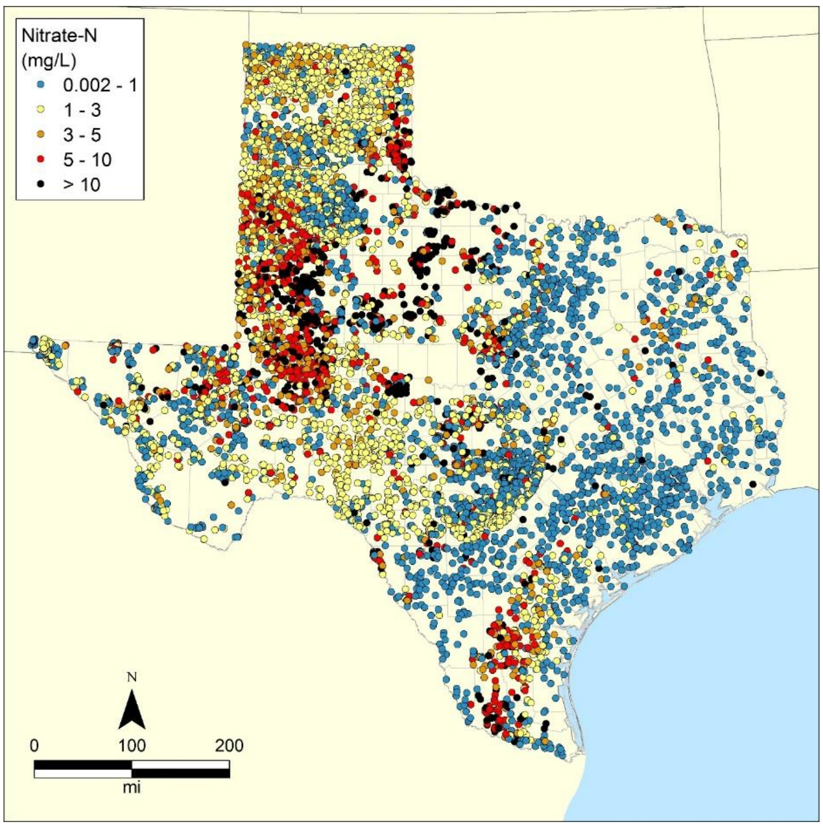
Evaluation of Groundwater Nitrate Contamination in Major Aquifers in Texas



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Executive Summary

Nitrate is the most widespread groundwater contaminant in Texas and in the U.S.. There are many potential adverse health implications of elevated groundwater nitrate, including methemoglobinemia and cancer risks. There are a variety of sources of nitrate, including natural sources, inorganic and organic fertilizers (manure), output from concentrated animal feeding operations (CAFOs), septic tanks, and leaking sewer systems. Natural sources result from nitrogen fixation by legumes, mineralization of organic matter (nitrification), and natural geologic sources.

Many previous studies have been conducted on groundwater nitrate contamination in Texas. The early studies focused on source identification using nitrogen isotopes, mainly distinguishing between nitrate from fertilizers and septic tanks. Groundwater nitrate levels were expected to be high in the Ogallala Aquifer beneath playas adjacent to concentrated animal feeding operations; however, many studies showed that nitrate levels were reduced by denitrification attributed to high levels of organic matter. A recent study suggested that nitrate contamination has been increasing in the state over the past several decades and identified the Seymour aquifer in the Rolling Plains as a hotspot of groundwater nitrate contamination. A study evaluated controls on groundwater nitrate contamination using logistic regression, indicating that precipitation, percent of agricultural land, low density residential land, and soil organic matter were the dominant explanatory variables. Unsaturated zone sampling was used to link land surface processes to groundwater nitrate levels and suggested that much of the elevated nitrate levels in the Ogallala and Seymour aquifers could be attributed to high levels of natural nitrate prior to cultivation that was oxidized during cultivation and mobilized into the underlying aquifer.

The current study examined the distribution of groundwater nitrate in major and minor aquifers in the state using ~10,000 analyses from major aquifers and ~2,000 analyses from minor aquifers. Approximately 70% of the samples in the major and minor aquifers exceeded the detection levels for nitrate. The majority of the samples are from rural domestic and irrigation wells. A total of 5.5% of the samples from the major aquifers exceeded the MCL, with the highest level of contamination in the Seymour Aquifer (61% of sampled > MCL), followed by the Pecos Valley Aquifer (11%), Ogallala Aquifer (9%), Edwards Trinity High Plains (6%) and the remaining major aquifers < 2%. Groundwater nitrate concentrations generally decreased with depth.

A total of 7.2% of the samples from the minor aquifers exceeded the MCL, with the highest level of contamination in the Lipan Aquifer (59% of sampled > MCL), followed by the Edwards Trinity High Plains and Blaine aquifers (18%). The number of analyses from many of the minor aquifers is limited, reducing

confidence in the nitrate contamination assessment. Groundwater nitrate concentrations generally decreased with depth. The results from the major and minor aquifers are consistent with the nitrate hotspot in the Seymour and nearby Lipan aquifers, both located in the Rolling Plains. High levels of contamination in this region are attributed to coarse textured soils, shallow water tables, excessive fertilization, and nearby septic systems adjacent to many wells.

A much more in depth examination of groundwater nitrate is required to delineate contamination sources, assess processes (mitigation etc), and examine temporal trends from frequently sampled wells.

Introduction

Nitrate is the most pervasive contaminant in groundwater in Texas and in the U.S. (TCEQ, 2002; Nolan et al., 2002). Elevated levels of groundwater nitrate can adversely impact human health. Infants can suffer from methemoglobinemia which is potentially fatal which is related to ingesting high nitrate groundwater resulting in low levels of oxygen in the blood (Spalding and Exner, 1993). Previous studies suggested that eight spontaneous abortions in four women in Indiana (1991 – 1994) may be linked to elevated levels of nitrate (19 – 29 mg/L nitrate) in domestic well water in rural regions of Indiana (Centers for Disease Control and Prevention, 1996).

Elevated risk of non-Hodgkin's lymphoma has also been linked to nitrate concentrations exceeding 4 mg NO_3-N/L in community water supply wells in Nebraska (Ward et al., 1996). Toxicological studies suggest that exposure to multi-contaminants may increase negative health impacts relative to exposure to single contaminants because of synergistic interactions among compounds (Squillace et al., 2002). For example, adverse health impacts are much higher for mixtures of nitrate and pesticides (Porter et al., 1999) and indicate that the MCL for nitrate should be decreased in the future, which would greatly affect water availability in Texas. Previous studies show that groundwater NO_3-N levels greater than 2 mg/L are thought to be affected by humans (Mueller and Helsel, 1996). Elevated levels of groundwater nitrate can also adversely affect water quality of streams and estuaries by causing eutrophication and algal blooms (e.g. Mississippi River and Gulf of Mexico, Chesapeake Bay) (Donner and Kucharik, 2003; Jordan et al., 1997).

The chemical characteristics of nitrate include high water solubility and low ion exchange (Stumm and Morgan, 1996). Nitrate is an anion and does not sorb onto clay particles which are also negatively charged under normal pH conditions. Nitrate reductions are not possible through volatilization because it is nonvolatile. Nitrate is readily leached through the soil profile to underlying aquifers because of its high solubility and mobility. Nitrate is not impacted by chlorination, the most common method of treating most public water. Nitrate removal from water can be done by reverse osmosis; however, RO is expensive. Alternative treatment technologies include ion exchange and denitrification (Kapoor and Viraraghavan, 1997). Commonly, water supply companies reduce nitrate levels by blending water with groundwater/or surface water that contains low nitrate levels. Another water treatment option includes deepening wells where nitrate levels are often lower (McMahon et al., 2003).

Various sources of groundwater nitrate contamination include atmospheric deposition, natural sources, inorganic and organic fertilizers (manure), output from concentrated animal feeding operations (CAFOs), septic tanks, and leaking sewer systems. Natural sources result from nitrogen fixation by legumes, mineralization of organic matter (nitrification), and natural geologic sources. Elevated groundwater nitrate levels in parts of the northern High Plains have been attributed to geologic sources in glacial sediments (Boyce et al., 1976). Data on fertilizer applications, including inorganic and organic fertilizer applications are available from county level fertilizer sales from National Agricultural Statistics Service (www.nass.usda.gov). It is difficult to quantify nutrient loading at the land surface because of lack of historical recording of land use and limited information on nutrient application rates. Time lags between land surface applications of nitrate and elevated groundwater nitrate results in land application rates in the past being highly relevant for evaluating current nitrate levels in groundwater. It is difficult to assess best management practices designed to decrease nitrate loading to underlying aquifers because of limited data on nitrate levels in soil profiles. Previous research has examined source attribution for groundwater nitrate contamination. GIS overlay analyses and logistic regression have been used to assess different sources and controls on nitrate contamination on regional and national scales (Nolan et al., 1997; 2002; Squillace et al., 2002). Nitrogen and oxygen isotopes of nitrate have been used at regional and local scales to relate groundwater nitrate to fertilizer and human and animal waste sources (Kreitler, 1975; Fogg et al., 1998; Bohlke et al., 2002).

Previous Studies in Texas

Many studies have been conducted on nitrate in soils and groundwater in different parts of Texas. Nitrogen isotopes were used by Kreitler (1975) to distinguish various sources of nitrate contamination. Kreitler (1975) conducted a study in Runnels County with the highest mean groundwater nitrate concentrations in Texas (53 mg/L NO_3). The nitrogen isotopes were used to distinguish nitrate derived from mineralization of soil organic nitrogen in cultivated soils in Runnels County ($\delta^{15}N$ of 2 to 8) from animal waste near barnyards ($\delta^{15}N$ of +10 to +22) (Kreitler, 1975; Kreitler and Jones, 1975). Nitrogen isotopes showed that nitrate in the Edwards Aquifer could be attributed to naturally occurring nitrogen compounds in the recharge streams with $\delta^{15}N$ of 73 groundwater samples (+1.9 to +10 ‰) similar to the range in recharge streams (+1 to +8.3 ‰) (Kreitler and Browning, 1983). The lack of enrichment in $\delta^{15}N$ indicated that animal waste sources of nitrogen were not present. Nitrate contamination in the Seymour Aquifer were examined and results showed that fertilizer to be the primary nitrate source in cultivated fields and animal wastes in domestic well water (Kreitler, 1979). The elevated $\delta^{15}N$ of 20 soil nitrate samples (+2 to +14) relative to that of the fertilizer (-7.4 to +1.9 ‰) was attributed to ammonium fertilizer volatilization. However, Bartolino (1994) indicated that high nitrate in the Seymour aquifer (late 1950s) predates fertilizer applications which began in the mid-1960s and may be attributed to symbiotic nitrogen fixation by mesquite trees that were replaced by crops. Cultivation oxygenated the soils converting organic nitrogen to nitrate and increased recharge leaching nitrate to the underlying aquifer.

Playas in the Texas High Plains have been used for many different purposes, including disposal of industrial wastewater, sewage and feedlot runoff. Nitrate loading related to wastewater discharge from concentrated animal feeding operations (CAFOs) to playas was examined in previous studies. Previous studies showed nitrate concentrations decreasing with depth beneath playas receiving waste water discharge from feedlots (e.g. 189 mg/kg at 0.3 m depth to 1.5 mg/kg at 1.2 m depth) (Lehman et al., 1970; Fryar et al., 2000). Similar decreases in nitrate concentrations were found when this site was resampled 5 yr later; however, chloride levels had increased by factors of 2 to 5 (Clark, 1975). Other studies found similar reductions in nitrate levels with depth beneath other playas adjacent to feedlots (Stewart et al., 1994; Daniel, 1997). Decreases in nitrate from CAFO runoff was attributed to deposition of suspended solids sealing surface soils and causing denitrification (Lehman and Clark, 1975; Roswell et al., 1985; Barrington and Broughton, 1988). A study of wells adjacent to 26 feedlots indicated that the highest nitrate level was 9.5 mg/L NO_3. A study by Fryar et al. (2000) of the unsaturated and saturated zone in the Southern High Plains confirmed that unsaturated zone denitrification reduced nitrate levels. Evidence for denitrification included elevated groundwater $\delta^{15}N$ values (> 12.5 ‰) and correlations between $\delta^{15}N$ and the natural log of nitrate; however, high groundwater O_2 concentrations suggest that denitrification is not likely in groundwater. The denitrification process in the upper unsaturated zone was supported by the presence of denitrifying bacteria in cores, soil gas $\delta^{15}N$ values < 0 ‰ , and reductions in NO_3/Cl and SO_4/Cl ratios with depth in cores.

A recent nitrate study examined spatiotemporal variability in groundwater nitrate concentrations on a county basis in Texas, with special emphasis on the Texas Rolling Plains (TRP), using data collected between 1960 and 2010 (Chaudhuri et al., 2012). This study showed that groundwater NO_3 concentrations have significantly increased in many counties since the 1960s, with NO_3-N concentrations exceeding the maximum contamination level (MCL) for NO_3-N of 10 mg/L in >30% of the observations in 25 counties in the 2000s relative to 8 counties in the 1960s. Exceedances were greatest in the Texas Rolling Plains (Haskell and Knox counties) with all analyses greater than the MCL in 2000. The increasing NO_3-N concentrations were positively correlated area of crop lands, fertilized croplands, and irrigated croplands linking agriculture in groundwater NO_3 concentrations. This study highlighted the large reduction in sampling over time and inadequate recent observations. This study indicated a marked deterioration in groundwater quality by NO_3 attributed to agricultural activities, highlight the need for more intensive spatial sampling.

A study was conducted by the Bureau of Economic Geology to assess controls on nitrate contamination in major porous media aquifers in the state by comparing groundwater nitrate levels with nitrogen loading and aquifer susceptibility parameters (Scanlon et al., 2004). Attributes characterizing nitrogen loading include atmospheric deposition, inorganic and organic fertilizers, land use, proxies for sewage and septic input, population density, precipitation, and irrigation. Attributes characterizing aquifer susceptibility to contamination include percent land surface slope, percent well drained soils, clay content, and organic matter content. Multivariate logistic regression was used to relate the probability of nitrate concentrations in shallow wells (≤ 30 m) exceeding a pre-specified threshold value of 4 mg/L nitrate-N with potential explanatory variables representing nitrogen loading and aquifer susceptibility. The final regression model included precipitation, percent agricultural land, low density residential land, and soil organic matter. Observed and predicted probabilities of elevated nitrate concentrations were highly correlated in calibration and validation data sets (R^2, 0.96; 0.98). The inverse relationship between precipitation and nitrate concentration may be related to dilution in high precipitation areas and possibly evapoconcentration in low precipitation areas. Although nitrate loading is not explicitly represented in the final model, percent agricultural land may be considered a proxy for nitrogen loading from agricultural sources and low density residential land use may be considered a proxy for septic tank effluent. Percent organic matter may reflect the influence of denitrification in some regions. This GIS and logistic regression analysis described in this study provides valuable insights into controls on the distribution of nitrate concentrations in groundwater and should be supplemented in future studies with field sampling to ground reference the GIS and logistic regression analysis of this study and to assess the impact of different processes such as dilution and denitrification on nitrate concentrations.

