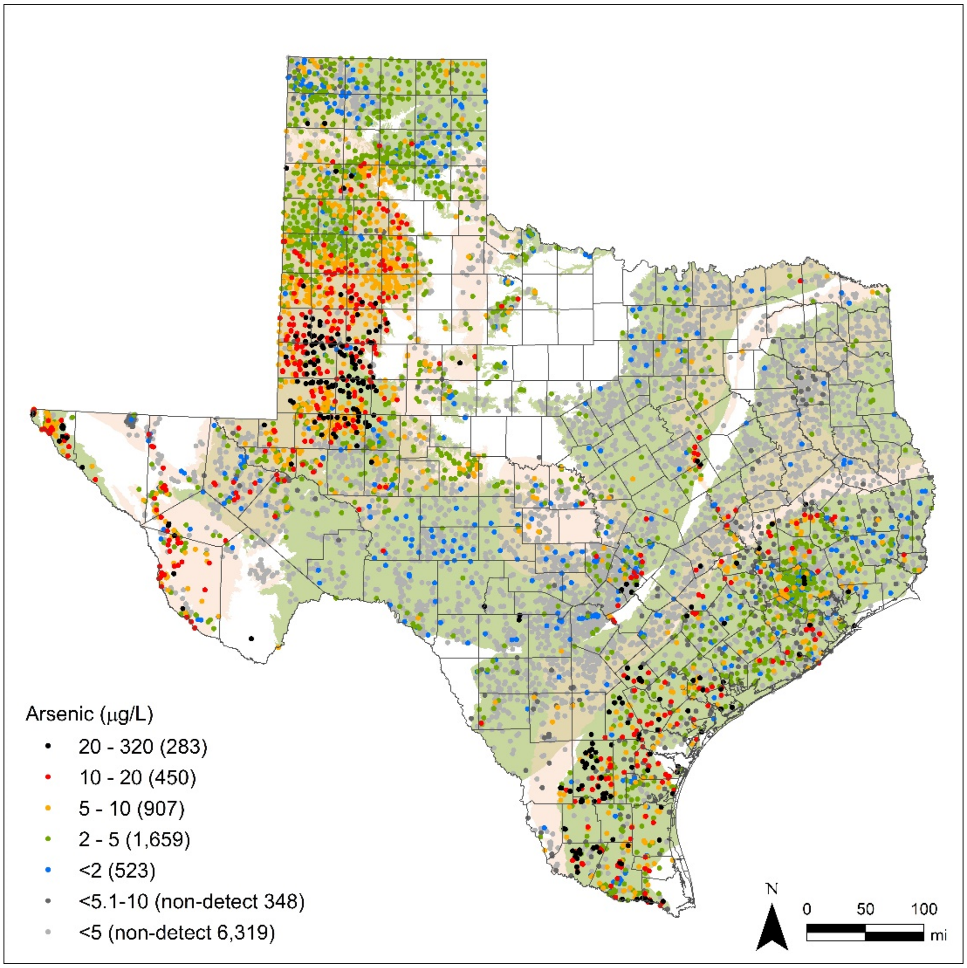
Assessment of Arsenic in Groundwater and Water Supply Systems in Texas



by

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Executive Summary

Understanding the spatial distribution of elevated groundwater arsenic levels is a critical issue because of adverse health effects of arsenic. Many previous studies indicate that elevated arsenic concentrations in groundwater primarily originate from natural geologic sources. The objective of this study was to quantify the distribution of groundwater arsenic in the major aquifers in Texas and assess linkages to populations using this water. Groundwater arsenic data were compiled from 10,489 wells sampled between 1992 and 2017. The spatial distribution of elevated arsenic concentrations was mapped by aquifer using indicator kriging based on two threshold concentrations: 5 μg/L representing nominal background concentration and 10 μg/L representing the EPA Maximum Contaminant Level (MCL). The current number of non-compliant PWS systems and associated populations were obtained from EPA listings and the estimated populations with non-compliant non-PWS system water (domestic/self-supplied systems) were obtained from the U.S. Geological Survey water use data.

Results show that a total of 733 samples exceeded the arsenic MCL of 10 μg/L, representing 19% of all analyses with detectable arsenic and 7% of all samples used in this study and 6,667 samples (64% of all samples) were below the detection limit. The remaining samples with detectable arsenic levels (3,822 samples, 36% of all samples) have a median concentration of 4.3 μg/L arsenic. The range of arsenic concentrations is fairly narrow.

The majority of the population has access to PWS systems (26.2 million in 2015; 95% of the total population of 27.5 million) with a much lower number of people relying on domestic or non-PWS supply systems (1.3 million, 5% of total population). A total of 7.7% of samples (671 samples) from major aquifers exceeded the arsenic MCL of 10 μg/L. The highest concentrations are found in the southern Gulf Coast, southern High Plains, and the Trinity aquifer. A total of 78 PWS systems were non-compliant in terms of arsenic with an associated population of almost 100,000. The most affected populations are located in the southern Gulf Coast area (Gulf Coast aquifer, 25 systems with 43,141 people), the general Waco metropolitan areas (Trinity aquifer, 12 systems with 40,226 people), and large areas of the High Plains region (Ogallala aquifer, with 37 systems, 14,860 people). While the State has been making considerable progress towards bringing PWS systems into compliance, there are still a number of non-compliant PWS. The domestic population at risk from arsenic contamination (about 81,500 people) is similar to the PWS population at risk in non-compliant systems (~100,000 people). There are a variety of approaches for managing arsenic contamination in small PWS systems, including point of entry and point of use systems.

Introduction

Arsenic (As) contamination in groundwater is a widespread problem in the U.S. (Nordstrom, 2002 Smedley and Kinniburgh, 2002; Welch and Stollenwerk, 2003). The maximum contaminant level (MCL) for arsenic was reduced from 50 µg/L to 10 µg/L in 2001 with water systems being required to comply with the standard in January 2006 (USEPA, 2018). This regulation applies to public water systems; however domestic wells (privately owned) are not regulated. A recent analysis evaluated the domestic well population vulnerable to arsenic contamination in the U.S. (Ayotte *et al.*, 2017). This results of this study indicate that an estimated 2.1 million (M) people out of a population of 44 M people using domestic wells in the U.S. are using groundwater water arsenic exceeding 10 µg/L. Texas ranks 7th in terms of domestic population impacted by arsenic contamination, with ~95,000 people affected. This study used logistic regression with 42 variables used as proxies for arsenic, including climate, groundwater recharge, soil properties, and geologic variables etc.

Groundwater arsenic levels exceeding the MCL are considered a health hazard. The form of arsenic determines the health impacts. Inorganic forms or arsenic are ~100 times more toxic than organic forms and trivalent arsenite is ~60 times more toxic than hexavalent arsenate (Kain and Ali, 2000). The primary exposure pathway for humans is in food; however, organic forms of arsenic in food negligible toxicity (Abernathy et al., 2003). Long-term exposure to arsenic from drinking-water has been linked to cancer, skin lesions, cardiovascular disease, and diabetes. Long term exposure to arsenic in groundwater is also linked to skin, lung, bladder, kidney, and liver cancers. Arsenic can also cause various noncancerous diseases, including hypertension, diabetes, skin lesions, and hyperkeratosis of hand and feet (Tseng et al., 2000). In utero and early childhood exposure has been related to impairment of cognitive development and higher mortality in young adults (Farzan *et al.*, 2013; Tolins *et al.*, 2014). Arsenic is routinely added to chicken feed to make chickens more robust (Rutherford et al., 2006). Arsenic is associated with coal burning in China. Lesikar et al. (2006) also reviewed health effects of arsenic relative to Texas aquifers.

Previous studies in Texas examined the distribution of naturally occurring contamination in major and minor aquifers in the State quantifying exceedances of U.S. Environmental Protection Agency (EPA) primary and secondary maximum contaminant levels (MCL) for drinking water (Reedy et al., 2011). An estimated 14% of the aquifer volume in the state was estimated to be in the high risk category of primary MCL exceedance. Any primary MCL exceedance in the high probability category is greatest for the Hueco-Mesilla Bolson, Seymour, and Ogallala aquifers and lowest for the Edwards (BFZ) Aquifer by both aquifer area and volume. Arsenic was found to be the most widespread contaminant in the high probability category in major aquifers, followed by fluoride, alpha radiation, nitrate-N, and combined radium.

It is important to understand the processes affecting groundwater arsenic levels. Although arsenic is widely distributed in rocks, mobilization of arsenic into groundwater is often the limiting factor to the occurrence of elevated arsenic levels in groundwater (Smedley *et al.*, 2002). Critical factors related to the distribution of elevated groundwater arsenic levels include

(1) An arsenic source
(2) A process for mobilizing arsenic into groundwater
(3) Low recharge rates limited arsenic flushing in aquifers

Previous studies have identified important factors for delineating aquifer vulnerability to arsenic contamination (Smedley *et al.*, 2002). Environments with elevated groundwater arsenic levels include (1) low temperature (1a – non-mining; 1b – mining) and (2) high temperature (geothermal) settings, with low-temperature, non-mining areas having the most widespread distribution of high arsenic (Smedley and

Kinniburg, 2002). Mobilization mechanisms in these non-mining areas include (1) dissolution of and desorption from Fe oxides in reducing conditions and (2) mineral weathering and evaporation and desorption from Fe oxides and in oxidizing conditions (Smedley *et al.*, 2002). An example of processes operating in oxidizing conditions is shown by aquifers in Argentina which have a high influx of arsenic influx from volcanic glass dissolution, followed by arsenic adsorption onto hydrous Fe or Al oxides, and then mobilization related to elevated pH (8–9) related to mineral weathering (Smedley *et al.*, 2005; Bhattacharya *et al.*, 2006). Previous studies have identified elevated concentrations of arsenic in the southern High Plains (SHP) aquifer in Texas (Nativ and Smith, 1987; Nativ, 1988; Hudak, 2000). This region falls into the low temperature, non-mining area in the classification of Smedley and Kinniburgh (2002). Groundwater is under oxidizing conditions based on O_2 (DO), NO_3, and SO_4 levels. High arsenic levels were originally attributed to application of arsenical pesticides to defoliate cotton because of the spatial coincidence of elevated groundwater arsenic and cotton production areas, higher arsenic levels in groundwater in shallow water table areas, and linkages with other contaminants related to agriculture, such as nitrate (Nativ, 1988; Hudak, 2000). Later studies that involved intensive drilling of the unsaturated zone and sampling of soil profiles and chemical analyses, show that water-extractable arsenic from application of pesticides is limited to the zone near the land surface (60 cm) and is also linked with elevated PO_4 levels from application of fertilizers (Reedy *et al.*, 2007). Elevated arsenic levels > 3 ft depth beneath native rangeland and cropland regions are attributed to a geologic source because native rangelands were never subjected to pesticide applications and elevated PO_4 levels were not found at depth beneath native rangeland and cropland settings.

Detailed studies of groundwater arsenic contamination have been conducted in hot spots of arsenic contamination in Texas, including the southern High Plains and southern Gulf Coast regions (Gates *et al.*, 2011; Scanlon *et al.*, 2009). In the southern High Plains, almost 50% of the analyses were found to have arsenic levels exceeding the MCL. Contamination with arsenic was linked to F, V, Se, B, Mo and SiO_2 suggesting a common origin in volcanic ashes, which are found in the southern High Plains and assumed to originate from the Rocky Mountains to the west. The sequence of processes is thought to be leaching of ashes occurring early on, followed by arsenic adsorption on hydrous metal oxides throughout the southern High Plains, as shown by high correlations between arsenic and other anion such as F and oxyanion forming elements such as V, Se, B and Mo (Scanlon *et al.*, 2009). In oxidizing systems, such as the southern High Plains, the most widespread mechanism for mobilizing arsenic is increased pH associated with increased TDS; however, pH in the southern High Plains is near neutral; therefore, this mechanism is not causing arsenic mobilization. The data indicate that arsenic mobilization through the southern High Plains Aquifer is likely attributed to the counter-ion effect related to a water chemistry change from Ca- to Na-rich water, associated with upward migration of groundwater with high Na and high TDS from the underlying Dockum aquifer. This explanation is supported by the correlation between arsenic and $Na/(Ca)^{0.5}$ ratios in the aquifer ($r = 0.57$). This counter-ion effect is likely responsible for mobilizing other ions as evidenced by high correlations between arsenic and these elements (F, $\rho = 0.56$; V, $\rho = 0.88$; Se, $\rho = 0.54$; B, $\rho = 0.51$; Mo, $\rho = 0.46$ and SiO_2, $\rho = 0.41$).

Detailed studies were also conducted in the southern Gulf Coast hotspot of arsenic contamination (Gates *et al.*, 2011). Concentrations of arsenic were found to decrease downdip from the Catahoula Formation, consistent with Miocene volcanic ash in this unit being the primary source of groundwater arsenic in the region. Correlations between arsenic and V, SiO_2 and K were found to be high, attributed to weathering of volcanic sediments. The aquifers are characterized by circum-neutral pH and oxidizing conditions, typically associated with immobilization of arsenic by adsorption of arsenate onto Fe oxides and clays. However, water in ~30% of the wells had arsenic levels exceeding the MCL. High levels of Si co-released with arsenic may compete for sorption sites and decrease the arsenate adsorption capacity.

The objectives of this study were to evaluate the distribution of arsenic in the major aquifers in Texas, considering two threshold levels, 5 µg/L and 10 µg/L (MCL). Indicator kriging was used to evaluate the probability of exceeding these threshold values in the aquifers. The probability of exceeding these thresholds was linked to the population being served by these water sources to determine the vulnerability of the population to elevated arsenic levels. This study builds on previous studies that examined groundwater contamination from a variety of natural sources (Reedy *et al.*, 2007) and detailed process studies examining unsaturated zone and groundwater arsenic levels in the southern High Plains and southern Gulf Coast aquifers (Gates *et al.*, 2009; Reedy *et al.*, 2007; Scanlon *et al.*, 2009).

Methods

Data Sources

Data on groundwater arsenic concentrations for this study were obtained primarily from two sources: the Texas Water Development Board (TWDB) groundwater database and the Texas Commission of Environmental Quality (TCEQ) public water supply (PWS) database. Samples in the TWDB database contain water analyses sampled from groundwater well-heads prior to any treatment processes and the results are accepted as representative of groundwater conditions at that location at the time of sampling. In contrast, the PWS database contains both well-head samples and samples obtained from various locations in the water distribution system. In the initial analysis for this study, only PWS database groundwater well-head samples were used (samples attributed as "raw" water in the database) because samples obtained from locations within the distribution system might reflect post-treatment conditions.

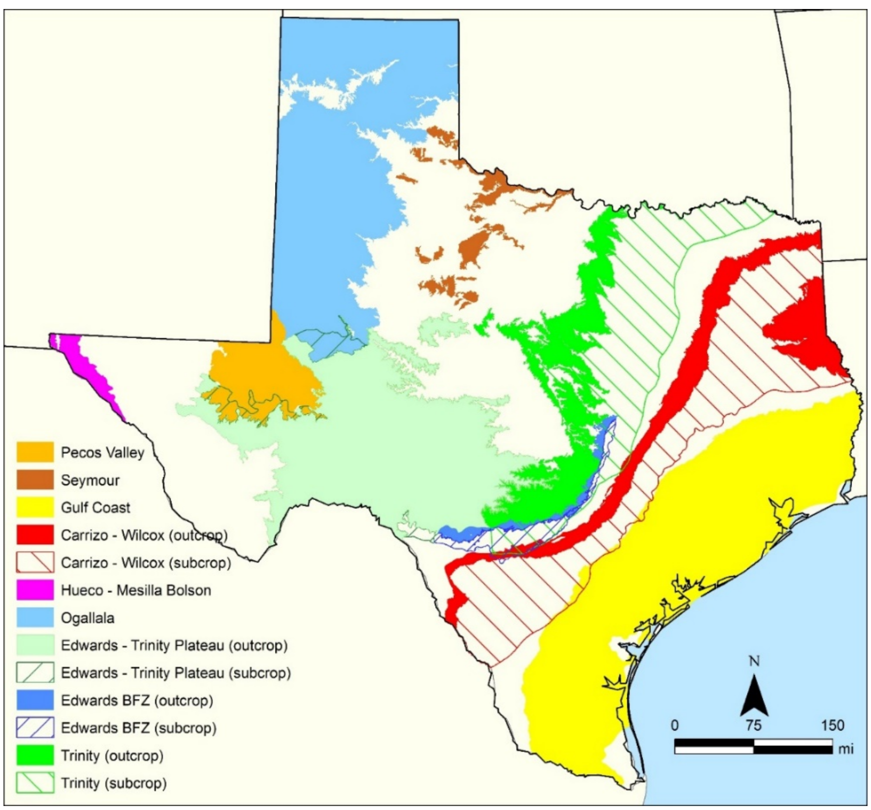


Figure 1. Major Aquifers of Texas.

The source aquifer for pumped water is identified for all groundwater wells in both databases. Only samples from wells that were completed in a single aquifer, which represent 98% of all samples, were used in this study. The aquifers represented in this study include the nine major aquifers (Figure 1) and 21 minor aquifers (Figure 2) identified and named by the TWDB. Sample data from the PWS and TWDB databases were compared to avoid duplication.

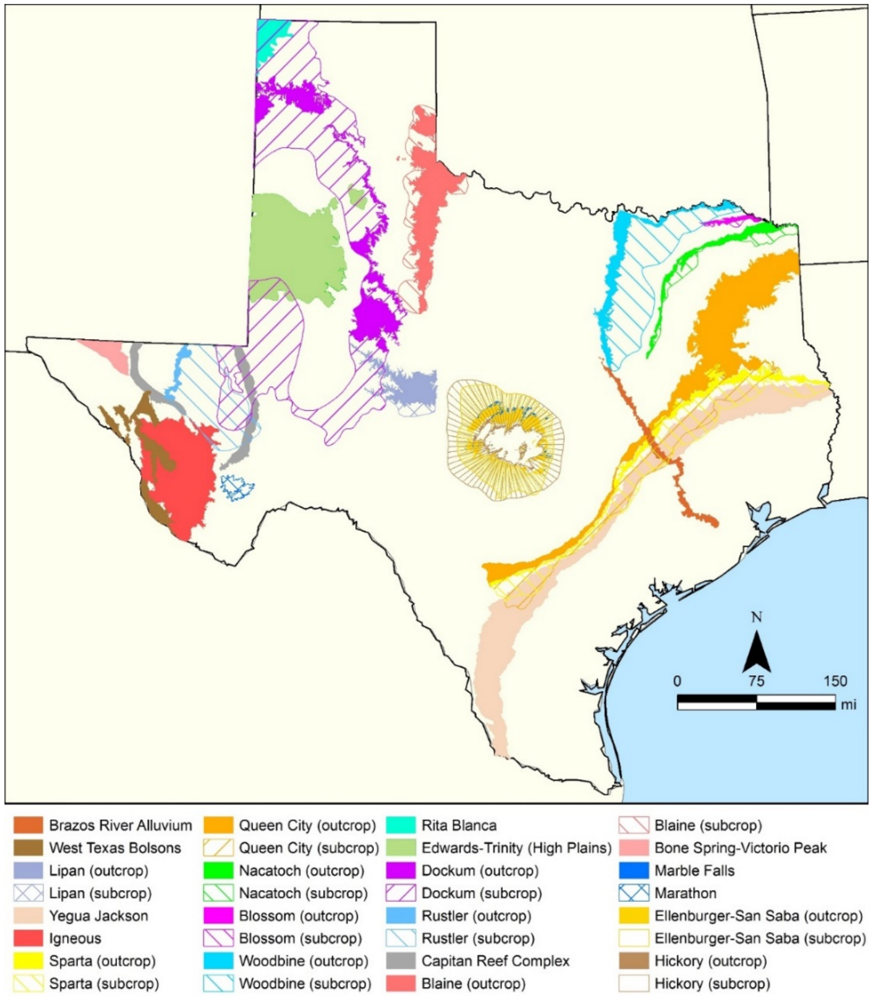


Figure 2. Minor Aquifers of Texas. There are 22 aquifers on the list. The Cypress aquifer was recently removed from the list and a newly defined minor aquifer, the Cross Timbers, was added to the list in August 2017. However, the Cross Timbers is not included in this study as there are no water quality data available.

Due to technological improvements in analytical precision and corresponding lower detection limits, only samples obtained during or after 1992 were used in this study, excluding analyses prior to 1992. Only the latest sample from a given well was used in this study. Arsenic concentrations are reported in units of micrograms per liter (µg/L). Analytical detection limits for arsenic varied based on the laboratory and method used. Analytical results for samples with undetectable arsenic concentrations are deemed "non-detects" and results are shown with the "<" symbol followed by the method detection limit.

Samples from 10,489 groundwater wells in Texas are represented in this study (Figure 3). Among these are 6,667 samples with arsenic concentrations below the various method detection limits, representing 64% of all samples (Figure 4). The highest non-detect concentration level included in this study is equal to the US Environmental Protection Agency (EPA) drinking water Maximum Contamination Level (MCL) of 10 µg/L, representing 340 samples, or ~3% of all samples. A small number of samples with detection limits above the MCL were rejected. Most of the non-detect samples (6,026, 57% of all samples) have a detection limit of 2 µg/L.

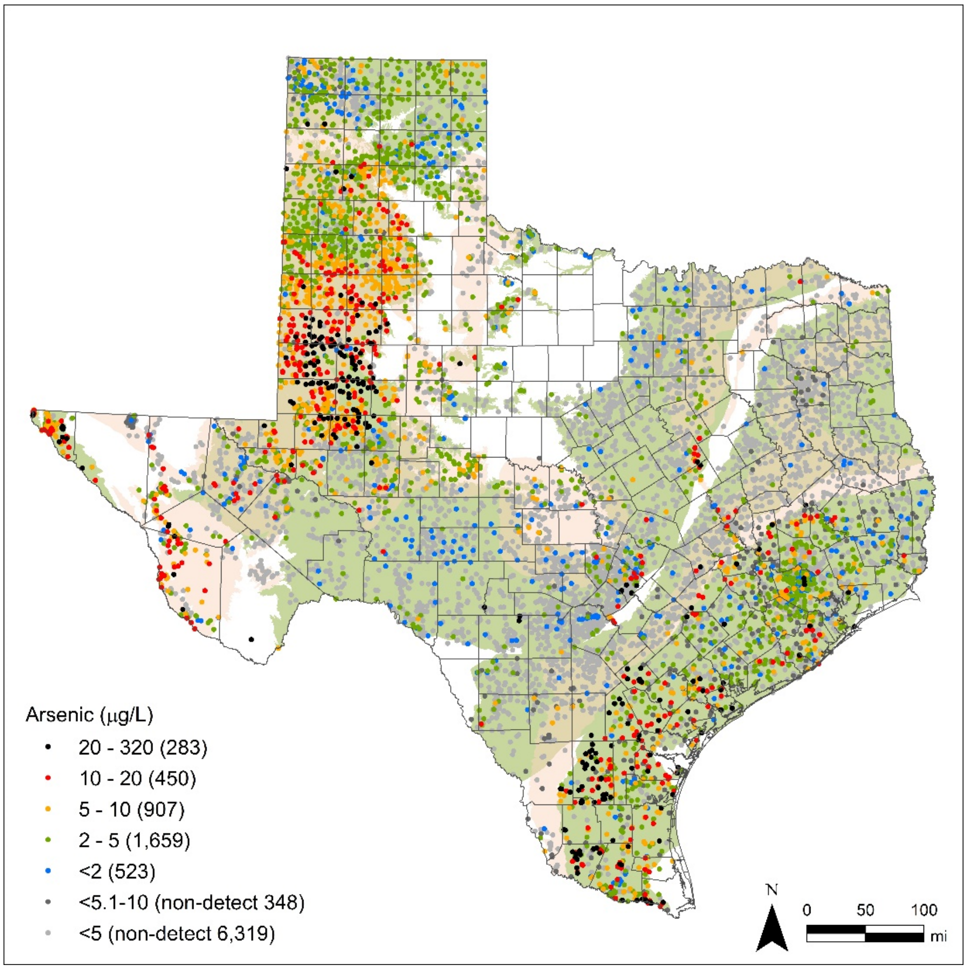


Figure 3. Spatial distribution of groundwater arsenic concentrations in Texas groundwater, including samples collected from 1992 – 2017 with detected concentrations (<2 – 320 µg/L) and non-detected concentrations (<5 and <10 µg/L). The numbers of samples within the stated concentration ranges are shown in parenthesis and include some samples that are not in a named major or minor aquifer and not used in this study.

The remaining 3,823 samples had arsenic concentrations above the various method detection limits, representing 36% of all samples (Figure 5). Of these, the median concentration is 4.3 µg/L and 733 samples exceeded the 10 µg/L MCL concentration, representing 19% of detected concentrations and 7% of all the arsenic data in this study.

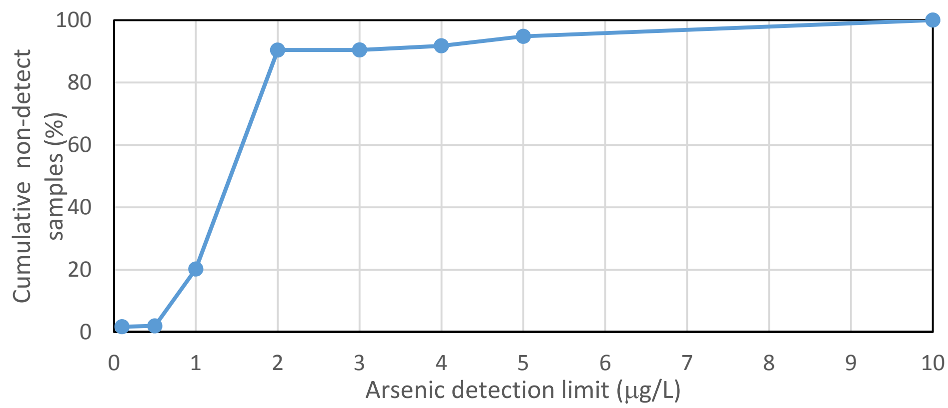


Figure 4. Distribution of arsenic analytical non-detect concentrations used for this study.

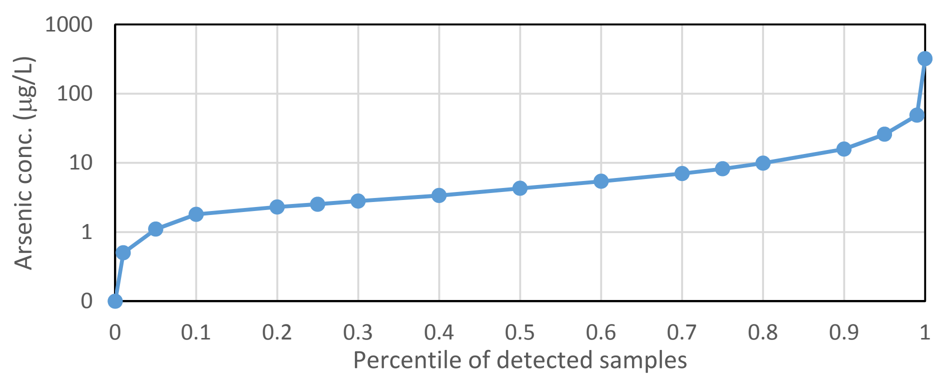


Figure 5. Distribution of arsenic analytical detect concentrations in the data set used for this study.

Data Analysis

Arsenic concentrations were evaluated by aquifer for both statistical and spatial distributions. Statistical analyses include simple determinations of the numbers of samples, numbers of non-detects, the mean, minimum and maximum concentrations, and selected percentile concentrations. The Geostatistical Analyst extension in ArcMap 10.3 was used to generate maps representative of the arsenic spatial distribution in the different aquifers. Indicator kriging was used as this method can incorporate the non-detect data as well as the detect data. It also has the advantage that no assumptions are made regarding normality of the underlying (and unknown) distribution of the concentration data.

Indicator kriging does not result in a concentration map. Rather, the output is a map of the estimated probability that arsenic concentrations exceed a selected threshold value. Two threshold values were used. A lower threshold of 5 µg/L representing a conservative estimate to identify areas where the likelihood that groundwater arsenic concentrations exceed “background”.

A higher threshold value of 10 µg/L was used to identify areas where the likelihood that groundwater arsenic concentrations exceed the MCL for drinking water. Maps were generated for both threshold values for each aquifer having sufficient data points to warrant application of the method. As a general rule-of-thumb, it is desirable to have 100 or more data points and 50 is considered the minimum required to obtain a statistically stable and meaningful result using kriging methods, with consideration further given to the spatial distribution of points within the modeled area. There were sufficient data for all 9 of the major aquifers while there were sufficient data for only half (11) of the minor aquifers.

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

The resulting maps depict the estimated spatial distribution of the probability or likelihood of exceeding the threshold value on an integer scale between 0% and 100%. For this study we characterized the probability ranges using seven categories with descriptive terms, including none (0%), very low (<10%), low (10-25%), moderate (25-50%), elevated (50-75%), high (75-90%), and very high (>90%). The maps should be interpreted in part with consideration given to the spatial distribution of the underlying data as data may be clustered in some areas and relatively sparse elsewhere. Some artifacts may be present in the maps that arise primarily from low data density in given subareas and/or from (directional) anisotropy in the underlying semi-variogram structure.

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

At Risk Population Estimates

A separate assessment was performed to estimate the various populations at risk of exposure to arsenic concentrations both above nominal background and above the MCL. The analysis focused on two general classes of water supply systems that were assessed separately, including 1) public water supply systems that are regulated by the TCEQ and 2) domestic or otherwise self-supplied systems that are not regulated.

Public Water Supply Systems

Public water supply (PWS) systems in Texas are regulated by the TCEQ and ultimately by the US EPA and must provide distribution system water sample analyses to monitor system performance with regard to various potential contaminants of concern, including arsenic. Sample data from the TCEQ database were assessed to estimate the at-risk PWS populations for arsenic concentrations in excess of the nominal background level (> 5µg/L) in the distribution systems. These assessments are based on whether the PWS system had least one distribution water sample with > 5µg/L during the period from January 2012 through about July 2017.

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

Public Water Supply System Type

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

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

Compliance Status

- *"Serious Violator*
    - *'Yes' indicates a public water system with unresolved serious, multiple, and/or continuing violations that is designated as a priority candidate for formal enforcement, as directed by EPA's Drinking Water Enforcement Response Policy.*
    - *EPA designates systems as serious violators so that the drinking water system and primacy agency will act quickly to resolve the most significant noncompliance. Many public water systems with violations, however, are not serious violators. Operators and the primacy agencies are expected to correct the violations at non-serious violators as well, but without the more strict requirements and deadlines applicable to serious violators. If the violations at a non-serious violator are left uncorrected, that system may become a serious violator. When a serious violator has received formal enforcement action or has returned to compliance, it is no longer designated a serious violator. EPA updates its serious violator list on a quarterly basis.*
- *Health-Based Violations*
    - *Violations of maximum contaminant levels (MCLs) or maximum residual disinfectant levels (MRDLs), which specify the highest concentrations of contaminants or disinfectants, respectively, allowed in drinking water; or of treatment technique (TT) rules, which specify required processes intended to reduce the amounts of contaminants in drinking water. MCLs, MRDLs, and treatment technique rules are all health-based drinking water standards."*

Compliance Points

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

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

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

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

Non-Public Water Supply Systems

Domestic and self-supplied systems are not regulated by the TCEQ. These systems are generally located in rural areas or are otherwise not connected to a regulated PWS system and are referred to in this study are non-PWS systems. Estimates of the at-risk non-PWS population were made by aquifer using the kriging probability maps discussed earlier coupled with estimates of the non-PWS county populations from the United States Geological Survey (USGS, 2015, https://water.usgs.gov/watuse/). The spatial mean probability of exceeding the 10 µg/L MCL threshold value was estimated for each unique aquifer-county area using the GIS probability maps. The spatial means were then multiplied by the non-PWS populations for each county to obtain initial estimates of the at-risk populations. The initial estimates were finally adjusted to remove populations in county areas not underlain by the given aquifers. The final county results were summed across each aquifer.

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

Results

PWS and Non-PWS system populations

The total population of Texas increased by a factor of about 3 between 1960 (9.6 million) and 2015 (27.5 million) and further to a present population of approximately 28.3 million in 2018 (Figure 6). The percentage of the population served by PWS systems has varied between about 80-95% during that time and was 26.2 million in 2015 (Table 2). The population served by non-PWS systems generally fluctuated between about 0.9 to 2.7 million people during that time and was estimated to be 1.3 million in 2015. As a percentage of the total population, the non-PWS population ranged from 10% to 22% between 1960 and 1980 and decreased to 5% to 10% afterwards.

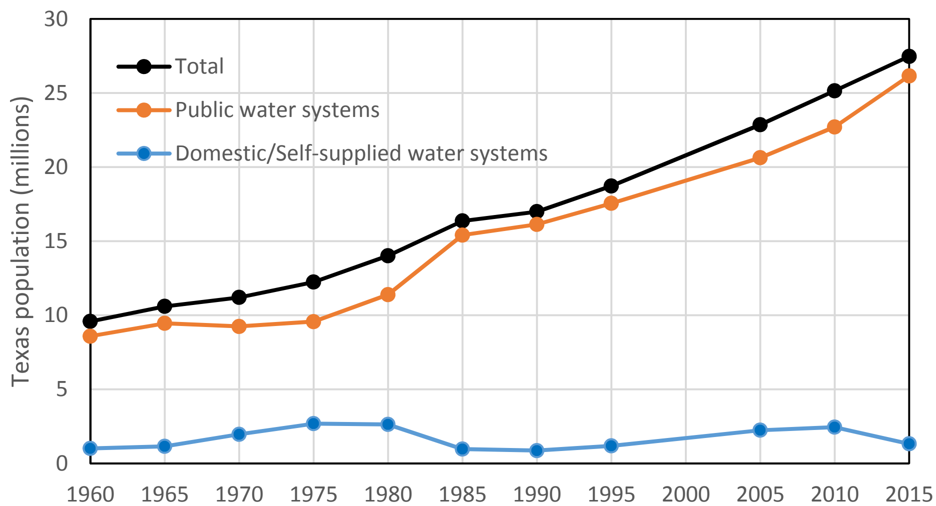


Figure 6. Historical evolution of Texas population relying on Public (PWS) vs Domestic/Self-supplied (non-PWS) water systems (USGS, https://water.usgs.gov/watuse/data/).

