Trends in Nitrate Levels in Iowa's Community Water Systems (2000-2022): Characteristics of Systems Vulnerable to MCL Exceedances and Future Regulatory Scenarios

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Abstract
This study examines trends in nitrate contamination in Iowa's community water systems (CWS) from 2000 to 2022, focusing on the characteristics of CWS that are most vulnerable to elevated nitrate levels and those likely to be impacted by a lower maximum contaminant level (MCL). Using Safe Drinking Water Act (SDWA) compliance data for CWSs currently without nitrate removal, we analyzed nitrate levels across CWS types, source water type, well characteristics, and geography. Results show that large urban CWS frequently exceed 5 mg-N/L due to their reliance on surface water that is vulnerable to non-point source pollution. Small systems (<10,000 consumers) often exhibit episodic spikes in nitrate, often during spring and early summer, coinciding with fertilizer use and rainfall-driven leaching. Shallow and pre-1990 wells were disproportionately affected. Geospatial mapping analysis identified nitrate hotspots in agriculturally intensive regions. A future MCL based on an annual average of 5 mg/L-N would only affect ~25 CWS annually, far fewer than those impacted under a scenario where any instance above 5 mg/L-N would be a violation. These data-driven findings support future policy for nitrate regulation and drinking water protection.

Keywords:
Nitrate contamination, drinking water quality, spatial analysis, seasonal trends, nitrate regulation, maximum contaminant level (MCL), public health risk, water infrastructure

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1. Introduction

Human activities, such as the use of commercial fertilizers, the application of manure, and sewage treatment, can pollute drinking water sources with nitrate (Craswell, 2021; Ward et al., 2018). Nitrate contamination in drinking water is increasingly recognized as a significant environmental and public health issue globally (Abascal et al., 2022; Ward et al., 2018; Shrestha et al., 2025). This pollutant readily infiltrates soils, contaminating both ground water and surface water sources (Khan et al., 2018). The primary anthropogenic sources of nitrate include nitrogen-based fertilizers, animal manure, wastewater treatment plant discharges, septic systems, and industrial emissions (Moloantoa et al., 2022; Yu et al., 2019). Once introduced, nitrate can enter ground water through leaching or reach surface waters via runoff, ultimately affecting drinking water supplies and posing health risks to humans and animals (Chen et al., 2016; WHO, 2016). Multiple studies have reported widespread nitrate pollution in the United States, especially in shallow or unconfined aquifers beneath agricultural regions with intensive fertilizer use and well-drained soils (Burkart & Stoner, 2002; Burow et al., 2010; Hubbard & Sheridan, 2020).

The health implications of high nitrate levels in drinking water are well-documented. One of the most severe health risks is methemoglobinemia, or "blue baby syndrome," a condition that reduces the blood's ability to carry oxygen, leading to serious illness and potentially fatal outcomes in infants (Johnson, 2019; Knobeloch et al., 2000; Ward et al., 2005). Pregnant women are also at higher risk, as nitrate can interfere with the oxygen-carrying capacity of their blood, impacting fetal development (Manassaram et al., 2010). Moreover, there is growing evidence that chronic exposure to high nitrate levels may be linked to various cancers, including stomach, esophageal, colorectal, and bladder cancers, as well as thyroid dysfunction and other metabolic disorders (Garcia 2022; Ward et al., 2010). The toxicological mechanisms underlying these health effects are still being studied, but they are believed to involve the conversion of nitrate to nitrite, which is subsequently converted to N-nitroso compounds, potent carcinogens (Seyyedsalehi et al., 2023; Swann, 1975; van Breda et al., 2019).

Iowa, one of the leading agricultural states in the United States, faces a particularly high risk of nitrate contamination in its public water systems due to its extensive agricultural activities (Pollans, 2016; Weigel, 2024; Cikmaz et al., 2025). This risk is heightened because the state's economy is heavily reliant on agriculture, with vast areas of land dedicated to crops such as corn and soybeans that require substantial nitrogen fertilization to achieve high yields (ITS, 2020; Jarchow et al., 2012; Tanir et al., 2024). Additionally, the use of synthetic nitrogen fertilizers, while boosting crop productivity, also increases the potential for nitrate runoff (Craswell, 2021; Liu et al., 2021). During precipitation events, nitrate can leach from the soil into groundwater or be carried by surface runoff into rivers, lakes, and reservoirs, which are often sources of drinking water. Compounding these pathways, the hydrological characteristics of Iowa, including its permeable soils and widespread drainage systems (Craswell 2021; Keeney & Olson, 1986; Weber et al., 2018), further facilitate the movement of nitrate into water bodies during rainfall and flood events, exacerbating the problem (Roth, 2010). Consequently, improving public awareness and promptly disseminating clear, accessible information on nitrate levels and associated health risks—

especially to vulnerable populations, can reduce exposure and strengthen community support for mitigation measures (Demir et al., 2009; Vald et al., 2024; Samuel et al., 2024).

Although the Safe Drinking Water Act (SDWA) has implemented regulatory mechanisms to monitor and manage nitrate levels in public water sources, nitrate pollution remains an ongoing problem in Iowa (Jones et al., 2018; Wheeler et al., 2015). The US Environmental Protection Agency (EPA) has established a maximum contamination limit (MCL) for nitrate in drinking water at 10 milligrams per liter (mg/L) as nitrogen (Dieter et al., 2018; Dubrovsky et al., 2010). This threshold has been specifically developed to safeguard human health against acute health effects, including methemoglobinemia. Nevertheless, a significant number of public water systems in Iowa have reported nitrate levels that are nearing or over this threshold (Jones et al., 2020; Wheeler, 2015). This has raised concerns among public health experts, lawmakers, and the general population, primarily because the US EPA has acknowledged the need for, but has yet to complete, a revised health assessment for nitrate that considers new data on carcinogenicity and development effects in their 2nd Six Year Review of Drinking Water Standards in 2010 (Office of the Federal Register, 2010).

This research article provides a comprehensive examination of nitrate levels in the finished water provided by community water systems (CWS) in Iowa from 2000 to 2022. The study aims to identify the types of CWS in Iowa that are most often susceptible to elevated nitrate concentrations. We also conducted an extensive temporal analysis to identify periods characterized by elevated nitrate levels, which may align with distinct agricultural cycles, such as planting and fertilizing seasons, or climatic occurrences, such as intense rainfall and flooding. Moreover, we investigated the spatial distribution of nitrate contamination throughout Iowa's CWS, identifying areas with consistently high concentrations, often referred to as "hot spots," by mapping nitrate levels geographically. The primary goal of this work was to use this spatial and temporal analysis to assess the vulnerabilities of different CWS based on their size and water source, while also considering those CWS most likely to be impacted by future regulatory scenarios that may result in a stricter MCL for nitrate (e.g., 5 mg/L as N). These results could support information and data visualization systems for public awareness and decision-making (Demir and Beck, 2009; Mount et al., 2024).

2. Methodology

2.1. Data Acquisition

This study utilized data on nitrate concentrations in finished drinking water collected from public water systems (PWSs) across Iowa between 2000 and 2022 for SDWA reporting. The dataset, sourced from the Iowa Department of Natural Resources (IDNR), includes a total of 1,838 PWS, with 1,034 nitrate measurements from active Community Water Systems (CWSs). Initially, the data were georeferenced using GPS coordinates and geocoded addresses to ensure spatial accuracy. Only active CWSs were considered in this analysis. Furthermore, because we were using reported nitrate concentrations in finished drinking water as a proxy for spatial and temporal trends in source water contamination by nitrate, we excluded 64 CWS, including the Des Moines Water

Works, known to employ nitrate mitigation strategies (e.g., ion exchange, reverse osmosis) during treatment to lower nitrate concentrations.