Previous studies conducted by researchers at the Bureau of Economic Geology drilled and sampled several unsaturated zone profiles and measured NO_3-N in the soil water to link land surface processes and potential groundwater contamination (Olyphant, 2009; Scanlon et al., 2008). The objective of the analysis was to quantify NO_3-N reservoirs beneath various ecosystems, including natural rangelands and irrigated and rainfed agricultural ecosystems in regions of high groundwater NO_3-N contamination in the Seymour, southern High Plains, and southern Gulf Coast aquifers. We drilled profiles beneath natural (24), and irrigated (22) and nonirrigated (44) ecosystems in these regions. Levels of NO_3-N beneath natural rangeland ecosystems are generally low in the different aquifer regions (median 48.7 kg/ha, range 4.3 to 1035 kg/ha); however, NO_3-N accumulations are much higher at depth beneath cultivated areas which were attributed to pre-cultivation rangeland conditions (median 392 kg/ha, range 8.0 to 1727 kg/ha). These results indicate that NO_3-N accumulations under current rangeland conditions may not reflect those beneath rangeland conditions prior to cultivation. Accumulations of NO_3-N beneath rainfed agriculture are moderate (median 80.3 kg/ha, range 0.4 to 1657 kg/ha), attributed to generally low to moderate fertilizer application rates in addition to pristine precipitation. However, NO_3-N levels beneath irrigated agriculture are generally high (median 276 kg/ha, range 3.7 to 4677 kg/ha). In the Southern High Plains, high NO_3-N levels beneath irrigated areas are attributed to deficit irrigation and lack of flushing and may result in soil salinisation. Various sources of evidence suggest that high groundwater contamination in the Seymour aquifer may be related to natural nitrate sources prior to irrigation and to irrigation recycling because of (1) high levels of groundwater nitrate contamination prior to fertilization and irrigation, (2) low to moderate fertilizer application rates, and (3) low to moderate unsaturated zone nitrate accumulations. High levels of groundwater nitrate contamination in the High Plains are focused in the southern part of the southern High Plains and are related to the shallow water table (~82 ft) and low saturated thickness (~45 ft). Nitrate loading is moderate to high in this region and nitrate reservoirs in the unsaturated zone are high in deep profiles representing rangeland conditions prior to cultivation. Large nitrate reservoirs in soil zones beneath irrigated areas are attributed to evapotranspirative concentration related to deficit irrigation. Groundwater nitrate contamination may increase in the future if these nitrate reservoirs are mobilized.

Data Sources and Analyses

Groundwater nitrate concentrations were obtained from the TWDB database on ambient groundwater quality. Other forms of nitrogen, such as ammonia (NH_3) or nitrite (NO_2) were not included because of their low concentrations attributed to reduced mobility, chemical instability, and lower loadings relative to nitrate (Nolan et al., 2002). All nitrate concentrations in this study are reported as elemental nitrogen. The detection limit for nitrate in the database was 0.1 mg/L. The TWDB database includes information on the well location and depth, drill date, primary water use (domestic, irrigation industrial, commercial), water quality sampling time, and major ion chemistry. To avoid overrepresentation of wells that were sampled multiple times, the TWDB database was screened for the most recent water quality sample between 1988 and 2014. This time period was used to provide the greatest number of records and because no time trends were obvious from the data. The resultant set of sampled wells contained 14,985 records. Nitrate levels in major and minor aquifers were evaluated (Figs. 1 and 2). The data set included 9,811 samples from major aquifers and 1990 samples from minor aquifers (Tables 1a and 2a). The majority of samples for the major aquifers are from the public water system category (39%), followed by rural domestic wells (25%), irrigation (15%), stock (11%) and other (Table 3a). The representation of wells in the minor aquifers is slightly different with the dominant category being rural domestic wells (32%), followed by public water systems (22%), stock (21%), irrigation (13%) and other (Table 4a).

Results and Discussion

Groundwater Nitrate Concentrations in Major Aquifer

Nitrate-N concentrations exceeded detection limits in ~70% of the samples from the major aquifers (Figure 3). Nitrate concentrations exceeded the MCL of 10 mg/L in 5.5% of all samples (9,811) evaluated in major aquifers (Table 1, Figures 3 and 4). Maps of nitrate concentrations for all major aquifers are shown in Figures 5 – 13. Water samples exceeding the nitrate MCL are predominantly from wells in the rural domestic category (45%) followed by irrigation wells (21%) (Table 3b). The Seymour Aquifer has the highest level of exceedances, with 61% of the samples exceeding the MCL, followed by the Pecos Valley (11.4%), Ogallala (9%), and the Edwards Trinity Plateau (6%). The remaining major aquifers had MCL exceedances < 2.3% of the samples analyzed in each of the aquifers (Carrizo-Wilcox, Edwards [Balcones Fault Zone, BFZ], Edwards Trinity Plateau, Hueco Mesilla Bolson, and Trinity aquifers. These results are consistent with previous studies which showed highest levels of nitrate contamination in the Seymour Aquifer in Rolling Plains region, attributed to the shallow water table, coarse textured soils, and intensive agriculture (Chaudhuri et al., 2012). The Pecos Valley and Southern Ogallala aquifers have similar attributes.

Approximately 20% of the groundwater samples from the major aquifers exceeded 3 mg/L NO_3-N (Table 1a), which is considered background level of NO_3-N. The percentage of samples exceeding 3 mg/L NO_3-N follow a similar trend to those exceeding the MCL of 10 mg/L, with the Seymour Aquifer ranked highest (86% of samples), followed by the Ogallala Aquifer (37%), Pecos Valley Aquifer (36%), and the Edwards Trinity Plateau Aquifer (33%). The remaining major aquifers have < 10% of samples exceeding 3 mg/L. A similar pattern was found for NO_3-N concentrations exceeding 1 mg/L. Major aquifers with the lowest levels of NO_3-N have the highest percentages of non-detects, with 72% of the samples registering as non-detects in the Carrizo Wilcox Aquifer, following by the Gulf Coast Aquifer (51%), Trinity Aquifer (42%), and the remaining aquifers having < 13% non-detects.

Nitrate concentrations in groundwater generally decreased with depth, suggesting a surface source for nitrate (Figure 14). The Trinity Aquifer shows the most marked reduction in nitrate concentrations to a depth of ~400 ft. The shapes of the nitrate percentile plots for the different aquifers help characterize the distribution of nitrate concentrations. Major aquifers with generally low levels of nitrate have similar shapes (Carrizo Wilcox, Trinity, and Gulf Coast aquifers, Figure 15a). The Seymour Aquifer stands out relative to all the other major aquifers with having the highest percentiles of nitrate exceeding the MCL (Figure 15c).

Groundwater Concentrations in Minor Aquifers

The analysis of groundwater nitrate concentrations in minor aquifers included almost 2000 analyses (Table 2a). The aquifers with the most analyses include the Dockum (379 analyses), Queen City (228), Woodbine (178), Ellenburger-San Saba (150), Yegua-Jackson (149), Hickory (145), Sparta (130), and West Texas Bolson (111). All other minor aquifers had less than ~ 100 analyses. Approximately 30% of the analyses were non detects with detection limits ranging from 0.002 to 1.00 mg/L NO_3-N (Table 2a). A total of 7% of the analyses exceeded the nitrate MCL and 20% of the analyses exceeded 3 mg/L NO_3-N, and 37% exceeded 1 mg/L. Water samples exceeding the nitrate MCL are predominantly from wells in the rural domestic category (48%) followed by irrigation wells (22%) (Table 4b).The minor aquifers with the highest level of nitrate MCL exceedances are ranked as follows: Lipan (59%>10 mg/L), Blaine (18%), Edwards-Trinity High Plains (18%), Bone Springs-Victoria Peak (13%), Rustler and Brazos River Alluvium, and Dockum aquifers (~10 – 11%) with the remaining aquifers < 10%. Percentages exceeding background levels of ~ 3 mg/L NO_3-N generally follow a similar order to the ranking of aquifers exceeding MCLs, with the Lipan having the highest percentage (84%), followed by the Blain (66%), Bone Springs-Victoria Peak (57%) Rustler (~40%) etc.

A map of the spatial distribution of nitrate concentrations in the minor aquifers is shown in Figure 16. The median nitrate concentration is highest in the Lipan Aquifer (13.9 mg/L), followed by the Blaine Aquifer (4.7 mg/L), the Bone-Springs Victoria Peak (4.0 mg/L), and the Edwards Trinity High Plains aquifer (2.5 mg/L). The remaining aquifers have median nitrate concentrations generally < ~ 1.6 mg/L. Most of the minor aquifers show large reductions in nitrate concentrations with depth (Figure 17). The shapes of the percentile plots are distinctive, Minor aquifers with highest nitrate concentrations have similar shapes (Lipan, Blaine, Bone Springs Victoria Peak) (Figure 18g).

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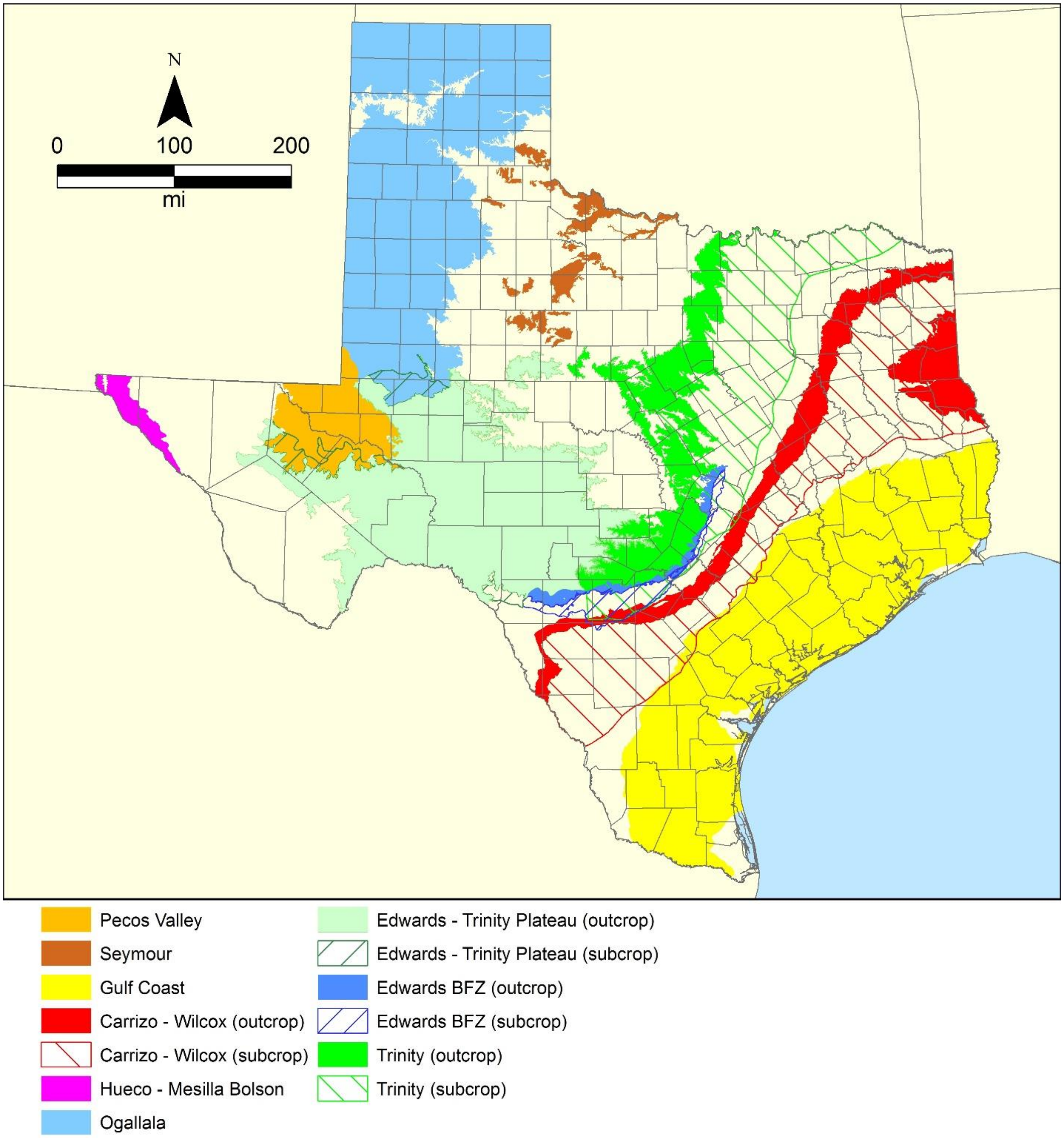


Figure 1. The major aquifers of Texas. The extents of outcrop areas are shown in solid colors and subcrop extents are shown with hatched areas. Aquifers are defined by the extent of water with a total dissolved solids concentration ≤ 3000 mg/L and do not necessarily define either geologic or hydrologic boundaries.

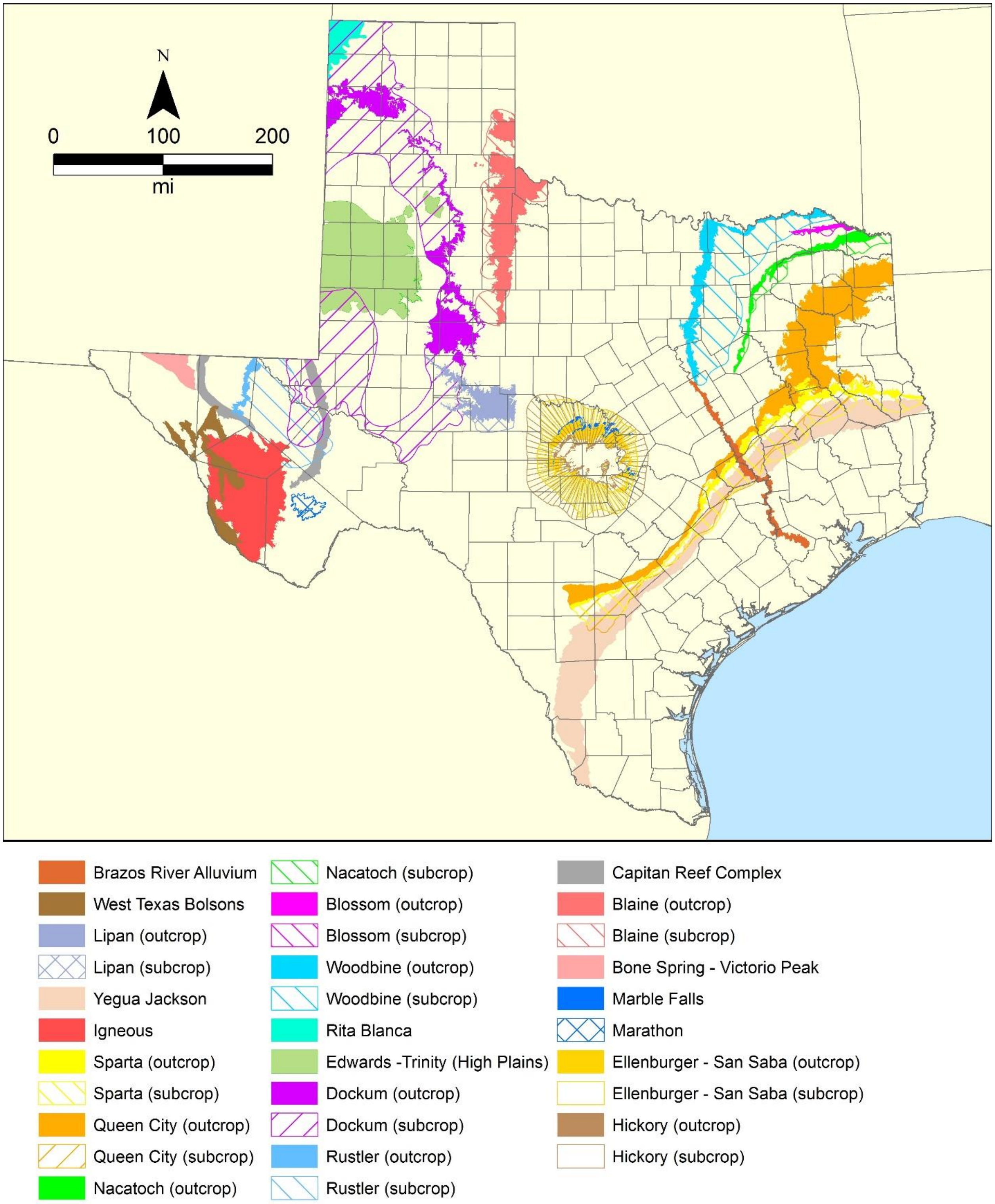


Figure 2. The minor aquifers of Texas. The extents of outcrop areas are shown in solid colors and subcrop extents are shown with hatched areas. Aquifers are defined by the extent of water with a total dissolved solids concentration ≤ 3000 mg/L and do not necessarily define either geologic or hydrologic boundaries.

