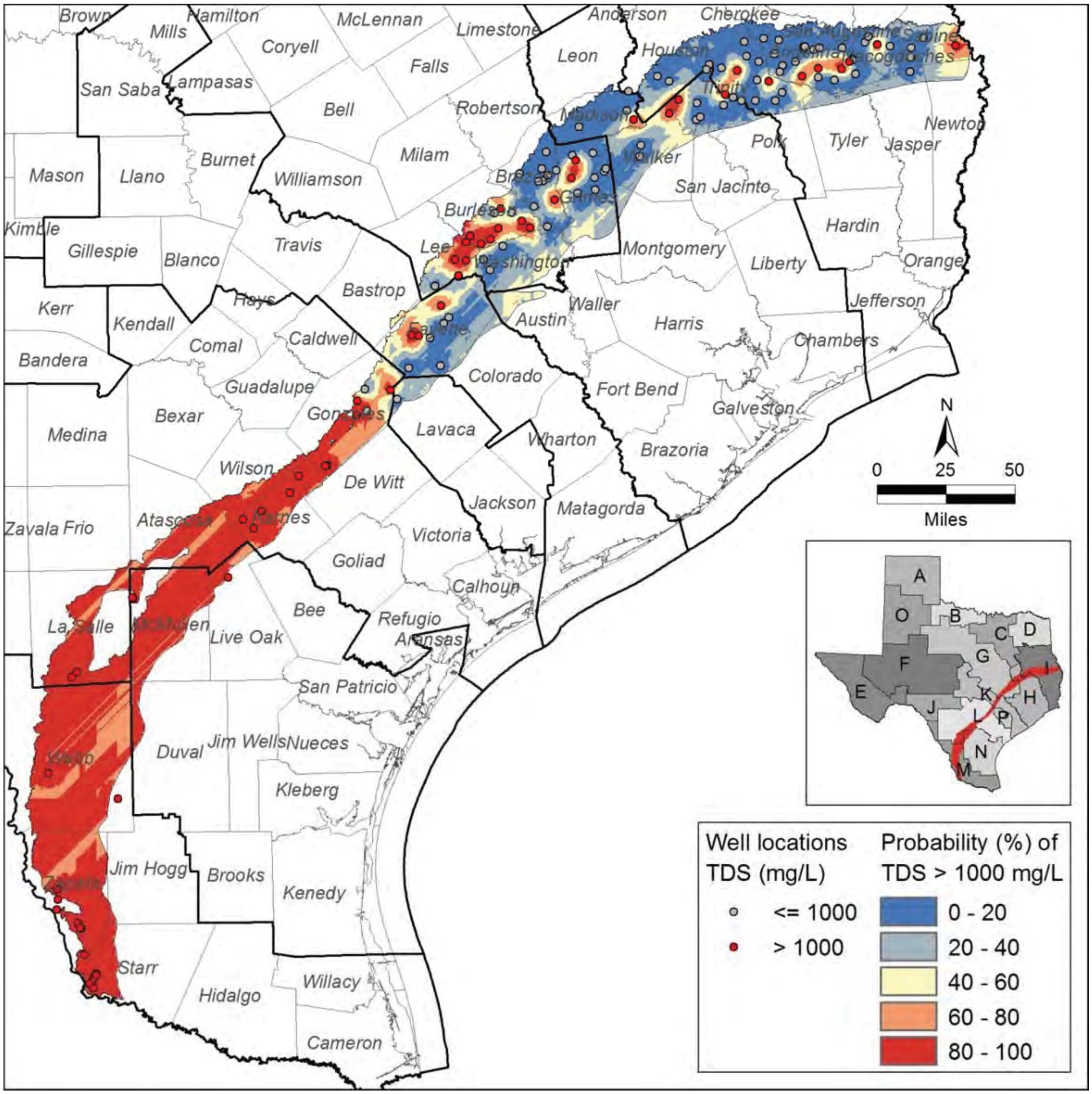

Figure 75. Yegua-Jackson Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Bone Spring-Victorio Peak

The Bone Spring-Victorio Peak Aquifer consists of Permian limestones and extends over a area of 716 mi^2. Primary MCL exceedances include uranium, gross alpha, nitrate-N, and thallium. There are very few wells with analyses (Table 54); these are mostly clustered in the northeastern region of the aquifer in or near Dell City where water use is almost exclusively irrigation (Figure 76). Due to the distribution of wells in this aquifer and the lack of saturated thickness information, there are currently insufficient data to characterize the areas and volumes at risk of exceeding MCL concentrations in this aquifer. There are no clear concentration trends with well depth (Appendix 25). Secondary MCL exceedances are dominated by TDS, related to sulfate and chloride MCL exceedances, followed by fluoride exceedances. Median TDS is very high (3,400 mg/L) with maximum TDS up to 17,500 mg/L.

Table 54. Summary of MCL violations in Bone Spring-Victorio Peak Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	23	1	22	NA	4.0	4.0	0	0
Arsenic	10	μg/L	43	2	41	1.24	1.24	3.2	0	0
Barium	2,000	μg/L	47	25	22	13.2	10.8	26	0	0
Beryllium	4	μg/L	20	0	20	NA	NA	NA	0	0
Cadmium	5	μg/L	23	1	22	NA	5.0	5.0	0	0
Chromium	100	μg/L	24	16	8	8.6	1.06	21.5	0	0
Copper	1,300	μg/L	46	20	26	6.0	1.43	27.9	0	0
Fluoride	4	μg/L	41	39	2	1.5	0.5	3.25	0	0
Lead	15	μg/L	24	3	21	NA	1.0	4.19	0	0
Mercury	2	μg/L	3	0	3	NA	NA	NA	0	0
Nitrate-N	10	mg/L	47	47	0	4.04	0.20	30.2	7	**15**
Nitrite-N	1	mg/L	31	1	30	NA	0.01	0.01	0	0
Selenium	50	μg/L	47	17	30	5.71	3.45	26.4	0	0
Thallium	2	μg/L	20	4	16	0.67	0.42	2.5	1	5
Gross alpha	15	pCi/L	30	24	6	10	3.8	96	12	**40**
Gross beta	50	pCi/L	31	30	1	20	9.1	150	2	6
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	2	2	0	NA	16.8	35.8	1	50
Secondary MCL										
Aluminum	50	μg/L	24	3	21	NA	1.62	5.24	0	0
Chloride	300	mg/L	42	42	0	676	16.1	7,960	37	88
Copper	1,000	μg/L	46	20	26	6.0	1.43	27.9	0	0
Fluoride	2	mg/L	41	39	2	1.5	0.5	3.25	10	24
Iron	300	μg/L	44	13	31	4.53	2.62	567	2	5
Manganese	50	μg/L	47	7	40	0.14	0.14	588	1	2
Silver	100	μg/L	1	0	1	NA	NA	NA	0	0
Sulfate	300	mg/L	42	42	0	1,580	594	3,210	42	100
TDS	1,000	mg/L	42	42	0	3,360	1,090	17,520	42	100
Zinc	5,000	μg/L	47	25	22	11.6	5.2	508	0	0
pH	6.5-8.5		47	47	0	6.93	6.63	7.36	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

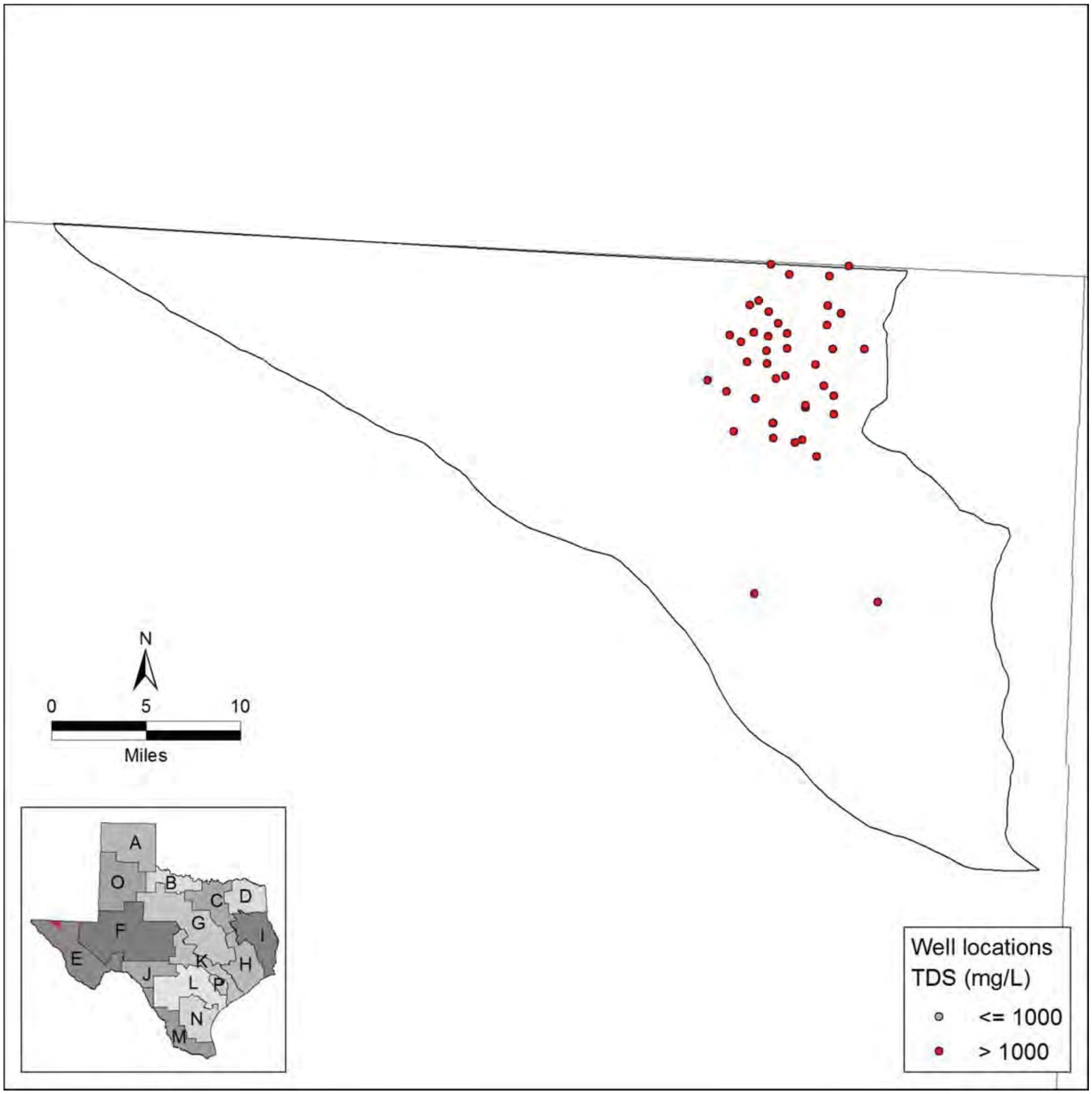

Figure 76. Bone Spring-Victorio Peak point map of TDS.

Brazos River Alluvium

The Brazos River Alluvium Aquifer occurs in the flood plain of the Brazos River and is Quaternary in age. The high risk category of exceeding any primary MCL represents 1 percent of the area while the high risk category of exceeding the secondary MCL for TDS represents 2 percent of the area. Due to the lack of saturated thickness information, there are currently insufficient data to characterize the volumes at risk of exceeding MCL concentrations in this aquifer. Primary MCL exceedances include nitrate-N, gross alpha, barium, and arsenic (Table 56 and Table 56), mainly occurring in the north (Figure 77).

Secondary MCL exceedances are dominated by TDS, with maximum TDS up to 2,300 mg/L (Figure 78). High TDS reflects high chloride and sulfate levels. Iron and manganese secondary MCL exceedances are high, with maximum concentrations up to 10,600 for iron and 1,700 for manganese. These levels of iron and manganese are similar to those found in the adjacent Carrizo-Wilcox Aquifer. Wells are generally very shallow in this aquifer and there are no significant concentration trends with well depth (Appendix 26).

Table 55. Brazos River Alluvium Aquifer percent area within MCL exceedance probability categories. Brazos River Alluvium Aquifer area is 1,060 mi^2.

	Percent of area		
MCL	*Low*	*Moderate*	*High*
Any primary	81	8	11
Arsenic	100	0	0
Barium	95	5	0
Nitrate-N	86	3	10
TDS	79	16	2

Table 56. Summary of MCL violations in Brazos River Alluvium Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	32	0	32	NA	NA	NA	0	0
Arsenic	10	µg/L	36	17	19	1.1	1.0	17.3	2	**6**
Barium	2,000	µg/L	36	36	0	110	29.3	2812	3	**8**
Beryllium	4	µg/L	32	0	32	NA	NA	NA	0	0
Cadmium	5	µg/L	25	0	25	NA	NA	NA	0	0
Chromium	100	µg/L	25	8	17	NA	1.08	9.88	0	0
Copper	1,300	µg/L	36	17	19	1.6	1.17	34.7	0	0
Fluoride	4	µg/L	36	35	1	0.25	0.05	1.42	0	0
Lead	15	µg/L	36	0	36	NA	NA	NA	0	0
Mercury	2	µg/L	12	0	12	NA	NA	NA	0	0
Nitrate-N	10	mg/L	36	28	8	0.24	0.02	19.3	4	**11**
Nitrite-N	1	mg/L	9	2	7	NA	0.01	0.01	0	0
Selenium	50	µg/L	36	7	29	NA	5.37	9.59	0	0
Thallium	2	µg/L	30	0	30	NA	NA	NA	0	0
Gross alpha	15	pCi/L	10	2	8	2.6	2.6	18.1	1	**10**
Gross beta	50	pCi/L	9	2	7	NA	5.8	8.4	0	0
Comb. radium	5	pCi/L	1	0	1	NA	NA	NA	0	0
Uranium	30	µg/L	3	2	1	1.93	1.93	4.33	0	0
Secondary MCL										
Aluminum	50	µg/L	32	13	19	2.1	1.4	181	1	3
Chloride	300	mg/L	36	36	0	69.5	18	595	5	14
Copper	1,000	µg/L	36	17	19	1.6	1.17	34.7	0	0
Fluoride	2	mg/L	36	35	1	0.25	0.05	1.42	0	0
Iron	300	µg/L	36	28	8	908	5.0	10,600	21	58
Manganese	50	µg/L	36	33	3	319	2.5	1,730	26	72
Silver	100	µg/L	12	0	12	NA	NA	NA	0	0
Sulfate	300	mg/L	36	35	1	86	3.8	636	5	14
TDS	1,000	mg/L	36	36	0	819	321	2,290	11	31
Zinc	5,000	µg/L	36	30	6	12	4.55	143	0	0
pH	6.5-8.5		35	35	0	7.03	6.67	7.57	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

