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PAPER

Trends in nitrate contamination: implications for communities reliant on groundwater for drinking

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Abstract

Nebraska's vulnerability to nitrate contamination in water systems is highlighted by agrochemical inputs with leaching potential and the state's reliance on groundwater for drinking. Nitrate is a regulated compound in drinking water due to its association with methemoglobinemia and other chronic health conditions. This study examines water quality in Nebraska's groundwater over several decades, focusing on temporal and spatial variations in nitrate concentrations across different well types. The findings reveal increasing statewide trends in nitrate levels, with considerable spatial variability. Private-domestic wells, particularly in agricultural areas, are more susceptible to contamination. These trends suggest a growing risk for communities without access to regulated public water systems. The study emphasizes the need for targeted interventions in vulnerable regions, and provides insights into the broader implications of agricultural contaminant leaching on groundwater quality and public health.

1. Introduction

Nitrate contamination of groundwater sources can be attributed to various factors, including stormwater runoff, leaky septic systems, and agricultural inputs. Among these, groundwater contamination from agricultural runoff and agricultural input leaching has become an increasingly significant issue in farming regions across the United States (Spalding and Exner 1993, Syswerda *et al* 2012). The accumulation of nitrate in groundwater (and surface water), when it exceeds federal safety standards, represents a significant public health concern, particularly for populations dependent on private-domestic wells[6]. Private-domestic wells are not subject to the same regulatory oversight as public water systems[7] under the United States Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA) (Kross *et al* 1993, Liu *et al* 2005, United States Environmental Protection Agency 2024b). The concern surrounding nitrate contamination in drinking water arises from its association with serious health issues, including methemoglobinemia in infants, as well as potential long-term health concerns such as cancer and adverse birth outcomes (Centers for Disease Control and Prevention 1996, Knobeloch *et al* 2000, Weyer *et al* 2001, Schullehner *et al* 2018, Temkin *et al* 2019, Richards *et al* 2022).

Nitrate and nitrite are significant contaminants in Nebraska's drinking water, impacting more people than other harmful substances (Nebraska Department of Health and Human Services 2018). Research on nitrate-

6 Wells that are used for domestic water needs, including cooking and drinking, that are privately owned by individuals or households.
7 Public water systems provide water for more than one household. Public water systems include community water systems, non-community transient water systems, and non-community non-transient water systems. See (Jayasekera *et al* 2024) pp-05 for more information.

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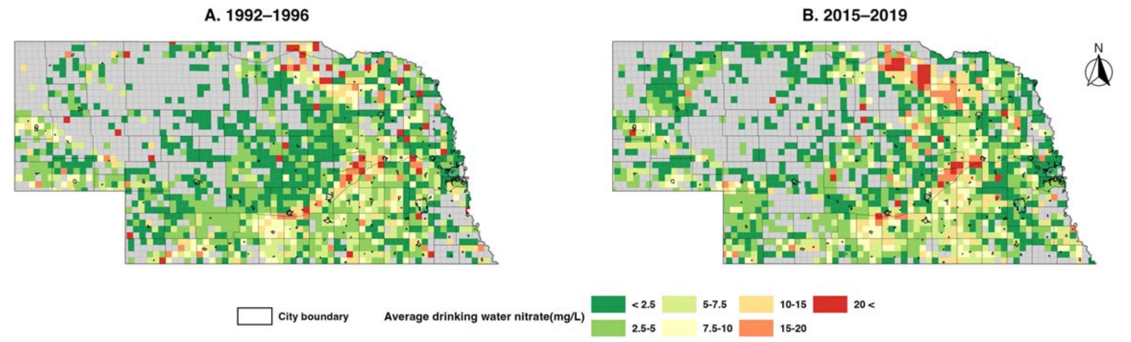

