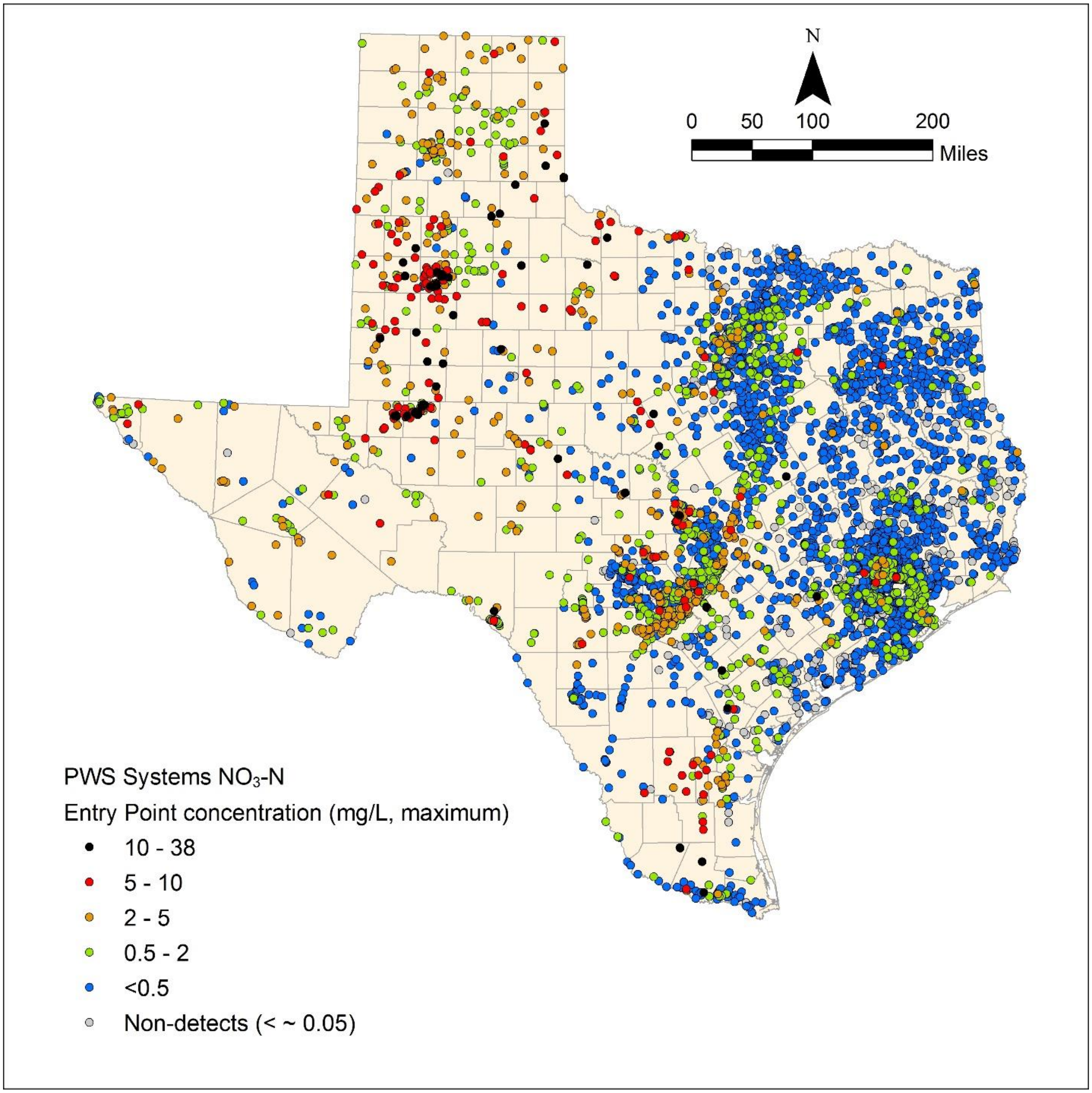
Evaluation of Groundwater Nitrate Contamination in Public Water Systems and Major and Minor Aquifers in Texas



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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. Sources of nitrate include 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 groundwater nitrate contamination in public water systems (PWS) and also in the major and minor aquifers in the state to better understand the spatial distribution of nitrate levels. The vast majority of PWS systems (99.13%) and people served by PWS systems (99.96%) in Texas are compliant with respect to nitrate-N, with nitrate-N levels less than the EPA maximum contaminant level (MCL) of 10 mg/L nitrate-N. A total of 60 PWS systems serving ~10,000 people were identified as having nitrate-N in excess of the 10 mg/L MCL entering at least one system entry point. Most of these systems (45, 75%) source their groundwater from one of the major aquifers. Almost 50% (28 systems) of these PWS systems are sourced in the Ogallala Aquifer. Of the remaining systems, six are sourced in the Seymour Aquifer, five in the Edwards-Trinity Plateau Aquifer, four the Gulf Coast Aquifer, and two in the Trinity Aquifer. The remaining 15 noncompliant PWS systems are sourced in various minor or local aquifers. The distribution of non-compliant PWS systems is consistent with ambient levels of groundwater nitrate-N based on analysis of the Texas Water Development Board (TWDB) database.

The distribution of groundwater nitrate-N in major and minor aquifers in the state provides context to better understand nitrate contamination in PWS systems. A total of ~8,800 analyses from major aquifers and ~1,800 analyses from minor aquifers were evaluated. Approximately 70% of the samples in the major and minor aquifers exceed the detection levels for nitrate-N. The majority of the samples are from rural domestic and irrigation wells. A total of 5.5% of the samples from the major aquifers exceed the MCL, with the highest level of contamination in the Seymour Aquifer (63% of samples > MCL), followed by the Pecos Valley Aquifer (13%), Ogallala Aquifer (9%), Edwards-Trinity Aquifer (6%), and the remaining major aquifers < 2%.

A total of 6.9% of the samples from the minor aquifers exceed the MCL, with the highest level of contamination in the Lipan Aquifer (59% of samples > MCL), followed by the Blaine (19%), Bone Spring-Victoria Peak (15%), Brazos River Alluvium (12%), and Dockum and Hickory (10%). The number of analyses from many of the minor aquifers is limited, reducing confidence in the nitrate contamination assessment. 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.

A variety of factors can influence groundwater nitrate-N contamination, including nitrate-N input, soil types affecting transport from the land surface to underlying aquifers, unconfined versus confined aquifer systems, and water table depths in unconfined aquifers. The highest nitrogen loading does not necessarily correspond to the hot spots of groundwater nitrate contamination. The general lack of correspondence between nitrate loading and groundwater nitrate contamination suggests that soil texture, aquifer status (confined vs unconfined), and water table depths are more important factors controlling nitrate contamination. High levels of groundwater nitrate, particularly in the Seymour, Lipan, and southern Ogallala aquifers are attributed to natural sources and fertilizer inputs, coarse soils, unconfined aquifers, and shallow water tables.

Although it is difficult to assess temporal variations in groundwater nitrate-N contamination because of differing degrees of sampling over past decades, the hotspots of groundwater nitrate-N levels have been known for decades because the attributes of the system that lead to nitrate contamination are not changing. The regional distribution of high nitrate levels adjacent to the noncompliant PWS systems, with most occurring in rural areas, makes it difficult to mitigate nitrate contamination in these PWS. Future studies should involve a more in depth evaluation of groundwater nitrate levels to delineate sources of contamination in these hotspots, assess processes (mitigation etc), and evaluate temporal trends from frequently sampled wells.

Introduction

Nitrate is the most widespread contaminant in groundwater in Texas and in the U.S. (Nolan et al., 2002). Adverse health impacts of elevated nitrate levels include methemoglobinemia in infants (blue baby syndrome), which is potentially fatal and results in low blood oxygen levels (Spalding and Exner, 1993). The Centers for Disease Control (1996) also suggested that eight spontaneous abortions in women in Indiana (1991 – 1994) may be linked to high nitrate-N levels (19 – 29 mg/L) in domestic well water in rural regions of Indiana. Increased risk of non-Hodgkin's lymphoma has also been linked to nitrate-N levels exceeding 4 mg/L in community water supply wells in Nebraska (Ward et al., 1996). Previous studies indicate that groundwater NO_3-N levels exceeding 2 mg/L are thought to be affected by humans (Mueller and Helsel, 1996).

Sources of groundwater nitrate include atmospheric deposition, natural sources, inorganic and organic fertilizers (manure), concentrated animal feeding operations (CAFO) output, septic tanks, and leaking sewer systems. Natural sources include nitrogen fixation by legumes, organic matter mineralization (nitrification), and natural geologic sources. 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). 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).

Recent Studies of Nitrate Levels in Texas Aquifers

Many studies have been conducted on nitrate in soils and groundwater in different parts of Texas. The spatiotemporal variability in groundwater nitrate levels in Texas was examined in a recent study on a county basis, focusing primarily on the Texas Rolling Plains (TRP), based on nitrate analyses between 1960 and 2010 (Chaudhuri et al., 2012). This study indicated that NO_3 levels in many aquifers increased significantly in many counties since the 1960s, with NO_3-N levels exceeding the nitrate-N MCL in >30% of the observations in 25 counties in the 2000s versus 8 counties in the 1960s. MCL exceedances were highest in the Texas Rolling Plains (Haskell and Knox counties) with all analyses greater than the MCL in

2000. Increasing nitrate-N levels are positively correlated cropland areas, fertilized croplands, and irrigated croplands linking agriculture to groundwater nitrate levels. This study noted a large reduction in groundwater sampling over time with limited recent observations, making it difficult to assess temporal trends. The results of this study indicate a marked deterioration in groundwater quality by nitrate attributed to agriculture, underscoring the need for more intensive spatial sampling in the future.

We conducted a study at the Bureau of Economic Geology to evaluate 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). Nitrogen loading included atmospheric deposition, inorganic and organic fertilizers, land use, proxies for sewage and septic input, population density, precipitation, and irrigation. Aquifer vulnerability to contamination was based on 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.

We also conducted studies sampling several unsaturated zone profiles and measuring nitrate-N in soil water to link land surface processes and potential groundwater contamination (Olyphant, 2009; Scanlon et al., 2008). The objective of the studies was to quantify nitrate-N reservoirs beneath various ecosystems, including natural rangelands and irrigated and rainfed agricultural ecosystems in regions of high groundwater nitrate-N levels 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. The studies found that nitrate-N levels beneath natural rangeland ecosystems are generally low in the different aquifer regions; however, nitrate-N accumulations are much higher at depth beneath cultivated areas which were attributed to pre-cultivation rangeland conditions. 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, attributed to generally low to moderate fertilizer application rates in addition to pristine precipitation. However, nitrate-N levels beneath irrigated agriculture are generally high. In the Southern High Plains, high nitrate-N levels beneath irrigated areas are attributed to deficit irrigation and lack of flushing and may result in soil salinisation. Evidence suggests that high groundwater levels 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 (Bartolino et al., 1994). High levels of groundwater nitrate contamination in the High Plains are focused in the southern part of the southern High Plains and are attributed 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 soil 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 and reach the underlying water tables.

Public Water Supply Systems and Nitrate Compliance

The procedure for dealing with PWS that are noncompliant is as follows:

When a PWS system reports exceeding an MCL, a Notice of Violation is given to the PWS system that requires mandatory public notification of the violation. Violations are added up and accumulate points (based on the constituent or action). Once an entity accumulates 11 points, they are then sent to internal TCEQ review, who may then send them to enforcement or to legal. The point system is ranked on the risk to public health, with acute and non-acute constituents ranked as follows:

- Nitrate - 10 points
- Arsenic - 5 points
- Fluoride and Radionuclides - 5 points each
- Chlorine - 10 points
- Missing a sample for nitrate - 5 points

The higher number of points for nitrate relative to arsenic or fluoride is related to the acute issues related to methemoglobinemia from elevated nitrate-N levels. This ranking system is for each sampling point. For example, two sampling points in the system exceeding nitrate-N MCL would result in a doubling of the points to a total of 20 points.

Data Sources and Analyses

Groundwater nitrate concentrations were obtained from the TCEQ Public Water Supply (PWS) database for water quality specifically related to public water supply systems. PWS systems routinely sample water at system entry points and following any treatment processes to be analyzed for an array of potential contaminants of concern, including nitrate-N. For this study, we focused on PWS systems that obtain their water either entirely or in part from groundwater sources and further restricted our analysis to the operational entry points of those systems, disregarding entry points used for other purposes, such as inactive, non-drinking water, or emergency sources. The PWS database contains nitrate-N concentration information for samples from 6,933 public drinking water systems. Of these, 6,005 systems (86%) obtain at least part of their water supply from groundwater. Of these groundwater-reliant systems, 87% (5,218 systems) rely on one of the major aquifers and 13% (787 systems) rely on one of the minor aquifers (Table 1).

Only the latest water sample analysis was used for each entry point and for systems with more than one entry point, the highest concentration of any entry point samples for each respective system was used characterize the violation status. The latest sample dates for 96% of systems ranged between 2015 and 2017 and the oldest sample of the remaining systems was analyzed in 2005. Detection limits for nitrate-N in the TCEQ database range somewhat lower overall as compared to the TWDB database, with a maximum value of <0.05 mg/L nitrate-N, with 81% of non-detects with concentrations <0.01 mg/L nitrate-N. PWS systems that exceed the EPA nitrate-N MCL of 10 mg/L were compiled (Table 2, Figure 1). The aquifers associated with these non-compliant PWS systems were also examined.

Groundwater nitrate concentrations were also obtained from the TWDB database on ambient groundwater quality. All nitrate concentrations in this study are reported as elemental nitrogen (nitrate-N). The detection limit for nitrate-N in the database is 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 1992 and 2017. 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 10,602 records. A map of Texas major aquifers is shown in Figure 2 and nitrate-N levels in the major aquifers is shown in Figure 3. Corresponding maps of the minor aquifers are shown in Figure 4 and Figure 5, respectively. The data set includes 8,779 samples from major aquifers (Table 3) and 1,823 samples from minor aquifers (Table 4). The majority of samples for the major aquifers are from the PWS category (35%), followed by rural domestic wells (27%), irrigation (14%), stock (12%) and other (**Error! Reference source not found.**). The representation of wells in the minor aquifers is slightly different with the dominant category being rural domestic wells (33%), followed by stock (21%), PWS systems (18%), irrigation (13%) and other (**Error! Reference source not found.**).

The Net Anthropogenic Nitrogen Input (NANI) program produces national reports at the county-level of estimates of the net sum of annual nitrogen loading accounting for various components of that loading, including fertilizers, human and livestock wastes, and net imports and exports of nitrogen in various forms, such as food products (Hong et al., 2011). These estimates are based primarily on data from the USDA Census of Agriculture conducted every 5 years and additionally on data provide by the US Bureau of Census and the National Atmospheric Deposition Program (NADP). The primary risks of nitrate contamination from the groundwater perspective that were examined for this study include the potentially mobile forms of nitrogen in fertilizers, human and animal waste products, and atmospheric deposition.

Probability maps of nitrate-N exceeding two different nitrate-N threshold concentrations were developed using indictor kriging methods for all nine major aquifers. The 18 minor aquifers generally do not have sufficient spatial data to confidently map these probabilities. The two concentration threshold values were 1) 2 mg/L nitrate-N, which approximates background concentrations for areas that have not been significantly impacted by human activity, and 2) 10 mg/L, representing the US EPA MCL drinking water standard. The spatial distributions of probabilities were subdivided into five general classes: probability < 10% (extremely low), 10 – 40% (low), 40 – 60% (moderate), 60 – 90% (high), and ≥90% (extremely high).

While ordinary kriging methods, which require actual or log-transformed concentration values, result in maps that estimate the spatial distribution of concentrations and assume that the data are normally distributed, actual concentrations of many MCL constituents in groundwater samples are frequently below analytical detection limits and are reported as non-detect or "less than" values and additionally are not normally or log-normally distributed. Ordinary kriging methods cannot incorporate non-detect values. In contrast, indicator kriging uses cut-off transformed values to produce maps that estimate the probability of exceeding a selected cut-off or threshold value. Indicator kriging requires no *a priori* assumption regarding the normality of the data distribution and can incorporate non-detect values that are less than or equal to the selected threshold concentration. Concentration values that exceed a given threshold value are assigned a value of "1" and concentrations that do not exceed the threshold are assigned a value of "0".

Results and Discussion

Public Water Systems

The number of operational PWS systems in Texas totaled 6,933 (Figure 1). These systems serve ~26 million people through ~9.4 million connections. This accounts for most of the population in the state (27.9 million in 2016). Of the 6,933 systems, 5,200 systems (75%) rely totally on groundwater and provide water to ~5 million people (~20% of the population). A further 444 systems (6%) rely in part on groundwater providing water to a further ~9 million people (35% of the population). The vast majority of systems (99.1%) and people served (99.96%) in Texas are compliant with respect to nitrate-N (i.e. have nitrate-N concentrations less than the 10 mg/L U.S. EPA MCL).

A total of 60 systems serving ~10,000 people were identified as having nitrate-N in excess of the 10 mg/L MCL in at least one system entry point (Table 2; Figure 6). Most of these systems (45 systems, 75% of the total number) source their groundwater from one of the major aquifers (Table 2). Almost 50% (28 systems) of these systems are sourced in the Ogallala aquifer (Figure 6b). Of the remaining systems, six are sourced the Seymour Aquifer, five in the Edwards-Trinity Plateau Aquifer, four the Gulf Coast Aquifer, and two the Trinity Aquifer. The remaining 15 source their groundwater from various minor or local aquifers. The distribution of nitrate-N concentrations in all of the 6,933 PWS systems is shown in Figure 1 for context. Approximately 96% of the samples were obtained during the period 2015-2017 and none were obtained prior to 2005. The number of people impacted by non-compliant PWS systems is provided in Table 1 with county population data based on 2010 census shown in Figure 7 for background. Most of the non-compliant systems are in rural areas with low population densities.

Groundwater Nitrate Concentrations in Major Aquifers

Nitrate-N concentrations exceed detection limits in ~70% of the samples from the major aquifers (Table 3, Figure 3). Nitrate-N concentrations exceed the MCL of 10 mg/L in 5.5% of all samples (8,779) evaluated in major aquifers (Table 3). The Seymour Aquifer has the highest level of exceedances, with 63% of the samples exceeding the MCL, followed by the Pecos Valley (13%), Ogallala (9%), and the Edwards-Trinity Plateau (6%) aquifers. The remaining major aquifers have MCL exceedances < 3% of the samples analyzed in each of the aquifers (Carrizo-Wilcox, Edwards [Balcones Fault Zone, BFZ], Gulf Coast, Hueco-Mesilla Bolson, and Trinity aquifers). These results are consistent with previous studies which show highest levels of nitrate in the Seymour Aquifer in the Rolling Plains region, attributed to the shallow water table, coarse textured soils, and intensive agriculture (Chaudhuri et al., 2012; Scanlon et al., 2004). Similar attributes are found in the Pecos Valley and Southern Ogallala aquifers. The median nitrate concentration is highest in the Seymour Aquifer (13.1 mg/L), followed by the Ogallala Aquifer (2.0 mg/L), the Edwards Trinity Plateau (2.0 mg/L), and the Pecos Valley Aquifer (1.6 mg/L). The remaining aquifers have median nitrate concentrations generally < ~ 1.5 mg/L.

Approximately 30% of the groundwater samples from the major aquifers exceed 2 mg/L nitrate-N (Table 3), which is considered the background level for nitrate-N. The percentage of samples exceeding 5 mg/L nitrate-N follows a similar trend to those exceeding the MCL of 10 mg/L, with the Seymour Aquifer ranked highest (81% of samples), followed by the Pecos Valley Aquifer (27%), Ogallala Aquifer (19%), and the Edwards Trinity Plateau Aquifer (18%). The remaining major aquifers have < 8% of samples exceeding 5 mg/L. A similar pattern was found for nitrate-N concentrations exceeding 2 mg/L. Major aquifers with the lowest levels of nitrate-N have the highest percentages of non-detects, with 71% of the samples registering as non-detects in the Carrizo Wilcox Aquifer, following by the Gulf Coast Aquifer (50%), Trinity Aquifer (43%), and the remaining aquifers having < 12% non-detects.

Groundwater Nitrate Concentrations in Minor Aquifers

The analysis of groundwater nitrate concentrations in minor aquifers included ~ 1,800 analyses (Table 4, Figure 5). The aquifers with the most analyses include the Dockum (298 analyses), Queen City (227), Woodbine (168), Ellenburger-San Saba (135), Yegua-Jackson (139), Hickory (120), Sparta (131), and West Texas Bolson (107). 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 0.5 mg/L nitrate-N (Table 4). A total of 7% of the analyses exceeded the nitrate MCL and 14% of the analyses exceeded 5 mg/L nitrate-N, and 26% exceed 2 mg/L. The minor aquifers with the highest level of nitrate MCL exceedances are ranked as follows: Lipan (59%>10 mg/L), Blaine (19%), Bone Springs-Victoria Peak (15%), Brazos River Alluvium (12%), and the Dockum and Hickory (10% each) with the remaining aquifers < 10%. Percentages exceeding background levels of ~ 2 mg/L nitrate-N generally follow a similar order to the ranking of aquifers exceeding MCLs, with the Lipan having the highest percentage (89%), followed by the Blaine (73%), Bone Springs-Victoria Peak (70%), and the Edwards-Trinity (High Plains) (50%).

A map of the spatial distribution of nitrate concentrations in the minor aquifers is shown in Figure 5. The median nitrate concentration is highest in the Lipan Aquifer (17.7 mg/L), followed by the Blaine Aquifer (4.2 mg/L), the Bone-Springs Victoria Peak (4.0 mg/L), and the Edwards Trinity High Plains aquifer (2.0 mg/L). The remaining aquifers have median nitrate concentrations generally < ~ 1.6 mg/L.

Vulnerability of Groundwater to Nitrate Contamination

A number of factors impact aquifer vulnerability to nitrate contamination. The soils map indicates that many regions of elevated nitrate-N concentrations correspond to areas of coarse textured soils, particularly in the Seymour and Lipan aquifers and southern Ogallala Aquifer (Figure 8). Nitrogen input to the system is also important. The Net Anthropogenic Nitrogen Input (NANI) map by county shows that elevated groundwater nitrate levels do not necessarily correspond to high nitrogen inputs (Figure 9), particularly in the eastern part of the State where many of the aquifers are confined and protected from inputs at the land surface. However, the net nitrogen map includes components that may mask the risk to groundwater when included in the net total. A map of the primary nitrate loading risk factors to groundwater, including fertilizer, animal waste, and atmospheric deposition shows much higher aggregate nitrate inventories across the state (Figure 10) as compared to the net results map. It is also useful to examine these components individually.

The distribution of fertilizer loading is generally wide-spread across Texas and is based primarily on agricultural applications (Figure 11) while non-agricultural loading is minor by comparison and is primarily restricted to urban areas from landscape and golf course/public space applications (Figure 12). While regions of high fertilizer loading co-incide with some areas of elevated groundwater nitrate concentrations, in particular the southern areas of the Ogallala aquifer and in the southern Gulf Coast aquifer, most regions of high fertilizer loading are not coincident with elevated groundwater nitrate. Studies have shown that most (75%) of the nitrate presently found in Southern High Plains groundwater is the result of natural-occurring organic forms of soil nitrate that were mineralized and flushed into the groundwater following increased recharge rates that resulted from initial cultivation (Scanlon et al., 2008). The Seymour aquifer, which also has high nitrate concentrations in most agricultural areas, does not have particularly high fertilizer loading rates and high nitrate concentrations were present in the groundwater prior to the wide-spread use of fertilizers in that region.

The NANI program also tracks livestock waste production by species. The most significant quantities of livestock waste in Texas are produced by beef, dairy, and poultry livestock. As with agricultural fertilizers, beef/cattle nitrogen loading is wide-spread but loading rates are generally greater by at least an order of magnitude (Figure 13). Similar to agricultural fertilizer loading, there is no consistent pattern between groundwater nitrate concentration and nitrate loading from beef/cattle waste nitrogen. Nitrate loading by dairy (Figure 14) is generally much more localized as compared to beef/cattle loading and one area of high dairy concentration located in Erath and Comanche counties is associated with elevated concentrations of groundwater nitrate in the Trinity aquifer outcrop.

Poultry operations are generally located in the eastern regions of Texas and while nitrate loading rates are very high and similar to those of agricultural fertilizers, beef, and dairy (Figure 15), there do not appear to be any generalized impacts from poultry operations on groundwater nitrate concentrations in those areas. There may be localized impacts in the eastern Carrizo-Wilcox outcrop area in Shelby and Nacogdoches counties. High nitrate loading from poultry in Gonzales County is located above confined areas of the Carrizo-Wilcox and there are no impacts to groundwater nitrate there.

Atmospheric deposition is generally of similar magnitude to fertilizer application rates but shows a generalized eastward increase in loading rates and the highest rates are located primarily near the major urban centers of Dallas/Ft Worth, Houston, San Antonio, and Austin (Figure 16).

Probability Maps of Nitrate-N Exceedances in Major Aquifers

Point maps of groundwater nitrate-N levels are shown for each of the major aquifers (Figure 17– Figure 25). In addition, probability maps of exceeding background nitrate-N levels (~ 2 mg/L) and the EPA MCL (10 mg/L) are also shown. Nitrate-N levels in the Carrizo-Wilcox Aquifer are generally low because much of the aquifer is confined (Figure 17a). Exceedance probabilities relative to background and MCL levels are also low (Figure 17b, c). Nitrate-N levels are also generally low in the Edwards (BFZ) Aquifer with some localized areas exceeding background concentrations and a few hotspots with high probabilities of nitrate-N MCL exceedances (Figure 18a, b, and c). The Edwards-Trinity Plateau Aquifer has an area of elevated nitrate-N levels, mostly in counties in the northern portion of the aquifer (e.g. Ector, Midland, Glasscock, Upton and Reagan counties) (Figure 19a). The exceedance probability maps are consistent with the point maps, showing > 90% probability of exceeding background levels but still low levels 10 – 40% of exceeding the MCL in this northern region (Figure 19b, c). The Gulf Coast Aquifer is generally characterized by low nitrate-N levels, except in the southwestern region (Figure 20a). Probabilities of exceeding background nitrate-N levels are high in this region but only moderate for MCL exceedances (Figure 20b, c). The number of analyses for nitrate-N for the Hueco-Mesilla Bolson aquifers is limited, reducing confidence in the spatial distribution of nitrate-N concentrations. A hot spot of elevated nitrate-N is found in the vicinity of El Paso where nitrate levels exceed background levels but not MCLs (Figure 21a, b, and c).

The Ogallala Aquifer shows high percentages of primary MCL exceedances for nitrate-N in the southern part of the southern Ogallala Aquifer (Figure 22a, b, c). High levels of nitrate-N in this region may be related to the fact that the aquifer is thin (median thickness 50 feet) relative to the northern part of the southern Ogallala in Texas (median thickness 150 feet), and nitrate-N levels are not as readily diluted. High nitrate contamination is related to cropland. Unsaturated zone profiles show that much of the high nitrate could be attributed to conversion of soil organic nitrogen under rangeland vegetation to nitrate with oxidation during initial cultivation (Scanlon et al., 2008). In addition to mineralization of soil organic nitrogen, fertilizer application also results in groundwater nitrate contamination because nitrate is readily leached through the soil profile. Nitrate-N exceedances are likely to continue to increase on the basis of mobilization of large nitrate inventories measured in unsaturated zone profiles. Finer grained soils in the northern part of the southern High Plains and the Central High Plains (Pullman clay loam and equivalent soils) also restrict water movement from the land surface and minimize nitrate loading to the underlying aquifer in these regions. The Pecos Valley Aquifer is divided into two troughs formed by subsidence caused by evaporite dissolution: Monument Draw trough to the east and Pecos Valley trough to the west (Figure 23a, b, and c). The probability of exceeding nitrate-N MCL based on relatively sparse and locally variable data is generally estimated as highest in the part of aquifer lying east of the Pecos River while there is a cluster of high nitrate in central Reeves County west of the Pecos River. Groundwater in the Seymour Aquifer is dominated by nitrate-N MCL percent exceedances, attributed to oxidation of soil organic nitrogen during initial cultivation followed by leaching of fertilizers (Figure 24a, b, and c) (Olyphant, 2009). The aquifer generally has a low saturated thickness. Probabilities of exceeding nitrate-N MCL are uniformly highest in the Haskell-Knox counties pod of the aquifer. The Trinity Aquifer mostly has low nitrate-N levels except for a zone in the vicinity of Erath County in the western outcrop zone where dairies are concentrated (Figure 25a, b, and c). Probabilities of exceeding background levels are high in this region but probabilities of exceeding nitrate-N MCLs are low.