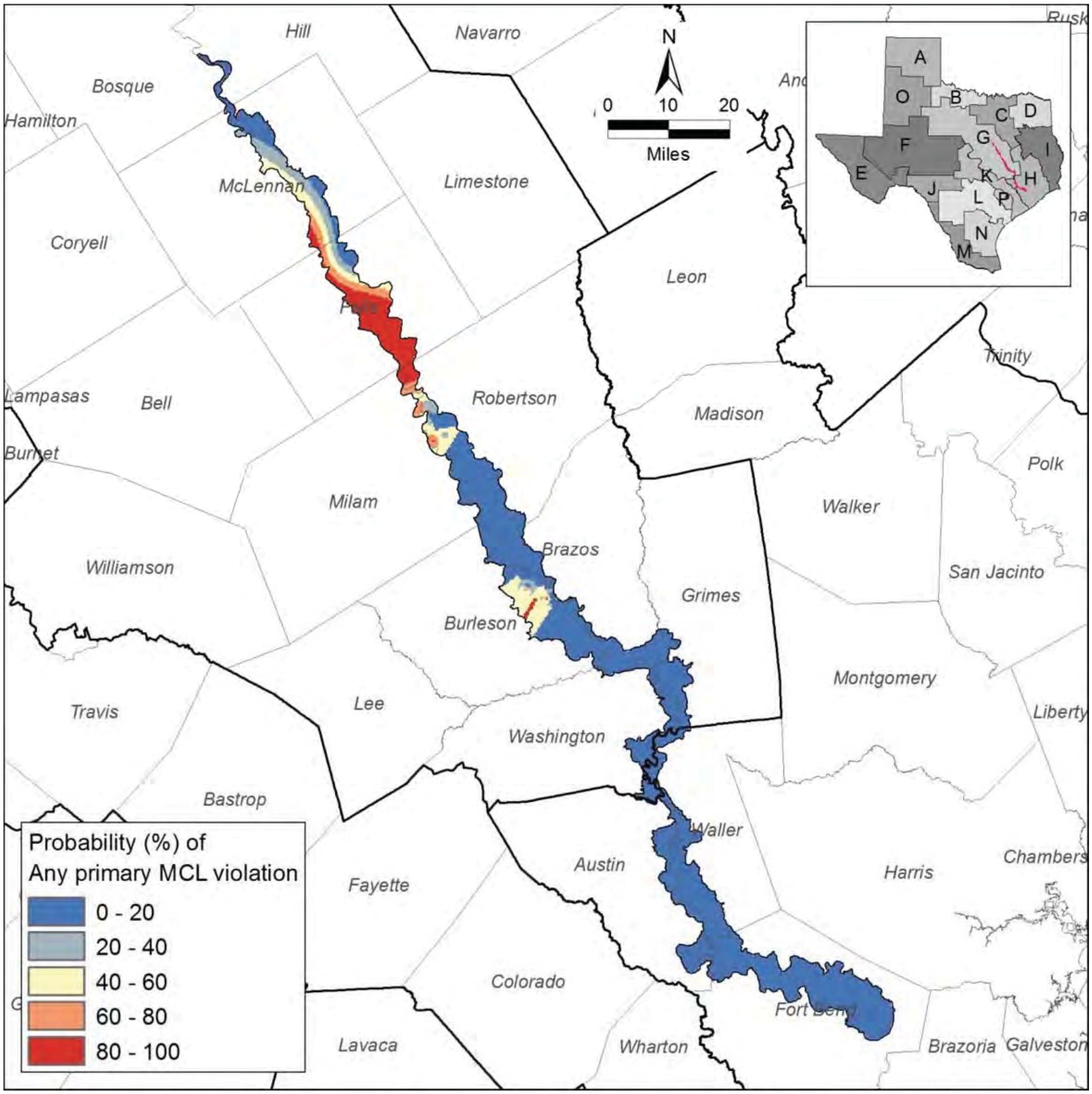

Figure 77. Brazos River Alluvium Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

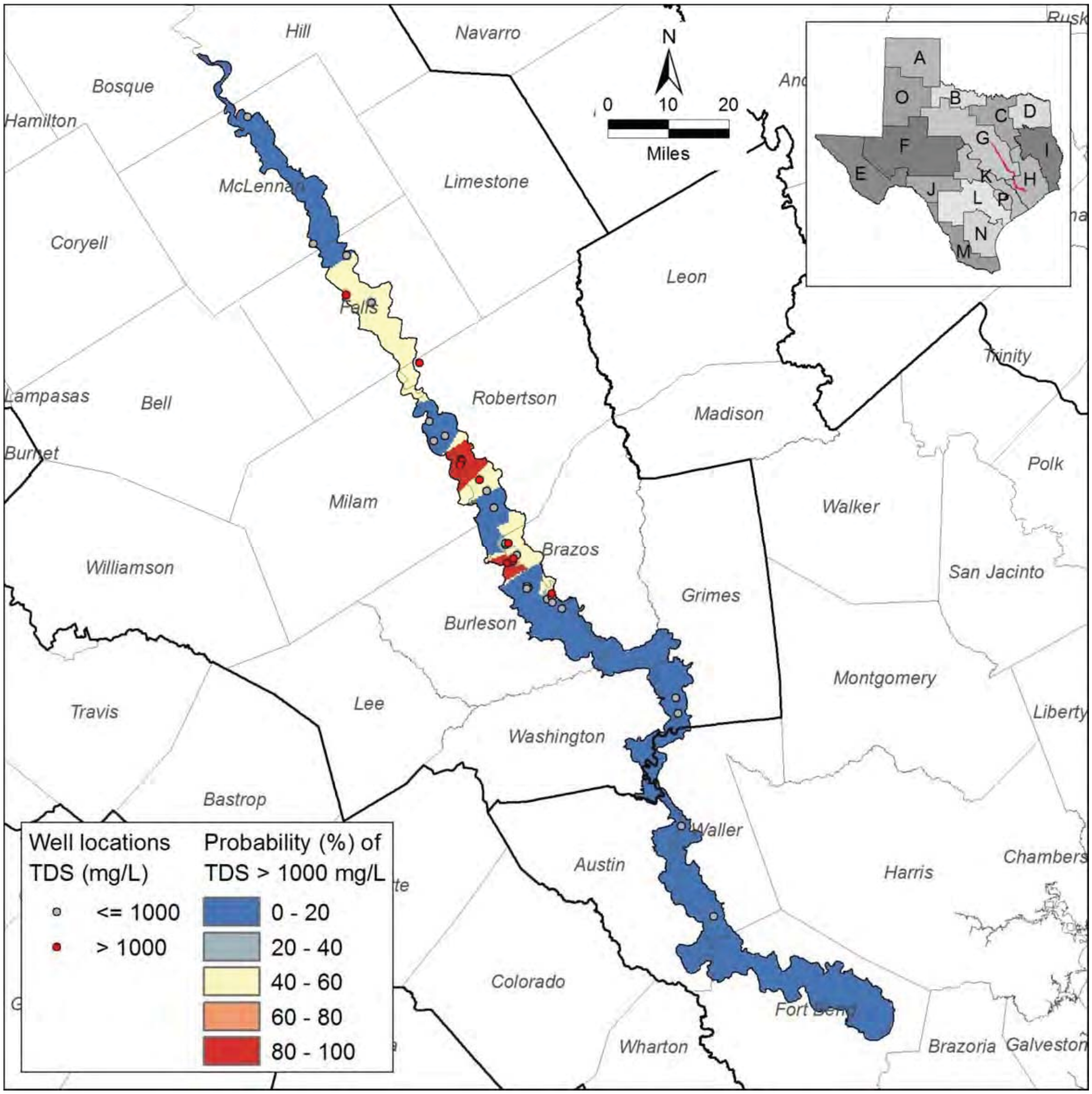

Figure 78. Brazos River Alluvium Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Capitan Reef

The Capitan Reef Aquifer consists of Permian age limestones and dolomites and has combined radium, gross alpha, gross beta, and minor percents of arsenic and antimony primary MCL exceedances, as determined from the limited number of wells sampled (Table 57 and Table 58Table 58). The high risk category of exceeding any primary MCL (gross alpha) represents 9 percent of the area while the high risk category of exceeding the secondary MCL for TDS represents 72 percent of the area. Due to the lack of saturated thickness information, there are currently insufficient data to characterize the volumes at risk of exceeding MCL concentrations in this aquifer. Total dissolved solids concentrations tend to be greatest in the deepest wells (Appendix). The primary MCL exceedances are found mostly in the eastern lobe of the aquifer (Figure 79). Secondary MCL percent exceedances are dominated by TDS, reflecting mostly sulfate exceedances followed by chloride exceedances. TDS exceedances are found in both lobes of the aquifer (Figure 80) and TDS concentrations are highest in the deepest wells (Appendix 27). Fluoride, iron, and manganese MCL exceedances are moderately high and all secondary exceedances are expected to affect at least half of aquifer volumes.

Table 57. Capitan Reef Aquifer percent area within MCL exceedance probability categories. Capitan Reef Aquifer area is 1,850 mi^2.

	Percent of area		
MCL	*Low*	*Moderate*	*High*
Any primary (gross alpha)	63	29	9
TDS	16	12	72

Table 58. Summary of MCL violations in Capitan Reef Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	32	1	31	NA	6.4	6.4	1	3
Arsenic	10	µg/L	34	7	27	NA	0.86	12.6	1	3
Barium	2,000	µg/L	35	33	2	18.9	1.0	222	0	0
Beryllium	4	µg/L	31	0	31	NA	NA	NA	0	0
Cadmium	5	µg/L	33	0	33	NA	NA	NA	0	0
Chromium	100	µg/L	33	9	24	NA	1.76	28	0	0
Copper	1,300	µg/L	33	14	19	1.0	1.0	6.6	0	0
Fluoride	4	µg/L	36	33	3	1.03	0.1	3.0	0	0
Lead	15	µg/L	32	5	27	NA	2.56	21.9	1	3
Mercury	2	µg/L	15	3	12	0.14	0.14	0.3	0	0
Nitrate-N	10	mg/L	32	20	12	0.4	0.04	12.2	1	3
Nitrite-N	1	mg/L	11	3	8	NA	0.01	0.05	0	0
Selenium	50	µg/L	34	21	13	2.58	1.0	230	1	3
Thallium	2	µg/L	32	0	32	NA	NA	NA	0	0
Gross alpha	15	pCi/L	18	15	3	8.2	2.3	108	6	**33**
Gross beta	50	pCi/L	17	14	3	16.5	4.7	79	2	12
Comb. radium	5	pCi/L	12	7	5	2.2	2.2	38.8	6	50
Uranium	30	µg/L	10	4	6	NA	2.43	6.95	0	0
Secondary MCL										
Aluminum	50	µg/L	31	10	21	NA	2.1	60	1	3
Chloride	300	mg/L	37	36	1	157	5.0	2,230	13	35
Copper	1,000	µg/L	33	14	19	1.0	1.0	6.6	0	0
Fluoride	2	mg/L	36	33	3	1.03	0.1	3.0	8	22
Iron	300	µg/L	35	22	13	7.43	4.75	7,900	9	26
Manganese	50	µg/L	34	24	10	5.21	0.141	400	6	18
Silver	100	µg/L	16	1	15	NA	112	112	1	6
Sulfate	300	mg/L	37	37	0	450	6.0	2,420	25	68
TDS	1,000	mg/L	36	36	0	1,080	262	7,260	22	61
Zinc	5,000	µg/L	34	28	6	8.98	2.02	1,640	0	0
pH	6.5-8.5		38	38	0	7.06	6.15	8.9	3	8

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

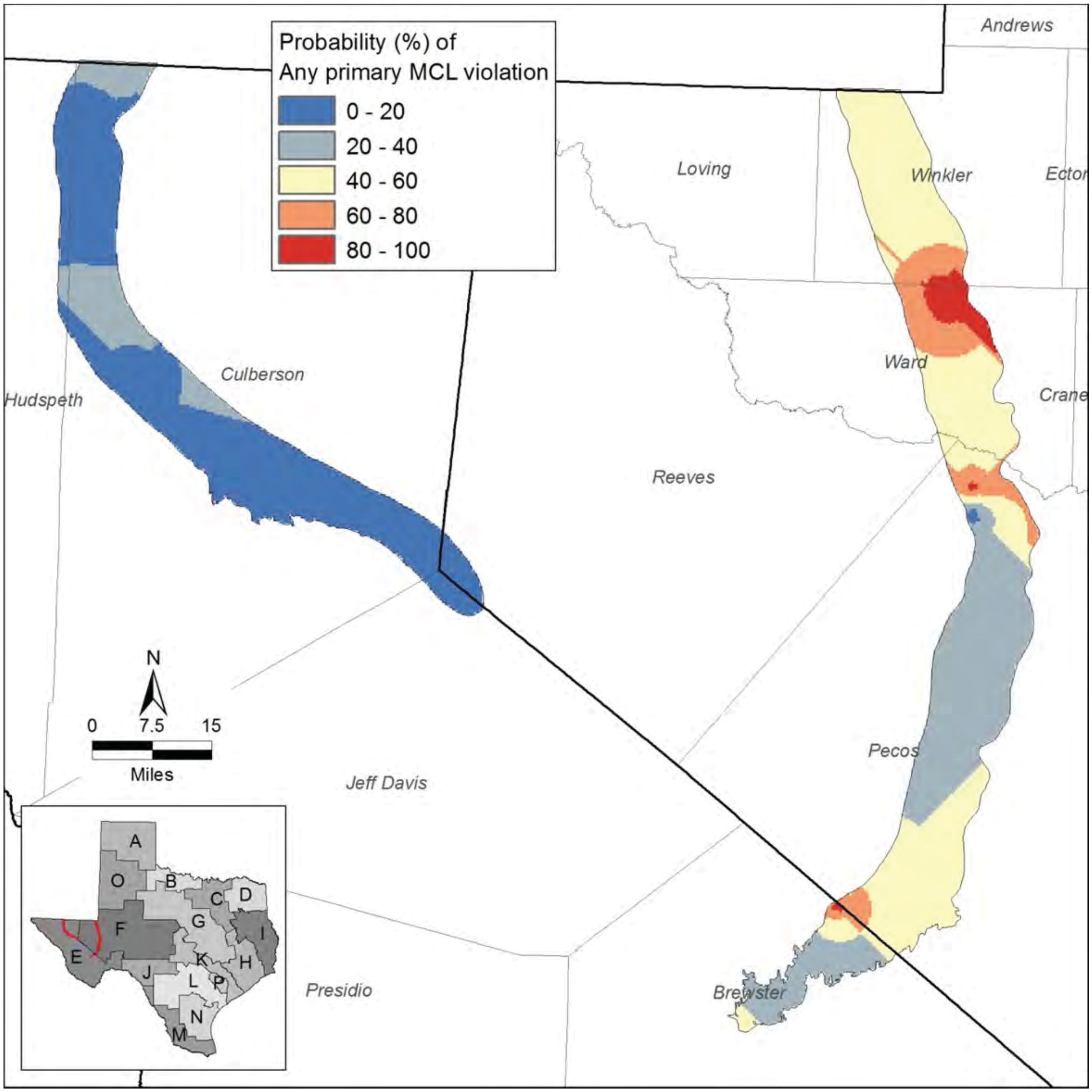

Figure 79. Capitan Reef Aquifer groundwater probability of any primary maximum contaminant level (MCL) violation