First, the PWS dataset was filtered to focus on CWS among the three types of PWS including Non-Transient Non-Community Water System (NTNCWS) and Non-Transient Non-Community Water System (NTNCWS). The dataset was further refined by categorizing CWSs based on the population served, dividing them into three size categories: small systems (with ≤10,000 residents), medium systems (with 10,000–100,000 residents), and large systems (with>100,000 residents). Additionally, since the type of water source can influence nitrate levels, CWSs were classified as either ground water (GW) or surface water (SW) systems. Systems classified as ground water under the Direct Influence of Surface Water were excluded from our analysis. Although they have a unique profile due to their surface water-like characteristics, our intent was to use readily available finished drinking water data from CWS without nitrate removal to evaluate trends in surface water and ground water resources in Iowa and implications for community water supplies. For CWSs relying on GW, information on well depths and well age was incorporated from well forecasting system (Sit et al., 2021) to assess whether aquifer depth and well construction influence nitrate vulnerability.

2.2. Statistical Analysis

A multi-faceted analytical approach was employed to examine nitrate contamination trends, incorporating statistical analysis, spatio-temporal analysis, geographic susceptibility assessment, and data visualization techniques. Descriptive statistics were calculated independently for ground water and surface water systems to analyze the variability in nitrate concentration, including the mean, median, standard deviation, and range. Given the significant differences between various sources, additional statistical studies were performed to identify critical parameters. Nitrate concentrations were correlated with well depth, the population served, and the type of water supply. This investigation determined whether shallower wells or smaller PWSs were more nitrate-prone. Moving averages and seasonal decomposition (STL analysis) were used to find temporal trends in nitrate concentrations. The investigation examined seasonal variability, focusing on periods of high agricultural activity when fertilizer application and runoff may peak nitrate levels in the water. This method revealed changes in yearly and seasonal nitrate contamination across system types.

2.3. Spatio-temporal Analysis

A GIS-based spatio-temporal analysis was employed to visualize and evaluate Iowa's nitrate pollution levels, taking into account regional differences. To comply with regulatory criteria, nitrate concentrations were divided into four classes based on natural break thresholds: low (<1.58 mg/L), moderate (1.58–5 mg/L), high (5–10 mg/L), and extreme (>10 mg/L). Natural break classification was used. However, the "extreme" class was added to illustrate nitrate concentrations exceeding 10 mg/L. Classifying contamination patterns and high-risk locations was helpful. GW and SW annual mean nitrate concentrations from 2000 to 2022 were displayed separately to assess long-term trends. Monthly nitrate values were aggregated to detect peak pollution periods, especially during the agricultural planting season. The results examined how precipitation, runoff, and land-use patterns affect nitrate levels in different regions.

2.4. Geographic Susceptibility and Hotspot Identification

An ArcGIS Pro heat map hotspot analysis identified areas with persistent nitrate contamination. This method aggregated active CWS nitrate concentration data and used a gradient color scheme to indicate contamination severity. Hotspots with high nitrate concentrations indicate ongoing issues with water quality.

2.5. Data Processing and Visualization

To ensure analytical consistency, the data underwent extensive preprocessing. To avoid skewing the analysis, abnormal nitrate amounts were detected and treated. Imputation was used to rectify missing data, and records with extensive missing data were excluded. Standards were also established to maintain uniformity across data sources. Several data visualization methods were employed to effectively communicate the findings. Boxplots illustrate variations in nitrate concentration between PWS sizes, highlighting contamination issues for smaller systems. Seasonal and long-term nitrate patterns are demonstrated in time-series charts. GIS-based spatial distribution maps visualize contaminated hotspots, making high-risk locations and their sources easier to identify. These visualization techniques helped to comprehend the dataset and turn results into practical insights.

2.6. Case Study Area

This study examines Iowa, a Midwestern state renowned for its extensive agricultural operations, which have a significant impact on the economy and water quality. Iowa has fertile land, undulating plains, and an agrarian environment, covering 56,272 square miles. The state has around 1,800 public water systems serving 3.2 million people. Approximately 80% of Iowa's public water systems rely on wells for drinking water. The systems range from large, centralized facilities in urban areas, such as Des Moines and Cedar Rapids, to smaller, decentralized systems in rural areas, reflecting the state's diverse geography and demographics.

3. Results and Discussion

3.1. Community Water System Overview

Table 1 presents summary statistics for the analysis of nitrate concentrations in finished drinking water for community water systems (CWSs) in Iowa that do not use any nitrate removal strategies. Statistics are presented for nitrate concentrations based on whether CWS rely on ground water (GW) or surface water (SW) as their source water, along with corresponding details of the population served. For CWS relying on GW, we also provide information on the wells used in Iowa.

Nitrate concentrations are generally higher in GW, ranging from 0 to 24 mg/L with a mean of 3.13 mg/L, when compared to SW, which ranges from 0 to 10.8 mg/L and has a lower mean value of 2.72 mg/L. The significantly higher maximum value for GW sources (24 mg/L, which is more than twice the SDWA MCL) compared to surface water sources (10.8 mg/L, just above the SDWA MCL) suggests that GW sources may be more vulnerable to fluctuations in nitrate concentrations over time. Well depths for CWSs relying on GW vary widely from 0 to 3,342 feet, with an average depth of 209 feet. Notably, the populations served by these sources differ significantly, with SW systems typically serving much larger communities (a mean of 55,477) compared to GW systems (a mean of 11,109). This holds implications for the capacity (e.g., revenue sources, trained personnel) of these smaller, ground water dependent communities to address high nitrate concentrations relative to larger, more populous surface water systems.

Table 1. Summary statistics of the Community Water Systems in Iowa, including minimum (min), maximum (max), average (mean), and median nitrate concentration, with standard deviation (SD) for 2000 - 2022. This table excludes information from the 64 CWS in Iowa that employ a nitrate removal strategy and those using ground water under the Direct Influence of Surface Water.

CWS Attribute	**Min**	**Max**	**Mean**	**Median**	**SD**
Ground water (*n = 740*)					
Nitrate Concentration (mg/L)	0	24	3.1	2.5	3.1
Population Served	25	69,193	11,109	2,143	19,636
Well-depth (ft)	0	3,342	208	69	371.21
Surface water (*n = 20*)					
Nitrate Concentration (mg/L)	0	10.8	2.7	2.6	1.9
Population Served	25	147,720	55,477	68,753	25,361

Figure 1 illustrates the spatial distribution of CWS across Iowa, categorized by mean nitrate concentration levels (in mg/L as N) from 2000 to 2022. Each well contains 22 years of nitrate concentration data from 2000 to 2022. The figure displays the average concentration at each location, with each point on the map representing a CWS. Color gradations indicate varying ranges of nitrate concentration across sites. The classification of the data is based on a natural break classification system, where the two class intervals (5 and 10 mg/L-N) were chosen to illustrate the distribution in those classes. Blue points signify low nitrate levels (<1.58 mg/L), while orange, yellow, and red points depict moderate to high nitrate concentrations (1.58-5 mg/L-N, 5-10 mg/L-N, and >10 mg/L, respectively). Levels near and above 5 mg/L-N correspond to concentrations that recent studies have associated with chronic health impacts from nitrate exposure through drinking water, including certain forms of cancer and birth defects (Ward et al. 2018).

The distribution pattern reveals that communities vulnerable to high nitrate concentrations tend to be concentrated in specific areas of Iowa, with notable clusters of elevated nitrate levels in communities located primarily in the northeastern quadrant and the far western edge of the state. These regions exhibit a higher occurrence of data in the moderate to high nitrate concentration category, indicating more persistently high nitrate levels in finished drinking water and potential nitrate hotspots where future intervention (e.g., nitrate removal technologies) may be needed. Conversely, central and southeastern Iowa display predominantly low nitrate concentrations (blue data points), suggesting lower nitrate levels across these portions of the state.