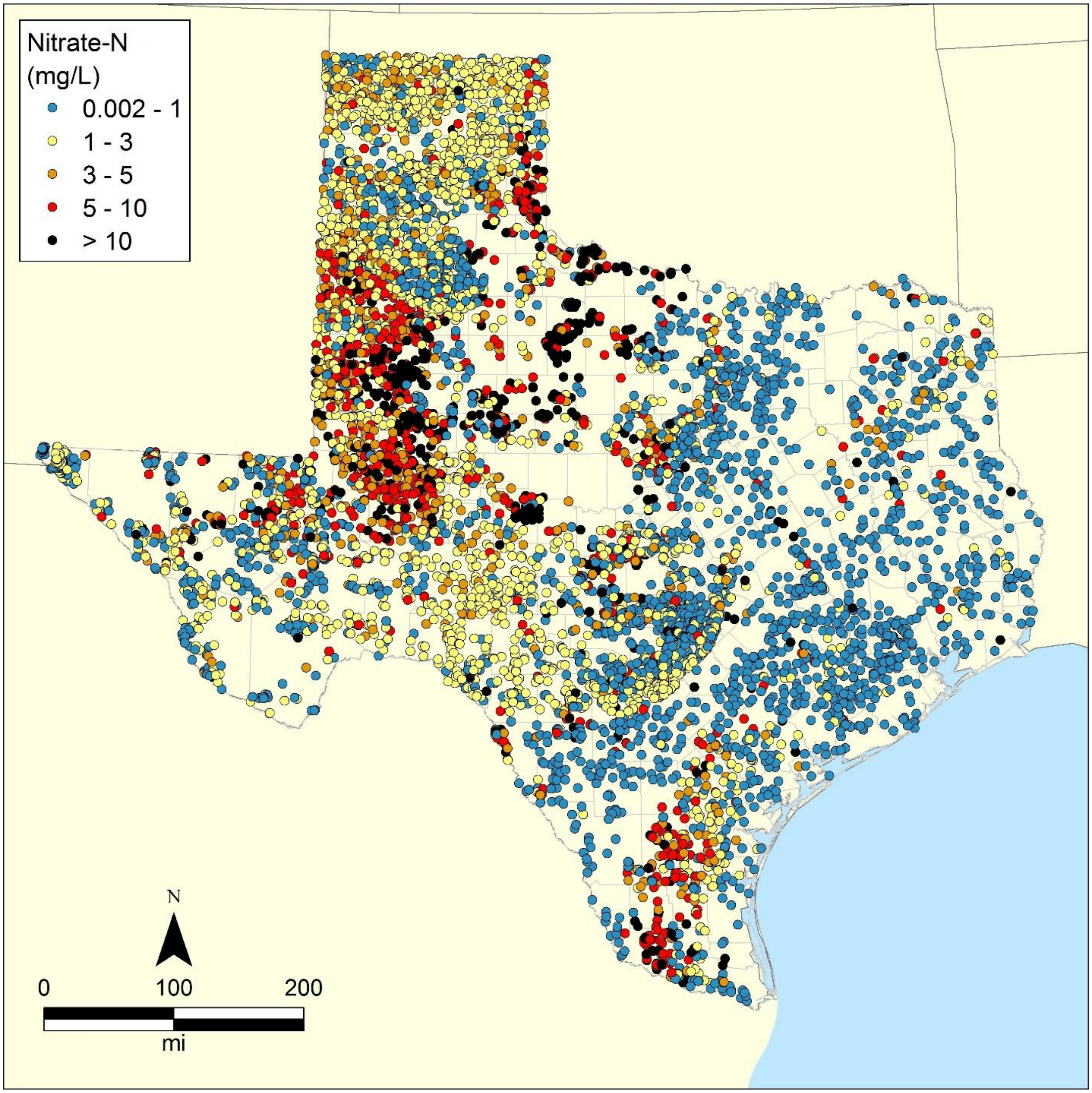


Figure 3. Locations of groundwater wells in Texas with detected nitrate-N concentrations.

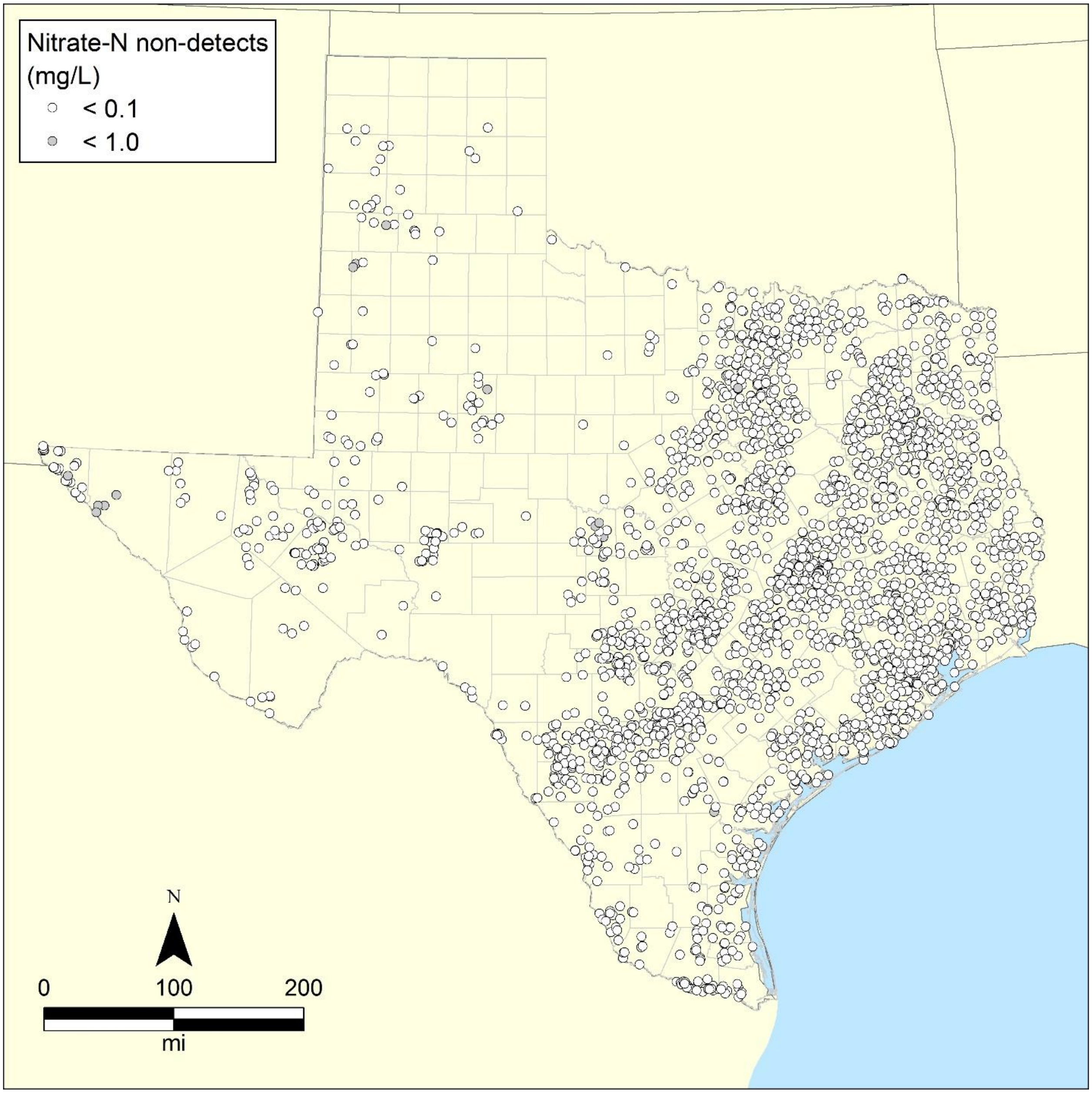


Figure 4. Locations of groundwater wells in Texas with non-detected nitrate-N concentrations.

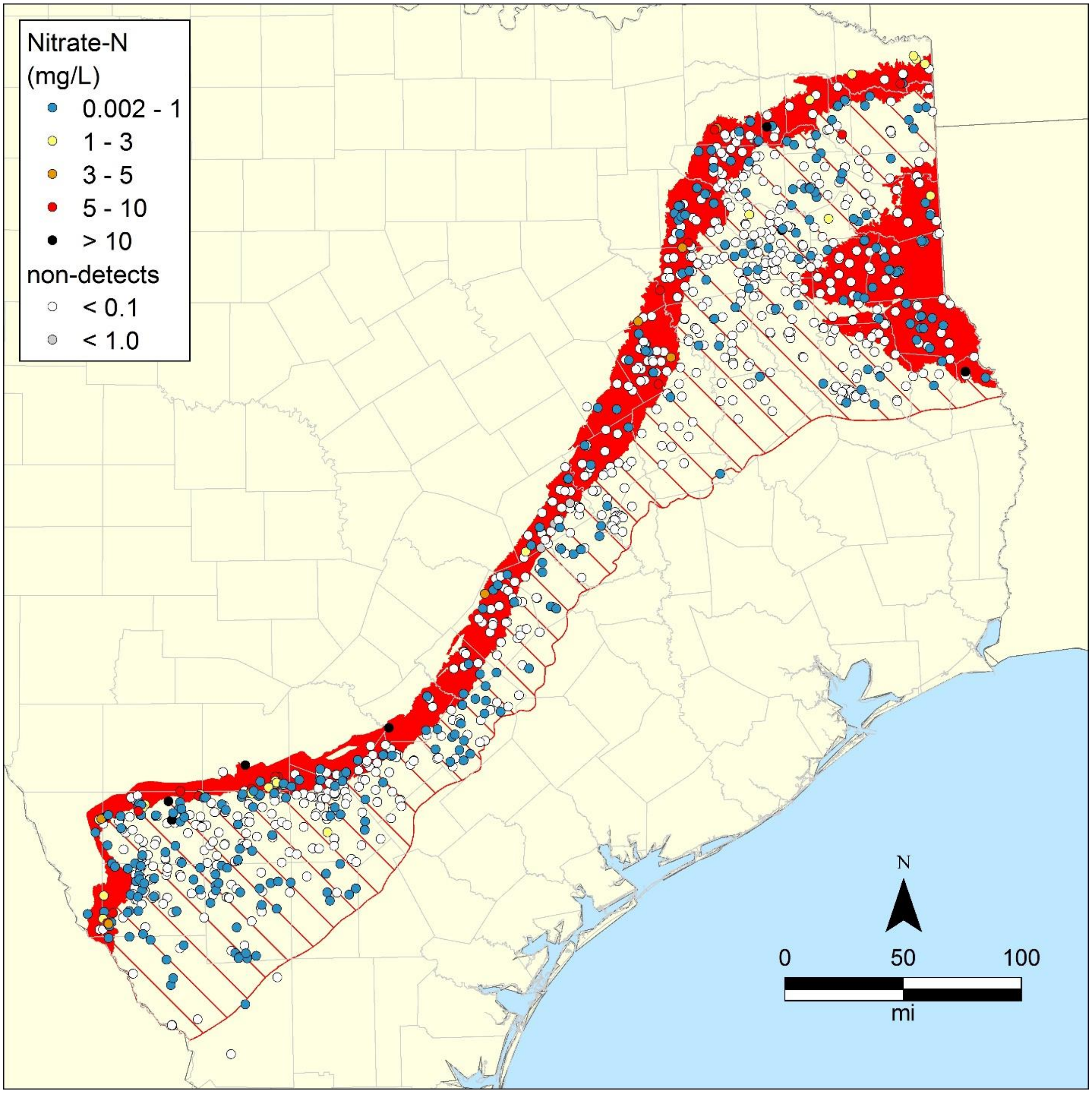


Figure 5. Carrizo-Wilcox aquifer nitrate-N concentrations.