Figure 1. Average nitrate concentration in Nebraska 1992-1996 and 2015-2019. Figure shows average nitrate concentrations in groundwater. The time periods were selected to compare nitrate concentrations in groundwater between 1992–1996, the years following the EPA's enforceable nitrate standard, and 2015–2019, the most recent data available for this analysis. The color-coded nitrate averages are presented by township. Data does not distinguish between well types. Areas in light gray indicate missing values, likely due to sparse well distribution in low-population regions. The map also includes county and city boundaries in Nebraska to distinguish rural and urban areas. Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021) City boundaries are recreated using the *Municipal Boundaries* spatial data file provided by the State of Nebraska (State of Nebraska 2025).

related water quality in Nebraska highlights the state's vulnerability due to its land-use (Almasri and Kaluarachchi 2004, Exner *et al* 2014, Juntakut *et al* 2019) and the geological characteristics of its aquifer system (Nolan *et al* 1998). Over 90% of the state's land is used for agriculture (Killpack and Buchholz 1993, Fazal *et al* 2003, Jansen and Stokes 2020), involving fertilizer applications and livestock effluents[8]. Previous studies have highlighted the potential for nitrate leaching due to agricultural practices (Saint-Fort *et al* 1991, Ribaudo 1989, Yin *et al* 2021, Locke *et al* 2008, Exner *et al* 2014). Despite these risks, Nebraska has maintained a strong commitment to monitoring groundwater quality, driven by the economic importance of groundwater as a primary source for irrigated agriculture. This commitment is also influenced by the state's decentralized natural resource management approach, with local oversight provided by Natural Resources Districts (NRDs) (Bleed and Babbitt 2015). Figure 1 illustrates the state of nitrate contamination in groundwater, comparing data from 2015-2019 - most recent data used in this analysis, with data from 1992-1996 - the years immediately following the EPA's enforceable nitrate standard. Assuming other factors remain constant, nitrate levels have generally increased in eastern Nebraska over this period. The average nitrate contamination and urban boundaries reported in figure 1 suggest that nitrate levels have generally increased over time, with more pronounced increases occurring outside urban centers, indicating a spatial concentration of rising nitrate contamination in less densely populated areas.

The regulatory framework in Nebraska as it relates to nitrate is composed of various institutional actors, each playing distinct roles in managing water quality. Central to this framework are the NRDs, which function as local governance entities overseeing water quality through Groundwater Management Areas (GMAs). NRDs collaborate with stakeholders to address water contamination, using both regulatory and incentive-based strategies[9]. Furthermore, the Nebraska Department of Water, Energy, and Environment (DWEE) and Nebraska Department of Health and Human Services (NDHHS) coordinate efforts to regulate and protect water quality in Nebraska, with specific mandates for addressing contamination and ensuring safe drinking water standards[10]. DWEE was established on July 01, 2025, through the consolidation of Nebraska Department of Natural Resources (DNR) and Nebraska Department of Environment and Energy (NDEE).

In addition to health concerns, nitrate contamination has significant economic implications as well. When nitrate concentrations exceed the EPA's maximum contaminant level (MCL) of 10 mg/L, water treatment becomes necessary, which increases costs for both water suppliers and consumers (Juntakut *et al* 2020, Vedachalam *et al* 2018, United States Environmental Protection Agency 2022). Costs are typically absorbed by local residents and municipalities, while those responsible for the contamination are often not held accountable

[8] Nebraska is a major nitrogen fertilizer user, accounting for 6.8% of total U.S. fertilizer purchases in 2017, following Illinois (8.1%) and Iowa (10.2%). Author calculations using data accessed from United States Environmental Protection Agency (2022).

[9] At the local level, NRDs are integral to managing soil and water resources. Established in 1972 to consolidate over 150 single-purpose districts into 23 larger entities based on river basins, NRDs are funded by local property taxes and governed by locally elected boards. They have broad authority over soil and water conservation and administer federal agricultural programs. Under state groundwater law, NRDs regulate groundwater usage and manage agrochemical applications within GMAs to manage contamination.

[10] NDEE (now part of DWEE) is responsible for implementing federal environmental policies, including those outlined in the Clean Water Act (CWA). It oversees non-point source pollution, including groundwater contamination, and can direct NRDs to develop remediation plans if groundwater quality within a GMA is deemed inadequate (Jayasekera *et al* 2024). The NDHHS enforces the Safe Drinking Water Act in Nebraska, with a focus on protecting public water supplies from contaminants.