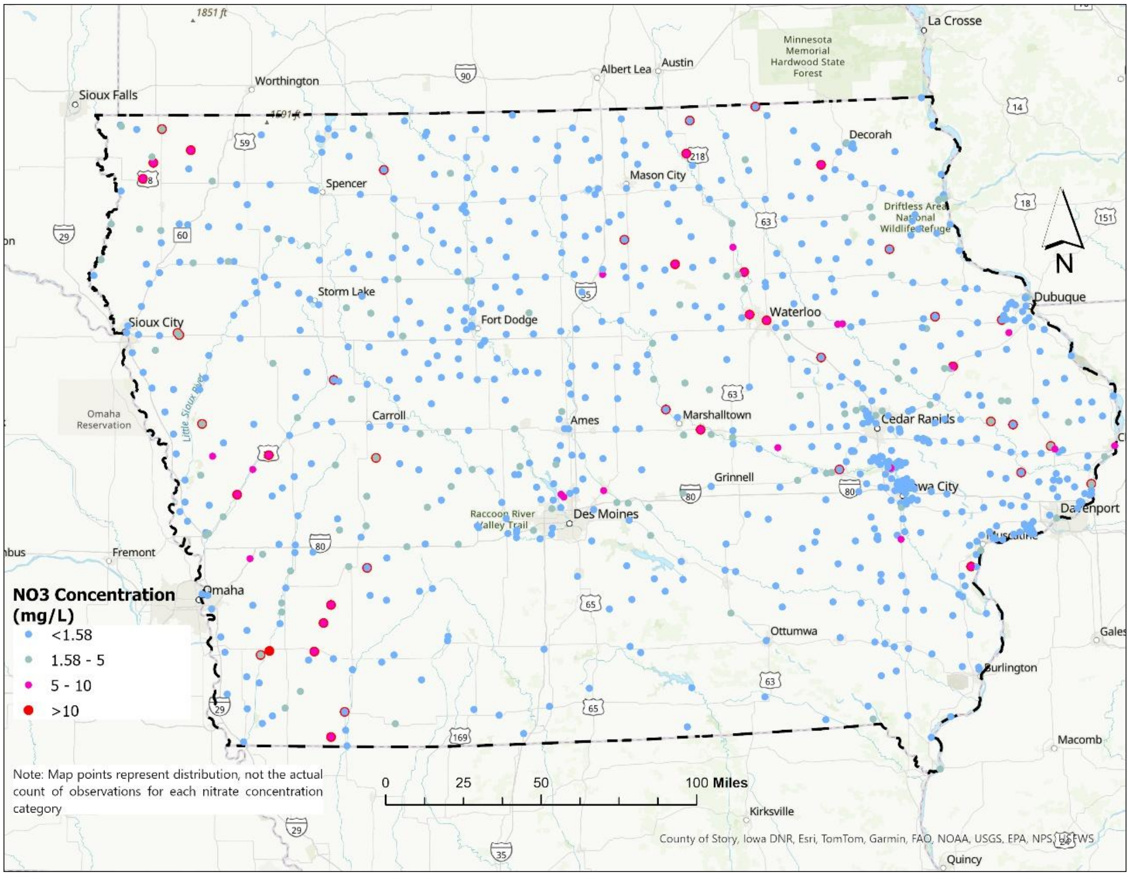

Figure 1. Spatial distribution of mean nitrate concentrations (mg/L as N) in CWS across Iowa relying on either ground water or surface water and not using nitrate treatment. Color coding indicates nitrate levels: blue (< 1.58 mg/L-N), yellow (1.58–5 mg/L-N), orange (5–10 mg/L-N), and red (>10 mg/L-N).

3.2. Temporal Analysis

3.2.1. Seasonal Variability

Monthly nitrate concentration distributions for CWS using ground water and surface water from 2000 to 2022 are shown as a box and whisker plot in Figure 2. A red dashed line represents the 5 mg/L nitrate threshold for reference. We have chosen this reference level because several studies have used 5 mg/L-N as a threshold above which associations between drinking water nitrate and adverse chronic health outcomes are more frequently observed, and it may represent a more health-protective regulation for nitrate in drinking water compared to the EPA's current maximum contaminant level (MCL) of 10 mg/L-N (Ward et al., 2018). Other recent analyses of nitrate in Iowa drinking water have also used 5 mg/L-N as a threshold for identifying communities vulnerable to nitrate. Notably, Mantey et al. (2025) recently conducted a statewide assessment of 871 Iowa Public Water Systems (PWSs) over the 2012–2022 period and also adopted the 5 mg L^{-1} threshold to identify "high-risk" systems, revealing that 2.5% of Iowa's PWSs consistently exceeded this level and disproportionately affected socioeconomically disadvantaged and racially marginalized communities.

Across the state, surface water (green boxes) shows apparent seasonal increases in nitrate concentrations during May, June, and July. Median concentrations rise closer to or above the 5 mg/L-N threshold during these months, with an overall wider distribution of values, suggesting higher variability. This behavior is consistent with increases in surface water nitrate during the planting and growing seasons, presumably due to runoff from land-applied fertilizers (e.g., commercial anhydrous ammonia and livestock manure), given that 70% of Iowa's land is used for corn-soybean production (USDA, 2018). For example, prior work has demonstrated that runoff from livestock manure, commonly applied as a supplemental nutrient source for crops, can be a significant contributor to surface water nitrate concentrations in watersheds with a large number of animal units (Jones et al., 2019).

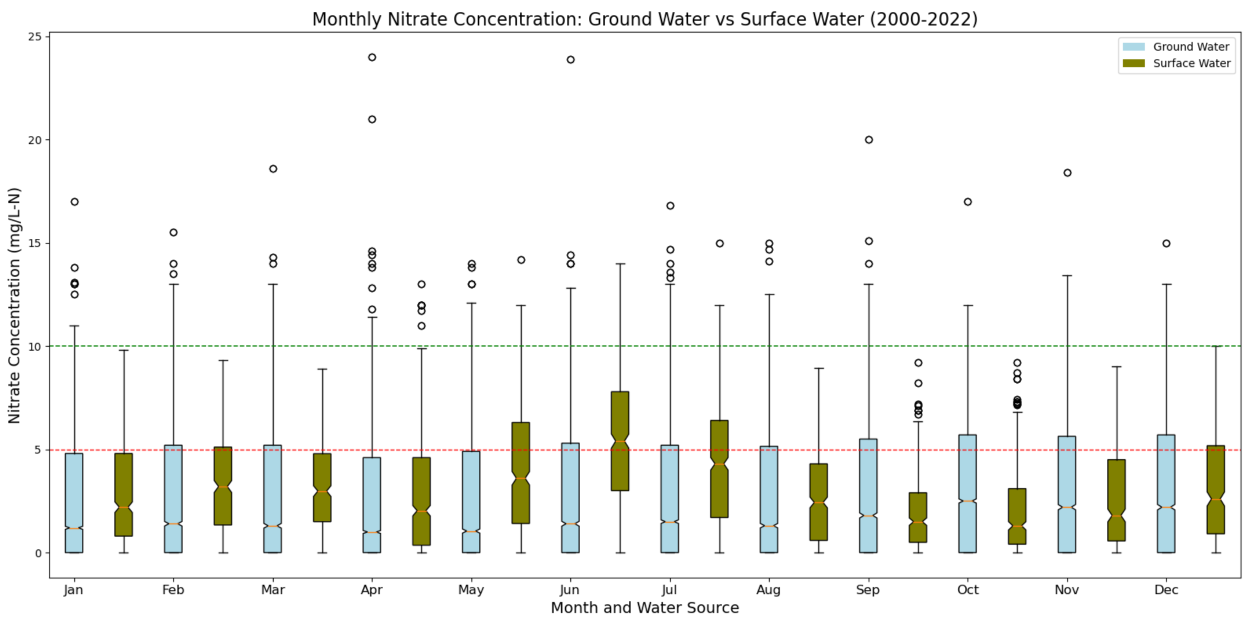

Figure 2. Seasonal variability in monthly nitrate concentrations (mg/L) for CWS not using nitrate removal and relying on ground water (blue) and surface water (green) from 2000 to 2022. The red and green dashed lines represent the 5 and 10 mg/L-N reference points, respectively, for elevated nitrate levels that may be of concern for chronic health effects.