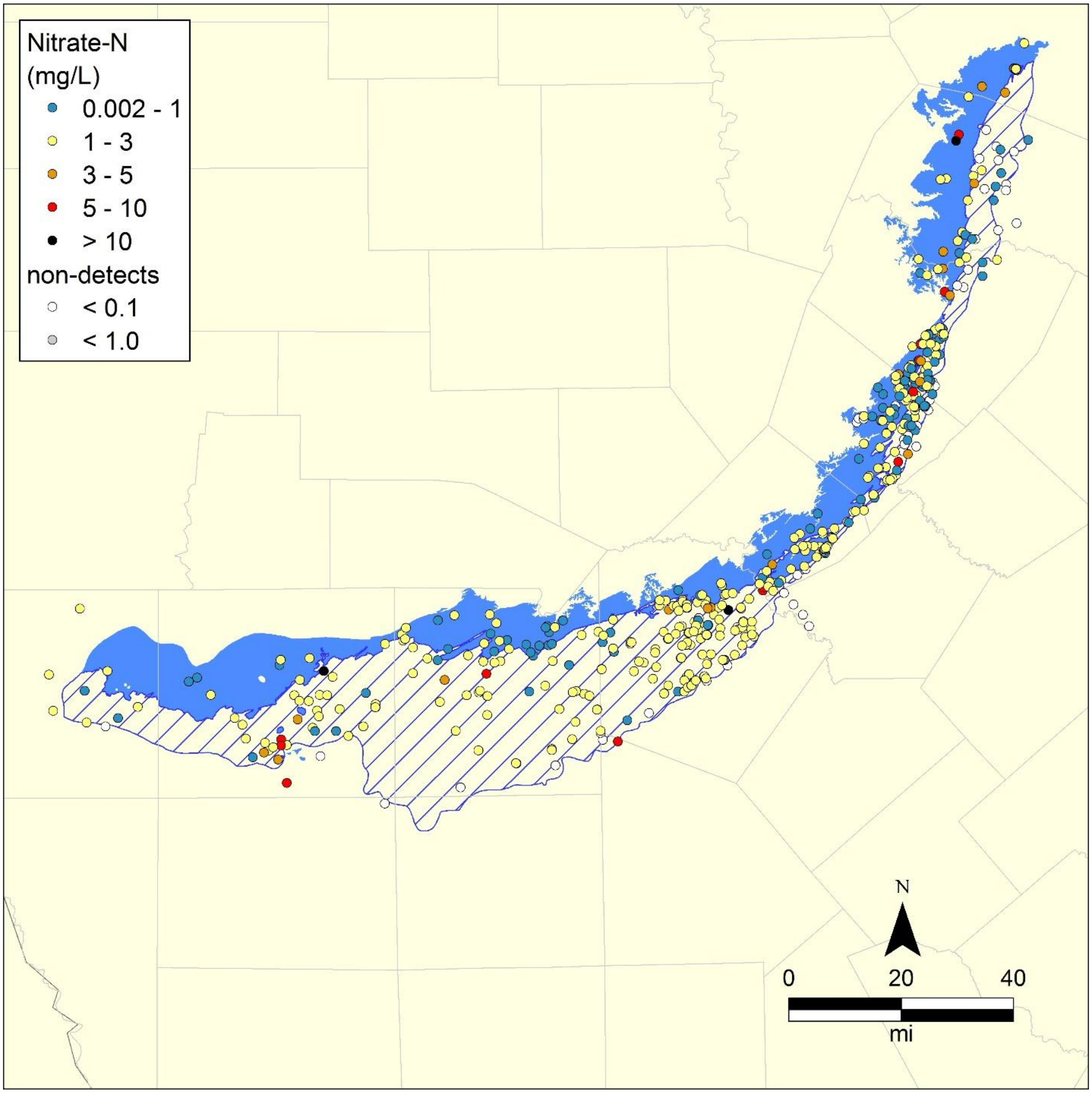


Figure 6. Edwards (Balcones Fault Zone) aquifer nitrate-N concentrations.

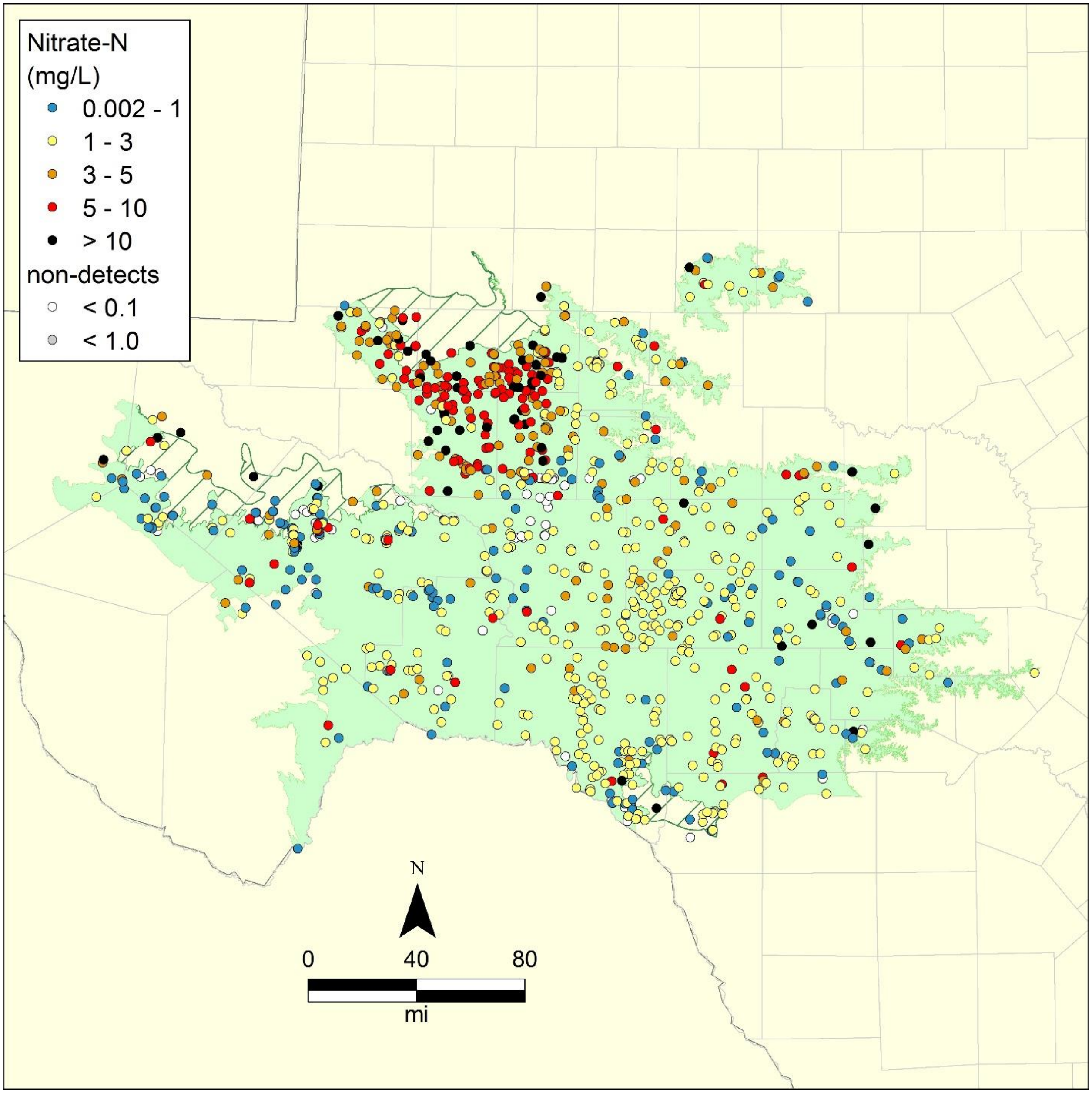


Figure 7. Edwards-Trinity Plateau aquifer nitrate-N concentrations.

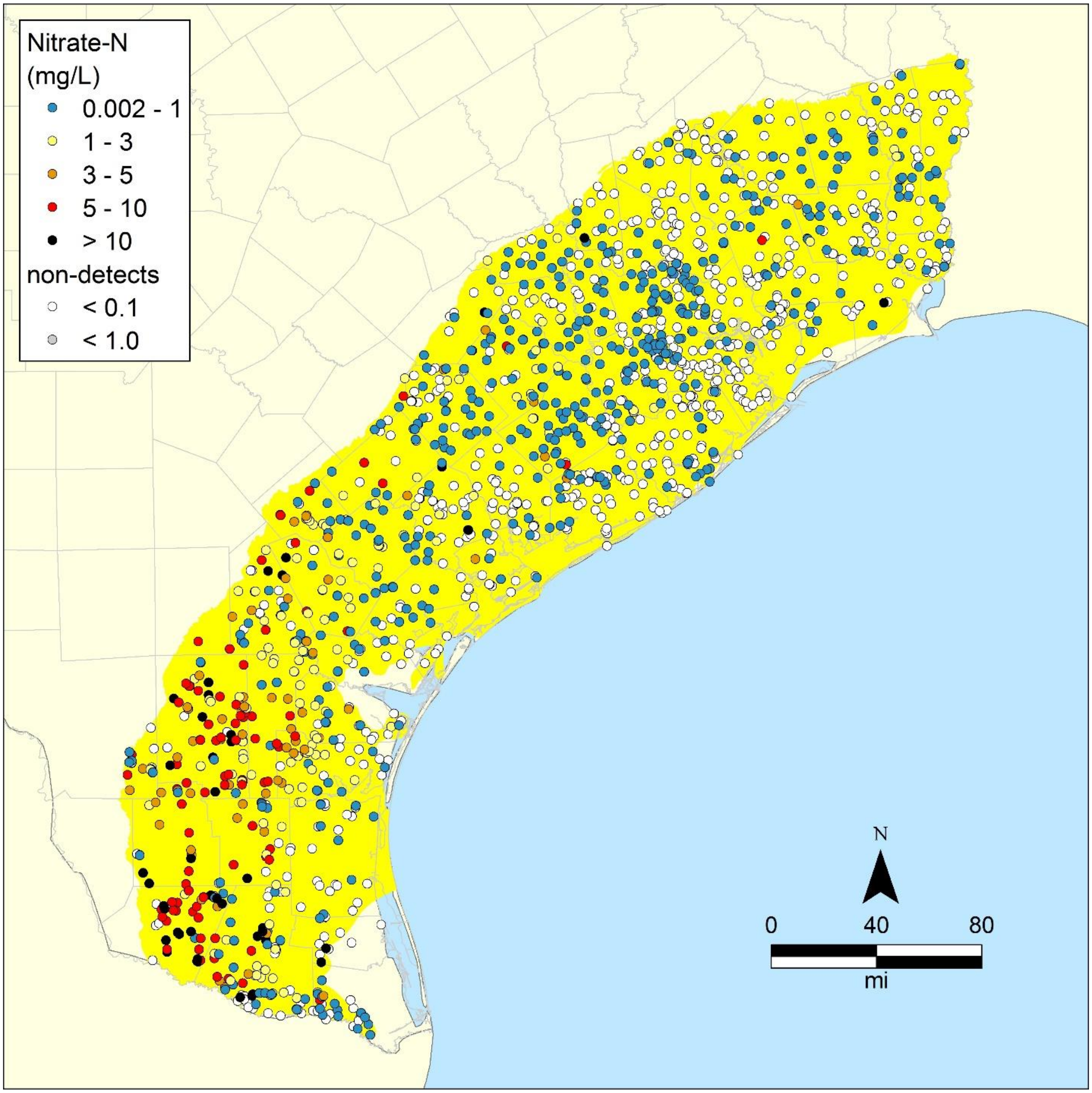


Figure 8. Gulf Coast aquifer nitrate-N concentrations.

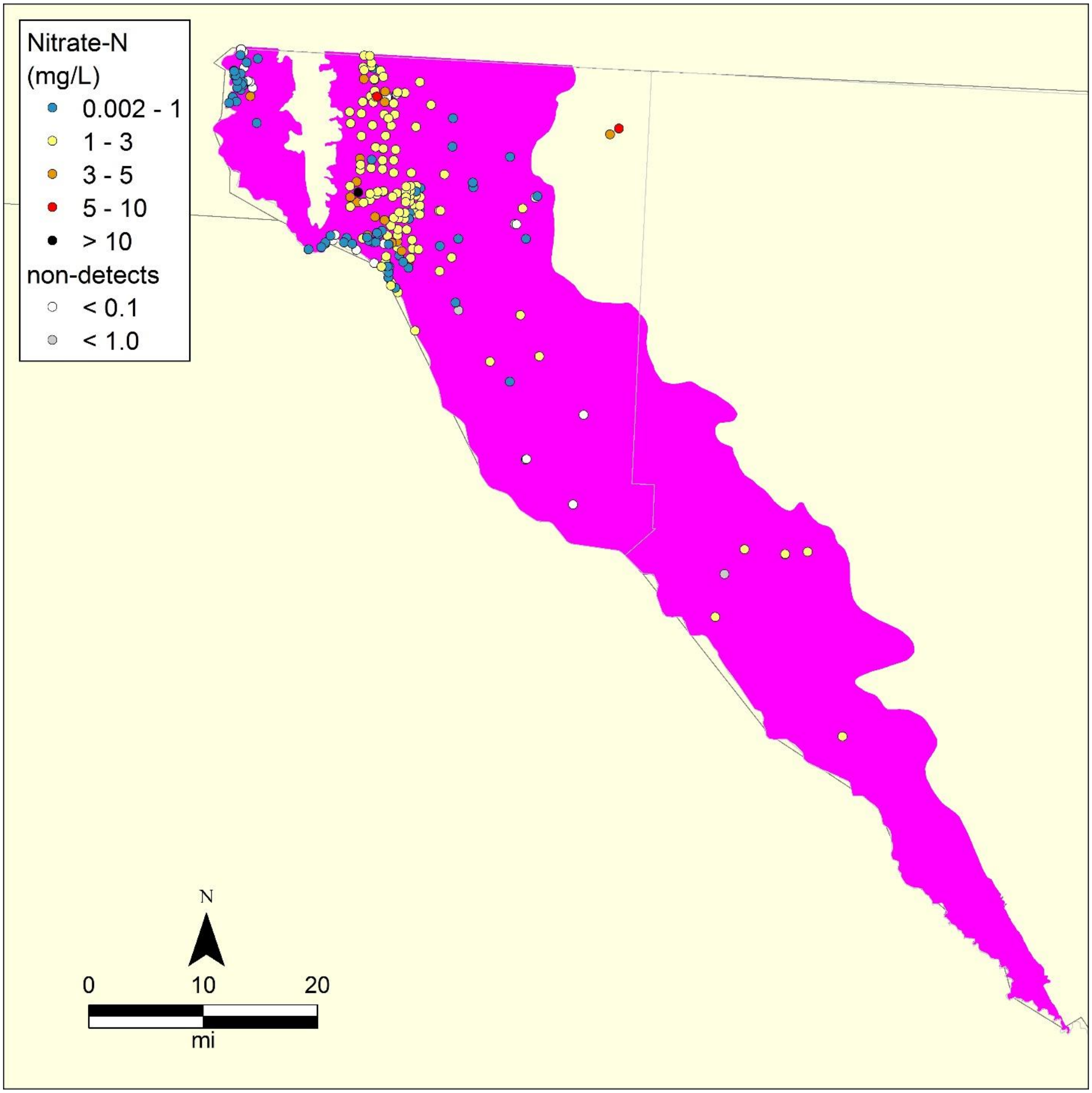


Figure 9. Hueco-Mesilla Bolson aquifer nitrate-N concentrations.