Management of Nitrate Contamination in Public Water Systems

Various approaches can be used to treat groundwater nitrate levels. Examples of systems with nitrate removal include the City of Seymour which uses a reverse osmosis treatment system (http://cityofseymour.org/utilities/reverse-osmosis-water-treatment-plant/). The City of Wheeler also operates a reverse osmosis treatment plant (http://www.team-psc.com/engineering/wheeler-ro-wtp/). A more in depth evaluation of treatment options should be conducted in the future.

Summary

Analysis of groundwater nitrate contamination in public water systems (PWS) also in the major and minor aquifers in Texas provides a comprehensive understanding of the spatial variability of groundwater nitrate levels in the State. Most PWS systems (99.13%) and people served by PWS systems (99.96%) in Texas are compliant with EPA nitrate-N MCL of 10 mg/L. A total of 60 PWS systems serving ~10,000 people have nitrate-N exceeding the MCL in at least one system entry point. The majority of these systems (45, 75%) source their groundwater from one of the major aquifers, with ~ 50% from the Ogallala Aquifer with the remaining systems sourced in the Seymour, Edwards-Trinity Plateau, Gulf Coast, and Trinity aquifers. The distribution of non-compliant PWS systems is consistent with groundwater nitrate-N levels from the Texas Water Development Board (TWDB) database.

Groundwater nitrate-N levels in major and minor aquifers is based on evaluation of ~8,800 analyses from major aquifers and ~1,800 analyses from minor aquifers. Approximately 70% of the samples in the major and minor aquifers exceed the detection levels for nitrate-N. Most samples are from rural domestic and irrigation wells. A total of 5.5% of the samples from the major aquifers exceed the MCL. MCL exceedances are highest in the Seymour Aquifer (63% of samples > MCL), followed by the Pecos Valley Aquifer (13%), Ogallala Aquifer (9%), Edwards-Trinity Aquifer (6%), and the remaining major aquifers < 2%.

A total of 6.9% of analyses from the minor aquifers exceed the MCL. MCL exceedances are highest in the Lipan Aquifer (59% of samples > MCL), followed by the Blaine (19%), Bone Spring-Victoria Peak (15%), Brazos River Alluvium (12%), and Dockum and Hickory (10%). 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.

Evaluation of controls on groundwater nitrate contamination indicates that the dominant factors impacting nitrate contamination include coarse textured soils and unconfined aquifers, with shallow water tables. These factors explain elevated nitrate in the Seymour, Lipan, and Southern High Plains aquifers. Previous studies have showed that nitrogen input to these systems is derived from natural sources and nitrate fertilizer. The highest nitrogen loading generally does not coincide with these hot spots of nitrate contamination. One exception is locally high nitrate in the vicinity of Erath County in the Trinity Aquifer outcrop area coinciding with a high density of dairy farms. These results of this study suggest limited opportunities for mitigating nitrate contamination by reducing loading to the system. Information from a limited number of PWS systems indicates that nitrate in some municipalities is being mitigated by reverse osmosis systems. Future studies should examine groundwater nitrate mitigation strategies in more detail.

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Table 1. Numbers of Public Water Supply systems by Aquifer.

Aquifer	*Number of PWS Systems*
All Major Aquifers	*5,218*
Carrizo-Wilcox	598
Edwards	189
Edwards-Trinity Plateau	162
Hueco-Mesilla Bolson	37
Gulf Coast	2,736
Ogallala	314
Pecos Valley	16
Seymour	31
Trinity	1,135
All Minor Aquifers	*787*
Blaine	5
Blossom	2
Bone Spring-Victorio Peak	4
Brazos River Alluvium	1
Dockum	62
Edwards-Trinity (High Plains)	1
Ellenburger-San Saba	32
Hickory	26
Igneous	19
Lipan	7
Marathon	2
Marble Falls	1
Nacatoch	26
Queen City	30
Sparta	18
West Texas Bolson	6
Yegua-Jackson	111
Other/Unknown Aquifers	*434*

Table 2. Public Water Supply (PWS) systems with current entry point samples that exceed the MCL for nitrate-N (>10 mg/L NO_3-N)

PWS ID	*PWS Name*	*County*	*Aquifer*	*Sample date*	*# of samples*	*Nitrate-N (mg/L)*
0130018	BLUEBERRY HILLS WATERWORKS	Bee	Gulf Coast	01/11/16	5	10.2
0230002	CITY OF QUITAQUE	Briscoe	Other	04/18/17	1	13.5
0440001	WELLINGTON MUNICIPAL WATER SYSTEM	Collingsworth	Blaine	05/16/17	1	10.3
0440002	CITY OF DODSON	Collingsworth	Seymour	05/16/17	1	18.9
0450043	LONE STAR INN	Colorado	Gulf Coast	06/01/17	2	22.01
0470019	SIDNEY ISD	Comanche	Trinity	07/10/17	1	25.4
0480011	EOLA WSC	Concho	Lipan	05/17/17	1	38
0580011	CITY OF ACKERLY	Dawson	Ogallala	07/11/17	1	12.3
0580013	WELCH WSC	Dawson	Ogallala	06/15/17	1	13.7
0580025	KLONDIKE ISD	Dawson	Ogallala	07/11/17	2	18.9
0680013	NORTHGATE MOBILE HOME PARK 1	Ector	Dockum	04/19/17	5	13.8
0680051	CANYON DAM MOBILE HOME PARK	Ector	Edwards-Trinity Plateau	06/08/17	1	14.8
0680210	JUDY K S KOUNTRY KITCHEN	Ector	Edwards-Trinity Plateau	07/13/17	1	11.1
0730023	FOREST GLEN SPRINGS	Falls	Alluvial	05/24/17	1	10.4
0830018	GAINES COUNTY PARK	Gaines	Ogallala	04/03/17	1	14.9
0940089	RIVER RIDGE APARTMENTS	Guadalupe	Alluvial	03/16/16	1	11.6
0960003	TURKEY MUNICIPAL WATER SYSTEM	Hall	Alluvial	04/18/17	1	17.2
0960014	LAKEVIEW WSC	Hall	Seymour	04/18/17	1	10.9
1080147	LAZY PALMS RANCH	Hidalgo	Gulf Coast	07/10/17	1	18.6
1080238	SOL Y MAR	Hidalgo	Unknown	04/12/17	1	15.2
1100011	WHITHARRAL WSC	Hockley	Ogallala	04/26/17	1	19.9
1100034	WAYNEBOS STORE	Hockley	Ogallala	01/19/17	1	14.6
1280015	BROWNS CORNER RV	Karnes	Yegua-Jackson	05/09/17	1	13.5
1350001	RRA GUTHRIE DUMONT WATER SYSTEM	King	Other	05/23/17	1	14.8
1380006	RRA TRUSCOTT GILLILAND WATER SYSTEM	Knox	Seymour	05/23/17	1	12.1
1400010	SPADE WSC	Lamb	Ogallala	04/11/17	1	10.7
1500023	CAMP LONG MOUNTAIN ON LAKE LBJ	Llano	Alluvial	04/12/17	2	13.5
1520046	WILDWOOD MOBILE HOME VILLAGE	Lubbock	Ogallala	07/12/17	3	10.4
1520080	FRANKLIN WATER SYSTEMS 3	Lubbock	Ogallala	06/07/17	6	17.8
1520123	ROOSEVELT ISD	Lubbock	Ogallala	02/02/17	4	21.9

Table 2 (cont). PWS systems with current entry point samples that exceed the MCL for nitrate-N (>10 mg/L NO_3-N)

PWS ID	*PWS Name*	*County*	*Aquifer*	*Sample date*	*# of EP samples*	*Nitrate-N (mg/L)*
1520128	SPIRIT RANCH	Lubbock	Ogallala	04/11/17	3	12.1
1520147	SHORT ROAD WATER SUPPLY	Lubbock	Ogallala	05/18/17	1	10.7
1520179	STRIPES 121	Lubbock	Ogallala	05/18/17	1	10.3
1520225	FAY BEN MOBILE HOME PARK	Lubbock	Ogallala	07/11/17	2	13.1
1520257	J&G RENTALS	Lubbock	Ogallala	11/11/14	1	13.4
1520279	AFFORDABLE RV STORAGE & SHOPS	Lubbock	Ogallala	04/03/17	1	11.3
1520286	DOLLAR GENERAL STORE 14889	Lubbock	Ogallala	07/12/17	1	12.0
1530005	GRASSLAND WSC	Lynn	Ogallala	04/12/17	1	13.8
1540014	UNIMIN	McCulloch	Hickory	05/04/17	1	12.9
1590002	MARTIN COUNTY FWSD 1	Martin	Ogallala	07/11/17	1	11.5
1650022	SHERWOOD ESTATES MANUFACTURED TOWNHOME C	Midland	Ogallala	06/08/17	1	16.5
1650024	PECAN GROVE MOBILE HOME PARK	Midland	Ogallala	05/01/17	1	10.5
1650029	MIDESSA OIL PATCH RV PARK	Midland	Edwards-Trinity Plateau	04/19/17	1	14.3
1650043	PEAK PROPERTIES	Midland	Ogallala	05/11/17	2	16.0
1650044	STANLEY MOBILE HOME PARK	Midland	Ogallala	04/20/17	2	23.4
1650048	GREENWOOD TERRACE MOBILE HOME SUBDIVISIO	Midland	Ogallala	04/20/17	1	18.3
1650057	TWIN OAKS MHP MIDLAND	Midland	Edwards-Trinity Plateau	04/20/17	1	13.4
1650077	SOUTH MIDLAND COUNTY WATER SYSTEMS	Midland	Ogallala	07/19/16	1	16.0
1650111	COUNTRY VILLAGE MOBILE HOME ESTATES	Midland	Ogallala	06/08/17	2	12.8
1650131	REYNAS DELI	Midland	Unknown	04/28/15	1	13.9
1650135	STEPPING STONE MINISTRY	Midland	Ogallala	07/13/17	1	21.2
1650152	COUNTRY RV PARK	Midland	Unknown	05/01/17	1	11.1
1670013	MULLIN INDEPENDENT SCHOOL DISTRICT	Mills	Trinity	07/17/17	3	12.5
2080022	COLORADO RIVER MWD SNYDER WELL FIELD	Scurry	Dockum	11/24/09	5	15.6
2140030	1017 CAFE	Starr	Gulf Coast	10/25/16	2	13.1
2330033	ROUGH CANYON	Val Verde	Edwards-Trinity Plateau	05/02/17	1	10.1
2420002	WHEELER MUNICIPAL WATER SYSTEM	Wheeler	Ogallala	04/25/17	2	11.3
2440003	NORTHSIDE WSC	Wilbarger	Seymour	04/25/17	1	14.8
2440005	RRA HINDS WILDCAT WATER SYSTEM	Wilbarger	Seymour	04/25/17	1	14.9
2440008	RRA LOCKETT WATER SYSTEM	Wilbarger	Seymour	04/25/17	4	16.0

Table 3. Summary of nitrate-N concentration (mg/L) in the Major Aquifers of Texas based on the Texas Water Development Board (TWDB) groundwater database. Values are based on the latest well samples between 1992 and 2017. Non-detects represent nitrate-N concentrations below the detection limits of the analytical methods used, with 75% of non-detects <0.1 mg/L and a highest detection limit of 0.5 mg/L.

Aquifer	*Number of Samples*			*% of Samples*		*Concentrations*			*Concentration Percentile Distributions*					*Samples exceeding threshold concentration values*					
	Total	*Non-detects*	*Detects*	*Non-detects*	*Detects*	*Mean*	*Min*	*Max*	*0.05*	*0.25*	*0.5*	*0.75*	*0.95*	*>2*	*>5*	*>10*	*% >2*	*% >5*	*% >10*
Carrizo-Wilcox	1,100	784	316	71.3	28.7	1.3	0.002	70.7	0.00	0.00	0.02	0.06	0.98	39	18	7	3.5	1.6	0.6
Edwards (Balcones Fault Zone)	611	69	542	11.3	88.7	1.9	0.005	17.0	0.02	0.79	1.48	1.93	4.19	133	21	3	21.8	3.4	0.5
Edwards-Trinity Plateau	1,076	65	1,011	6.0	94.0	3.7	0.009	67.4	0.05	1.09	2.03	3.84	**10.53**	541	194	65	**50.3**	18.0	6.0
Gulf Coast	1,708	856	852	50.1	49.9	2.3	0.002	41.0	0.00	0.01	0.04	0.48	6.75	255	127	43	14.9	7.4	2.5
Hueco-Mesilla Bolson	241	28	213	11.6	88.4	0.0	0.002	16.2	0.02	0.45	1.20	2.03	4.70	62	11	3	25.7	4.6	1.2
Ogallala	2,258	15	2,243	0.7	99.3	3.8	0.002	128.0	0.25	1.07	2.03	3.94	**13.22**	1,149	422	196	**50.9**	18.7	8.7
Pecos Valley	184	21	163	11.4	88.6	6.1	0.029	174.7	0.03	0.49	1.56	5.36	**17.88**	81	49	23	44.0	26.6	12.5
Seymour	169	1	168	0.6	99.4	13.6	0.079	44.6	0.82	6.90	**13.10**	**18.31**	**28.38**	152	137	107	**89.9**	**81.1**	**63.3**
Trinity	1,432	621	811	43.4	56.6	3.2	0.002	505.0	0.00	0.01	0.05	0.49	4.80	148	70	39	10.3	4.9	2.7
All Major Aquifers	8,779	2,460	6,319	28.0	72.0	3.5	0.002	505.0	0.00	0.02	0.75	2.35	10.60	2,560	1,049	486	28.3	11.9	5.5

Table 4. Summary of nitrate-N concentration (mg/L) in the Minor Aquifers of Texas based on the Texas Water Development Board (TWDB) groundwater database. Values are based on the latest well samples between 1992 and 2017. Non-detects represent nitrate-N concentrations below the detection limits of the analytical methods used, with 75% of non-detects <0.1 mg/L and a highest detection limit of 0.5 mg/L.

Aquifer	*Number of Samples*			*% of Samples*		*Concentrations*			*Concentration Percentile Distributions*					*Samples exceeding threshold concentration values*					
	Total	*Non-detects*	*Detects*	*Non-detects*	*Detects*	*Mean*	*Min*	*Max*	*0.05*	*0.25*	*0.5*	*0.75*	*0.95*	*>2*	*>5*	*>10*	*% >2*	*% >5*	*% >10*
Blaine	75	2	73	2.7	97.3	6.1	0.041	27.2	0.19	1.91	4.22	7.89	18.36	55	33	14	**73.3**	44.0	18.7
Blossom	22	15	7	68.2	31.8	2.8	0.063	11.3	0.01	0.07	0.10	0.18	5.11	2	2	1	9.1	9.1	4.5
Bone Spring-Victorio Peak	47	0	47	0.0	100.0	5.7	0.201	30.2	0.57	1.60	4.04	7.12	**18.21**	33	18	7	**70.2**	38.3	14.9
Brazos River Alluvium	43	9	34	20.9	79.1	6.2	0.020	105.0	0.01	0.04	0.40	3.14	**14.66**	12	9	5	27.9	20.9	11.6
Capitan Reef Complex	35	14	21	40.0	60.0	2.0	0.036	12.2	0.01	0.03	0.40	0.87	5.63	5	2	1	14.3	5.7	2.9
Dockum	298	61	237	20.5	79.5	4.7	0.012	54.4	0.01	0.06	1.16	4.10	**17.17**	117	67	30	39.3	22.5	10.1
Edwards-Trinity (High Plains)	18	4	14	22.2	77.8	4.0	0.360	16.0	0.01	0.41	1.96	4.34	9.17	9	4	1	**50.0**	22.2	5.6
Ellenburger-San Saba	135	19	116	14.1	85.9	2.2	0.002	15.2	0.00	0.21	1.05	2.05	8.93	34	11	5	25.2	8.1	3.7
Hickory	120	36	84	30.0	70.0	4.0	0.002	42.5	0.00	0.03	0.40	2.15	**16.14**	33	19	12	27.5	15.8	10.0
Igneous	77	2	75	2.6	97.4	1.3	0.007	5.3	0.07	0.42	1.03	1.82	3.35	14	1	0	18.2	1.3	0.0
Lipan	61	1	60	1.6	98.4	21.5	0.009	85.3	0.06	5.77	**17.70**	**33.20**	**57.40**	54	47	36	**88.5**	**77.0**	**59.0**
Marathon	24	3	21	12.5	87.5	2.4	0.025	14.5	0.00	0.10	0.43	2.26	**11.22**	7	2	2	29.2	8.3	8.3
Marble Falls	16	3	13	18.8	81.3	1.6	0.090	5.1	0.01	0.10	0.99	1.55	4.21	3	1	0	18.8	6.3	0.0
Nacatoch	38	24	14	63.2	36.8	0.4	0.009	2.2	0.00	0.01	0.02	0.10	1.10	1	0	0	2.6	0.0	0.0
Queen City	227	100	127	44.1	55.9	1.4	0.002	33.5	0.00	0.02	0.05	0.50	3.65	22	7	3	9.7	3.1	1.3
Rita Blanca	14	0	14	0.0	100.0	0.9	0.034	2.8	0.04	0.28	0.54	1.35	2.52	2	0	0	14.3	0.0	0.0
Rustler	28	9	19	32.1	67.9	3.7	0.002	15.1	0.00	0.01	0.03	4.21	7.17	12	6	1	42.9	21.4	3.6
Sparta	131	63	68	48.1	51.9	0.8	0.009	11.2	0.00	0.01	0.04	0.13	3.29	9	5	1	6.9	3.8	0.8
West Texas Bolson	107	5	102	4.7	95.3	2.3	0.002	18.2	0.02	0.49	1.60	2.53	6.28	40	6	4	37.4	5.6	3.7
Woodbine	168	98	70	58.3	41.7	1.1	0.002	23.0	0.00	0.01	0.03	0.06	1.46	7	5	1	4.2	3.0	0.6
Yegua-Jackson	139	76	63	54.7	45.3	0.5	0.009	14.3	0.00	0.02	0.02	0.07	0.44	2	2	1	1.4	1.4	0.7
All Minor Aquifers	1,823	544	1,279	29.8	70.2	3.8	0.002	105.0	0.00	0.02	0.35	2.11	12.69	473	247	125	25.9	13.5	6.9

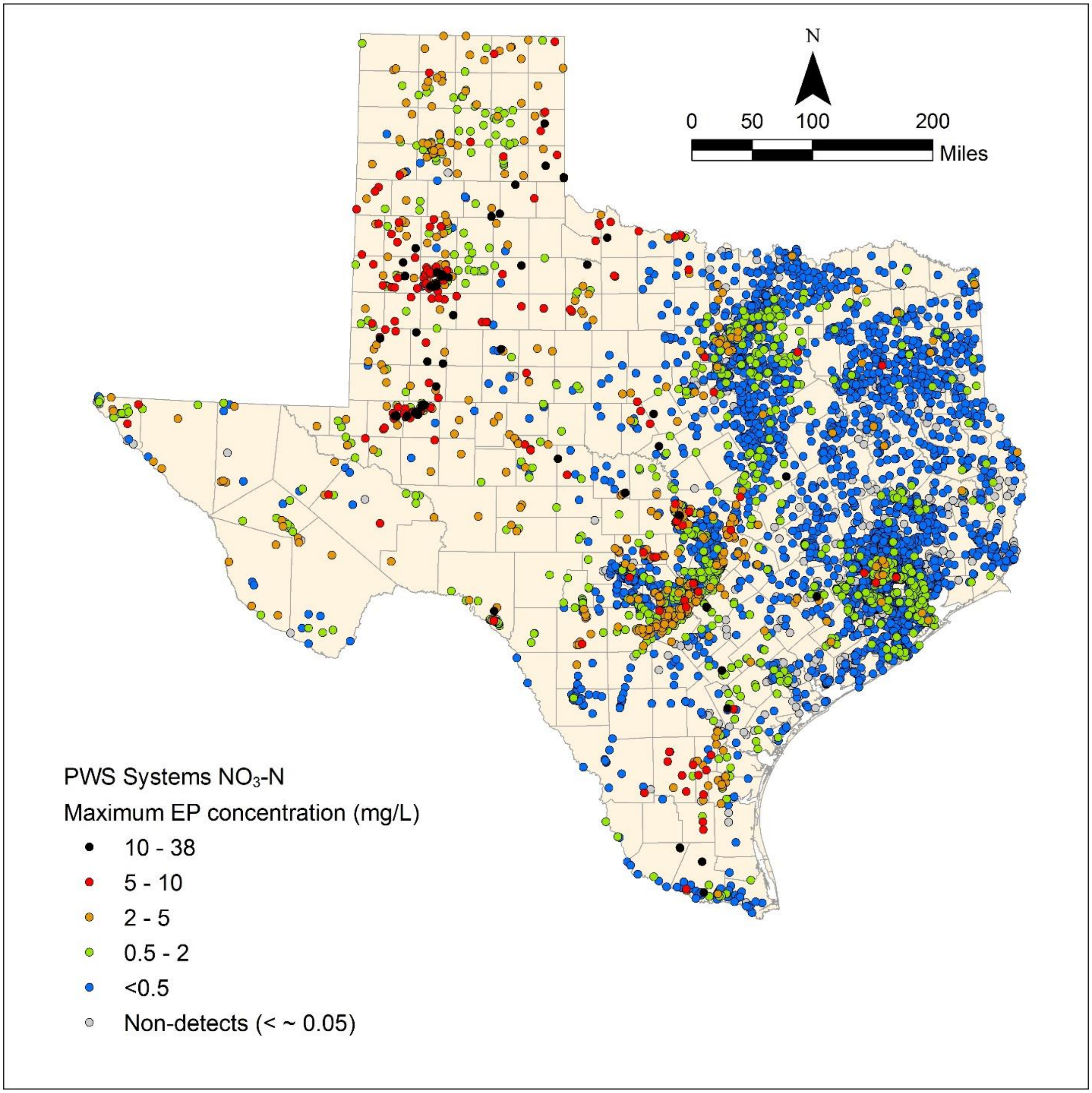

Figure 1. Entry point (EP) sample nitrate-N concentrations for Public Water Supply (PWS) systems in Texas based on the Texas Commission on Environmental Quality PWS water quality database. Each of the 6,933 PWS systems is represented by a single point located at the average latitude and longitude coordinate of all entry points for a given system. Only entry points that were listed as operational in 2017 were used and only the latest sample concentration for each entry point was used. Systems with multiple entry points are represented by the maximum concentration of all entry point samples for that system. Approximately 96% of the samples were obtained during the period 2015-2017 and none were obtained prior to 2005.

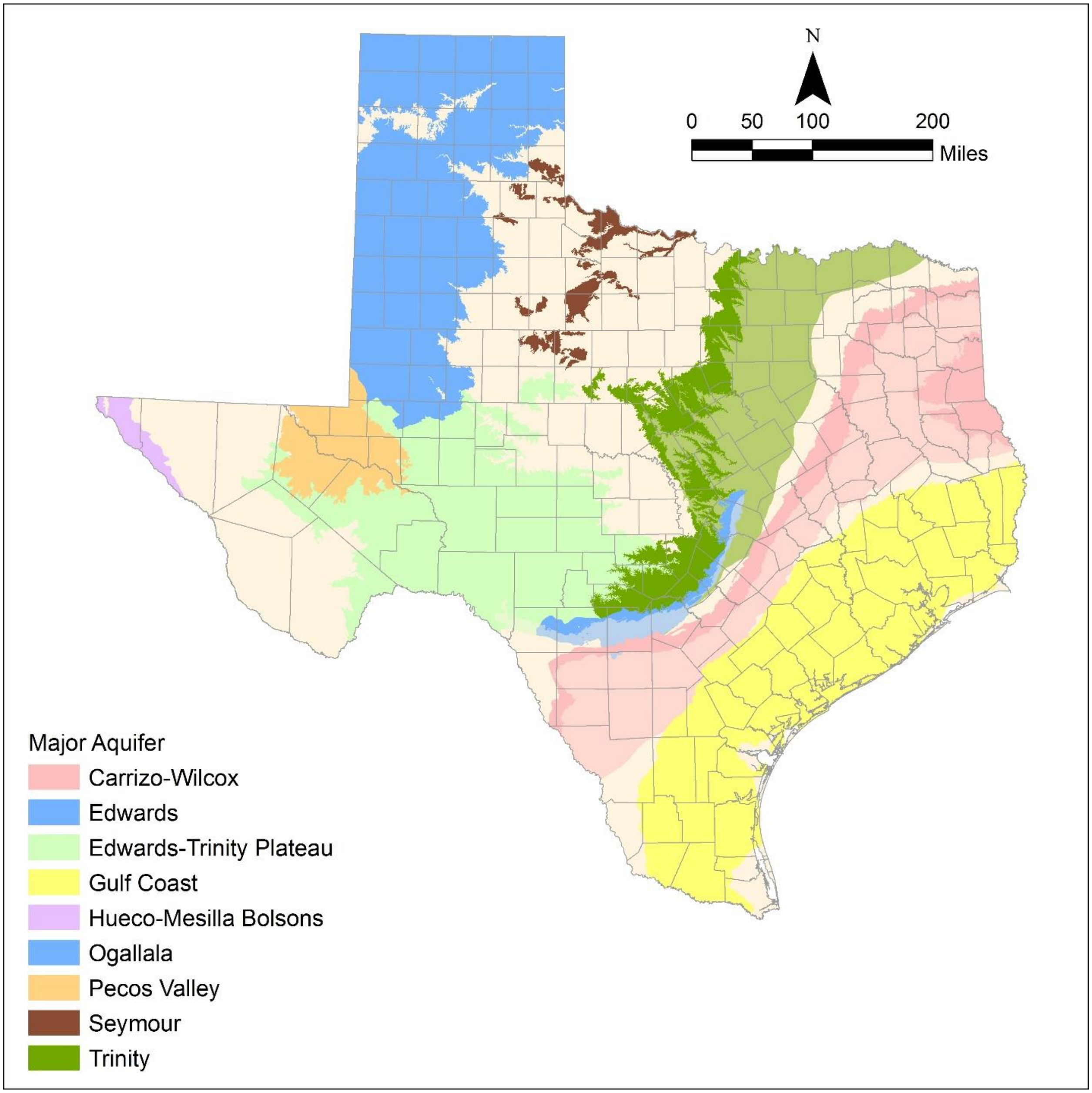

Figure 2. Major Aquifers of Texas.