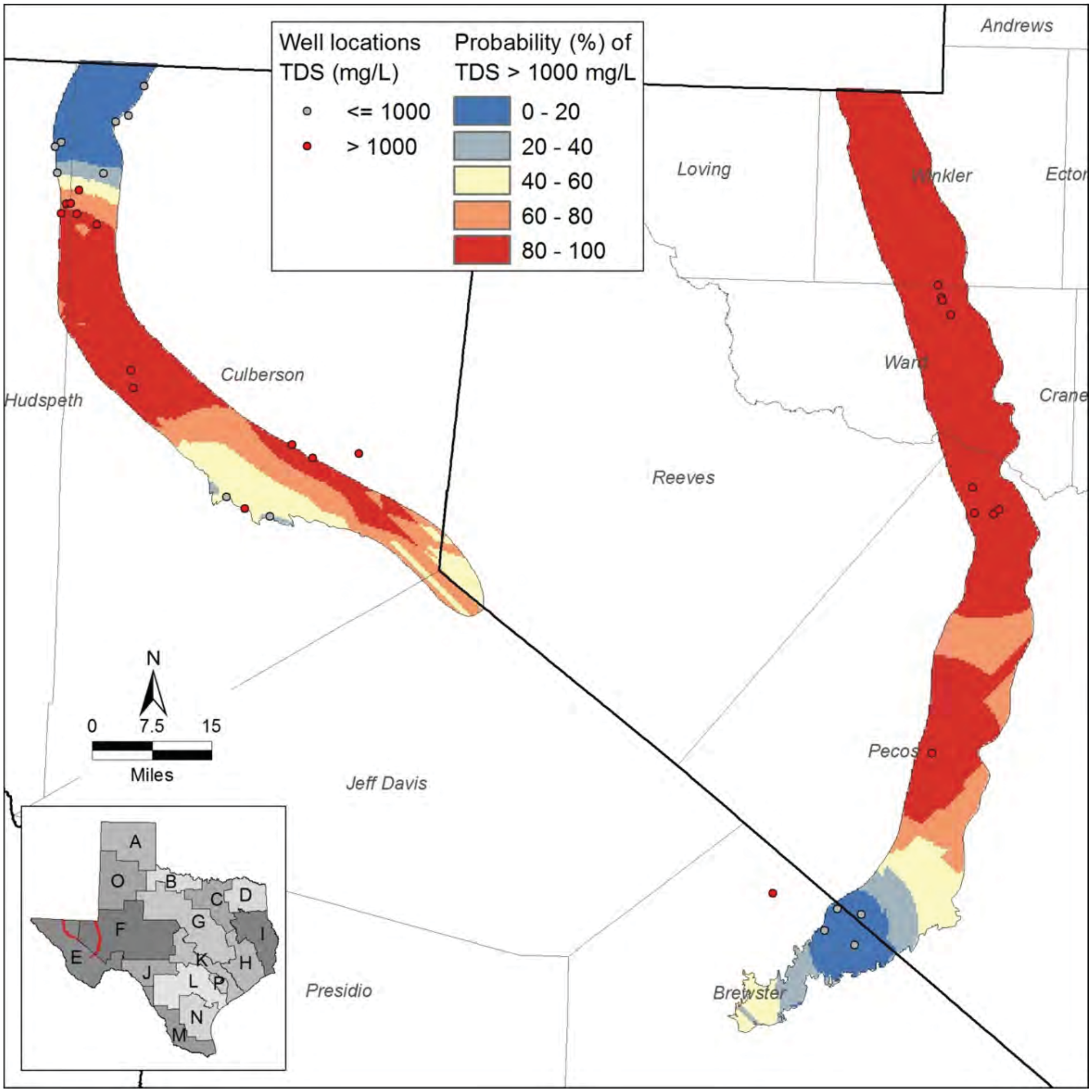

Figure 80. Capitan Reef Aquifer probability of total dissolved solids (TDS) secondary MCL violation

Marathon

The Marathon Aquifer extends over an area of 39 mi^2 and has very few analyses (Table 59); therefore, it is difficult to characterize the groundwater quality. Due to the lack wells and of saturated thickness information, there are currently insufficient data to characterize the areas and volumes at risk of exceeding MCL concentrations in this aquifer. The analyses only record a single nitrate-N primary MCL exceedance from a well in the town of Marathon, in the northwestern portion of the aquifer. There are no secondary MCL exceedances and TDS concentrations are below 1000 mg/L (Figure 81).

Table 59. Summary of MCL violations in Marathon Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	4	0	4	NA	NA	NA	0	0
Arsenic	10	μg/L	4	0	4	NA	NA	NA	0	0
Barium	2,000	μg/L	4	4	0	73.3	61.4	102	0	0
Beryllium	4	μg/L	4	0	4	NA	NA	NA	0	0
Cadmium	5	μg/L	4	0	4	NA	NA	NA	0	0
Chromium	100	μg/L	4	2	2	NA	17	26	0	0
Copper	1,300	μg/L	4	3	1	1.0	1.0	4.2	0	0
Fluoride	4	μg/L	4	4	0	0.92	0.9	1.5	0	0
Lead	15	μg/L	4	2	2	NA	1.0	1.0	0	0
Mercury	2	μg/L	1	0	1	NA	NA	NA	0	0
Nitrate-N	10	mg/L	4	4	0	2.43	1.22	14.5	1	25
Nitrite-N	1	mg/L	1	1	0	NA	0.01	0.01	0	0
Selenium	50	μg/L	4	4	0	5.6	4.0	7.7	0	0
Thallium	2	μg/L	4	0	4	NA	NA	NA	0	0
Gross alpha	15	pCi/L	1	1	0	NA	5.0	5.0	0	0
Gross beta	50	pCi/L	1	1	0	NA	5.0	5.0	0	0
Comb. radium	5	pCi/L	0	NA	NA	NA	NA	NA	NA	NA
Uranium	30	μg/L	0	NA	NA	NA	NA	NA	NA	NA
Secondary MCL										
Aluminum	50	μg/L	4	2	2	NA	7.9	8.3	0	0
Chloride	300	mg/L	4	4	0	90	36.2	176	0	0
Copper	1,000	μg/L	4	3	1	1.0	1.0	4.2	0	0
Fluoride	2	mg/L	4	4	0	0.92	0.9	1.5	0	0
Iron	300	μg/L	4	3	1	40	40	254	0	0
Manganese	50	μg/L	4	2	2	NA	3.1	6.2	0	0
Silver	100	μg/L	1	0	1	NA	NA	NA	0	0
Sulfate	300	mg/L	4	4	0	93	64.1	144	0	0
TDS	1,000	mg/L	4	4	0	555	392	796	0	0
Zinc	5,000	μg/L	4	4	0	15.3	4.0	255	0	0
pH	6.5-8.5		4	4	0	6.72	6.69	7.27	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

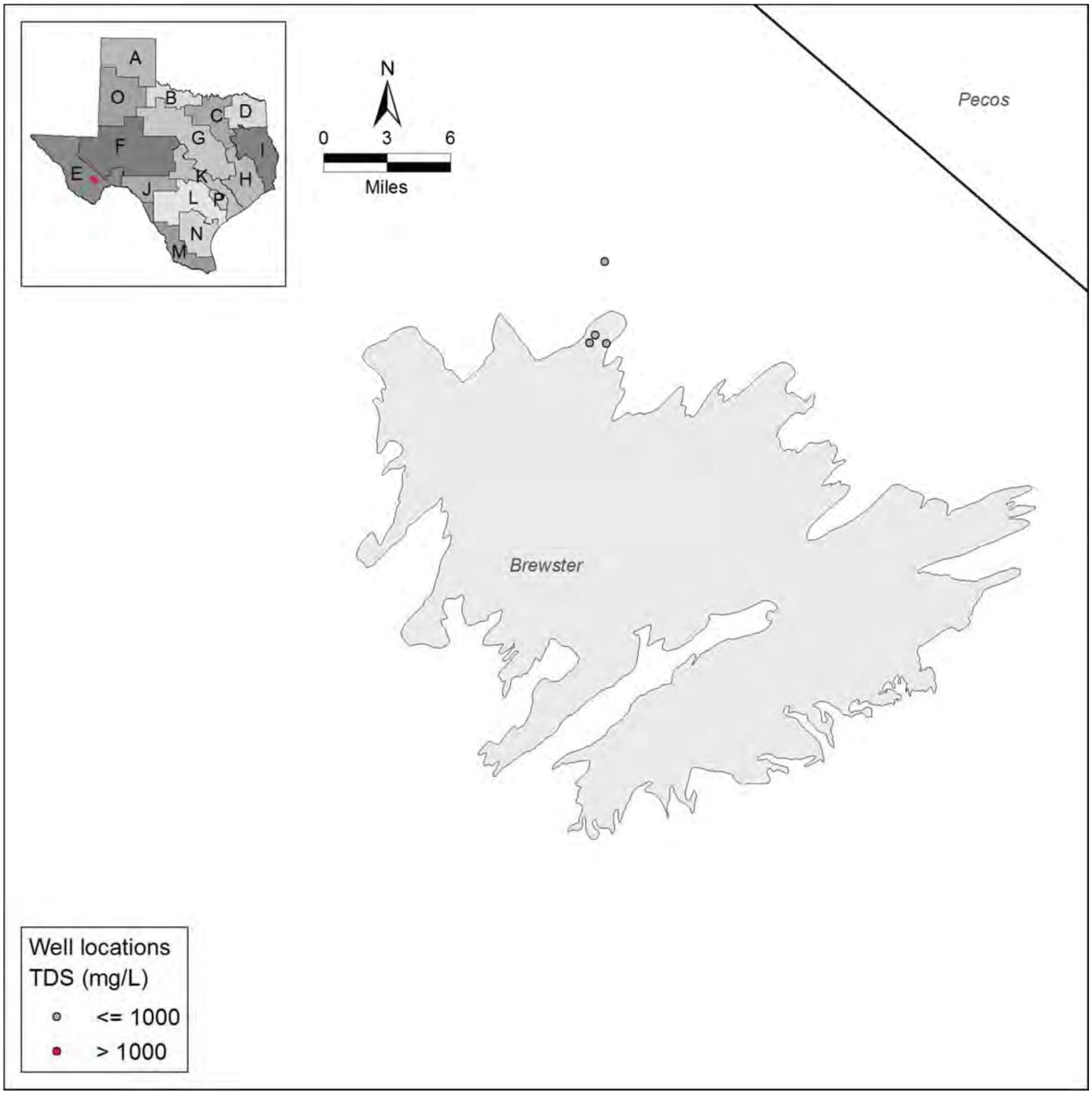

Figure 81. Marathon TDS locations

Marble Falls

The Marble Falls Aquifer consists of limestones of Pennsylvanian age surrounding the Llano Uplift (Ashworth and Hopkins, 1995) and exists as isolated pods that occupy a total area of 215 mi^2. Sampling is limited; there are no primary and very low levels of secondary MCL exceedances (TDS and sulfate) (Table 60 and Figure 82) and no discernable relationship exists between TDS and depth (Appendix 29). Due to the lack wells and of saturated thickness information, there are currently insufficient data to characterize the areas and volumes at risk of exceeding MCL concentrations in this aquifer.

Table 60 Summary of MCL violations in Marble Falls Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	µg/L	13	0	13	NA	NA	NA	0	0
Arsenic	10	µg/L	19	2	17	NA	2.2	5.7	0	0
Barium	2,000	µg/L	20	20	0	96	23.6	330	0	0
Beryllium	4	µg/L	13	0	13	NA	NA	NA	0	0
Cadmium	5	µg/L	9	0	9	NA	NA	NA	0	0
Chromium	100	µg/L	9	3	6	NA	1.67	1.74	0	0
Copper	1,300	µg/L	16	10	6	4.4	1.19	20.3	0	0
Fluoride	4	µg/L	18	16	2	0.49	0.16	2.48	0	0
Lead	15	µg/L	14	6	8	NA	1.1	9.2	0	0
Mercury	2	µg/L	7	0	7	NA	NA	NA	0	0
Nitrate-N	10	mg/L	19	15	4	1.20	0.09	7.8	0	0
Nitrite-N	1	mg/L	5	1	4	NA	0.53	0.53	0	0
Selenium	50	µg/L	16	1	15	NA	21	21	0	0
Thallium	2	µg/L	13	0	13	NA	NA	NA	0	0
Gross alpha	15	pCi/L	20	12	8	4.0	0.9	15	0	0
Gross beta	50	pCi/L	14	8	6	6.4	3.1	8.2	0	0
Comb. radium	5	pCi/L	1	0	1	NA	NA	NA	0	0
Uranium	30	µg/L	1	1	0	NA	7.3	7.3	0	0
Secondary MCL										
Aluminum	50	µg/L	16	1	15	NA	20.5	20.5	0	0
Chloride	300	mg/L	19	19	0	60	6	962	1	5
Copper	1,000	µg/L	16	10	6	4.4	1.19	20.3	0	0
Fluoride	2	mg/L	18	16	2	0.49	0.16	2.48	1	6
Iron	300	µg/L	20	5	15	NA	18	250	0	0
Manganese	50	µg/L	19	8	11	1.6	1.3	49.1	0	0
Silver	100	µg/L	4	0	4	NA	NA	NA	0	0
Sulfate	300	mg/L	19	19	0	30.9	7	327	1	5
TDS	1,000	mg/L	19	19	0	533	239	1,980	1	5
Zinc	5,000	µg/L	19	11	8	13	12.4	1,540	0	0
pH	6.5-8.5		17	17	0	6.92	6.53	7.54	0	0