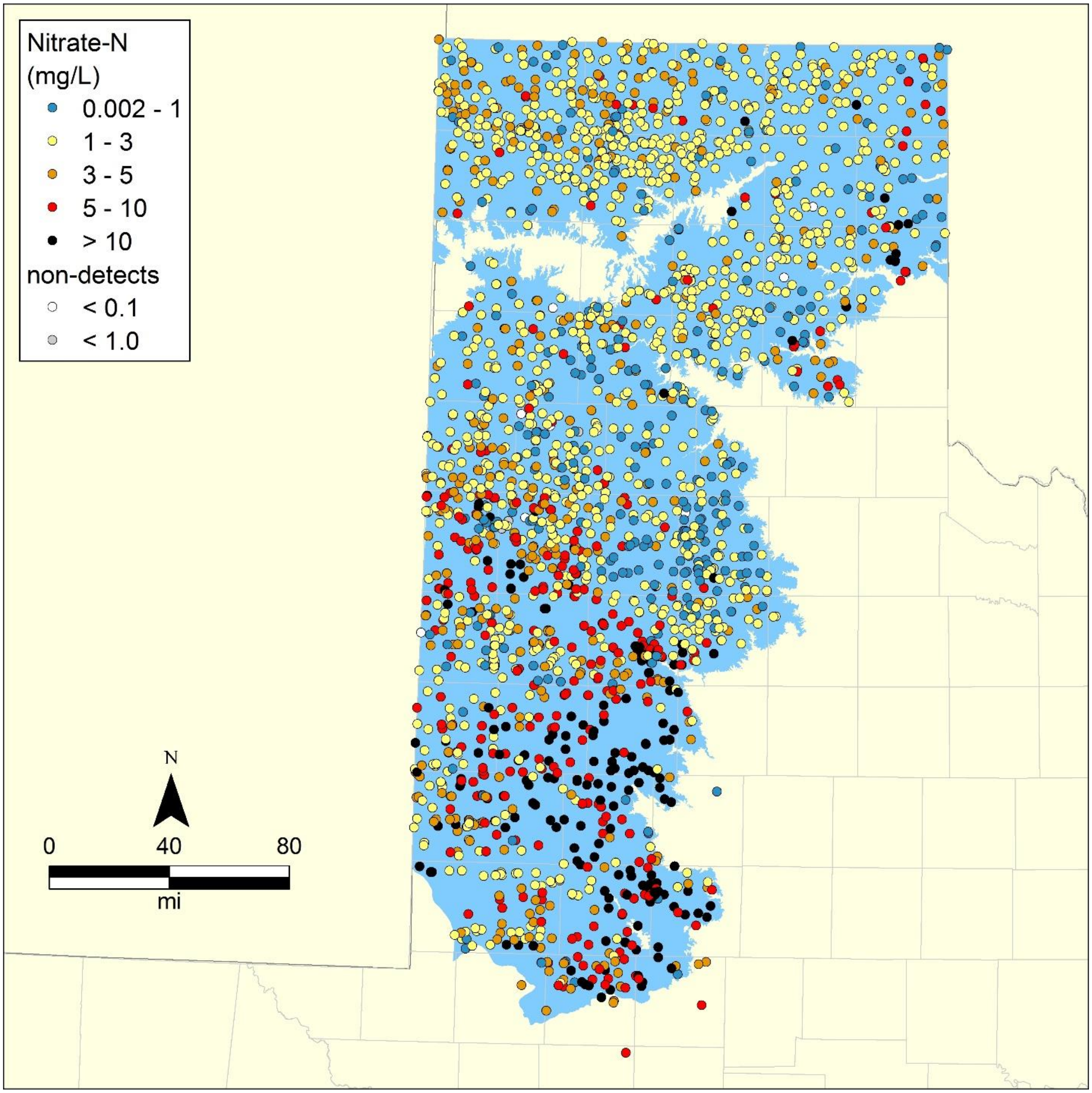


Figure 10. Ogallala aquifer nitrate-N concentrations.

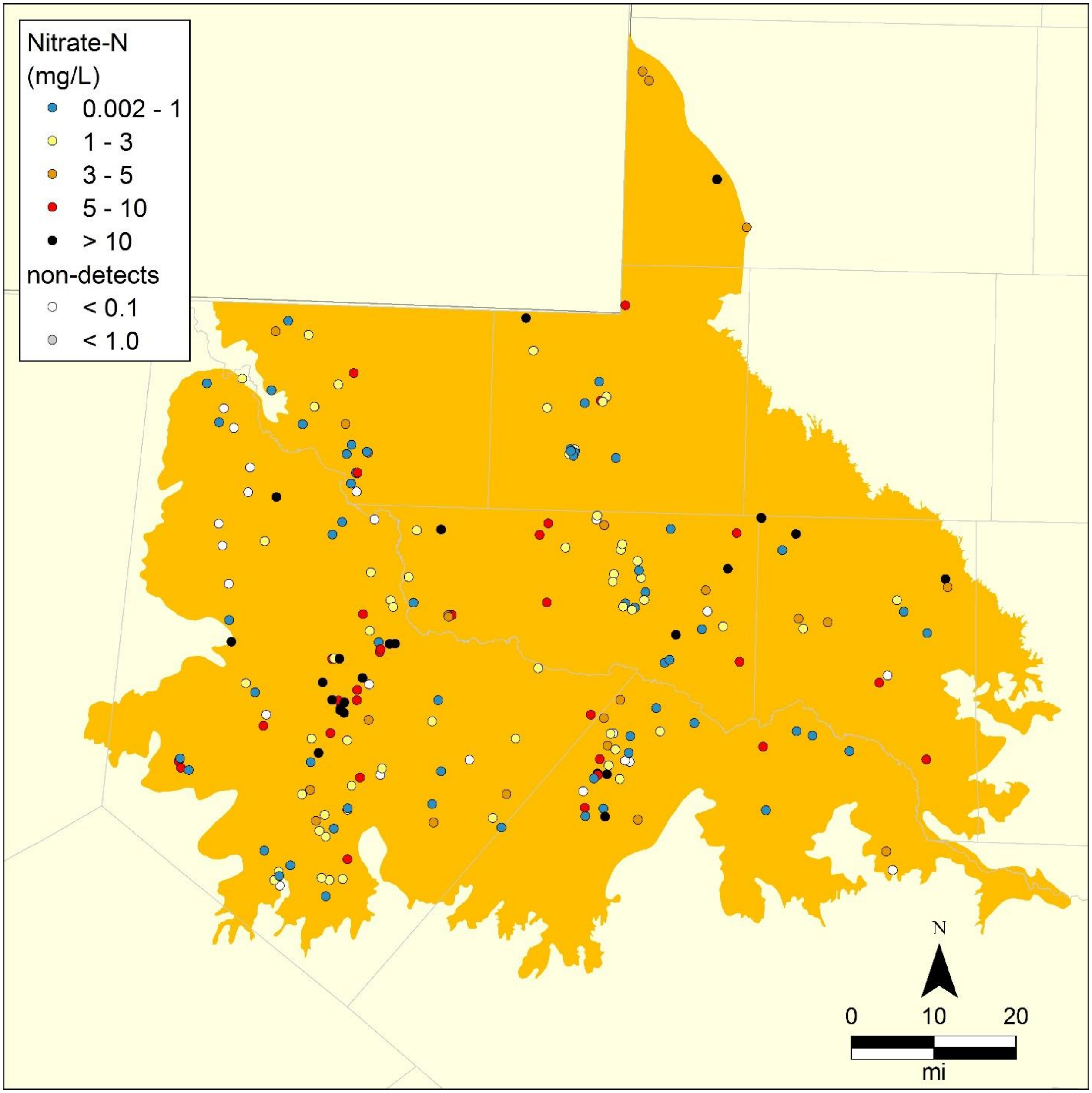


Figure 11. Pecos Valley aquifer nitrate-N concentrations.

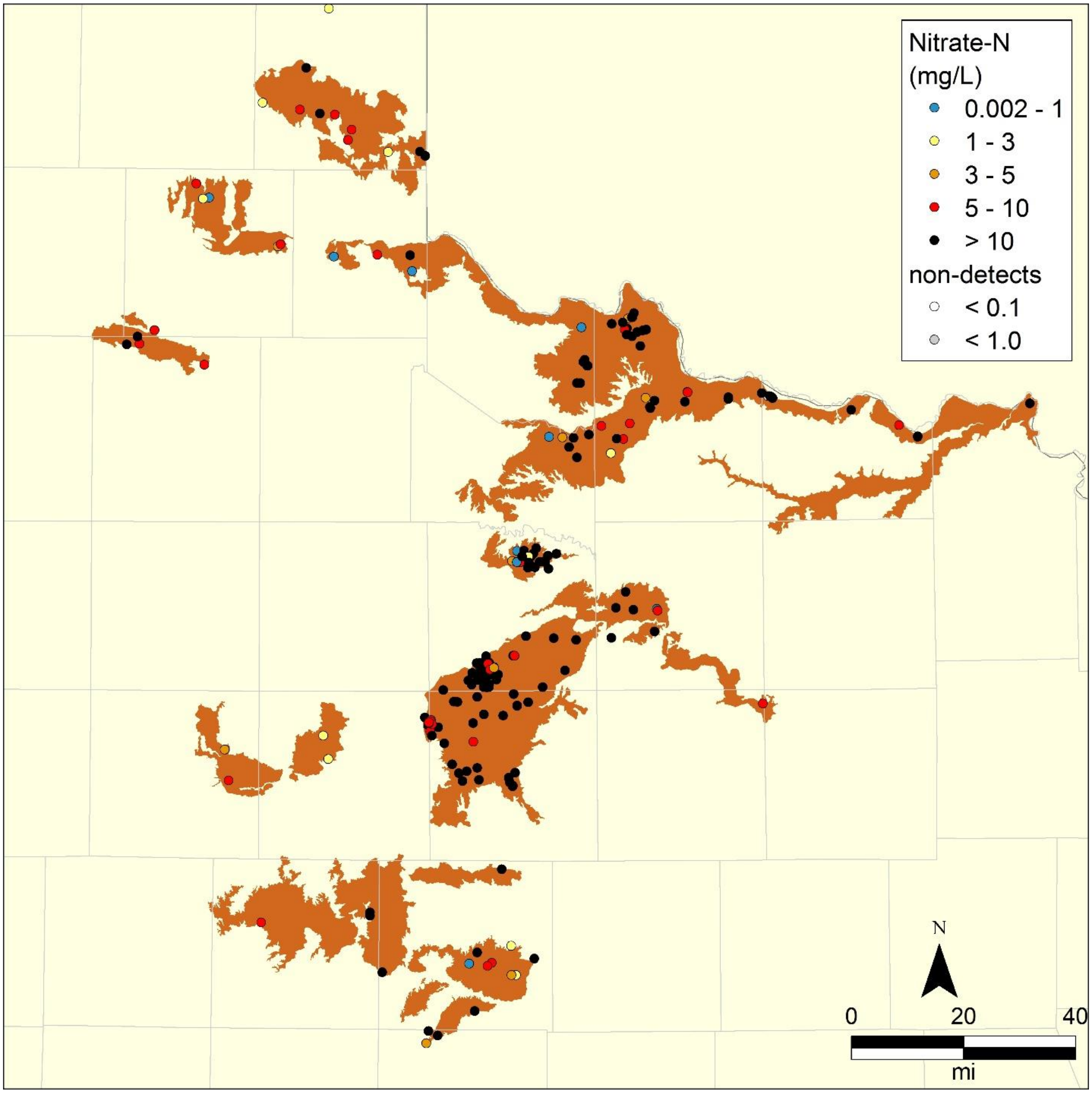


Figure 12. Seymour aquifer nitrate-N concentrations.

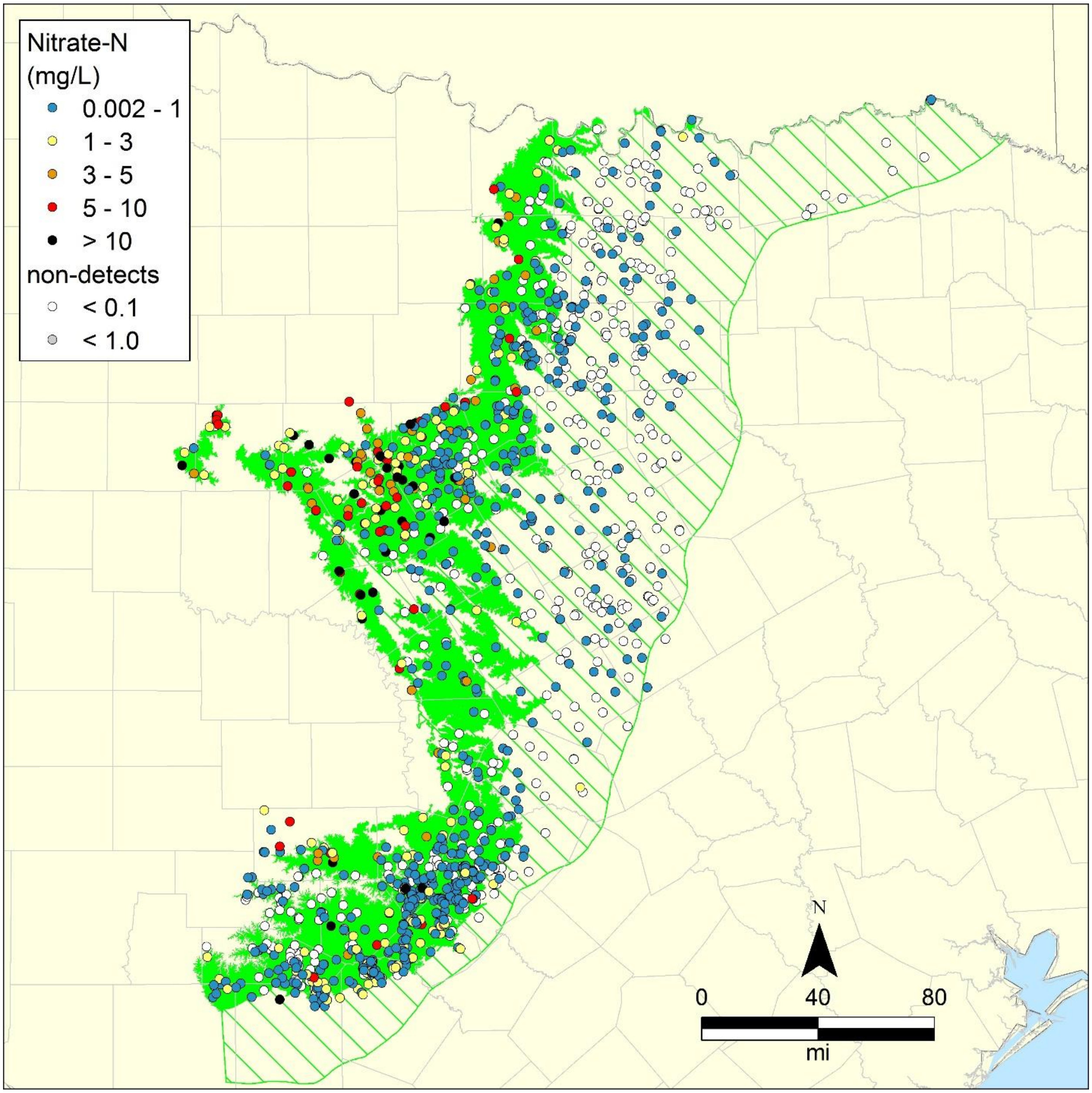


Figure 13. Trinity aquifer nitrate-N concentrations.