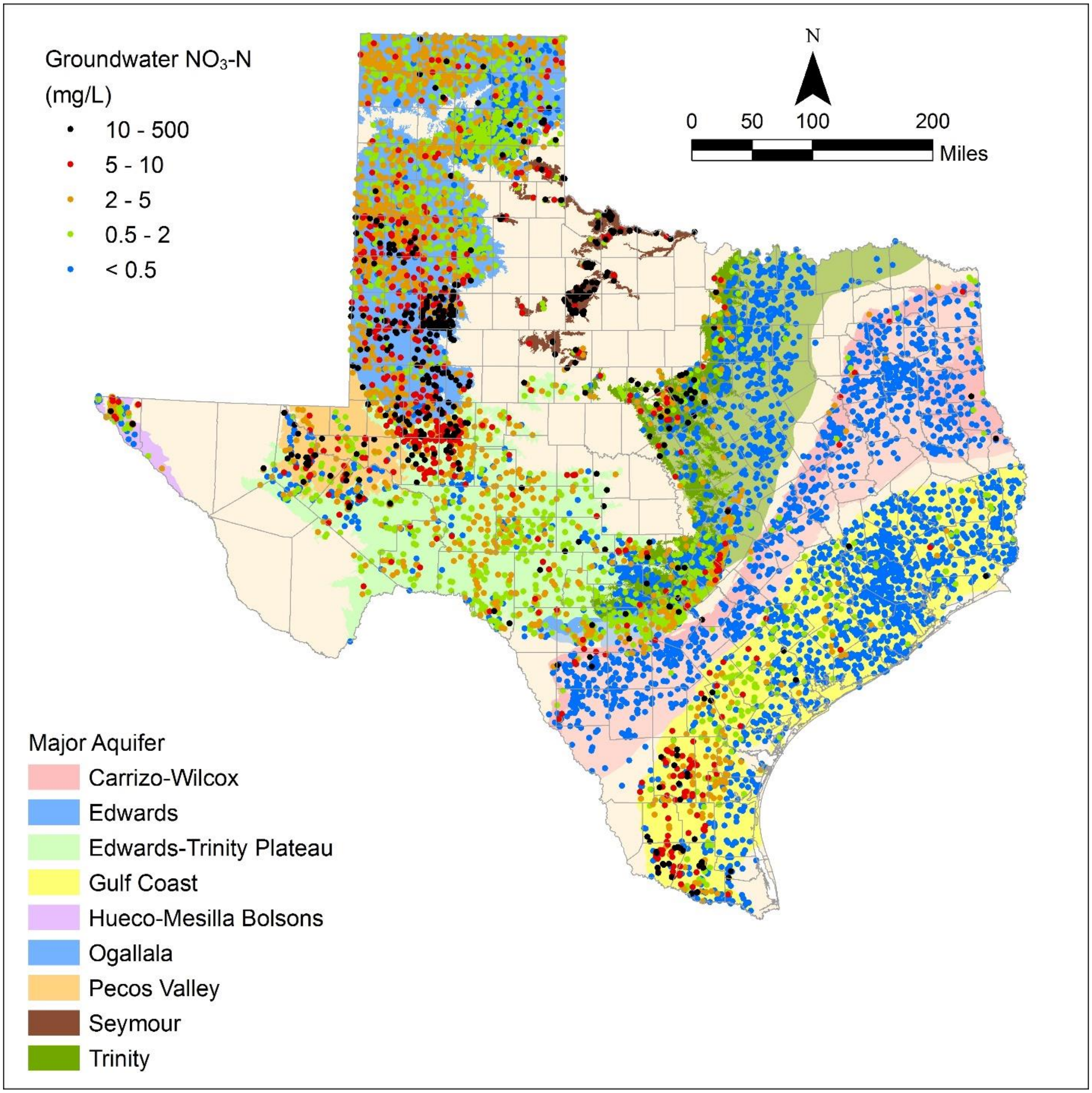

Figure 3. Nitrate-N concentrations in Texas Major Aquifer groundwater based on the Texas Water Development Board (TWDB) groundwater database. Samples represent the latest sample for each well between 1992 and 2017. All non-detects (samples with nitrate-N concentrations below the analytical detection limit concentration) are represented in the <0.5 mg/L category, which also includes detected concentrations in this range.

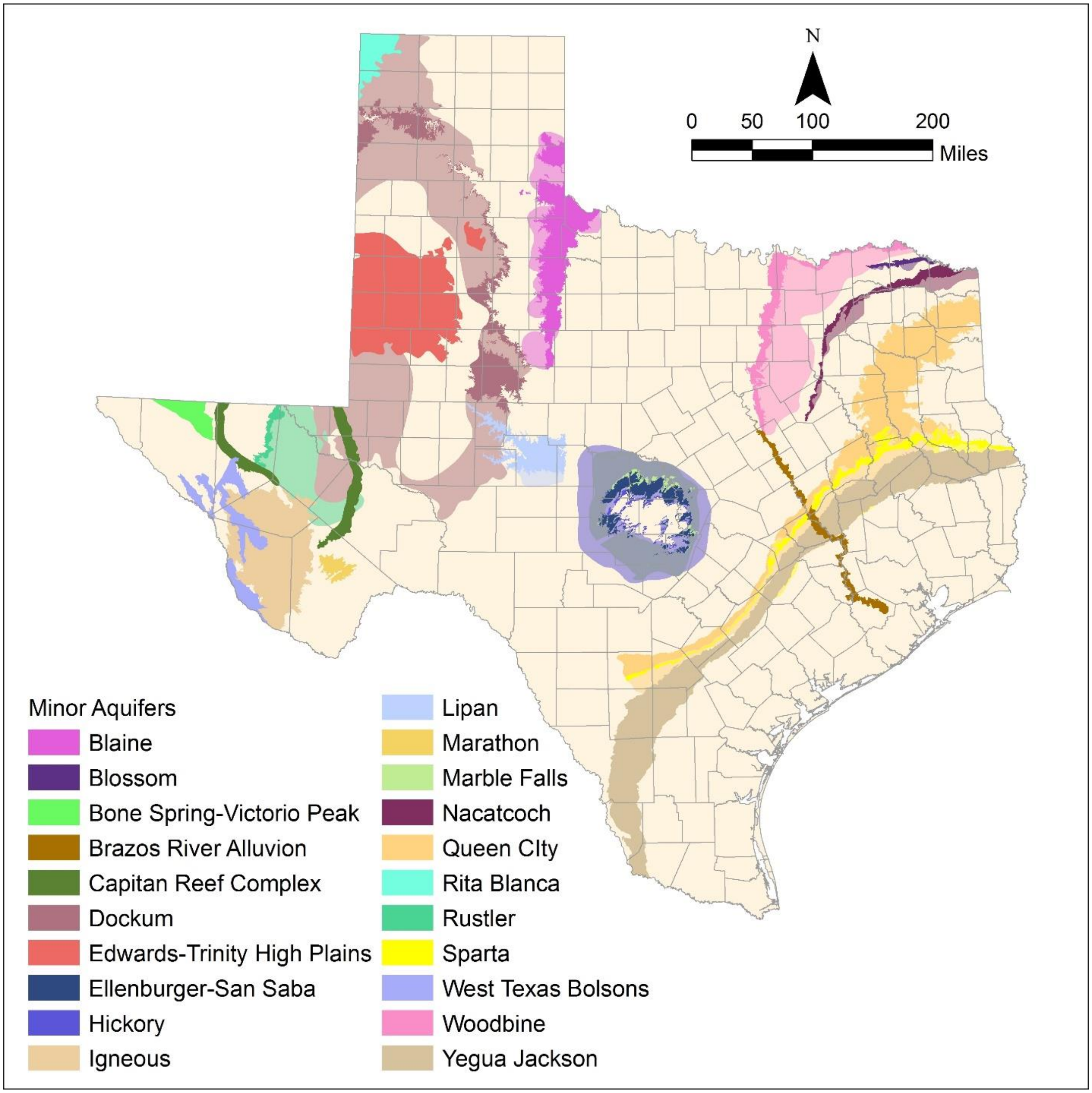

Figure 4. Minor Aquifers of Texas.

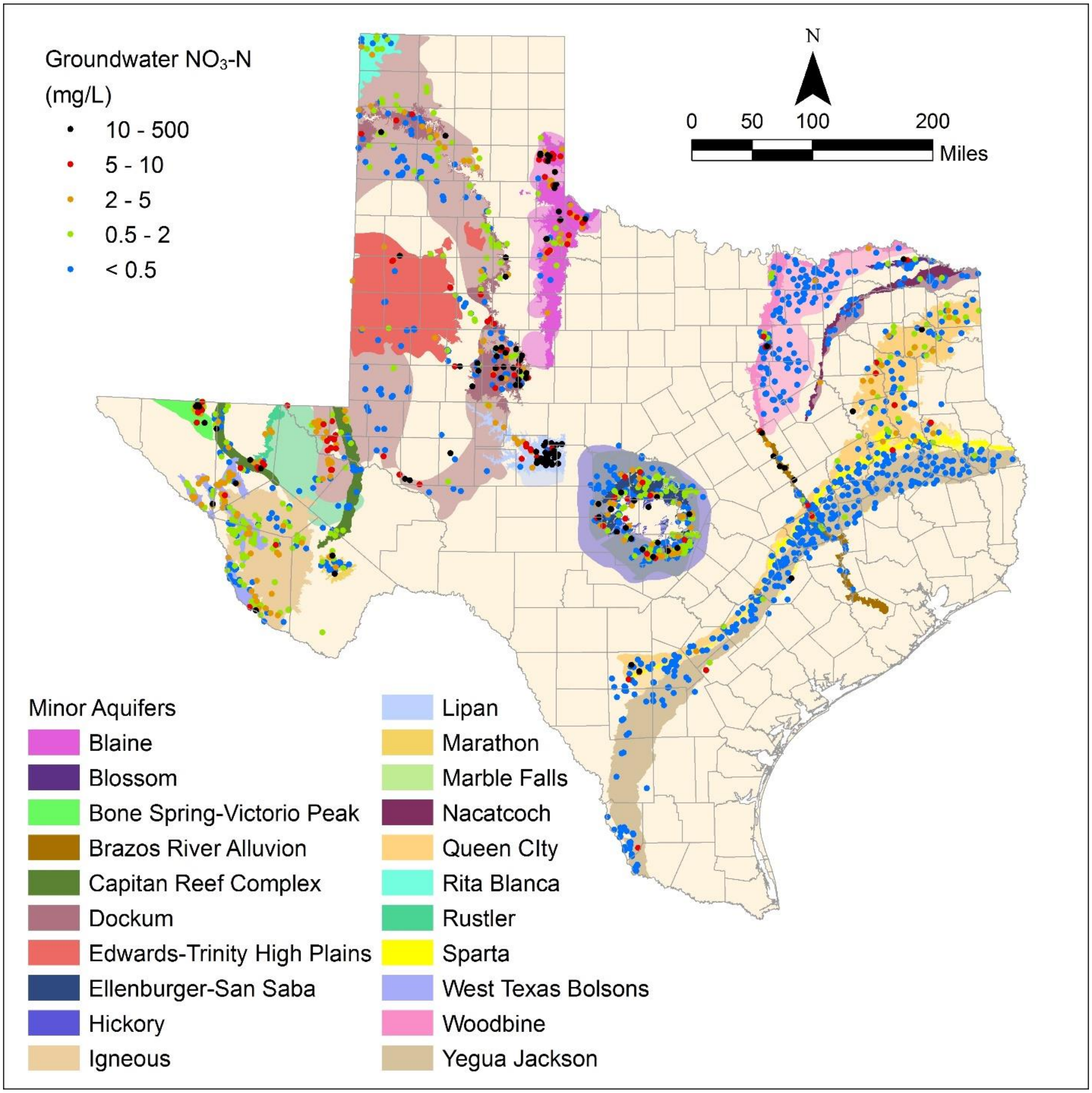

Figure 5. Nitrate-N concentrations in Texas Minor Aquifer groundwater based on the Texas Water Development Board (TWDB) groundwater database. Samples represent the latest sample for each well between 1992 and 2017. All non-detects (samples with nitrate-N concentrations below the analytical detection limit concentration) are represented in the <0.5 mg/L category, which also includes detected concentrations in this range.

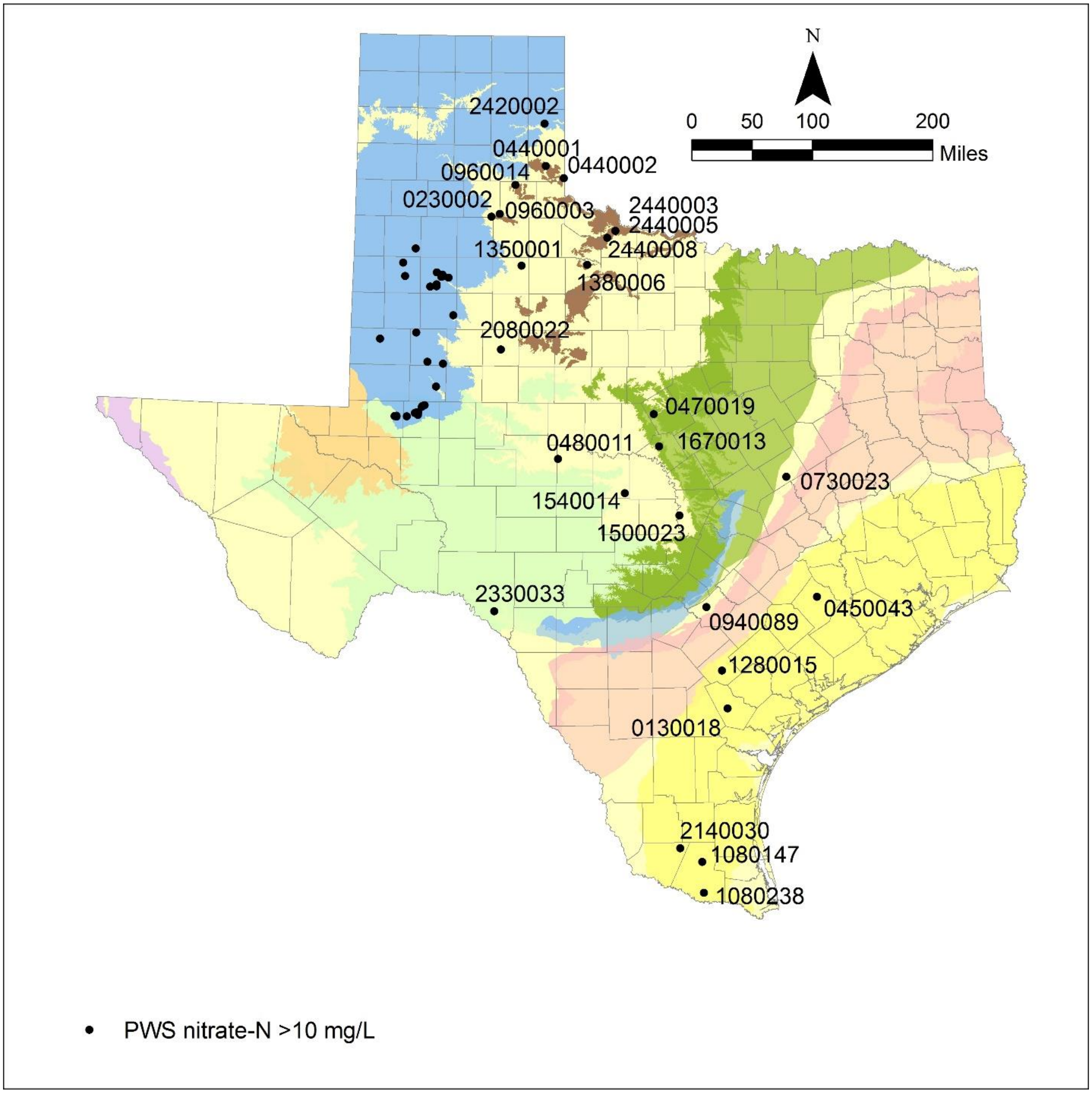

Figure 6a. PWS systems with nitrate-N violations based on the latest entry point sample analyses. Major aquifer outcrop and subcrop areas are shown for reference. See separate detail Figure 6b for systems in the southern Ogallala region.

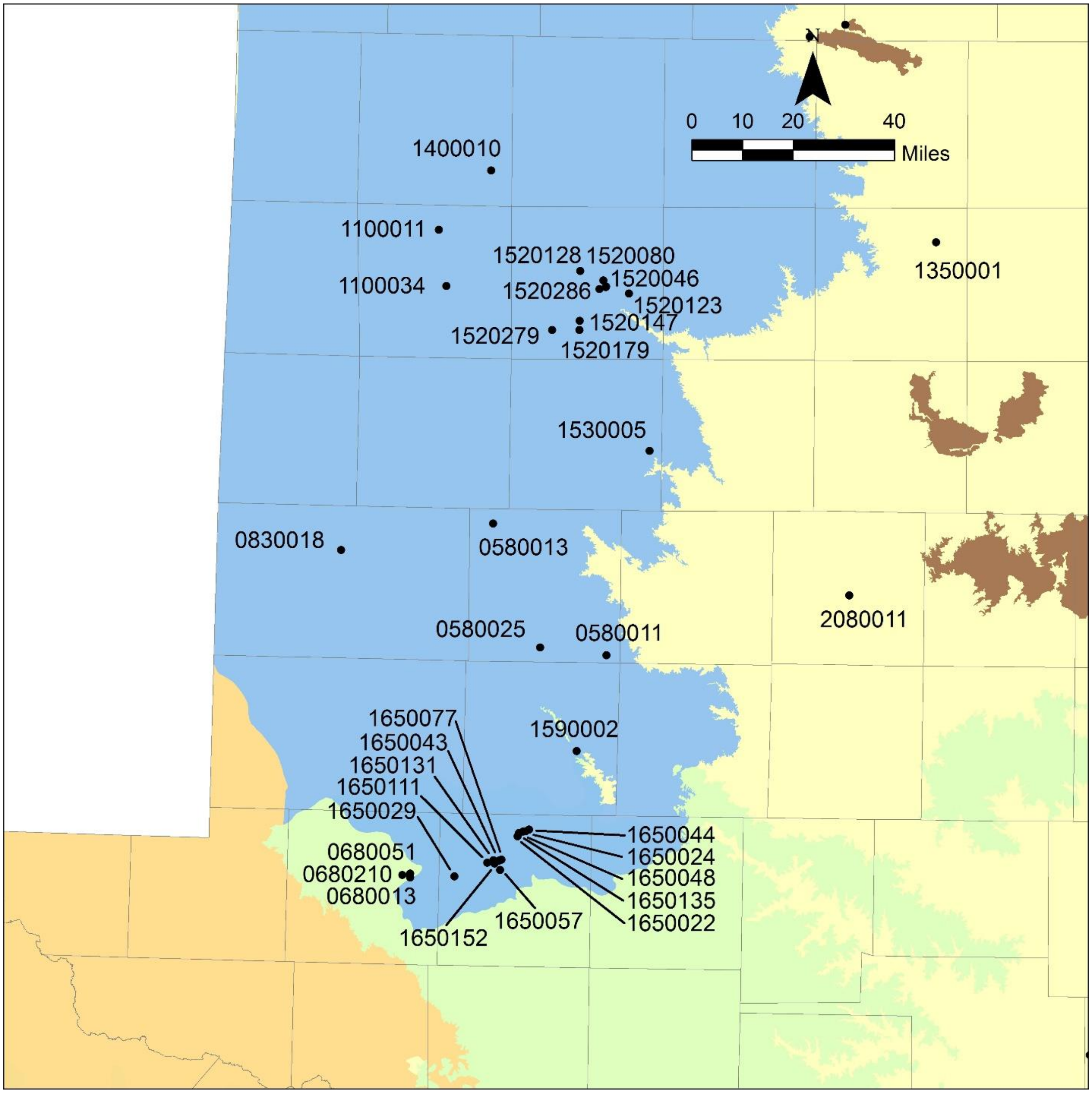

Figure 6b. PWS systems with nitrate-N violations based on the latest entry point sample analyses in the southern Ogallala region. Major aquifer outcrop and subcrop areas are shown for reference.

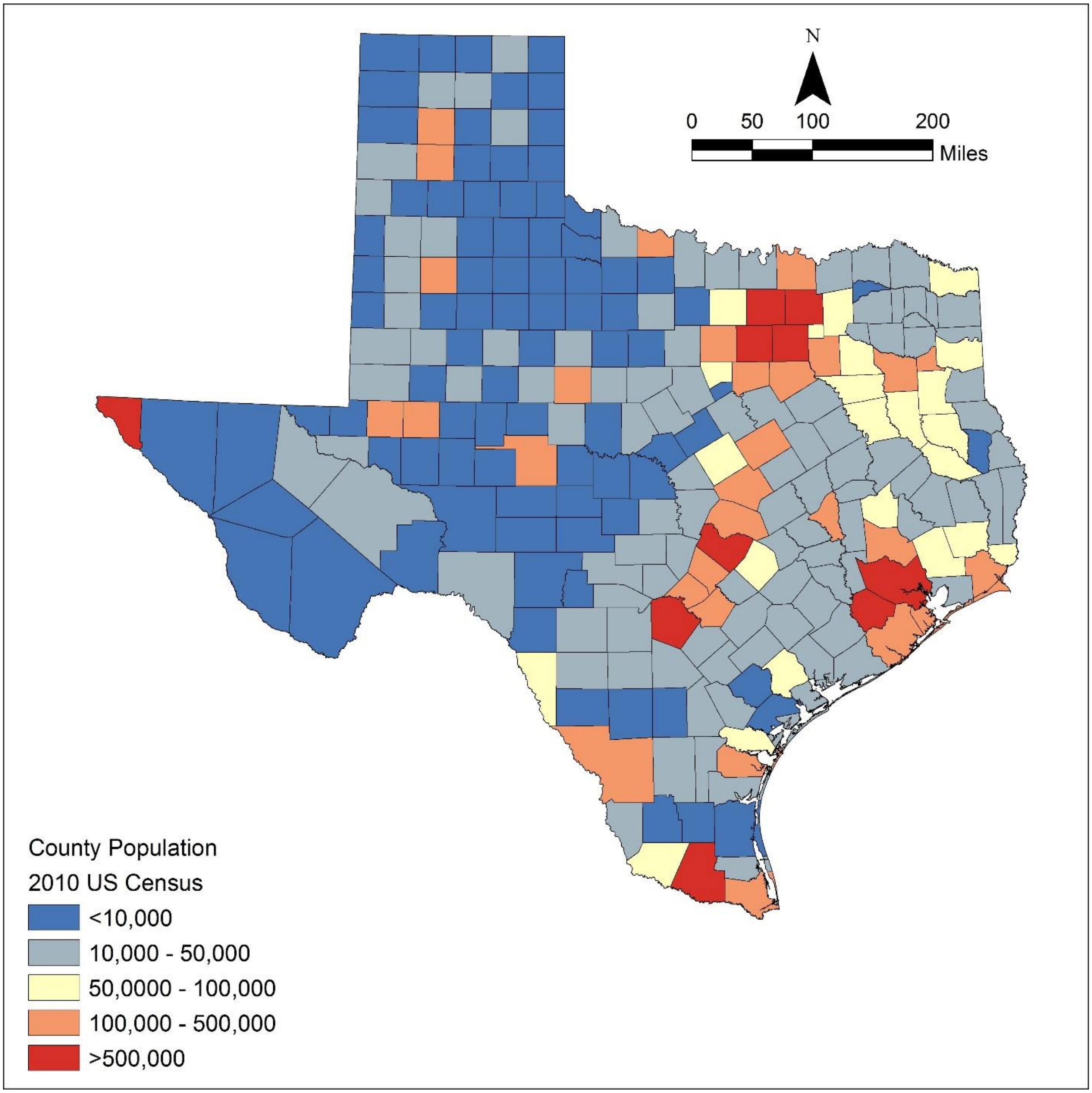

Figure 7. Texas county populations based on 2010 U.S. Census data.