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

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

General Results

Fully 81% of the groundwater arsenic concentration data in this study (8,501 samples) are at or below the 5 µg/L threshold while 7% (733 samples) had arsenic concentrations above the 10 µg/L MCL threshold. Most of the data are from the nine major aquifers (8,717 samples), representing 83% of the data. The remaining 17% are from the 22 minor aquifers (1,772 samples).

Among the major aquifers, there were 671 samples with arsenic > 10 µg/L and all of the major aquifers had at least one sample above the MCL (Figure 7). The Hueco-Mesilla Bolson had the greatest percentage of samples exceeding the MCL (30%), followed by the Ogallala (18%), Gulf Coast (12%), and Pecos Valley (5.7%) aquifers. The remaining major aquifers had from 0.1% to 1.6% of samples above the MCL.

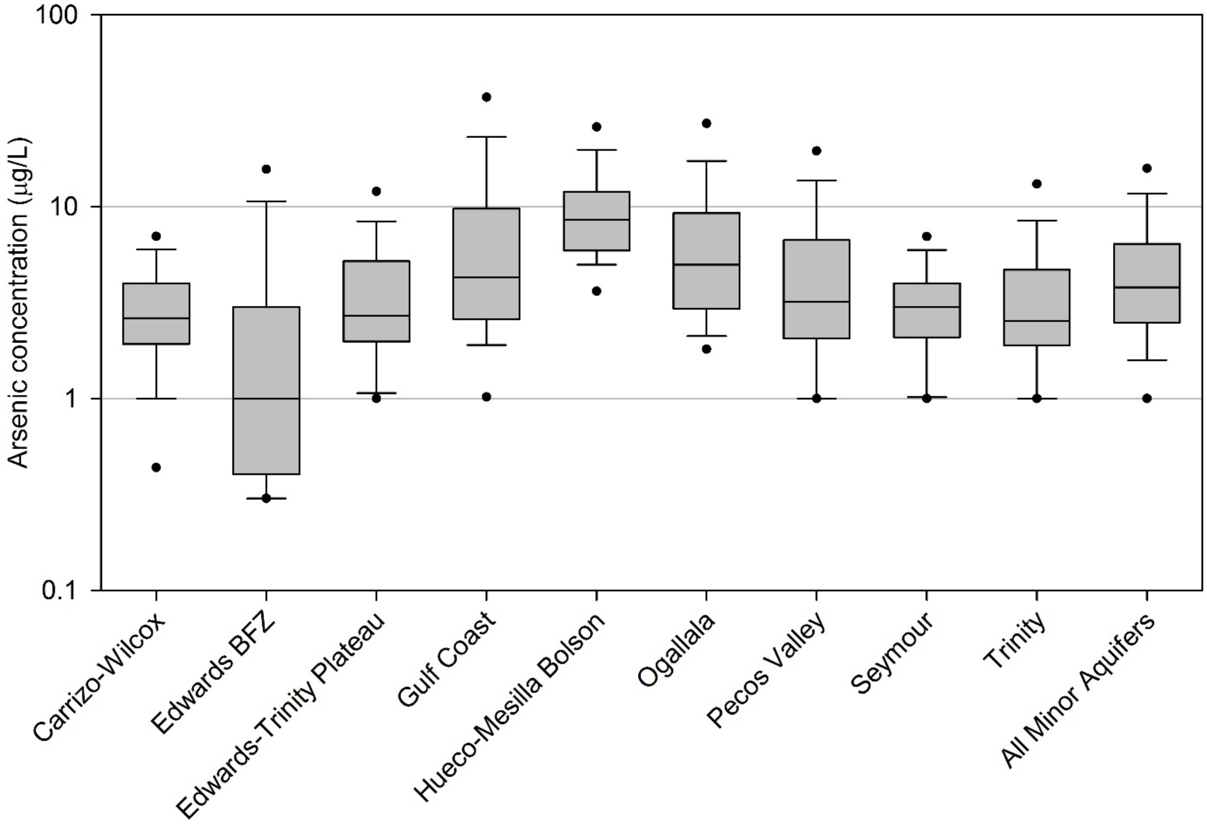


Figure 7. Distribution of detected groundwater arsenic concentrations in the individual major aquifers (3,328 samples, 87% of data) and in the combined minor aquifers (494 samples, 13% of data) of Texas. The lines inside the shaded boxes represent the 50th percentiles (medians), the shaded boxes represent the 25th to 75th percentile ranges, the upward and downward lines extending from the boxes are terminated by horizontal lines at the 10th and 90th percentiles, and the points represent the 5th and 95th percentiles.

Among the minor aquifers, there were 62 samples (3.5%) with arsenic > 10 µg/L and nine of the minor aquifers had samples above the MCL. The data are generally sparse among the minor aquifers, with the numbers of samples ranging from 14 (Rita Blanca) to 294 (Dockum) and eleven aquifers have fewer than 50 samples. The Edwards-Trinity High Plains had the greatest percentage of samples exceeding the MCL

(33%), followed by the Igneous and West Texas Bolsons aquifers (19% each). The remaining minor aquifers had from 0% to 5.4% of samples above the MCL.

Based on the EPA database, a total of 99,190 people are served by 78 PWS systems that have been non-compliant with respect to drinking water arsenic concentrations in at least one of the last 12 quarters (July 2015 – June 2018) representing 0.35% of the 2018 Texas total population (Figure 8). Most (99.7%, 98,923 people) are associated with PWS systems that source their water from one of the major aquifers while the remaining (0.3%, 267 people) are associated with minor aquifer PWS systems.

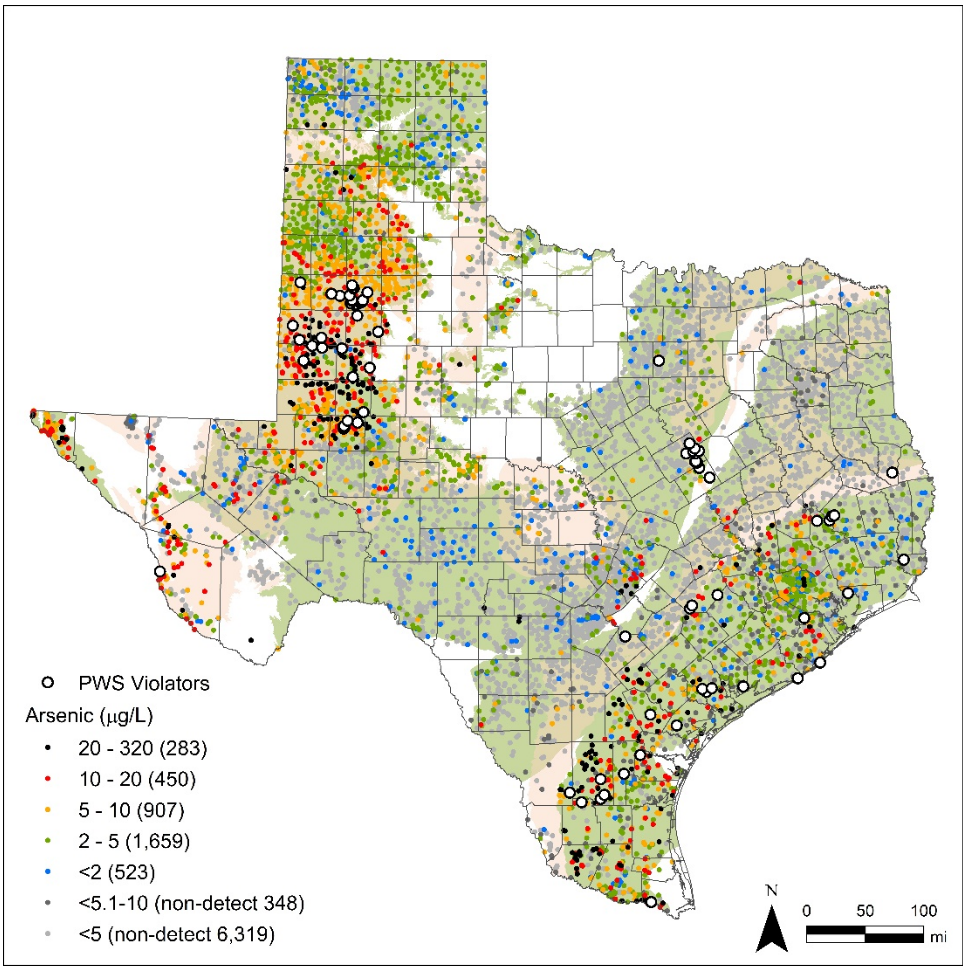


Figure 8. Locations of 78 PWS systems that have health-related non-compliance violations for arsenic concentration in distributed water based on the EPA database. The violating systems are located primarily in the southern High Plains, the Gulf Coast, and the Waco metropolitan area.

Based on the aquifer GIS analyses coupled with the USGS county water use population data for 2015, an estimated total of 81,546 people, representing about 0.29% of the 2018 Texas total population, are served by non-PWS water systems with arsenic concentrations above the 10 μg/L MCL threshold (Table 3). As with the PWS systems, these are predominantly major aquifer non-PWS systems (98%, 79,911 people), with relatively small populations associated with minor aquifer systems (2%, 1,635 people). Thus, the Texas population served by either PWS or non-PWS systems with arsenic concentrations above the MCL is estimated at about 181,000 people, representing about 0.64% of the 2018 Texas total population.

Based on the TCEQ database, a total of 4,091,802 people (about 14% of the 2018 Texas total population) are served by PWS systems that have distributed water with arsenic concentrations above the background threshold of 5 µg/L (this includes the MCL violations). Again, most (99.3%, 4,065,360 people) are associated with PWS systems that source their water from one of the major aquifers while the remaining are associated with minor aquifer PWS systems.

Table 3. Texas populations served by PWS and non-PWS systems with arsenic concentrations above background (>5 µgl/L) and above the MCL (>10 µgl/L).

Water Source	*PWS population*		*Non-PWS population*	*PWS & Non-PWS population*
	Arsenic > 5 µgl/L	*Arsenic > 10 µg/L*	*Arsenic > 10 µg/L*	*Arsenic > 10 µg/L*
All Major Aquifers	4,065,360	98,923	79,911	178,834
All Minor Aquifers	26,442	267	1,635	1,902
Total	4,091,802	99,190	81,546	180,736

Comparison with PWS systems in other States

With a total at-risk population of 99,653 people associated with PWS systems having recent arsenic MCL violations, Texas ranks second behind California which has 109,123 (Table 4). (The Texas number includes 463 people associated with violating PWS systems that obtain their water from unknown or unnamed aquifers not included in this study). The top five states together account for about 76% of the total at-risk US population of 393,895 people, including California (28%), Texas (25%), New Mexico (13%), Arizona (6%), and Oklahoma (4%).

Relative to in-state populations, New Mexico has by far the greatest percentage of population at-risk with 2.4%. The at-risk population represents about 0.35% of the total Texas state population, similar to the average of all 22 states having more than 1,000 people at-risk (0.31%, Table 4).

The total US population associated with PWS systems categorized with serious arsenic violations is 117,850, representing 30% of the total violation population. Texas leads the country with 38 PWS systems having serious arsenic violations, though the associated populations are larger in New Mexico (38,492) than in Texas (21,761) (Table 4). Other states with large populations associated with serious PWS system arsenic violations include Virginia (14,595), Arizona (8,001), Louisiana (7,373), Nevada (5,459), and Oregon (5,288).

Table 4 Comparison by state of PWS system populations with recent arsenic MCL violations. States are ranked by the population at risk. Only the contiguous 48 states are included.

State	*Total Population*	*Rank*	*PWS Violations*				*Serious Violations*	
			Systems	*Population At Risk*	*Population (% of non-compliant)*	*Population (% of state)*	*Systems*	*Population At Risk*
California	39,540,000	1	144	109,123	27.704	0.276	1	80
Texas	28,300,000	2	81	99,653	25.299	0.352	38	21,761
New Mexico	2,088,000	3	13	50,462	12.811	2.417	9	38,492
Arizona	7,016,000	4	27	23,441	5.951	0.334	10	8,001
Oklahoma	3,931,000	5	10	15,346	3.896	0.390	2	169
Virginia	8,470,000	6	2	14,595	3.705	0.172	2	14,595
Nebraska	1,920,000	7	15	12,769	3.242	0.665	1	567
Louisiana	4,684,000	8	7	8,498	2.157	0.181	4	7,373
Nevada	2,998,000	9	20	6,225	1.580	0.208	13	5,459
New Hampshire	1,343,000	10	21	6,222	1.580	0.463	11	998
Oregon	4,143,000	11	12	6,046	1.535	0.146	5	5,288
Illinois	12,800,000	12	10	5,633	1.430	0.044	2	1,735
West Virginia	1,816,000	13	10	4,197	1.066	0.231	10	4,197
Utah	3,102,000	14	10	4,023	1.021	0.130	0	0
Idaho	1,717,000	15	11	4,021	1.021	0.234	3	358
Montana	1,050,000	16	8	3,345	0.849	0.319	0	0
New York	19,850,000	17	11	3,212	0.815	0.016	4	241
Michigan	9,962,000	18	17	2,818	0.715	0.028	6	505
Washington	7,406,000	19	7	2,403	0.610	0.032	2	515
Georgia	10,430,000	20	5	2,317	0.588	0.022	3	2,238
Pennsylvania	12,810,000	21	8	2,004	0.509	0.016	7	1,854
Wisconsin	5,795,000	22	7	1,291	0.328	0.022	6	1,243
Colorado	5,607,000	23	7	820	0.208	0.015	4	549
Minnesota	5,577,000	24	7	801	0.203	0.014	5	621
Maine	1,336,000	25	9	660	0.168	0.049	3	195
Ohio	11,660,000	26	3	517	0.131	0.004	0	0
Kansas	2,913,000	27	2	516	0.131	0.018	0	0
Vermont	624,000	28	3	484	0.123	0.078	1	65
New Jersey	9,006,000	29	2	471	0.120	0.005	0	0
Maryland	6,052,000	30	3	447	0.113	0.007	1	300
Florida	20,980,000	31	3	409	0.104	0.002	2	134
Indiana	6,667,000	32	4	385	0.098	0.006	1	39
South Dakota	870,000	33	3	260	0.066	0.030	2	185
Iowa	3,146,000	34	3	113	0.029	0.004	0	0
Massachusetts	6,860,000	35	1	110	0.028	0.002	0	0
North Carolina	10,270,000	36	2	85	0.022	0.001	0	0
Tennessee	6,716,000	37	1	80	0.020	0.001	0	0
Connecticut	3,588,000	38	1	48	0.012	0.001	1	48
Wyoming	579,000	39	1	45	0.011	0.008	1	45
Delaware	962,000	40	0	0	0.000	0.000	0	0
Kentucky	4,454,000	40	0	0	0.000	0.000	0	0
Mississippi	2,984,000	40	0	0	0.000	0.000	0	0
Missouri	6,114,000	40	0	0	0.000	0.000	0	0
North Dakota	755,000	40	0	0	0.000	0.000	0	0
Rhode Island	1,060,000	40	0	0	0.000	0.000	0	0
South Carolina	5,024,000	40	0	0	0.000	0.000	0	0
Arkansas	3,004,000	40	0	0	0.000	0.000	0	0
Alabama	4,875,000	40	0	0	0.000	0.000	0	0
Contiguous US Total	322,854,000		511	393,895			160	117,850

Major Aquifers Results

There were sufficient data to perform indicator kriging on arsenic concentrations for all nine of the major aquifers in Texas. There were 8,717 samples in the major aquifers, representing 83% of all samples included in this study (Table 5). Of the major aquifer samples, 38% (3,328) had detectable concentrations while 62% (5,389) had non-detectable concentrations. A total of 17% (1,463) of the major aquifer samples exceeded the nominal arsenic background concentration of 5 µg/L and 7.7% (671) samples exceeded the MCL of 10 µg/L. All nine of the major aquifers had at least one sample with arsenic >10 µg/L. Median detected arsenic concentrations ranged from 1.0 µg/L in the Edwards BFZ aquifer to 8.6 µg/L in the Hueco-Mesilla Bolson aquifer (Table 6). Median detected concentrations were ≤5 µg/L in all but the Hueco-Mesilla Bolson aquifer.

The TCEQ database lists about 6,950 active PWS systems in Texas. During the period 2012-2017, a total of 565 systems (8%) with distribution water derived at least in part from one of the major aquifers had arsenic >5 µg/L. This includes 190 public entities and 375 distribution systems with an associated population of about 4 million people (Table 7).

Based on the US EPA database, 76 PWS systems had non-compliant water samples with arsenic >10 µg/L, with a total associated population of almost 100,000 (Table 7). Of these, 34 systems were categorized as serious violators with an associated total population of about 21,400. The most affected populations are located in the southern Gulf Coast area (Gulf Coast aquifer, 25 systems with 43,141 people), the general Waco metropolitan area (Trinity aquifer, 12 systems with 40,226 people), and large areas of the southern High Plains region (Ogallala aquifer, with 37 systems, 14,860 people).

Table 5. Numbers of arsenic samples from the major aquifers in Texas since 1992. Values are based on the latest samples from the TWDB groundwater database and raw water samples from the TCEQ PWS database. Samples from wells completed in multiple aquifers were excluded.

Major Aquifer	*Total Number of Samples*	*Number of Detects*	*Number of Non-detects*	*As >5 µg/L*		*As >10 µg/L*	
				Number	*%*	*Number*	*%*
Carrizo-Wilcox	1,172	44	1,128	7	0.6	1	0.1
Edwards BFZ	610	50	560	8	1.3	5	0.8
Edwards-Trinity Plateau	1,085	239	846	63	5.8	17	1.6
Gulf Coast	2,048	1,012	1,036	1,036	21.7	244	11.9
Hueco-Mesilla Bolson	152	134	18	120	78.9	46	30.3
Ogallala	1,844	1,504	340	748	40.6	333	18.1
Pecos Valley	174	79	95	27	15.5	10	5.7
Seymour	195	121	74	17	8.7	3	1.5
Trinity	1,437	145	1,292	29	2.0	12	0.8
All Majors	8,717	3,328	5,389	1,463	16.8	671	7.7

Table 6. Distributions of arsenic concentrations above detection limits from the major aquifer samples in Texas since 1992. Values are based on the latest samples from the TWDB groundwater database and raw water samples from the TCEQ PWS database. Samples from wells completed in multiple aquifers were excluded.

Major Aquifer	*Samples*	*Mean (μg/L)*	*Percentile (μg/L)*								
			Min	*0.05*	*0.1*	*0.25*	*0.50*	*0.75*	*0.90*	*0.95*	*Max*
Carrizo-Wilcox	44	3.1	0.2	1.0	1.0	2.0	2.6	4.0	5.3	6.7	10.8
Edwards BFZ	50	4.2	0.2	0.3	0.3	0.4	1.0	2.9	8.3	13.1	79.6
Edwards-Trinity Plateau	239	4.6	0.8	1.0	1.1	2.0	2.7	5.2	8.3	11.8	47.0
Gulf Coast	1,012	9.5	0.1	1.0	1.9	2.6	4.3	9.8	23.0	37.0	320.0
Hueco-Mesilla Bolson	134	10.7	2.3	3.9	5.0	5.9	8.6	12.0	19.5	24.2	60.1
Ogallala	1,504	8.2	0.1	1.8	2.1	2.9	5.0	9.3	17.2	27.0	164.1
Pecos Valley	79	5.8	1.0	1.0	1.0	2.1	3.2	6.7	12.9	16.0	51.0
Seymour	121	3.3	0.7	1.0	1.1	2.1	3.0	4.0	5.8	6.9	12.5
Trinity	145	4.0	0.3	1.0	1.0	2.0	2.5	4.7	8.3	12.9	23.4

Table 7. Numbers of major aquifer PWS systems with arsenic concentrations greater than nominal background (> 5 μg/L) and greater than the MCL (> 10 μg/L). The populations shown are those associated with PWS distribution systems. The numbers of public entity supply systems are also shown. Public entity systems provide non-utility access to the public and do not have and associated fixed population number.

Aquifer	*TCEQ database Arsenic concentrations (>5 μg/L)*			*EPA non-compliant PWS Systems (Arsenic >10 μg/L)*			
				Systems		*Population*	
	Public Entity	*Distribution Systems*	*PWS At-risk Population*	*Total*	*Serious*	*Total*	*Serious*
Carrizo-Wilcox	3	2	6,946	1	1	456	456
Edwards BFZ	0	0	0	0	0	0	0
Edwards-Trinity Plateau	7	8	4,954	1	1	240	240
Gulf Coast	109	238	2,986,633	25	9	43,141	12,827
Hueco-Mesilla Bolson	6	13	686,466	0	0	0	0
Ogallala	59	82	189,450	37	22	14,860	7,624
Pecos Valley	2	3	10,642	0	0	0	0
Seymour	0	1	740	0	0	0	0
Trinity	4	28	179,529	12	1	40,226	234
Total Major Aquifers	190	375	4,065,360	76	34	98,923	21,381

Table 8. Estimated non-PWS system populations with groundwater arsenic concentrations greater than the MCL (> 10 µg/L) in the Major Aquifers. The populations shown are estimated from the GIS map mean county-by-county probability multiplied by the estimated non-PWS system population.

Aquifer	*Non-PWS At-risk Population*
Carrizo-Wilcox	63
Edwards	302
Edwards-Trinity Plateau*	1,408
Gulf Coast	27,737
Hueco-Mesilla Bolson	5,397
Ogallala	39,399
Pecos Valley	1,645
Seymour	200
Trinity	3,759
Total Major Aquifers	79,911

*Includes areas that do not overlap with the Ogallala and Pecos Valley aquifers.

Carrizo-Wilcox Aquifer

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

There were 1,172 samples analyzed for arsenic during the study period with only 44 samples (3.8%) having detectable concentrations. The probability of arsenic exceeding 5 µg/L is zero over most (82%) of the aquifer area with only (18%) of the aquifer area in south and south-central Texas having a very low to low probability of arsenic >5 µg/L, located mostly in confined areas. The median concentration of samples with detectable concentrations is 2.6 µg/L and the 5th-95th percentile range is 1.0–6.7 µg/L. Only one sample near the border with Mexico exceeded the MCL with a concentration of 10.2 µg/L.

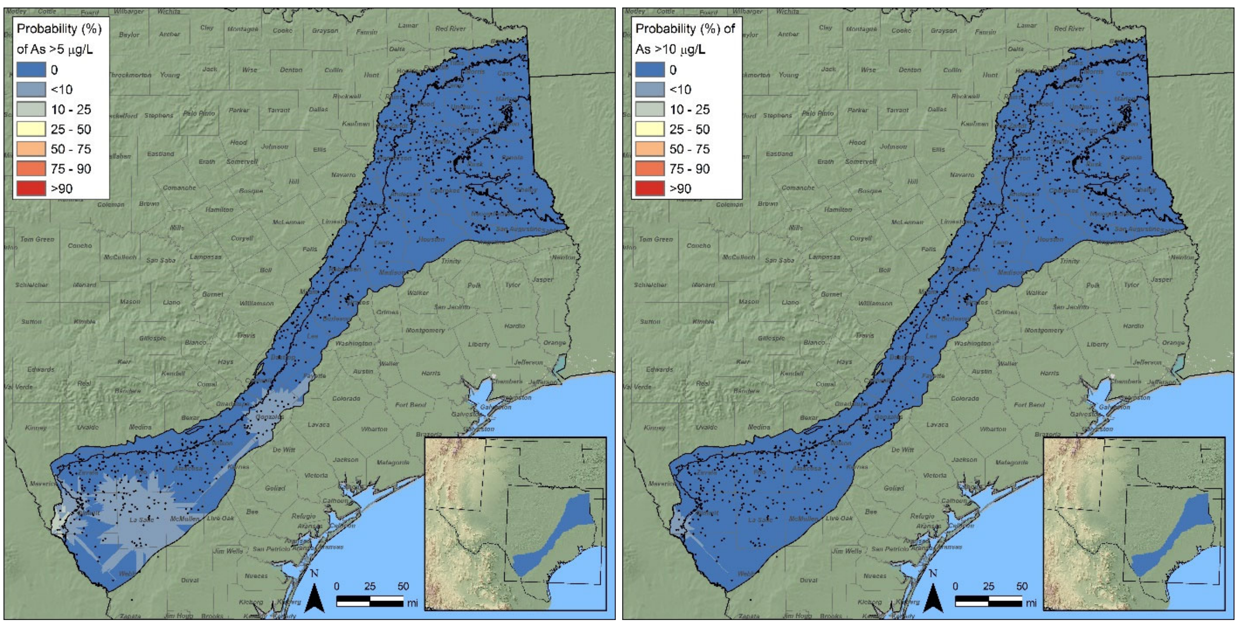


Figure 9. Carrizo-Wilcox aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of five PWS water supply systems are impacted by arsenic concentrations >5 µg/L, including three public entities and two distribution systems with a population of 6,946 people. Based on the EPA PWS database, there is one community water system that is non-compliant for arsenic with a population of 456 and the violations are listed as serious (Table 9). The non-PWS system at-risk population of >10 µg/L arsenic is very low at 63, located in southern Maverick County along the international border with Mexico.

Table 9. Carrizo-Wilcox aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
2470020	Lake Valley Water	Comm.	GW	Private	Yes	12	456

Edwards (Balcones Fault Zone) Aquifer

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

There were 610 samples analyzed for arsenic during the study period with only 50 samples (8%) having detectable concentrations. Most (79%) of the aquifer area has no probability of arsenic >5 µg/L with only (21%) of the area in the down-dip edges in confined regions of the aquifer having a very low to low probability of arsenic >5 µg/L. The median concentration of samples with detectable concentrations is 1.0 µg/L and the 5th-95th percentile range is 0.3–13.1 µg/L. A total of 5 samples (0.8%) exceeded the MCL with a range of concentrations from 11 µg/L to 17 µg/L in 4 wells and 80 µg/L in one well.

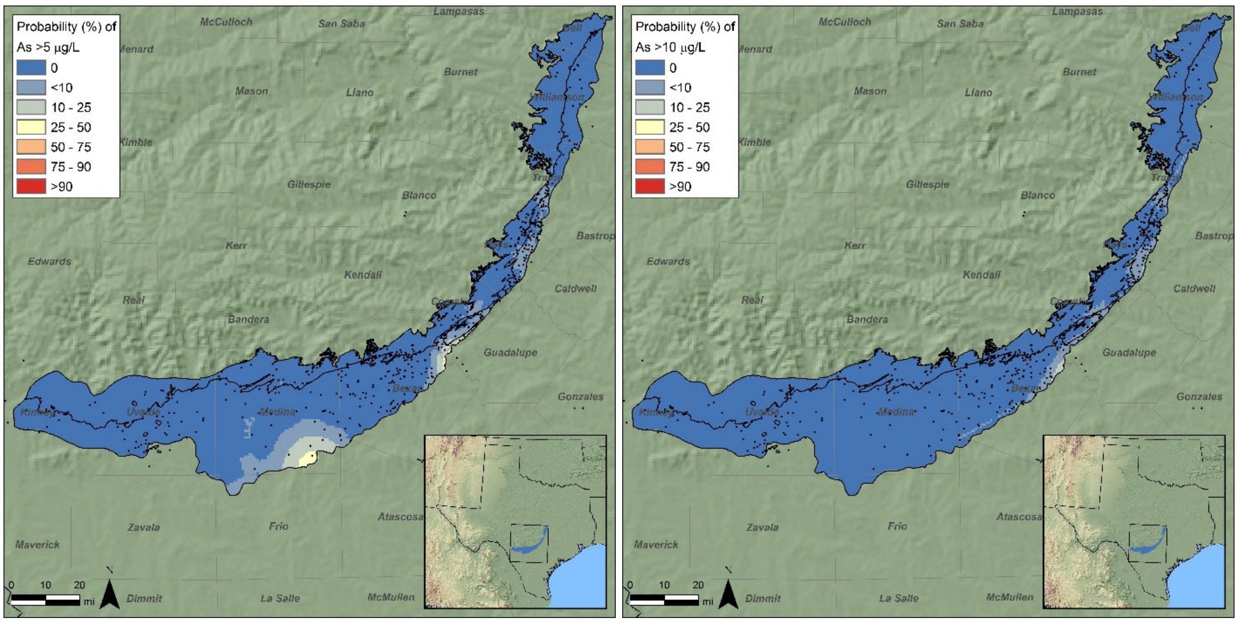


Figure 10. Edwards (BFZ) aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ and EPA PWS databases, there are no PWS systems impacted by arsenic concentrations >5 µg/L and there are no PWS systems with arsenic concentrations exceeding the MCL in the Edwards BFZ aquifer. The non-PWS system at-risk population of >10 µg/L is 302 people located primarily in the furthest down-dip areas of the aquifer in Bexar, Travis, and Hays counties.

Edwards-Trinity Plateau Aquifer

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

There were 1,075 samples analyzed for arsenic during the study period with 239 samples (22%) having detectable concentrations. Most (79%) of the aquifer area has no probability of arsenic >5 µg/L. About 18% of the area has very low to moderate probability of arsenic >5 µg/L, primarily in the areas adjacent to the international border with Mexico. About 3% of the total aquifer area, located primarily in the confined areas beneath the Ogallala aquifer and to locally in areas just to the southeast of the Ogallala. The median concentration of samples with detectable concentrations is 2.7 µg/L and the 5^{th}-95^{th} percentile range is 1.0–11.8 µg/L. A total of 17 samples (1.6%) exceeded the MCL with a range of concentrations from 10.3 µg/L to 47 µg/L with the highest concentrations located in or adjacent to the confined areas beneath the Ogallala in Andrews, Ector, and Midland counties.

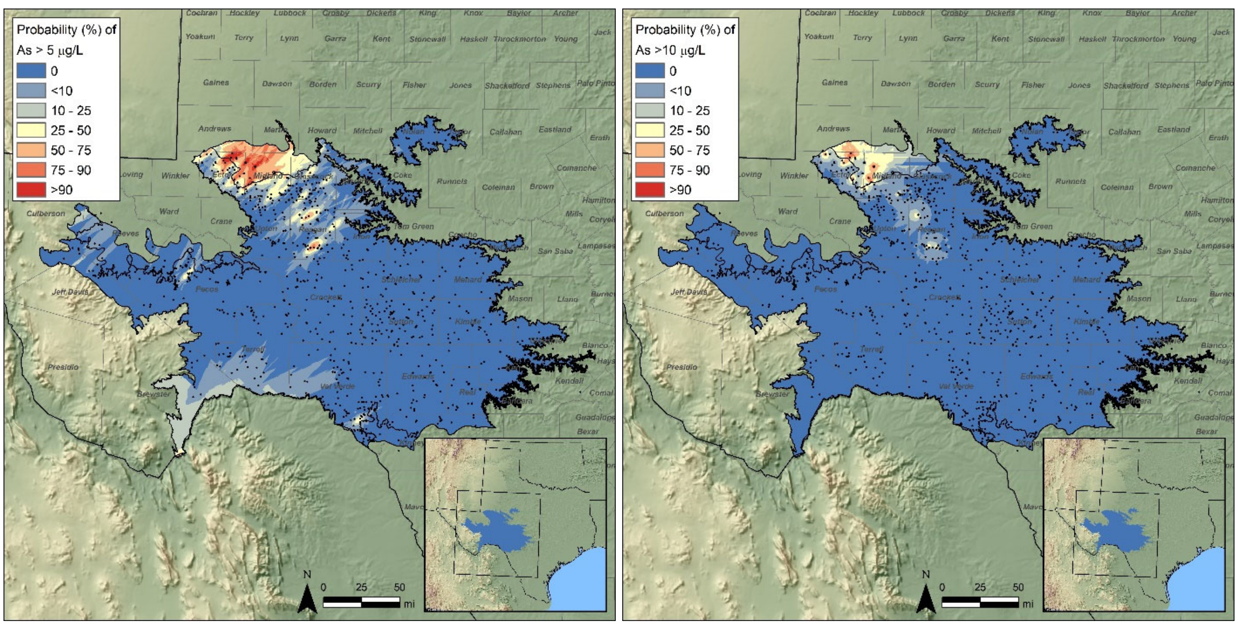


Figure 11. Edwards-Trinity Plateau aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 15 PWS water supply systems are impacted by arsenic concentrations >5 µg/L, including 7 public entities and 8 distribution systems with a population of 4,954 people. Based on the EPA PWS database, there is one community PWS system impacted by arsenic concentrations >10 µg/L with a population of 240 people and the violation is serious (Table 10). Adjusted for areas overlapped by the Ogallala and Pecos Valley aquifers, the estimated non-PWS system at-risk population of >10 µg/L is 1,408 people.

Table 10. Edwards-Trinity Plateau aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
1650084	Warren Road Subdivision WS	Comm.	GW	Private	Yes	12	240

Gulf Coast Aquifer System

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

There were 2,048 samples analyzed for arsenic during the study period with 1,012 samples (49%) having detectable concentrations. Arsenic occurrence is widespread in the Gulf Coast aquifer and concentrations tend to increase toward the south, along the inland aquifer boundary, and locally near the coast. Only 7% of the aquifer area has no probability of arsenic >5 µg/L. About 74% of the area has very low to moderate probability of arsenic >5 µg/L. About 20% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L, located primarily in the southern third of the region. The median of samples with detectable concentrations is 4.3 µg/L and the 5^{th}-95^{th} percentile range is 1.0–37 µg/L. The highest concentrations of groundwater arsenic in Texas are associated with the Gulf Coast aquifer. A total of 244 samples (11.9%) exceeded the MCL with a range of concentrations from 10.1 µg/L to 320 µg/L. This includes 23 samples with concentrations ≥50 µg/L and three samples ≥100 µg/L.