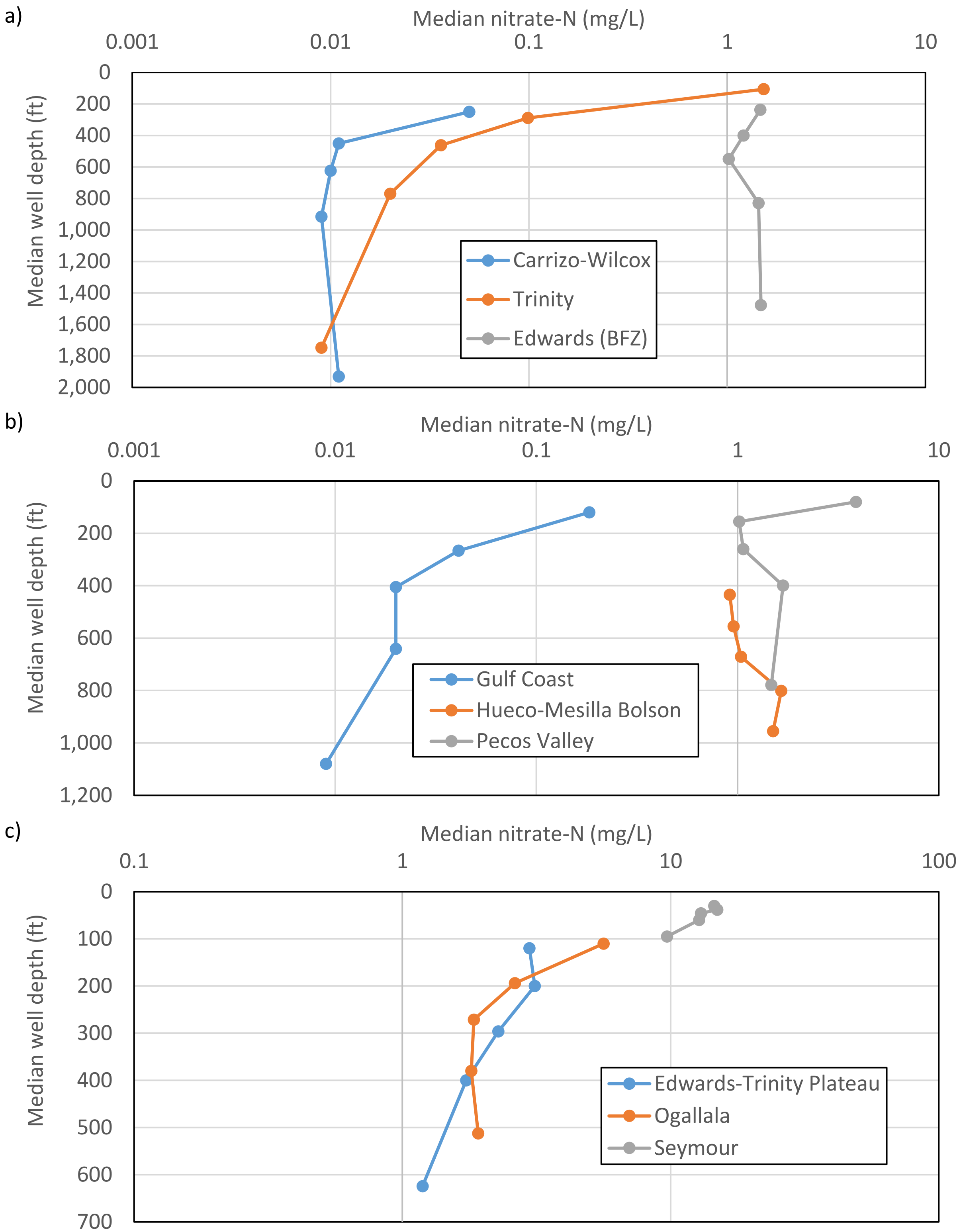


Figure 14. Nitrate-N concentrations with depth in the major aquifers of Texas. Concentration data in Table 5 are plotted against the median well depths within 20th percentile well depth groups for each aquifer.

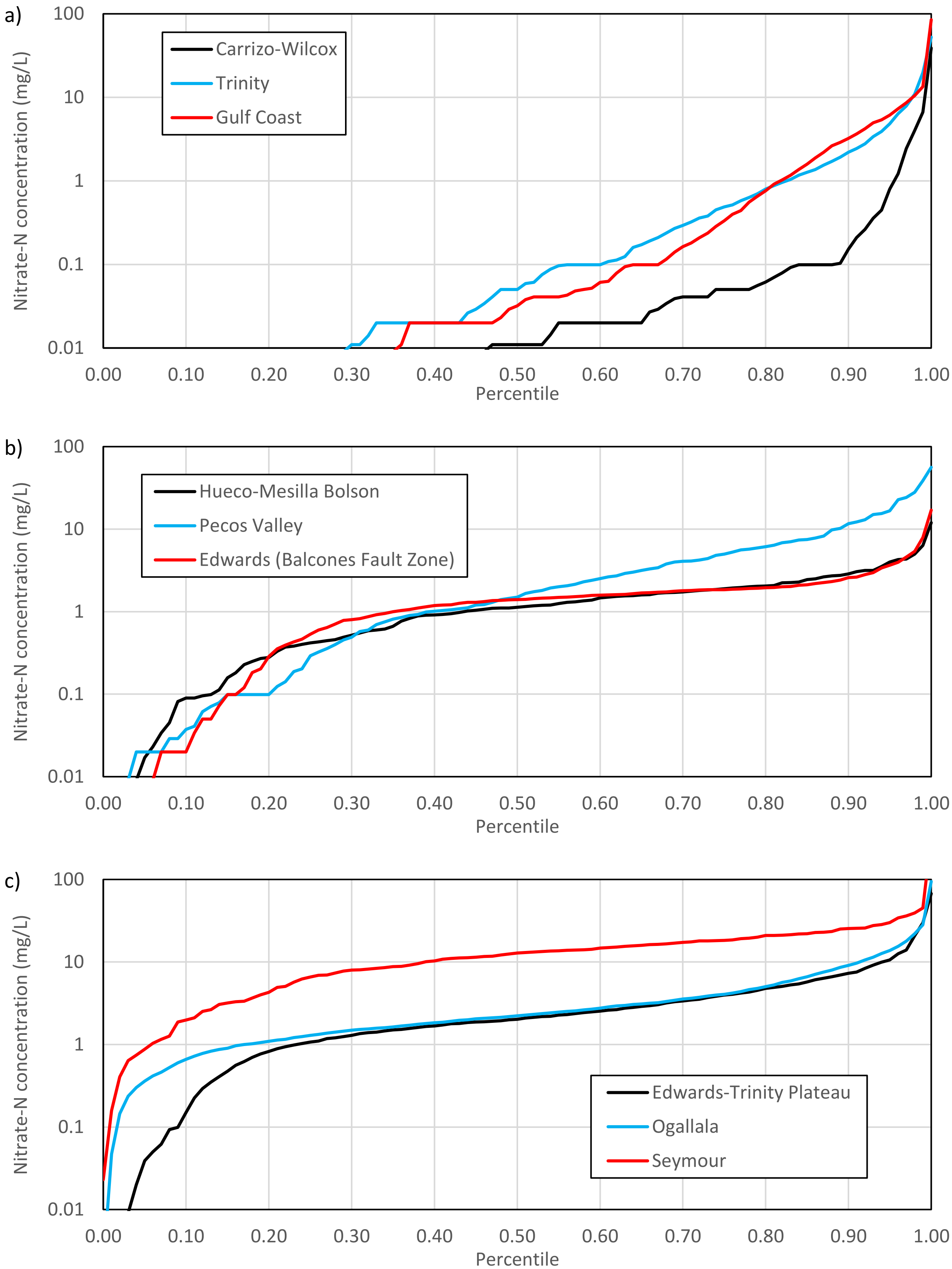


Figure 15. Nitrate-N concentration distributions in the major aquifers of Texas

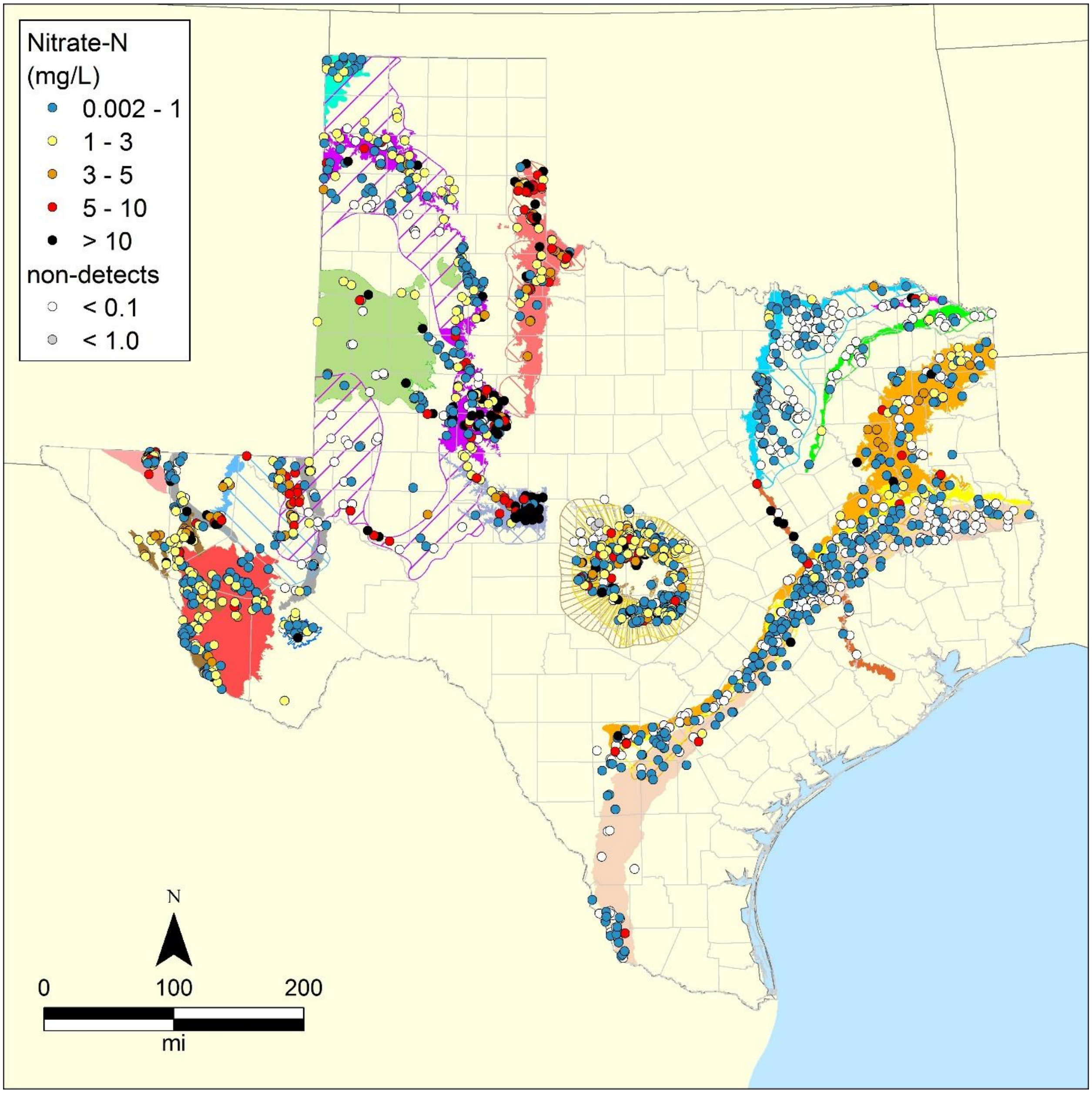


Figure 16. Minor aquifer nitrate-N concentrations.

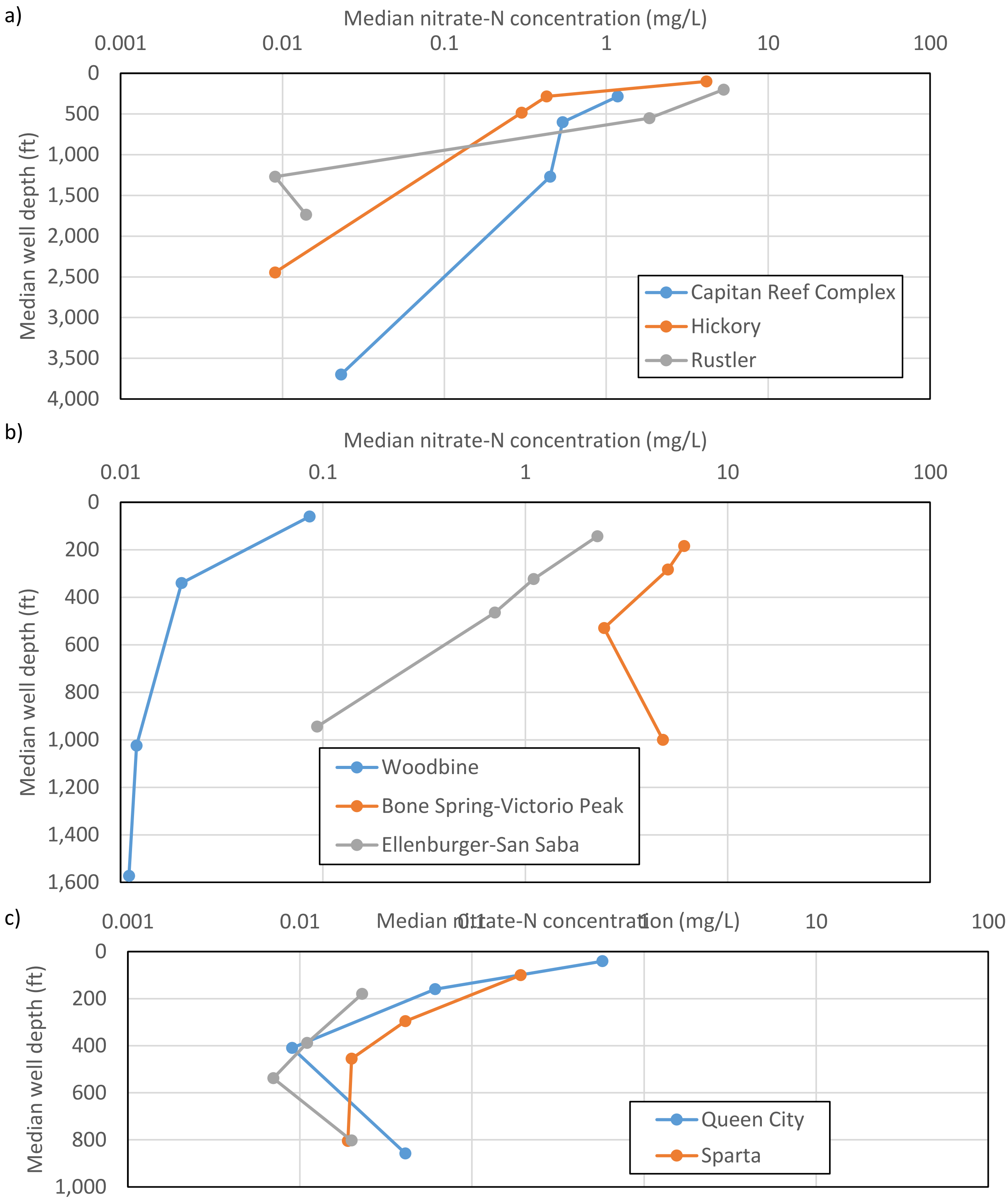
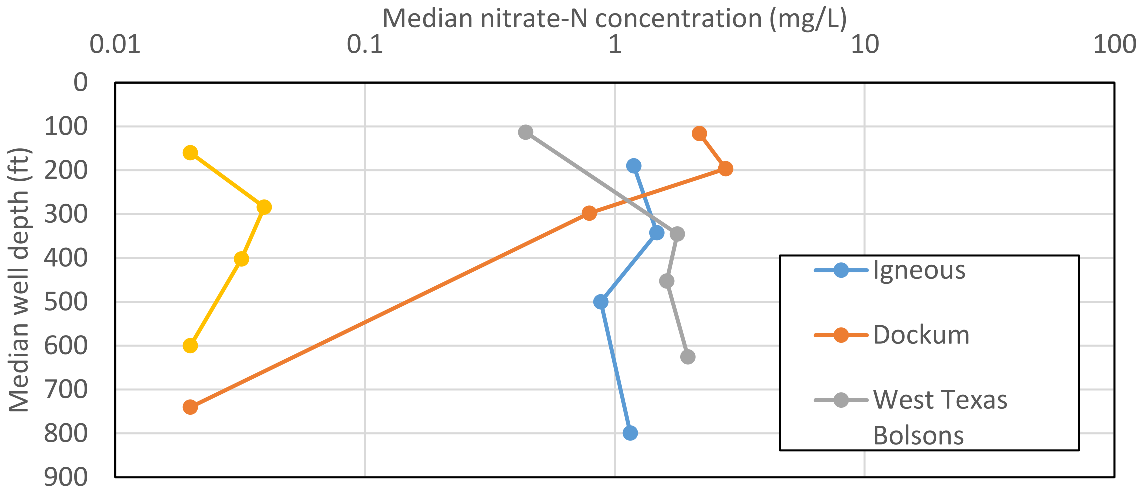