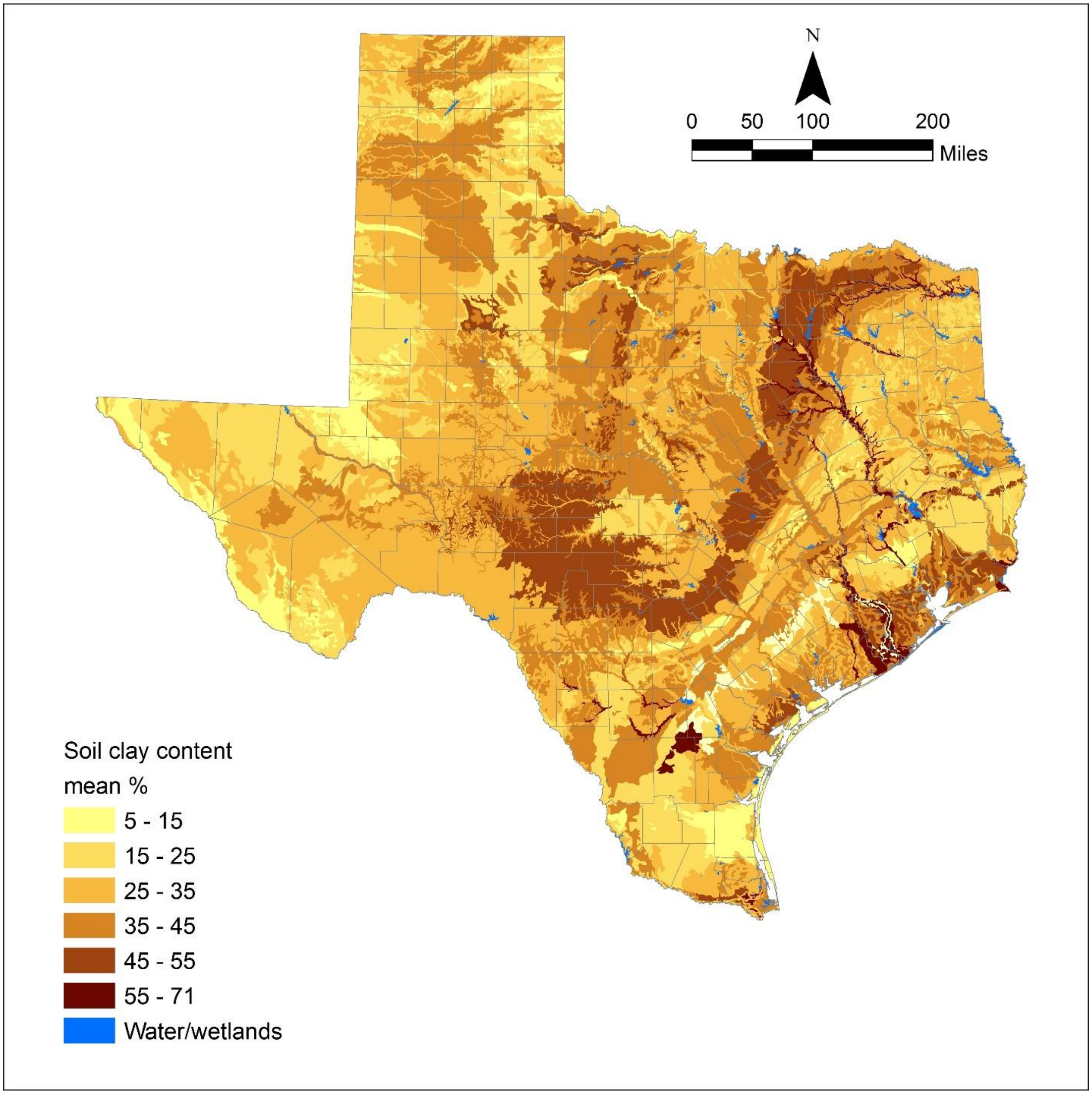

Figure 8 . Soil clay content based on STATSGO.
https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629

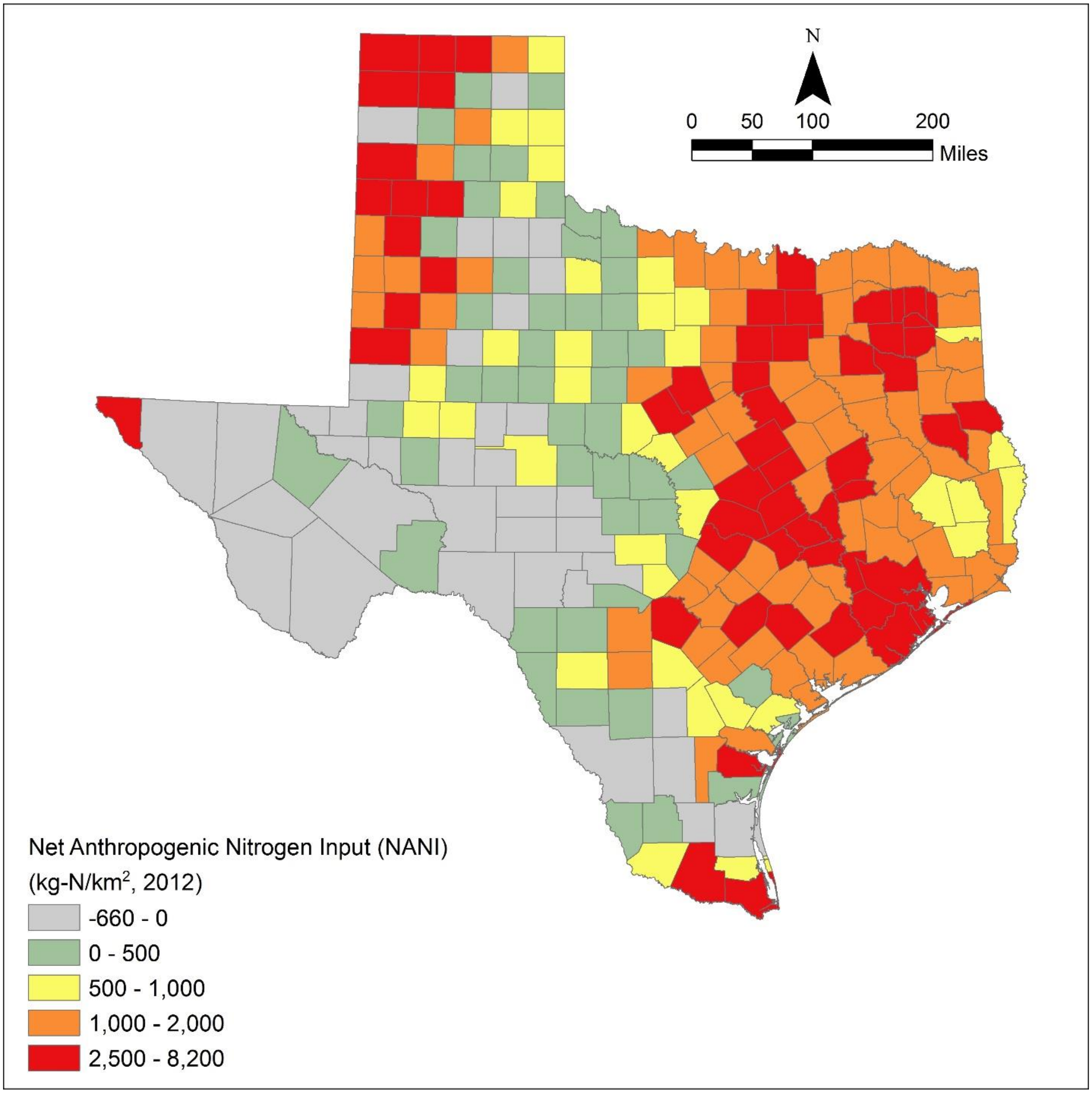

Figure 9. Net Anthropogenic Nitrogen Input (NANI) for 2012, represent the net total annual sum of all nitrogen inputs and exports at the county level. Conversion factor: 1,000 kg/km^2 = 8.92 lb/acre. http://www.eeb.cornell.edu/biogeo/nanc/nani/nani.htm

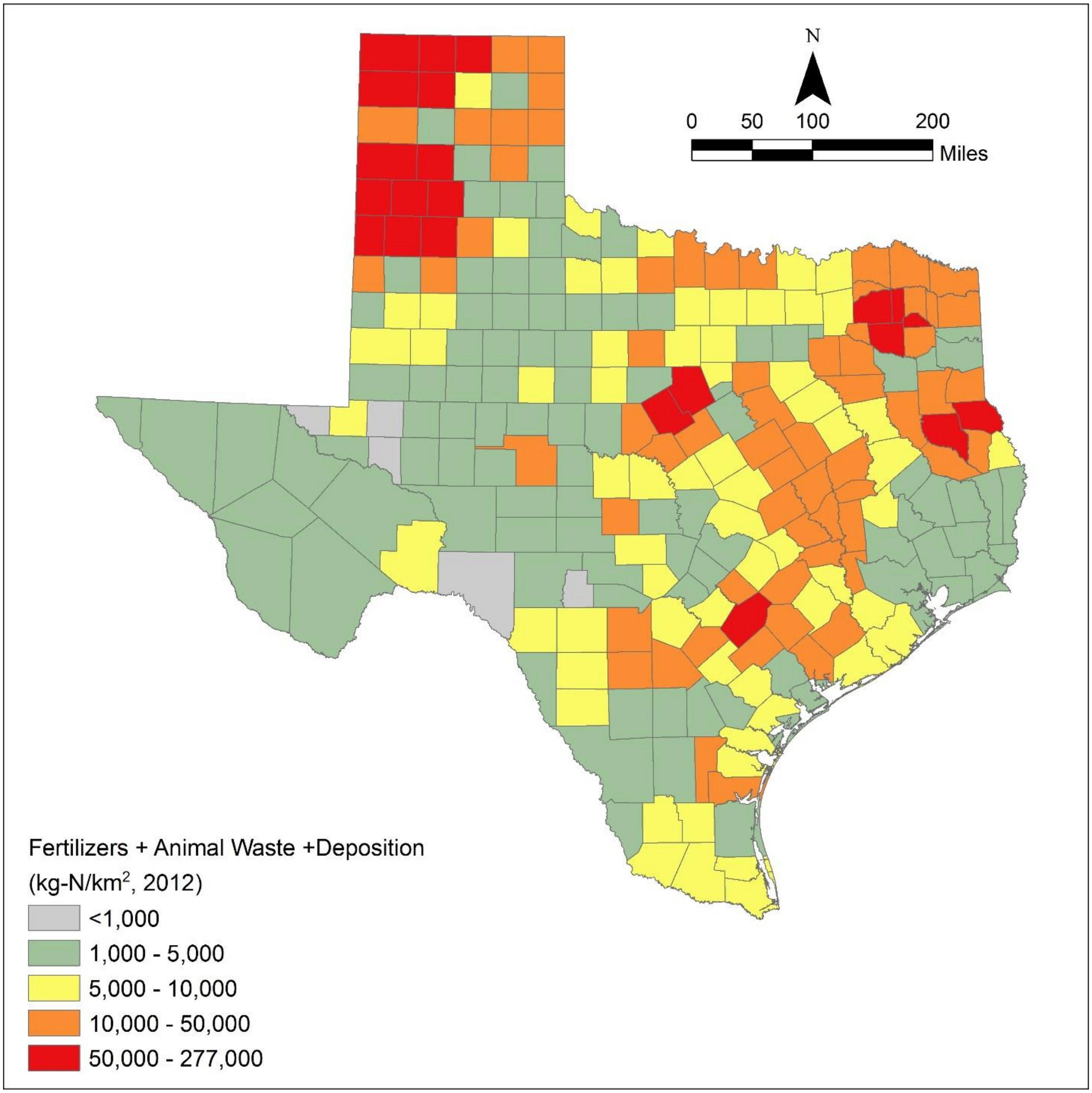

Figure 10. Net Anthropogenic Nitrogen Input (NANI) for 2012, representing the primary risks to groundwater contamination at the county level, including fertilizers, animal waste, and atmospheric deposition. Conversion factor: 10,000 kg/km^2 = 89.2 lb/acre.

http://www.eeb.cornell.edu/biogeo/nanc/nani/nani.htm

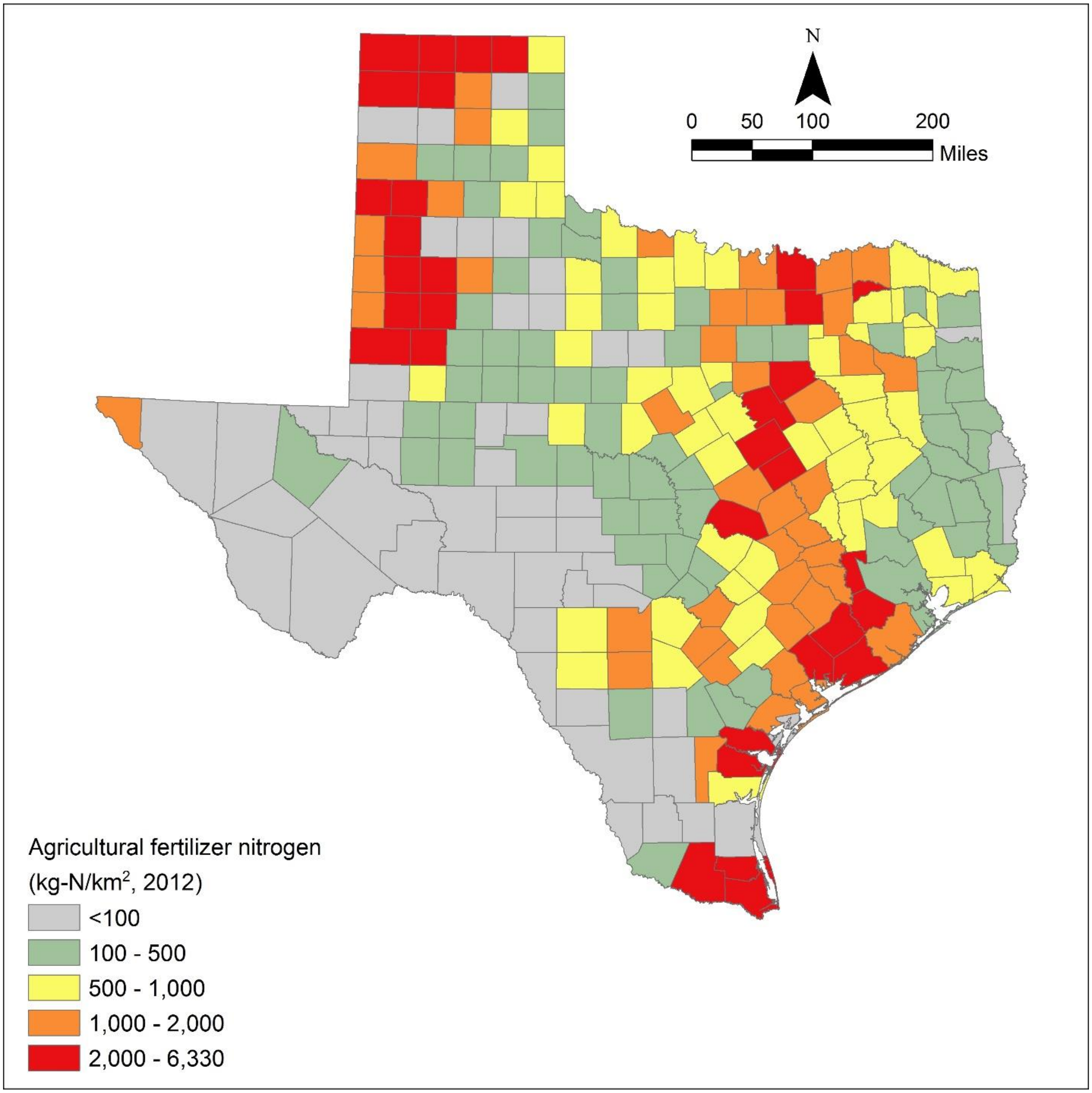

Figure 11. Distribution of nitrate-N applied in agricultural fertilizers based on Net Anthropogenic Nitrogen Input (NANI) for 2012. Conversion factor: 1,000 kg/km^2 = 8.92 lb/acre.

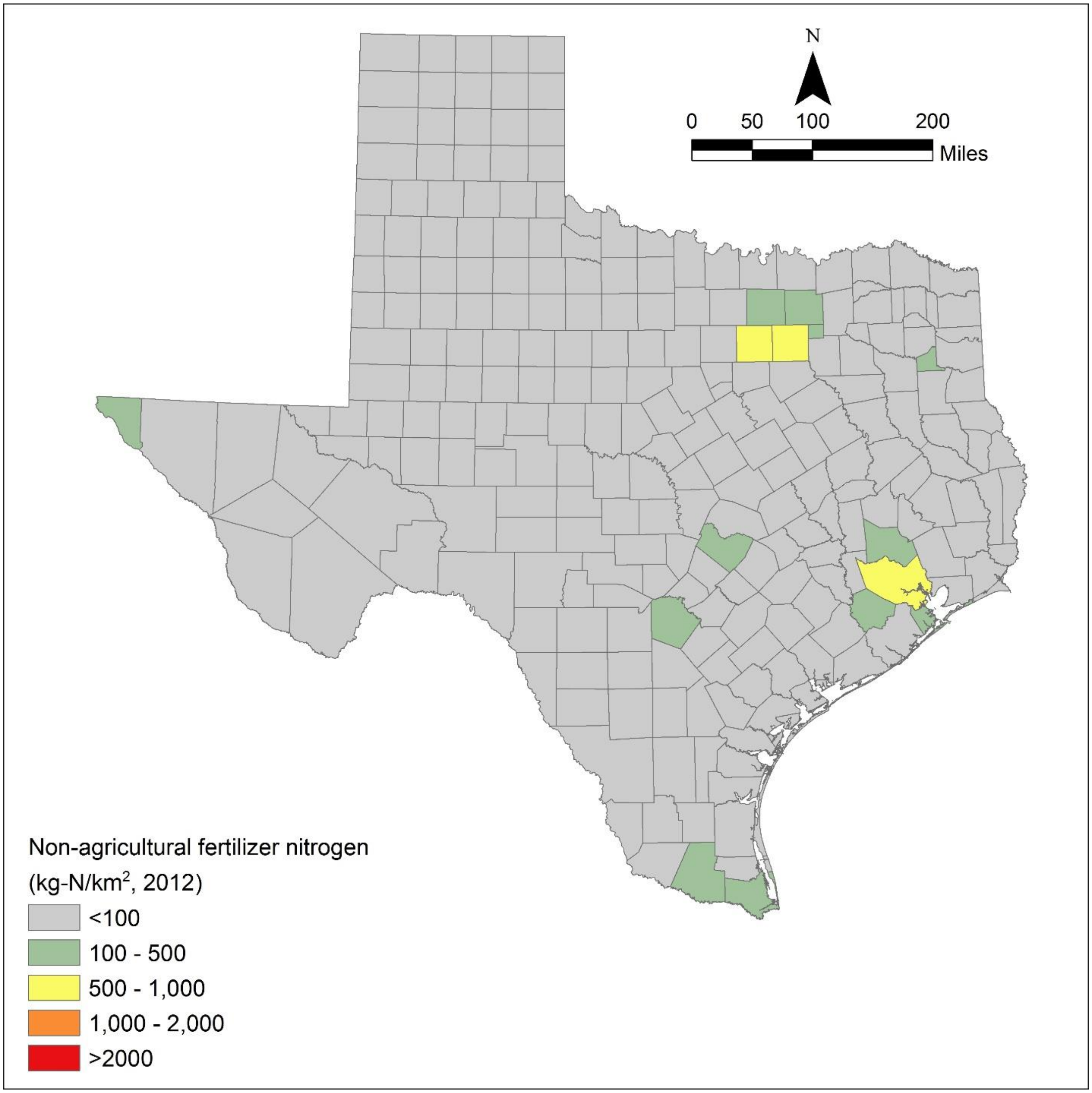

Figure 12. Distribution of nitrate-N applied in non-agricultural fertilizers based on Net Anthropogenic Nitrogen Input (NANI) for 2012. Conversion factor: 1,000 kg/km^2 = 8.92 lb/acre.

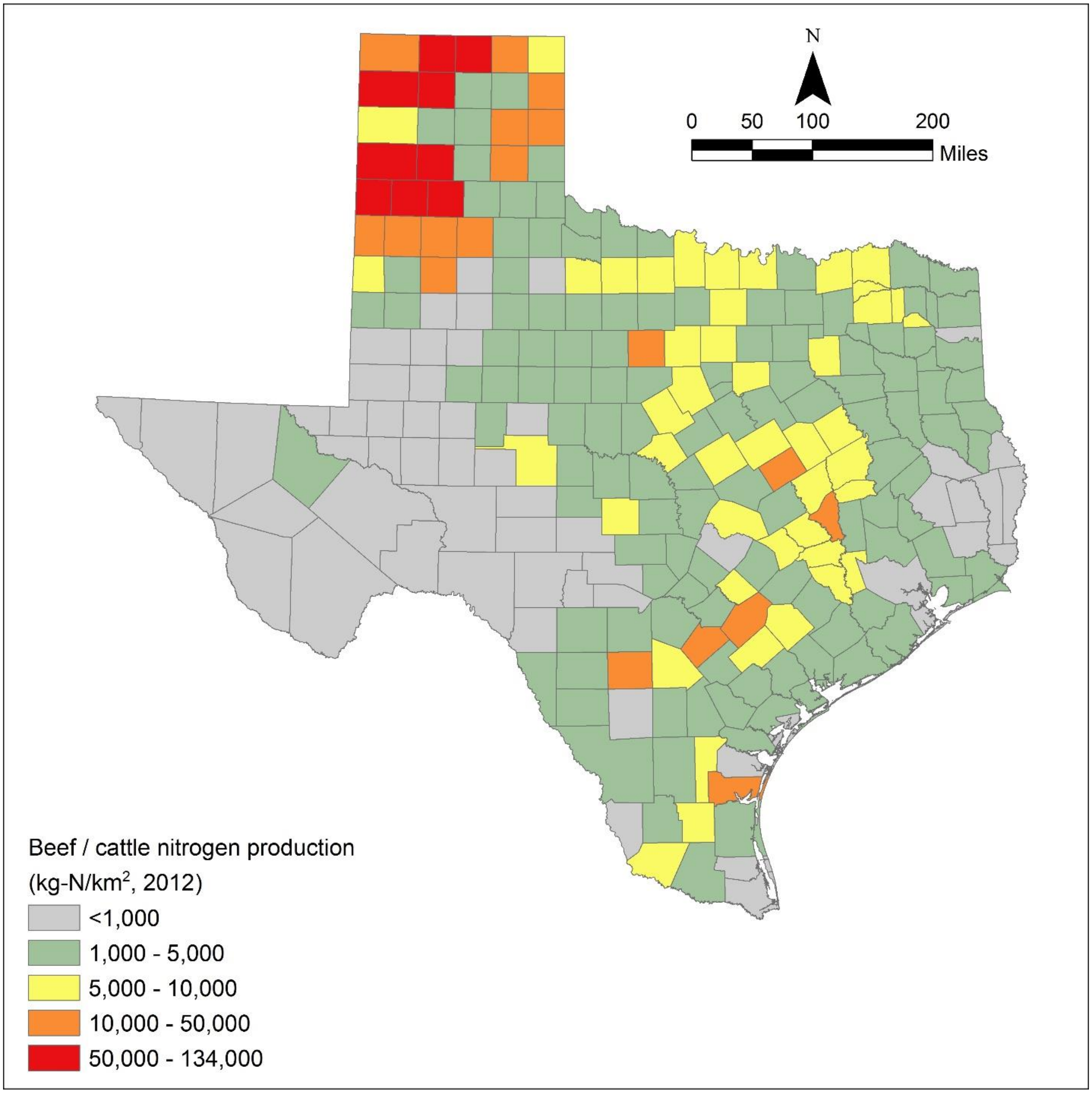

Figure 13. Distribution of nitrate-N generated by beef/cattle livestock based on Net Anthropogenic Nitrogen Input (NANI) for 2012. Conversion factor: 1,000 kg/km^2 = 8.92 lb/acre.

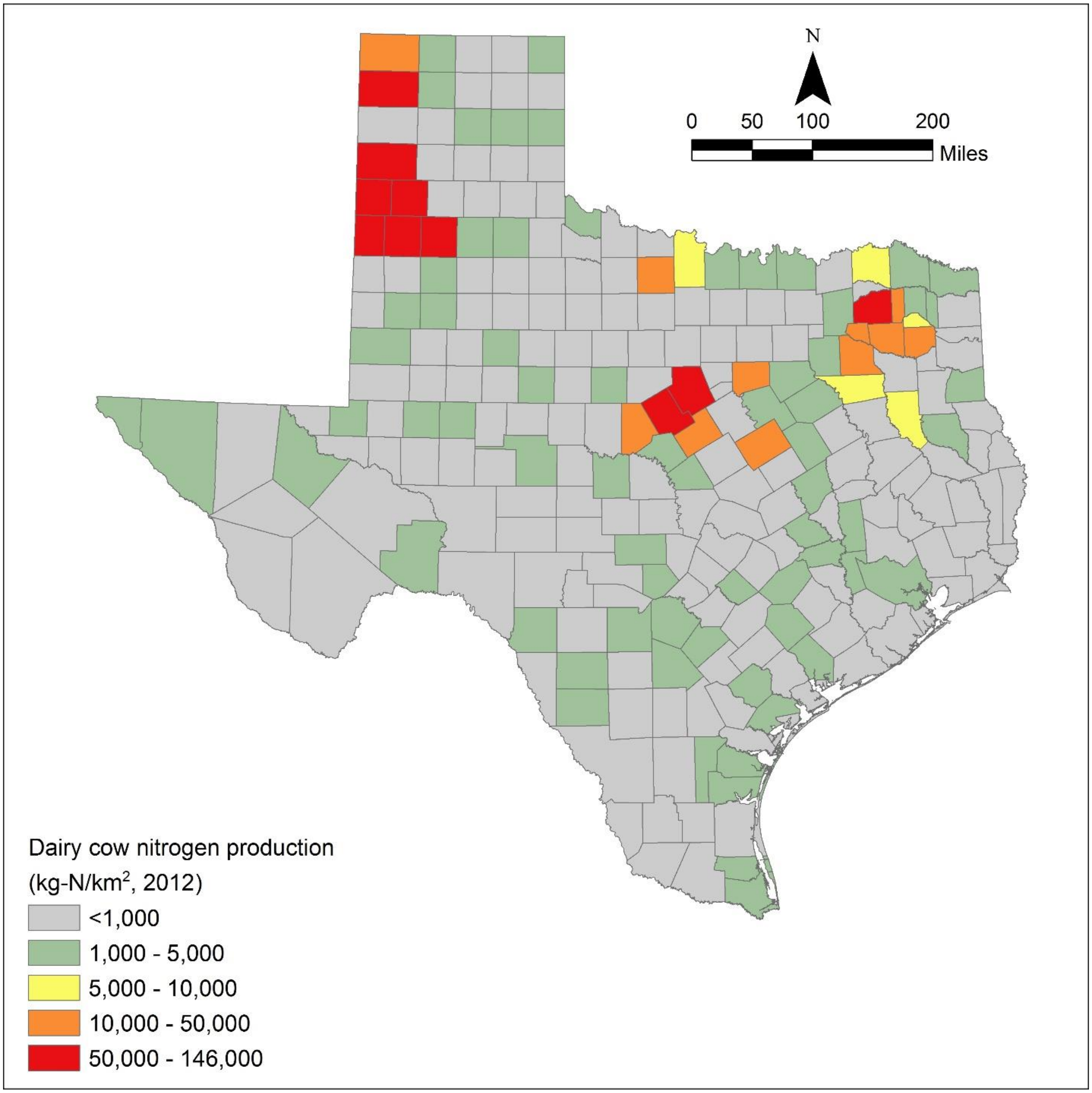

Figure 14. Distribution of nitrate-N generated by dairy livestock based on Net Anthropogenic Nitrogen Input (NANI) for 2012. Conversion factor: 10,000 kg/km^2 = 89.2 lb/acre.

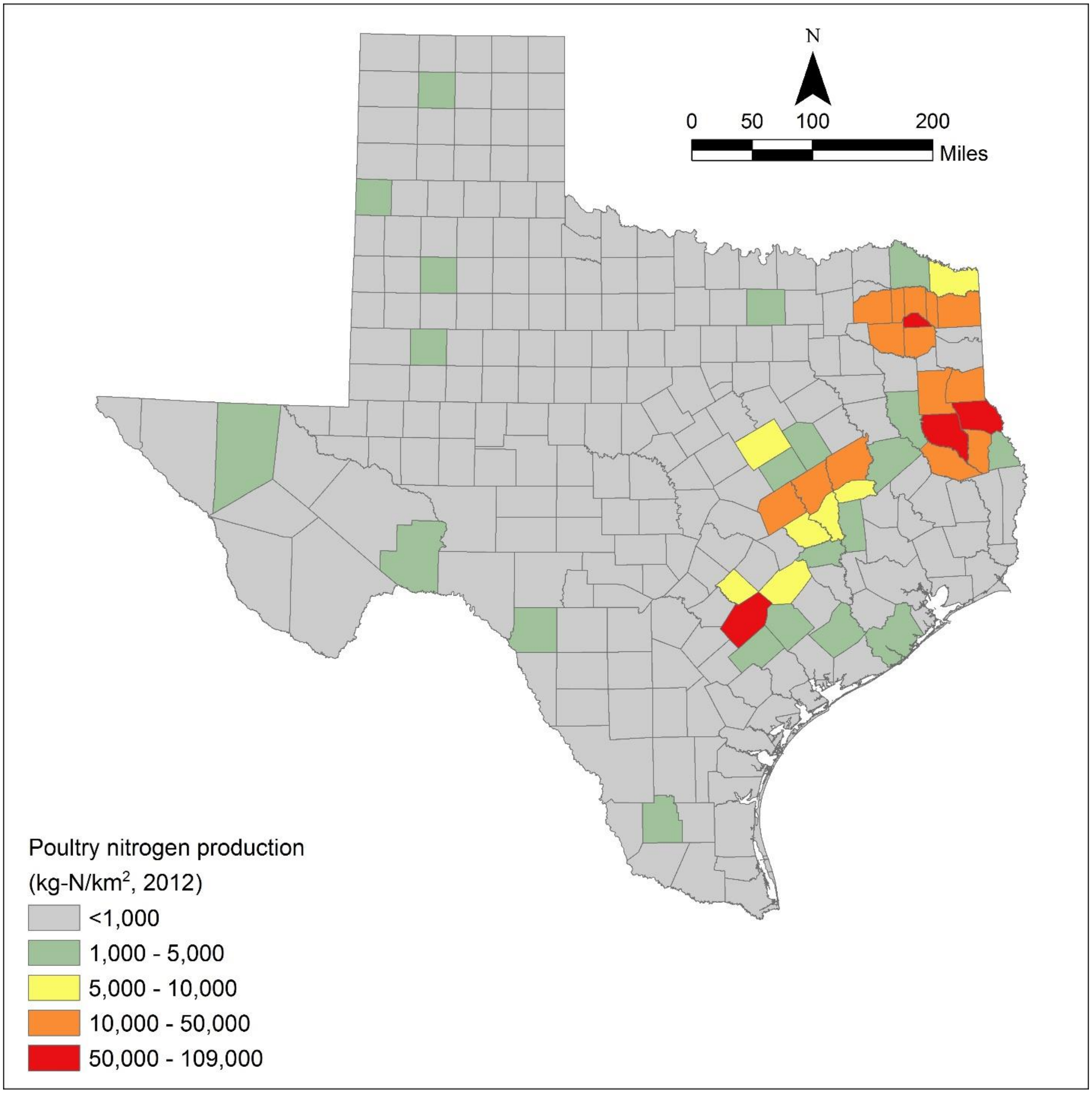

Figure 15. Distribution of nitrate-N generated by poultry livestock based on Net Anthropogenic Nitrogen Input (NANI) for 2012. Conversion factor: 10,000 kg/km^2 = 89.2 lb/acre.