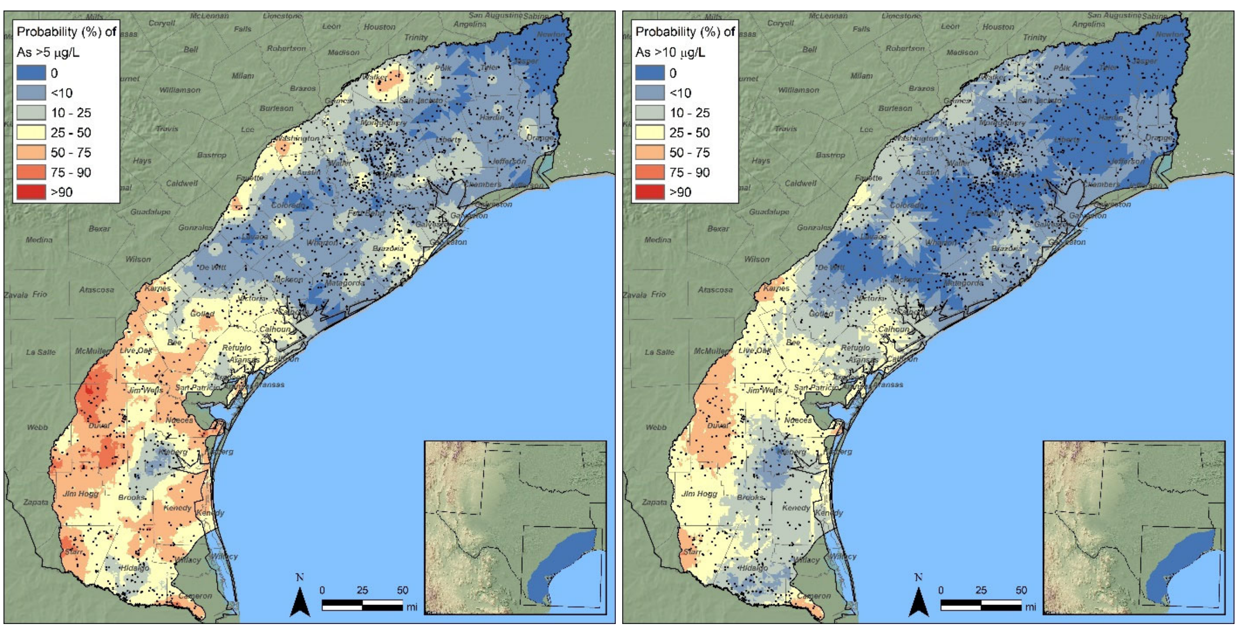


Figure 12. Gulf Coast aquifer system probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 347 PWS systems are impacted by arsenic concentrations >5 µg/L, including 109 public entities and 238 distribution systems with a population of 2,986,633 people. Based on the US EPA database, there are a total of 25 PWS systems that are impacted by arsenic concentrations >10 µg/L with a population of 43,141 people (Table 11). Of these, 9 systems have had serious arsenic violations in the past 12 quarters with a population of 12,827 people. The non-PWS system at-risk population of >10 µg/L is the second highest in the state at 27,737 located primarily in the southern areas of the aquifer, in up-dip areas along the inland boundary of the aquifer, and locally near the coast .

Table 11. Gulf Coast aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
0130058	Country Villa MHP	Comm.	GW	Private	Yes	12	50
0200037	Village of Surfside Beach	Comm.	GW	Public	No	12	3,477
0360004	Cotton Bayou Bark	Comm.	GW	Private	No	12	132
0660001	Duval County CRD Benavides	Comm.	GW	Public	No	12	1,362
0660015	Duval County CRD Concepcion	Comm.	GW	Public	No	12	161
0750002	City of Flatonia	Comm.	GW	Public	No	11	2,370
0750014	Ellinger Sewer and WSC	Comm.	GW	Public	No	12	462
0750044	Whispering Hills Achiev. Ctr	Non	GW	Private	No	12	29
0790424	Kidacious Academy	Non	GW	Private	Yes	11	100
1080067	Military HWY WSC Las Rusias	Comm.	GUI	Public	No	12	16,890
1200028	Tri County Point Water Syst 3	Comm.	GW	Private	No	12	297
1240001	Jim Hogg County WCID 2	Comm.	GW	Public	Yes	12	5,526
1250030	Jim Wells County FWSD 1	Comm.	SWP	Public	No	12	2,064
1610016	Matagorda County WCID 2	Comm.	GW	Public	No	12	471
1780050	Cyndie Park 2 WSC	Comm.	GW	Public	Yes	12	45
1810034	Sawmill Addition	Comm.	GW	Private	No	12	72
1870020	Lake Livingston Indian Hills 2	Comm.	SWP	Private	Yes	12	627
1870105	Tempe WSC 1	Comm.	GW	Public	Yes	12	1,704
1870149	Spring Creek Pure Utilities	Comm.	GW	Private	No	12	271
1960003	Town of Woodsboro	Comm.	GW	Public	Yes	11	1,494
2040024	Point Blank & Stephens Creek	Comm.	GW	Public	No	12	1,828
2350001	Victoria County WCID 1	Comm.	GW	Public	Yes	12	2,459
2350006	Victoria County WCID 2	Comm.	GW	Public	Yes	12	822
2350051	Victoria County Nav. District	Non	GW	Public	No	11	78
2400003	Bruni Rural WSC	Comm.	GW	Public	No	12	350

System Type: Community water system (Comm.) or Non-Transient non-community (Non)
Primary Source: Groundwater (GW), Groundwater under the influence of surface water (GUI), purchased surface water (SWP)
Quarters: number of quarters with violations in the past 3 years (12 quarters).

Hueco-Mesilla Bolson Aquifer

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

There were 152 samples analyzed for arsenic during the study period with 134 samples (88%) having detectable concentrations. Arsenic occurrence is widespread in the Hueco-Mesilla Bolson aquifer and concentrations tend to increase toward the south. Only about 9% of the area has very low to moderate probability of arsenic >5 µg/L. About 91% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L. However, most of the samples are clustered in the north and the sample spatial distribution in most of the southern aquifer areas is very sparse, particularly in Hudspeth County. The median concentration of samples with detectable concentrations is 8.6 µg/L and the 5th-95th percentile range is 3.9–24.2 µg/L. A total of 46 samples (30.3%) exceeded the MCL with a range of concentrations from 10.2 µg/L to 60 µg/L.

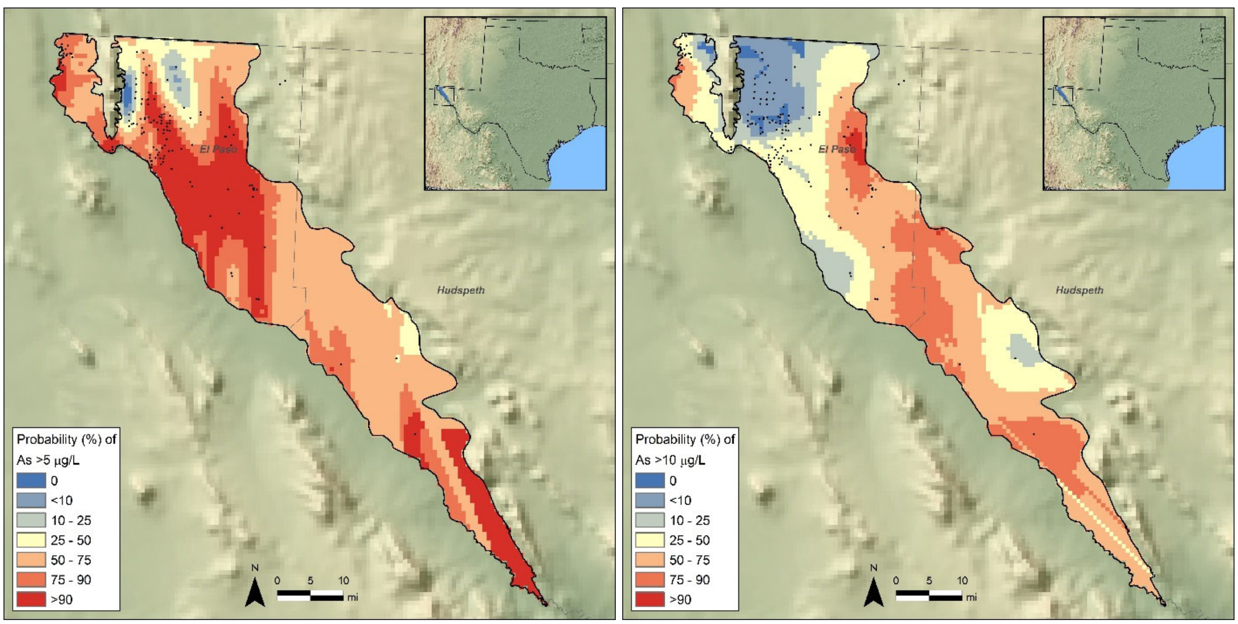


Figure 13. Hueco-Mesilla Bolson aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 19 PWS water supply systems are impacted by arsenic concentrations >5 µg/L, including 6 public entities and 13 distribution systems with a population of 686,466 people. Based on the EPA PWS database, there are no PWS water supply systems impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is moderate at 5,397 located primarily in El Paso County.

Ogallala Aquifer

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

There were 1,844 samples analyzed for arsenic during the study period with 1,504 samples (82%) having detectable concentrations. Arsenic occurrence is widespread in the Ogallala aquifer and concentrations are notably higher in the southern areas. About 19% of the area has no probability of arsenic > 5µg/L and a further 39% has very low to moderate probability of arsenic >5 µg/L. About 18% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L and fully 25% of the aquifer area has a very high probability. The median concentration of samples with detectable concentrations is 5.0 µg/L and the 5th-95th percentile range is 1.8–27 µg/L. A total of 333 samples (18.1%) exceeded the MCL with a range of concentrations from 10.1 µg/L to 164 µg/L.

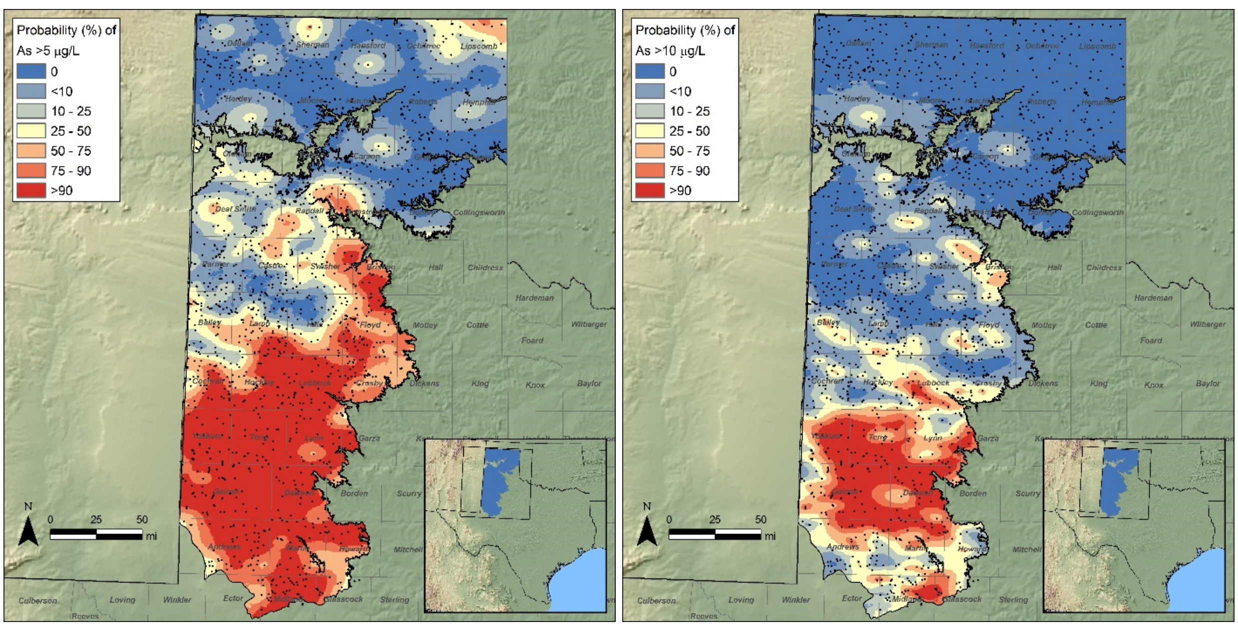


Figure 14. Ogallala aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 141 PWS water supply systems are impacted by arsenic concentrations >5 µg/L, including 59 public entities and 82 distribution systems with a population of 189,450 people. Based on the EPA PWS database, there are a total of 37 PWS water supply systems that are impacted by arsenic concentrations >10 µg/L with a total population of 14,960 people (Table 12). Of these, 22 systems have serious violations in the last 12 quarters, with a population of 7,624 people. The non-PWS system at-risk population of >10 µg/L is the highest in the state at 39,399 located primarily in the areas of the aquifer south of Lubbock.

Table 12. Ogallala aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
0170010	Borden County Water System	Comm.	GW	Public	No	12	250
0400001	City of Morton	Comm.	GW	Public	No	12	2025
0580013	Welch WSC	Comm.	GW	Public	No	12	315
0580025	Klondike ISD	Comm.	GW	Public	Yes	12	231
0830001	City of Seagraves	Comm.	GW	Public	Yes	12	2196
0830011	Loop WSC	Comm.	GW	Public	Yes	12	300
0830031	Seminole Gas Processing Plant	Non	GW	Private	Yes	11	100
1100010	City of Smyer	Comm.	GW	Public	No	12	474
1100030	City of Opdyke West	Comm.	GW	Public	No	12	273
1520039	Pecan Grove MHP	Comm.	GW	Private	Yes	12	108
1520064	Fort Jackson mMobile Estates	Comm.	GW	Private	Yes	12	61
1520067	114th Street MHP	Comm.	GW	Private	No	12	50
1520080	Franklin Water Systems 3	Comm.	GW	Private	Yes	12	92
1520094	Town North Village Water Sys	Comm.	GW	Private	Yes	12	335
1520147	Short Road Water Supply	Non	GW	Private	Yes	12	149
1520149	Whorton MHP	Comm.	GW	Private	Yes	12	60
1520152	Town North Estates	Comm.	GW	Private	Yes	12	210
1520188	Seven Estates	Comm.	GW	Private	Yes	12	261
1520192	Terrells MHP	Comm.	GW	Private	No	12	70
1520198	Valley Estates	Comm.	GW	Private	Yes	12	70
1520199	Wolfforth Place	Comm.	GW	Private	No	12	460
1520217	Southwest Garden Water	Comm.	GW	Private	Yes	12	375
1520225	Fay Ben MHP	Comm.	GW	Private	Yes	12	125
1520247	Country View MHP	Comm.	GW	Private	Yes	12	55
1520265	Cash Register Services	Non	GW	Private	Yes	12	40
1520283	New Generation Comm. Chrch	Trans	GW	Private	Yes	12	75
1530004	City of New Home	Comm.	GW	Public	No	12	334
1590001	City of Stanton	Comm.	SW	Public	Yes	12	2492
1650022	Sherwood Esta. Man.	Comm.	GW	Private	No	12	102
1650043	Peak Properties	Comm.	GW	Private	Yes	12	99
1650057	Twin Oaks MHP Midland	Comm.	GW	Private	No	12	234
1650077	South Midland Cnty Wat Syst.	Comm.	GW	Private	Yes	12	165
1650078	Greenwood Water System	Comm.	GW	Private	No	4	888
2230003	City of Wellman	Comm.	GW	Public	No	12	225
2510002	City of Plains	Comm.	GW	Public	No	12	1481
2510023	Wasson CO2 Recovery Plant	Non	GW	Private	Yes	12	25
1530005	Grassland WSC	Comm.	GW	Public	No	12	55

System Type: Community water system (Comm.) or Non-Transient non-community (Non)

Primary Source: Groundwater (GW), surface water (SW)

Quarters: number of quarters with violations in the past 3 years (12 quarters).

Pecos Valley Aquifer

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

There were 174 samples analyzed for arsenic during the study period with 79 samples (45%) having detectable concentrations. Higher arsenic concentrations are restricted to the northeastern half of the aquifer. About 44% of the area has no probability of arsenic > 5µg/L and a further 31% has very low to moderate probability of arsenic >5 µg/L. About 25% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L. The spatial pattern of probabilities displays artifacts of limited data density, particularly in the areas with the higher concentrations. The median concentration of samples with detectable concentrations is 3.2 µg/L and the 5^{th}-95^{th} percentile range is 1.0–16 µg/L. A total of 10 samples (1.5%) exceeded the MCL with a range of concentrations from 11 µg/L to 51 µg/L.

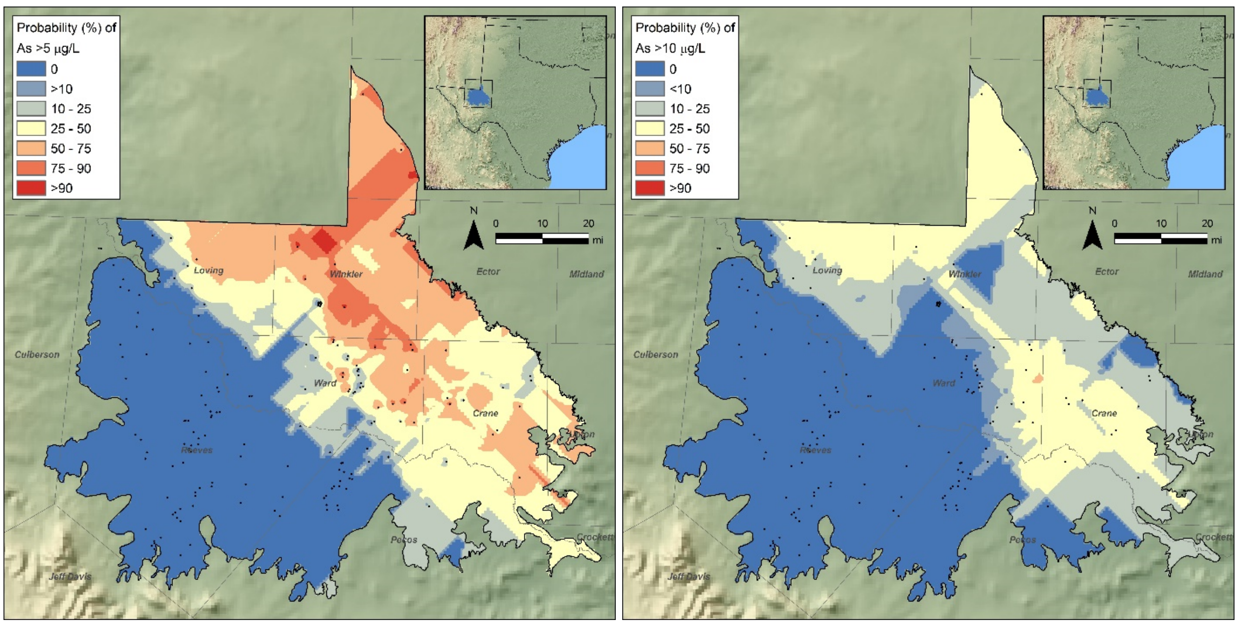


Figure 15. Pecos Valley aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 5 PWS water supply systems are impacted by arsenic concentrations >5 µg/L, including 2 public entities and 3 distribution systems with a population of 10,642 people. Based on the EPA PWS database, there are no PWS systems impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is low at 1,645 located primarily in Ector, Andrews, and Crane counties.

Seymour Aquifer

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

There were 195 samples analyzed for arsenic during the study period with 121 samples (62%) having detectable concentrations. About 31% of the area has no probability of arsenic > 5µg/L and a further 66% has very low to moderate probability of arsenic >5 µg/L. Only about 3% of the total aquifer area has elevated probabilities of arsenic >5 µg/L. The spatial pattern of probabilities displays artifacts of limited data density, particularly in the areas with the higher concentrations in the south in the Fisher-Jones county area. The median concentration of samples with detectable concentrations is 3.0 µg/L and the 5th-95th percentile range is 1.0–6.9 µg/L. A total of 3 samples (1.5%) exceeded the MCL with a range of concentrations from 10.7 µg/L to 12.5 µg/L.

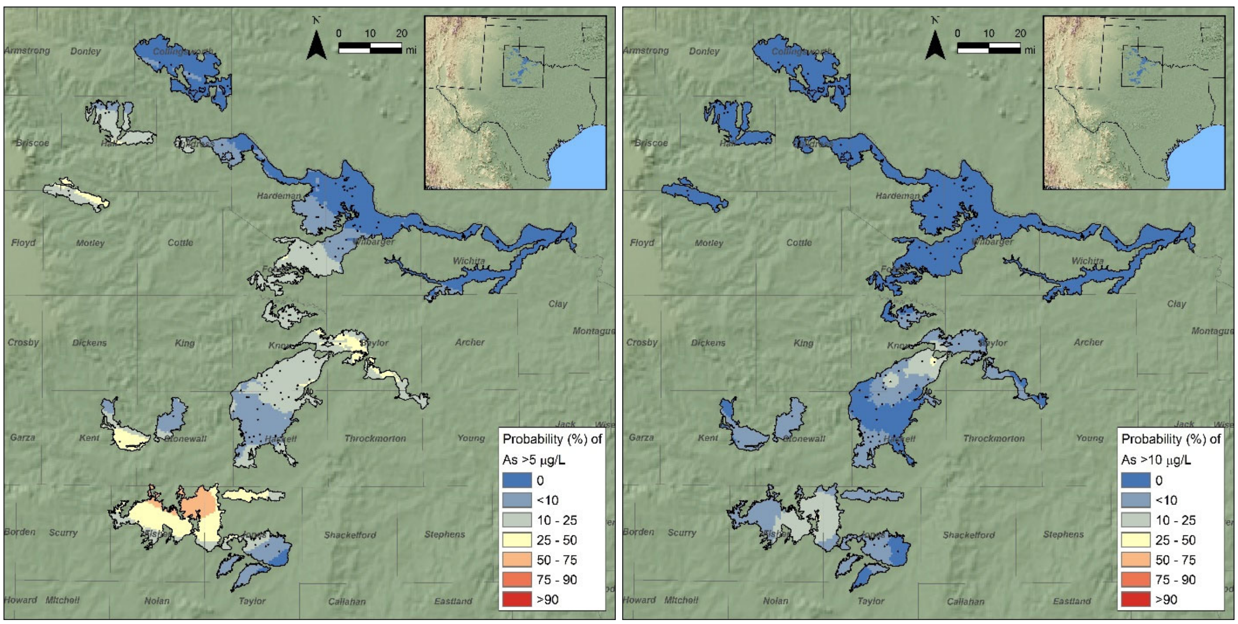


Figure 16. Seymour aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, one PWS supply distribution system is impacted by arsenic concentrations >5 µg/L with a population of 740. Based on the EPA PWS database, there are no PWS water supply systems that are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is very low at 199 located primarily in Fisher and Jones counties. However this is based on only one sample in that region and the results may not be reliable.

Trinity Aquifer

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

There were 1,448 samples analyzed for arsenic during the study period with 145 samples (10%) having detectable concentrations. About 76% of the area has no probability of arsenic > 5 µg/L and a further 23% has very low to moderate probability of arsenic >5 µg/L. Only about 1% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L. The spatial pattern of probabilities displays artifacts of limited data density, particularly in the down-dip confined areas. The median concentration of samples with detectable concentrations is 2.5 µg/L and the 5th-95th percentile range is 1.0–12.9 µg/L. A total of 12 samples (0.8%) exceeded the MCL with a range of concentrations from 11 µg/L to 23.4 µg/L.

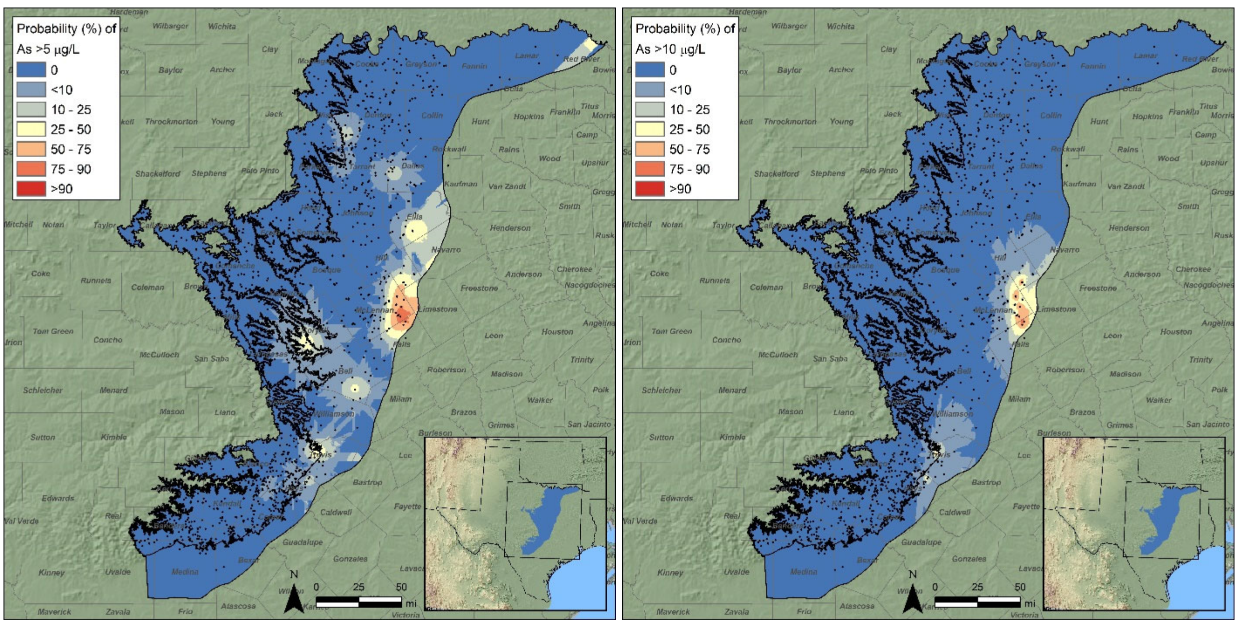


Figure 17. Trinity aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 32 PWS systems are impacted by arsenic concentrations >5 µg/L, including 4 public entities and 28 distribution systems with a population of 179,529 people. Based on the EPA PWS database, there are a total of 12 PWS water supply systems that are impacted by arsenic concentrations >10 µg/L with a population of 40,226 people. None of these systems have had any serious violations in the last 12 quarters. The non-PWS system at-risk population of >10 µg/L is moderate at 3,764 located primarily in Travis, McLennan, and Falls counties.

Table 13. Trinity aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
0730004	Tri County SUD	Comm.	GW	Public	No	12	5,013
0730016	Perry WSC	Comm.	GWP	Public	No	12	420
1470011	Prairie Hill WSC	Comm.	GW	Public	No	12	2,100
1550001	City of Bellmead	Comm.	GW	Public	No	6	9,900
1550016	Axtell WSC	Comm.	GW	Public	No	12	1,780
1550025	EOL WSC	Comm.	GW	Public	No	12	1,917
1550027	Leroy Tours Gerald WSC	Comm.	GW	Public	No	12	1,626
1550037	M S WSC	Comm.	GW	Public	No	12	744
1550040	City of Riesel	Comm.	GW	Public	No	12	1,009
1550127	Moores Water System	Comm.	GWP	Private	Yes	12	234
1550136	R M S WSC	Comm.	GW	Private	No	12	0
2200081	City of White Settlement	Comm.	SWP	Public	No	12	15,483

System Type: Community water system (Comm.) or Non-Transient non-community (Non)
Primary Source: Groundwater (GW), surface water (SW)
Quarters: number of quarters with violations in the past 3 years (12 quarters).

Minor Aquifer Results

There were sufficient data (≥50 samples) to perform indicator kriging on arsenic concentrations for eleven of the minor aquifers in Texas. Maps were not generated for the remaining ten minor aquifers with <50 data points. Data for the minor aquifers represent 1,772 samples, representing only 17% of all samples included in this study (Table 14). Of all the minor aquifer samples, 28% (494) had detectable concentrations while 72% (1,278) had non-detectable concentrations. A total of 10% (177) of the minor aquifer samples exceeded the nominal arsenic background concentration of 5 µg/L and 3.5% (62) samples exceeded the MCL of 10 µg/L. Nine of the minor aquifers had at least one sample with arsenic >10 µg/L. Median detected arsenic concentrations ranged from 1.5 µg/L in the Queen City aquifer to 7.0 µg/L in the Blossom aquifer (Table 15).

Table 14. Numbers of arsenic samples from the minor aquifers in Texas since 1992. Values are based on the latest samples from the TWDB groundwater database and raw water samples from the TCEQ PWS database. Samples from wells completed in multiple aquifers are not included.

Minor Aquifer	*Number of Samples*	*Number of Detects*	*Number of Non-detects*	*Detects >5 µg/L*		*Detects >10 µg/L*	
				Number	*%*	*Number*	*%*
Blaine	74	20	54	2	2.7	0	0.0
Blossom	20	3	17	2	10.0	1	5.0
Bone Spring-Victorio Peak	43	2	41	0	0.0	0	0.0
Brazos River Alluvium	43	20	23	9	20.9	2	4.7
Capitan Reef Complex	37	8	29	2	5.4	2	5.4
Dockum	294	158	136	54	18.4	15	5.1
Edwards-Trinity High Plains	18	16	2	11	61.1	6	33.3
Ellenburger-San Saba	119	14	105	6	5.0	0	0.0
Hickory	136	24	112	3	2.2	0	0.0
Igneous	64	40	24	20	31.3	12	18.8
Lipan	62	50	12	9	14.5	0	0.0
Marathon	24	0	24	0	0.0	0	0.0
Marble Falls	17	3	14	1	5.9	0	0.0
Nacatoch	35	6	29	2	5.7	0	0.0
Queen City	223	15	208	0	0.0	0	0.0
Rita Blanca	14	10	4	5	35.7	0	0.0
Rustler	26	1	25	0	0.0	0	0.0
Sparta	119	5	114	2	1.7	1	0.8
West Texas Bolson	91	67	24	40	44.0	17	18.7
Woodbine	168	13	155	1	0.6	0	0.0
Yegua-Jackson	145	19	126	8	5.5	6	4.1
All Minors	1,772	494	1,278	177	10.0	62	3.5

Table 15. Distributions of detected arsenic concentrations from the minor aquifer samples in Texas since 1992. Values are based on the latest samples from the TWDB groundwater database and raw water samples from the TCEQ PWS database. Samples from wells completed in multiple aquifers are not included.

Minor Aquifer	*Detect Samples*	*Mean (µg/L)*	*Percentile (µg/L)*								
			Min	*0.05*	*0.1*	*0.25*	*0.50*	*0.75*	*0.90*	*0.95*	*Max*
Blaine	20	3.2	2.1	2.1	2.1	2.3	2.8	3.9	4.7	5.3	5.4
Blossom	3	7.9	2.0	2.5	3.0	4.5	7.0	10.9	13.2	13.9	14.7
Bone Spring-Victorio Peak	2	2.2	1.2	1.3	1.4	1.7	2.2	2.7	3.0	3.1	3.2
Brazos River Alluvium	20	5.2	1.0	1.1	1.2	2.3	3.3	6.6	10.2	15.4	17.3
Capitan Reef Complex	8	4.3	0.9	1.2	1.5	2.0	2.3	4.5	10.9	11.7	12.6
Dockum	158	5.7	0.8	2.1	2.2	2.7	4.0	6.1	9.8	14.7	45.1
Edwards-Trinity HP	16	13.5	3.1	3.1	3.2	4.3	6.5	14.7	25.7	41.3	72.6
Ellenburger-San Saba	14	3.6	0.7	0.8	0.8	1.3	2.3	5.4	7.1	8.2	9.0
Hickory	24	3.0	0.7	0.8	0.9	1.0	2.8	4.0	5.0	7.0	10.0
Igneous	40	7.4	1.0	1.3	1.4	3.0	4.9	11.2	15.5	17.8	33.1
Lipan	50	3.6	2.0	2.2	2.3	2.7	3.1	4.4	5.7	6.5	6.9
Marathon	0	-	-	-	-	-	-	-	-	-	-
Marble Falls	3	3.4	2.2	2.2	2.2	2.3	2.3	4.0	5.0	5.4	5.7
Nacatoch	6	3.9	2.0	2.0	2.1	2.5	3.6	4.8	6.1	6.5	7.0
Queen City	15	2.1	0.9	1.0	1.1	1.4	1.5	2.8	3.5	3.7	4.3
Rita Blanca	10	4.7	1.0	1.2	1.4	1.7	5.1	7.0	7.6	8.7	9.9
Rustler	1	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Sparta	5	4.5	1.3	1.3	1.3	1.4	3.8	5.2	8.4	9.5	10.6
West Texas Bolson	67	8.4	1.0	2.2	2.9	4.3	6.7	9.7	15.1	19.2	46.7
Woodbine	13	2.6	0.4	0.4	0.5	1.0	2.3	3.0	5.0	6.2	8.0
Yegua-Jackson	19	9.4	0.7	2.1	2.3	2.5	3.7	12.9	19.6	26.6	47.0

Table 16. Numbers of minor aquifer PWS systems with arsenic concentrations greater than nominal background (> 5 µg/L) and greater than the MCL (> 10 µg/L) The populations shown are those associated with PWS distribution systems. The numbers of public entity supply systems are also shown. Public entity systems provide non-utility access to the public and do not have and associated fixed population number.