Figure 17. Nitrate-N concentrations with depth in the minor aquifers of Texas. Concentration data in Table 6 are plotted against the median well depths within 25th percentile well depth groups for each aquifer.

d)



e)

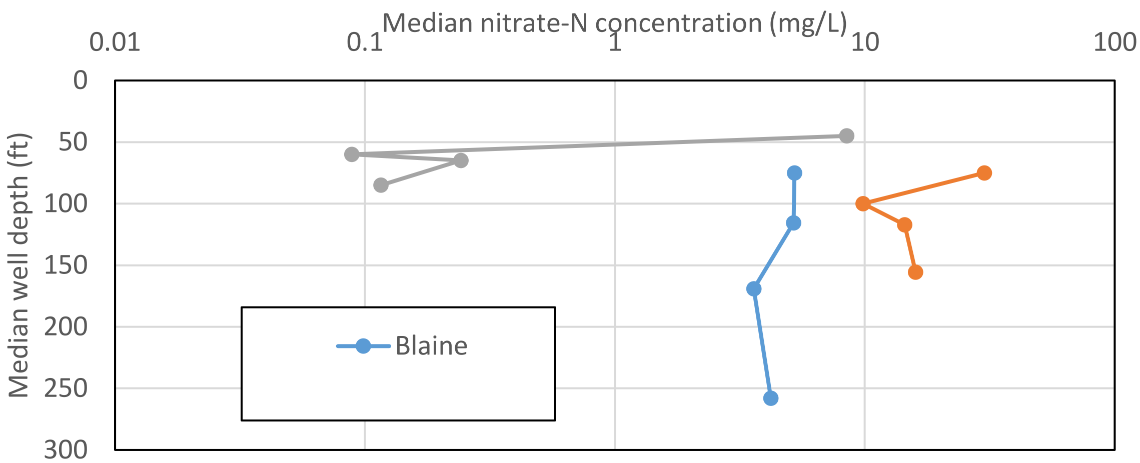


Figure 17 (cont). Nitrate-N concentrations with depth in the minor aquifers of Texas. Concentration data in Table 6 are plotted against the median well depths within 25th percentile well depth groups for each aquifer.

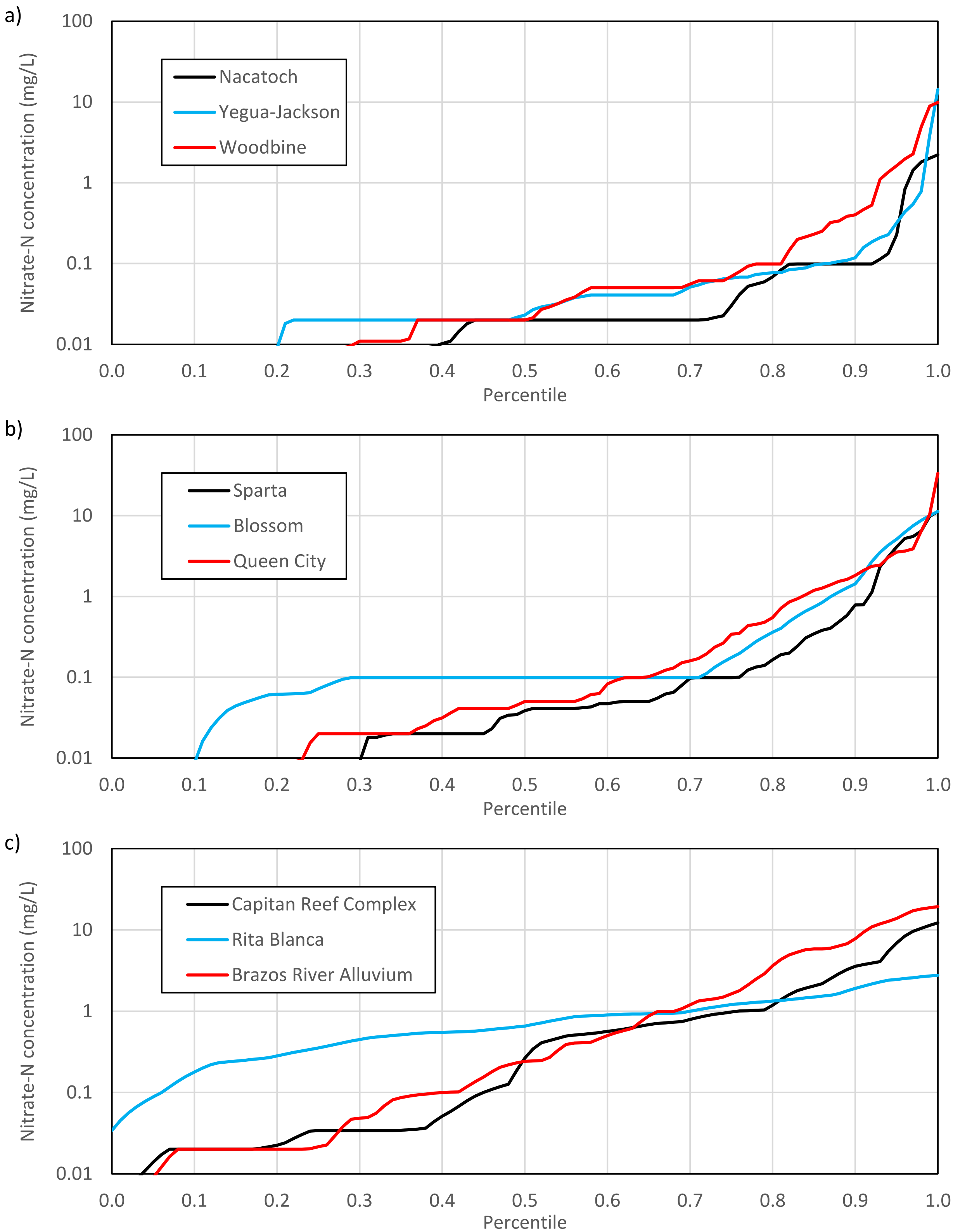


Figure 18. Nitrate-N concentration distributions in the minor aquifers of Texas

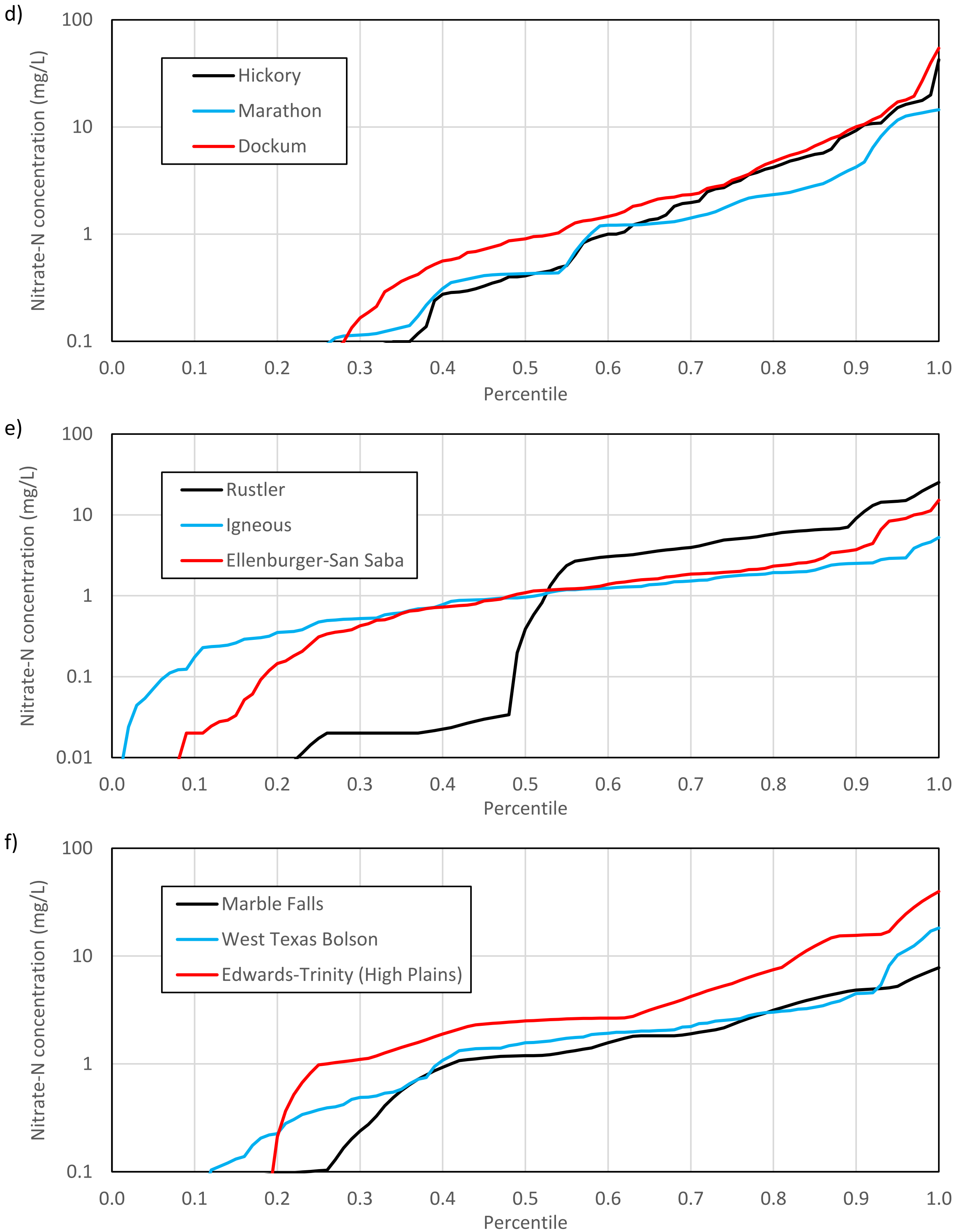


Figure 18 (cont). Nitrate-N concentration distributions in the minor aquifers of Texas g)

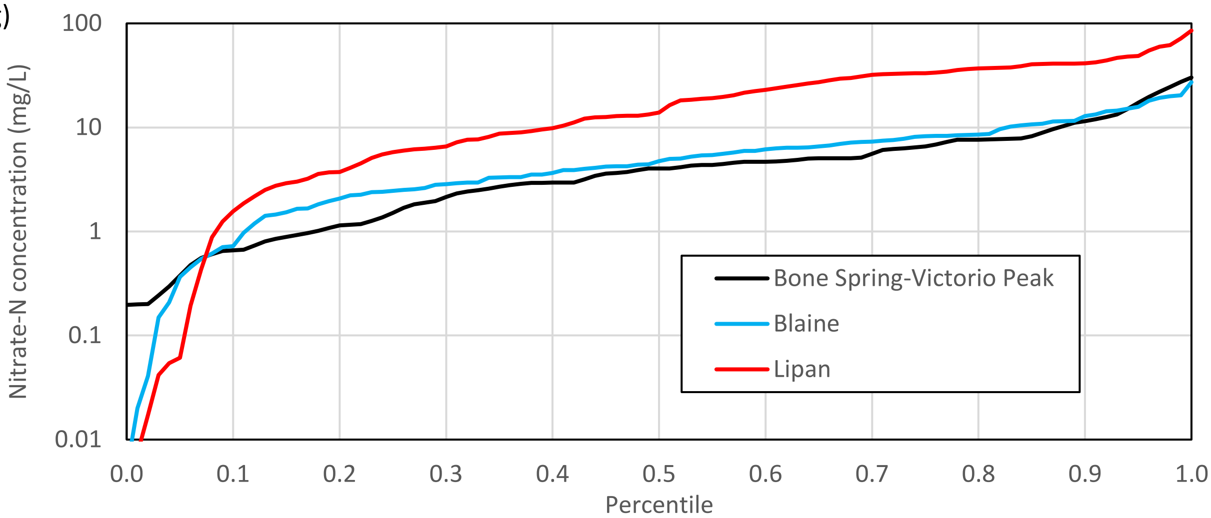


Figure 18 (cont). Nitrate-N concentration distributions in the minor aquifers of Texas

Table 1a. Summary of nitrate-N concentration distributions for groundwater wells completed in the major aquifers of Texas (Figure 1). Non-detects (<’s) represent the number of samples that were below the detection limits of the analytical method. Detection limits ranged from 0.002 mg/L to 1.00 mg/L with mean 0.023 mg/L for all major aquifer samples. Percentiles indicate the percentage of samples with nitrate-N concentrations greater than the given value. For example in the Seymour aquifer, nitrate-N exceeds 1.0 mg/L in 94.1% of samples and 10 mg/L in 61.2 % of samples. Natural background concentrations are generally considered to range from 2–4 mg/L. A value of 3 mg/L nitrate-N is used in this study to represent natural or background threshold concentration. The EPA Maximum Contamination Level (MCL) for nitrate-N in drinking water is 10 mg/L.

Aquifer	***Sample Dates***			***Number of Samples***		***Percentiles (mg/L)***		
	Range	*Mean*	*Median*	*Total*	*<’s*	*>1*	*>3*	*>10*
Carrizo-Wilcox	1988-2014	2004	2005	1,335	963	4.4	2.7	0.5
Edwards (BFZ)	1988-2015	2003	2003	610	76	65.1	6.7	0.5
Edwards-Trinity Plateau	1988-2015	2004	2003	1,108	72	76.8	33.1	6.0
Gulf Coast	1988-2015	2003	2004	2,007	1,030	18.3	10.6	2.3
Hueco-Mesilla Bolson	1988-2014	1998	2000	231	27	56.7	9.1	0.4
Ogallala	1988-2014	2001	2000	2,449	21	83.0	36.6	8.7
Pecos Valley	1988-2012	2001	2002	228	25	61.0	36.0	11.4
Seymour	1988-2015	2000	1998	237	1	94.1	86.1	61.2
Trinity	1988-2015	2002	2002	1,606	680	17.4	8.0	2.3
All major aquifers	1988-2015	2002	2003	9,811	2,895	45.7	20.3	5.5

Table 1b. Summary of nitrate-N concentration distributions for major aquifers of Texas (Figure 1). Non-detects were included in the distributions at their detection concentrations. Distribution statistics shown are therefore estimates and values equal to or less than the maximum non-detect concentration are qualified with less-than (<) symbols. Mean non-detect concentrations are also shown. Distribution populations and numbers of non-detects in each aquifer data set are shown in Table 1a.