In contrast, nitrate levels in ground water (blue) sources appear more stable throughout the year, with median concentrations remaining below the 5 mg/L-N reference level in most months. However, occasional outliers indicate sporadic nitrate spikes in April, as well as in other months during the planting and harvest seasons. These outliers could be attributed to highly vulnerable ground water sources, such as shallow wells affected by localized runoff or contamination. For example, the more elevated nitrate levels in June, shown as outliers in Figure 2, may indicate a delayed influence from Spring manure application, which typically occurs in March and April prior to planting. Nevertheless, despite these extremes, the overall distribution of ground water nitrate concentrations remains more consistent and less susceptible to seasonal variation than surface water sources across most months in Iowa.

Figure 3 shows annual mean values for drinking water nitrate concentrations (mg/L-N) for CWS using either ground water (GW) and surface water (SW) sources from 2000 to 2022. Yearly trends largely align with those from seasonal observations previously discussed in the monthly data (see Figure 2). Once again, CWS that relies on surface water experience far more variability in nitrate concentrations from year to year compared to those using a ground water source, with mean nitrate concentrations ranging between 1.17 and 4.2 over this period. In contrast, CWSs relying on ground water exhibited significantly less year-to-year variability, with mean nitrate concentrations ranging from 2.8 to 3.4 mg/L.

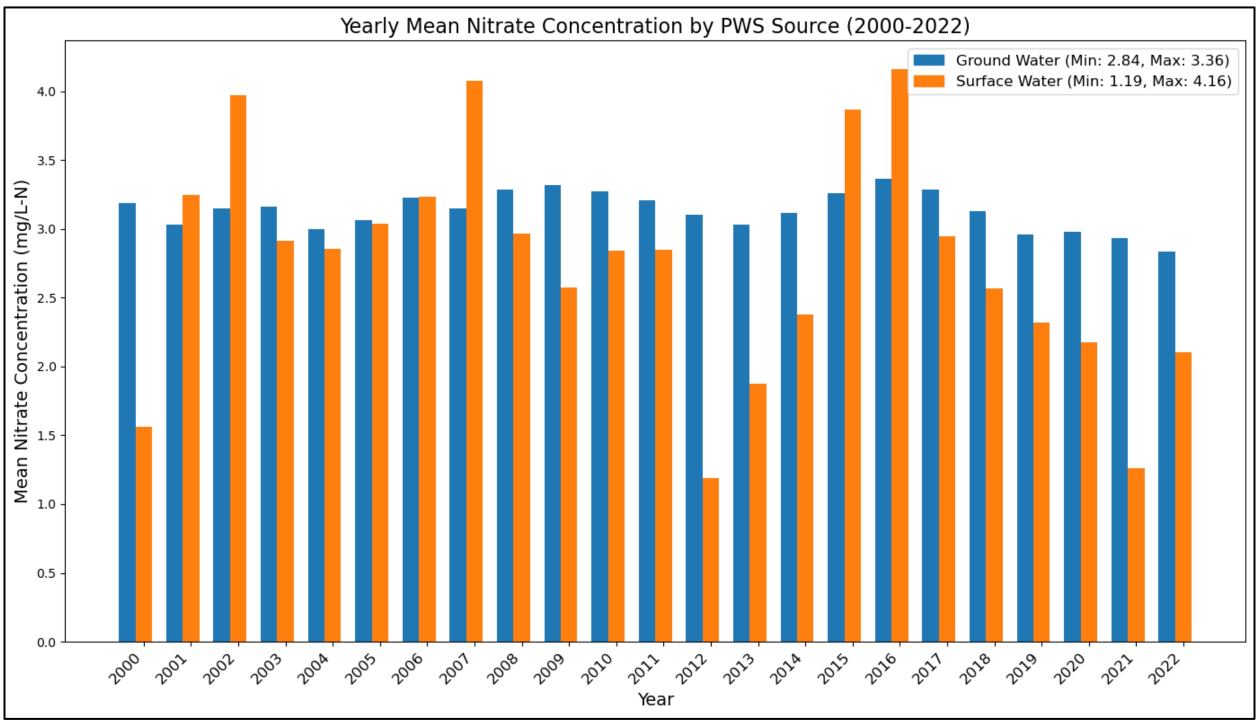

Figure 3. Yearly mean drinking water nitrate concentrations for CWS not using nitrate removal and relying on ground water (blue) and surface water (orange) sources during the 2000-2022 period.

Surface water variability in nitrate concentrations can often be attributed to precipitation patterns that influence non-point source runoff containing nitrate. Notably, significant peaks in drinking water nitrate concentrations for surface water systems were observed in 2002, 2003, 2015, and 2016. These years are documented as having higher-than-average precipitation rates, aligning with increased runoff events. For example, NOAA's Climate Data Online provides detailed records that confirm these years experienced substantial rainfall, likely enhancing nitrate runoff from agricultural lands (National Oceanic and Atmospheric Administration - NOAA, 2023a). Additionally, the NOAA Storm Events Database lists specific storm events during these years that could have contributed to elevated nitrate levels by increasing runoff (NOAA, 2023b). This correlation suggests that surface water systems are particularly vulnerable to nitrate pollution during wet years, a concern that is likely to escalate with the expected increase in precipitation variability under climate change scenarios.

3.3. Nitrate Levels Across Different CWS Sizes

Figure 4 illustrates nitrate concentrations in ground water and surface water systems categorized by CWS size based on population served, either as small (<10,000; n = 662), mid-sized (10,000–100,000; n = 97), or large (>100,000) systems. Note that Iowa only has two large surface water systems, of which one was excluded because it uses nitrate removal (i.e., the Des Moines Water Works), and Iowa has no large systems (>100,000) that rely on ground water as a drinking water source. Thus, the data in Figure 4, shown for large surface water systems, are limited to the data available for the only extensive system considered in our analysis (i.e., Cedar Rapids system).

Across small and mid-sized CWS, ground water nitrate concentrations remain relatively consistent from year to year, with limited fluctuations in median values, consistent with the results in Figure 3. Mid-sized CWSs generally exhibit slightly higher nitrate concentrations than smaller systems, including several years with significant fractions of tests above the 5 mg/L-N reference level and several over the US EPA MCL of 10 mg/L-N. Analysis of mean concentrations confirms this pattern, with mid-sized systems showing a range of mean nitrate concentrations from 3.2 mg/L to 4.2 mg/L-N, compared to smaller systems, which range from 2.1 mg/L to 3.1 mg/L-N. Thus, while ground water systems are generally more stable, specific regions or well configurations remain vulnerable to contamination, including unsafe levels of nitrate based on the current MCL.