Aquifer	*As concentrations (>5 µg/L)*			*EPA non-compliant PWS Systems (>10 µg/L)*			
				Systems		*Population*	
	Public Entity	*Distribution Systems*	*PWS At-risk Population*	*Total*	*Serious*	*Total*	*Serious*
Dockum	6	5	2,337	0	0	0	0
Edwards-Trinity High Plains	0	1	474	0	0	0	0
Hickory	0	1	5,324	0	0	0	0
Igneous	0	4	2,808	1	1	84	84
Lipan	0	1	1,425	0	0	0	0
Sparta	0	2	5,055	0	0	0	0
West Texas Bolson	0	1	156	0	0	0	0
Yegua-Jackson	0	5	8,863	1	1	183	183
Total Minor Aquifers	6	20	26,442	4	3	267	267

Table 17. Estimated non-PWS system at risk populations with groundwater arsenic concentrations greater than the MCL (> 10 µg/L) in the Minor Aquifers. The populations shown are estimated from the GIS map mean county-by-county probability multiplied by the estimated non-PWS system population. Also shown are the estimated populations for any areas with multiple overlapping aquifers and the relevant aquifer names.

Aquifer	*Non-PWS At-risk Population*
Igneous	146
Sparta	253
West Texas Bolsons	49
Yegua-Jackson	1,187
Total Minor Aquifers	1,635

Blaine Aquifer

The Blaine aquifer covers 5,700 mi^2 and extends across parts of 17 counties across an area varying from 20 to 60 miles wide extending southward from the eastern Panhandle region (Figure 18). The aquifer is of Permian age and includes stratigraphic components of the Blaine Formation. The saturated thickness averages 137 ft ranging up to 300 ft. Water quality is generally poor with concentrations generally between 3,000 and 10,000 mg/L TDS with high sulfate concentrations.

There were 74 samples analyzed for arsenic during the study period with 20 samples (27%) having detectable arsenic concentrations. Most of the samples are located in the northern half of the aquifer so the kriging results are skewed toward that region. About 80% of the area has no probability of arsenic > 5 µg/L and a further 20% has very low to moderate probability of arsenic >5 µg/L. Less than 1% of the total aquifer area has elevated of arsenic >5 µg/L. The median concentration of samples with detectable concentrations is 2.8 µg/L and the 5^{th}-95^{th} percentile range is 2.1–5.3 µg/L. There are no samples that exceeded the MCL.

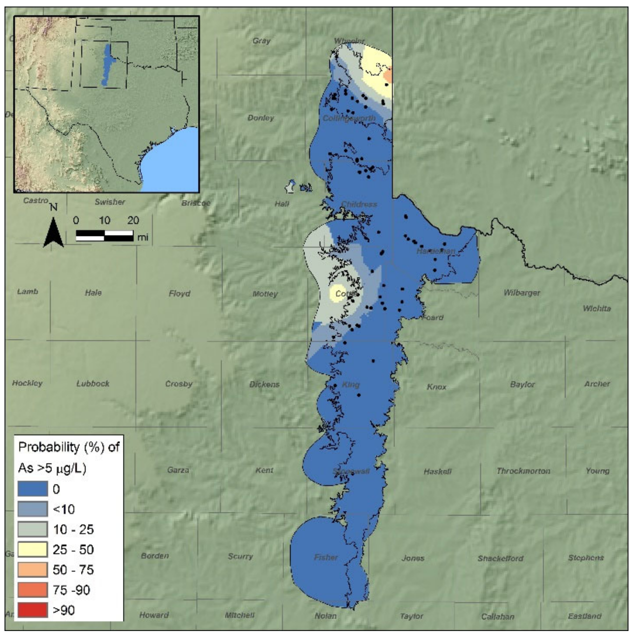


Figure 18. Blaine aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Blane aquifer that exceed the 10 µg/L MCL concentration.

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Dockum Aquifer

The Dockum aquifer covers 25,300 mi^2 and extends across parts of 46 counties from the Oklahoma border in the northwestern Panhandle to south to the general area of Midland, Texas (Figure 19). The aquifer is Late Triassic age and includes the stratigraphic components of the Dockum Group, including the Santa Rosa, Tecovas, Trujillo, and Copper Canyon formations. Water quality is generally poor with fresh water present primarily in the outcrop areas in the north and southeast. The Dockum underlies the Ogallala, Pecos Valley, Edwards-Trinity Plateau, and Edwards-Trinity High Plains aquifers.

There were 294 samples analyzed for arsenic during the study period with 158 samples (54%) having detectable concentrations. About 38% of the area has no probability of arsenic > 5 µg/L and a further 60% has very low to moderate probability of arsenic >5 µg/L. Only about 2% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L. The spatial pattern of probabilities displays artifacts of limited data density, particularly in the confined areas. The median concentration of samples with detectable concentrations is 2.7 µg/L and the 5th-95th percentile range is 0.8–9.8 µg/L. A total of 15 samples (5.1%) exceeded the MCL with a range of concentrations from 11.3 µg/L to 45.1 µg/L.

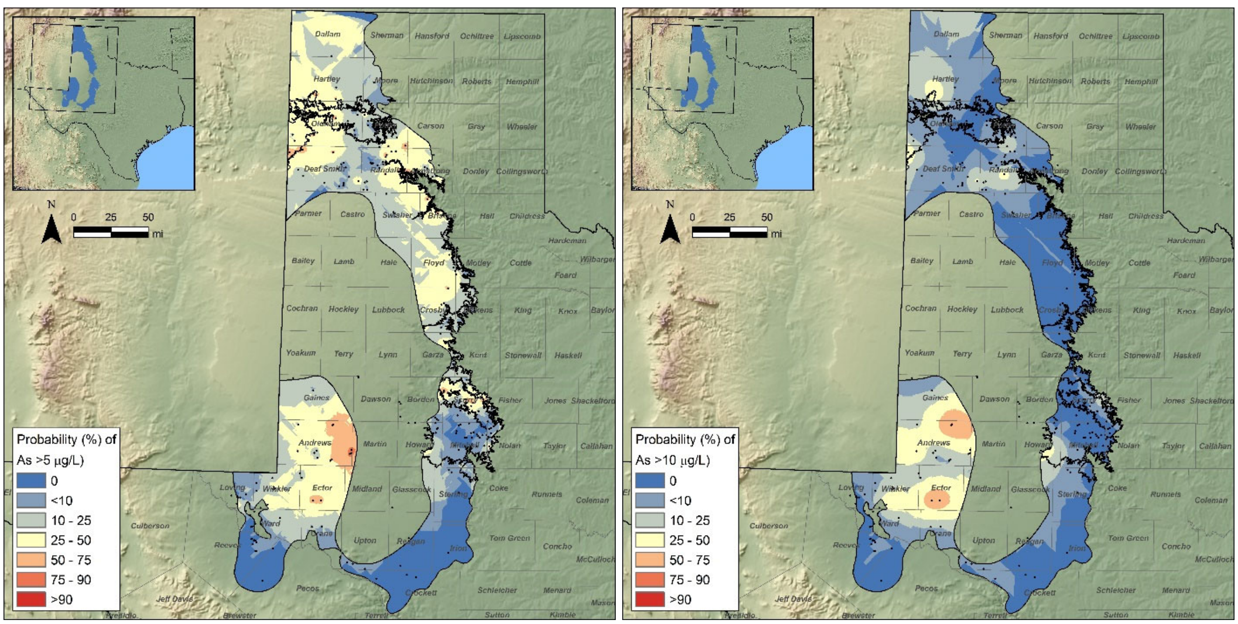


Figure 19. Dockum aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right). While the Dockum is continuous and present in the central “empty” region of the figure, the TWDB limits the extents of the defined aquifer to regions that have water with total dissolved solids (TDS) <3000 mg/L.

Based on the TCEQ PWS database, a total of 11 PWS systems are impacted by arsenic concentrations >5 µg/L, including 6 public entities and 5 distribution systems with a population of 2,337 people. Based on the EPA PWS database, there are no PWS water supply systems that are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is high at 14,057 located primarily in Randall, Potter, and Deaf Smith counties in the north and Ector, Andrews, Gaines and Howard counties in the south. However, these areas also lie within the limits of the Ogallala aquifer and the numbers of domestic wells in the Dockum is likely very small. Accordingly, the estimated non-PWS at-risk population is zero.

Ellenburger-San Saba Aquifer

The Ellenburger-San Saba aquifer covers 5,400 mi^2 and extends across parts of 16 counties surrounding the Llano Uplift in central Texas (Figure 20). The aquifer is composed of a limestones and dolomites of the Tanyard, Gorman, and Honeycut formations of the Ellenburger Group and the San Saba limestone of the Wilberns Formation and total thickness ranges up to 2,700 ft thick. The confined areas of the aquifer dip away from the uplift to depths of 3,000 ft and are compartmentalized by regional block faulting.

There were 119 samples analyzed for arsenic during the study period with only 14 samples (12%) having detectable concentrations. About 63% of the area has no probability of arsenic > 5 µg/L and a further 37% has very low to moderate probability of arsenic >5 µg/L. Only about 0.1% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L. The kriging results display artifacts limited data in large areas of the aquifer and the high probability areas are confined to very small areas around the offending well, potentially due to the fault compartmentalization. The median concentration of samples with detectable concentrations is 2.3 µg/L and the 5^{th}-95^{th} percentile range is 0.7–8.2 µg/L. There are no samples that exceed the 10 µg/L MCL.

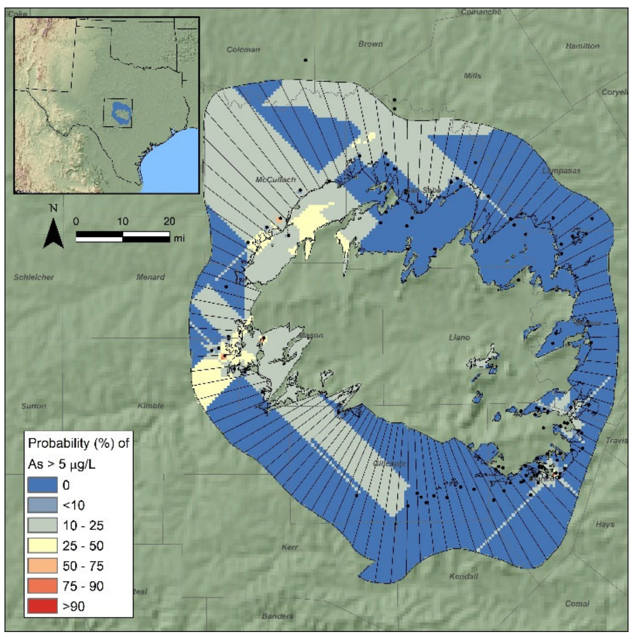


Figure 20. Ellenburger-San Saba aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Ellenburger-San Saba aquifer that exceed the 10 µg/L MCL concentration.

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Hickory Aquifer

The Hickory aquifer covers 8,600 mi^2 and extends across parts of X counties surrounding the Llano Uplift in central Texas (Figure 21). The aquifer is composed of parts of the Hickory Sandstone Member of the Riley Formation with a total thickness ranging up to 480 ft thick. While water quality is generally good in the Hickory aquifer with TDS < 1,000 mg/L, the primary contaminants of concern are radium and associated radon and gross alpha radiation.

There were 136 samples analyzed for arsenic during the study period with only 24 samples (18%) having detectable concentrations. The kriging results display artifacts resulting from limited data in large areas of the aquifer and the high probability areas are confined to very small areas around the offending wells, potentially due to fault compartmentalization similar as in the Ellenburger-San Saba aquifer. About 90% of the Hickory area has no probability of arsenic > 5 µg/L and a further 5% has very low to moderate probability of arsenic >5 µg/L. About 4% of the area has elevated to high probabilities, and only about 1% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L. The median concentration of samples with detectable concentrations is 2.8 µg/L and the 5th-95th percentile range is 0.8–7.0 µg/L. There are no samples that exceed the 10 µg/L MCL.

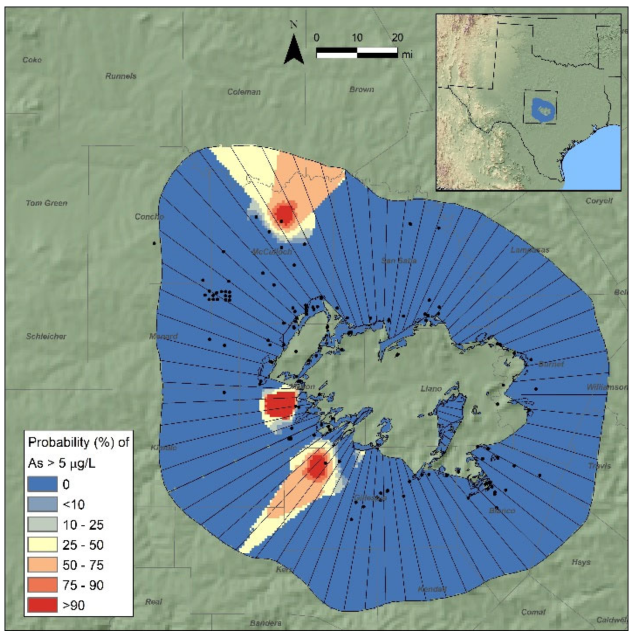


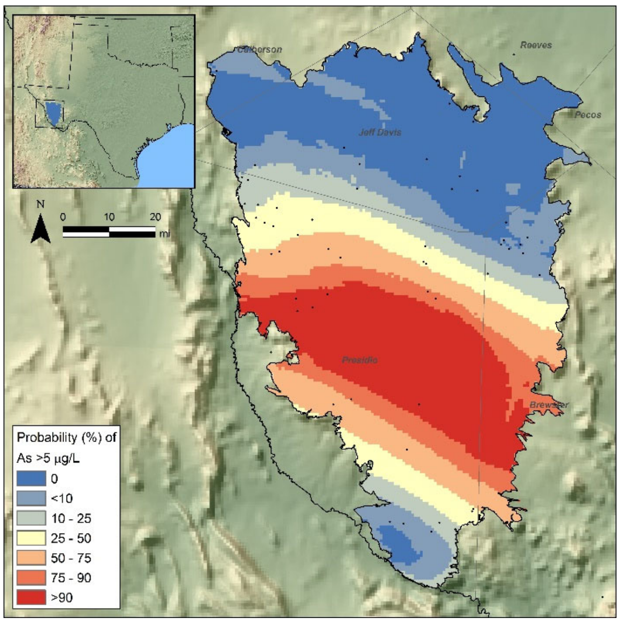
Figure 21. Hickory aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Hickory aquifer that exceed the 10 µg/L MCL concentration.

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Igneous Aquifer

The Igneous aquifer covers 6,100 mi^2 and extends across parts of 6 counties in western Texas primarily in Presidio, Jeff Davis, and Brewster counties with minor areas in Culberson, Reeves, and Pecos counties (Figure 22). The aquifer is composed of a complex series of pyroclastic and volcanoclastic sediments up to 6,000 ft thick. The Igneous underlies parts of the West Texas Bolson aquifer.

There were 64 samples analyzed for arsenic during the study period with 40 samples (63%) having detectable concentrations. About 28% of the area has no probability of arsenic > 5 µg/L and a further 31% has very low to moderate probability of arsenic >5 µg/L. About 41% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L. There are limited data particularly in the central region where probabilities are the highest. The median concentration of samples with detectable concentrations is 4.9 µg/L and the 5th-95th percentile range is 1.3–17.8 µg/L. A total of 12 samples (19%) exceeded the MCL with a range of concentrations from 10.9 µg/L to 33.1 µg/L.



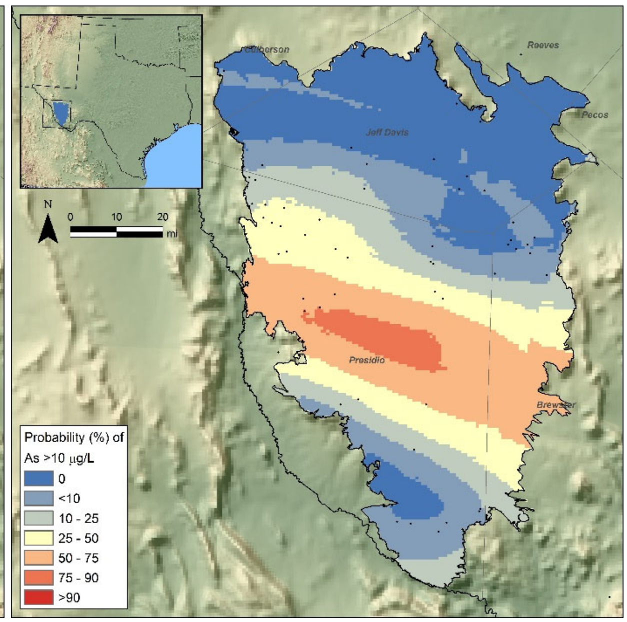


Figure 22. Igneous aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database, a total of 4 PWS systems, all distribution systems, are impacted by arsenic concentrations >5 µg/L with a total population of 2,808 people. Based on the EPA PWS database, there is 1 PWS water supply distribution system that is seriously impacted by arsenic concentrations >10 µg/L with a population of 84 people (Table 18). The estimated non-PWS system at-risk population of >10 µg/L is small at 146. However, this is possibly an over-estimate as the population density is generally very low in this region.

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

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
1890011	Candelaria Water Supply Co.	Comm.	GW	Public	Yes	12	84

Lipan Aquifer

The Lipan aquifer covers 2,000 mi^2 and extends across parts of x counties in western Texas primarily in Presidio, Jeff Davis, and Brewster counties with minor areas in Culberson, Reeves, and Pecos counties (Figure 22). The aquifer is composed of valley fill alluvium with up to about 125 ft of saturated thickness. General water quality in the Lipan ranges from about 350 mg/L to 3,000 mg/L TDS. The primary contaminant of concern in the Lipan is nitrate and the aquifer is used primarily for irrigation.

There were 62 samples analyzed for arsenic during the study period with 50 samples (81%) having detectable concentrations. About 60% of the area has no probability of arsenic > 5 µg/L and a further 37% has very low to moderate probability of arsenic >5 µg/L. About 3% of the total aquifer area has elevated to high probabilities of arsenic >5 µg/L. The data are limited to the central region of the valley floor and there are no samples from the narrower upland regions to the west and northwest or from the southern confined region. The median concentration of samples with detectable concentrations is 3.1 µg/L and the 5th-95th percentile range is 2.2–6.5 µg/L. There are no samples that exceeded the 10 µg/L MCL.

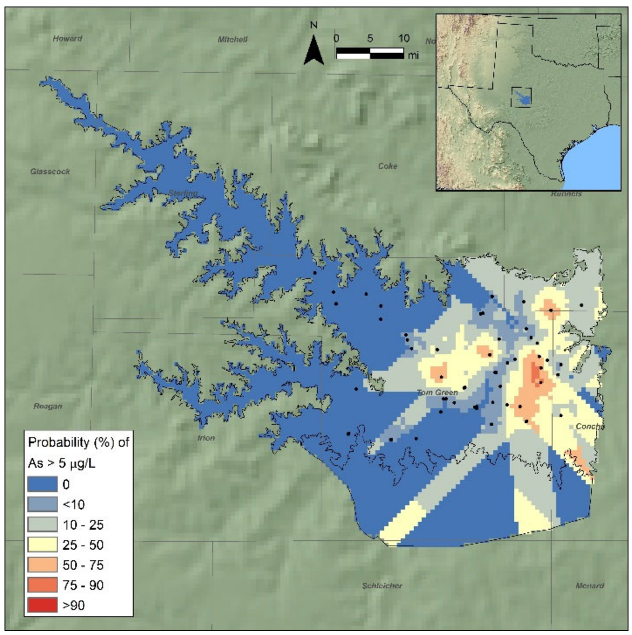


Figure 23. Lipan aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Lipan aquifer that exceed the 10 µg/L MCL concentration.

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Queen City Aquifer

The Queen City aquifer covers 15,800 mi^2 and extends across parts of 42 counties in the upper coastal plain of Texas (Figure 24). The aquifer is composed of sands and loosely cemented sandstones with an average fresh water saturated thickness of 140 ft. General water quality in the Queen City is generally less than 1,000 mg/L.

There were 223 samples analyzed for arsenic during the study period with only 15 samples (7%) having detectable concentrations. The entire aquifer area has no probability of arsenic > 5 µg/L as the highest concentration measured is 4.3 µg/L. The median concentration of samples with detectable concentrations is 1.5 µg/L and the 5th-95th percentile range is 1.0–3.7 µg/L. There are no samples that exceeded the 10 µg/L MCL.

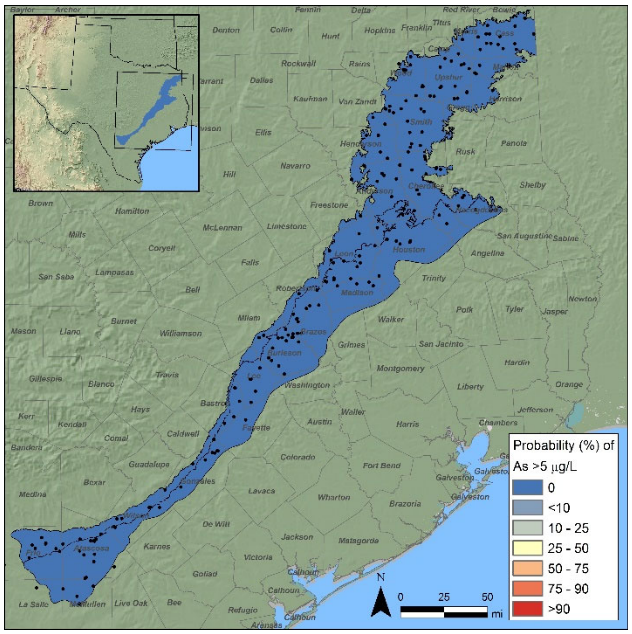


Figure 24. Queen City aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Queen City aquifer that exceed the 10 µg/L MCL concentration.

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Sparta Aquifer

The Sparta aquifer covers 7,900 mi^2 and extends across parts of 25 counties in the upper coastal plain of Texas (Figure 25). The aquifer is represented by the Sparta Formation of the Claiborne Group with a freshwater saturated thickness of about 120 ft. General water quality in the Sparta is less than 1,000 mg/L TDS.

There were 119 samples analyzed for arsenic during the study period with only 5 samples (4%) having detectable concentrations. About 96% of the area has no probability of arsenic > 5 µg/L and a further 4% has a low probability of arsenic >5 µg/L. The median of samples with detectable concentrations is 3.8 µg/L and the 5th-95th percentile range is 1.3–9.5 µg/L. There is one sample that exceeded the 10 µg/L MCL (10.8 µg/L).

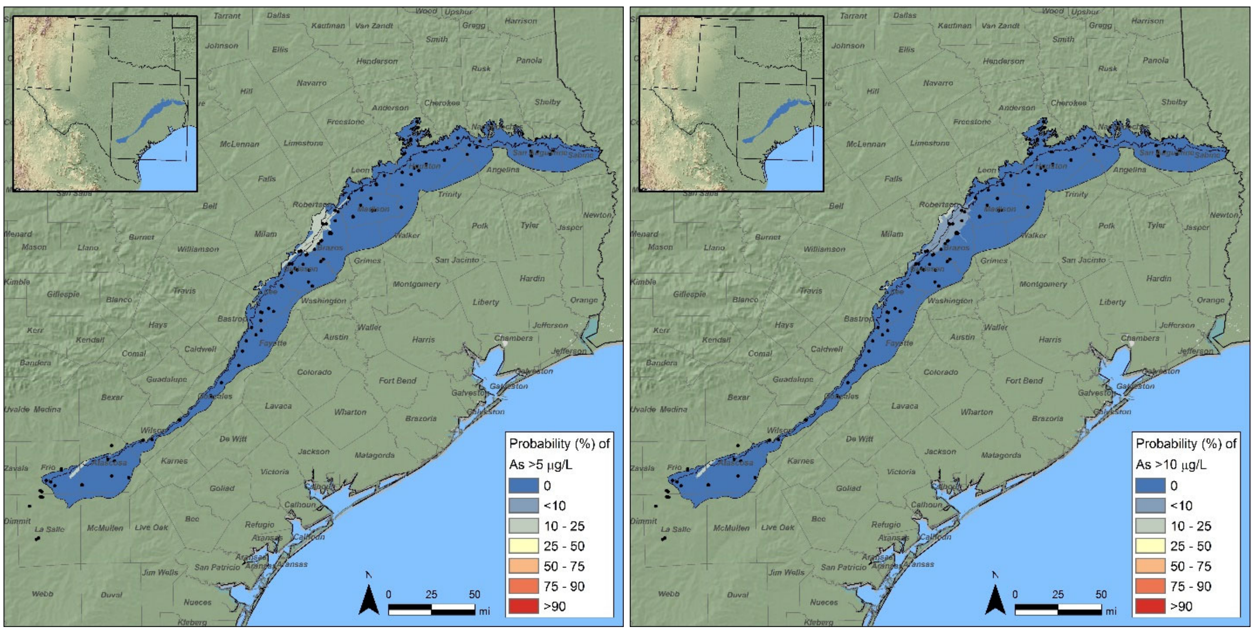


Figure 25. Sparta aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

There are no PWS systems impacted by arsenic concentrations >5 µg/L and therefore no PWS water supply systems are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is 253 people.

West Texas Bolsons Aquifer

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

There were 91 samples analyzed for arsenic during the study period with 67 samples (74%) having detectable concentrations. About 65% of the area has a very low to moderate probability of arsenic >5 µg/L. About 35% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L. There are limited data and one bolson has no data. The median concentration of samples with detectable concentrations is 6.7 µg/L and the 5th-95th percentile range is 2.2–19.2 µg/L. A total of 17 samples (19%) exceeded the MCL with a range of concentrations from 10.3 µg/L to 46.7 µg/L.

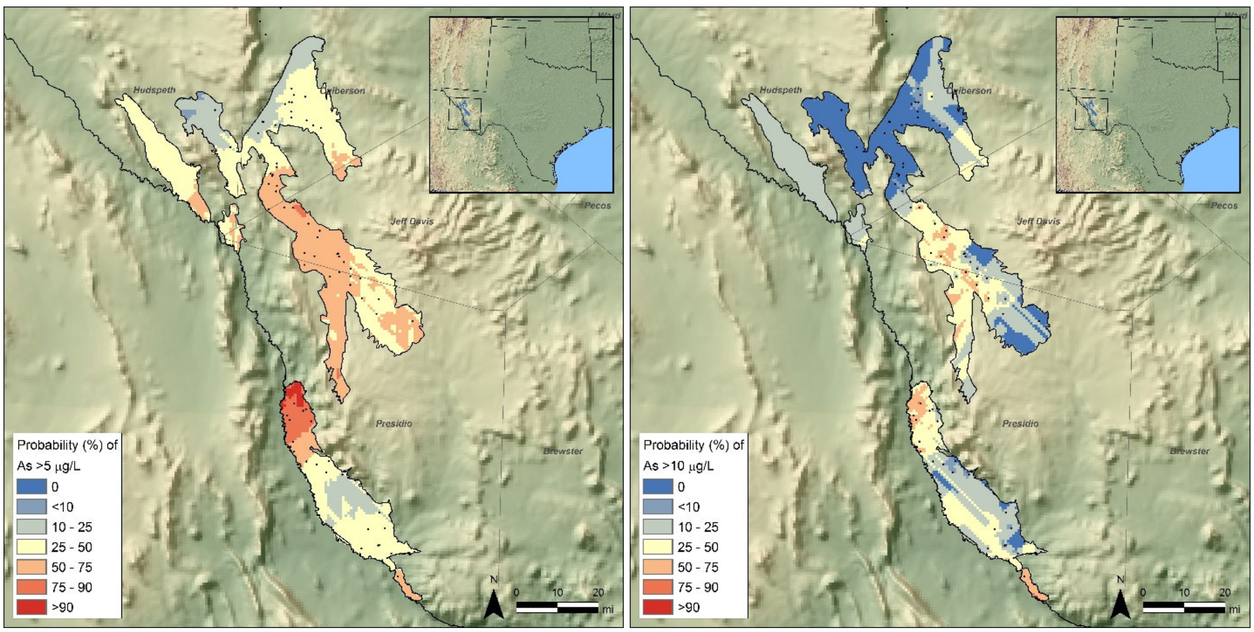


Figure 26. West Texas Bolsons aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database there is one PWS system impacted by arsenic concentrations >5 µg/L with a total population of 156 people. Based on the EPA PWS database, there are no PWS water supply distribution systems that are impacted by arsenic concentrations >10 µg/L. The estimated non-PWS system at-risk population of >10 µg/L is small at 49.

Woodbine Aquifer

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

There were 168 samples analyzed for arsenic during the study period with 13 samples (8%) having detectable arsenic concentrations. About 99.5% of the area has no probability of arsenic >5 µg/L. About 0.5% of the total aquifer area has elevated to very high probabilities of arsenic >5 µg/L. The median concentration of samples with detectable concentrations is 2.3 µg/L and the 5th-95th percentile range is 0.4–6.2 µg/L. There are no samples that exceed the 10 µg/L MCL.

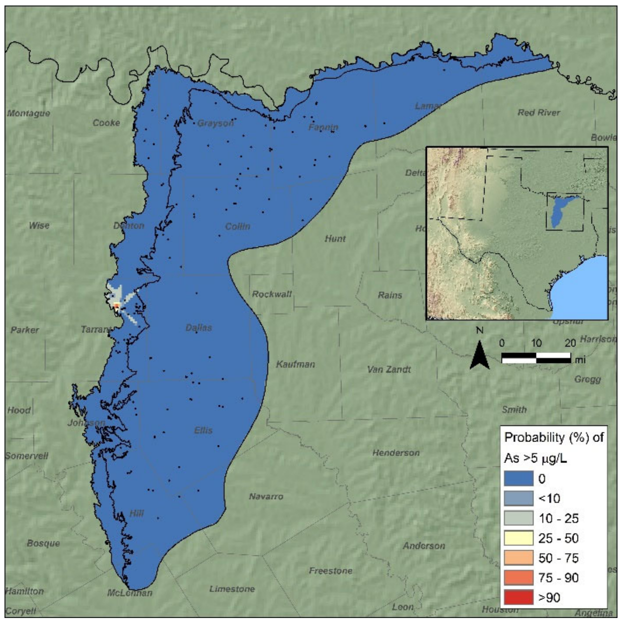


Figure 27. Woodbine aquifer probability distribution of arsenic >5 µg/L. There are no groundwater samples from the Woodbine aquifer that exceed the 10 µg/L MCL concentration.

Based on the TCEQ PWS database there are no PWS system impacted by arsenic concentrations >5 µg/L. Based on the EPA PWS database, there are no PWS water supply distribution systems that are impacted by arsenic concentrations >10 µg/L. The non-PWS system at-risk population of >10 µg/L is zero.

Yegua-Jackson Aquifer

The Yegua-Jackson aquifer covers 10,900 mi^2 and extends across parts of 34 counties in west Texas in Presidio, Jeff Davis, Culberson, and Hudspeth counties (Figure 28). The aquifer is composed of a series of basin-fill deposits ranging up to 3,000 ft thick with an average freshwater saturated thickness of 580 ft. Water quality is locally <1,000 mg/L TDS but ranges up to 4,000 mg/L TDS.

There were 145 samples analyzed for arsenic during the study period with 19 samples (13%) having detectable concentrations. About 25% of the area has no probability of arsenic >5 µg/L while 75% of the area has a very low to moderate probability of arsenic >5 µg/L. There are limited data in the southern areas of the aquifer where arsenic concentrations are the highest. The median concentration of samples with detectable concentrations is 3.7 µg/L and the 5^{th}-95^{th} percentile range is 2.1–26.6 µg/L. A total of 6 samples (4%) exceeded the MCL with a range of concentrations from 10.7 µg/L to 47 µg/L.

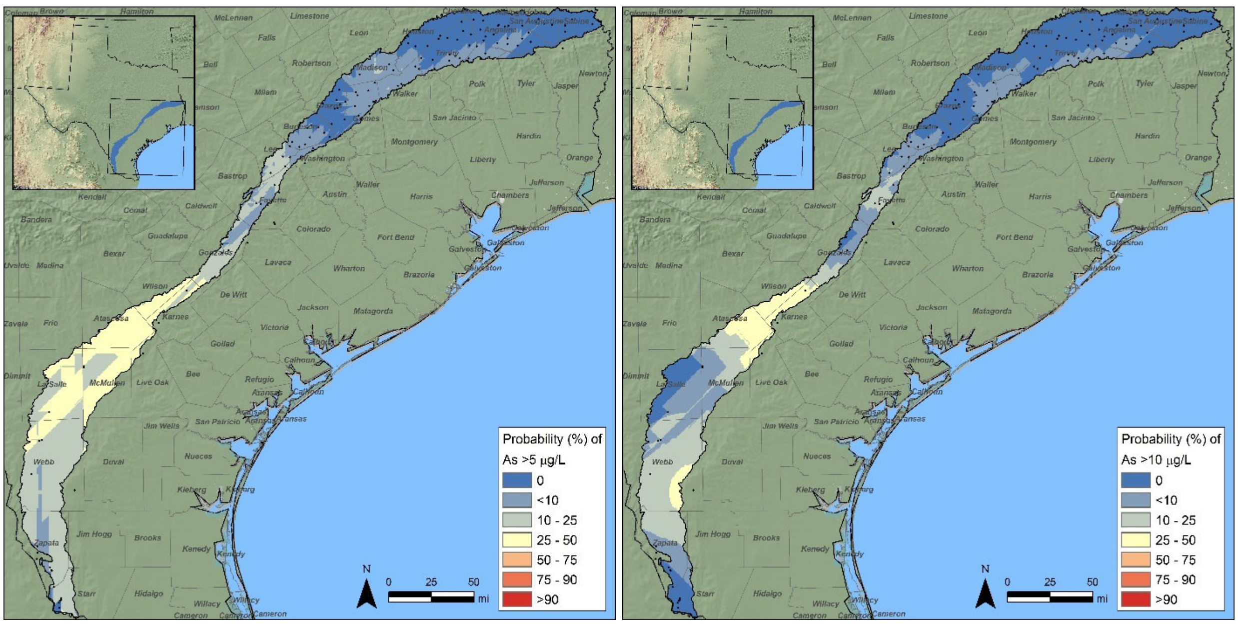


Figure 28. Yegua-Jackson aquifer probability distribution of arsenic >5 µg/L (left) and >10 µg/L (right).