(Coppess 2016, Vedachalam et al 2019, Juntakut et al 2020, Rauh and Hughes 2024). Furthermore, the financial burden of nitrate remediation—including infrastructure investments and health-related expenditures—often falls disproportionately on rural communities where private-domestic wells are more common (Liu et al 2005, Keeler and Polasky 2014, Keeler et al 2016, Moore et al 2011). Despite growing recognition of the societal costs associated with nitrate contamination, the full economic impact—particularly in rural and agricultural areas—remains poorly understood (Moore et al 2011, Keeler et al 2016). This lack of accounting for the externalities contributes to underestimating the broader societal costs of nitrate pollution (Mamun et al 2023).

This study contributes to the literature on nitrate contamination by analyzing a comprehensive dataset of groundwater quality observations from Nebraska spanning 1992 to 2019. Focusing on groundwater sources used for drinking in regions with intensive agricultural activity, we examine long-term temporal and spatial trends in nitrate levels using a non-parametric rank correlation method. By accounting for serial autocorrelation in the data, we address a key limitation of cross-sectional approaches applied to time-series questions and provide a more accurate representation of changes over time. Our analysis tests for heterogeneity in trends across geographic regions and well types, identifying areas where public water systems and private-domestic wells are more likely to experience rising nitrate concentrations. These spatial patterns highlight the need for localized water quality management strategies and may help inform targeted interventions. The findings offer insights into the public health risks associated with nitrate contamination and support efforts to prioritize regions and providers that may require more immediate attention.

2. Data

Historically, NRDs have been key players in nitrate management, initiating groundwater testing programs in the 1970s and 1980s and working with the University of Nebraska–Lincoln to create a statewide groundwater monitoring network in more recent years (Nebraska Association of Resources Districts 2025). This network, combined with education and outreach, has enabled NRDs to develop targeted nitrate management strategies. As a result, Nebraska has significantly advanced its ability to monitor nitrate contamination, with approximately 1.75 million water quality samples collected over six decades. This repository of water quality samples is known as the Nebraska Nitrate Clearinghouse (NNC). The NNC dataset provides valuable insights into nitrate trends and other contaminants, supporting evidence-based policy decisions. The data collection effort is managed by DWEE (previously NDEE) and has been funded through state agencies and EPA grants (Nebraska Department of Water, Energy, and Environment 2021).

Our analysis considers five well types: irrigation, domestic, livestock, monitoring, and public. Irrigation wells, used for agricultural purposes, do not provide water for human consumption. However, due to their proximity to households without access to community water systems, trends in irrigation wells may reflect those in private-domestic wells, particularly when sampling coverage is limited. Private-domestic wells are used for household purposes, including drinking water. Livestock wells are located within livestock operations and are primarily used for agricultural needs. Monitoring wells, typically constructed by local authorities or stakeholders such as NRDs or the Nebraska Geological Survey, were originally designed to measure groundwater quantity, though some are now also used for water quality monitoring. Some monitoring wells were constructed only to test groundwater quality. Public wells are regulated by federal drinking water standards and are divided into three categories: community wells, which supply year-round water to households; non-community non-transient wells, which provide water to specific groups such as schools or government offices; and non-community transient wells, which supply water to temporary users, such as at parks or rest stops (Jayasekera et al 2024). This study focuses on irrigation, domestic, and public wells in its trend analysis, as other well types lack sufficient observations across the geographies used in our study necessary for meaningful analysis.