In contrast, there are apparent differences in the year-to-year variability of drinking water nitrate as a function of system size for CWS relying on surface water (Figure 4, bottom). The data suggest that mid-sized and large surface water systems are most vulnerable to contamination by nitrate in drinking water. Mid-sized systems (10,000–100,000) and large systems (>100,000) exhibit mean drinking water nitrate levels that are consistently higher than those of small surface water systems (<10,000) each year. For example, mid-sized systems showed mean nitrate concentrations ranging from 0.9 mg/L to 2.7 mg/L-N, while large systems demonstrated even higher ranges, from 1.6 mg/L to 5.6 mg/L-N. Mid-sized and large CWS reliant on surface water also exhibit far greater year-to-year variability in drinking water nitrate, with some years exceeding both the 5 mg/L-N and 10 mg/L-N thresholds.

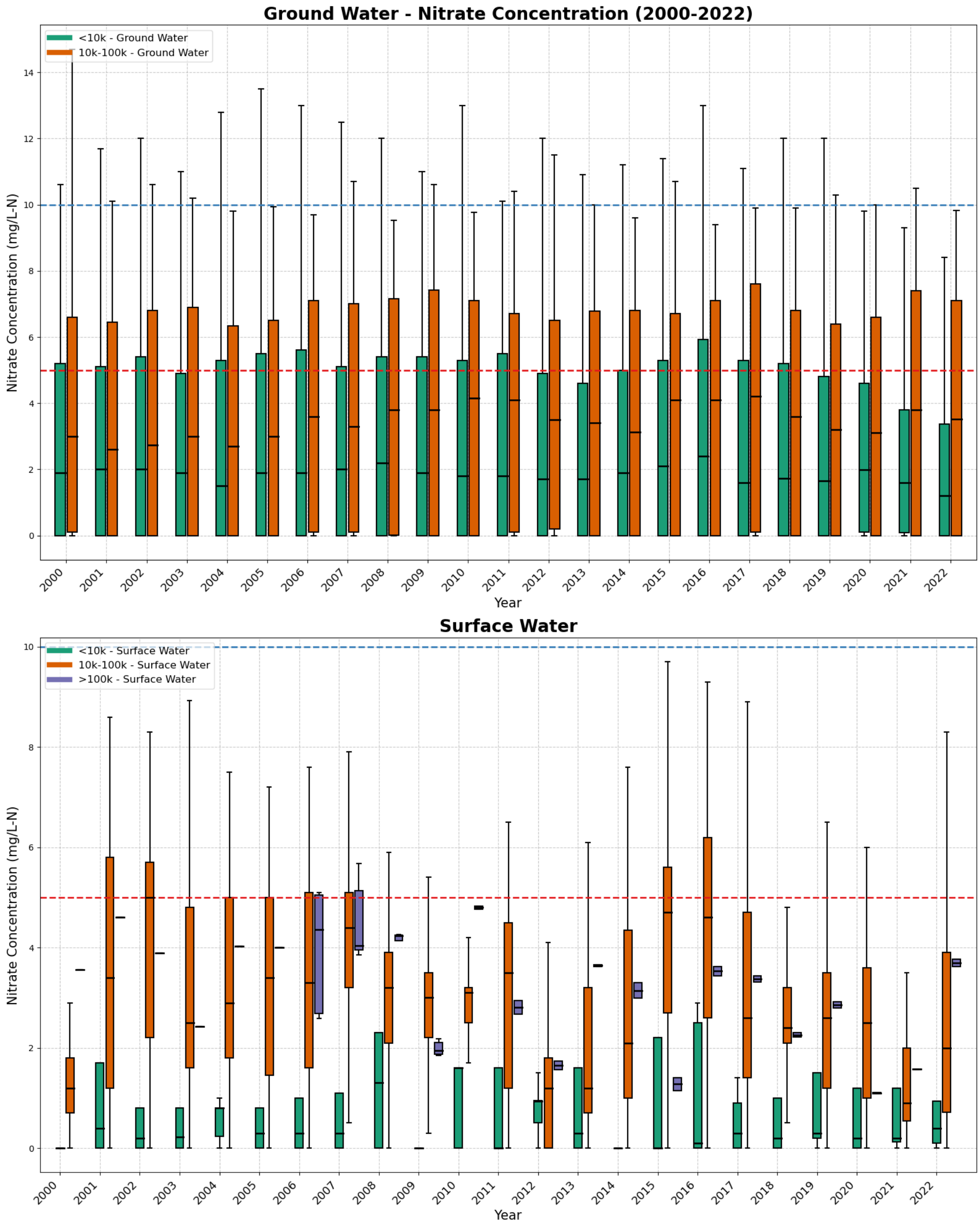

Figure 4. Nitrate concentrations for CWS in Iowa not using nitrate removal and relying on ground water (top) and surface water (bottom) as a function of system size: small (<10,000), mid-sized (10,000–100,000), and large (>100,000, surface water only). Box plots show the median, interquartile range, and variability from 2000 to 2022. Dashed lines mark the 5 mg/L-N reference level and the 10 mg/L-N US EPA maximum contaminant level.

3.3.1. Susceptibility Analysis

Susceptibility to nitrate contamination was assessed based on the proportion of concentrations exceeding the US EPA's maximum contaminant level (MCL) of 10 mg/L and a secondary threshold of 5 mg/L that would be more protective of public health. Figure 5 illustrates the distribution of nitrate concentrations across three population categories: small systems (<10,000), mid-sized systems (10,000–100,000), and large systems (>100,000), regardless of the source water type. The boxplot highlights median values, variability, and outliers for each category, regardless of source water type.

Small systems (<10,000) show the widest variability, with numerous outliers exceeding 5 mg/L and 10 mg/L thresholds. These systems often serve rural communities with limited resources for acquiring advanced nitrate treatment, leaving them vulnerable to contamination. In contrast, mid-sized systems (10,000–100,000) have higher median nitrate levels, with several results exceeding the 5 and 10 mg/L-N thresholds. However, mid-sized CWS have far fewer extreme outliers, perhaps reflecting less vulnerability in response to stressors that tend to exacerbate nitrate pollution. The third category, shown in Figure 5 (>100,000), reflects data from the only large CWS considered in our analysis (Cedar Rapids, which does not utilize nitrate removal), and is provided for comparison. The large system generally shows lower nitrate levels than the small and mid-sized systems, and there are no MCL exceedances.

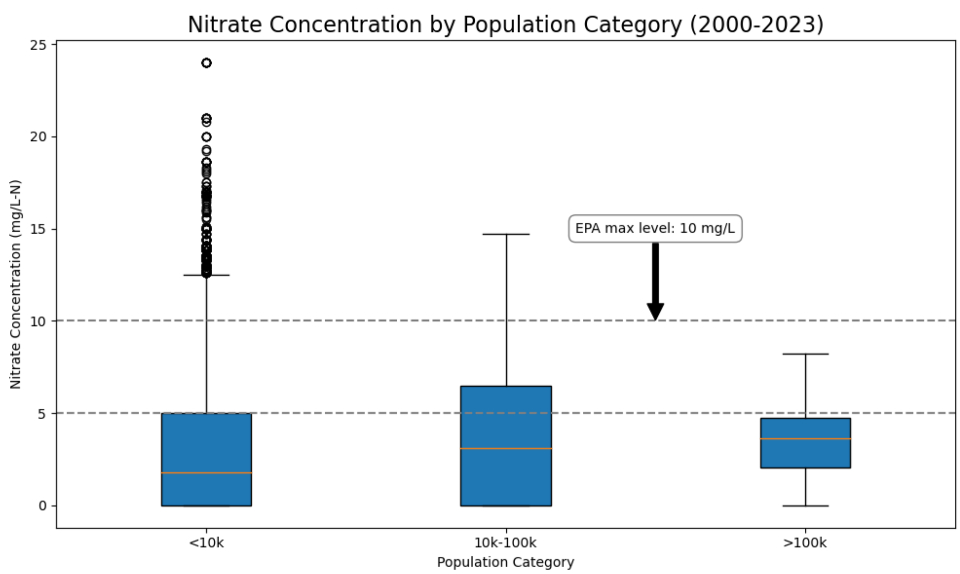

Figure 5. Boxplot of nitrate concentrations (2000–2022) across public water systems by population served (<10,000, 10,000–100,000, >100,000).