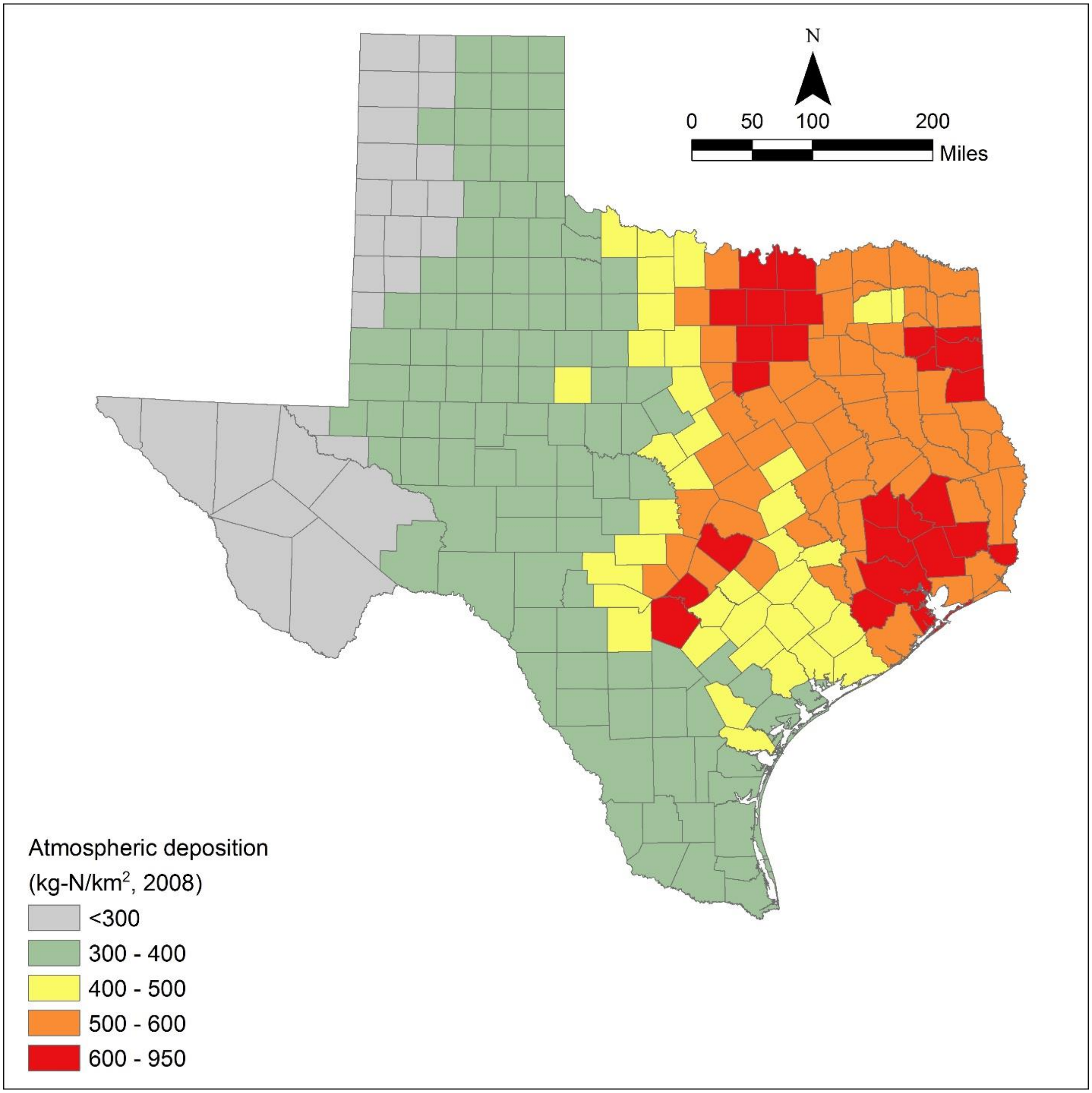

Figure 16. Distribution of nitrate-N atmospheric deposition based on Net Anthropogenic Nitrogen Input (NANI) for 2012 (in turn based on National Atmospheric Deposition Program, NADP, data from 2008). Conversion factor: 1,000 kg/km^2 = 8.92 lb/acre.

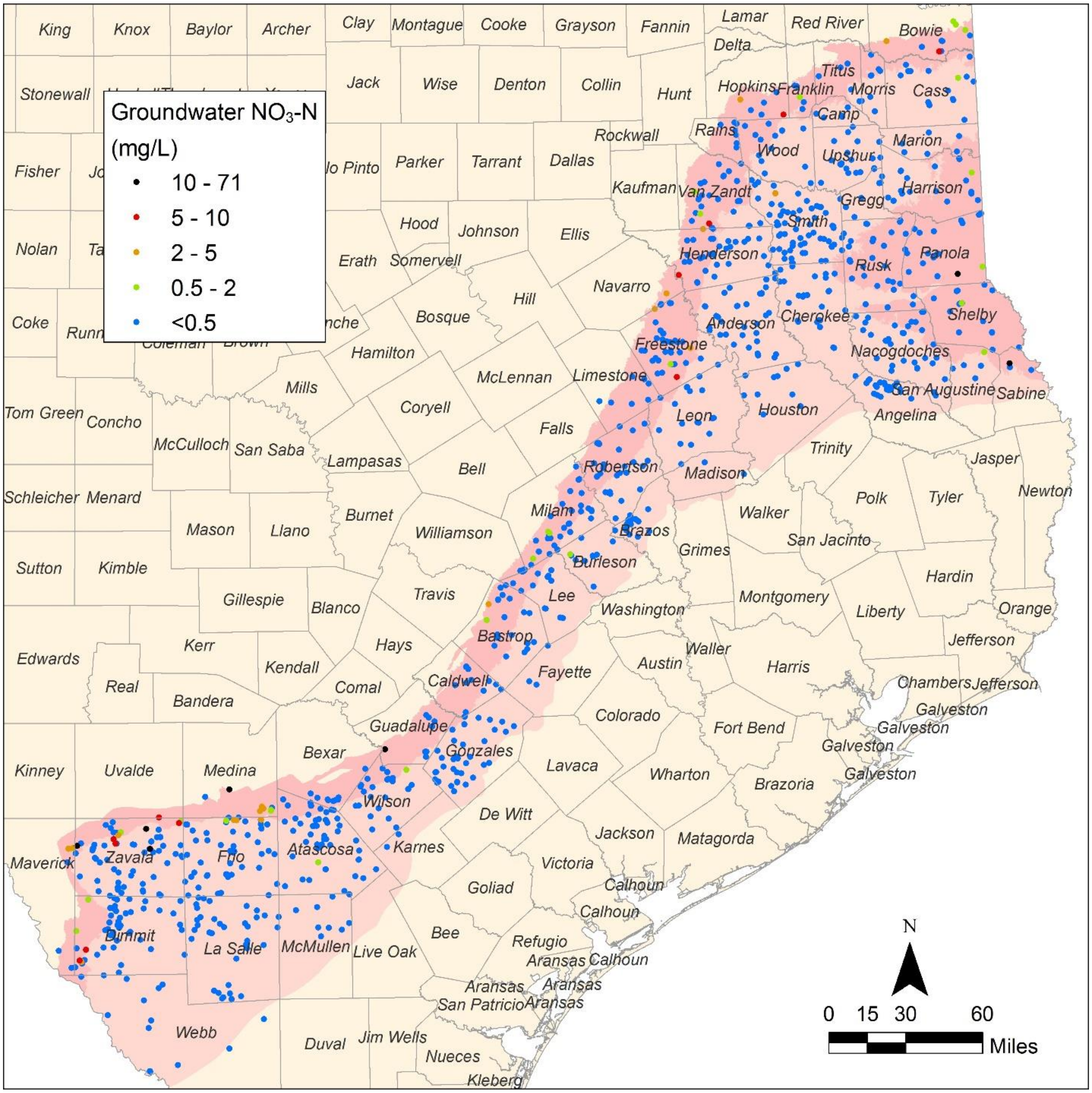

Figure 17a. Groundwater nitrate-N concentrations in the Carrizo-Wilcox aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017. Darker shaded area represents the aquifer outcrop and lighter shaded area represents the aquifer subcrop.

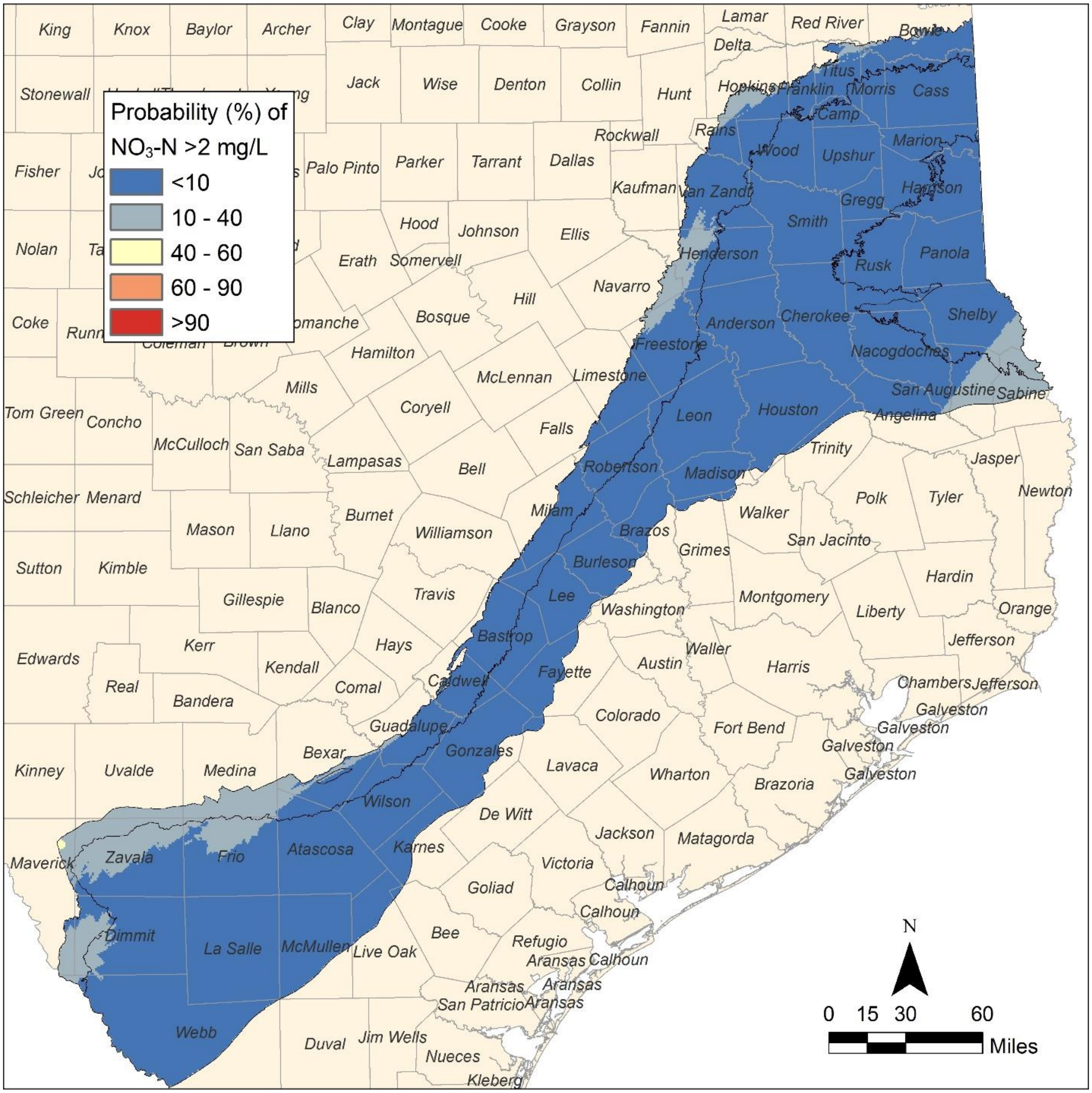

Figure 17b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Carrizo-Wilcox aquifer based in indicator kriging using TWDB concentration data.

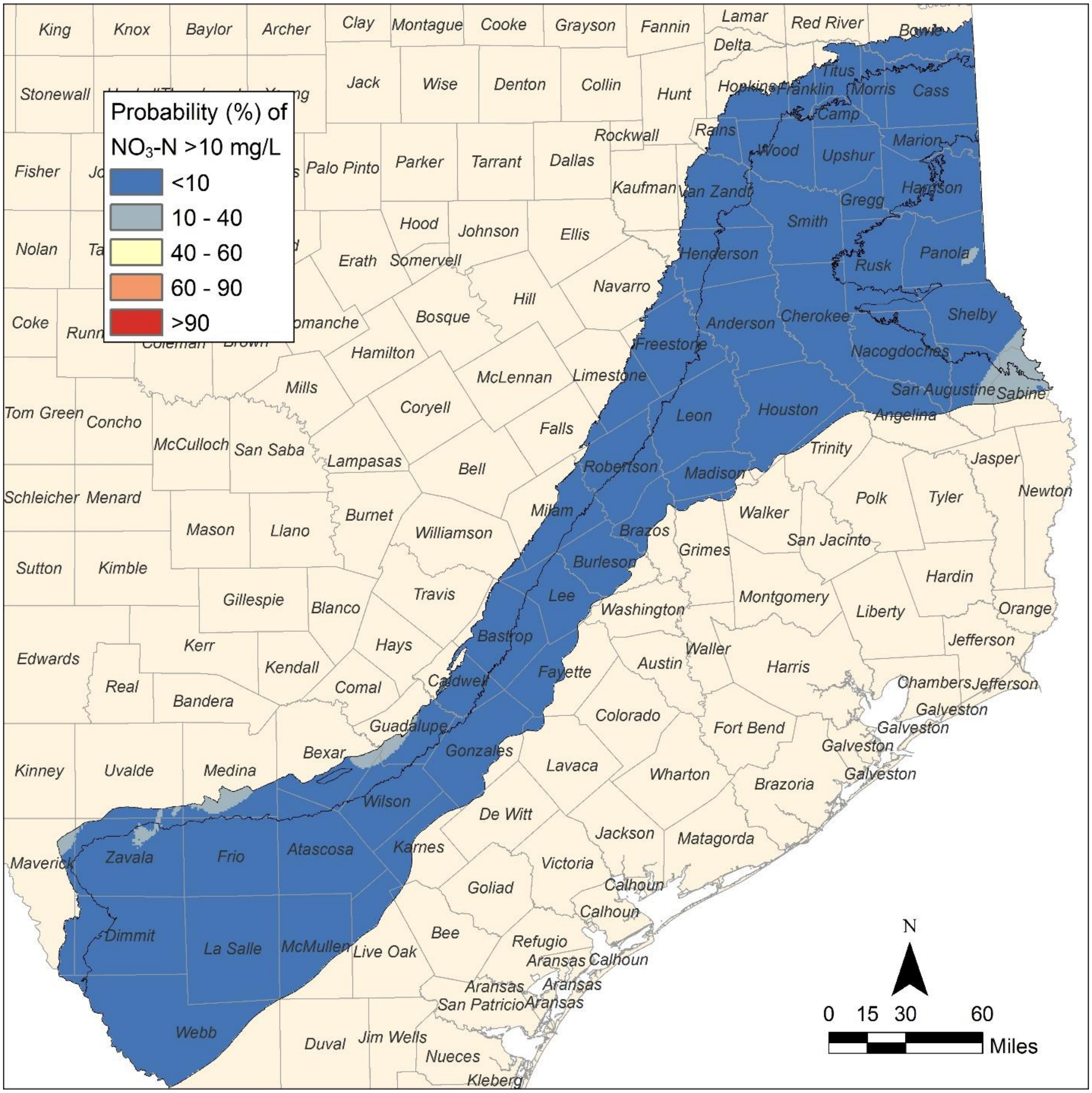

Figure 17c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Carrizo-Wilcox aquifer based in indicator kriging using TWDB concentration data.

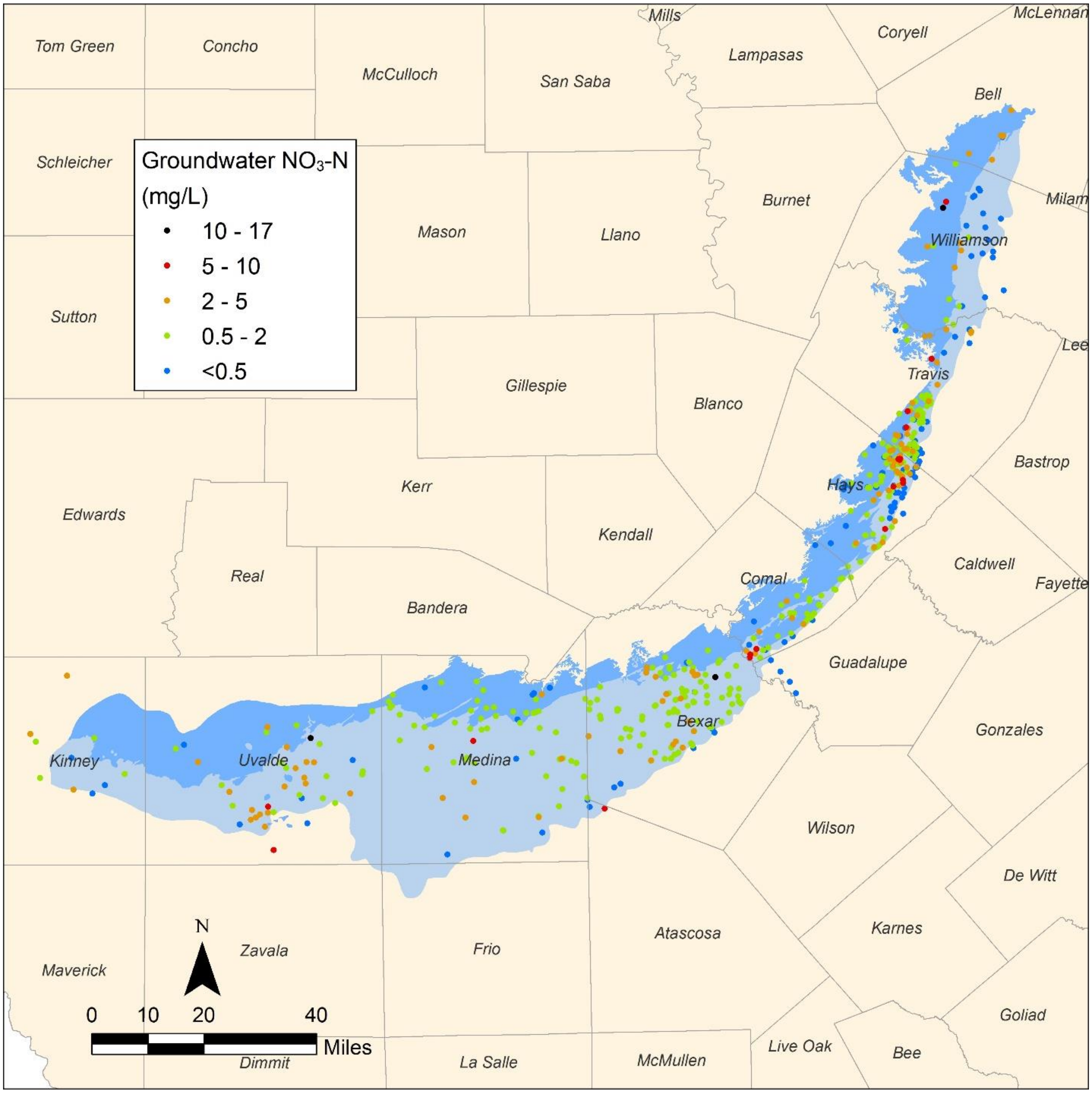

Figure 18a. Groundwater nitrate-N concentrations in the Edwards aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017. Darker shaded area represents the aquifer outcrop and lighter shaded area represents the aquifer subcrop.

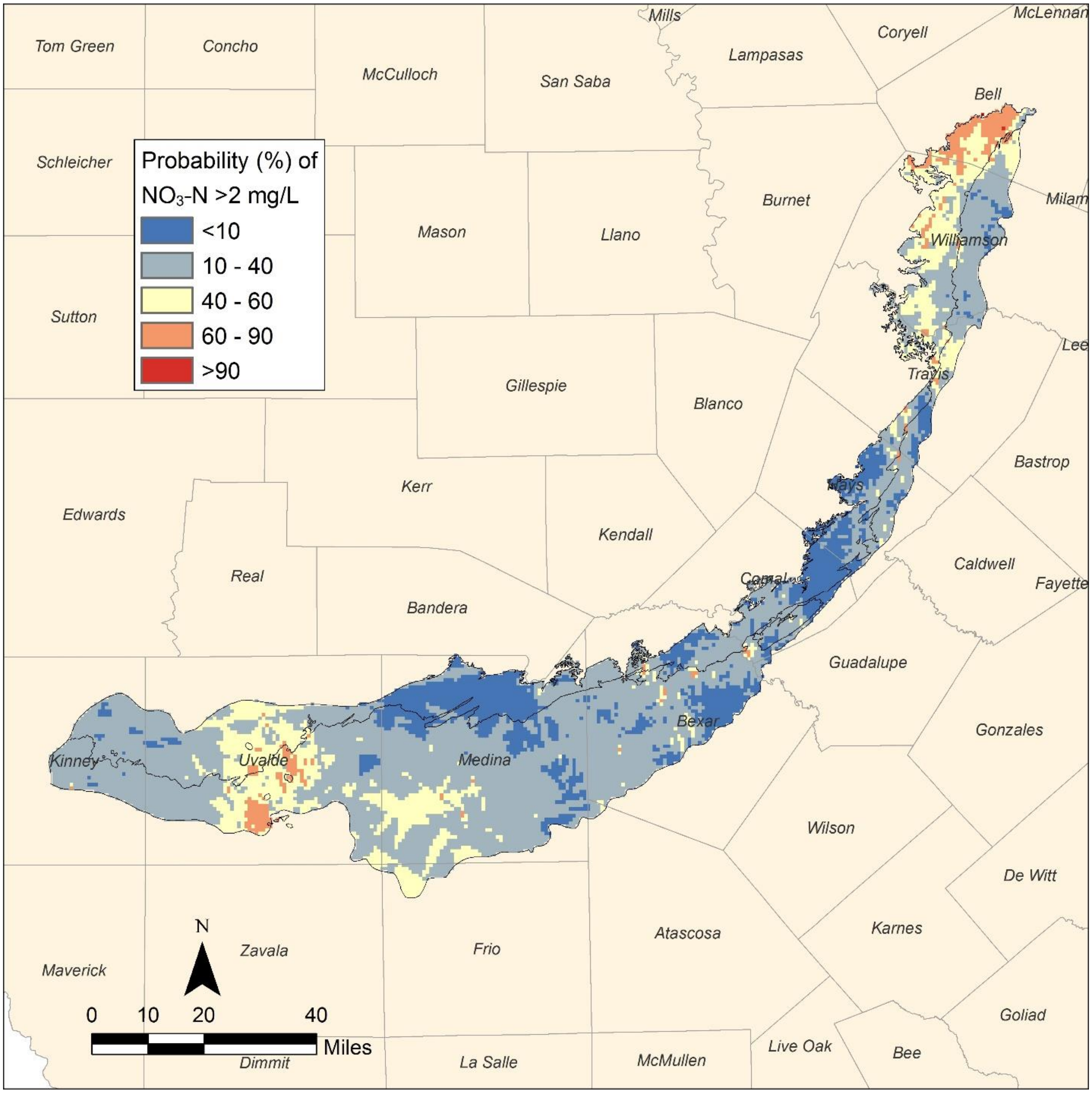

Figure 18b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Edwards aquifer based in indicator kriging using TWDB concentration data. Streaky appearance of probability values indicates areas of sparse data and may not be reliable.

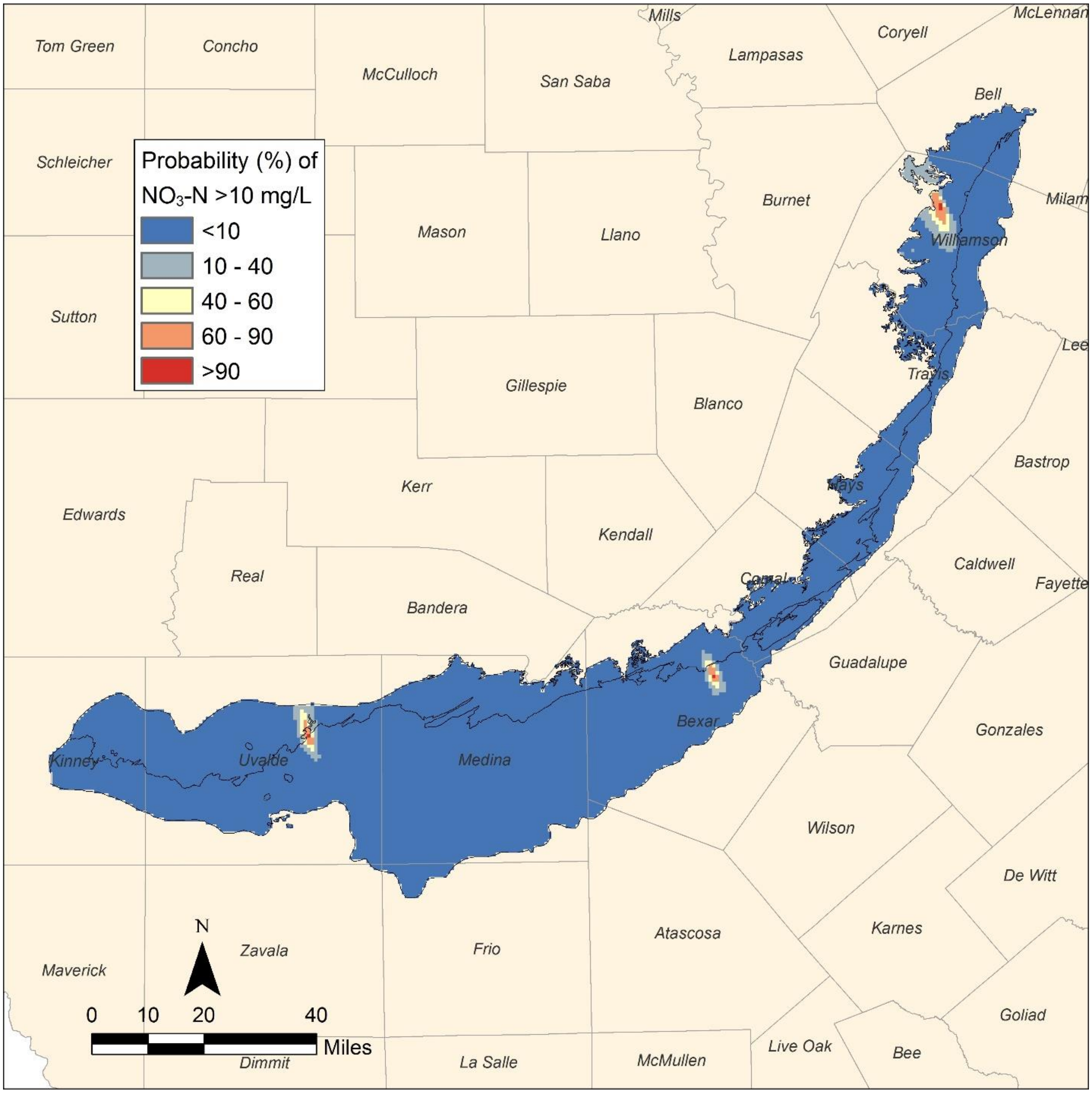

Figure 18c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Edwards aquifer based in indicator kriging using TWDB concentration data. Darker shaded area represents the aquifer outcrop and lighter shaded area represents the aquifer subcrop.