Based on the TCEQ PWS database there are four PWS system impacted by arsenic concentrations >5 µg/L with a total population of 8,863 people. Based on the EPA PWS database, there is one PWS water supply distribution system that is impacted by arsenic concentrations >10 µg/L with an associated population of 183 people (Table 19). The estimated non-PWS system at-risk population of >10 µg/L is 1,187 people.

Table 19. Yegua-Jackson aquifer PWS systems with violations for arsenic concentrations based on the US EPA database.

PWS ID	*Name*	*System Type*	*Primary Source*	*Ownership*	*Serious Violator*	*Quarters w/ Violations*	*Population Served*
2030010	Anthony Harbor Subdivision	Comm.	GW	Private	Yes	12	183

Summary

Quantifying the spatial distribution of groundwater arsenic concentrations in aquifers in Texas is critical for managing groundwater resources in the state. Previous studies show that arsenic hotspots in the southern High Plains and southern Gulf Coast aquifers originate from geologic sources. This study evaluated the probability of groundwater arsenic levels exceeding threshold levels of 5 µg/L, considered above background, and exceeding 10 µg/L (the EPA MCL) using 10,495 analyses from 1992 – 2017. Results of the study highlight hotspots of arsenic contamination with high probabilities (> 50%) in the southern Ogallala aquifer, southern Gulf Coast aquifer, the Hueco-Mesilla Bolson and West Texas Bolsons aquifers, and the Trinity aquifer. The number of water samples that exceeded the MCL totaled 733 (7% of all analyses).

Most of the Texas population is served with water from PWS systems, totaling 26.2 million in 2015 (95% of population of 27.5 million) whereas the number of people relying on domestic water supplies totaled 1.3 million in 2015 (5% of population). There are 78 non-compliant PWS systems that source water from one of the major or minor aquifers that provide water to ~100,000 people. These system locations are generally consistent with the hotspots of arsenic contamination, with 25 PWS systems in the southern Gulf Coast, 37 in the southern High Plains, and 12 in the Trinity Aquifer, east of Waco. The number of PWS systems does not reflect the populations being served with 12 systems in the Gulf Coast serving 43,141 people and 12 systems east of Waco serving 40,226 people. Texas ranks second in the nation for both the total state population at-risk of PWS arsenic violations (99,653 people) and the total number at risk of serious PWS violations (21,761). Based on a county level analysis, it is estimated that there are a further 81,500 people with non-PWS system water exceeding the EPA MCL in Texas.

Acknowledgements

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Appendix I – Enlarged Maps

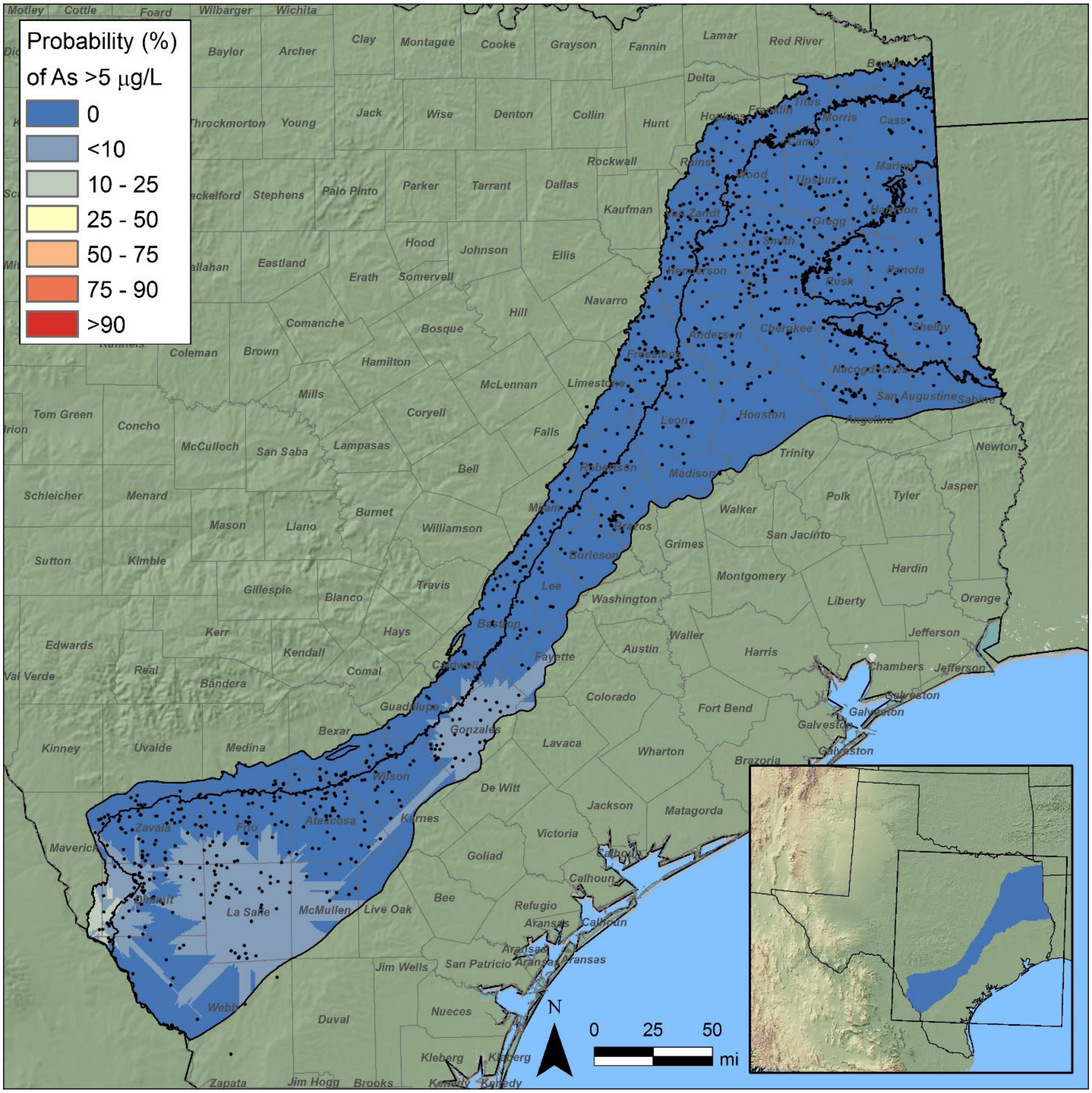

Figure 9. Carrizo-Wilcox aquifer probability distribution of arsenic >5 μg/L.

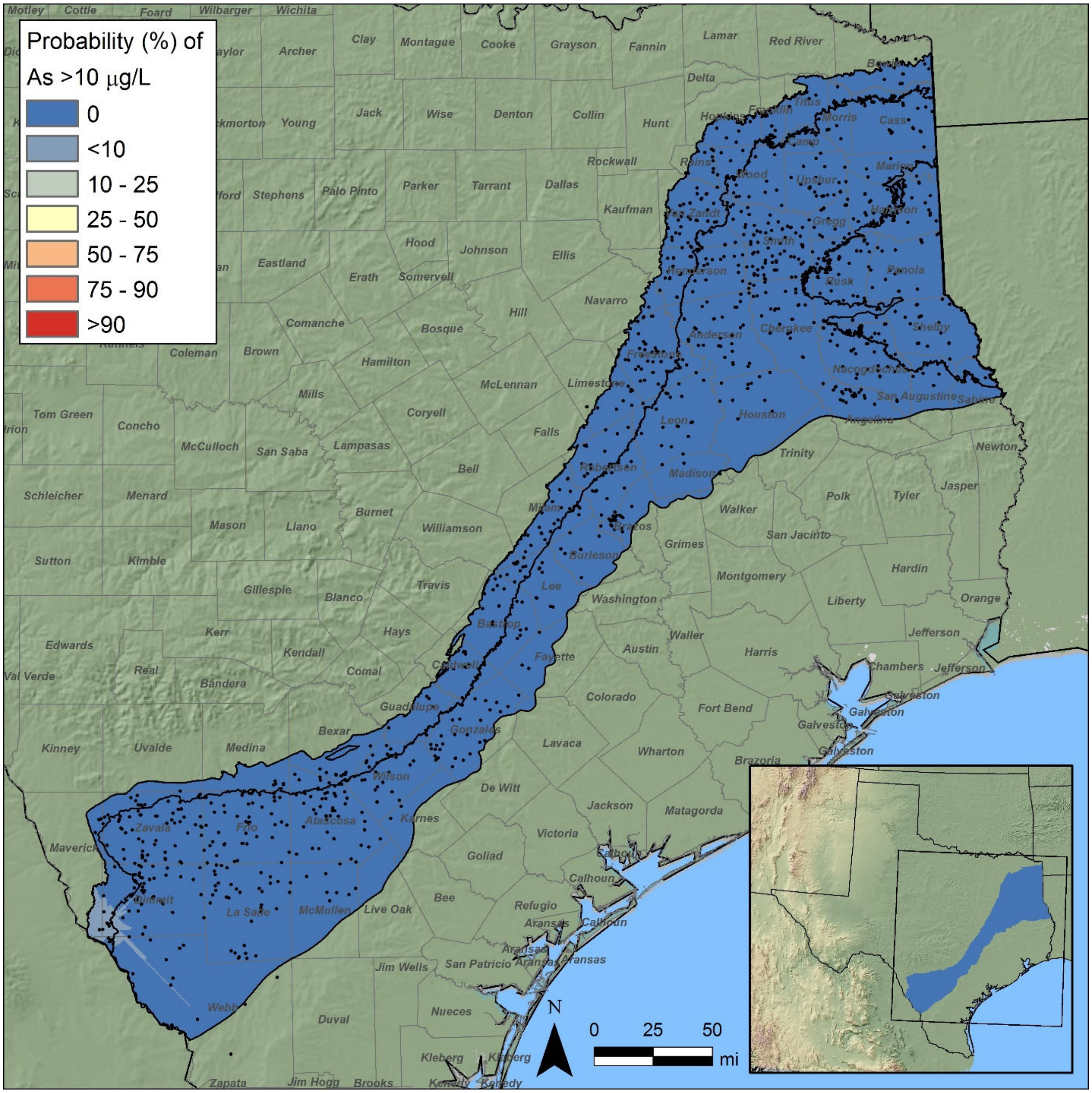

Figure 9. Carrizo-Wilcox aquifer probability distribution of arsenic >10 µg/L.

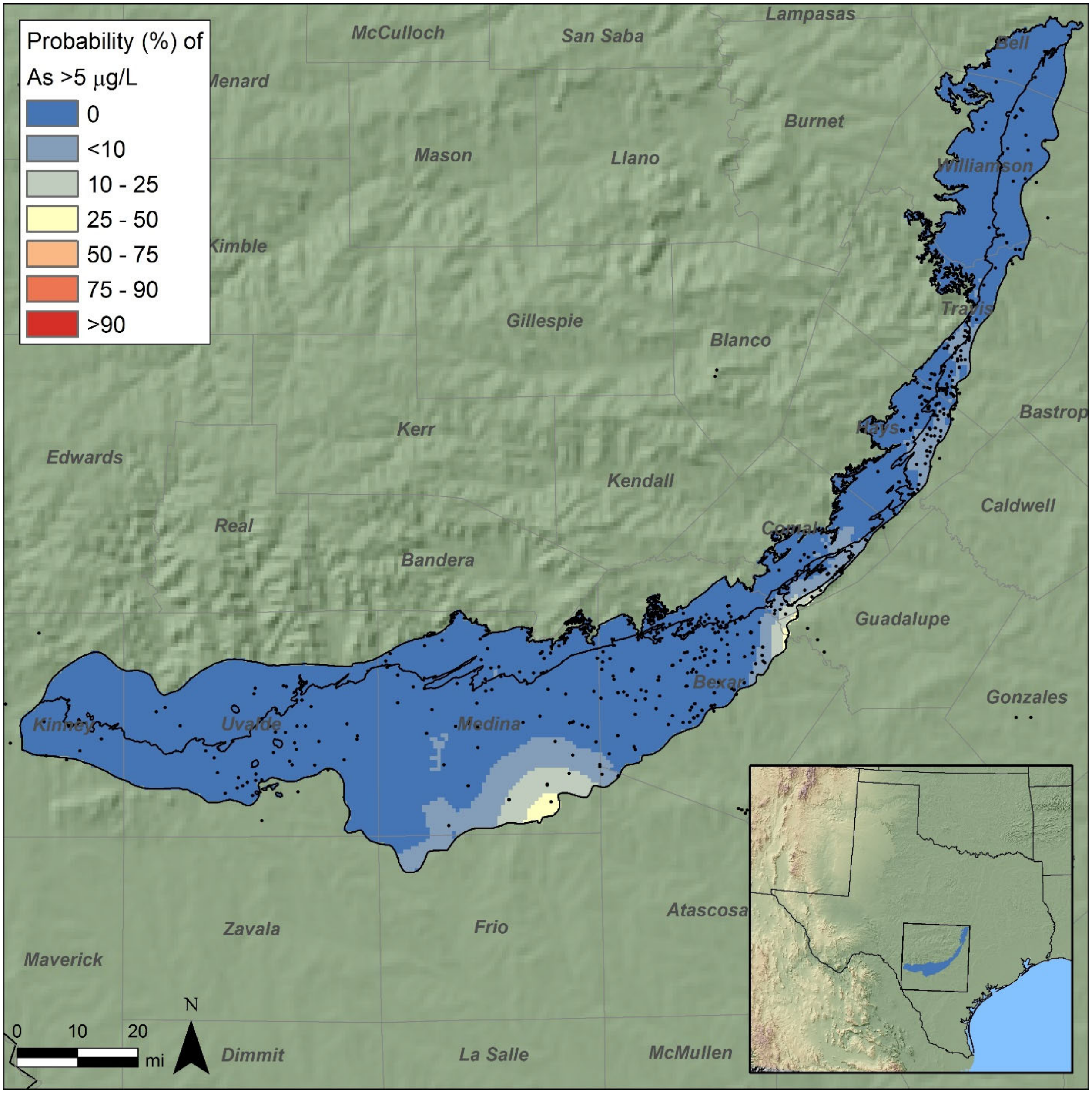

Figure 10. Edwards (BFZ) aquifer probability distribution of arsenic >5 µg/L.

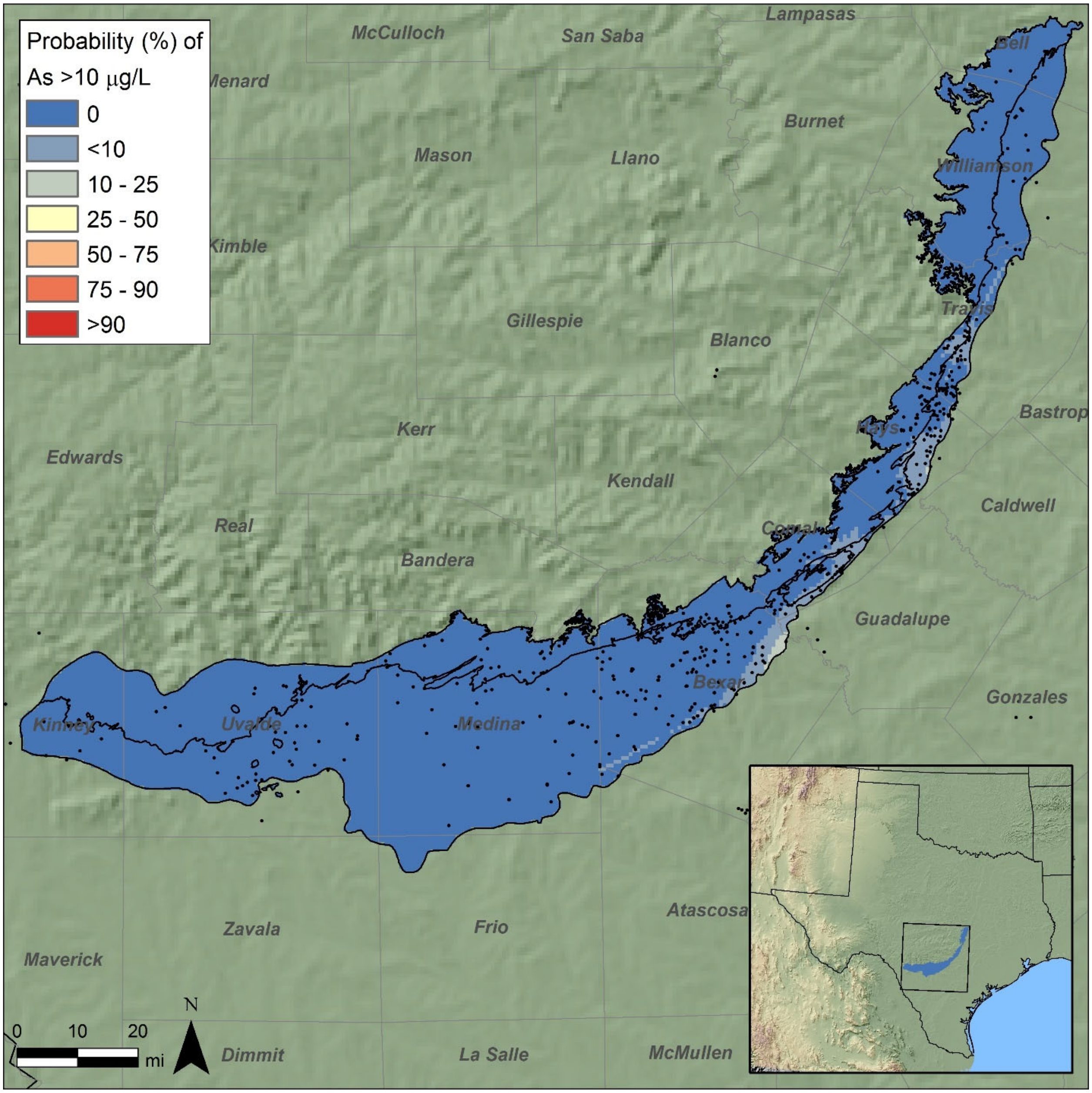

Figure 10. Edwards (BFZ) aquifer probability distribution of arsenic >10 μg/L.

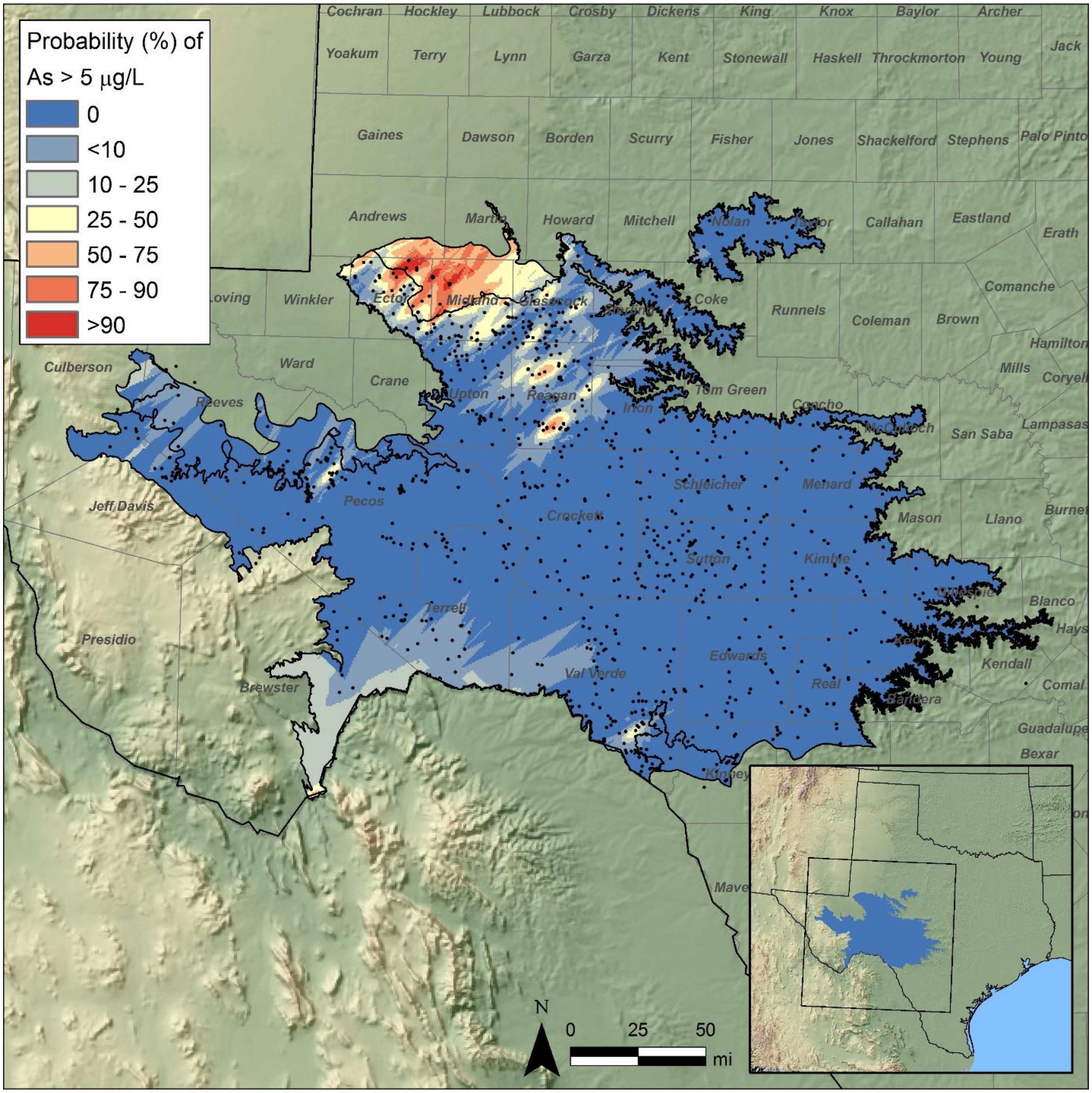

Figure 11. Edwards-Trinity Plateau aquifer probability distribution of arsenic >5 µg/L.

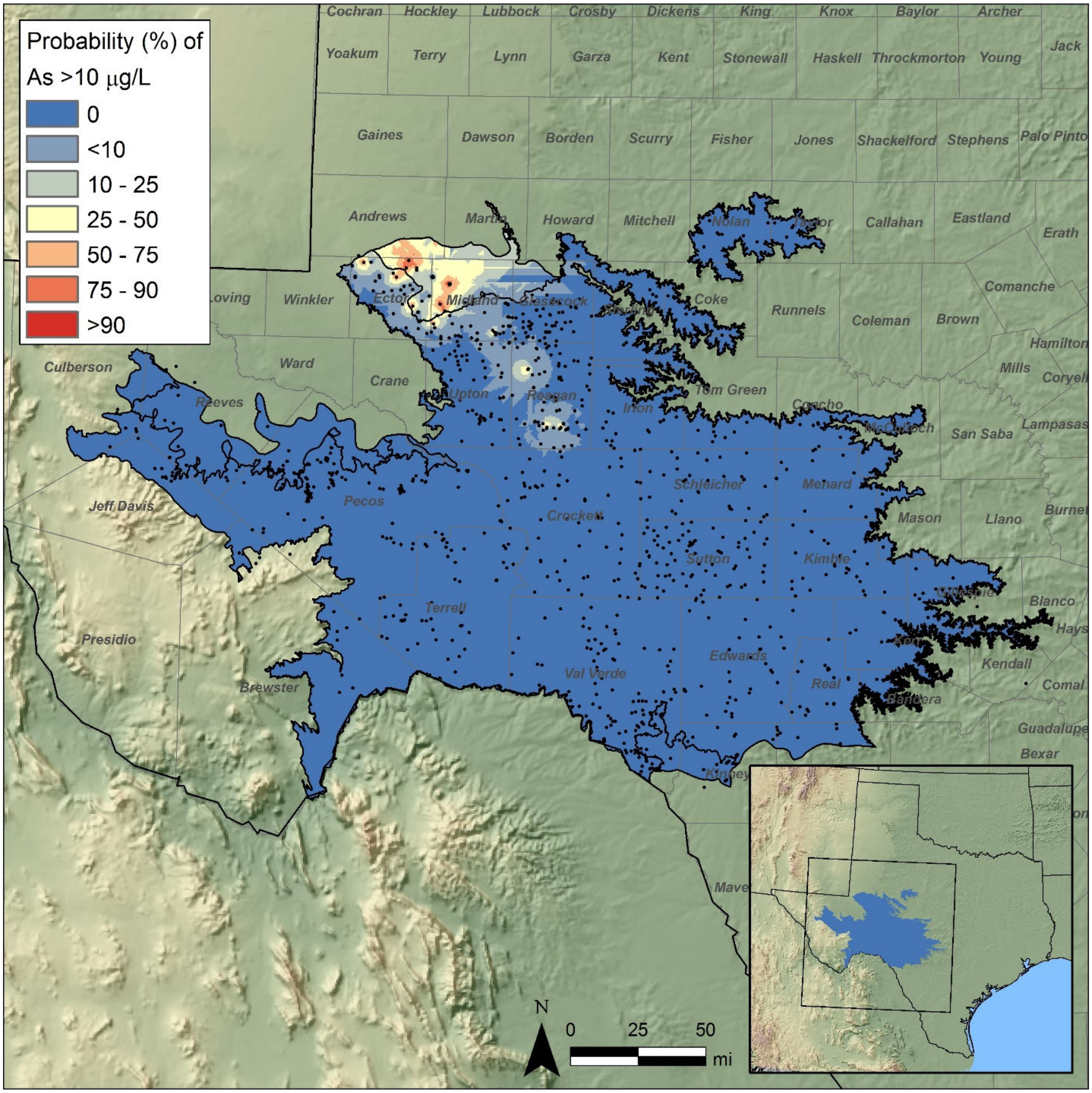

Figure 11. Edwards-Trinity Plateau aquifer probability distribution of arsenic >10 µg/L.

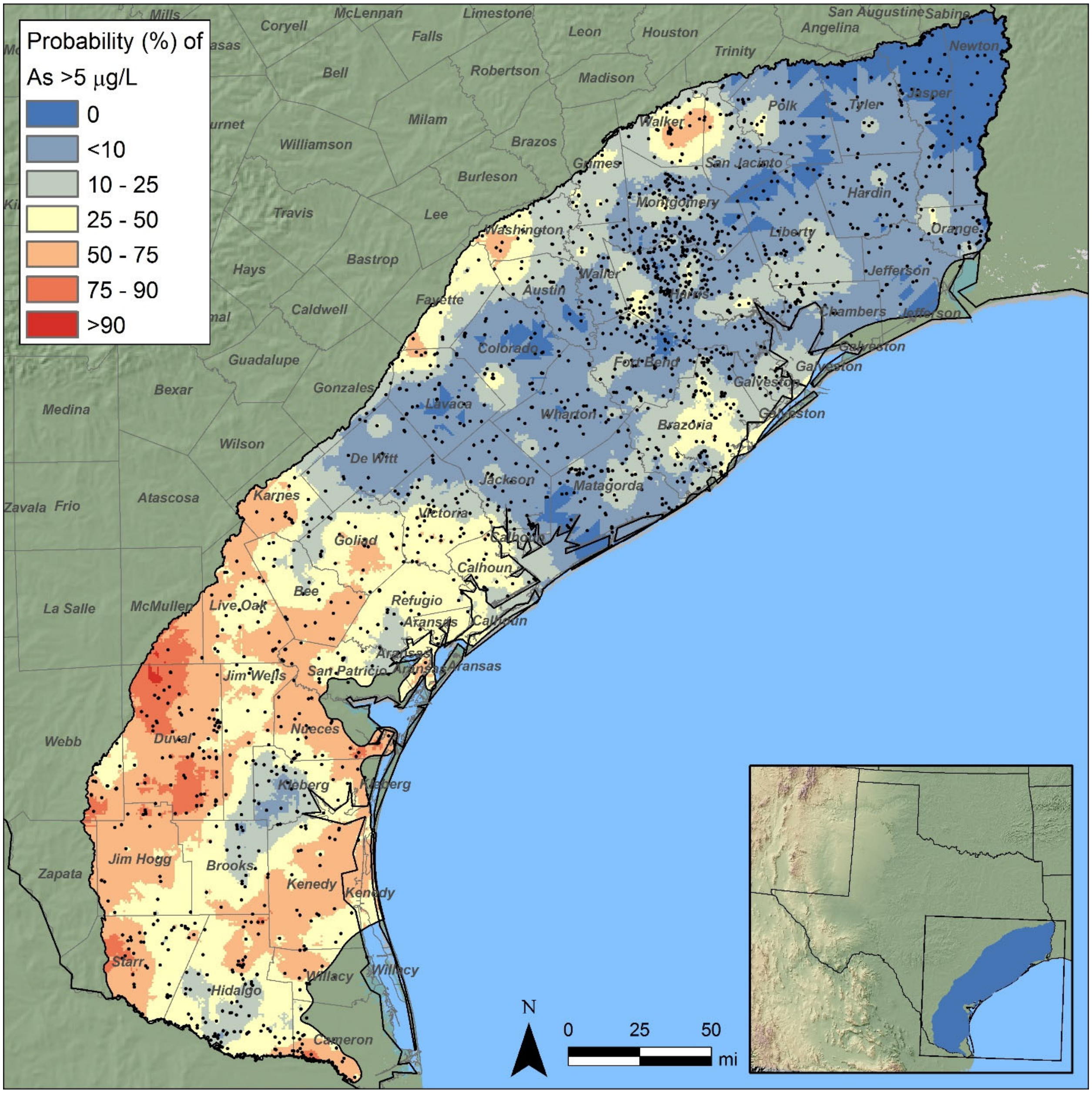

Figure 12. Gulf Coast aquifer system probability distribution of arsenic >5 µg/L.

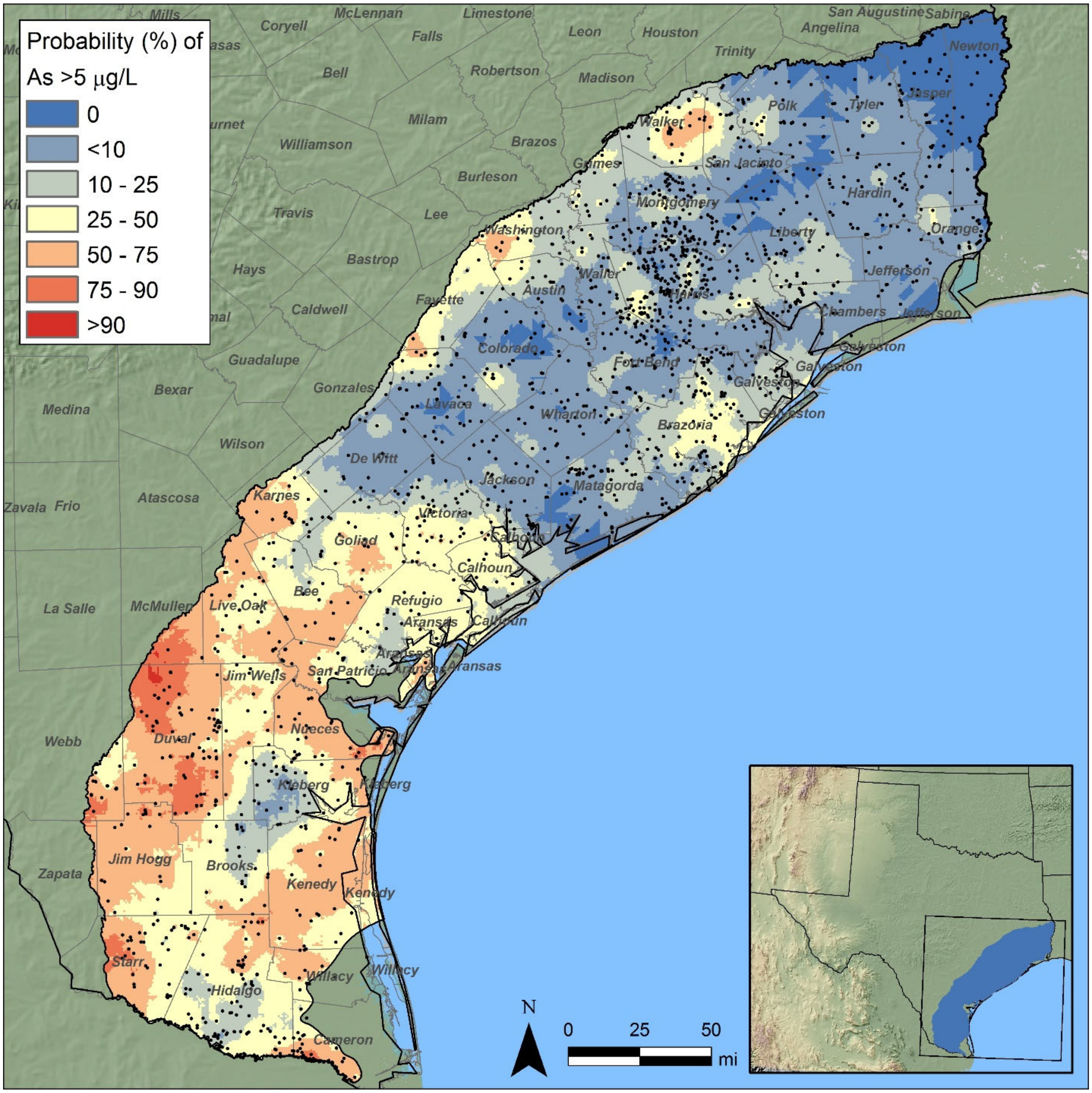

Figure 12. Gulf Coast aquifer system probability distribution of arsenic >10 μg/L.