The NNC dataset is structured around several key parameters, including well type, location (when available), sample date, and the specific contaminants analyzed. Each well is assigned a unique identification number, which ensures accurate tracking and facilitates subsequent analysis. The dataset includes a total of 208,540[11] nitrate samples collected from 33,451 unique wells[12]. Table 1, provides a summary of descriptive statistics for each well type. Among the well types analyzed, monitoring wells exhibited the highest average nitrate levels, with a maximum concentration of 128 mg/L. In our view, this suggests that monitoring wells may be disproportionately located in areas already known for elevated nitrate concentrations. Public supply wells and domestic wells also reported high maximum nitrate concentrations, exceeding 250 mg/L in some instances. However, the average nitrate concentrations for these well types ranged from 4.03 mg/L to 7.14 mg/L,

[11] Note that the sum of the column representing the number of nitrate samples in table 1 reflects only those associated with the specific well type. The total number of samples includes additional wells that may belong to other well types or are not categorized.

[12] Note that the sum of the column representing the number of wells in table 1 reflects only those associated with each well type. The total number of wells include others that may belong to unreported well types or are not categorized.

Table 1. Descriptive statistics of well characteristics and nitrate levels (1969-2019).

Panel A: Observations and coverage

	Drinking water	Total		Growing season	
		Wells	Samples	Wells	Samples
Domestic	Yes	6,219	15,267	4,205	9,145
Public supply	Yes	4,192	62,576	1,598	23,414
Irrigation	No	18,826	80,635	18,209	77,719
Livestock	No	726	1,307	604	945
Monitoring	No	2,800	38,554	1,352	16,710

Panel B: Descriptive statistics

	Total				Growing season			
	Nitrate (mg/L)							
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Domestic	7.14	12.08	0	260	7.45	11.93	0	260
Public supply	4.03	4.30	0	280	3.63	4.27	0	280
Irrigation	8.90	8.95	0	196	8.96	8.98	0	196
Livestock	10.83	16.60	0	155	9.21	15.15	0	155
Monitoring	11.37	11.92	0	128	10.66	11.41	0	128

	Total				Growing season			
	Well depth (feet)							
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Domestic	135.12	87.82	1	970	132.90	88.93	1	970
Public supply	175.88	99.63	7	1150	173.21	97.32	15	1150
Irrigation	206.27	106.64	18	1223	206.18	106.26	18	1223
Livestock	100.08	83.63	7	520	104.61	86.39	7	520
Monitoring	84.17	76.55	2	920	87.00	74.33	4	920

Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021). Growing season - May, June, July, and August. Domestic wells refer to private-domestic wells.

indicating that, while some individual wells exhibit elevated nitrate levels, the majority of samples from these well types fall within lower concentration ranges. These findings emphasize that, despite the presence of high nitrate concentrations in certain locations, most wells within each category have relatively low nitrate concentrations, which drives the overall lower average values observed in the dataset. Well depth also plays a significant role in understanding groundwater quality trends (Burow *et al* 2010, Spalding and Exner 1993, Nolan *et al* 1998). The deepest wells in the sample are irrigation wells, followed by public supply and private-domestic wells. Well depth is correlated with nitrate levels, as deeper wells are generally less influenced by short-term variations in contaminants that may enter the groundwater. In contrast, shallower wells tend to exhibit higher nitrate concentrations. Because nitrate levels can vary seasonally, we also examined data from the growing season (May through August). The distribution of nitrate concentrations and well samples during this period did not differ significantly from the full dataset. As shown in Panel A of table 1, the majority of samples from private-domestic, irrigation, and livestock wells—and approximately half of those from monitoring wells—were collected during the growing season.

Our full dataset spans fromanalysis primarily focuses on data collected between 1960 to and 2019. However, to ensure reliable trend interpretation of trends, only data from 1992 onward are considered. This time frame is chosen to avoid selection biases, as standardized water sample testing protocols for nitrate were implemented after 1992, improving data consistency. Several factors contributed to this improved consistency: (1) the inclusion of nitrate as a regulated compound under the Safe Drinking Water Act (SDWA) in 1992 (Pennino *et al* 2017), (2) the introduction of domestic well registration requirements in Nebraska in 1993 (Jayasekera *et al* 2024), and (3) the enactment of the Nebraska Wellhead Protection Area (WPA) Act in 1998 (Jayasekera *et al* 2024). Additionally, water quality projects conducted by NRDs in Nebraska have contributed to a more consistent sampling over time.