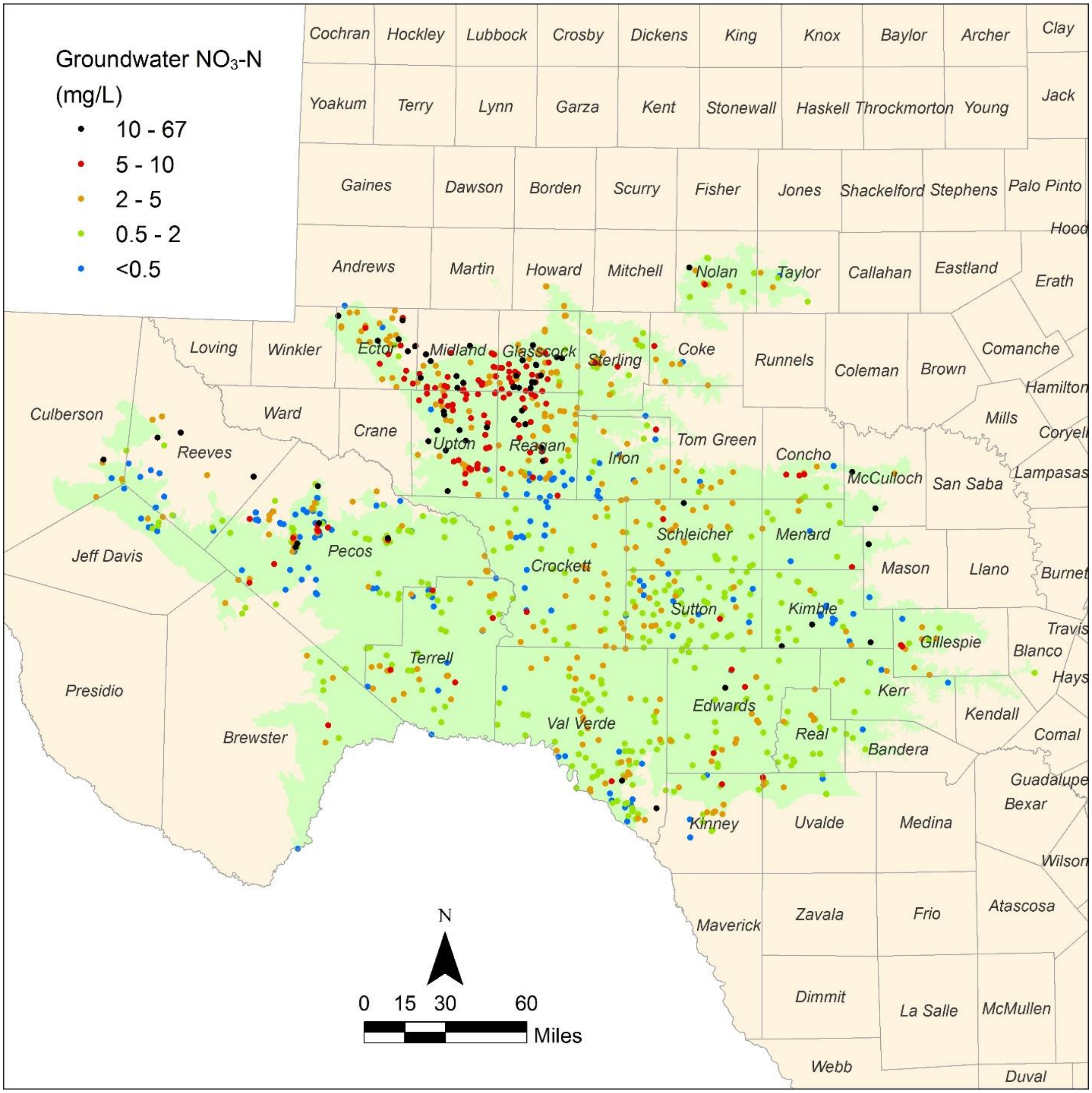

Figure 19a. Groundwater nitrate-N concentrations in the Edwards-Trinity Plateau aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

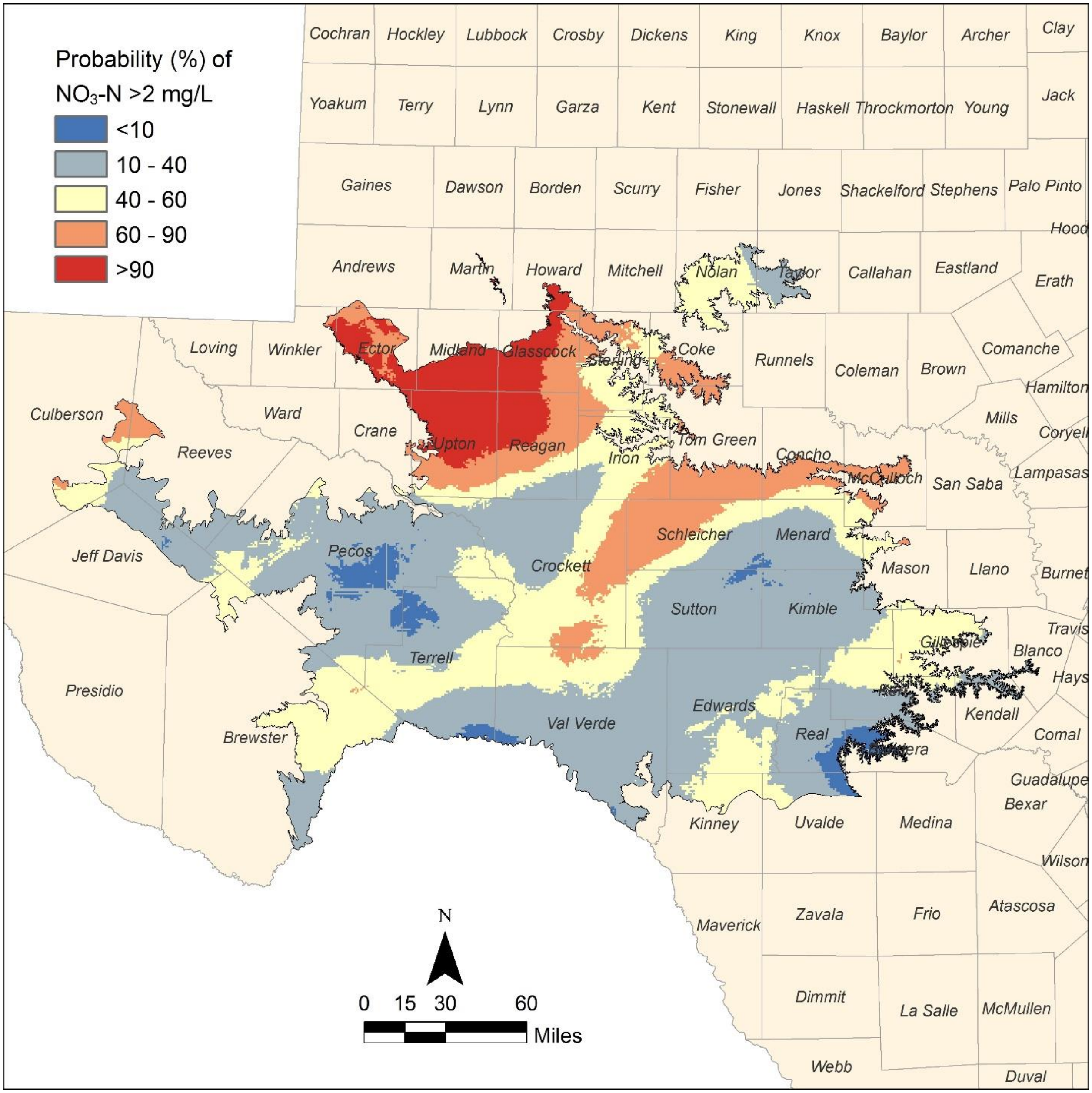

Figure 19b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Edwards-Trinity Plateau aquifer based in indicator kriging using TWDB concentration data. Streaky appearance of probability values indicates areas of sparse data and may not be reliable.

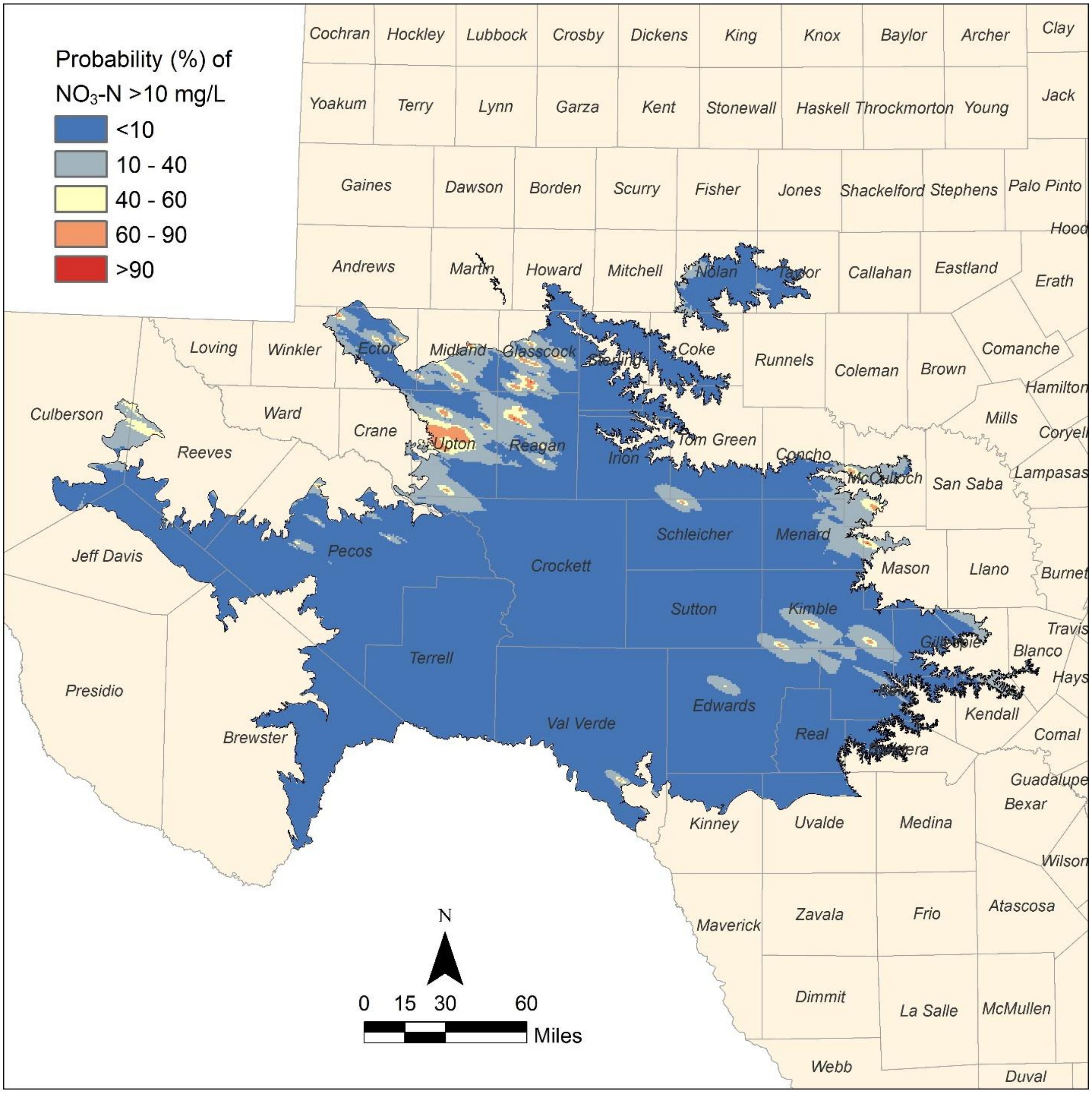

Figure 19c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Edwards-Trinity Plateau aquifer based in indicator kriging using TWDB concentration data.

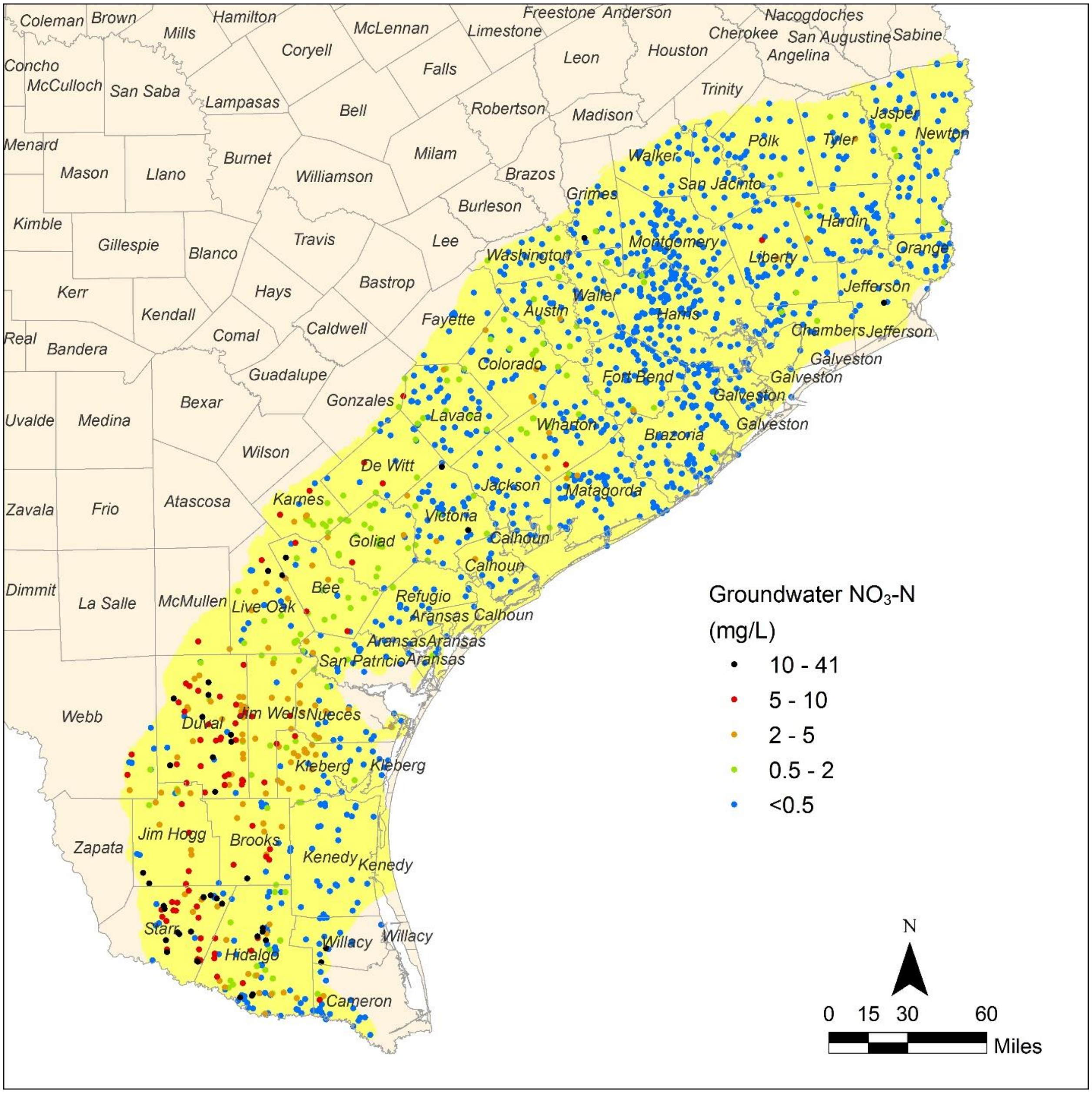

Figure 20a. Groundwater nitrate-N concentrations in the Gulf Coast aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

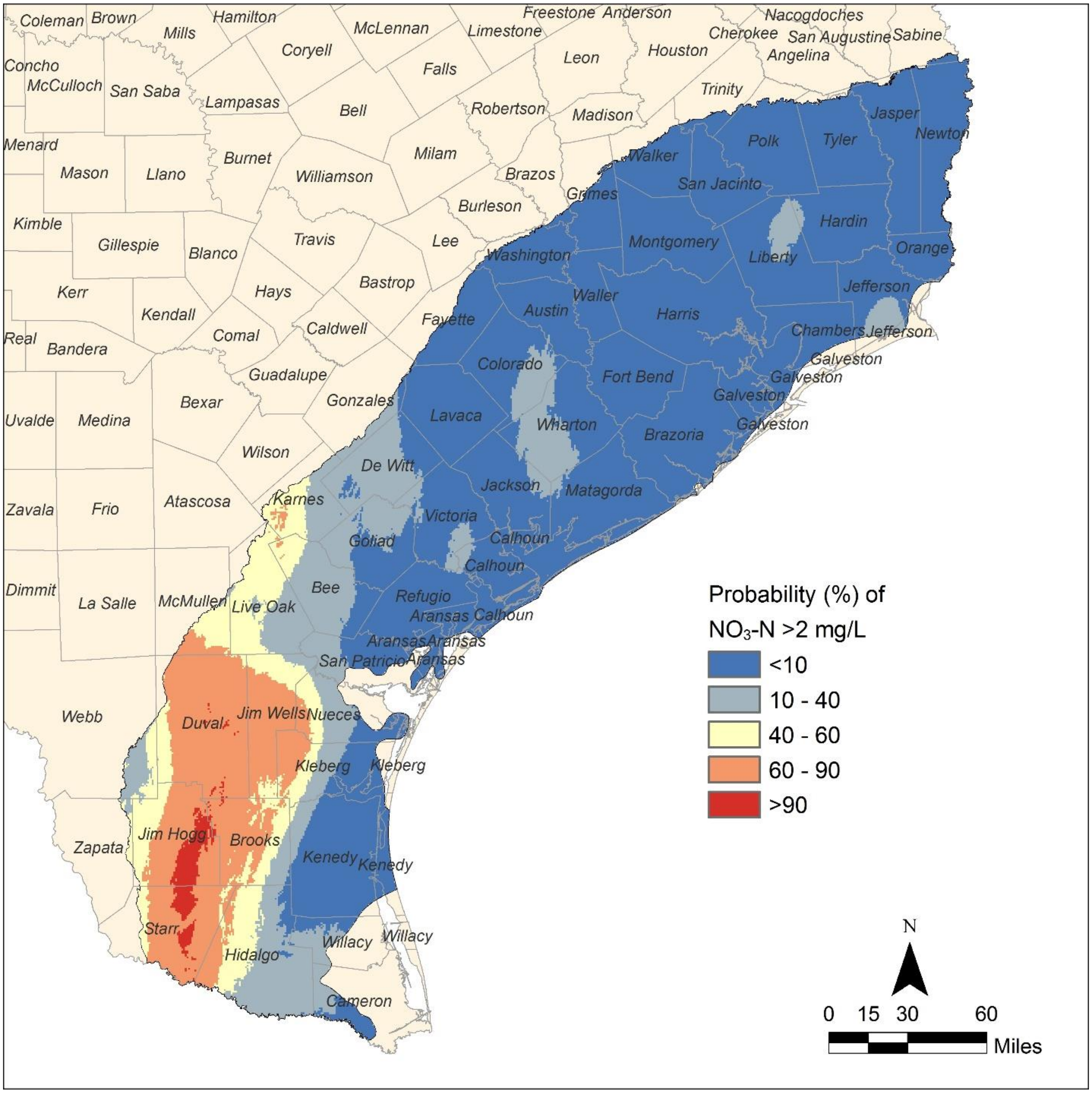

Figure 20b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Gulf Coast aquifer based in indicator kriging using TWDB concentration data.

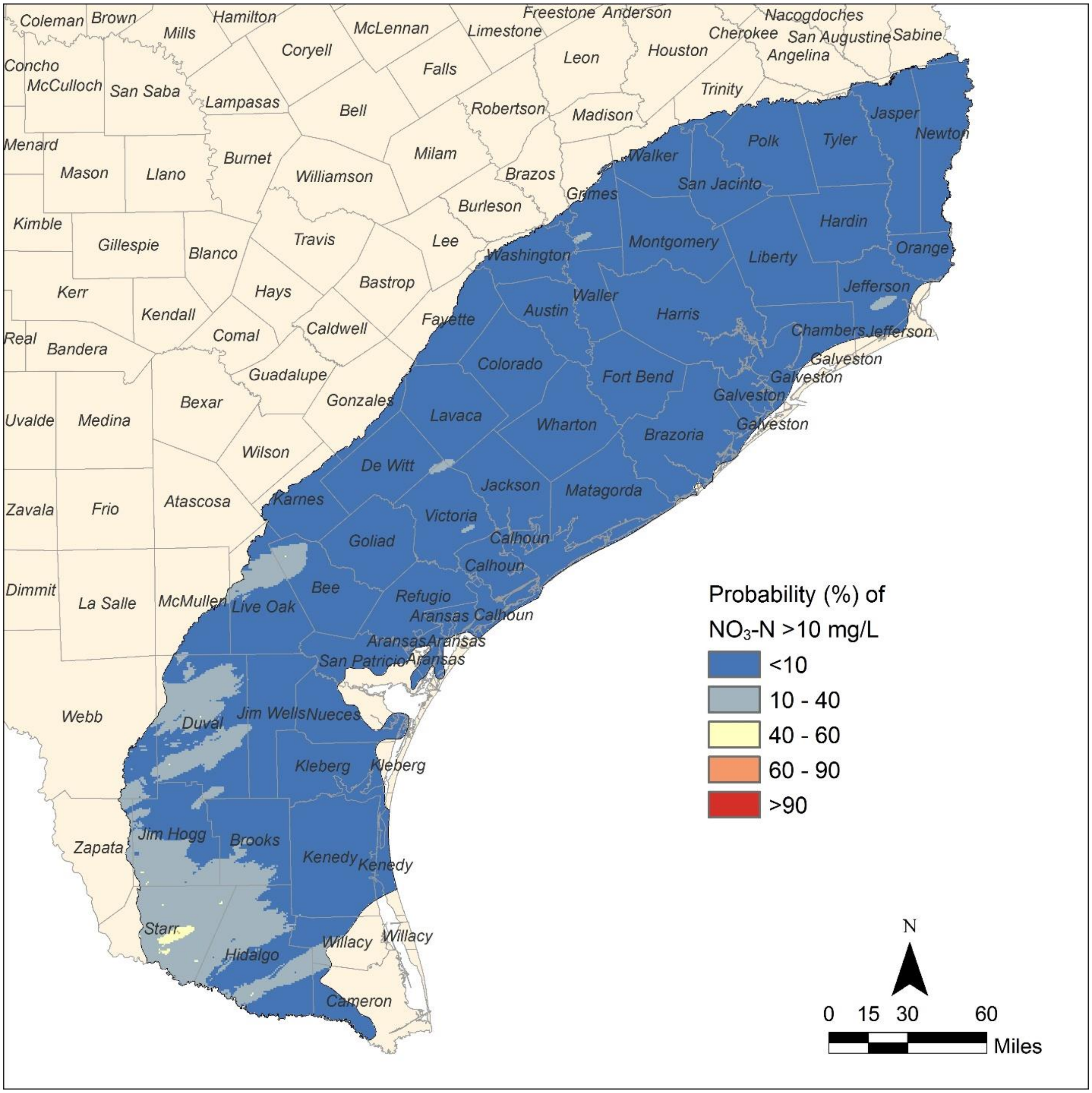

Figure 20c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Gulf Coast aquifer based in indicator kriging using TWDB concentration data.