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

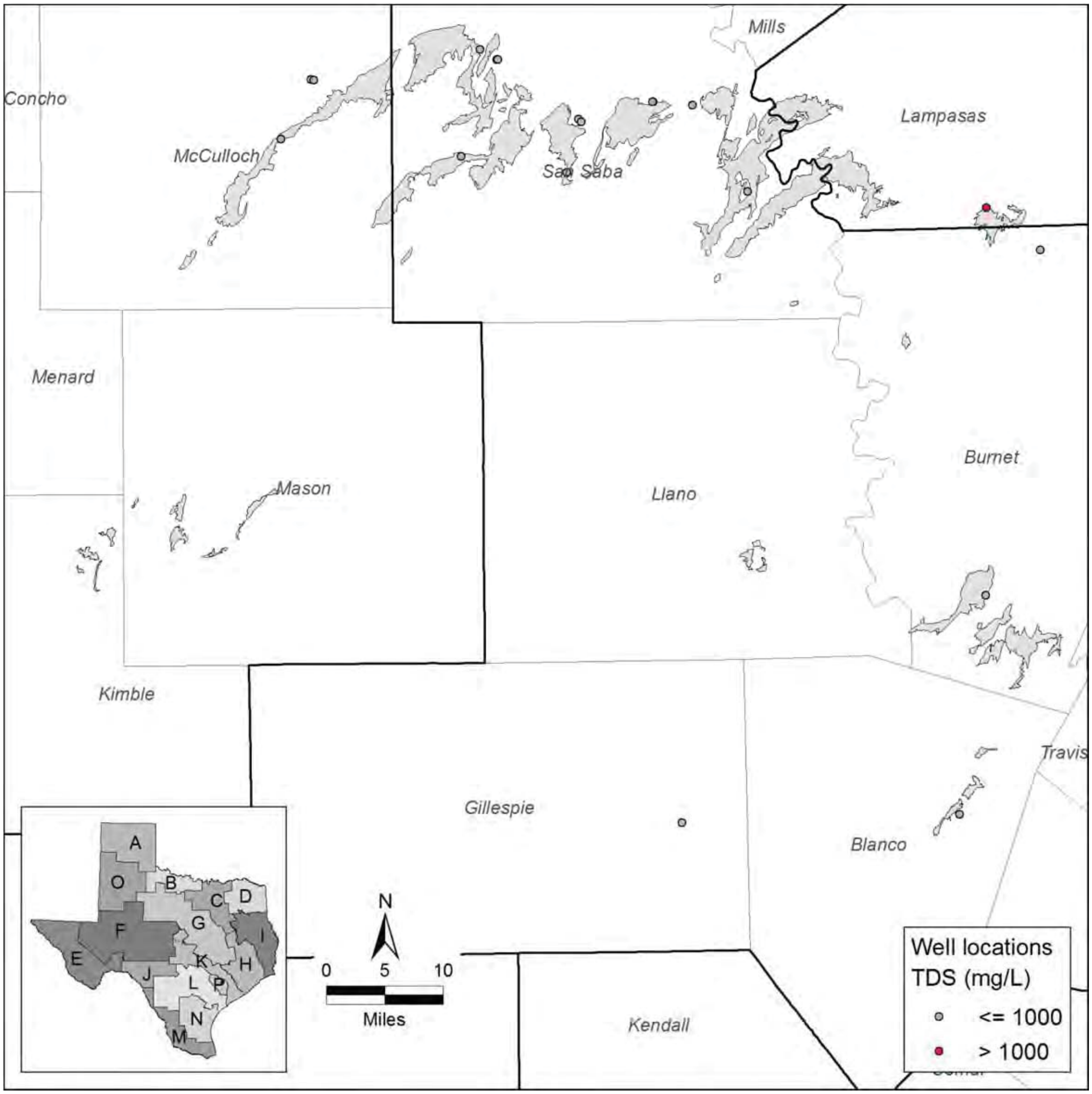

Figure 82. Marble Falls TDS locations

Rustler

The Rustler Aquifer is of Permian age extending over an area of 1,300 mi^2 with limited sampling (Table 61). Due to the clustered locations of wells and the lack of saturated thickness information, there are currently insufficient data to characterize the areas and volumes at risk of exceeding MCL concentrations in this aquifer. Primary MCL exceedances include combined radium, gross alpha, and gross beta. Secondary MCL exceedances include TDS, which reflects mostly sulfate exceedances and, to a lesser extent, chloride exceedances (Figure 83). There are also secondary fluoride and iron exceedances. Conceivably 90 percent of the volume of groundwater is affected by secondary (mainly TDS and sulfate) exceedances, and potentially three-fourths is affected by primary (gross alpha and combined radium) primary MCL exceedances (Appendix 30).

Table 61. Summary of MCL violations in Rustler Aquifer groundwater wells

	MCL	*Units*	*Analyses*	*Detects*	*Non-detects*	*Median*	*Min*	*Max*	*> MCL*	*% MCL*
Primary MCL										
Antimony	6	μg/L	25	3	22	NA	2.8	5.5	0	0
Arsenic	10	μg/L	27	1	26	NA	2.31	2.31	0	0
Barium	2,000	μg/L	27	25	2	13.6	6.0	84	0	0
Beryllium	4	μg/L	20	0	20	NA	NA	NA	0	0
Cadmium	5	μg/L	26	0	26	NA	NA	NA	0	0
Chromium	100	μg/L	23	2	21	NA	1.5	5.8	0	0
Copper	1,300	μg/L	23	5	18	NA	1.34	21	0	0
Fluoride	4	μg/L	27	26	1	2.0	0.39	2.8	0	0
Lead	15	μg/L	26	0	26	NA	NA	NA	0	0
Mercury	2	μg/L	13	0	13	NA	NA	NA	0	0
Nitrate-N	10	mg/L	31	20	11	0.03	0.01	15.1	2	6
Nitrite-N	1	mg/L	18	4	14	NA	0.01	0.06	0	0
Selenium	50	μg/L	27	9	18	NA	5.56	49.2	0	0
Thallium	2	μg/L	25	1	24	NA	9.7	9.7	1	4
Gross alpha	15	pCi/L	17	17	0	75	5.6	277	13	**76**
Gross beta	50	pCi/L	18	17	1	63	5.2	396	9	50
Comb. radium	5	pCi/L	2	2	0	NA	32.8	246	2	100
Uranium	30	μg/L	6	1	5	NA	2.13	2.13	0	0
Secondary MCL										
Aluminum	50	μg/L	22	4	18	3.0	3.0	1,590	2	9
Chloride	300	mg/L	33	33	0	59.6	7.0	49,800	12	36
Copper	1,000	μg/L	23	5	18	NA	1.34	21	0	0
Fluoride	2	mg/L	27	26	1	2.0	0.39	2.8	12	44
Iron	300	μg/L	28	21	7	110	46	7,590	8	29
Manganese	50	μg/L	27	20	7	4.5	1.0	840	2	7
Silver	100	μg/L	16	1	15	NA	60	60	0	0
Sulfate	300	mg/L	33	33	0	1,700	352	6,510	33	100
TDS	1,000	mg/L	30	30	0	2,610	686	89,700	28	93
Zinc	5,000	μg/L	23	16	7	11	4.32	452	0	0
pH	6.5-8.5		32	32	0	7.1	6.5	8.92	1	3

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of analyses above the MCL concentration.

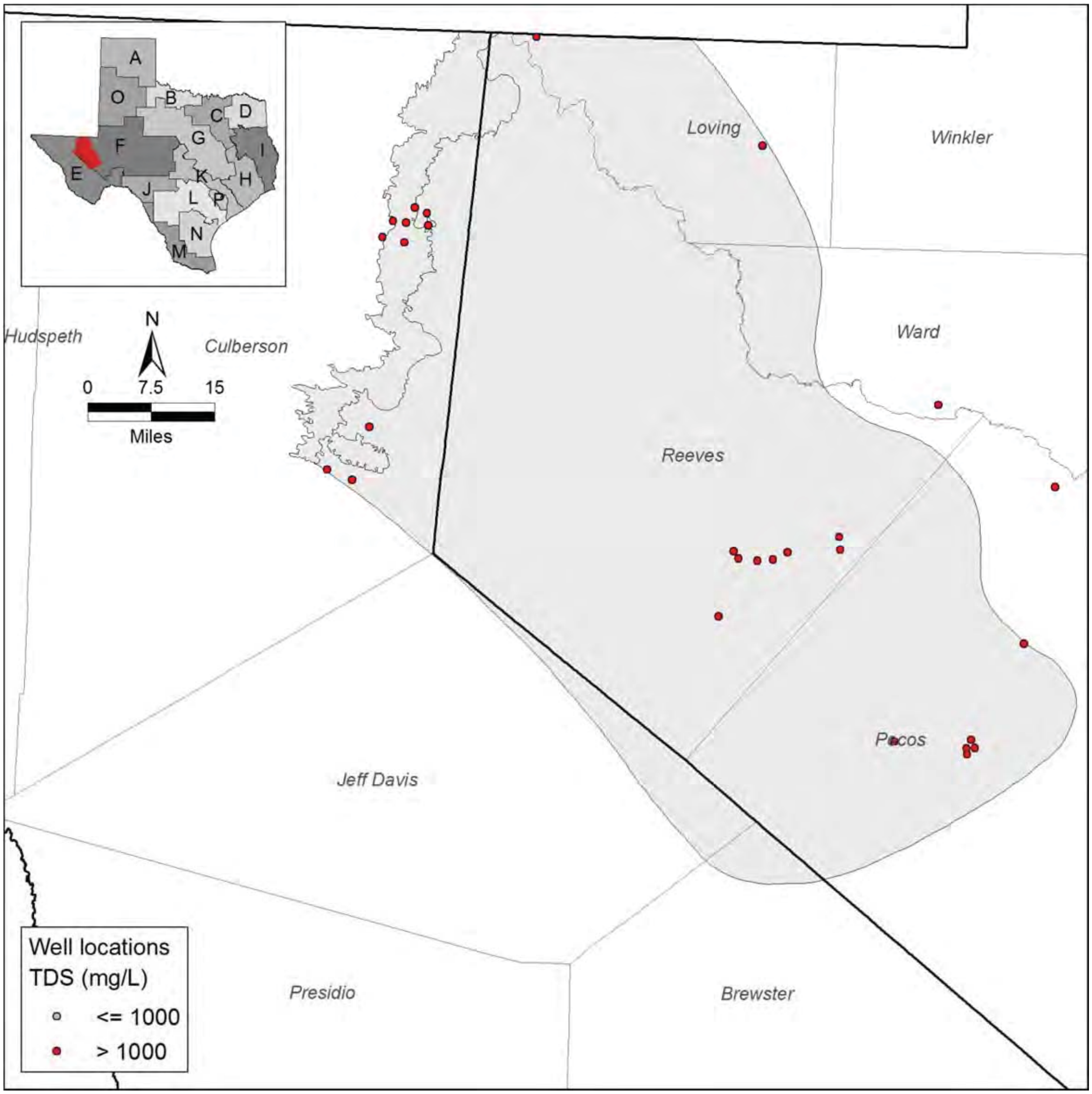

Figure 83. Rustler TDS well locations

3.1d Water Quality Effects on Water Quantity by Regional Water Planning Area

The impacts of groundwater quality on groundwater quantity were evaluated for each of the 16 Regional Water Planning Area (RWPA) regions (Figure 84) and by aquifer within each RWPA region (Table 62). Each region has from 3 to 14 aquifers contributing to their groundwater. Percentages of aquifer volumes within RWPA's in the high risk category range from 0 (Region P) to 50 percent (Region F). The large percentage in the high risk category in Region F (50 percent) reflects the Pecos Valley, Dockum, Ellenburger-San Saba, Hickory, and Lipan aquifers. Region O also has high percentages in the high risk category (44 percent) reflecting exceedances in the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers. Region M (41 percent) and Region N (19%) have relatively high percentages in the high risk category reflecting exceedances in the southern Gulf Coast Aquifer. Regions B, E, and K have moderate percentages in the high risk category (14 to 15 percent). Regions A, C, D, G, H, I, J, L, and P all have less than or equal to 5 percent of total aquifer volume in the high risk category.

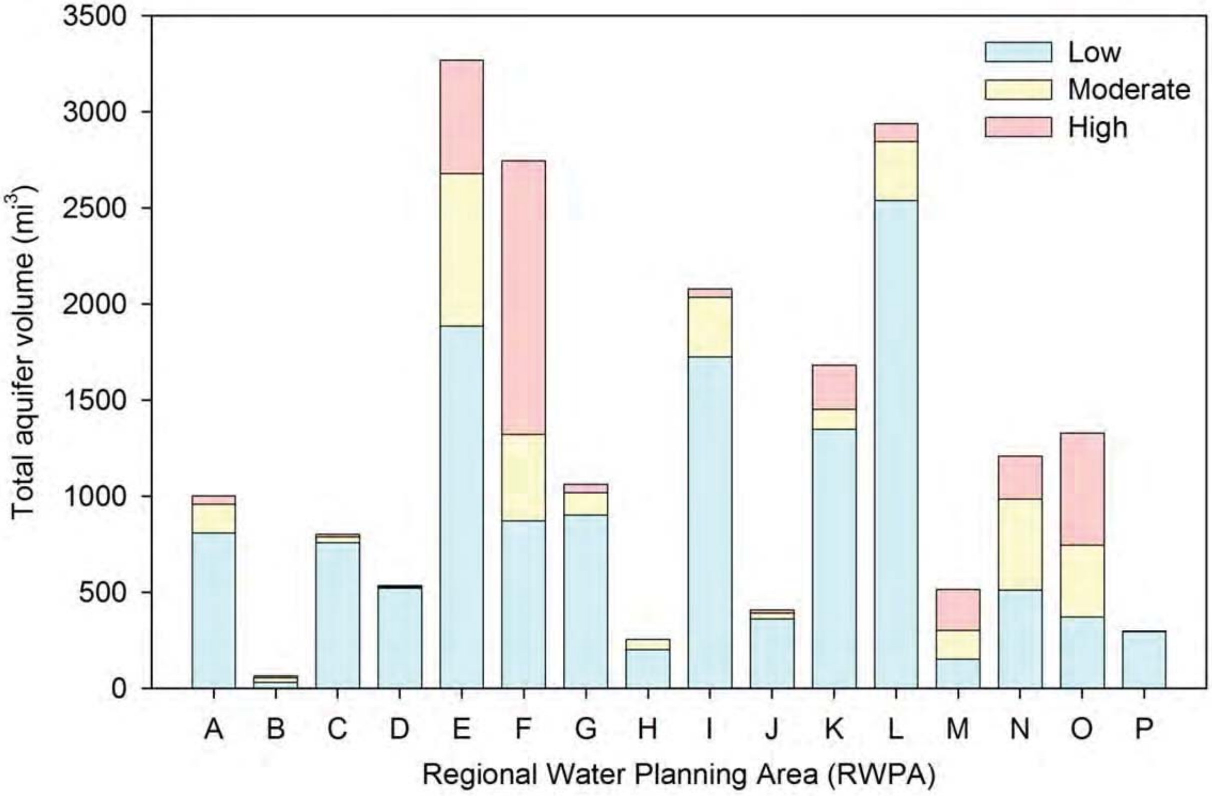

Figure 84. Summary of water quality impacts on water quantity by RWPA. Columns represent total volumes for all aquifers within each RWPA and the proportions of the total volume with low (0 – 40%), moderate (40 – 60%), and high (60 – 100%) probability of exceeding any primary MCL. Volumes represent aquifer volumes and do not represent water storage volumes.

Table 62. Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for “All” aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30.

RWPA	*Aquifer*	*Area* *mi^2*	*Volume* *mi^3*	*Low* *%*	*Moderate* *%*	*High* *%*
A	Ogallala	15,728	426	100	0	0
	Seymour	492	3	40	42	18
	Blaine	1,617	41	69	12	19
	Dockum	7,108	515	67	27	6
	Rita Blanca	390	14	60	13	27
	All		999	81	15	**4**
B	Trinity	445	7	100	0	0
	Seymour	1,282	5	56	37	7
	Blaine	1,963	52	41	41	18
	All		64	49	36	**15**
C	Carrizo-Wilcox	1,111	52	65	35	0
	Trinity	9,453	542	100	0	0
	Nacatoch	305	1	86	8	6
	Queen City	153	1	100	0	0
	Woodbine	5,685	203	89	5	6
	All		799	95	4	**1**
D	Carrizo-Wilcox	6,789	411	100	0	0
	Trinity	1,532	28	67	26	7
	Blossom	278	1	100	0	0
	Nacatoch	1,304	15	72	6	22
	Queen City	3,139	57	99	1	0
	Woodbine	863	23	100	0	0
	All		534	97	2	**1**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

Table 62 (continued). Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for "All" aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30. Aquifers without volume and percentage values do not have SWAP saturated thickness information available and are excluded from the calculations.