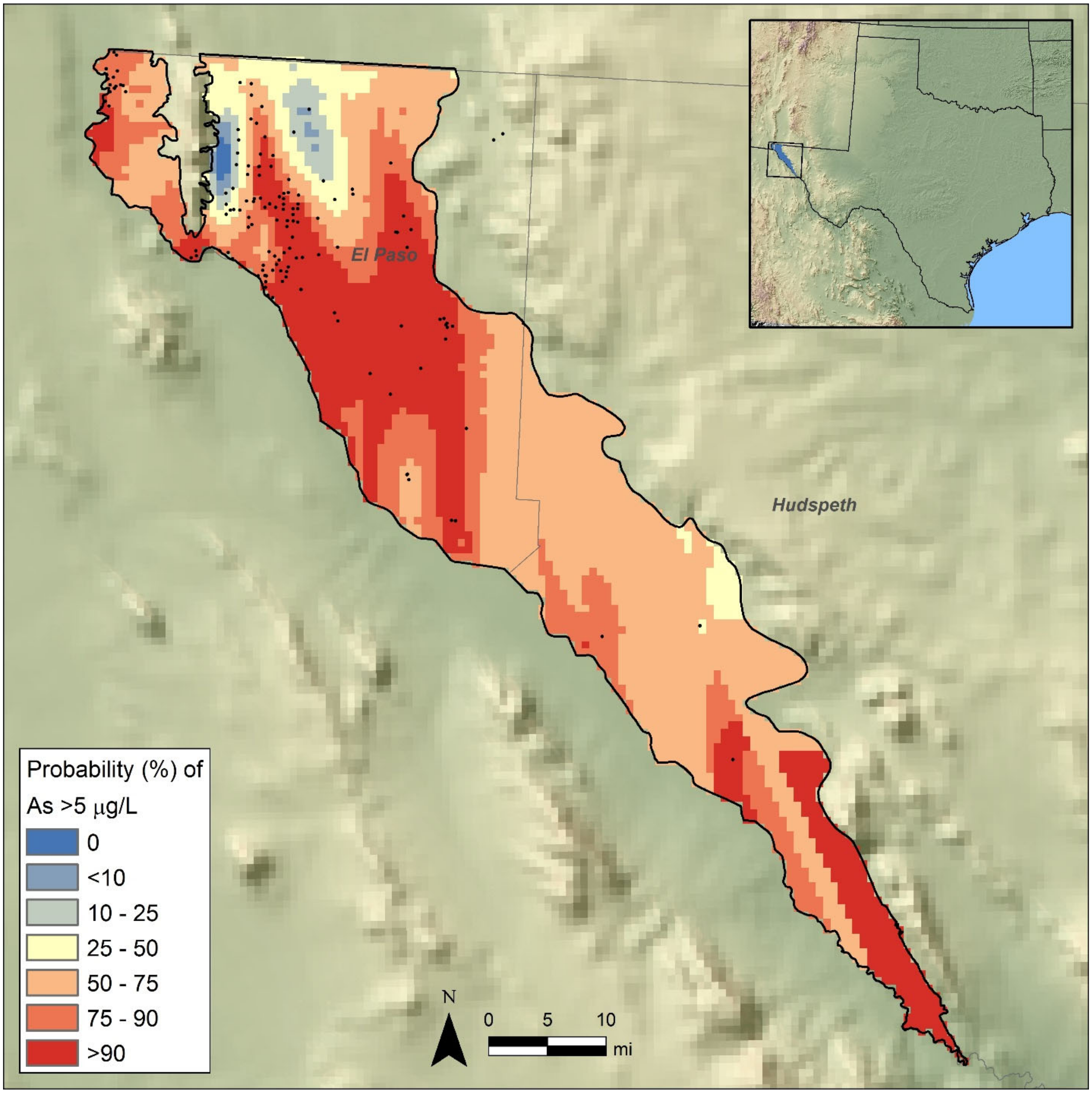

Figure 29. Hueco-Mesilla Bolson aquifer probability distribution of arsenic >5 µg/L.

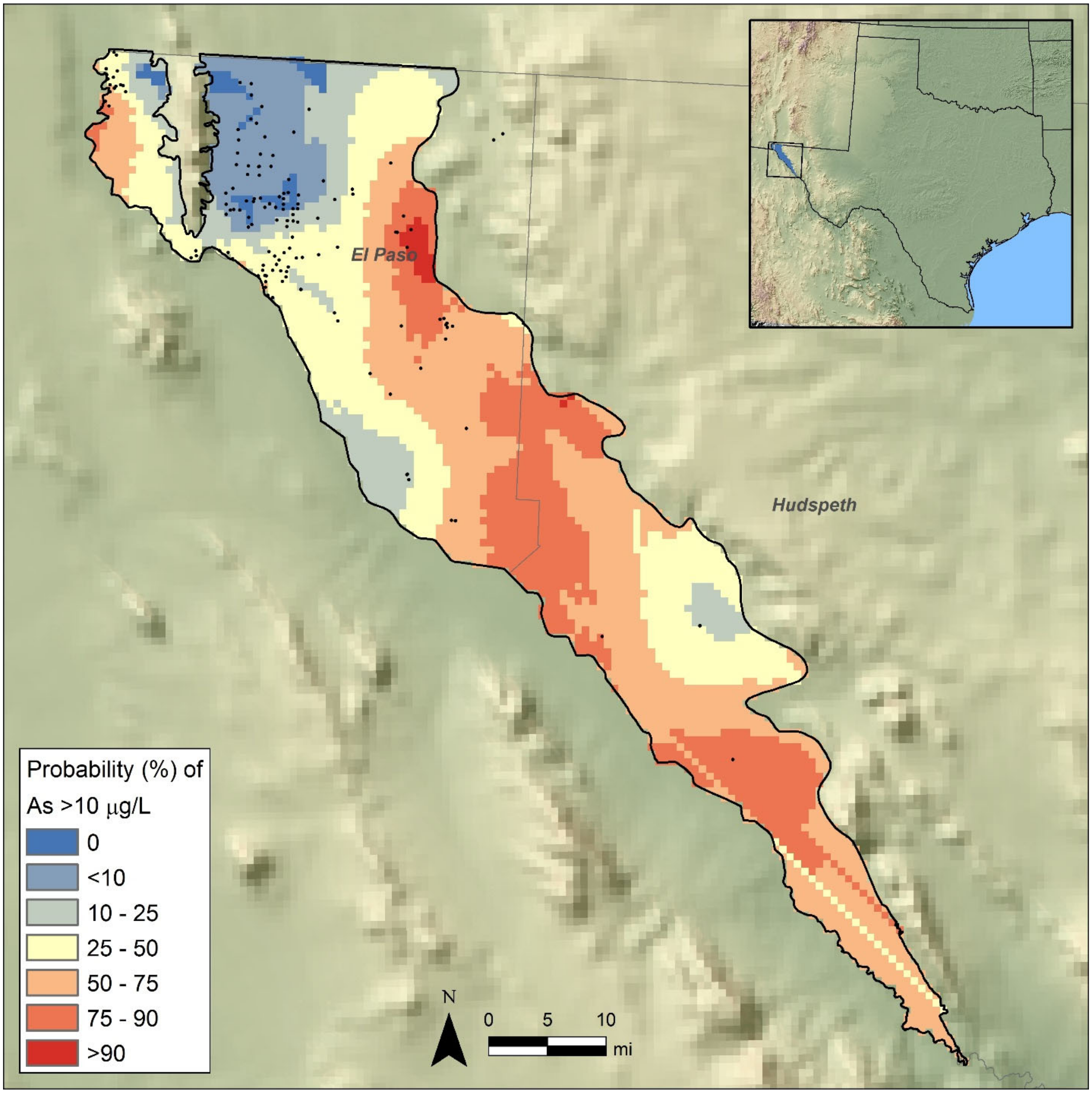

Figure 30. Hueco-Mesilla Bolson aquifer probability distribution of arsenic >10 µg/L.

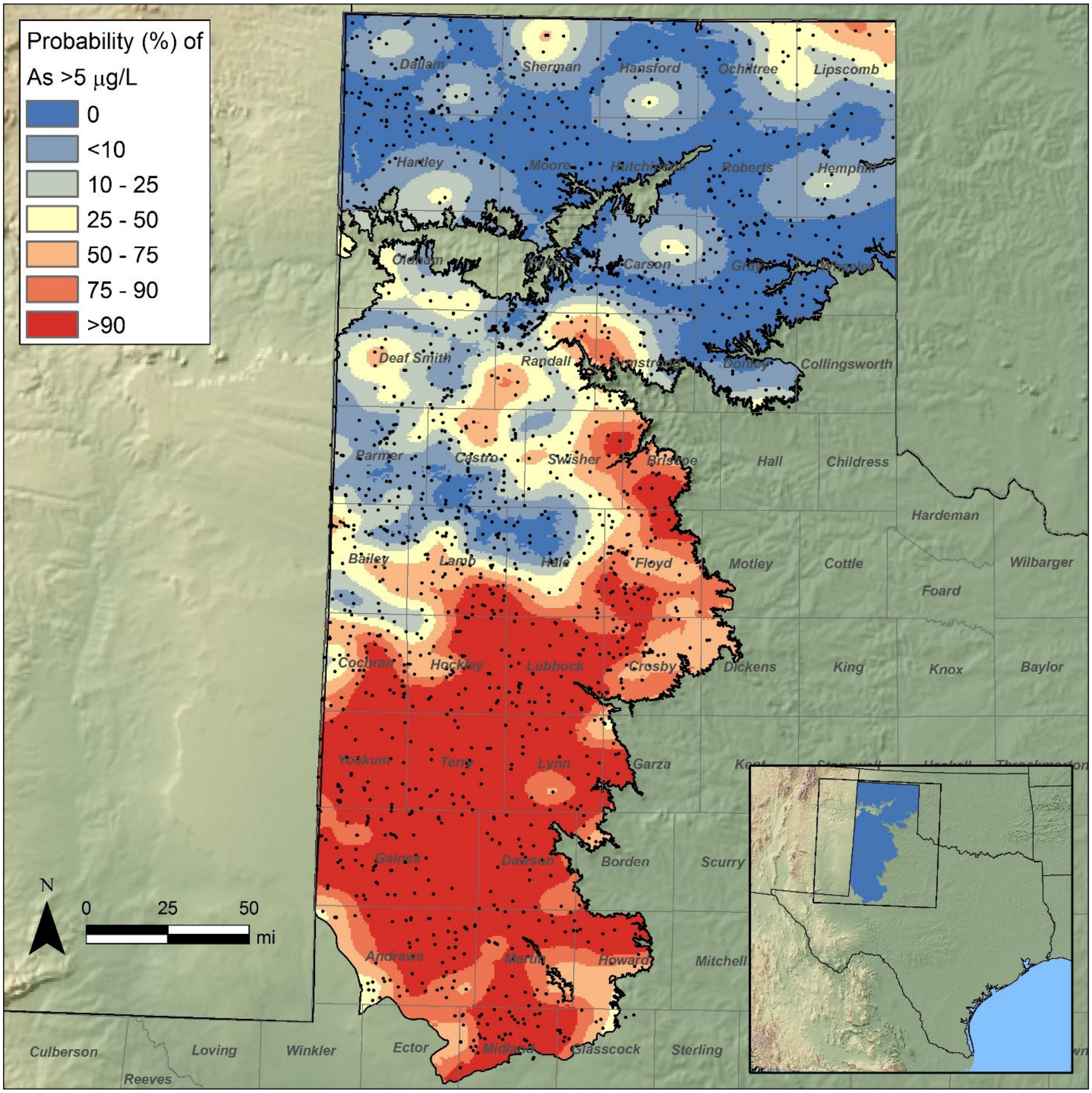

Figure 14. Ogallala aquifer probability distribution of arsenic >5 µg/L.

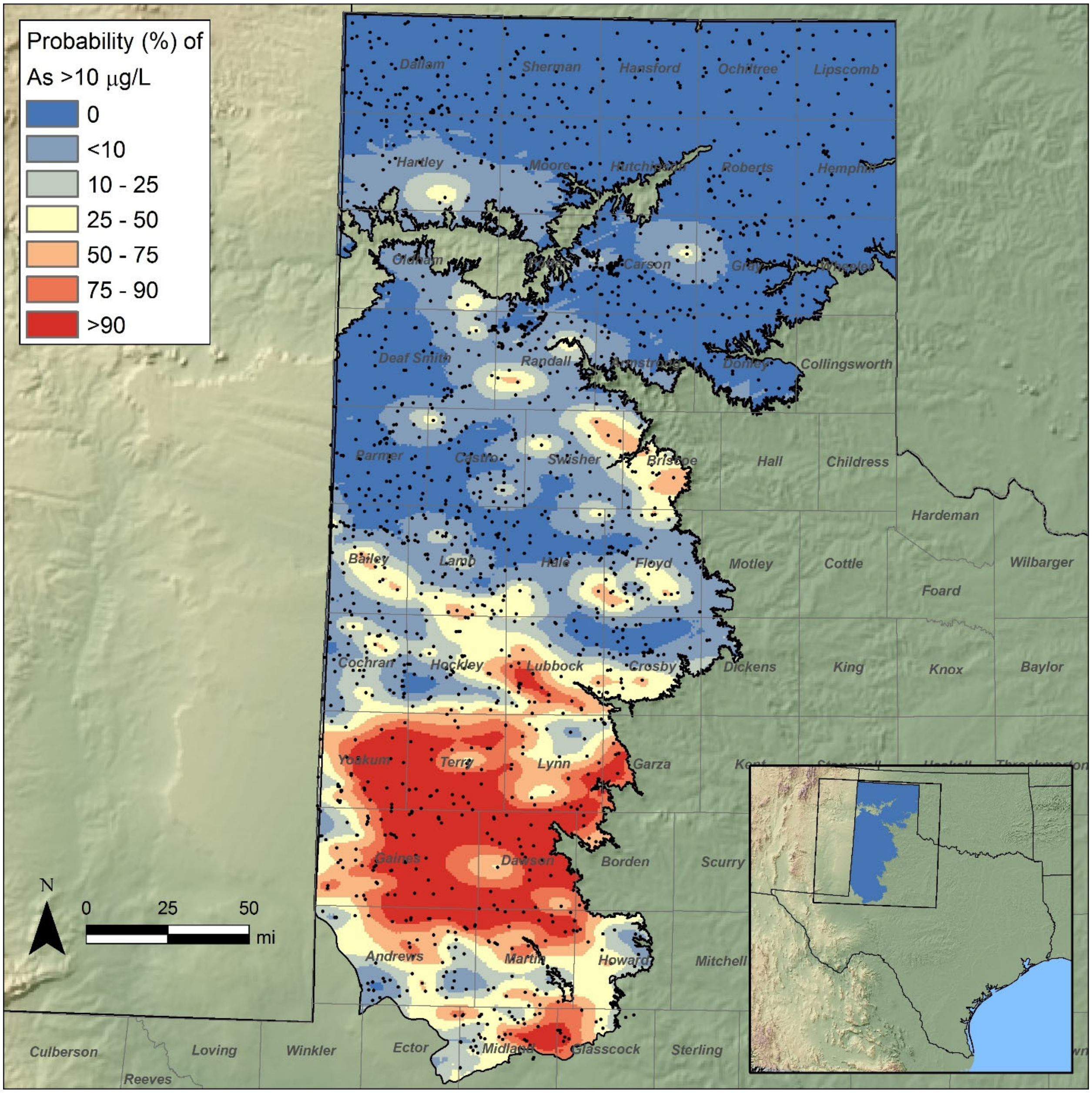

Figure 14. Ogallala aquifer probability distribution of arsenic >10 μg/L.

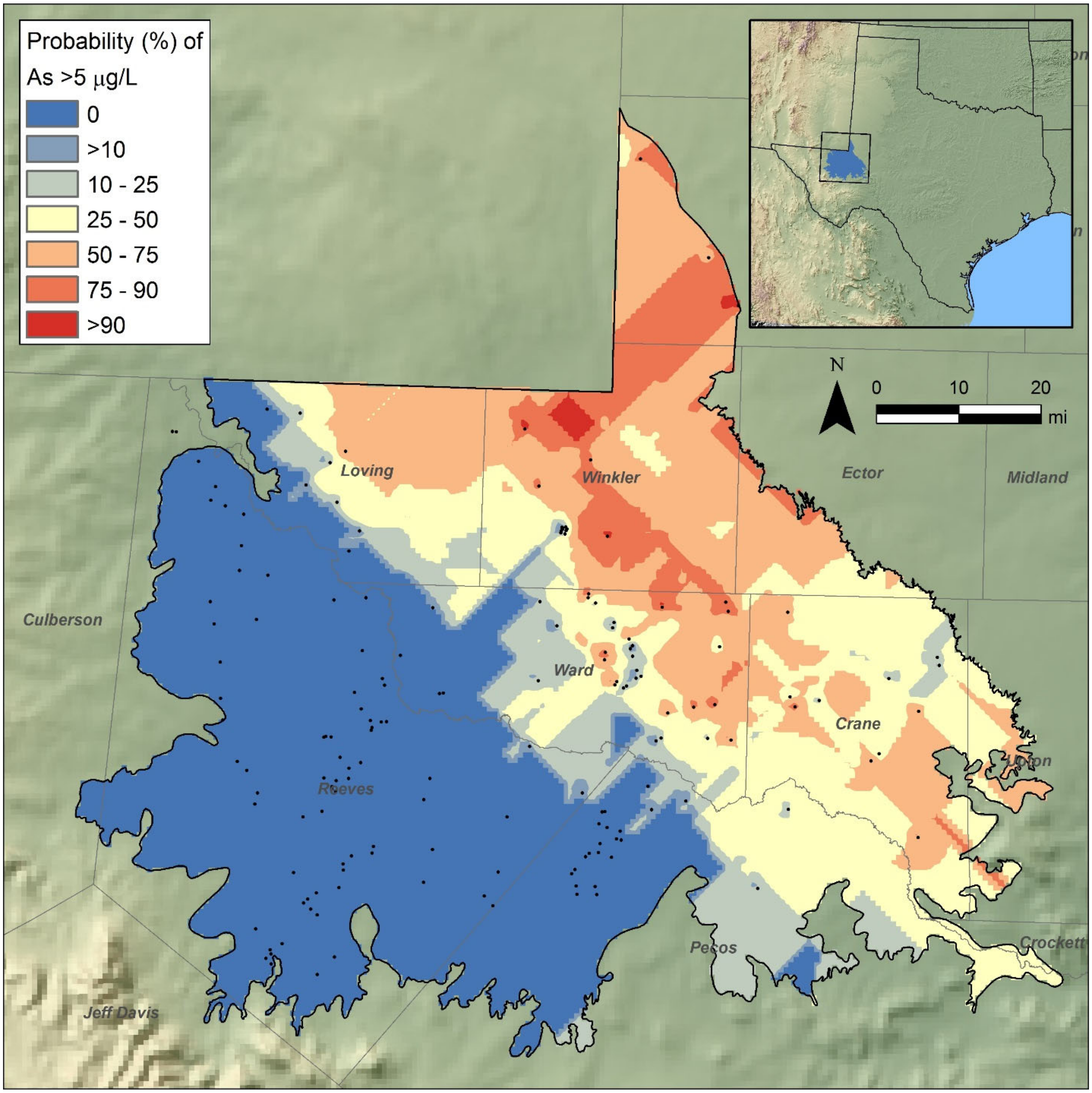

Figure 15. Pecos Valley aquifer probability distribution of arsenic >5 µg/L.

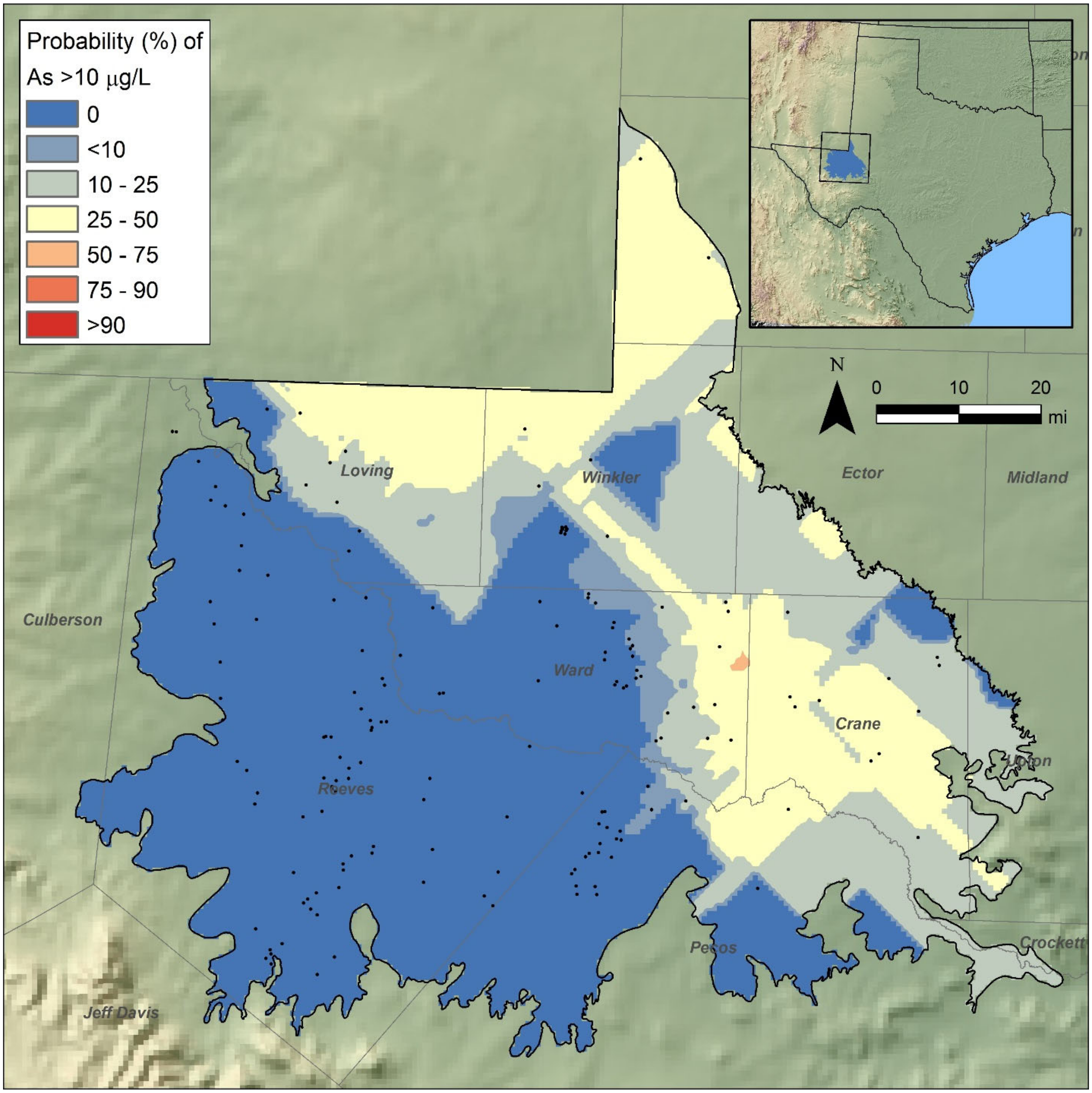

Figure 15. Pecos Valley aquifer probability distribution of arsenic >10 μg/L.

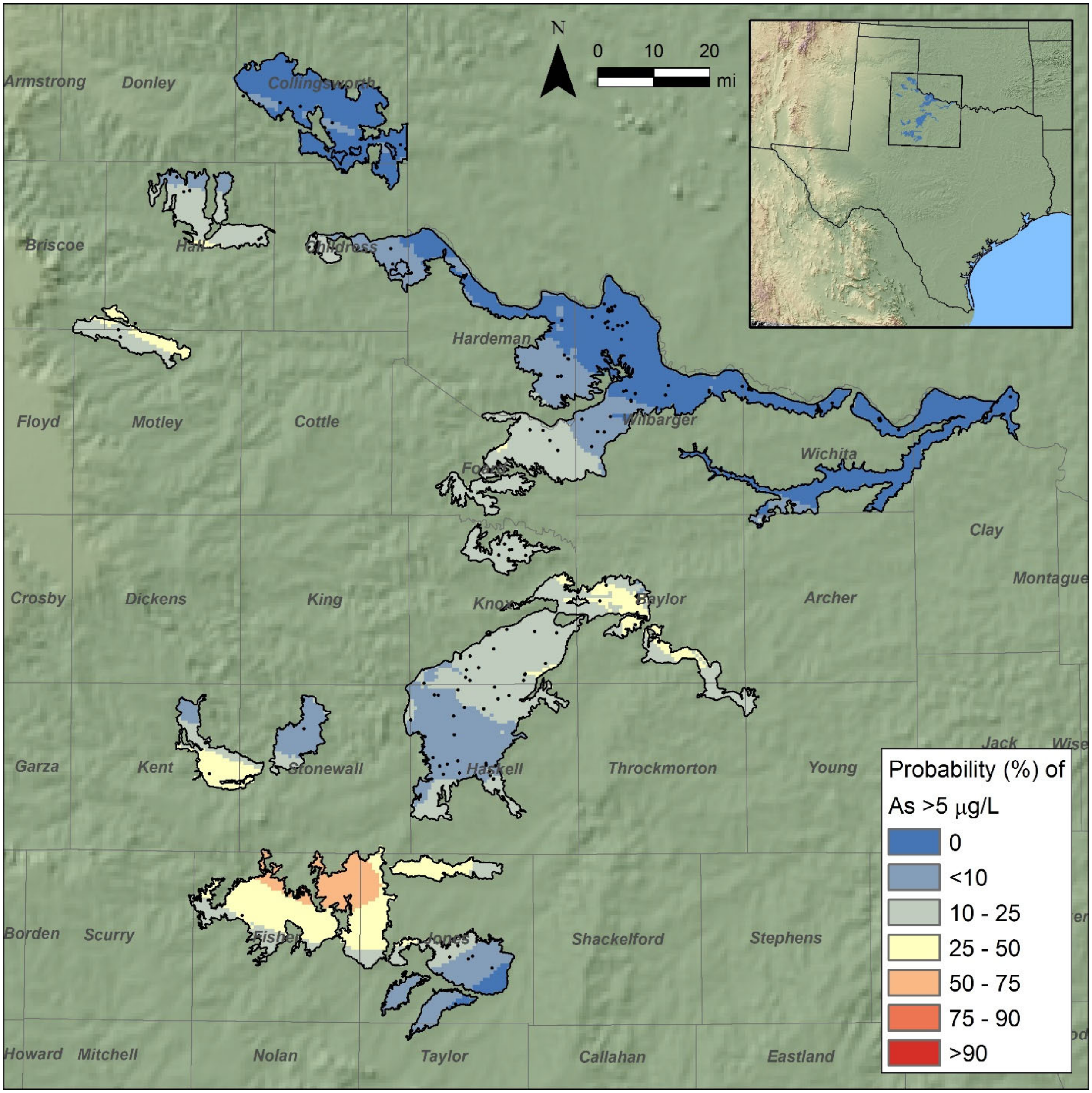

Figure 16. Seymour aquifer probability distribution of arsenic >5 µg/L.

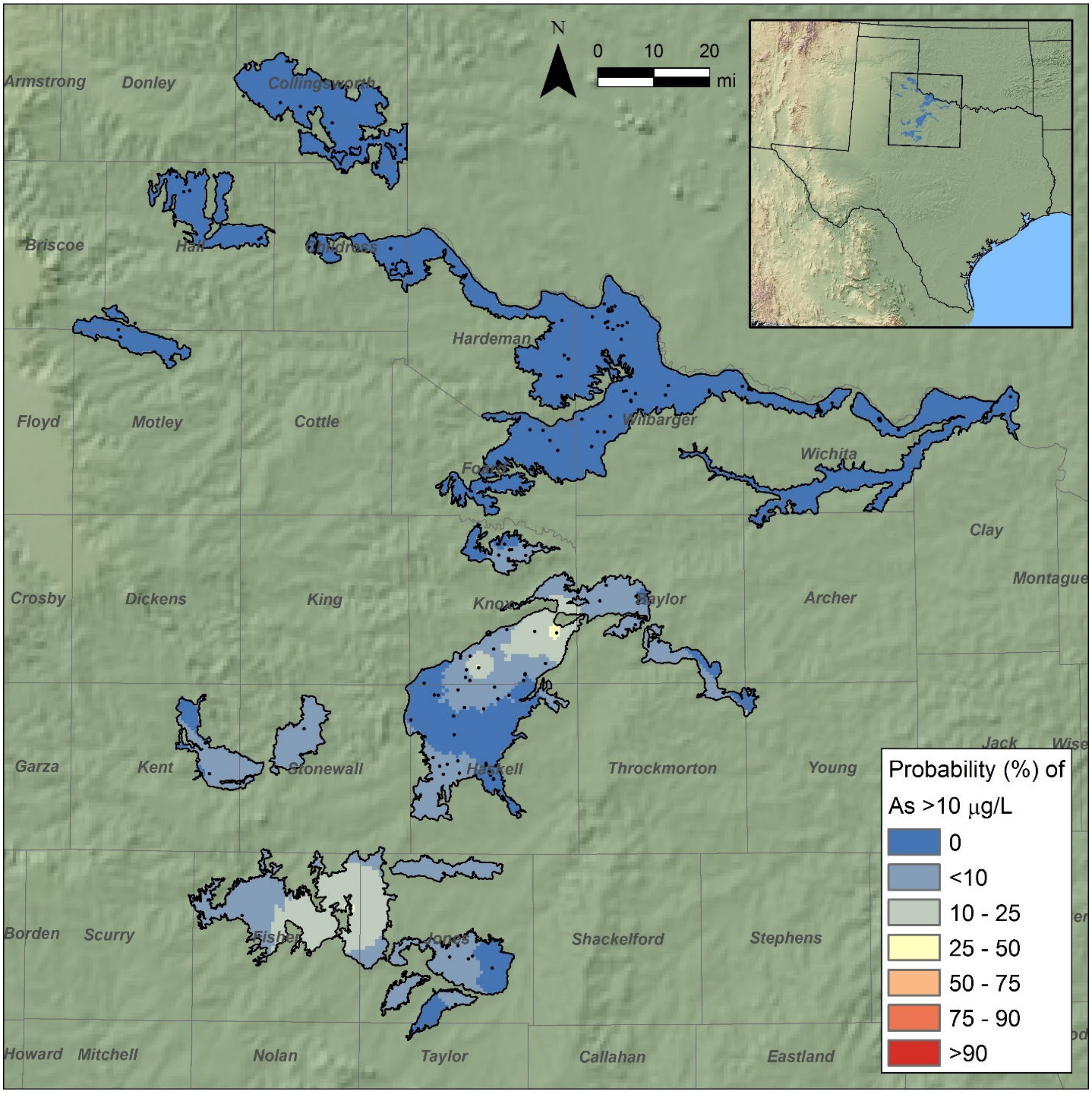

Figure 16. Seymour aquifer probability distribution of arsenic >10 µg/L.

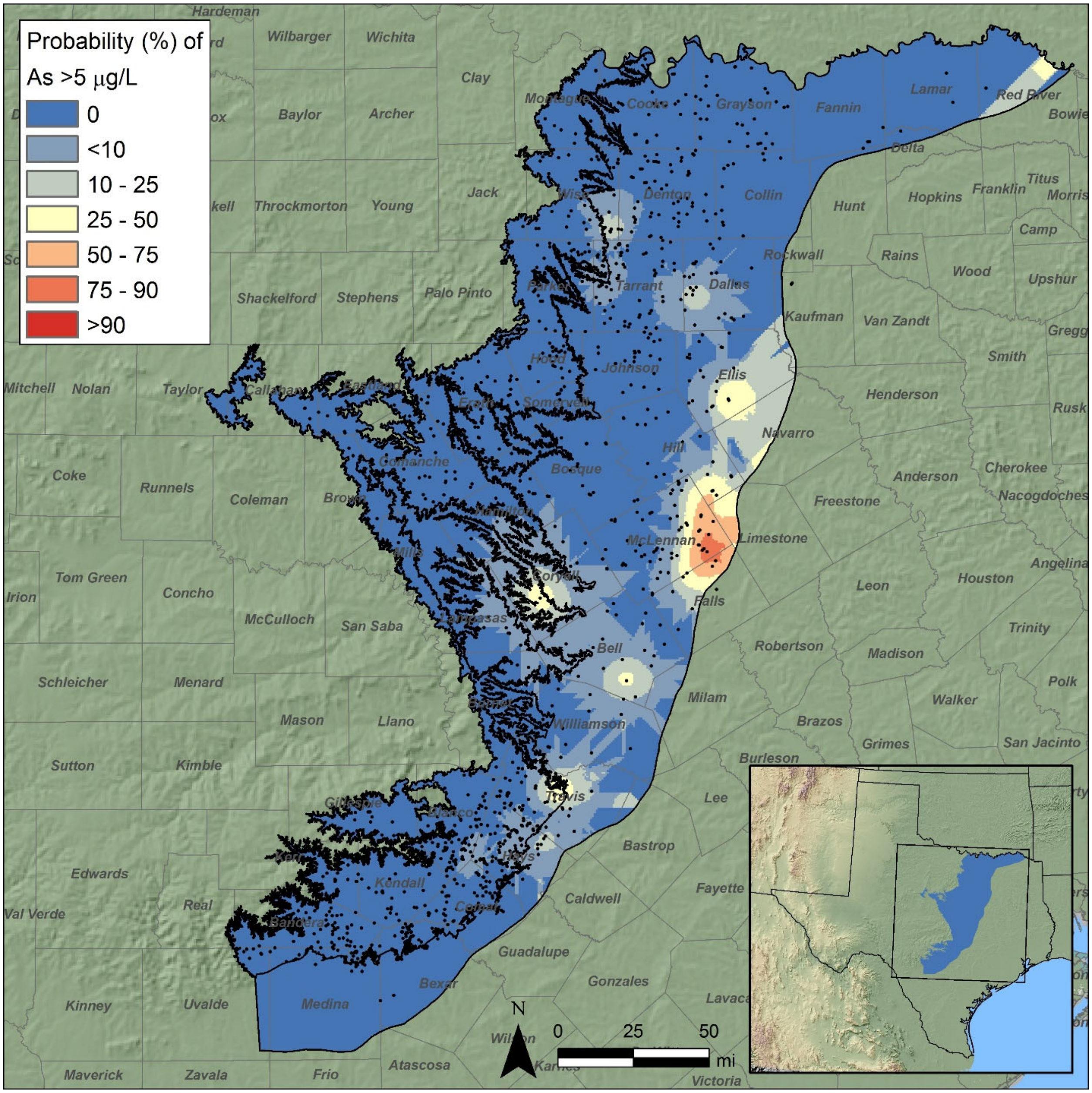

Figure 17. Trinity aquifer probability distribution of arsenic >5 µg/L.