3. Methodology

The objective of this study is to examine longer-term trends in groundwater nitrate levels in Nebraska. We first use a descriptive analysis to identify the broad trends in groundwater nitrate levels, aggregating data across the entire state. Second, we apply a non-parametric rank correlation methodology to account for potential serial autocorrelation, adapting it for time-series data to demonstrate temporal trends with spatial heterogeneity.

To explore the temporal variations and local patterns in nitrate concentrations descriptively, we employ Locally Weighted Scatterplot Smoothing (LOWESS) curves. LOWESS is a descriptive data analysis technique that estimates the underlying trend in a dataset by smoothing out fluctuations in the data. This method is particularly useful for identifying local patterns in data without assuming a global functional form. The LOWESS procedure involves fitting a weighted least squares regression to localized subsets of data, where the weight assigned to each data point decreases with distance from the target point. The bandwidth parameter, which determines the degree of smoothing, is selected to balance overfitting and underfitting, ensuring that the estimated curves capture meaningful local patterns.

The descriptive analysis allows us to visualize how nitrate concentrations evolve over time, but not their spatial distribution. Our approach follows methodologies from geophysical studies that analyzed trends in hydrological and geophysical time series (Meals *et al* 2011, Ayers *et al* 2019, Ducci *et al* 2020). Specifically, we apply the Mann-Kendall (MK) test to assess temporal trends in the dataset (see Mann 1945 and Hirsch *et al* 1982 for more details). The MK test provides a robust and flexible framework for detecting monotonic trends in environmental data, such as groundwater nitrate levels, without requiring strict parametric assumptions. Its ability to handle non-normal distributions, irregular sampling intervals, and missing values (Meals *et al* 2011, Blain 2013) makes it particularly suited for examining temporal trends in groundwater quality with spatial disaggregation.

The MK test statistic S is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(y_j - y_i) \tag{1}$$

Here, $sgn(g)$ takes values -1, 0, and $+1$ when $(y_i - y_j) < 0$, $(y_i - y_j) = 0$, and $(y_i - y_j) > 0$, respectively. The series y represents a sequence of time-based observations, with $j > i$. The difference $(y_j - y_i)$ represents the difference between later and earlier values in the series. To clarify: if y is a vector of observations $y_1, y_2, \ldots, y_i, y_j$, then $y_j - y_i = (y_2 - y_1) + (y_3 - y_2) + \ldots + (y_j - y_i)$. The sign of the S statistic indicates the direction of the trend (positive or negative). To test whether the trend is statistically significant, we calculate τ as follows:

$$\tau = \frac{S}{n(n-1)/2} \tag{2}$$

Where $n(n-1)/2$ is the total number of differences calculated in equation (1). The test statistic τ is used to assess whether the null hypothesis H_0 (no monotonic trend) can be rejected in favor of the alternative hypothesis H_a (monotonic trend).

The Mann-Kendall test assumes that the data are independent and identically distributed. When applied to time-series data, such as nitrate levels, autocorrelation between successive observations can introduce temporal dependencies, potentially affecting the precision and statistical significance of the test statistic (Helsel and Hirsch 1992, Noguchi *et al* 2011). Groundwater quality data often exhibit temporal relationships based on physical characteristics, such as soil profiles and elevation, which can vary spatially (Exner *et al* 2014). However, the assumption of independence between successive time points is problematic in time-series data (Loftis 1996, Härdle *et al* 2003, Chen *et al* 2022). To address this, we apply a "moving block" bootstrapping technique, which mitigates potential serial autocorrelation issues in time-series data, enhancing the robustness of the τ statistic (Noguchi *et al* 2011, Önöz and Bayazit *et al* 2012, Zhang *et al* 2016). The implementation of this method for the computation of τ statistic unfolds in the subsequent steps described here-

1. Draw 'blocks' of consecutive data from the original time-series with length l and create data set A. We used five consecutive years of data (l) in our analysis.