		Area	*Volume*	*Low*	*Moderate*	*High*
RWPA	*Aquifer*	*mi²*	*mi³*	*%*	*%*	*%*
E	Edwards-Trinity Plateau	3,676	405	56	43	2
	Hueco-Mesilla Bolson	1,371	695	44	9	47
	Igneous	5,649	1,966	72	24	4
	West Texas Bolsons	1,828	200	30	50	20
	Bone Spring-Victorio Peak	716	N/A	-	-	-
	Capitan Reef	807	N/A	-	-	-
	Marathon	39	N/A	-	-	-
	Rustler	817	N/A	-	-	-
	All		3,267	61	25	**14**
F	Ogallala	3,434	27	10	13	77
	Trinity	248	4	100	0	0
	Edwards-Trinity Plateau	21,328	861	64	18	18
	Pecos Valley Alluvium	5,789	269	75	11	14
	Dockum	11,391	1,104	8	19	73
	Edwards-Trinity (High Plains)	107	2	0	0	100
	Ellenburger-San Saba	1,816	143	43	12	44
	Hickory	3,391	267	2	6	92
	Lipan	670	67	15	14	71
	Capitan Reef	1,038	N/A	-	-	-
	Marble Falls	35	N/A	-	-	-
	Rustler	4,373	N/A	-	-	-
	All		2,743	34	16	**50**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

"N/A" not available, "-" insufficient data

Table 62 (continued). Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for “All” aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30. Aquifers without volume and percentage values do not have SWAP saturated thickness information available and are excluded from the calculations.

		Area	*Volume*	*Low*	*Moderate*	*High*
RWPA	*Aquifer*	*mi^2*	*mi^3*	*%*	*%*	*%*
G	Gulf Coast	1,034	43	78	22	0
	Carrizo-Wilcox	2,948	285	95	4	1
	Trinity	12,156	428	90	8	2
	Edwards-Trinity Plateau	686	9	100	0	0
	Seymour	1,462	7	49	16	36
	Edwards BFZ	814	31	24	76	0
	Dockum	269	3	2	22	77
	Ellenburger-San Saba	259	55	57	34	9
	Hickory	364	22	8	0	92
	Queen City	2,268	72	100	0	0
	Sparta	1,957	41	100	0	0
	Yegua-Jackson	2,218	64	74	21	5
	Brazos River Alluvium	697	N/A	-	-	-
	Marble Falls	25	N/A	-	-	-
	All		1,059	85	11	**4**
H	Gulf Coast	10,476	1,600	87	11	2
	Carrizo-Wilcox	1,565	145	71	29	0
	Queen City	1,433	35	100	0	0
	Sparta	1,112	24	100	0	0
	Yegua-Jackson	1,463	41	80	20	0
	Brazos River Alluvium	360	N/A	-	-	-
	All		1,846	74	21	**5**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

“N/A” not available, “-“ insufficient data

Table 62 (continued). Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for "All" aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30. Aquifers without volume and percentage values do not have SWAP saturated thickness information available and are excluded from the calculations.

		Area	*Volume*	*Low*	*Moderate*	*High*
RWPA	*Aquifer*	*mi²*	*mi³*	*%*	*%*	*%*
I	Gulf Coast	5,315	673	50	43	7
	Carrizo-Wilcox	9,014	1,233	100	0	0
	Queen City	4,084	78	100	0	0
	Sparta	2,623	66	100	0	0
	Yegua-Jackson	2,795	29	41	58	1
	All		2,079	83	15	**2**
J	Trinity	794	312	98	2	0
	Edwards-Trinity Plateau	1,235	1,426	86	14	0
	Edwards BFZ	250	28	81	19	0
	Ellenburger-San Saba	117	28	100	0	0
	Hickory	507	34	0	52	48
	All		1,828	86	12	**1**
K	Gulf Coast	3,562	472	99	1	0
	Carrizo-Wilcox	1,188	138	100	0	0
	Trinity	3,430	351	85	8	7
	Edwards-Trinity Plateau	588	28	92	8	0
	Edwards BFZ	300	16	92	7	1
	Ellenburger-San Saba	2,851	379	87	3	10
	Hickory	4,043	239	13	19	68
	Queen City	625	14	100	0	0
	Sparta	613	11	100	0	0
	Yegua-Jackson	970	33	60	30	10
	Marble Falls	155	N/A	-	-	-
	All		1,680	80	6	**14**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

"N/A" not available, "-" insufficient data

Table 62 (continued). Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for "All" aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30.

		Area	*Volume*	*Low*	*Moderate*	*High*
RWPA	*Aquifer*	*mi^2*	*mi^3*	*%*	*%*	*%*
L	Gulf Coast	4,821	474	88	11	1
	Carrizo-Wilcox	10,076	1,458	88	7	5
	Trinity	3,584	407	96	3	1
	Edwards-Trinity Plateau	394	77	99	1	0
	Edwards BFZ	2,887	261	54	46	0
	Ellenburger-San Saba	174	49	99	1	0
	Hickory	304	14	39	55	6
	Queen City	2,623	122	100	0	0
	Sparta	1,490	29	100	0	0
	Yegua-Jackson	2,283	46	54	31	15
	All		2,937	87	10	**3**
M	Gulf Coast	4,063	359	7	35	58
	Carrizo-Wilcox	1,939	131	98	1	1
	Yegua-Jackson	2,743	24	4	89	7
	All		514	30	29	**41**
N	Gulf Coast	9,448	1,002	32	46	22
	Carrizo-Wilcox	1175	170	100	0	0
	Queen City	250	15	100	0	0
	Sparta	60	1	100	0	0
	Yegua-Jackson	868	20	15	64	21
	All		1,209	42	39	**19**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

Table 62 (continued). Regional Water Planning Area (RWPA) aquifer areas, volumes, and primary MCL exceedance probabilities. Volumes represent aquifer volumes within each RWPA and do not represent water storage volumes. Exceedance probability values are expressed as area percentages within each RWPA and those for “All” aquifers represent the weighted total values for all aquifers with the RWPA. RWPA boundaries are shown in Figure 29 and Figure 30.

		Area	*Volume*	*Low*	*Moderate*	*High*
RWPA	*Aquifer*	*mi^2*	*mi^3*	*%*	*%*	*%*
O	Ogallala	16,842	197	56	9	35
	Seymour	62	2	0	51	49
	Dockum	6,804	946	24	35	41
	Edwards-Trinity (High Plains)	7,627	183	21	11	68
	All		1,328	28	28	**44**
P	Gulf Coast	2,167	293	99	1	0
	Carrizo-Wilcox	35	1	100	0	0
	Yegua-Jackson	115	3	86	14	0
	All		298	99	1	**0**

Area: total aquifer area within RWPA, *Volume*: total aquifer volume within RWPA calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Moderate*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

3.2 Treatment for Chemical Constituents in Domestic Well Water

Prior to selecting a treatment system to remove a chemical of concern, several preparatory steps should be taken. First, the quality of the water must be understood. Microbiological quality--It is important to verify the water supply is microbiologically safe. Typically this is determined by coliform organism tests which can be coordinated with local county health departments. Coliform organisms serve as “indicator” organisms of possible fecal pollution. If coliform testing reveals a series of “positive” samples it is highly recommended the supply receive continuous disinfection (typically hypochlorination or Ultraviolet Light (UV) near the well discharge line and prior to any potable uses). It makes little sense to expend resources to remove a chemical of concern that is typically a chronic/ long term ingestion health risk if the same supply has acute/short term health risks from microorganisms..

Chemical quality Different contaminants often require different treatment methodologies. Before buying water-treatment equipment, well owners should have their water supply tested by a recognized, National Environmental Laboratory Accreditation Conference (NELAC) certified water-testing laboratory. A NELAC certified laboratory can instruct the well owner in proper sample collection methods. Launching a treatment initiative based on faulty data can waste time and money. For a current listing of NELAC accredited water quality laboratories see:

http://www.nelac-institute.org/accred-labs.php. Also see this link for a full listing of drinking water standards in Texas: http://www.tceq.texas.gov/publications/rg/rg-346.html.

Once the water quality is understood, the following “non-treatment” options should be evaluated prior to treatment selection if the well water is found to contain chemical constituents above health-based standards (adapted from Texas AgriLife, Drinking Water L-5467):

- Purchase bottled water for drinking and cooking. In general, a water source with contaminants of concern that create only long term ingestion health risks can be used for non-consumption activities such as showering, bathing, and washing clothes.
- Connect to a public water system (PWS). Each PWS is required to test regularly for contaminants. Ask the closest PWS to provide their most recent “Consumer Confidence Report” (CCR). The CCR will contain a full disclosure of their water quality data
- Modify the well’s aquifer production zones (if more than one) or drill a new well into different water-bearing formations, possibly reducing contaminant levels. The evaluation of alternate acceptable groundwater can be accelerated by use of data collected in TCEQ/UT-BEG compliance studies on public water systems with chemical quality violations. See the following link and identify one or more studied PWS’s that are closest to your domestic well:

http://www.beg.utexas.edu/environqlty/TCEQ_ss2004-2007.htm

If water treatment is the desired route for good quality water, several issues should be considered:

Treatment flow volume: Water may be treated for the whole house atthe house Point of Entry (POE) to treatfor high calcium (Ca), magnesim (Mg), sulfate (SO_4), hydrogen sulfide (H_2S), iron (Fe), manganese (Mn), turbid particles, and microbes; or a smaller flow of potable water may be treated for drinking and cooking at Point of Use (POU), typically at a kitchen sink to treat for arsenic (As), fluoride (F), selenium (Se), uranium (U), nitrate (NO_3), and radium (Ra).

Cost: This includes initial purchase price plus installation and maintenance or operational costs.

Proof of performance: Does the considered technology work with similar water quality issues?

Verifying third party accreditation of a treatment technology can help discern efficacy for makes and models of treatment technologies. For example, treatment units listed as "NSF/ANSI 61" verifies the unit will not leach harmful components into treated water. At the very least, all treatment units used for potable water should bear this accreditation

- Certification to the relevant ANSI/NSF standards by an ANSI accredited third party certifier ensures the safety and performance of the residential treatment systems. In the U.S., the following certifiers have been accredited by ANSI to certify drinking water treatment systems:
- Canadian Standards Association International (www.csa-international.org);
- International Association of Plumbing & Mechanical Officials (www.iapmo.org);
- NSF International (www.nsf.org);
- Underwriters Laboratories Inc. (www.ul.com); and
- Water Quality Association (www.wqa.org).

It is recommended that POE/POU treatment units being considered for potable use have ANSI accreditation from one of the certifiers listed above.

3.2a Treated Volume Options:

Point of Entry (POE)

Typically where all water entering the home is treated, a volume of 120 gallons/person/day is often used for sizing POE units. POE is required when water has problems that affect all areas of the home. These problems relate to water containing high Ca or Mg (hard water) which are not hazardous for consumption, but may cause scale buildup in pipes and on fixtures, interfere with effectiveness of soap, and shorten the life of appliances such as dish washers and hot water heaters; high Fe or Mn, which may cause staining of lavatories and clothes being washed and contribute to bacterial growth; and H_2S which causes odor issues in water. Furthermore, POE water treatment systems are also available to adjust pH levels and add chlorine or other disinfectant.

Water from a domestic well that contains microbial contaminants should employ POE disinfection treatment. POE disinfection is required for microbe laden source water due to the potential risk of disease transmission via non-ingestion paths such as mucous membranes and skin cuts or unintentional ingestion when bathing, showering, or hand washing.

Point of Use (POU)

Where only water for drinking and cooking is treated. POU is sufficient to remove chemical contaminants linked to chronic health issues when directly consumed via ingestion.

3.2b Treatment Technologies

Reverse Osmosis (RO)

Reverse osmosis (RO) filtration removes large molecules and ions from solutions by applying pressure to the solution against a selective membrane. RO can be used to remove most primary and secondary MCLs from water (Table 63). The result is concentrated solute retention on the pressurized side of the membrane as purified solvent (water) is allowed to pass to the other side. The selective membrane does not allow large molecules or ions through the pores (holes), but allows smaller components of the solution (such as the solvent) to pass freely. The process is similar to membrane filtration. However, there are key differences between reverse osmosis and filtration. The predominant removal mechanism in membrane filtration is straining, or size exclusion; therefore, the process can theoretically achieve perfect exclusion of particles regardless of operational parameters such as influent pressure and concentration. Reverse osmosis, however, involves a diffusive mechanism so that separation efficiency is dependent on solute concentration, pressure, and water flux rate. Reverse osmosis may be adversely affected by competition between the ions being removed, e.g. arsenic, and other ions in solution such as chloride, sulfate, phosphate, silica, and TDS. The concentration limits for these competing ions are provided in Table 64. Competition with other ions is a widespread issue in Texas aquifers. Chloride commonly exceeds the limit of 300 mg/L, particularly in the southern Ogallala, west Texas, and Gulf Coast aquifers (Figure 85). Silica concentrations commonly exceed 20 mg/L (Figure 86). Sulfate concentrations also exceed the

100 mg/L limit in most aquifers (Figure 87). TDS concentrations exceed the 1,800 mg/L limit in much of the west and south of Texas (Figure 88).

Table 63. Treatment technology suitability for specific contaminants.

Location >	POU			Both		POE		
Contaminant	RO	Dist.	AA & IBM	Ion Exchange		Aeration and Air stripping	Water Softener	Oxidation Filter
				Cation	Anion			
Arsenic	✓	✓	✓		✓			
Calcium	✓	✓		✓			✓	
Carbonate	✓	✓			✓			
Chloride	✓	✓			✓			
Fluoride	✓	✓	✓					
H_2S					+	✓		✓
Iron	✓	✓		+		✓	+	✓
Magnesium	✓	✓		✓				✓
Manganese	✓	✓		+		✓	+	✓
Nitrate	✓	✓			✓			
Nitrite	✓	✓			✓			
Sodium	✓	✓		*				
Sulfate	✓	✓			✓			
Gross alpha	✓	✓			✓			
Radium	✓	✓		✓				
Uranium	✓	✓			✓			

POU: point of use, _POE_: point of entry, _RO_: reverse osmosis, _Dist_: distillation, _AA_: activated alumina, _IBM_: iron-based media

Table 64. Competing ions and their concentration limits for treatment

Treatment	Cl (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	PO_4 (mg/L)	Si (mg/L)	Fe^{3+} (mg/L)	TDS (mg/L)	TOC (mg/L)	Turbidity (NTU)
RO	300		100	5	20		1,800		5
IX		5	50				500		0.3
AA	250		360	1	30	0.5	1,000	4	0.30.3
IBM			50	1	10				

_AA_: activated alumina; _IX_: ion exchange; _IBS_: iron-based media; _RO_: reverse osmosis