The existing disparities in susceptibility to nitrate contamination highlight current and future challenges faced by small systems in Iowa. It is well documented (Rauh and Hughes, 2024) that smaller systems often lack the financial, technical, and personnel capacity to maintain safe water systems, and such CWS in Iowa are likely to be further stressed by the threat of worsening nitrate contamination. Targeted interventions, including subsidies for treatment technologies and enhanced source protection programs, are critical for safeguarding public health in these vulnerable communities.

Finally, for GW-sourced CWS, we investigated how changes in nitrate concentrations in drinking water over time may be associated with the age and characteristics of the source water infrastructure. Figure 6 shows scatter plots of nitrate concentrations in ground water sourced CWSs as a function of the depth of their ground water well (<500 ft, 500–1,000 ft, and >1,000 ft) based on the year of well construction. Each point represents the nitrate concentration in a well, plotted by the year the well was constructed. Perhaps not surprisingly, shallower wells (<500 ft) consistently exhibit higher nitrate concentrations, often exceeding the 5 mg/L-N reference level and often approaching and occasionally exceeding the US EPA's maximum contaminant level (MCL) of 10 mg/L-N. This trend is most pronounced in older wells constructed before 1990, which may suggest a shift in infrastructure toward deeper wells that are less susceptible to nitrate contamination. Wells built after 2010 tend to exhibit lower nitrate levels across all depth categories, which may also reflect improved well construction standards, enhanced source protection, and an increasing reliance on water sources known to be less vulnerable to nitrate contamination. The strong correlation between nitrate concentrations and well depth underscores the importance of proper design and maintenance in mitigating contamination risks, as well as the potential challenges that some communities face in securing safe and reliable source water in response to declining source water quality due to nitrate contamination.

Figure 7 displays a collection of heatmaps that demonstrate the frequency distribution of nitrate concentrations in ground water across three depth categories: shallow (<500 ft), intermediate (500–1000 ft), and deep (>1000 ft) wells. The intensity of color denotes the quantity of observations in each bin annually, with darker red hues indicating a higher frequency of observations. From the heat maps, shallow wells continuously exhibit elevated observation counts within moderate to high nitrate concentrations (2–10 mg/L-N), with ongoing detections around the EPA's maximum contamination threshold of 10 mg/L. Although intermediate and deep wells show far fewer high-nitrate observations in raw counts, this may partially reflect lower sampling frequency in these depth categories. Nevertheless, shallow wells consistently show elevated counts in the 2–10 mg/L-N range, with frequent observations near or above the EPA’s 10 mg/L-N threshold across the 23-year period. Moreover, temporal patterns in the shallow category reveal persistent nitrate dominance over the 23 years.

3.4. Geographic Analysis

3.4.1. Hot Spot Identification

For CWS currently without nitrate removal systems, geographic analysis using GIS identified several persistent hotspots of nitrate contamination across Iowa during the period 2000–2022 (Figure 8). The heat map was generated using ArcGIS Pro's heat map tool, which aggregates point data from active CWS based on density and applies a gradient color scale to represent nitrate concentrations. Denser areas with higher nitrate concentrations are displayed in red, while lighter colors represent lower densities, effectively highlighting spatial distribution patterns and areas of concern.

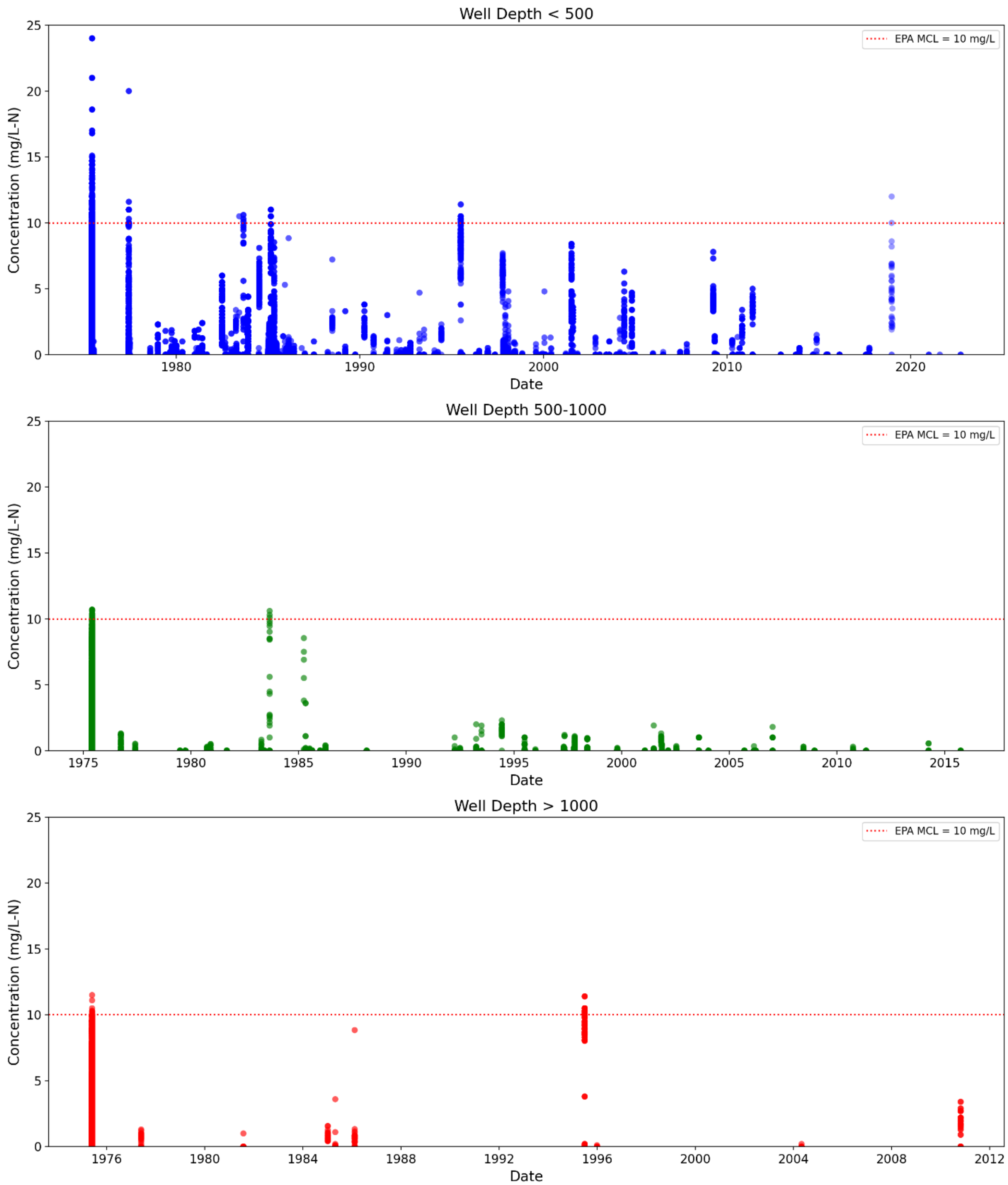

Figure 6. Scatter plots of nitrate concentrations in community water system wells, grouped by depth: shallow (<500 ft), intermediate (500–1,000 ft), and deep (>1,000 ft). Each point represents the nitrate concentration associated with a well, plotted by the year of well construction. The red dashed line indicates the EPA's maximum contaminant level of 10 mg/L-N. Note: Concentrations are not averaged; each dot represents an individual observation.