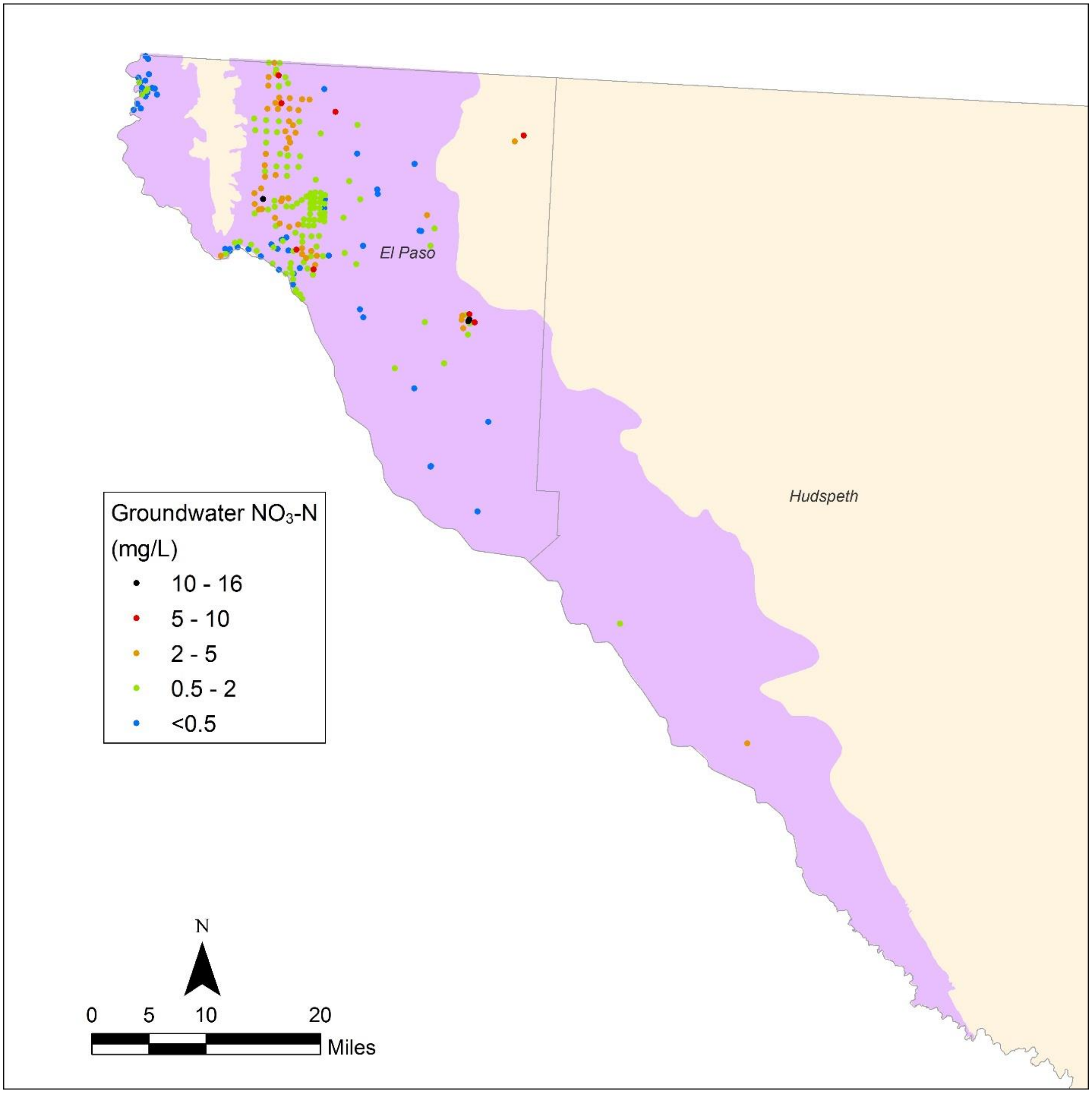

Figure 21a. Groundwater nitrate-N concentrations in the Hueco-Mesilla Bolson aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

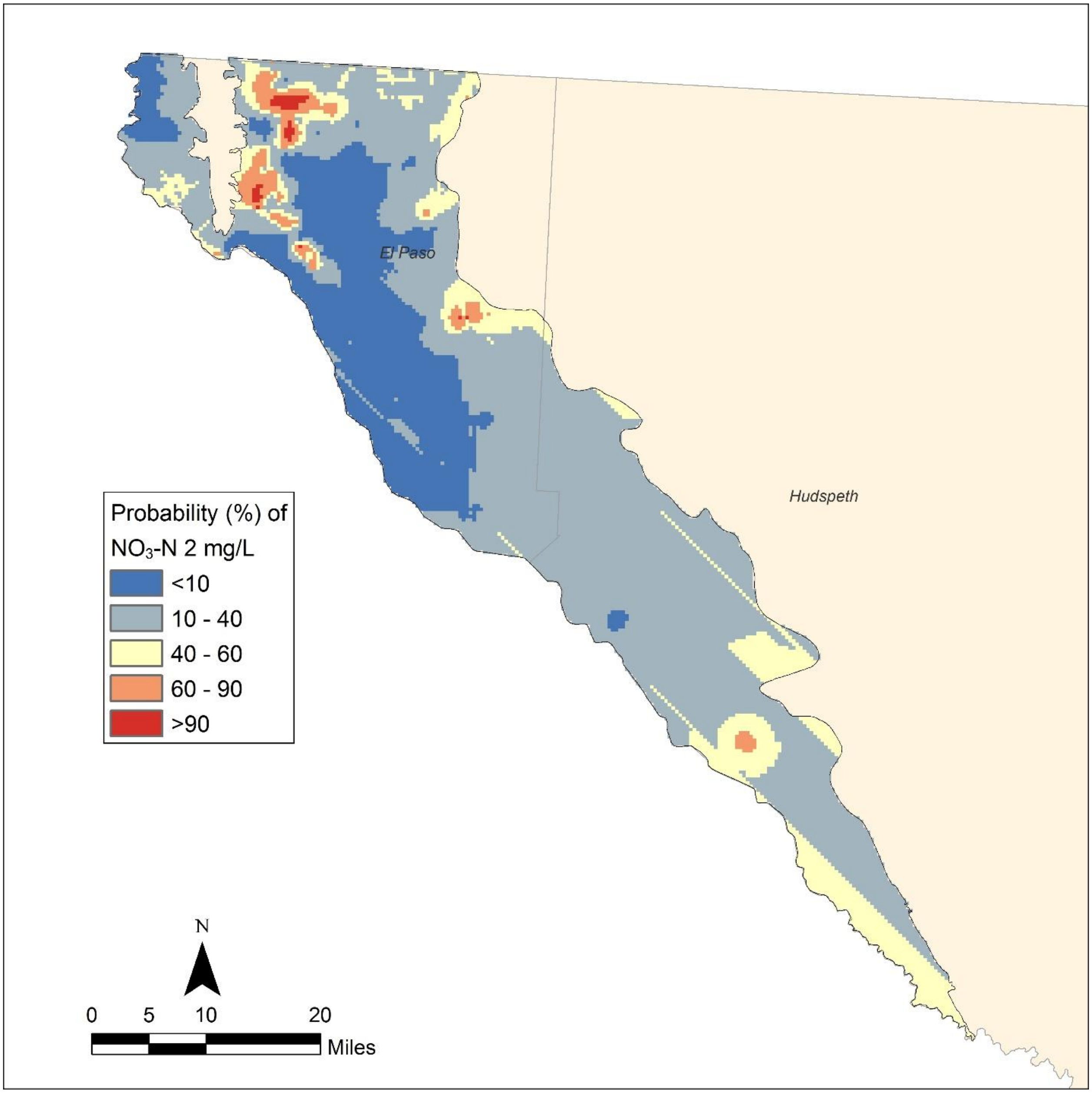

Figure 21b. Probability of groundwater nitrate-N exceeding 2 mg/L in Gulf Coast aquifer based in indicator kriging using TWDB concentration data. Streaky appearance of probability values indicates areas of sparse data and may not be reliable, particularly in Hudspeth County.

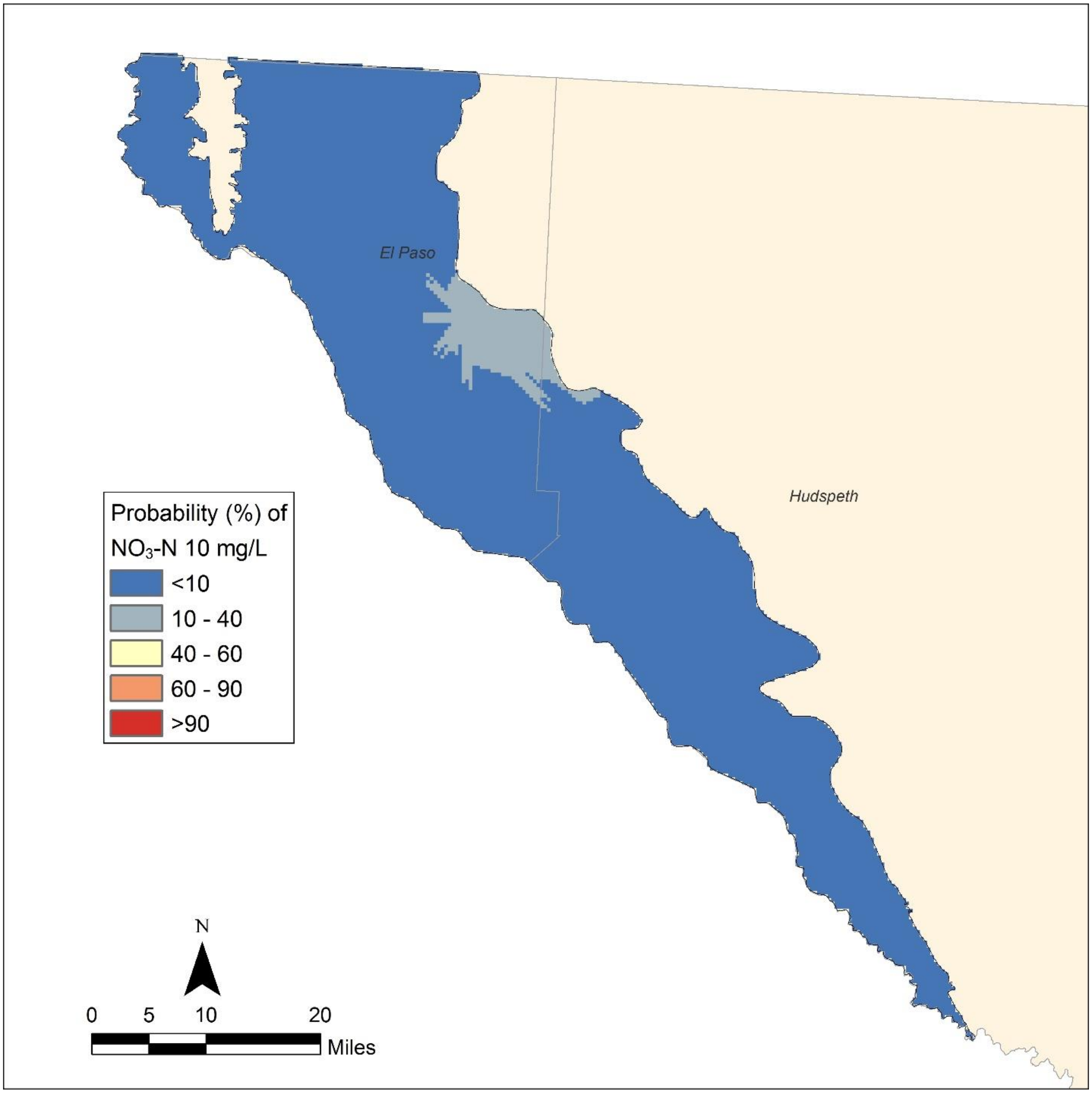

Figure 21c. Probability of groundwater nitrate-N exceeding 10 mg/L in Gulf Coast aquifer based in indicator kriging using TWDB concentration data.

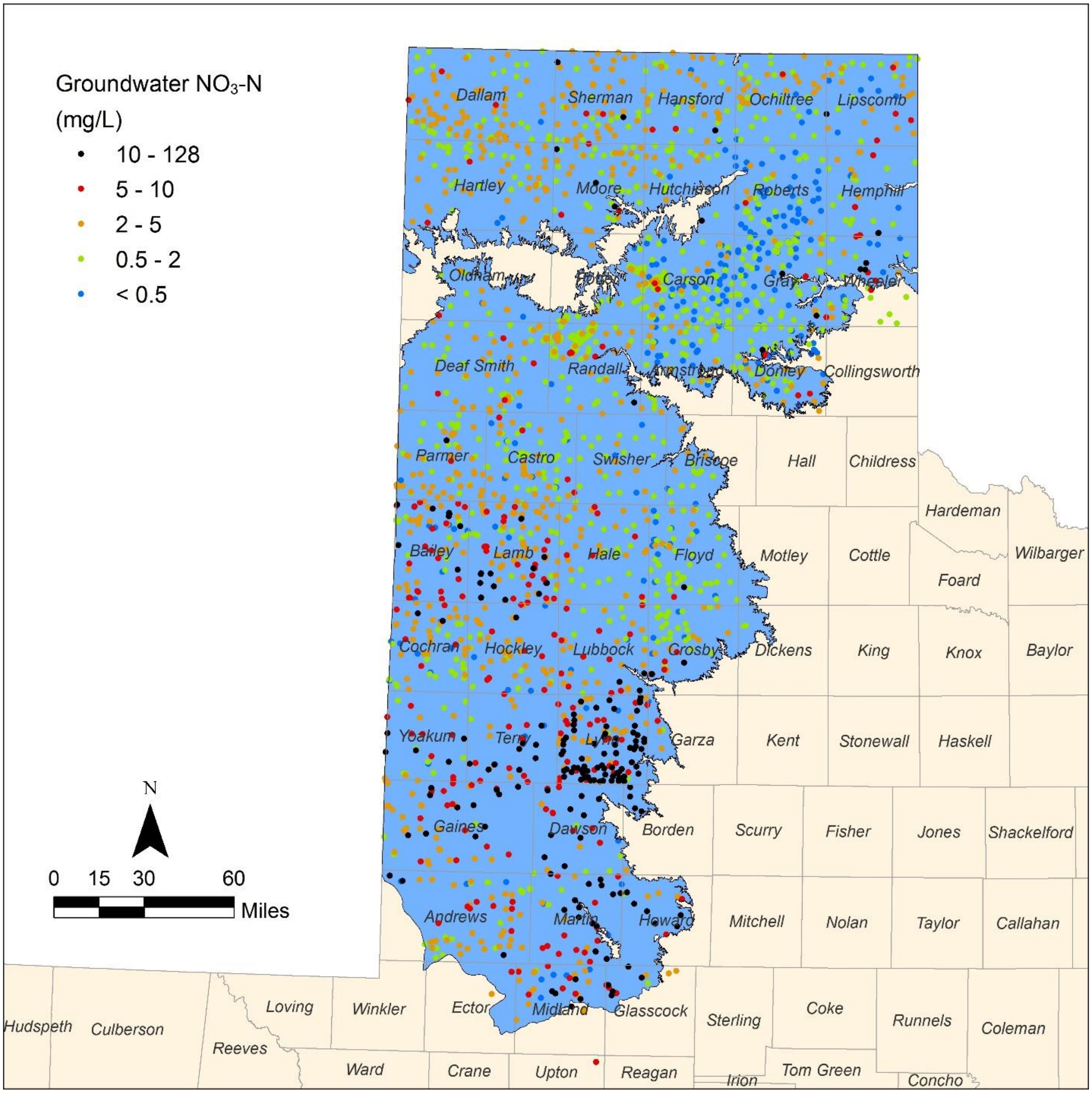

Figure 22a. Groundwater nitrate-N concentrations in the Ogallala aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

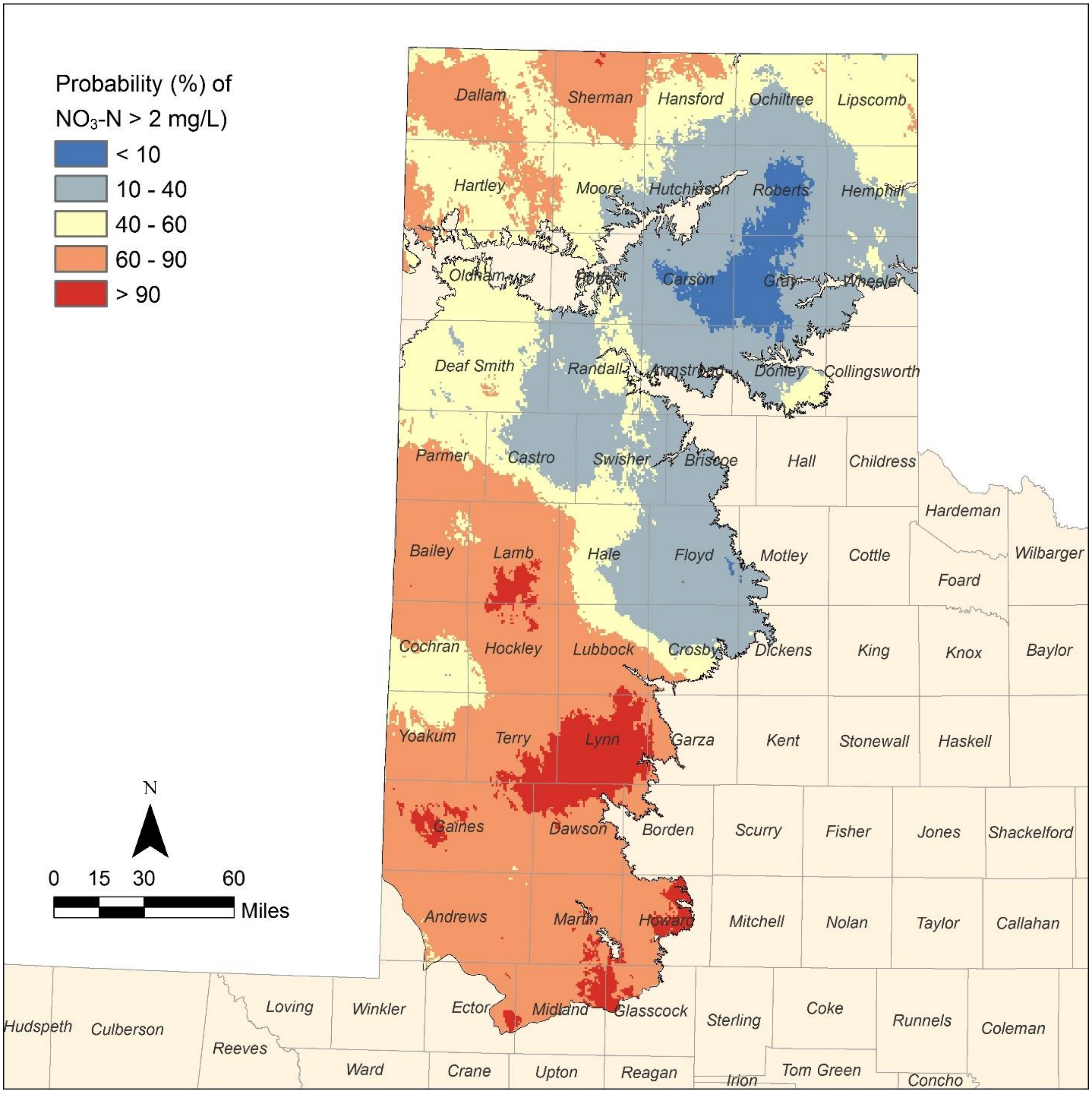

Figure 22b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Ogallala aquifer based in indicator kriging using TWDB concentration data.

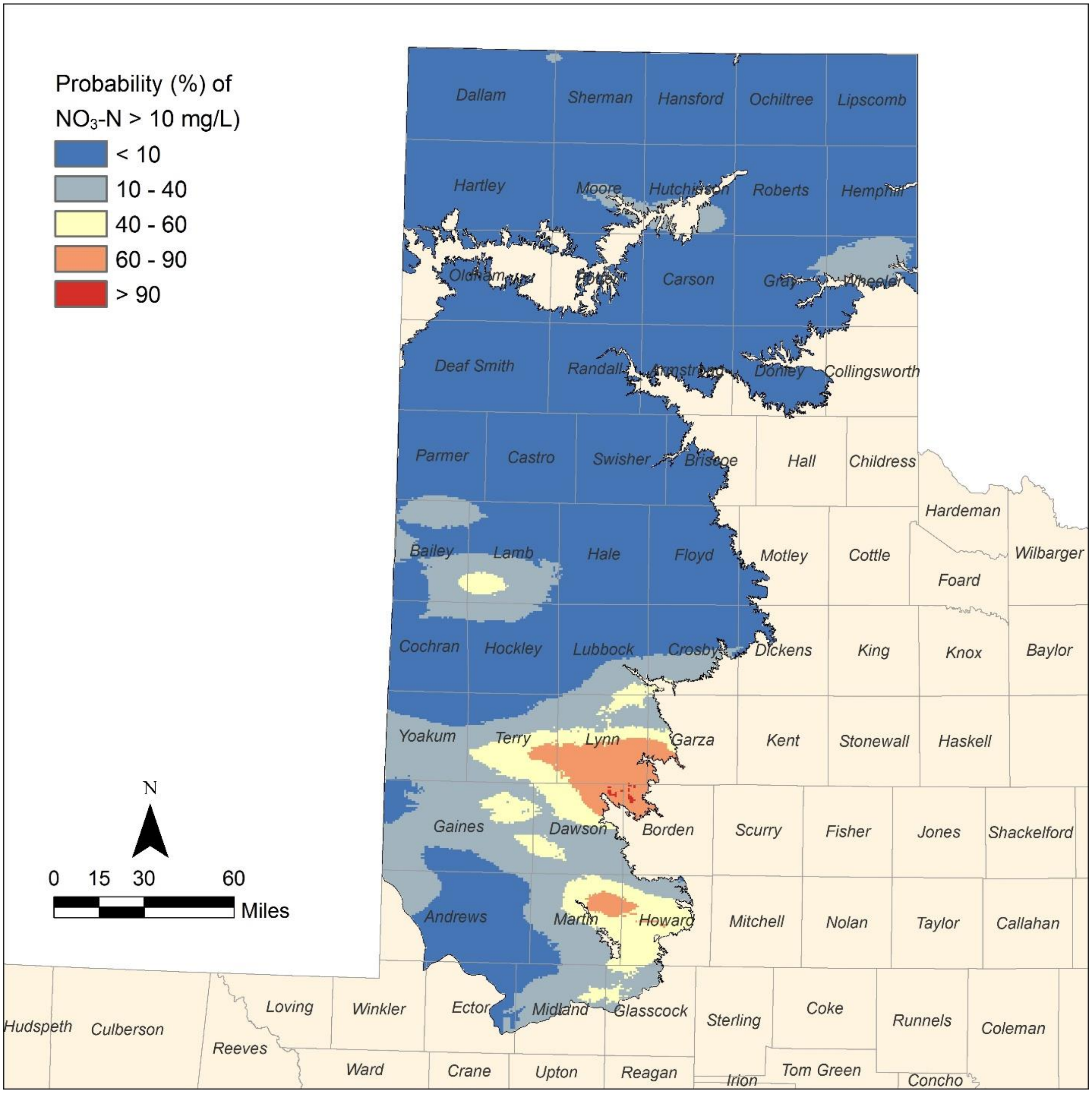

Figure 22c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Ogallala aquifer based in indicator kriging using TWDB concentration data.

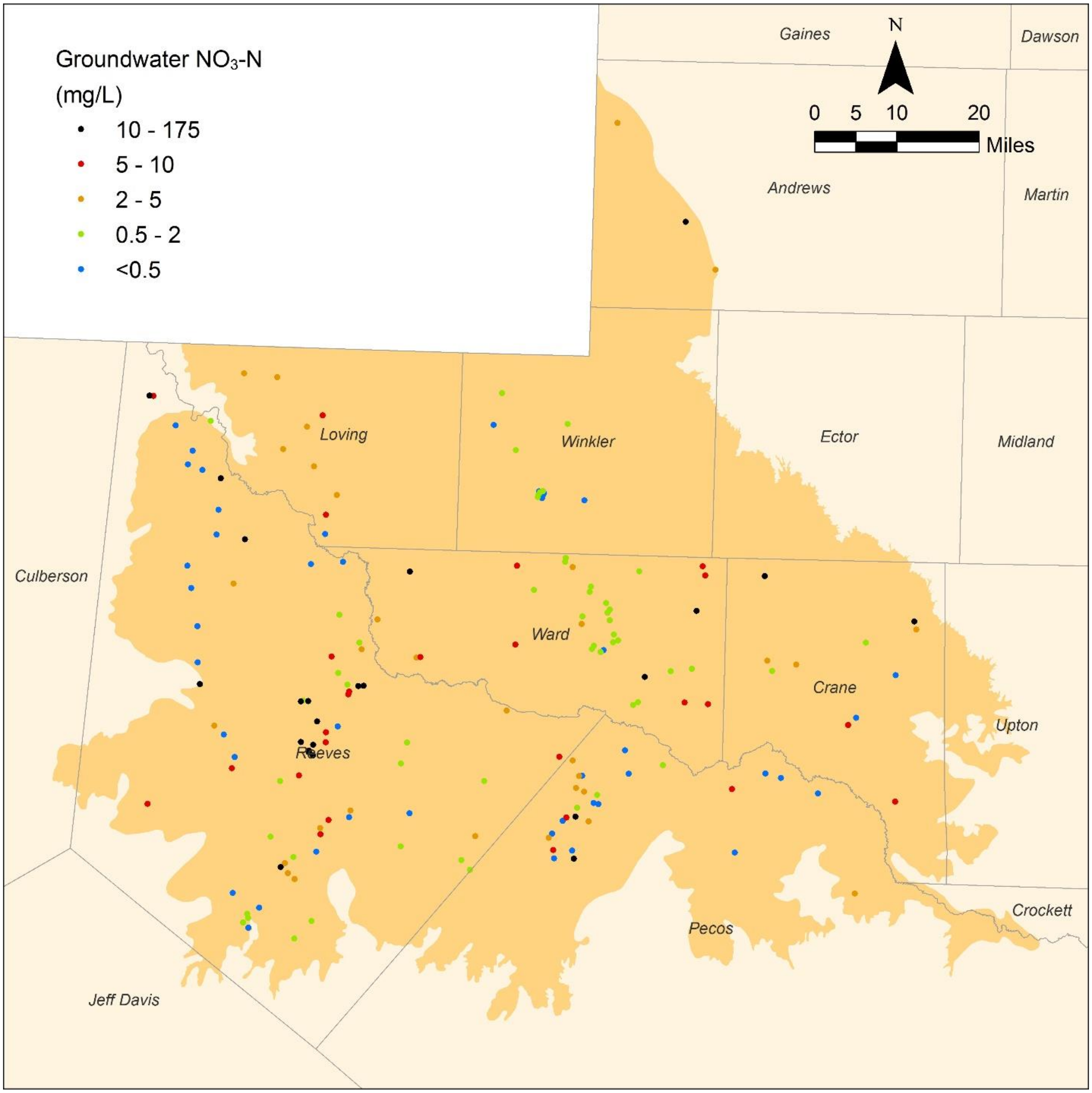

Figure 23a. Groundwater nitrate-N concentrations in the Pecos Valley Alluvium aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

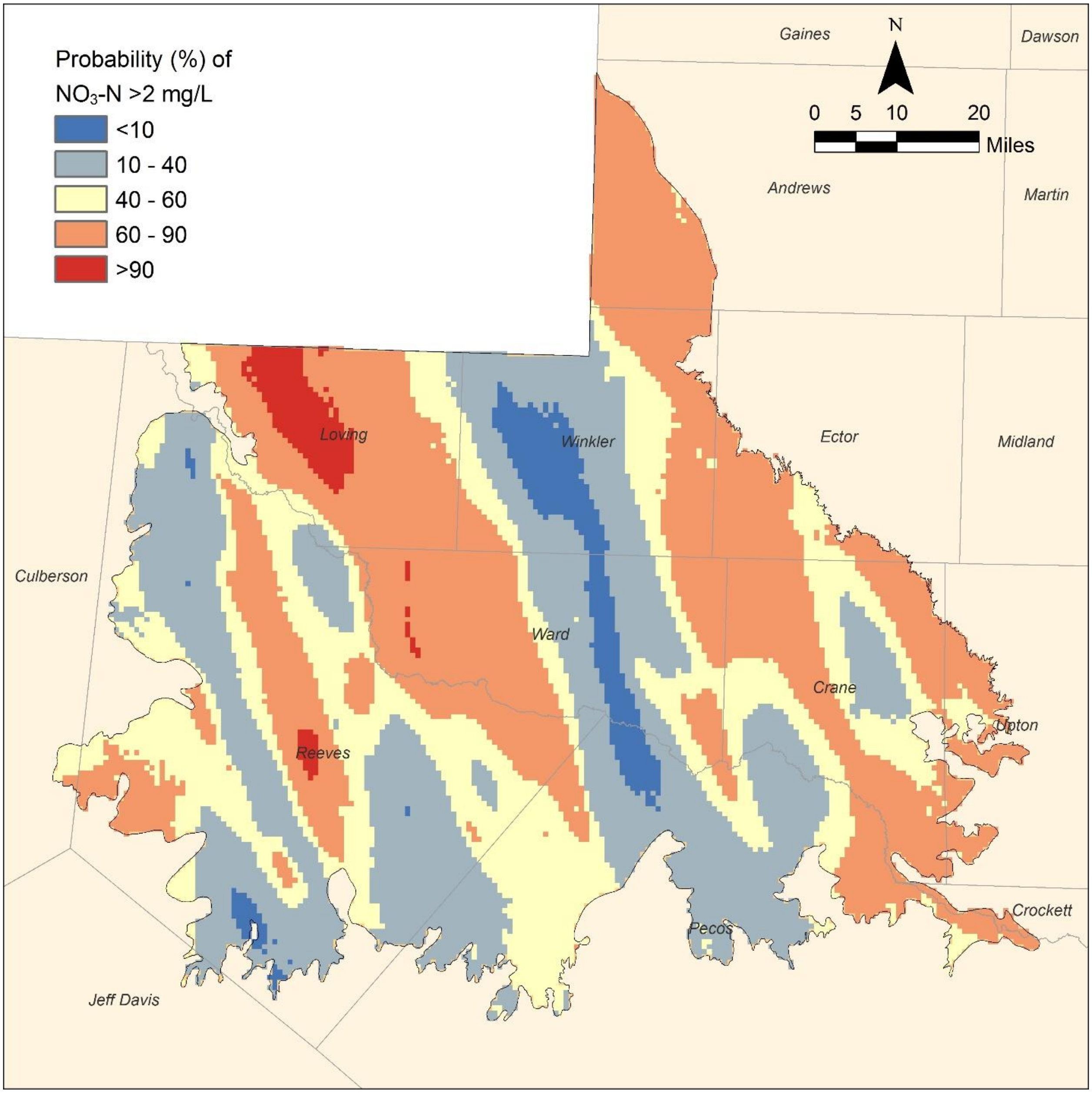

Figure 23b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Pecos Valley Alluvium aquifer based in indicator kriging using TWDB concentration data.