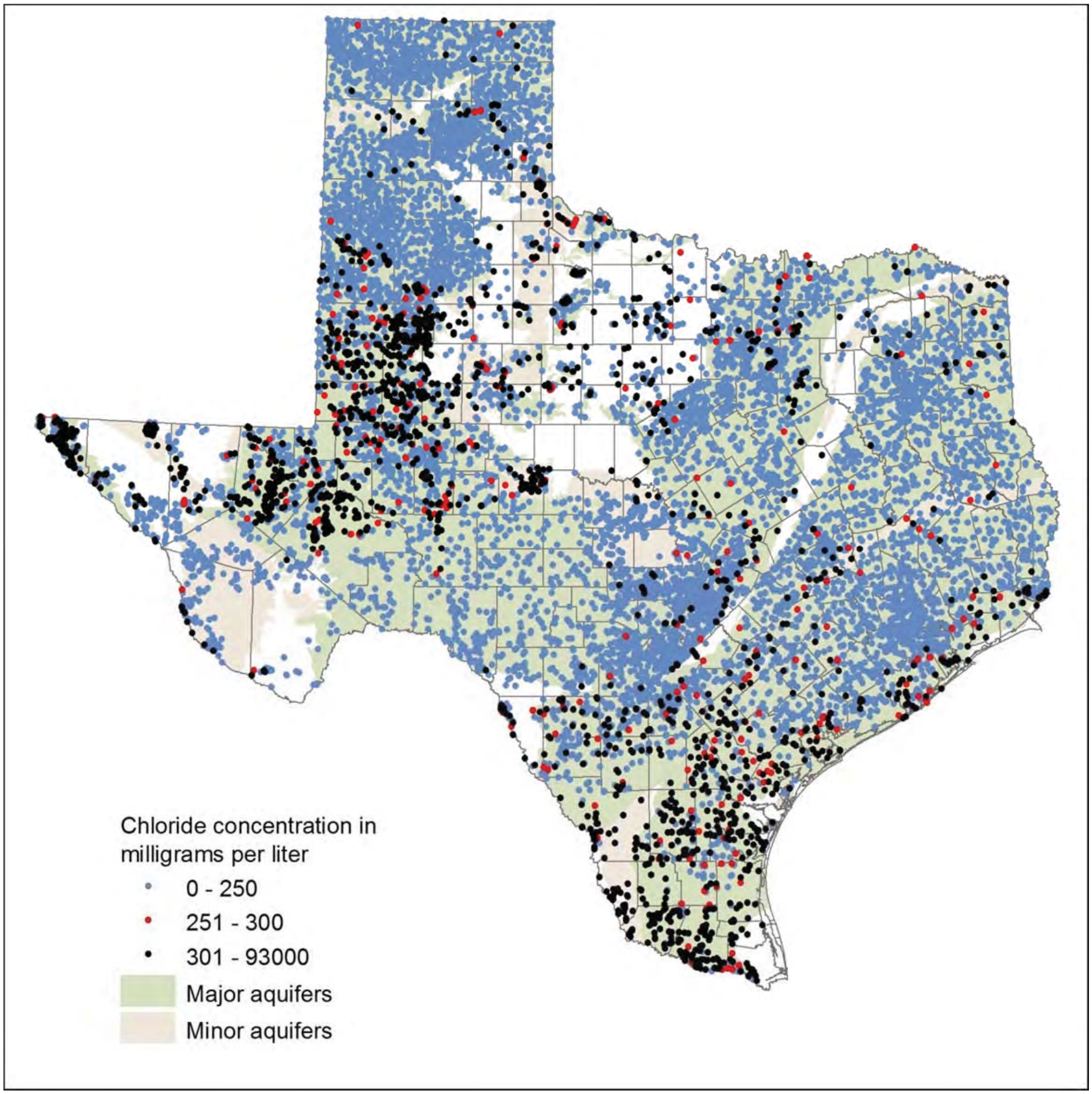

Figure 85. Treatment-limiting concentrations of chloride in Texas groundwater. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

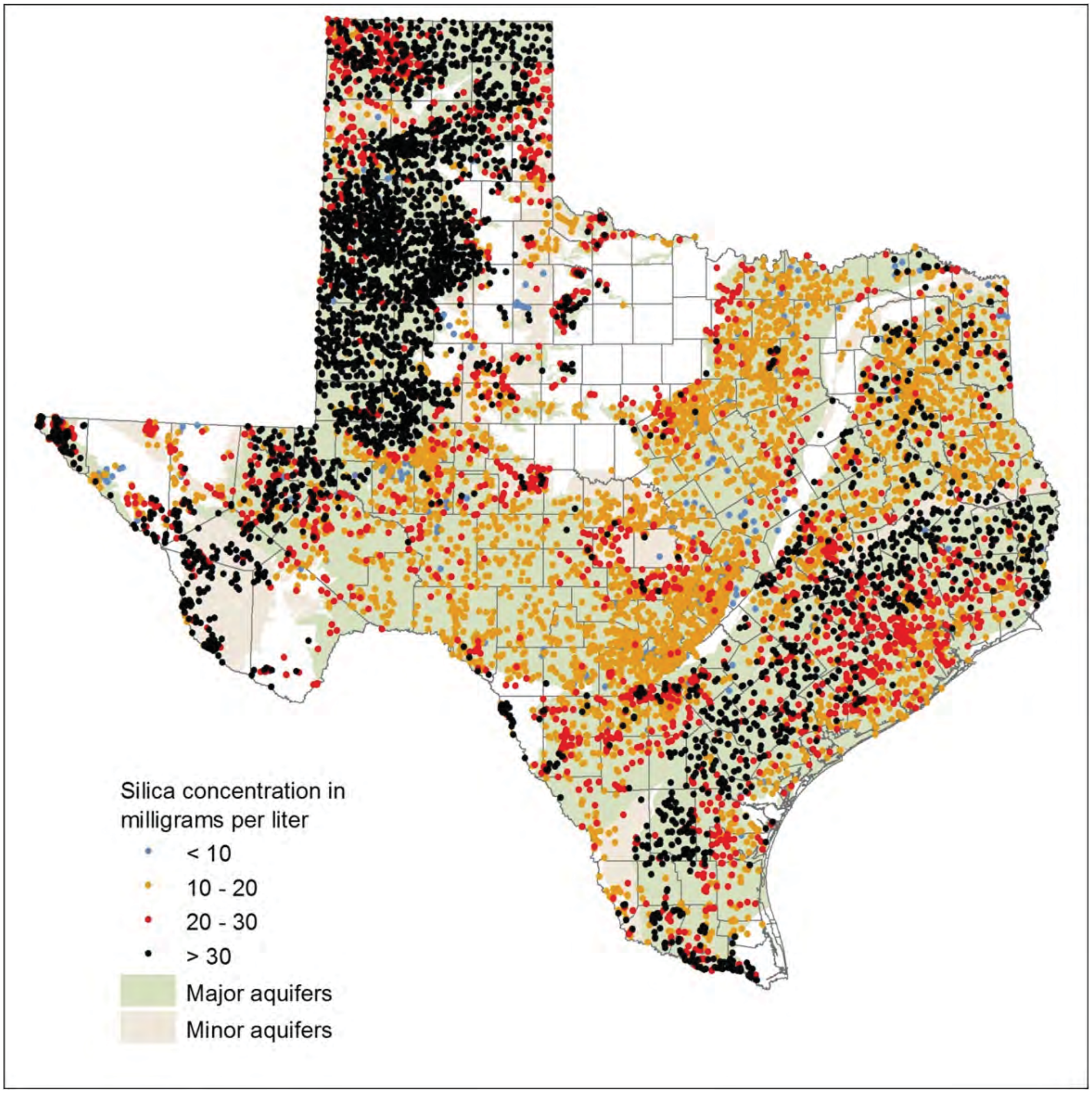

Figure 86. Treatment-limiting concentrations of silica in Texas groundwater. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

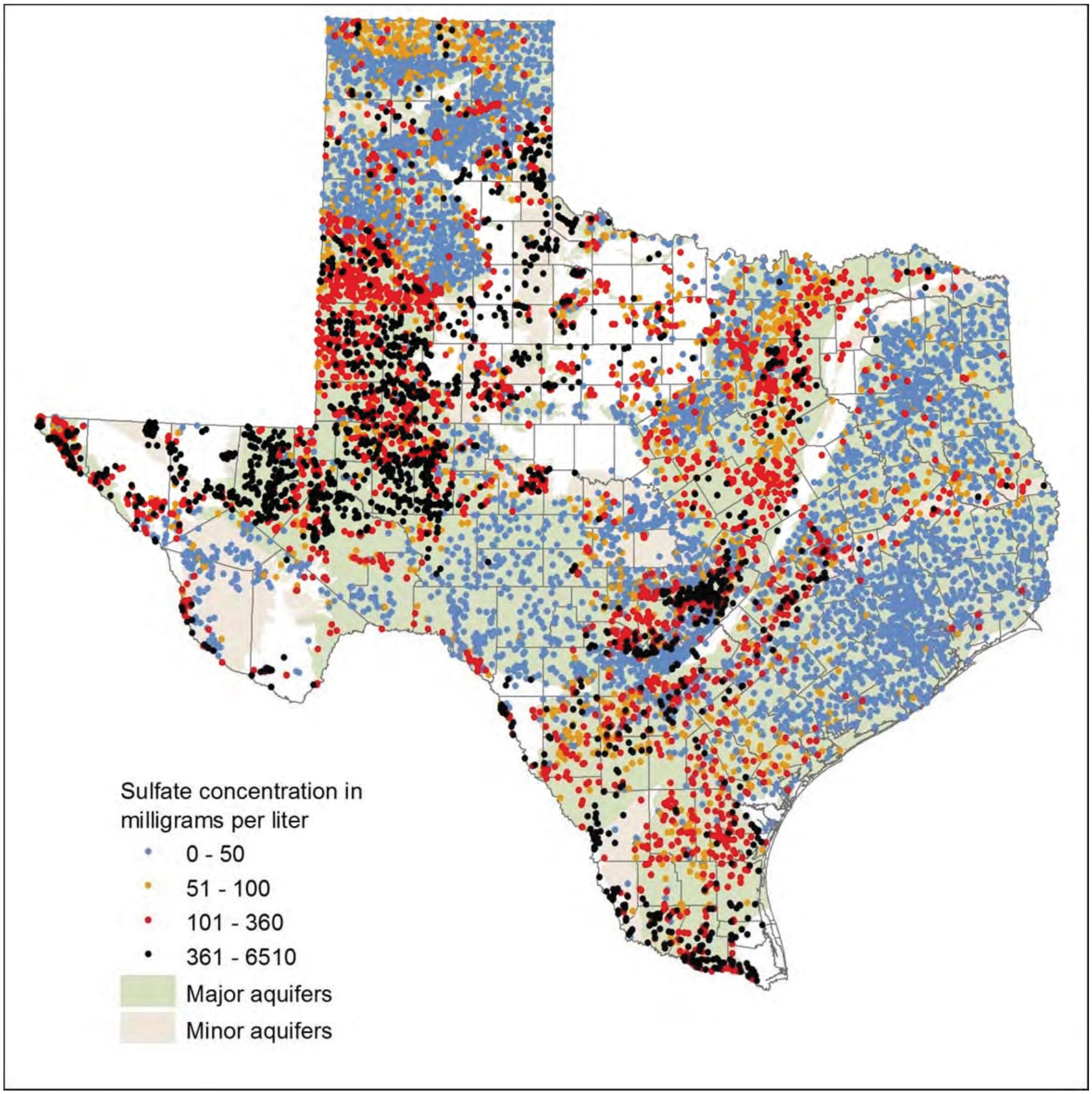

Figure 87. Treatment-limiting concentrations of sulfate in Texas groundwater. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

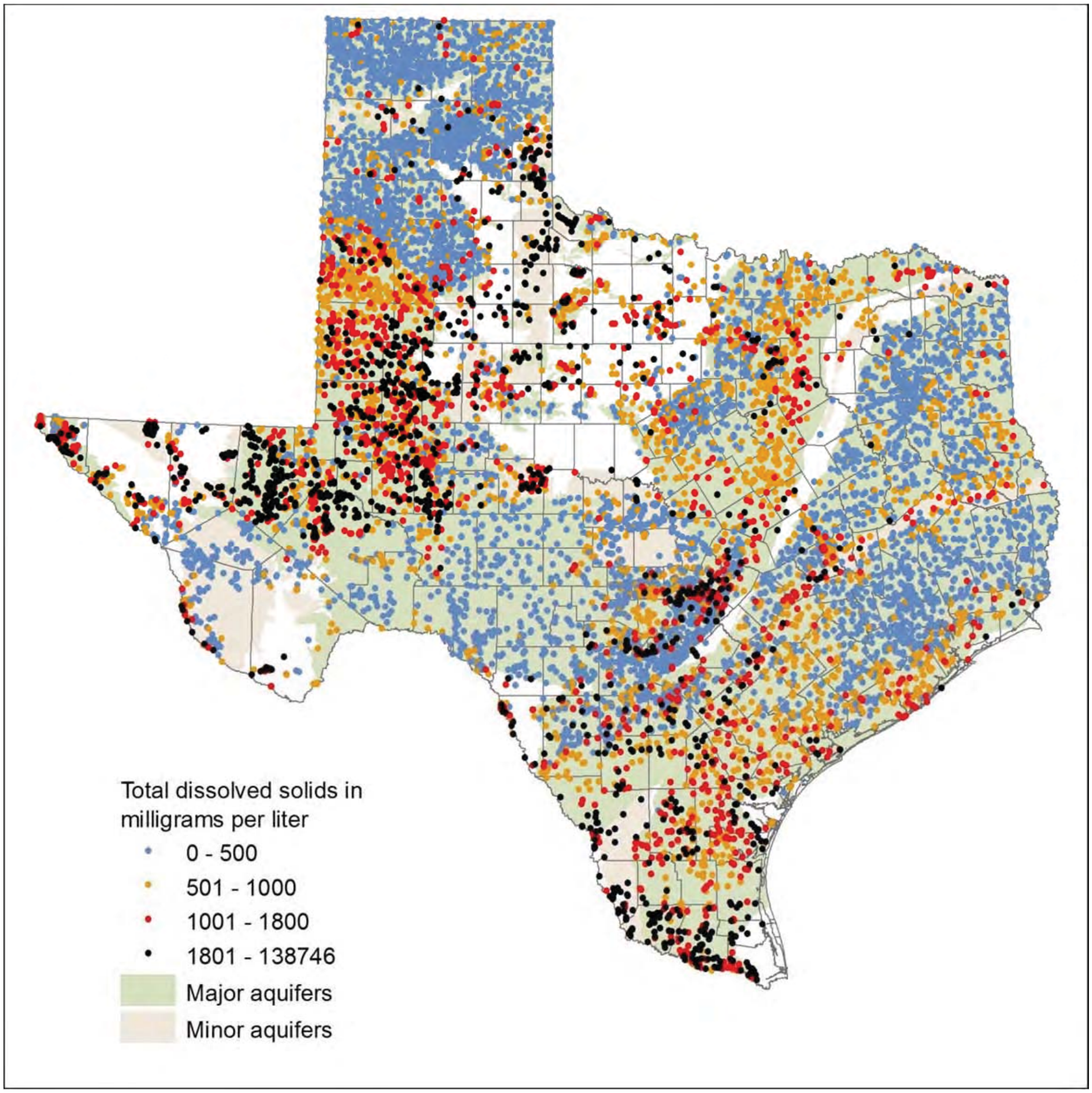

Figure 88. Treatment-limiting concentrations of TDS in Texas groundwater. Prepared by BEG for TWDB contract #1004831125, with data from TWDB, 2011.