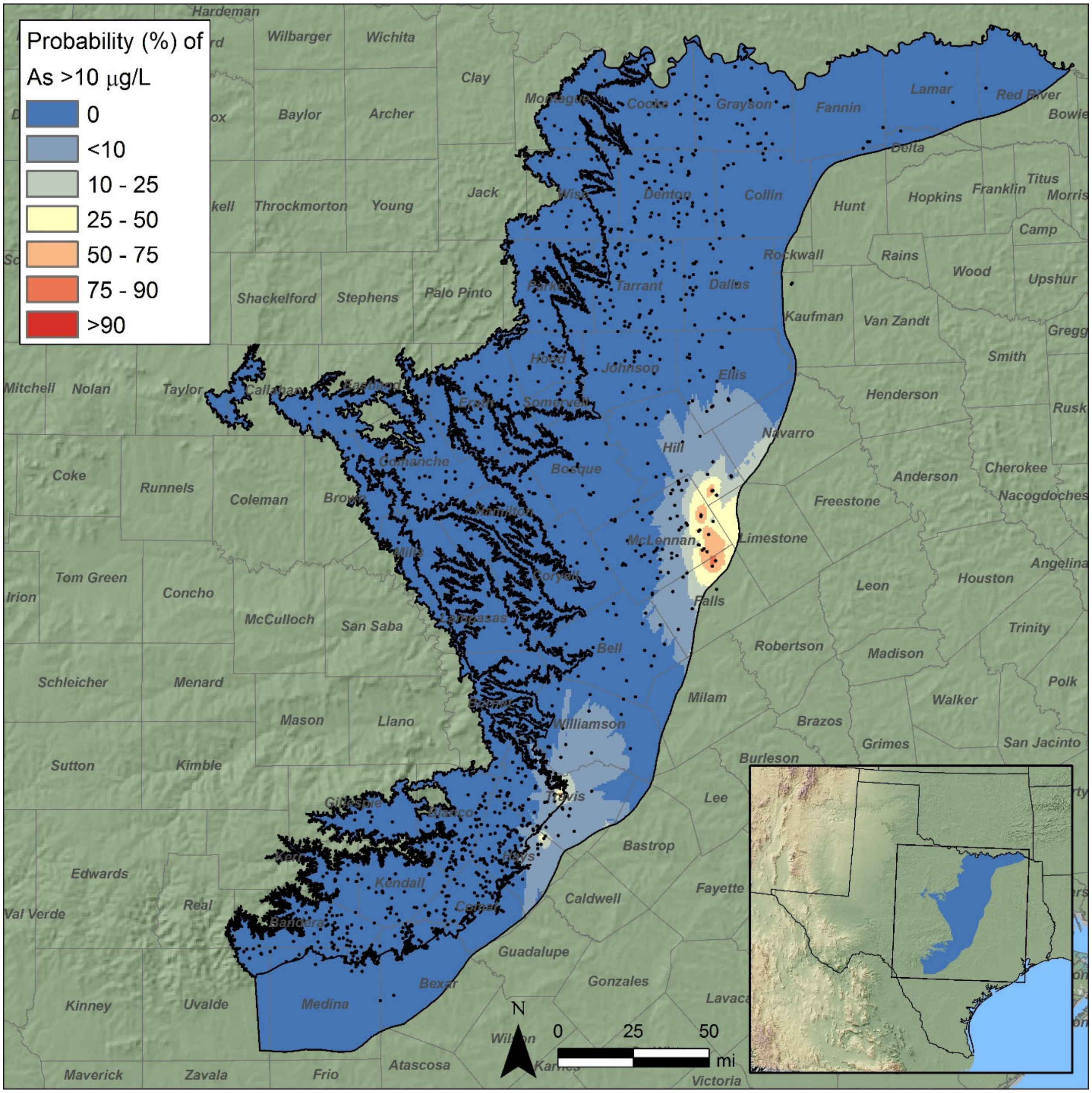

Figure 17. Trinity aquifer probability distribution of arsenic >10 μg/L.

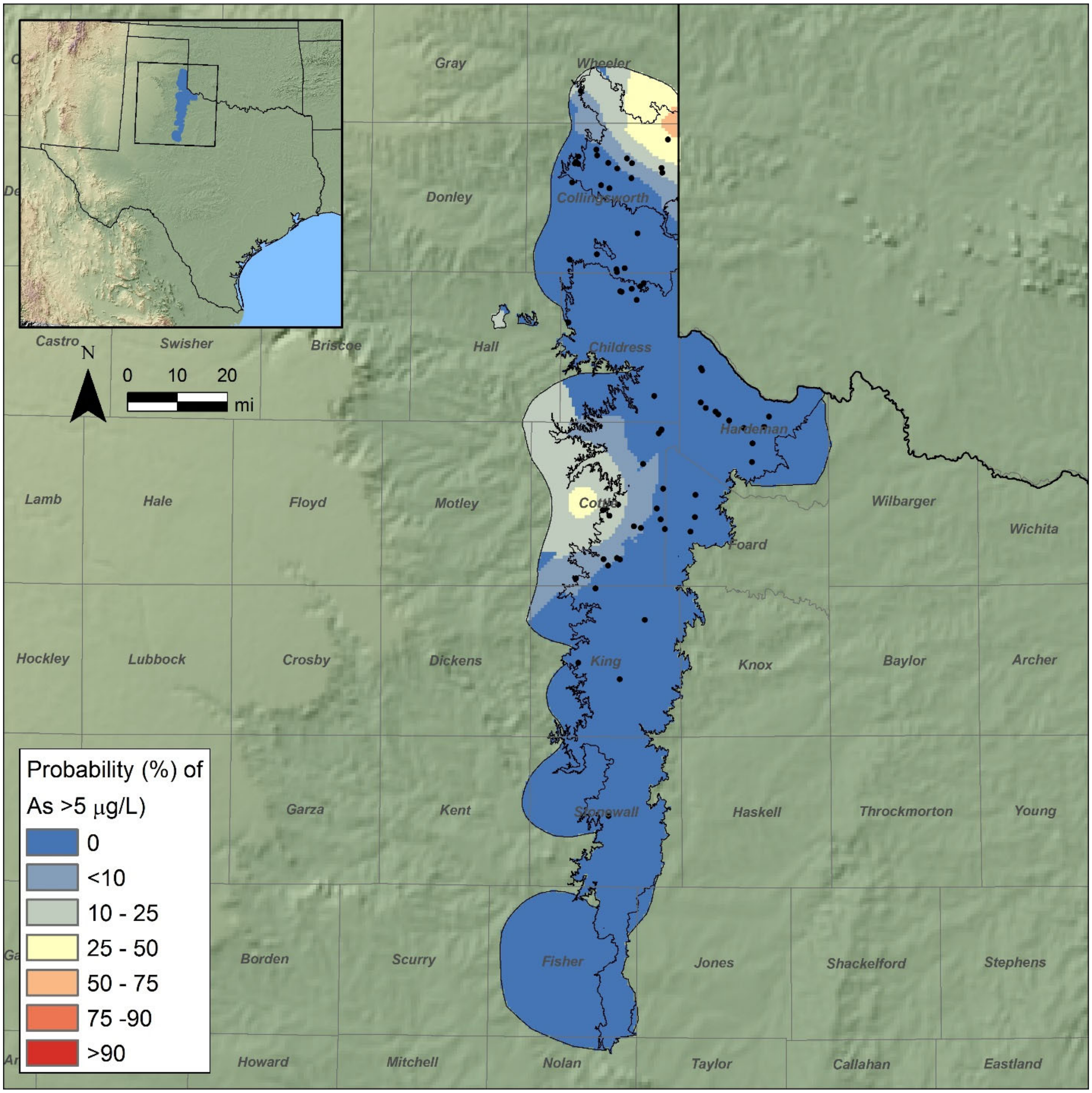

Figure 18. Blaine aquifer probability distribution of arsenic >5 μg/L.

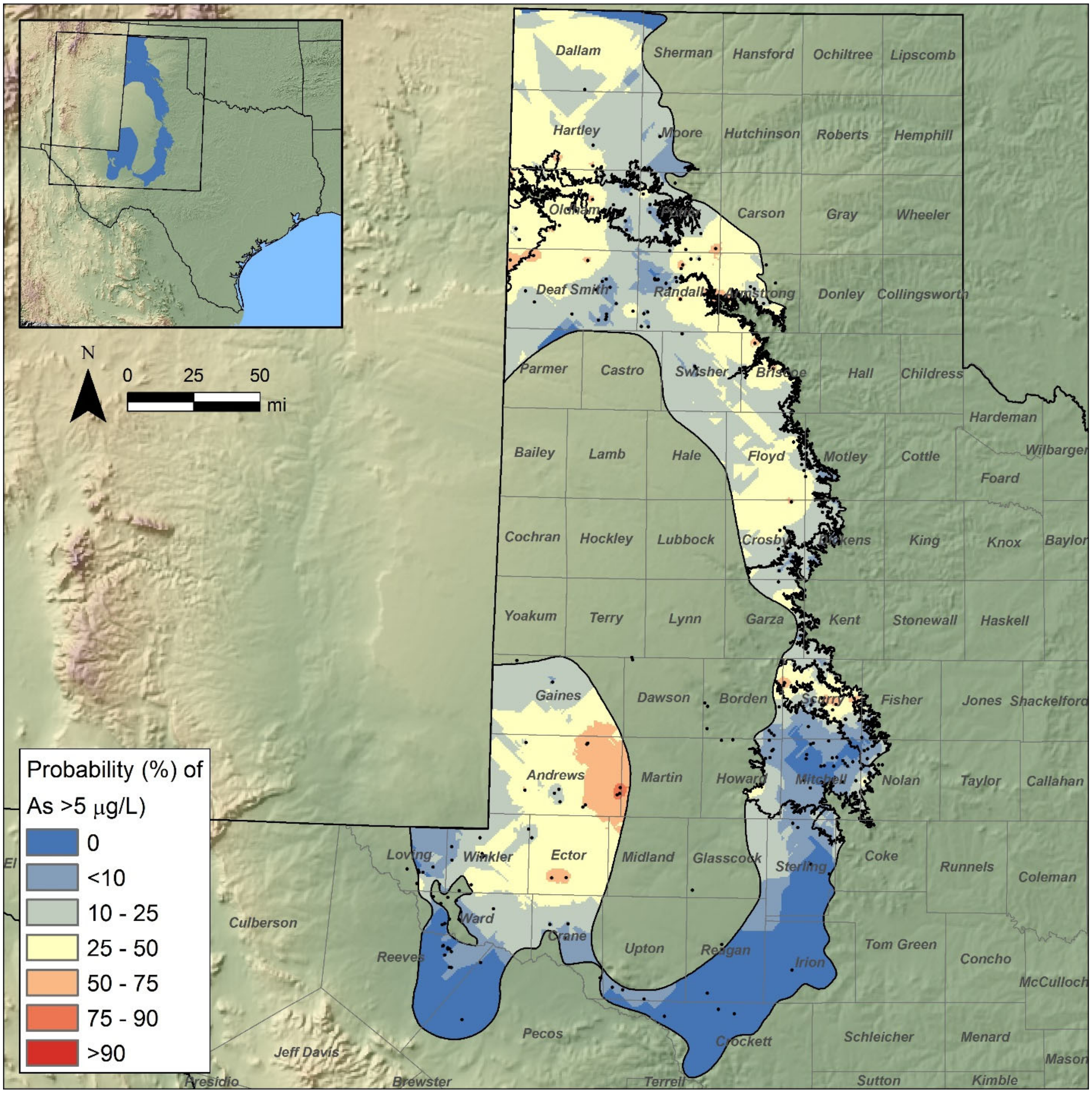

Figure 19. Dockum aquifer probability distribution of arsenic >5 µg/L.

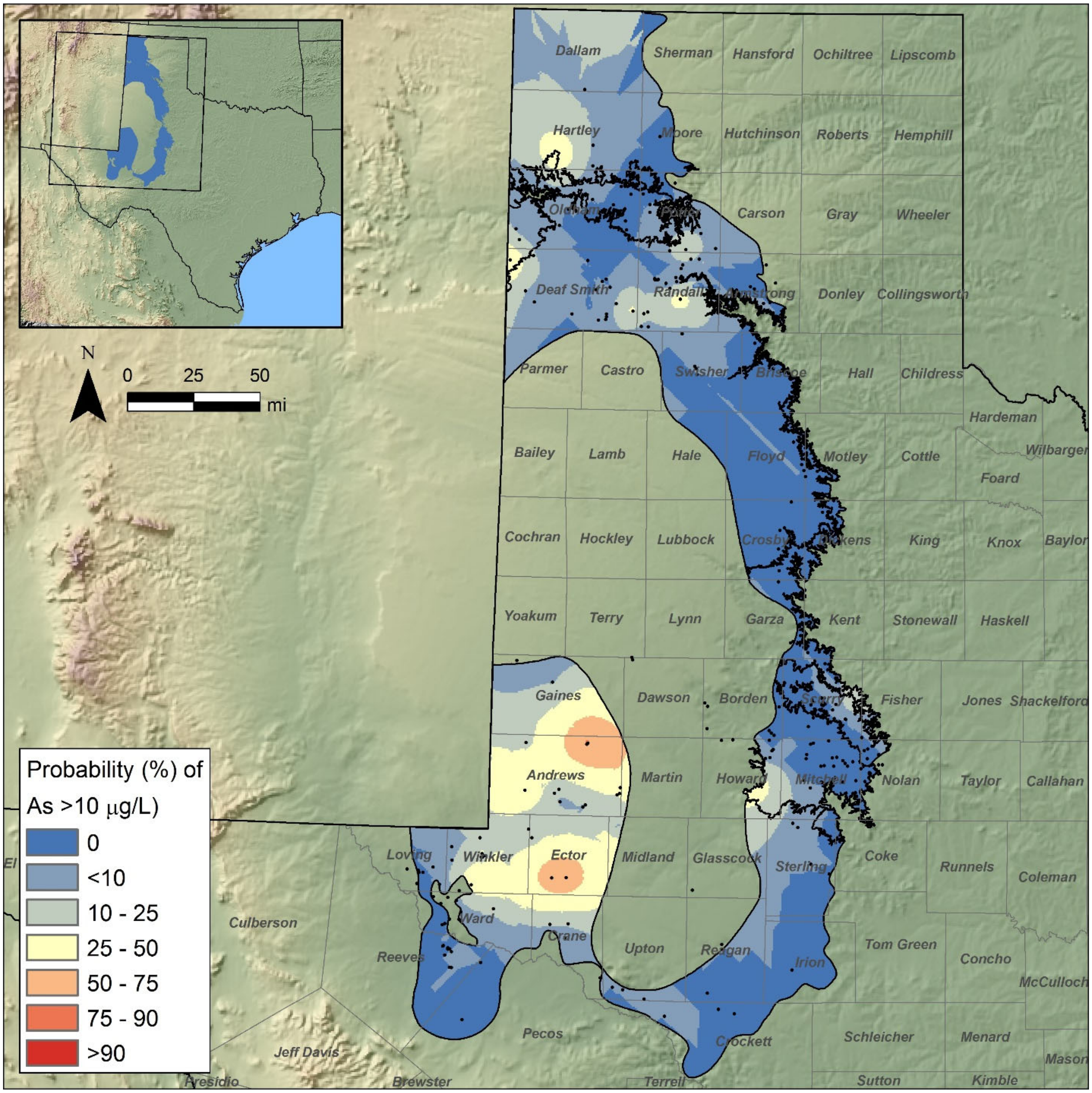

Figure 19. Dockum aquifer probability distribution of arsenic >10 μg/L.

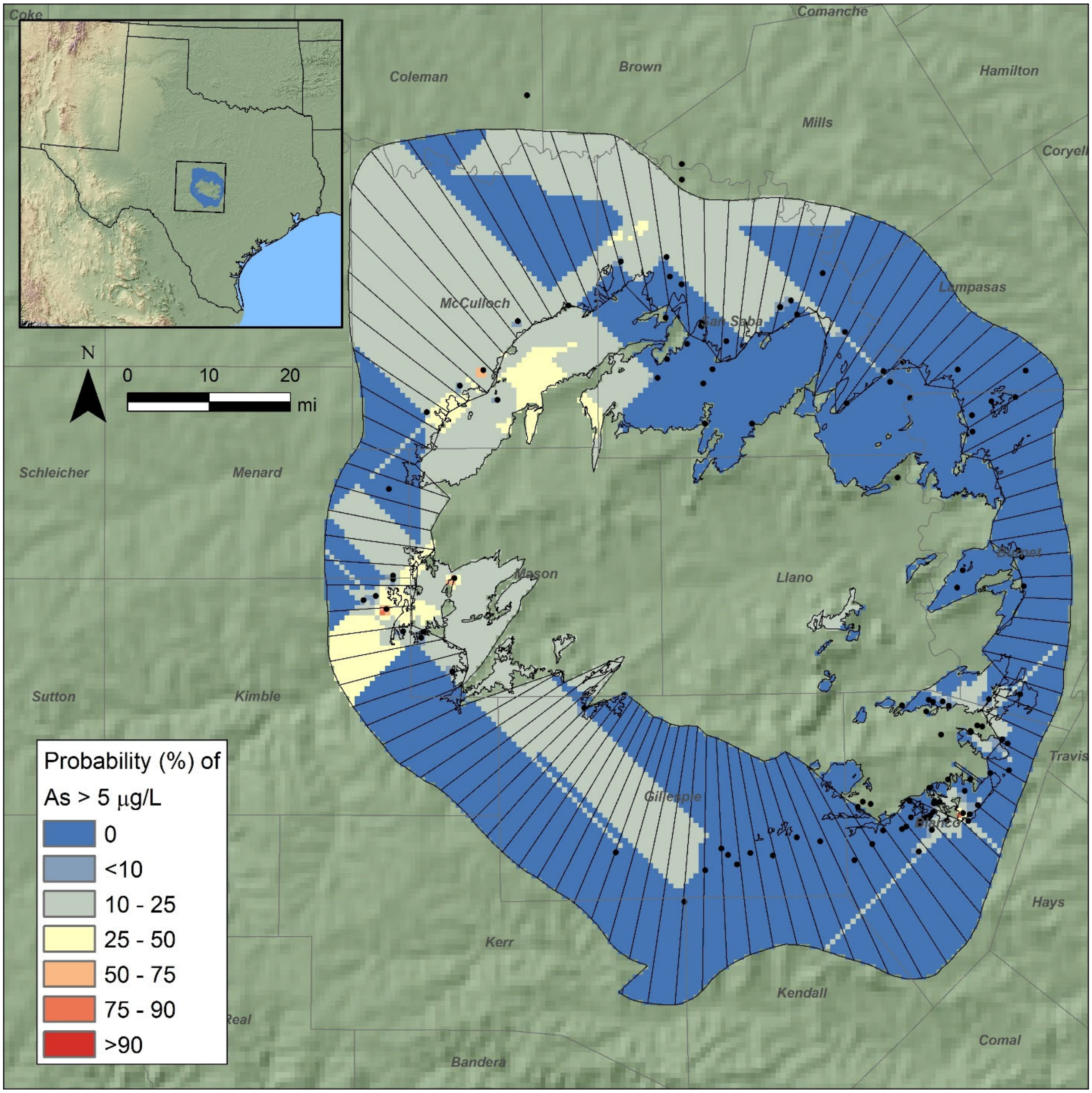

Figure 20. Ellenburger-San Saba aquifer probability distribution of arsenic >5 µg/L.

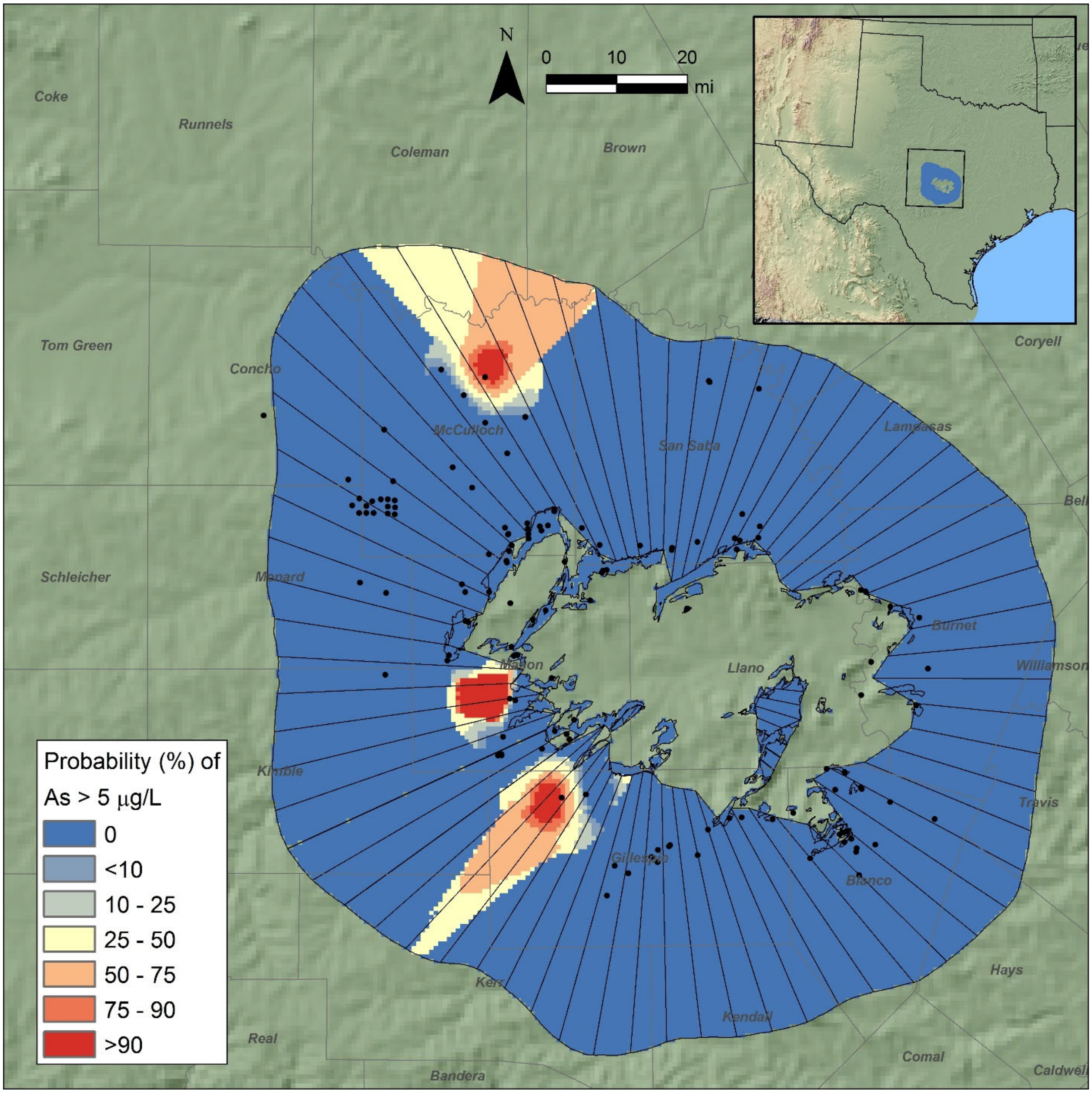

Figure 21. Hickory aquifer probability distribution of arsenic >5 μg/L.

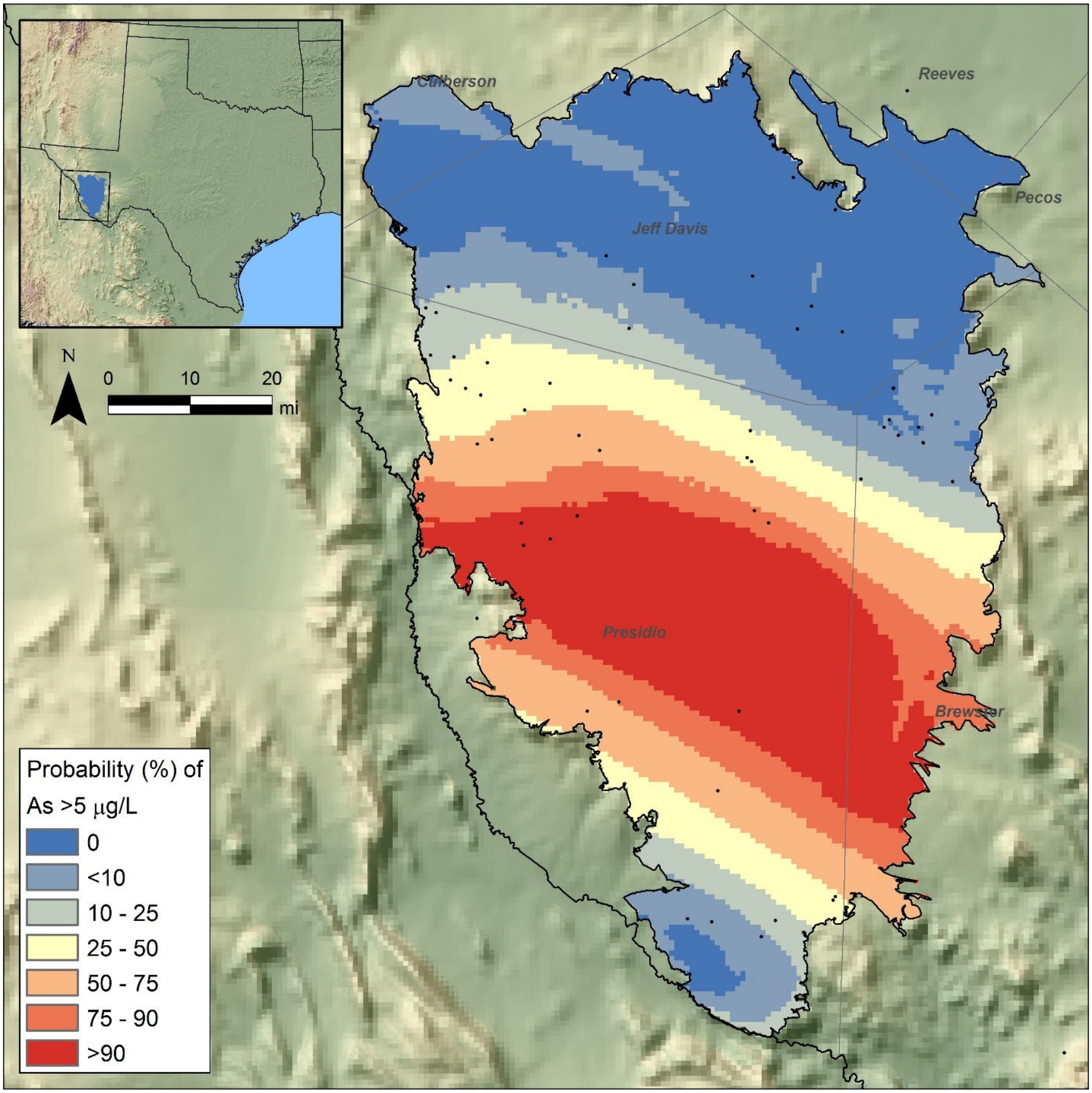

Figure 22. Igneous aquifer probability distribution of arsenic >5 μg/L.

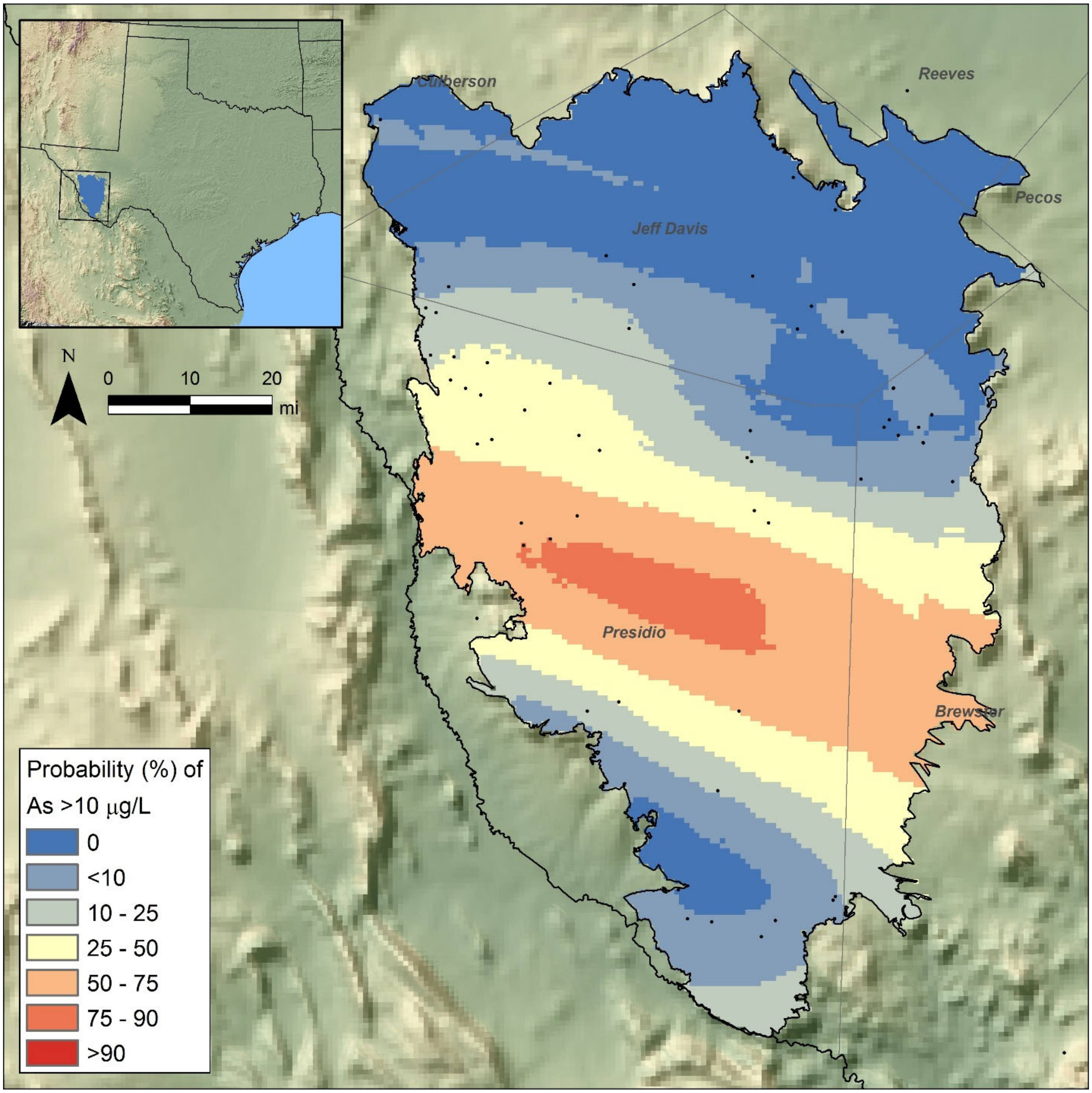

Figure 22. Igneous aquifer probability distribution of arsenic >10 μg/L.