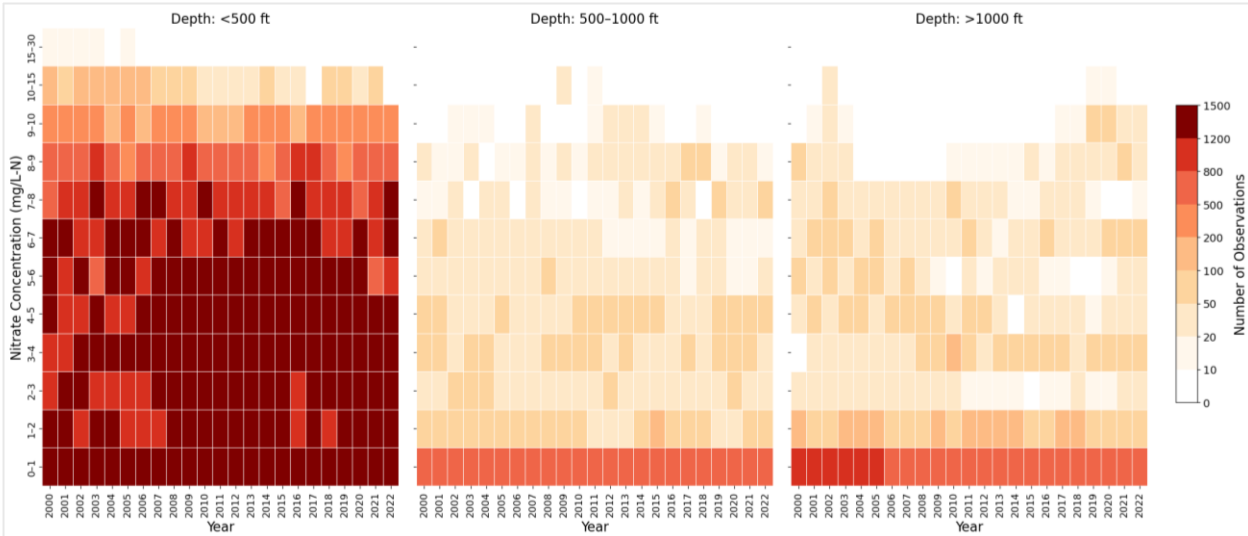

Figure 7. Heatmaps of the frequency distribution of nitrate concentrations for CWS not using nitrate removal and relying on ground water across three well depth categories: shallow (<500 ft), intermediate (500–1000 ft), and deep (>1000 ft) wells. The intensity of color denotes the quantity of observations in each bin annually, with darker red hues indicating a higher frequency of observations.

The heat map analysis reveals three prominent nitrate contamination hotspots, with the most notable areas surrounding Cedar Rapids, Waterloo, and the western regions of the state. Cedar Rapids (population ~136,000, according to the 2023 US census) and Waterloo (population ~67,000) are urban centers situated within the Cedar River watershed, a watershed dominated by agriculture with extensive row crop production (e.g., corn, soybeans) (USDA, 2018). These agricultural practices are closely associated with nitrate runoff from fertilizer application, which is transported into surface and ground water sources through tile drainage and runoff during precipitation events. In western Iowa, the heat map highlights another significant hotspot along the Missouri River watershed. This region is known for intensive agricultural activity, particularly high-density livestock operations, where irrigation practices and high fertilizer use can contribute to nitrate leaching into both surface water and shallow ground water sources. For instance, counties such as Monona and Harrison report some of the highest concentrations of animal units per square mile in the state, contributing significantly to nutrient loading in the watershed (Iowa DNR, 2022).

Additionally, data from the USDA indicates that this region has among the highest fertilizer application rates in Iowa, driven by extensive corn and soybean cultivation (USDA, 2018). These agricultural practices, combined with widespread irrigation, increase nitrate leaching into both surface water and shallow ground water sources, particularly in areas with permeable soils and limited natural filtration capacity. The combination of agricultural land use, hydrological pathways, and reliance on vulnerable water sources creates persistent nitrate issues in this region, as evidenced by the density of red hotspots on the map.

In Figure 8, we also note the small communities that had reported outliers (i.e., very high nitrate data) at least once (see Figure 5), suggesting vulnerabilities to annual shifts in nitrate levels. These are shown on the map as crosses. Top-tier vulnerabilities are the hotspots, and some of the smaller systems align with those hotspots. However, we would also identify these smaller systems, which occasionally report high values, as vulnerable. A commonality among these small systems is that most of them are reliant on GW for source water.

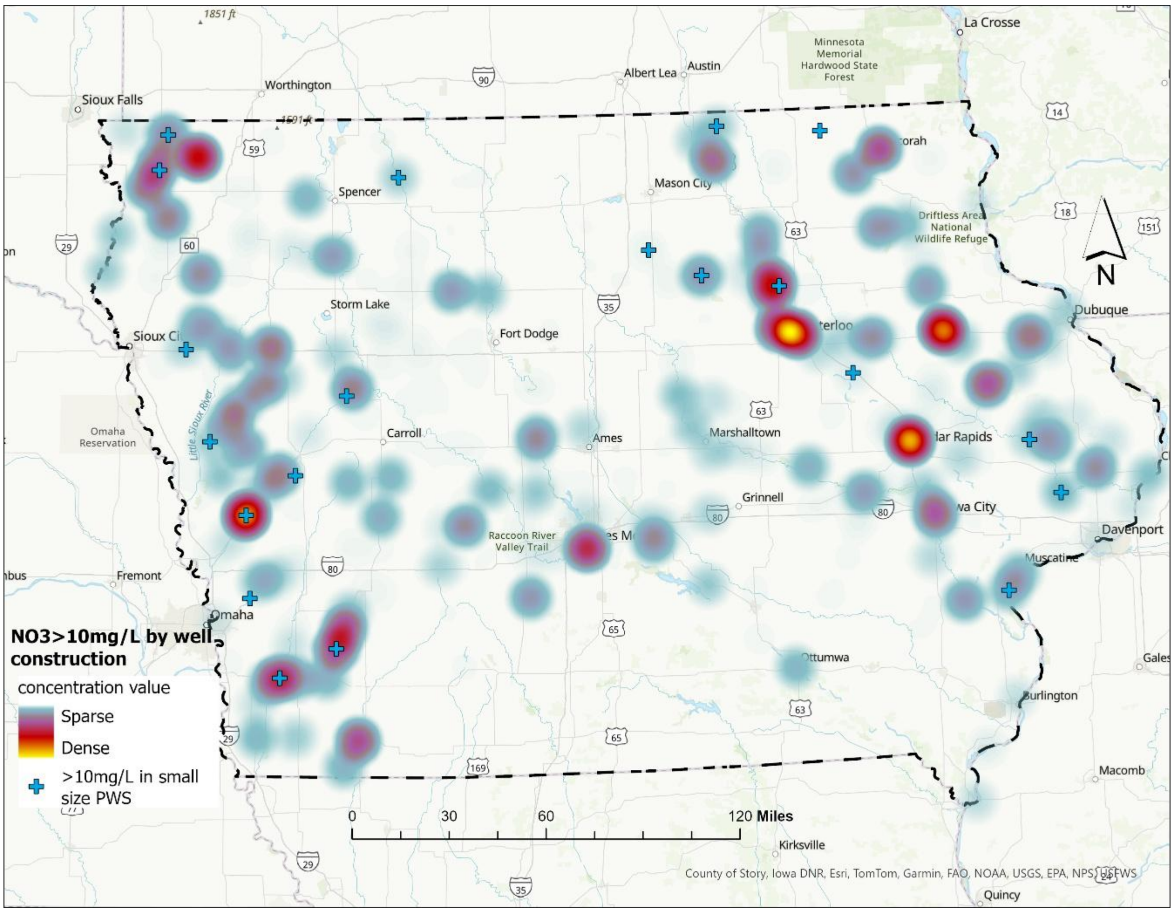

Figure 8. Location of the small PWS with nitrate concentration hotspots in Iowa (2000–2022) for CWS currently without nitrate treatment. The heat map illustrates the spatial distribution of contamination, with red areas indicating higher concentrations of nitrate.