Aquifer	*Non-detects*		*Distribution*							
	Max	*Mean*	*Mean*	*Min*	*5th*	*25th*	*50th*	*75th*	*95th*	*Max*
Carrizo-Wilcox	0.10	0.02	0.29	<0.002	<0.002	<0.005	<0.01	<0.05	0.78	38.9
Edwards (BFZ)	0.10	0.03	1.49	<0.002	<0.009	<0.53	1.40	1.85	3.68	17.0
Edwards-Trinity Plateau	0.10	0.03	3.52	<0.002	<0.04	1.07	2.03	3.96	10.55	67.4
Gulf Coast	0.10	0.02	1.09	<0.002	<0.002	<0.005	<0.03	0.33	6.12	85.0
Hueco-Mesilla Bolson	0.40	0.07	1.41	<0.002	<0.02	0.42	1.13	1.90	3.99	12.0
Ogallala	1.00	0.15	4.05	<0.002	<0.36	1.29	2.23	4.05	13.80	94.6
Pecos Valley	0.10	0.05	4.32	<0.002	<0.02	0.29	1.50	4.99	16.72	56.2
Seymour	0.02	0.02	14.70	<0.023	0.88	6.58	12.80	18.20	30.10	335
Trinity	0.23	0.02	1.02	<0.002	<0.002	<0.01	<0.05	0.49	4.83	52.6
All major aquifers	1.00	0.023	2.42	<0.002	<0.005	0.020	0.69	2.40	10.7	335

Table 2a. Summary of nitrate-N concentration distributions for groundwater wells completed in the minor aquifers of Texas (Figure 2). Non-detects (<'s) represent the number of samples that were below the detection limits of the analytical method. Detection limits ranged from 0.002 mg/L to 1.00 mg/L with mean 0.028 mg/L for all minor aquifer samples. Percentiles indicate the percentage of samples with nitrate-N concentrations greater than the given value. For example in the Lipan aquifer, nitrate-N exceeds 1.0 mg/L in 91.8% of samples and 10 mg/L in 59.0 % of samples. Natural background concentrations are generally considered to range from 2–4 mg/L. A value of 3 mg/L nitrate-N is used in this study to represent natural or background threshold concentration. The EPA Maximum Contamination Level (MCL) for nitrate-N in drinking water is 10 mg/L.

Aquifer	*Sample Dates*			*Number of Samples*		*Percentiles (mg/L)*		
	Range	*Mean*	*Median*	*Total*	*<'s*	*>1*	*>3*	*>10*
Blaine	1990-2015	2002	2004	101	2	88.1	66.3	17.8
Blossom	1997-2015	2006	2006	22	15	13.6	9.1	4.5
Bone Spring-Victorio Peak	1992-2007	1996	1993	46	-	82.6	56.5	13.0
Brazos River Alluvium	1993-2011	1999	1999	39	9	30.8	20.5	10.3
Capitan Reef Complex	1992-2012	2004	2007	30	12	26.7	13.3	3.3
Dockum	1989-2014	1999	2000	379	67	46.7	25.6	10.0
Edwards-Trinity (High Plains)	1996-2012	2006	2008	17	4	70.6	35.3	17.6
Ellenburger-San Saba	1988-2015	2002	2003	150	17	52.0	14.0	3.3
Hickory	1988-2015	2002	2004	145	45	39.3	25.5	9.7
Igneous	1990-2015	2000	1999	76	1	48.7	3.9	-
Lipan	1990-2015	2003	2001	61	1	91.8	83.6	59.0
Marathon	1998-2011	2009	2011	23	3	43.5	13.0	8.7
Marble Falls	1988-2015	1998	1996	20	3	60.0	20.0	-
Nacatoch	1991-2012	2002	2001	40	28	5.0	-	-
Queen City	1989-2014	2001	2002	228	99	16.7	6.1	1.3
Rita Blanca	1989-2011	2002	2004	17	-	29.4	-	-
Rustler	1988-2012	2001	1999	28	9	46.4	39.3	10.7
Sparta	1989-2014	2001	2002	130	63	8.5	6.2	1.5
West Texas Bolson	1990-2011	2000	2001	111	5	60.4	20.7	5.4
Woodbine	1988-2015	2002	2001	178	107	7.9	2.8	-
Yegua-Jackson	1988-2014	2003	2002	149	78	2.0	1.3	0.7
All minor aquifers	1988-2015	2001	2002	1,990	568	37.3	19.7	7.2

Table 2b. Summary of nitrate-N concentration distributions for minor aquifers of Texas (Figure 2). Non-detects were included in the distributions at their detection concentrations. Distribution statistics shown are therefore estimates and values equal to or less than the maximum non-detect concentration are qualified with less-than (<) symbols. Mean non-detect concentrations are also shown. Distribution populations and numbers of non-detects in each aquifer data set are shown in Table 2a.

Aquifer	***Non-detects***		***Distribution***							
	Max	*Mean*	*Mean*	*Min*	*5th*	*25th*	*50th*	*75th*	*95th*	*Max*
Blaine	0.02	0.01	6.03	<0.005	0.37	2.451	4.73	8.24	15.8	27.2
Blossom	0.10	0.07	0.94	<0.002	<0.005	<0.072	<0.099	0.17	5.11	11.3
Bone Spring-Victorio Peak	-	-	5.45	0.20	0.38	1.51	4.03	6.57	17.3	30.2
Brazos River Alluvium	0.02	0.02	2.51	<0.005	<0.009	<0.02	0.24	1.64	13.8	19.3
Capitan Reef Complex	0.10	0.03	1.33	<0.005	<0.014	<0.034	0.27	0.98	6.91	12.2
Dockum	0.20	0.02	3.49	<0.002	<0.009	<0.034	0.91	3.19	17.2	54.4
Edwards-Trinity (High Plains)	0.02	0.01	6.02	<0.005	<0.008	0.98	2.50	5.57	20.7	39.7
Ellenburger-San Saba	0.02	0.01	1.81	<0.005	<0.005	0.31	1.10	1.98	8.66	15.2
Hickory	1.00	0.08	2.82	<0.002	<0.002	<0.034	<0.41	3.01	15.1	42.5
Igneous	0.01	0.01	1.23	<0.005	0.07	0.47	0.96	1.76	2.91	5.3
Lipan	0.01	0.01	20.70	<0.005	0.06	5.77	13.9	33.2	48.6	85.3
Marathon	0.01	0.01	2.02	<0.005	<0.005	0.081	0.43	1.89	11.6	14.5
Marble Falls	0.01	0.01	1.83	<0.009	<0.009	0.10	1.19	2.32	5.25	7.8
Nacatoch	0.10	0.03	0.13	<0.002	<0.002	<0.009	0.02	0.03	0.23	2.2
Queen City	0.10	0.03	0.75	<0.002	<0.002	0.02	0.05	0.34	3.54	33.5
Rita Blanca	-	-	0.90	0.03	0.09	0.35	0.65	1.21	2.46	2.8
Rustler	0.02	0.01	3.63	<0.005	<0.005	<0.017	0.39	5.00	14.8	25.2
Sparta	0.10	0.02	0.55	<0.002	<0.003	<0.009	0.039	0.10	4.12	11.2
West Texas Bolson	0.02	0.02	2.30	<0.009	<0.02	0.38	1.57	2.58	10.2	18.2
Woodbine	0.10	0.03	0.36	<0.002	<0.002	<0.009	0.02	0.07	1.62	9.9
Yegua-Jackson	0.10	0.02	0.20	<0.002	<0.002	0.02	0.023	0.07	0.32	14.3
All minor aquifers	1.00	0.028	2.65	<0.002	<0.005	<0.02	0.37	2.21	12.9	85.3

Table 3a. Primary water uses for the major aquifer wells in this study

Aquifer	***Total Wells***	***Primary water use***				
		Public Supply	*Rural Domestic*	*Stock*	*Irrigation*	*All Other*
Carrizo-Wilcox	1,335	827	225	100	86	97
Edwards (BFZ)	610	282	107	37	37	147
Edwards-Trinity Plateau	1,108	142	394	336	114	122
Gulf Coast	2,007	1,014	504	180	88	221
Hueco-Mesilla Bolson	231	144	2	4	9	72
Ogallala	2,449	481	596	289	954	129
Pecos Valley	228	32	30	61	59	46
Seymour	237	56	80	21	42	38
Trinity	1,606	812	466	64	104	160
Total	9,811	3,790	2,404	1,092	1,493	1,032
% of total	100%	39%	25%	11%	15%	11%

Table 3b. Major aquifer wells with nitrate-N concentrations that exceed 10 mg/L (5.5% of major aquifer wells in this study).

Aquifer	***Total Wells***	***Primary water use***				
		Public Supply	*Rural Domestic*	*Stock*	*Irrigation*	*All Other*
Carrizo-Wilcox	7	1	2	2	1	1
Edwards (BFZ)	3	-	1	-	-	2
Edwards-Trinity Plateau	66	2	30	15	11	8
Gulf Coast	46	-	21	19	2	4
Hueco-Mesilla Bolson	1	-	-	-	-	1
Ogallala	212	23	102	11	57	19
Pecos Valley	26	-	4	8	9	5
Seymour	145	24	58	13	28	22
Trinity	37	1	26	3	5	2
Total	543	51	244	71	113	64
% of total	100%	9%	45%	13%	21%	12%

Table 4a. Primary water uses for the minor aquifer wells in this study.

Aquifer	***Total Wells***	***Primary water use***				
		Public Supply	*Rural Domestic*	*Stock*	*Irrigation*	*All Other*
Blaine	101	2	6	44	37	12
Blossom	22	6	7	2	2	5
Bone Spring-Victorio Peak	46	3	6	-	35	2
Brazos River Alluvium	39	-	2	4	25	8
Capitan Reef Complex	30	1	7	12	6	4
Dockum	379	76	102	107	26	68
Edwards-Trinity (High Plains)	17	1	5	4	5	2
Ellenburger-San Saba	150	26	72	25	9	18
Hickory	145	26	73	24	14	8
Igneous	76	21	17	24	6	8
Lipan	61	14	27	4	10	6
Marathon	23	1	2	18	-	2
Marble Falls	20	3	11	3	2	1
Nacatoch	40	19	14	4	1	2
Queen City	228	51	103	25	21	28
Rita Blanca	17	1	2	6	7	1
Rustler	28	-	2	11	12	3
Sparta	130	27	65	20	4	14
West Texas Bolson	111	7	32	47	11	14
Woodbine	178	106	14	1	13	44
Yegua-Jackson	149	49	58	25	9	8
Total	1,990	440	627	410	255	258
% of total	100%	22%	32%	21%	13%	13%

Table 4b. Minor aquifer wells with nitrate-N concentrations that exceed 10 mg/L (7.2% of minor aquifer wells in this study).

Aquifer	***Total Wells***	***Primary water use***				
		Public Supply	*Rural Domestic*	*Stock*	*Irrigation*	*All Other*
Blaine	18	-	5	7	5	1
Blossom	1	-	1	-	-	-
Bone Spring-Victorio Peak	6	-	-	-	6	-
Brazos River Alluvium	4	-	1	1	1	1
Capitan Reef Complex	1	-	-	1	-	-
Dockum	38	3	19	6	6	4
Edwards-Trinity (High Plains)	3	-	2	-	1	-
Ellenburger-San Saba	5	-	3	1	-	1
Hickory	14	-	11	1	1	1
Igneous	-	-	-	-	-	-
Lipan	36	1	20	1	10	4
Marathon	2	-	-	1	-	1
Marble Falls	-	-	-	-	-	-
Nacatoch	-	-	-	-	-	-
Queen City	3	-	2	-	-	1
Rita Blanca	-	-	-	-	-	-
Rustler	3	-	-	2	-	1
Sparta	2	-	2	-	-	-
West Texas Bolson	6	-	1	4	1	-
Woodbine	-	-	-	-	-	-
Yegua-Jackson	1	-	1	-	-	-
Total	143	4	68	25	31	15
% of total	100%	3%	48%	17%	22%	10%

Table 5. Nitrate-N concentrations with depth in the major aquifers of Texas. The number of wells with depth information is given along with the median nitrate-N concentrations (mg/L) within each 20th percentile depth interval. For example, the 20th percentile value represents the median nitrate-N concentrations for the shallowest 20% of wells in each aquifer. Median concentrations less than or equal to the maximum non-detect value for a given aquifer (Table 1b) are qualified with the "<" symbol. Relationships are plotted in Figure 3.

Aquifer	***Wells with depth***	***0-20th***	***20-40th***	***40-60th***	***60-80th***	***80-100th***
Carrizo-Wilcox	1,299	<0.05	<0.01	<0.01	<0.01	<0.01
Edwards (Balcones Fault Zone)	522	1.47	1.21	1.02	1.44	1.48
Edwards-Trinity Plateau	862	2.98	3.12	2.28	1.73	1.19
Gulf Coast	1,902	0.18	<0.04	<0.02	<0.02	<0.01
Hueco-Mesilla Bolson	228	0.92	0.96	1.04	1.65	1.50
Ogallala	2,006	5.63	2.63	1.85	1.81	1.92
Pecos Valley	204	3.87	1.02	1.07	1.68	1.47
Seymour	213	14.55	14.93	13.00	12.80	9.70
Trinity	1,506	1.53	<0.10	<0.04	<0.02	<0.01

Table 6. Nitrate-N concentrations with depth in the minor aquifers of Texas. The number of wells with depth information is given along with the median nitrate-N concentrations (mg/L) within each 25^{th} percentile depth interval. For example, the 25^{th} percentile value represents the median nitrate-N concentrations for the shallowest 25% of wells in each aquifer. Median concentrations less than or equal to the maximum non-detect value for a given aquifer (Table 2b) are qualified with the "<" symbol. Relationships are plotted in Figure 4.

Aquifer	***Wells with depth***	***0-25th***	***25-50th***	***50-75th***	***75-100th***
Capitan Reef Complex	27	1.18	0.54	0.45	<0.02
Hickory	133	4.16	<0.43	<0.30	<0.01
Rustler	23	5.31	1.84	<0.01	<0.01
Woodbine	176	<0.09	<0.02	<0.01	<0.01
Bone Spring-Victorio Peak	27	6.09	5.07	2.45	4.78
Ellenburger-San Saba	112	2.27	1.10	0.71	0.09
Queen City	222	0.57	<0.06	<0.01	<0.04
Sparta	129	0.19	<0.04	<0.02	<0.02
Nacatoch	40	<0.02	<0.01	<0.01	<0.02
Igneous	55	1.19	1.47	0.88	1.15
Dockum	355	2.18	2.78	0.79	<0.02
West Texas Bolson	83	0.44	1.78	1.62	1.96
Yegua-Jackson	139	<0.02	<0.04	<0.03	<0.02
Blaine	89	5.23	5.19	3.60	4.21
Lipan	57	30.10	9.84	14.45	15.95
Brazos River Alluvium	34	8.47	0.09	0.24	0.12
Not shown in Figure 6 (Insufficient data)					
Blossom	20	3.05	<0.10	<0.10	<0.10
Rita Blanca	17	0.90	0.74	1.31	0.40
Marathon	14	0.85	2.49	0.12	2.72
Edwards-Trinity (High Plains)	16	7.96	0.82	2.66	0.50
Marble Falls	16	3.91	1.20	0.10	1.45