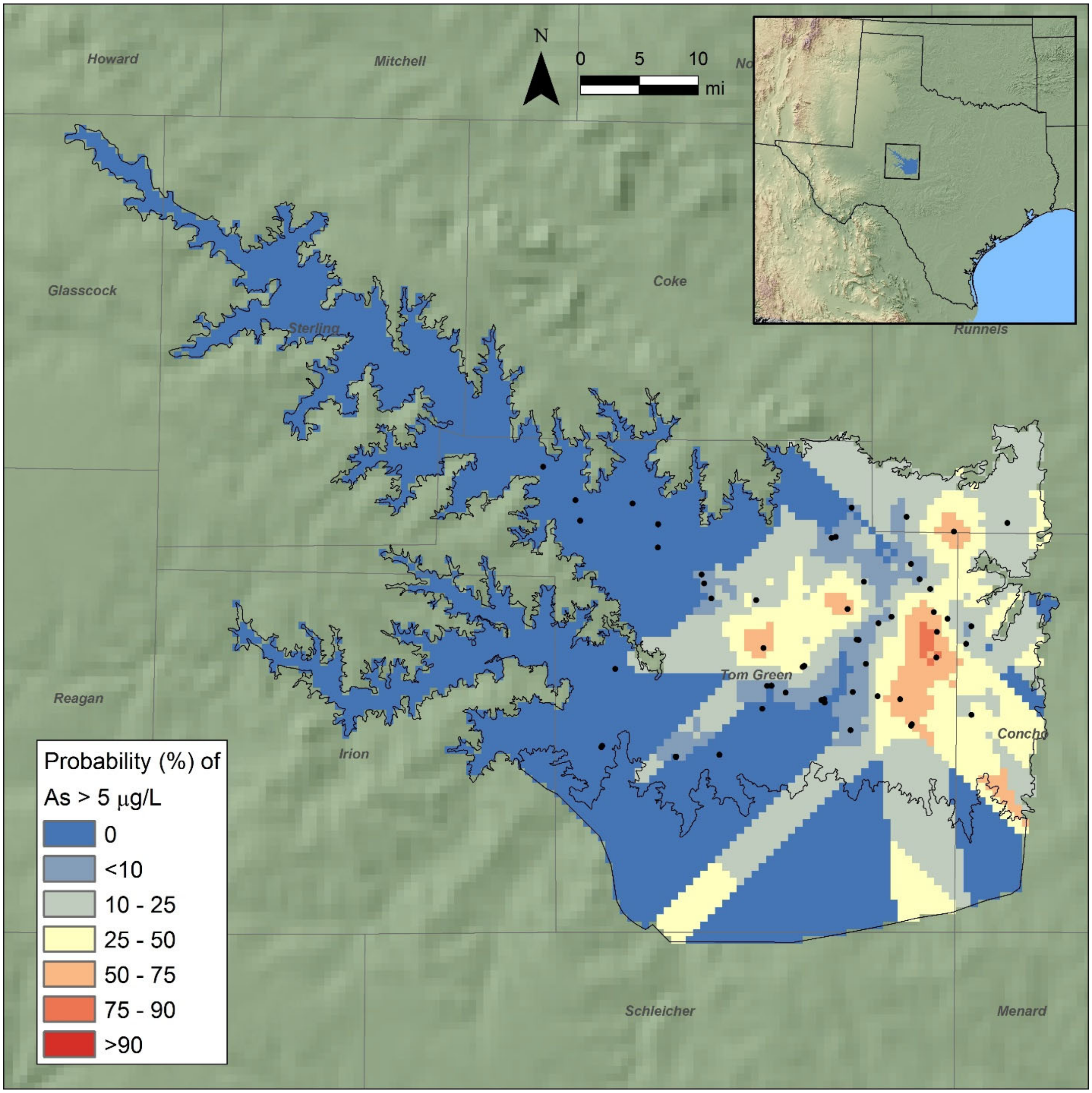

Figure 23. Lipan aquifer probability distribution of arsenic >5 μg/L.

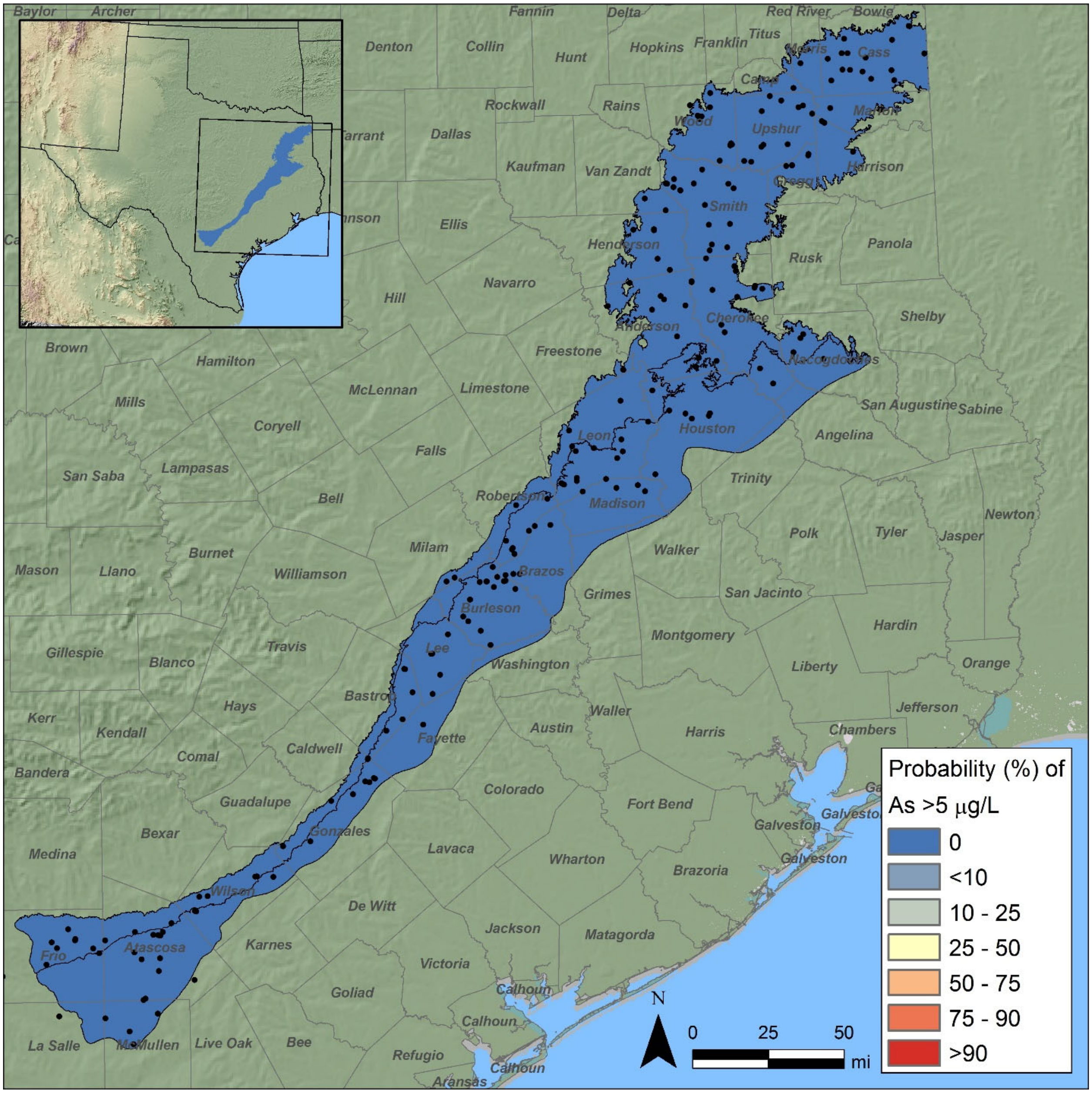

Figure 31. Queen City aquifer probability distribution of arsenic >5 µg/L.

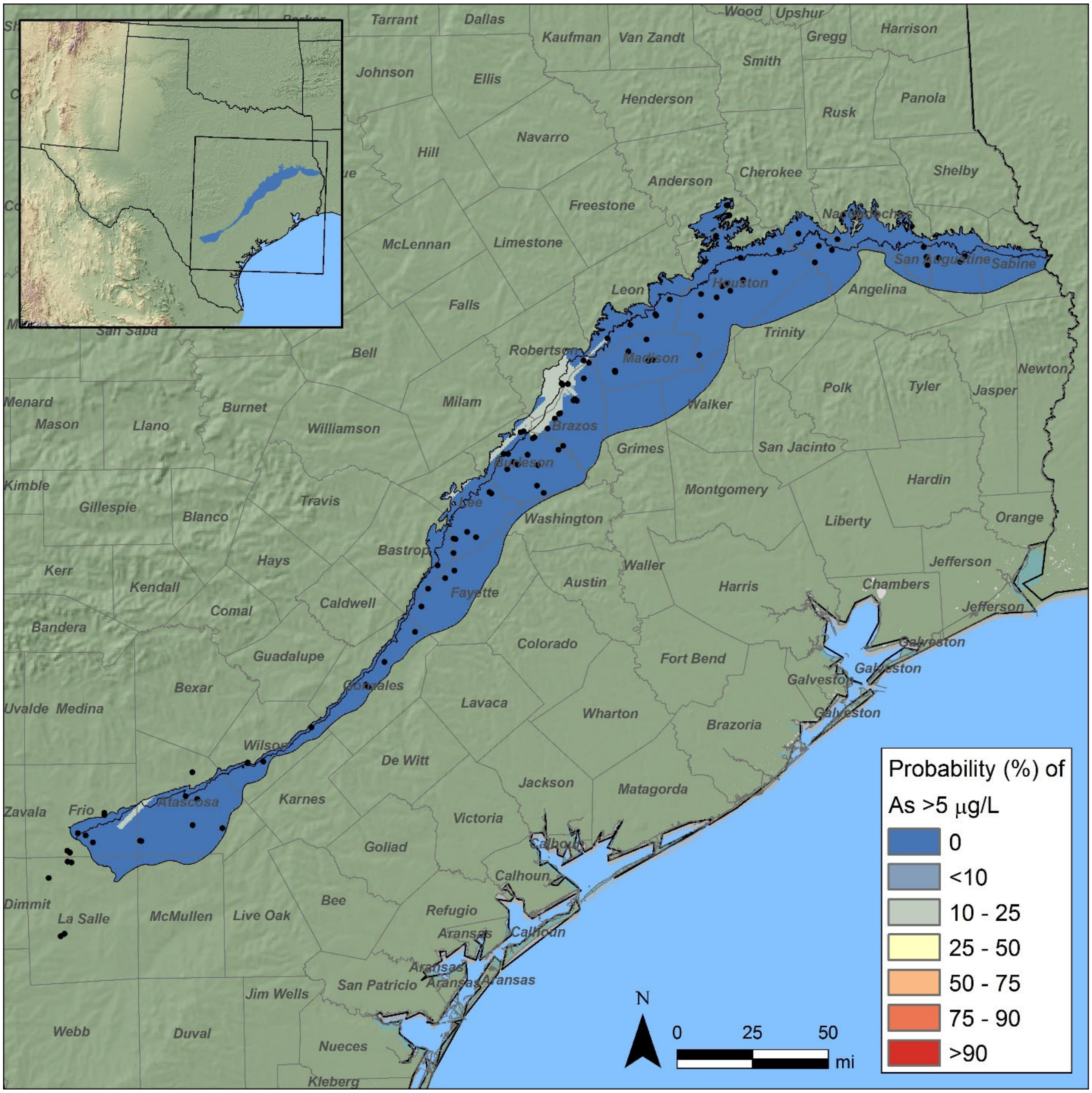

Figure 25. Sparta aquifer probability distribution of arsenic >5 µg/L.

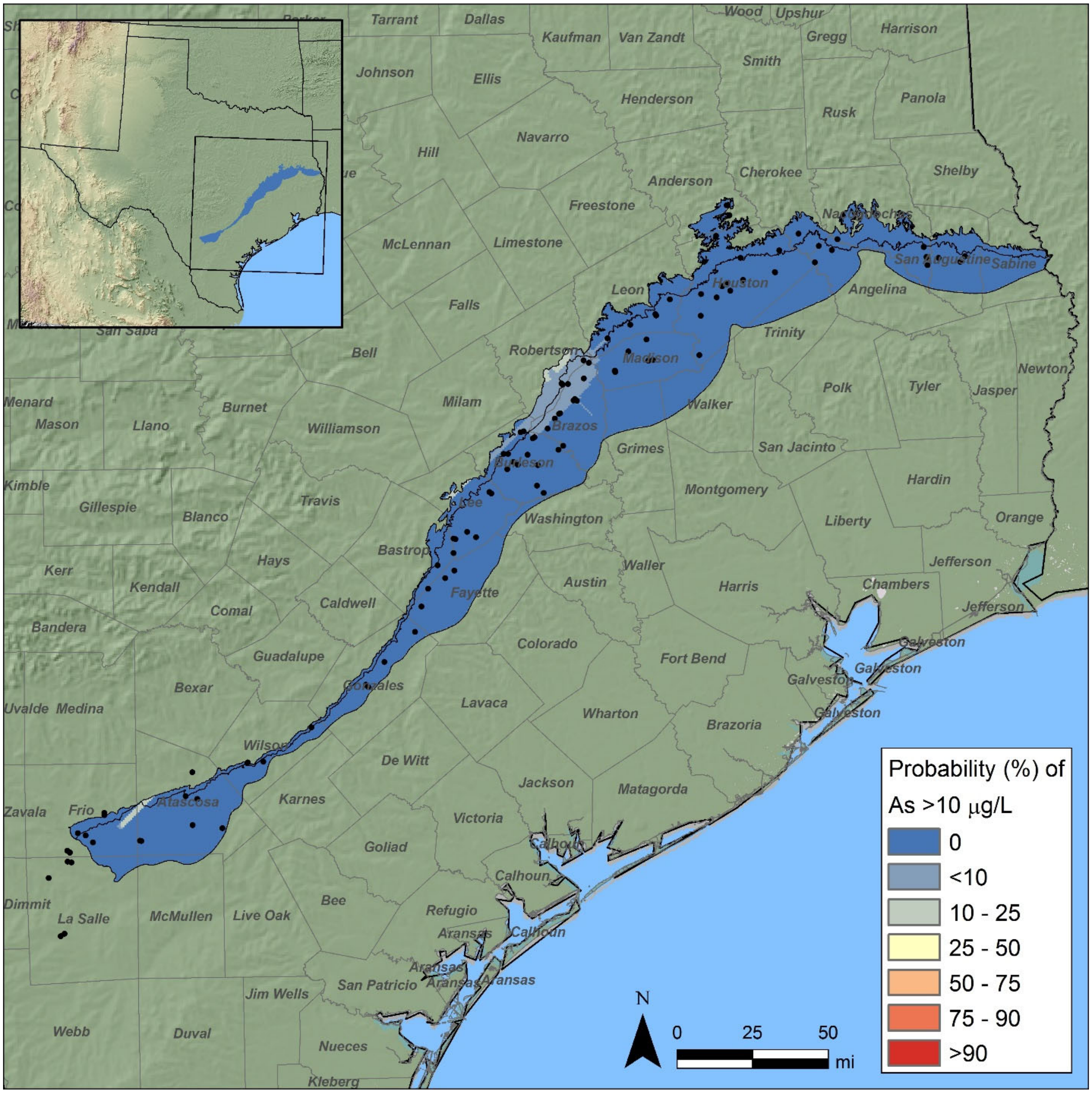

Figure 25. Sparta aquifer probability distribution of arsenic >10 µg/L.

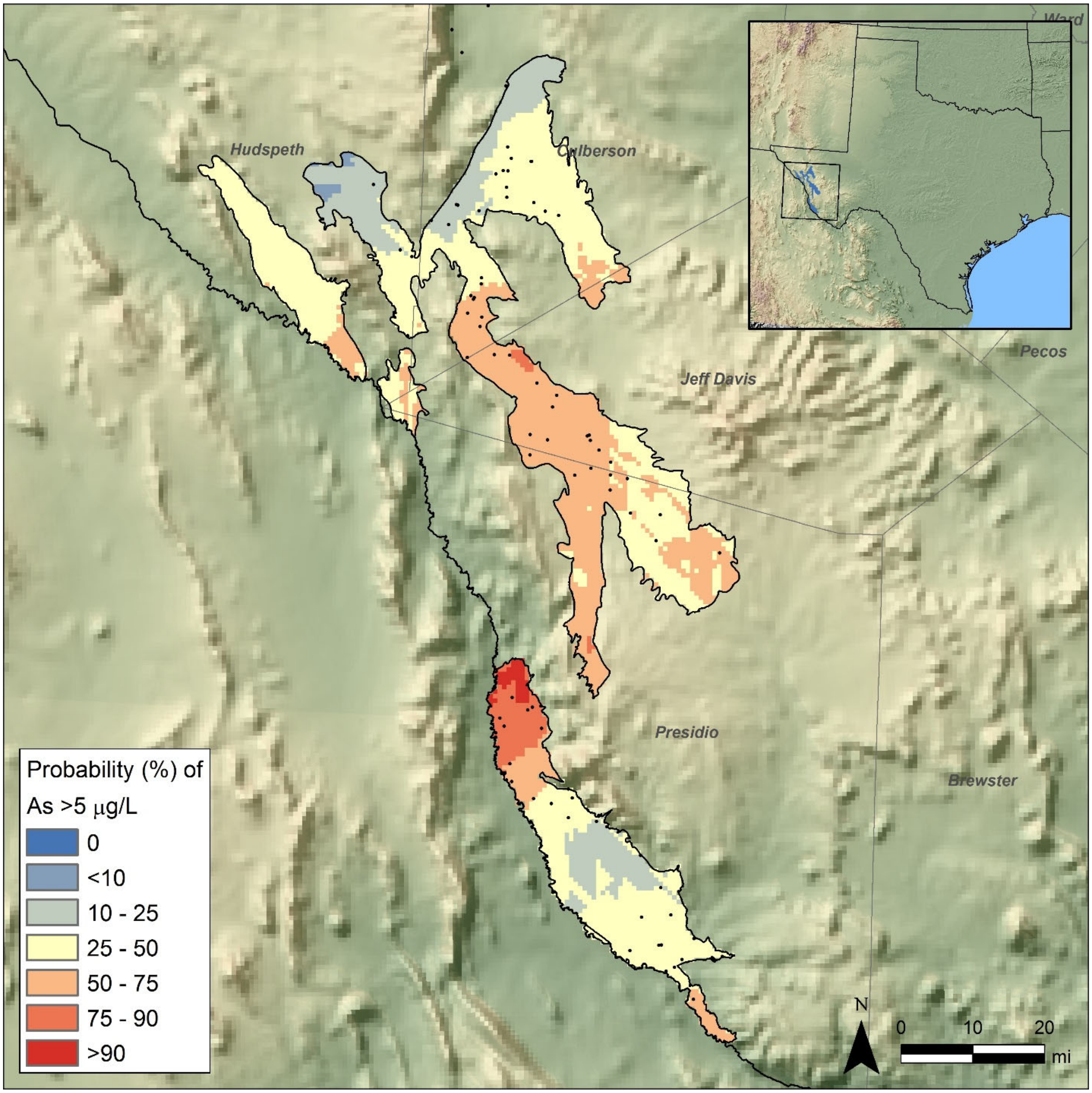

Figure 26. West Texas Bolsons aquifer probability distribution of arsenic >5 µg/L.

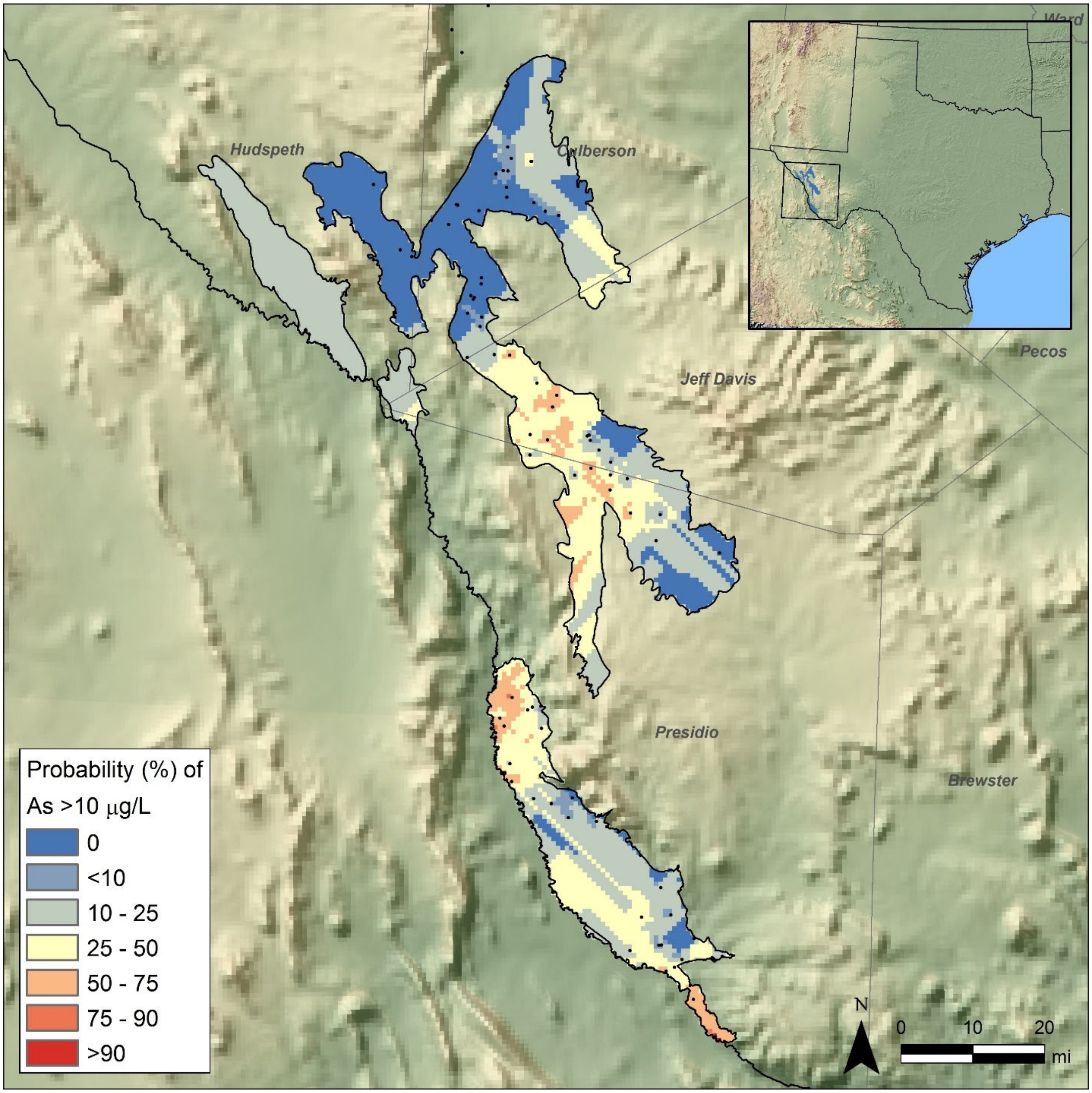

Figure 26. West Texas Bolsons aquifer probability distribution of arsenic >10 μg/L.

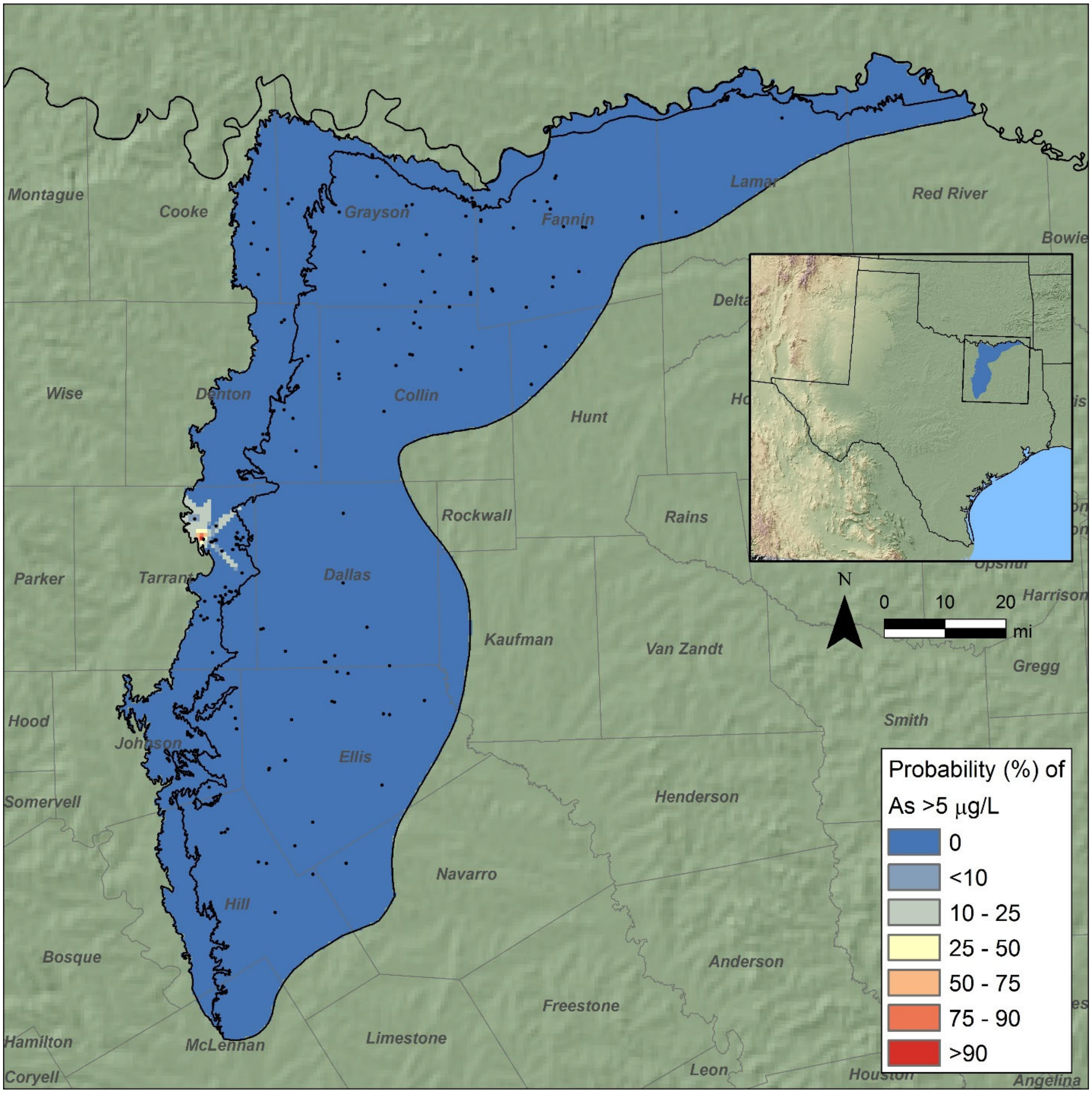

Figure 32. Woodbine aquifer probability distribution of arsenic >5 µg/L.

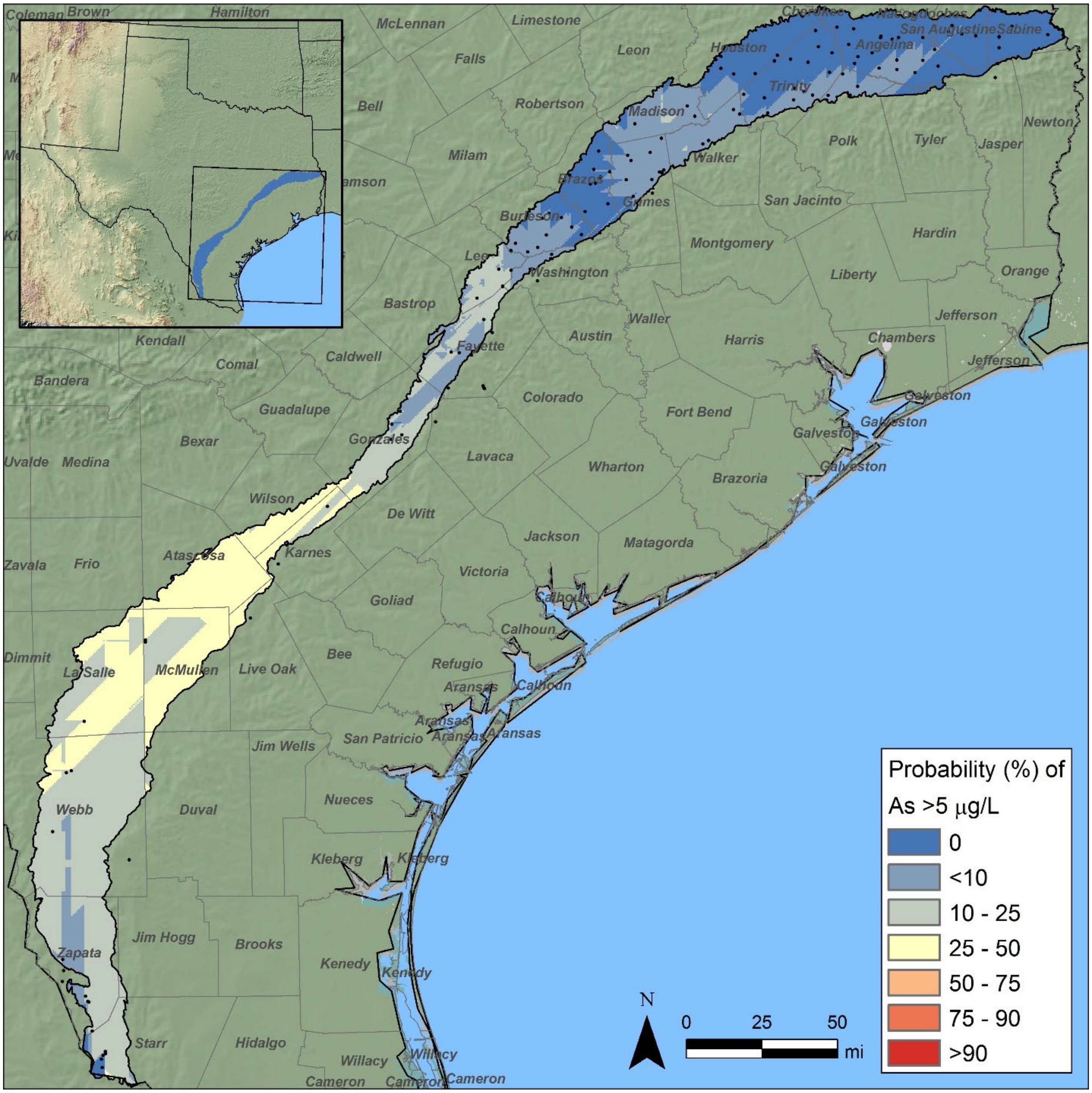

Figure 28. Yegua-Jackson aquifer probability distribution of arsenic >5 µg/L.

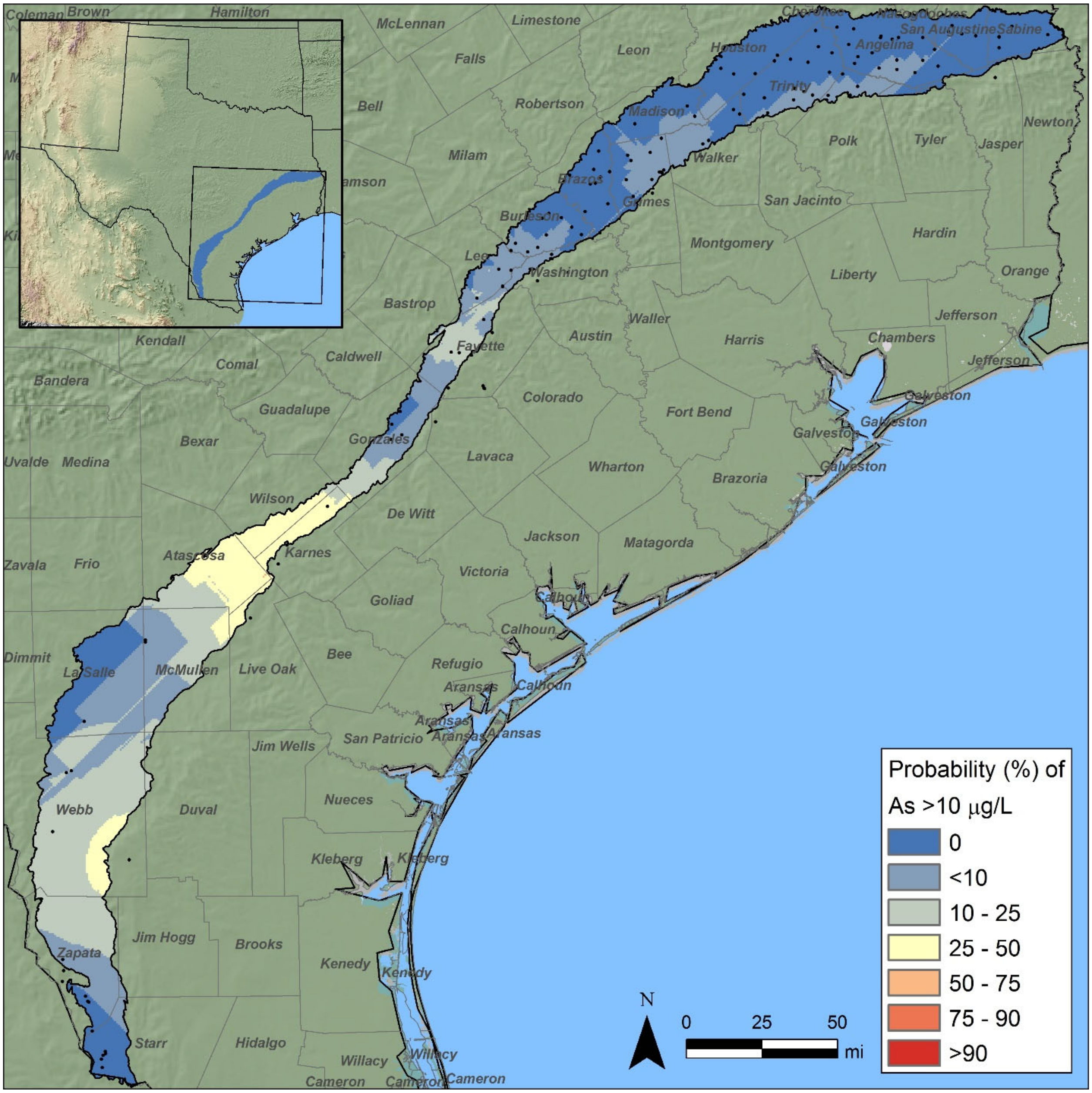

Figure 28. Yegua-Jackson aquifer probability distribution of arsenic >10 µg/L.