3.5. Potential Impact of Lowering the Nitrate MCL

To consider the number of water systems in Iowa that would be impacted by a lower nitrate MCL of 5 mg/L-N, we considered two hypothetical regulatory scenarios. The first is a new MCL as a hard cap, such that any instance of monitoring producing a water sample with nitrate above 5 mg/L-N would produce a health-based violation. The second considered an annual average, where a health-based violation would only be triggered if the annual average (considered herein to be a calendar year) for a water system exceeded 5 mg/L-N. This second scenario is in line with how drinking water contaminants like total trihalomethanes (TTHMs) and trihaloacetic acids (THAAs) are currently regulated, relying on an annual running average that is compared to the existing MCL.

In the first scenario, which assumes a hard cap of 5 mg/L-N, we limited our analysis to the last 10 years (from 2012 to 2022) and examined the percentage of tests for each CWS that exceeded the 5 mg/L-N limit. Over these 10 years, we found that 100 CWS in Iowa had at least one reported nitrate concentration above 5 mg/L-N. We identified 16 CWS that had over 90% of all reported nitrate values exceeding 5 mg/L-N, indicating that these systems would persistently violate a 5 mg/L-N standard on a yearly basis. Likewise, 43 CWS in Iowa had at least 50% of reported nitrate values above 5 mg/L-N, and these systems would likely also be in near-constant violation of the hard-cap MCL at 5 mg/L-N. These are generally smaller CWS, with the 100 systems reporting a nitrate level above 5 mg/L-N within the last decade serving a total of 735,555 consumers (roughly 23% of Iowa's population). These are systems and consumers that would likely need to seek out advanced nitrate treatment, which would need to operate almost year-round, or an alternative source water supply in the event of a stricter nitrate MCL of 5 mg/L-N.

Under the second scenario, which relies on an annual average of nitrate concentrations relative to the 5 mg/L-N threshold, we find that far fewer CWS would be impacted by new regulations. Examining the annual average in 2022, for instance, we observe that only 23 CWSs had averages above 5 mg/L-N (although three additional systems had averages above 4.8 mg/L-N). In years with higher surface water nitrate levels, typically corresponding to wetter years in Iowa, more systems would be at risk of violation. For example, in 2016, which is regarded as a year with some of the highest surface water nitrate levels in recent Iowa history, 53 CWS would have exceeded or met 5 mg/L-N as their annual average based on compliance testing (with another six CWS at or above 4.8 mg/L as N). Thus, while this scenario results in fewer CWS that would violate a stricter SDWA standard based on a hard cap of 5 mg/L-N, the number of systems in violation could reasonably be expected to vary considerably from year to year.

Because a new, stricter drinking water standard would likely address chronic exposure risks associated with nitrate in drinking water, using an annual average that better corresponds to sustained, long-term exposure would likely represent a more reasonable approach. Moreover, it would result in a smaller number of systems being affected by a stricter nitrate MCL and thus requiring the implementation of treatment and/or the acquisition of a new source water supply. This may, in turn, improve the outcomes of economic analyses that would need to be conducted to justify the cost of a new nitrate regulation, thereby increasing the likelihood that a new, lower nitrate MCL could be finalized and implemented.

4. Conclusion

Our study on nitrate concentrations in Iowa's CWSs from 2000 to 2022 provides insights regarding the spatial distribution, temporal changes, and factors contributing to nitrate pollution. The study revealed considerable variation in nitrate levels throughout the state, with concentrations ranging from 0 mg/L to 24 mg/L and an average of 3.17 mg/L. The results emphasize that nitrate contamination is not evenly distributed but rather is somewhat affected by variables such as the population being serviced, the depth of the well, the type of water source, and geographical location. Indeed, specific areas of nitrate contamination were identified through geospatial hotspot analysis, with areas surrounding Cedar Rapids, Waterloo, and portions of western Iowa consistently showing elevated levels. These higher-risk areas tended to reflect the interplay between source water type (e.g., surface water) and surrounding land-use practices in influencing nitrate vulnerability, as well as the necessity of more stringent regulations and localized management strategies to reduce nitrate contamination risk.

For ground water-reliant CWS, our research also found that older wells, particularly those constructed before 1990, exhibited higher nitrate concentrations, indicating potential weaknesses resulting from deteriorating infrastructure or outdated construction practices. Conversely, more recent wells constructed after 2010 tended to have reduced levels of nitrate, indicating enhancements in design and techniques for managing water. CWS reliant on surface water typically had greater nitrate concentrations than ground water systems. This emphasizes the vulnerability of surface water bodies to direct pollution from agricultural runoff. Seasonal and temporal trends revealed distinct peaks in nitrate concentrations during the spring and early summer months. This pattern aligns with periods of heightened fertilizer application and precipitation, which facilitate runoff flow into bodies of water. These findings underscore the importance of enhanced surveillance during critical periods to prevent sudden increases in nitrate levels and ensure the safety of drinking water.

Although smaller CWS tended to have lower nitrate levels than larger CWSs, there were notable exceptions among these systems with alarmingly high nitrate. Although fewer in number, these outliers are particularly problematic as they often represent more rural populations that may lack sufficient resources and infrastructure to install efficient nitrate removal technology. This highlights the need for targeted assistance and funding for advanced water treatment, ensuring that even the smallest resource-constrained communities can access safe drinking water.

Our study adds to the recent literature (Mantey et al., 2025) examining the scope and consequences of nitrate pollution on drinking water supplies in Iowa. Our study expands upon and complements recent prior work in several important ways. First, we extend the temporal coverage to include over two decades (2000–2022), enabling the identification of longer-term trends and potential climatic or land use shifts influencing nitrate dynamics. Second, our analysis incorporates a detailed seasonal characterization of nitrate variability, capturing hydrologically driven fluctuations in both surface and ground water systems—an aspect not examined by Mantey et al. (2025). Finally, our study emphasizes the role of geologic and hydrographic provinces (e.g., the Des Moines Lobe, Paleozoic Plateau, Loess Hills) in shaping spatial nitrate patterns, providing insights into the physical drivers of contamination. By integrating temporal, seasonal, and physiographic dimensions, our approach offers a complementary, comprehensive framework for evaluating nitrate risk and informing future decisions on water quality management in Iowa and beyond.

The results of our study hold implications for the fields of public health and water management in the state of Iowa. High levels of nitrate concentrations in drinking water are correlated with significant health hazards, such as methemoglobinemia (commonly known as blue baby syndrome) and probable connections to the development of cancer. Identifying susceptible populations and areas of high vulnerability is a foundation for targeted interventions, such as intensified surveillance, stricter limits on fertilizer usage, and investment in cutting-edge water treatment technologies. Prioritizing regular nitrate monitoring and updating treatment equipment is crucial for metropolitan regions and larger CWSs. Financial and technical assistance is vital for improving water treatment capacities, particularly in rural areas primarily served by small CWS.

Our inquiry highlights the complexity of managing nitrate pollution in community water systems, affecting several infrastructural, environmental and human elements. This research will provide policymakers, public health professionals, and water management authorities with significant insights into identifying the population categories and geographic locations that are most affected. This includes both large urban centers and small, vulnerable communities. Continuous monitoring and targeted measures can effectively limit the hazards of nitrate pollution, ensuring safe and clean drinking water for all communities in Iowa.

5. Acknowledgement

This project was funded by the National Science Foundation (#2230710).

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