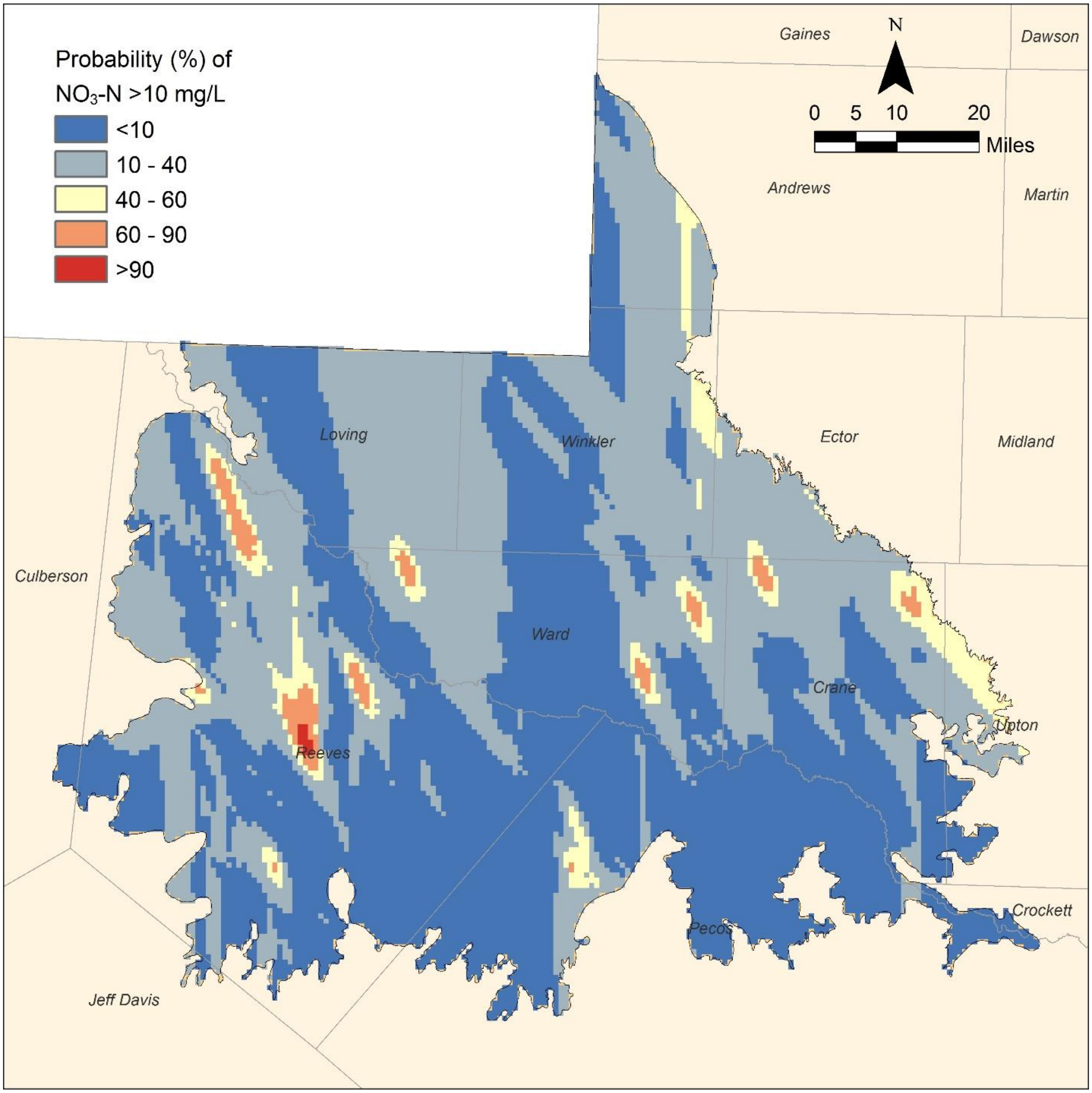

Figure 23c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Pecos Valley Alluvium aquifer based in indicator kriging using TWDB concentration data.

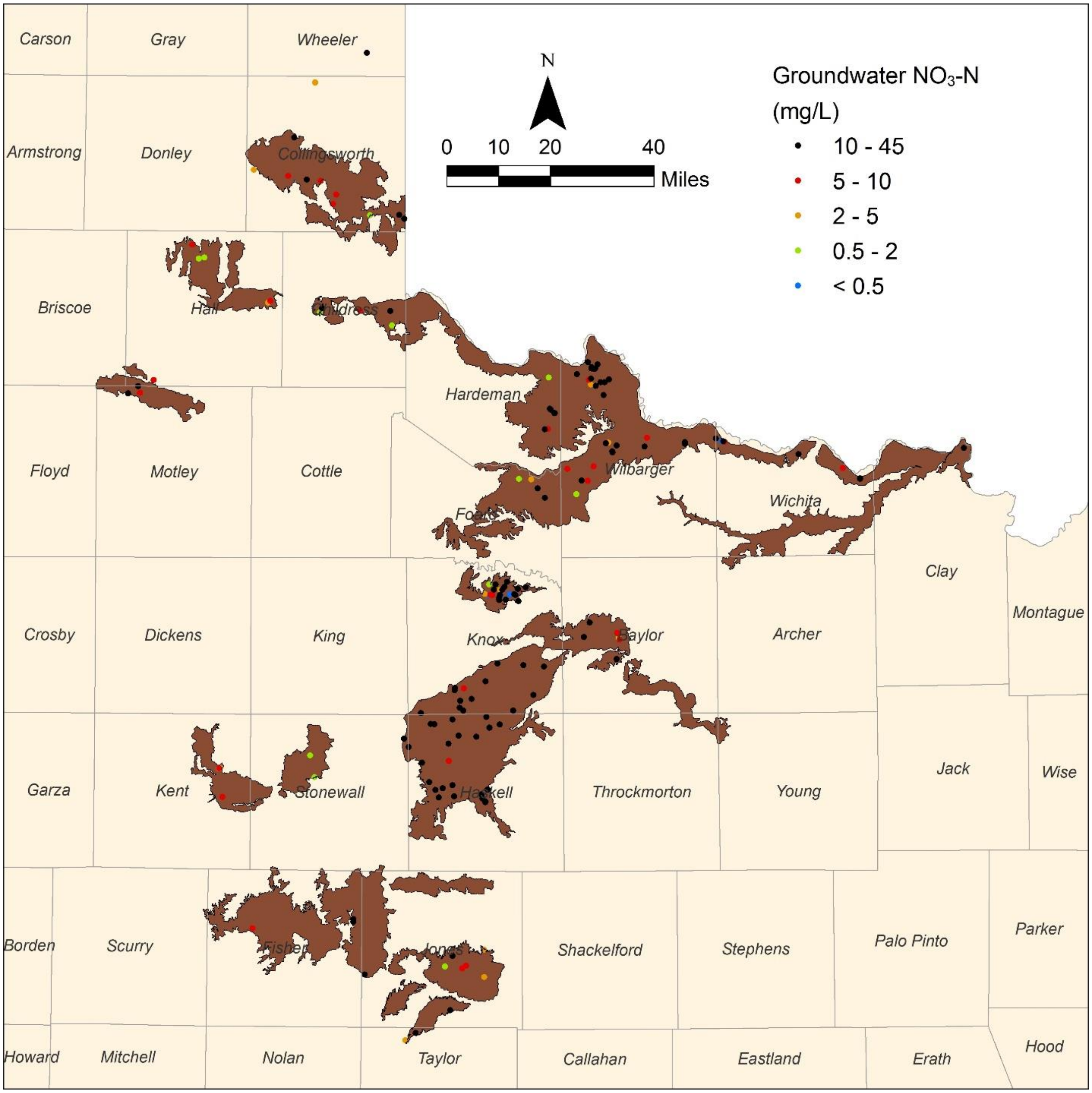

Figure 24a. Groundwater nitrate-N concentrations in the Seymour aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017.

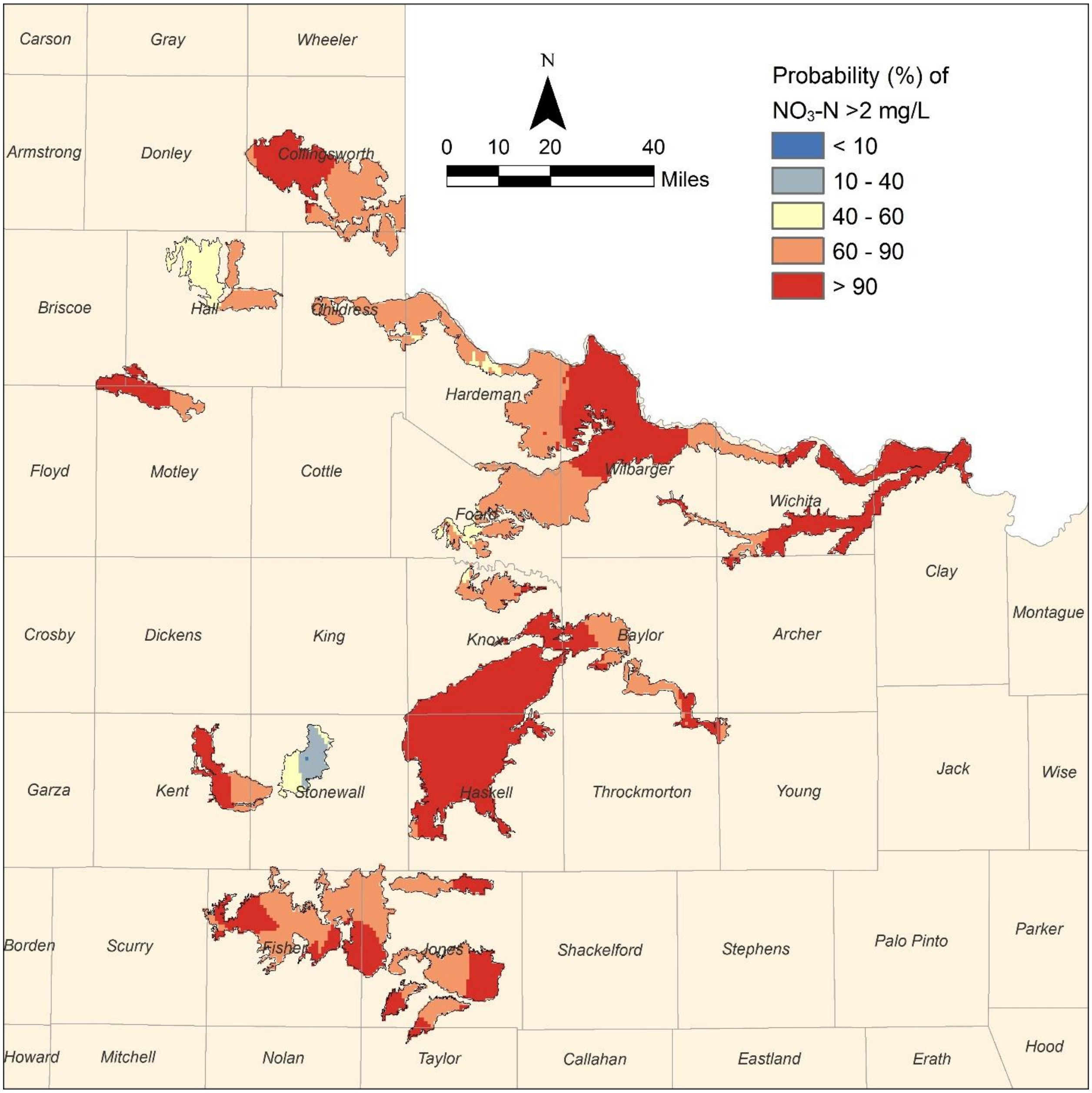

Figure 24b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Seymour aquifer based in indicator kriging using TWDB concentration data. Some areas of little to no data and the probabilities shown may not be accurate.

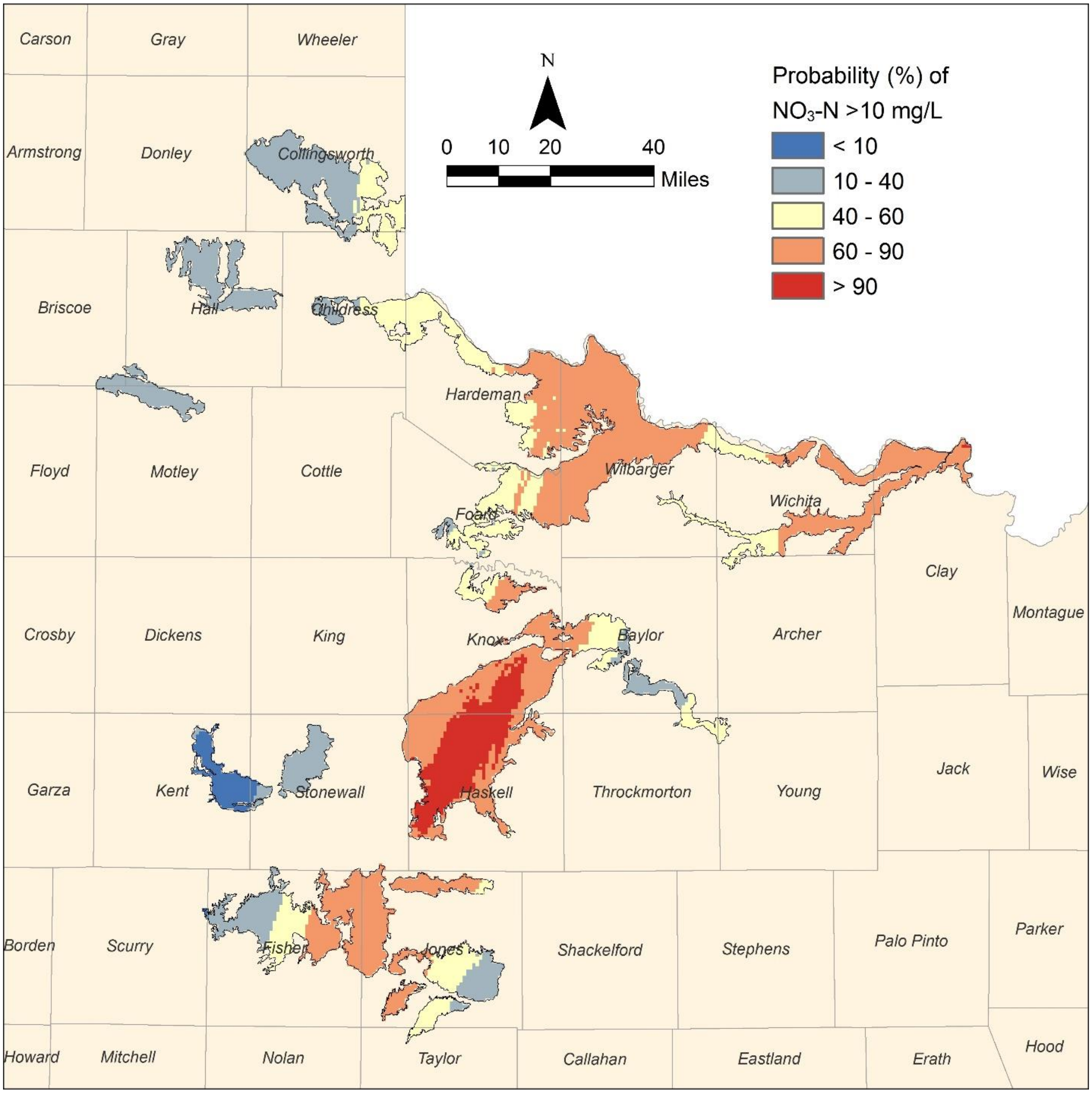

Figure 24c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Seymour aquifer based in indicator kriging using TWDB concentration data. Some areas of little to no data and the probabilities shown may not be accurate.

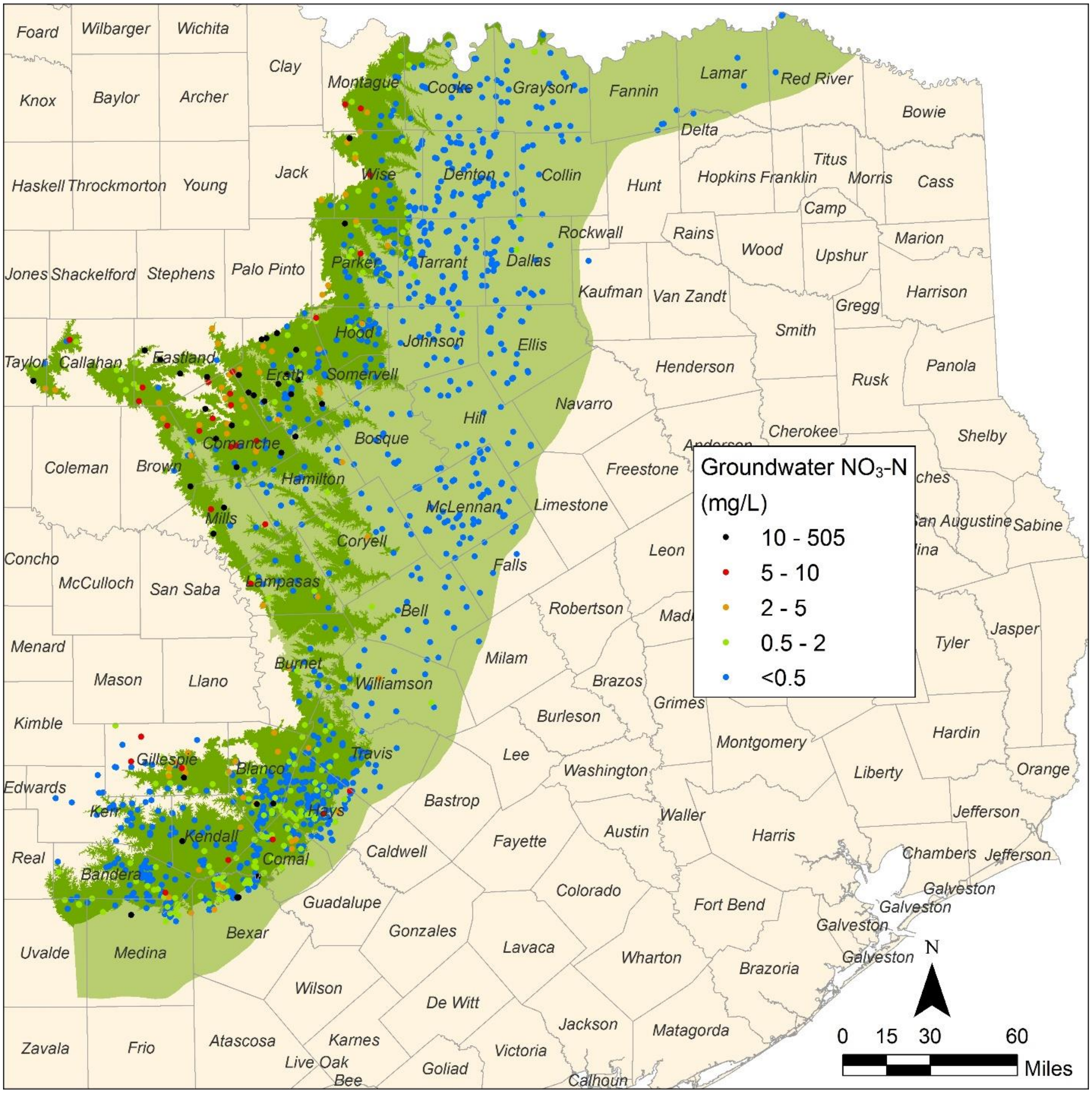

Figure 25a. Groundwater nitrate-N concentrations in the Trinity aquifer based on the TWDB groundwater database. Values represent the latest sample between 1992 and mid-2017. Darker shaded area represents the aquifer outcrop and lighter shaded area represents the aquifer subcrop.

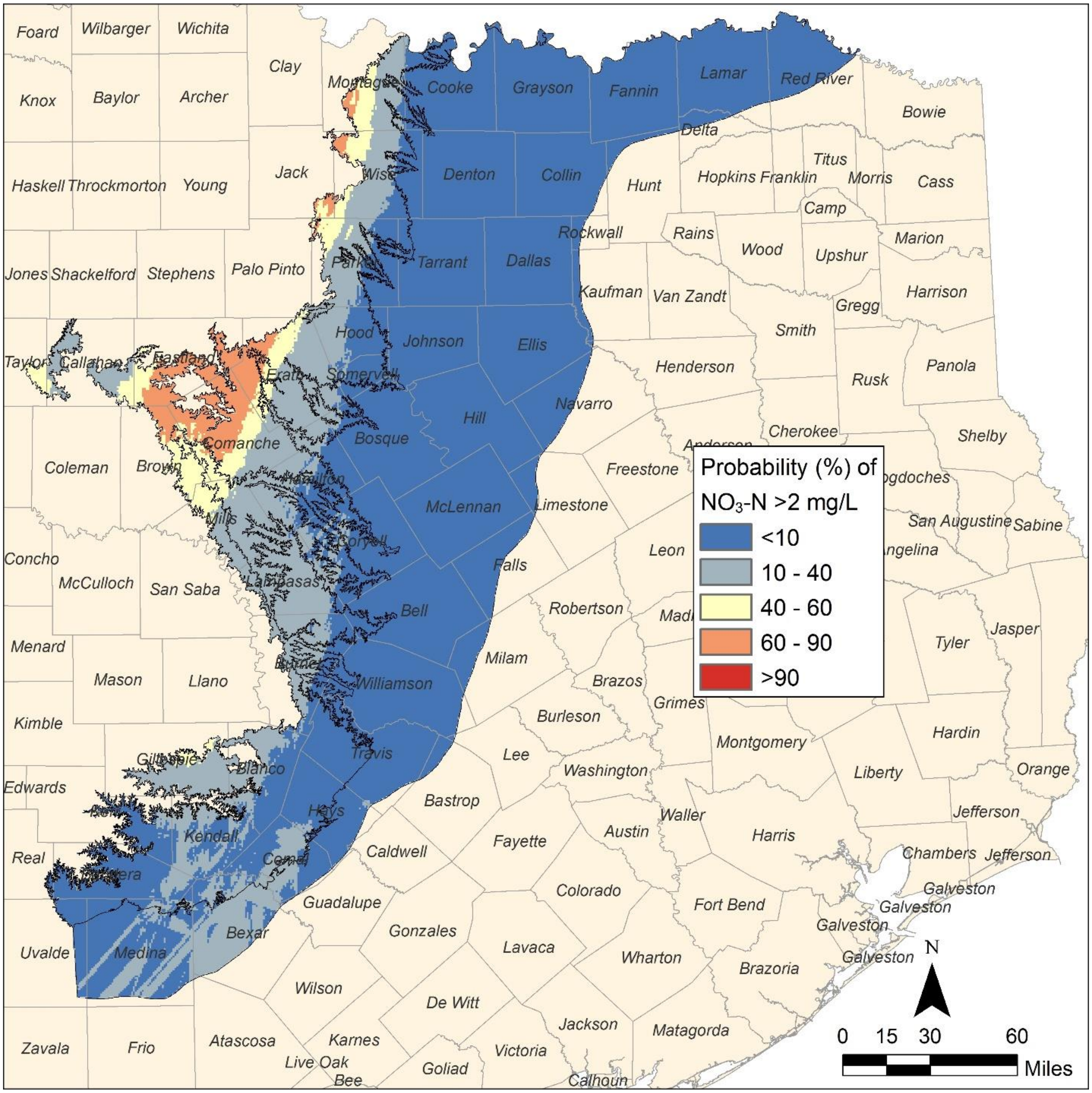

Figure 25b. Probability of groundwater nitrate-N exceeding 2 mg/L in the Seymour aquifer based in indicator kriging using TWDB concentration data. Streaky appearance of probability values indicates areas of sparse data and may not be reliable.

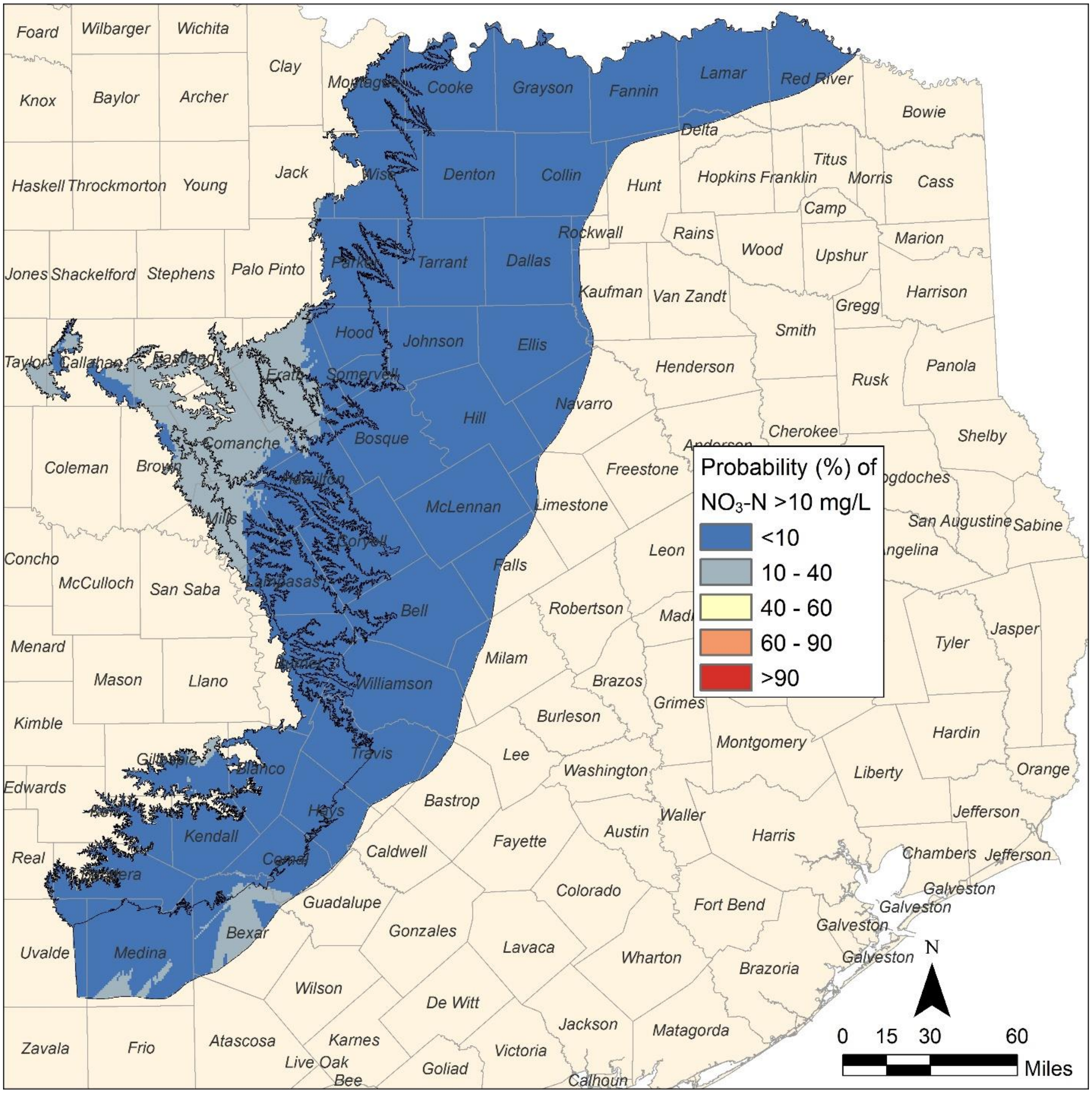

Figure 25c. Probability of groundwater nitrate-N exceeding 10 mg/L in the Seymour aquifer based in indicator kriging using TWDB concentration data. Streaky appearance of probability values indicates areas of sparse data and may not be reliable.