Commonly used RO membrane materials, cellulose acetate (CA), and thin film composite (TFC) each have distinctive features. CA membranes are much more resistant to chlorine residuals and bio-fouling, whereas TFC membranes are more effective at reducing chemical constituents and are the recommended membrane for nitrate removal. Effective pre-treatment is the critical key to prolonged life of any type of RO membrane. Fouled RO membranes may be caused by a number of potential foulants such as adsorption of organic material on the membrane surface and/or pore blocking, scaling due to precipitation of such materials as $CaC0_3$,and $CaS0_4$, and bio-fouling from microbial growth. Disinfection (typically hypo-chlorination or UV) is sometimes recommended treatment ahead of POU RO to avoid bio-fouling shortened membrane life. A common POU RO system consists of a sediment/chlorine pre-filter, the reverse-osmosis membrane, a water storage tank, and an activated-carbon post-filter.

Advantages of POU Reverse Osmosis:

- Significant reduction in most inorganic ions present in water and some organic compounds. With use of a high quality carbon filter to remove any organic materials that penetrate the filter, the purity of the treated water approaches that produced by distillation.
- Typically purifies more water per day than distillers and is less expensive to operate and maintain although it is slower than a carbon or sediment water filter.
- Does not use additional electricity as they operate from the well pump and pressure tank pressures.
- Supplier market is competitive with many available makers and models.

Disadvantages of Reverse Osmosis:

- POU RO units “waste” 60-80 percent of the water entering the system and may stress septic systems.
- Competition with other ions, including chloride, sulfate, phosphate, silica, and TDS, reduces lifespan of filters.
- Some pesticides, solvents, and other volatile organic chemicals (VOCs) are not completely removed by RO. A good quality activated carbon post-filter can reduce or eliminate these contaminants.
- Many conditions affect RO membrane's production efficiency. These include chemical properties of contaminants, membrane type and condition, and operating conditions (such as pH, water temperature, and water pressure). Thus site performance will be unique.
- Although POU RO filters do not typically use electricity for re-pressurization, they depend on a relatively high water pressure to force water molecules through the membrane. In an emergency situation where water pressure has been lost, these systems will not function.

- RO systems require maintenance. The pre- and post-filters and the reverse osmosis membranes must be changed according to the manufacturer's recommendation, and the storage tank must be cleaned periodically.
- Damaged membranes are not easily detected; therefore, it may be difficult to determine if the system is functioning as desired without water testing.

A POU RO system is a good option to reduce unacceptably high levels of TDS to improve taste of the water or when one wishes to remove more than one health-based inorganic chemicals in drinking water.

Distillation

Distillation is phase change (boiling) followed by condensation of the purified water. Modern distillation units are very compact and are provided in a large market of competitive suppliers. In distillation, water is vaporized and the pure (or mostly pure) steam leaves the nonvolatile contaminants behind. The steam moves to a different part of the unit and is cooled until it condenses into liquid water. The resulting distillate drips into a storage container. Ions and sediment remain in the distiller and must be removed. Distillation can effectively treat all primary and secondary MCLs (except VOCs). Although there is no MCL for radon and it was not considered in this study, radon is often associated with other radionuclides; however, it cannot be removed by distillation.

Advantages of distillation:

- Produces highly purified water. One of the few practical ways to concurrently remove multiple chemical contaminants. Removes micorganisms in water, mostly by heat and leaving them behind when water vapor evaporates.
- As long as the distiller is kept clean and is working properly, high quality treated water is consistently produced regardless of quality of incoming water - no reduction in quality over time.
- No filter cartridges to replace, unless a carbon filter is used to remove volatile organic compounds.
- No problems with competition with other ions.

Disadvantages of distillation:

- Distillation is time consuming; it can take two to five hours to make a gallon of distilled water.
- Distillers use electricity all the time the unit is operating.
- Distillers require frequent cleaning of the boiler, condensation compartment, and storage tank.
- Countertop distillation is one of the more expensive home water treatment methods, primarily due to additional electrical energy use for the process. The cost of distillation is high because of initial cost of the distillation unit and electrical energy costs per gallon of water produced. Costs can be estimated as follows from Lesikar et al., 2006a:

$$Cost\,/\,gal = 0.024 \times \frac{Unit\ wattage}{\Pr oduction\ (gal\,/\,d)} \times \cos t\ \ of\ \ electricity\ (\$\,/\,kWh)$$

- Most home distillation units require electricity, and will not function in an emergency situation when electrical power is unavailable.

Ion Exchange

Ion exchange (IX) is a physical-chemical process in which ions (anions, cations, or both) are exchanged between a solution and a solid resin. The solid resin is typically an elastic three-dimensional hydrocarbon network containing a large number of ionizable groups electrostatically bound to the resin. These groups are exchanged for ions of similar charge in solution that have a stronger exchange affinity (i.e. selectivity) for the resin. In this process, water passes through a media bed, usually sulfonated polystyrene beads. Ion exchange units can be made up of cation, anion, or mixed bed (cations and anions) resins. A common example of cation exchange resin is a water softener. In this application the beads are supersaturated with sodium or potassium. Conventional softening units are also highly efficient in removing radium from water even preferentially over magnesium and calcium. Anion exchange resins can be used to remove arsenate, nitrate, sulfate, chloride, carbonate, uranium and alpha emitters. Ion Exchange resins are being developed for many applications that are increasingly selective for capture of the target contaminant, thereby reducing the load from competing ions and increasing run time before servicing. When the ion exchange resin becomes saturated with contaminants, it must be recharged. Recharging is done by passing a brine solution through the resin. Typically concentrated sodium replaces the trapped contaminants in a cation exchange system and chloride replaces the trapped contaminant in an anion exchange system. The dislodged contaminant residuals are then discharged in the waste water. If the waste steam contains concentrated radionuclides, it must be disposed of according to state or federal regulations.

Factors governing efficiency of ion exchange include:

- Type & quality of resin used;
- Amount of regenerant per cubic foot of resin for regeneration;
- Regenerant concentration in resin bed during regeneration;
- Regenerant flow rate through resin bed (contact time) during regeneration;
- Raw water hardness;
- Raw water temperature – most ion exchange systems perform better at higher temperatures;
- Optimal flow rate of inlet water through resin bed.

Advantages of ion exchange:

- Targeted constituents are decreased.
- Concentrations of some other cation contaminants such as barium, radium, and iron may also be decreased depending on manufacturer's specifications.
- Less waste of water because a large portion of flow is usable (up to 98 percent)

Disadvantages of ion exchange:

- The process of regenerating ion exchange beds introduces large quantities of brine or other regenerant into the environment.
- Sodium-based regenerants elevate sodium concentration of most treated water and thus may be harmful to people on low sodium diets.
- Ion exchange does not decrease biological contaminants (bacteria, viruses, cysts); nor does the process decrease levels of most organic compounds.
- Typically, approximately 50 gallons of rinse water per cubic foot of resin are required to totally remove hardness and excess salt from the resin during each regeneration.
- Waste residuals with radionuclides may require special disposal in accordance with regulations.
- Cost of recharging resins may be high.
- May result in higher concentrations of the contaminant if column is not regenerated according to schedule. Chromatographic peaking and dumping of the retained contaminant can occur when the bed is saturated.

Adsorptive media

Adsorptive media cartridges are loaded with either activated alumina (AA) or a growing list of iron-based media (IBM).

Activated alumina is a hydrated aluminum oxide that has been heat-treated. The advantage of using AA filters is that it is an effective way to reduce levels of fluoride, arsenic, and selenium. Disadvantages of Activated Alumina filters include higher replacement costs (of convential AA) due to lower treatment capacity/unit versus other absorption strategies, sensitivity to competing ions (silica, sulfate, phosphate, iron, manganese, hydroxyl radical, etc), and the necessity to adjust pH in most domestic well schemes requiring an optimal treatment pH of 5.5 - 6.0 that is not typical in groundwater.

Iron-based media include granular ferric hydroxide (GFH), or other specialty iron-based media used primarily for arsenic removal. Iron-based media is typically generated in a proprietary process and may consist of granules of ferric oxide or ferric hydroxide, iron enhanced AA (FE-AA), or natural minerals impregnated with a substantial quantity of ferric hydroxide. Advantages of IBMs are their effectiveness over a wide pH (6-8.5) and decreased sensitivity to fouling from competing ions noted above. EPA demonstration studies indicate treatment capacities of 10 to 20 fold increase for treatment of arsenic with IBM versus conventional AA.

Aeration and Air Stripping

Aeration or air stripping is the induction of air or the spraying of water through air. Aeration adds oxygen to water for oxidation of iron and manganese or to release dissolved gases such as carbon dioxide or hydrogen sulfide. Air stripping can also be used to treat low levels of nitrate contamination. Because many of the compounds stripped by the air flow may be hazardous air pollutants, the air exiting a stripper may require emissions control using carbon adsorption.

Advantages of aeration and air stripping:

- Relatively simple oxidation for iron and manganese and release of volatiles.
- Capable of treating large amounts of water daily.

Disadvantages of aeration and air stripping:

- Air binding, or air coming out of solution and clogging filters and pipelines, may occur.
- Interrupts direct water flow from well into house and often requires additional infrastructure (storage, filtration and pumping).
- Increases operational complexity.
- Aeration is only partially effective at oxidizing Fe/Mn or hydrogen sulfide below pH 8.

Oxidation Filters

For most domestic well water applications, the most practical treatment for iron and manganese is an oxidation filter. This technology allows direct pressurization from the well pump and does not require continuous chemical feeds of oxidants, pH adjustment, or additional storage and re-pumping. The oxidation filter has the additional benefit of a large particulate holding capacity and is also good strategy if the inlet water has hydrogen sulfide at objectionable odor levels and/or arsenic at levels of concern. The filter substrate is one of the following: natural manganese greensand, manufactured silica gel, zeolite coated with manganese dioxide, plastic resin beads, or pumicite, These substrates are usually coated with a manganese oxide and are typically regenerated by using a potassium permanganate solution. An oxidizing filter supplies oxygen to convert many contaminants (Fe, Mn, H_2S, As) into a solid form which can be filtered out of the water by the filter media. Based on flow and loading, the greensand filter should be backwashed with potassium permanganate to remove solid particles and regenerate (recoat) the greensand to allow adsorption of more dissolved minerals. Synthetic filters, such as zeolite, require less backwash water and soften the water as it removes the iron and manganese. A new, high performing oxidation filter has emerged using mined, finely graded manganese dioxide and has shown great catalytic removal of iron, manganese,hydrogen sulfide, arsenic, and radium. The filteris recharged with a simple, low cost chlorination backwash. For details see: http://www.laynechristensen.com/Our_Services/Water_Technologies/Potable_Water_Treatment/LayneOx.aspx

Water Filters

Perhaps the most common treatment in use is fine sieve filtration. Contaminants are physically prevented from moving through the filter either by screening them out with very small pores and/or, in the case of carbon filters, by trapping them within the filter matrix by attracting them to the surface of carbon particles (the process of adsorption). There are thousands of different models manufactured that implement screening, adsorption, or both strategies. There are two main types of filters (sediment and activated carbon) that in some cases are combined into a single unit.

Sediment Filters

Fiber Filters: These filters contain a porous mesh of cellulose, rayon, or some other material. Suspended sediment is removed as water pressure forces water through the filter. These filters are available in a variety of pore sizes with 1-10 micron nominal pores commonly used. The finer the filter, the more particles are trapped and the more often the filter must be changed. Fiber filters are often used as pre-filters to reduce suspended contaminants that could clog carbon or RO filters. Fiber filters will not remove dissolved inorganic chemical contaminants or organic compounds.

Ceramic Filters: Ceramic filters are similar to fiber filters and use a process where water is forced through the pores of a ceramic filtration medium. This provides mechanical filtration only. This type of filter can decrease asbestos fibers, cysts (if the pores are one micron or less), some bacteria (with pore sizes in the 0.2 - 0.8 micron range), and other particulate matter. Ceramic filters will not remove contaminants that are dissolved in the water or other organic compounds. These filters may be used as pre- or post- filtration to provide a polished final removal of particulates.

Activated Carbon Filters: Activated carbon (AC) is a form of carbon that has been processed to make it extremely porous, resulting in a very large surface area for adsorption of a wide range of contaminants. Two basic types of carbon filters are: Granular Activated Carbon (GAC) and Solid Block Activated Carbon (SBAC).

Contaminant capture in AC filters takes place eitherthrough physical removal of contaminant particles, or adsorption during which a variety of dissolved contaminants are attracted to and held (adsorbed) on the surface of the carbon particles. The characteristics of the carbon material (particle and pore size, surface area, surface chemistry, density, and hardness) influence the efficiency of adsorption. AC filter cartridges become less effective as the pores clog with particles (slowing water flow) and the adsorptive surfaces in the pores become filled with contaminants (typically not affecting flow rate). There is often no noticeable indication that an AC filter is no longer removing contaminants; therefore, it is important to replace the cartridge according to the manufacturer's instructions related to volume or pressures.

Granular Activated Carbon (GAC): With GAC, water flows through a bed of loose activated carbon granules which trap some particulate matter and remove some chlorine, organic contaminants, and undesirable tastes and odors. Simple GAC filters are primarily used for aesthetic water treatment because they can reduce chlorine and particulate matter as well as improve taste and odor of the water. Loose granules of carbon do not restrict the water flow to the extent of Solid Block Activated Carbon (SBAC) filters. This enables them to be used in situations, such as whole house filters, where maintaining good water flow rate and pressure is important. Most dissolved minerals are not removed by activated carbon. GAC filters are effective and valuable water treatment devices, but their limitations always need to be considered. A uniform flow rate, not to exceed the manufacturer's specifications, needs to be maintained for optimal performance, and the filter cartridge must be replaced after treating the number of gallons the filter is rated for. Additionally, Heterotrophic Plate Count (HPC) bacteria can grow in the trapped organic debris and loose carbon aggregate and compromise quality.

Solid Block Activated Carbon (SBAC): Activated carbon is the primary raw material in solid carbon block filters; but instead of carbon granules comprising the filtration medium, the carbon has been specially treated, compressed, and bonded to form a uniform matrix. The effective pore size can be very small (0.5 – 1 micron). SBAC provides a larger surface area and longer contact time for adsorption to take place than GAC filters for better contaminant removal. This combination of features provides the potential for greater adsorption of many different chemicals (pesticides, herbicides, chlorine, chlorine byproducts, etc.) and greater particulate filtration of parasitic cysts, asbestos, etc. than many other purification processes available. SBAC filters, like all activated carbon filters, do not naturally decrease levels of soluble ions. By using other specialized materials along with specially prepared activated carbon, customized SBAC filters can be produced for specific applications or to achieve greater capacity ratings for certain contaminants such as lead, mercury, arsenic, etc. SBAC, like all filter cartridges, eventually become plugged or saturated with contaminants and must be changed according to manufacturer's specifications.

3.2c Treatment Selection and Costs for POU and POE

The overall water quality along with the concentration of the specific contaminant of concern drives selection of a unique scheme (potentially with pre-treatment and post-treatment) and makes comparison of a specific domestic well to the few published POU/POE studies difficult. Nevertheless, it is helpful for general planning purposes to provide a “ballpark” of selection approaches and costs from data gathered directly from vendors and published reports. Domestic well owners may wish to consult with local water treatment companies for product selection and turnkey pricing. “Do-it-yourself” individuals may wish to investigate options and prices at one of many online warehouses such as: http://www.excelwater.com/. Also EPA has produced a helpful guidance document on POU/POE treatment. . See this link for more details: http://www.epa.gov/ogwdw/smallsystems/pdfs/guide_smallsystems_pou-poe_june6-2006.pdf

Once a treatment scheme is selected and installed, routine water testing is highly recommended (using either manufacturer supplied field test kits or laboratory data) to verify effectiveness of treatment.

Competing ions – Many treatments are based on the affinity of a pollutant to sorb/exchange. Presence of competing ions in the inlet water may decrease the ability to remove pollutants. Table 64 includes various competing ions for different treatment technologies.

The following is an overview of likely treatment schemes and costs for more common chemical contaminants in Texas groundwater. Assumptions for POE cost estimates are based on a flow of 360 gallons/household/day with a one year maintenance cycle. POU costs estimates are based on flow of 4 gallons/household/day with a one year maintenance cycle.

POU Arsenic removal as a solo contaminant

Many aquifers in Texas have arsenic as a sole contaminant of concern, particularly the southern Ogallala, southern Gulf Coast, and west Texas aquifers. Previous studies of arsenic in the Ogallala and Gulf Coast aquifers found arsenic in the negatively charged oxidized form (arsenate) which can be removed through treatment. However, in cases where arsenic in aquifers occurs in the reduced state (arsenite), which has a neutral charge and is thus difficult to remove, arsenic should be oxidized to enhance removal. Hence arsenic removal at a domestic well with demonstrated arsenite should always be preceded by chlorination and carry a “free” residual of Cl. Alternatively, an oxidation filter can be used which can both oxidize arsenite to arsenate and then remove the arsenate via adsorption within the same unit. Options for POU removal of arsenic are: oxidation filters, adsorptive media cartridges, ion exchange, reverse osmosis, and distillation. A common and effective approach for POU removal of arsenic is often a selection of one of the many absorptive iron-based media cartridges due to their proven efficiency over a wide pH range and smaller sensitivity to competing ions. POU arsenic removal adsorption media can be saturated prematurely by competing ions, so careful cartridge selection is warranted. IBM such as iron-activated alumina (FE-AA) is less likely to have competing ion interferences and wider pH allowances, plus it can remove some fluoride if that constituent is excessive. An NSF study of arsenic removal efficacy showed FE-AA to have very high volumes of treatment capacity (25,000 bed volumes) before saturation versus 2,500 bed volumes for conventional AA. . For more details see:

http://www.nsf.org/regulatory/conferences/docs/Narasimhan.pdf

When using absorption media, it is recommended to use volume-metered cartridges to assure flow shut-off or alarms when the projected treatment volume of saturation is reached, thus signaling the need for cartridge replacement. An additional conservative strategy when using any absorption media is to install two cartridges in series with a rotation of the freshest unit to the downstream section during scheduled maintenance. This approach insures there is never a spike of excess arsenic load permeating the outlet water when saturation is reached (chromatographic peaking). Routine water testing for arsenic using either manufacturer-supplied field test kits or laboratory data is also highly recommended to verify effectiveness of arsenic removal.

POU Fe-AA cost estimate: Capital ($150-$300), Installation ($100), Annual replacement cartridges $50).

Note—EPA has developed an excellent decision tree to facilitate sound choices of technology for arsenic removal based on the unique quality of the source water. See the following link:

http://cfpub.epa.gov/safewater/arsenic/arsenictradeshow/arsenic.cfm?action=Decide

Removal of TDS and/or combinations of health based inorganic constituents such as Arsenic, Selenium, Fluoride, and/or Nitrate.

Arsenic is frequently found with other oxyanions including selenium and other contaminants derived from volcanic ashes, such as fluoride. Nitrate can also be found with arsenic, mostly from agricultural activities. Wells in the southern Ogallala aquifer and some wells in the southern Gulf Coast aquifer have many of these contaminants combined. When more than one contaminant is present, it is possible to combine two or more treatment schemes together;

however, this can complicate maintenance and increase total treatment costs such as possible re-pressurization equipment and electricity. Consequently, when multiple contaminants are present at levels of aesthetic or health concern, the generally accepted approach is to employ reverse osmosis (RO). Note—EPA also recognizes Distillation as a functional technology to remove multiple contaminants but does not include this in their official control technology list due to small volumes treated and slow water production. Commonly used RO membranes, Cellulose Acetate (CA) and Thin Film Composite (TFC), each have their positives and negatives. CA membranes are usually cheaper and are more chlorine resistant, whereas TFC membranes are more effective for TDS reduction and are recommended for nitrate removal. Thus if TFC is being deployed, it is critical for the carbon pre-filter to be adequately sized to fully remove any chlorine residual. Both CA and TFC units are widely available.

POU RO cost estimate: Capital ($400), Installation ($100), Annual replacement cartridges and maintenance ($100- $150)

POU Nitrate Removal Methods.

Adapted from "Ohio Department of Health, Bureau of Environmental Health, Treatment Technologies for Removing Nitrates in Drinking Water." Costs adapted from "An Assessment of the State of Nitrate Treatment Alternatives, FINAL REPORT, The American Water Works Association, June 2011."

Given the acute health risk posed by high nitrate in drinking water, it is important to have a good understanding of nitrate variability on the inlet water and post treatment. It is prudent to test the water supply water for nitrates periodically because nitrates and levels may fluctuate seasonally. Treatment technologies for nitrate reduction POU and POE systems are IX, RO, and Distillation. Ion Exchange is generally considered more for POE than for POU and requires disposal of concentrated waste brine. RO schemes are the most adopted treatment for nitrate reduction. While distillation is also effective, energy demands and slow water production make it less attractive.

POU RO units used for removing nitrates should use a TFC membrane. TFC membrane units can reduce nitrate by 60 to 95 percent. When nitrate levels exceed 30 mg/L, RO becomes less effective and other alternative treatment systems should be considered. CA membrane units are not recommended for nitrate removal for drinking water.

RO Nitrate Treatment costs Capital ($330- $1,430);nnual filter replacement ($110-$330/yr).

Ion exchange devices are primarily used for whole-house nitrate treatment. They work much the same way a water softener does but use an anion exchange resin that has a preferential affinity for nitrates to exchange chloride for nitrates. Note that when an anion exchange treatment system is used for nitrate reduction, the total combined concentration of nitrates and sulfates in the water must be known. The resins used in nitrate removal systems may have a preferential affinity for sulfate. This means that nitrates that have already been removed from the water will be re-released back into the drinking water in favor of sulfates when the resin has reached capacity. Also, in order to ensure the most efficient reduction of nitrates, a water softener should precede the anion exchange system to reduce the potential for fouling the nitrate selective exchange resin.

IX Nitrate Treatment costs - Capital ($660 - $2,425); Salt costs ($3.30 - $4.40/bag).

Distillation evaporates water and condensed water vapors are collected as drinking water leaving behind non-volatile chemicals such as nitrates or other contaminants. This type of treatment is not economical for whole-house treatment but can be used to treat small amounts of drinking water. One potential problem associated with distillation is that VOCs, if present, might be carried along with the evaporated water and would remain in the treated water.

Distillation Nitrate Treatment costs - Capital ($275- $1,650); Annual scale cleaning cost ($440-$550/yr).

POU Radionuclide Removal

The preferred treatment for a wide range of radionuclides is reverse osmosis (Lesikar et al., 2006a). RO can remove up to 98 percent of radium from groundwater and can decrease levels of uranium, alpha radiation, beta, and photon emitters. Typical capital costs range from $300 - $1,000 plus $110-$330/yr in filter replacement. Distillation can also be used to treat many radionuclides; however, it is generally more expensive. While ion exchange can be used for many radionuclides, disposal of waste residuals in higher POE volumes may be difficult to permit. But if allowed by the local onsite wastewater oversight agency or the POTW, this scheme could be cost effective.

Iron and Manganese Removal

If the total combined iron and manganese concentration is less than 15 mg/L, an oxidizing filter is a great option because the direct pressure unit does not require additional storage, pumps, pH adjustment, or inlet chlorination for oxidation.

POE oxidizing filter cost estimate: Capital ($1,000); Installation ($100-$300); annual permanganate regenerant ($1,000- $1500).

Disposal of domestic POE/POU waste residuals

The residuals that can be generated by the POU or POE devices include the following:

▪ Solid residuals, such as spent cartridges, media, resin, membranes, bulbs, and filters that require disposal at the end of their useful life, and

▪ Liquid waste streams. These will be generated by POU RO systems and POE IX, GAC, and adsorptive media systems if backwashed or regenerated. POU RO units produce a residual brine which is characterized by high contaminant concentrations. Backwashing and regeneration, required for proper operation of most POE IX, GAC, and adsorptive media treatment devices, will also result in the generation of intermittent liquid waste.

Because the residuals generated by POU and POE units installed in residences are collected from individual households, these wastes are exempt from Federal regulations as hazardous wastes under RCRA. However, State regulations and each State's implementation of Federal regulations can vary. In Texas, the TCEQ's Municipal Solid Waste Division recommends solid residuals produced by these treatment systems be disposed of like normal household waste and delivered to a local landfill or regenerated. Liquid residuals may usually be discharged to POTWs (upon approval from the POTW), or on-site wastewater systems which may require an authorization from the local permitting agency but in most cases is volume exempted from additional permits.

POU and POE devices in commercial installations may also be exempt from Resource and Conservation Recovery Act provisions if the quantity of waste generated is considered small (defined in 40 CFR Section 261.5 as generating no more than 100 kilograms of hazardous waste in that month).

Conclusions

The high risk category of primary MCL exceedance represents 18 percent of the total aquifer area and 14 percent of the total aquifer volume in Texas. Many aquifers are affected by multiple contaminants and the aquifer areas and volumes at high risk of any MCL exceedance are greater than those for individual MCL constituents. Primary MCL exceedances in the high probability category for major aquifers are greatest for the Hueco Mesilla Bolson, Seymour, and Ogallala aquifers and lowest for the Edwards (BFZ) Aquifer by both aquifer area and volume. Primary MCL exceedances in the high probability category for minor aquifers are greatest for the Hickory, Lipan, and Edwards Trinity (High Plains) aquifers and lowest for the Nacatoch, Queen City, and Sparta aquifers by both aquifer area and volume. The most widespread high probability category contaminant in major aquifers is arsenic, followed by fluoride, alpha radiation, nitrate-N, and combined radium. The most widespread high probability category contaminant in minor aquifers is combined radium, followed by arsenic, fluoride, alpha radiation, and nitrate-N by aquifer area and combined radium, followed by fluoride, arsenic, alpha, and nitrate-N by aquifer volume. The dominant secondary MCL exceedance for all aquifers is total dissolved solids.

Radionuclide MCL exceedances are widespread in major aquifers, including the Ogallala, Edwards-Trinity (Plateau), Gulf Coast, Pecos Valley, and Seymour aquifers. Gross alpha MCL exceedances are found in all these aquifers; however, analyses for radium and uranium are generally limited in many aquifers. Radionuclide exceedances are also widespread in the Dockum Aquifer attributed to uranium in the rocks and in the minor aquifers surrounding the Llano Uplift, particularly the Hickory and Ellenburger-San Saba aquifers, in which high levels of radionuclides are attributed to Precambrian rocks in the Llano Uplift. Percent of arsenic MCL exceedances increased markedly with reduction of the MCL from 50 to 10 μg/L. Arsenic contamination is highest in the Ogallala, Gulf Coast, Edwards Trinity (High Plains), Hueco-Mesilla Bolson, Igneous, and West Texas Bolsons aquifers and is geologic in origin originally derived from volcanic ashes and from igneous rocks. Widespread nitrate contamination is highest in the Seymour and Lipan aquifers with 67 and 61 percent nitrate MCL exceedances, respectively. Nitrate contamination also occurs in many other major aquifers (Pecos Valley, Ogallala, Edwards-Trinity Plateau) and minor aquifers with up to 15 percent MCL exceedances. Much of the nitrate in the High Plains and Seymour aquifers is derived from oxidation of soil organic nitrogen that was mobilized at the beginning of cultivation. Fluoride has both primary (4 mg/L) and secondary (2 mg/L) MCLs. Much higher fluoride secondary MCL percent exceedances relative to primary MCL exceedances, particularly in the Ogallala and Pecos

Valley major aquifers and some minor aquifers, indicate that if the fluoride MCL is reduced from 4 mg/L to 2 mg/L, MCL exceedances would increase from 4 to 47 percent in the Ogallala Aquifer and by lesser amounts in other aquifers.

The impact of water quality on groundwater quantity was evaluated by aquifer using the probability of any primary MCL exceedance categorized as low (0 – 40 percent probability), moderate (40 – 60 percent) and high (60 – 100 percent). The major aquifer with the highest percent volume of groundwater with any primary MCL exceedance in the high probability category is the Hueco-Mesilla Bolson Aquifer (47 percent), followed by the Seymour (26 percent), Ogallala and Pecos Valley (14 percent each), and Gulf Coast (10 percent) aquifers. The remaining primary aquifers had <10 percent by volume with exceedances in the high probability category. Primary MCL exceedances in the moderate category by aquifer volume were highest for the Edwards (BFZ) (45 percent), Seymour (31 percent), Gulf Coast (23 percent), and Edwards-Trinity Plateau (19 percent) aquifers. These volume percentages assume that the spatial distribution of exceedance probabilities from the well data can be projected with depth to the base of the aquifer. Major aquifers exceeding the secondary TDS MCL with the largest water volumes in the high probability category include the Pecos Valley (73 percent) and the Hueco-Mesilla Bolson (33 percent) aquifers. All other major aquifers have 17 percent or less water volume in the high probability of exceedance category for TDS.

The impacts of groundwater quality on groundwater quantity were also evaluated by major aquifer within each RWPA. The greatest percentages of aquifer volume in the high risk category are in Region F (50 percent), Region O (44 percent), and Region M (41 percent). The lowest percentage of aquifer volumes in the high risk category (≤ 5 percent) are in Regions A, C, D, G, H, I, J, and L.

Because private well owners are not regulated under the Safe Drinking Water Act, various point of entry (POE) and point of use (POU) water treatment options for the dominant contaminants in aquifers in the state. Reverse osmosis and distillation apply to most of the contaminants; however, concentrations of competing ions are high in many aquifers which would interfere with the treatment. An absorptive iron based media cartridge is suggested as a widely efficient scheme for arsenic removal due to high volume efficiency over a wide pH and smaller sensitivity to competing ions. Areas such as the southern Ogallala Aquifer that has multiple contaminants, including arsenic, fluoride, nitrate, and selenium, should be treated with reverse osmosis. Different types of membranes can be selected to optimize treatment. The preferred and most commonly used approach for nitrate treatment is also reverse osmosis. Although a variety of techniques can be used to treat radionuclides, reverse osmosis can be used to treat radium, uranium, alpha and beta emitters. Ion exchange can also be used but may be problematic because of disposal of residual wastes. Oxidation filtration is recommended for treating iron and manganese contamination, which is widespread in the Carrizo-Wilcox Aquifer. In most contaminant removal cases, POU systems are sufficient; however, POE systems would be required for iron and manganese and possibly some radionuclides.

The primary product from this study is the probability maps of exceeding any primary MCL in major aquifers in the state. The approach developed in this study can be applied to assessing suitability of groundwater for irrigation purposes in future studies. More extensive evaluation can be conducted on secondary MCL exceedances. This study highlights aquifers with limited data that should be targeted for future sampling. The results of this analysis should prove useful in groundwater planning in the state.

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