2. Sample $\frac{n}{l}$ numbers of blocks from A, where n is the number of observations in the original data. Stack the sampled 'blocks' in the order they were sampled.

3. Perform Kendall's τ calculation.

4. Repeat 2 and 3 Y times and save results. Y refers to the number of iterations, and for this study we used 2000 iterations.

The confidence intervals for the bootstrapped τ are calculated using the percentile method. After performing 2000 bootstrap iterations (based on the recommendations of (Önöz and Bayazit *et al* 2012)), the confidence interval for the bootstrapped τ is then constructed by selecting the $\alpha/2$th and the $1-\alpha/2$th percentiles from the distribution.

Non-parametric methods are particularly effective for groundwater quality analysis, especially when dealing with nitrate levels and their relationship to geospatial and physical factors. These methods are useful when the underlying data distribution is unknown, or when variable relationships are complex and cannot be adequately captured by traditional parametric models under data availability constraints. The Mann-Kendall test is particularly valuable for this type of analysis as it requires no assumptions regarding the distribution of data or the functional form of the relationship between the variable of interest and time. This allows for an interpretation of trends in nitrate-related water quality without imposing restrictive assumptions. Similarly, bootstrapping provides a straightforward method for empirically estimating statistics of interest and constructing confidence intervals, also without requiring parametric assumptions. The combination of these techniques mitigates the risk of overstating the presence of trends, a concern addressed by Type I errors[13] in statistical analyses. Önöz and Bayazit *et al* 2012 discusses the challenges associated with serially correlated data in the calculation of Kendall's τ statistic and highlights the effectiveness of bootstrapped Kendall's τ in reducing the risk of such errors.

In practical terms, the Mann-Kendall test and bootstrapping are valuable tools for environmental research, particularly in groundwater quality analysis, due to their simplicity, flexibility, and robustness. These methods are easily interpretable and do not rely on complex assumptions about the underlying data distribution, which is often unknown or difficult to determine. When data is noisy or affected by outliers, parametric methods may lead to biased conclusions if assumptions are incorrect. This is particularly important in resource-constrained settings, where inaccurate trend identification could lead to the misallocation of resources, such as for water testing or interventions like water filtration.

4. Results

In this section, we report both the descriptive and analytical results. Descriptive results reported in figure 2 are based on all of the observations available in the dataset (see table 1) aggregated by year. Analytical results reported in figures 3–5 respectively aggregate nitrate observations by year, by year and county, and by year and township. There are 93 counties and 2,245 townships in Nebraska.

Figure 2 presents the LOWESS curves, which descriptively illustrate a series of local fittings of the data, akin to a moving average calculated over time. This method allows for the capture of local trends, with each data point informed by preceding values. This 'fit' visually highlights patterns that may be missed by longer-term averages, such as those produced by Ordinary Least Squares (OLS) estimators. The upper panel (A) of figure 2 indicates that average nitrate levels have varied over the past five decades. Specifically, irrigation wells show a general upward trend in nitrate concentrations, while public wells exhibit a moderating effect. The lower panel (B) of figure 2 reveals more subtle temporal trends after accounting for data consistency. Nitrate levels from 1992 onward remain below the EPA's standard of 10mg/L in both domestic and public systems, although domestic wells are closer to this threshold.

Statewide monotonic trends, as shown in figure 3, summarize Kendall's τ values across various well types. The comparison of traditional Kendall's τ values with bootstrapped (de-trended) τ values shows that the bootstrapped τ values are more conservative estimates of the traditional τ. The bootstrapped τ values consistently show attenuation compared to traditional τ calculations, suggesting that the bootstrapped method better accounts for time-dependence in water quality time series, providing a more robust analysis. Each Kendall's τ value in figure 3 includes a 95% confidence interval. Except for irrigation and public wells, all other τ values fail to reject the null hypothesis of no observable trend. While this finding may be disappointing from a policy perspective, it indicates there may be significant spatial heterogeneity, where some areas exhibit increasing nitrate levels while others show decreases, resulting in a lack of overall trend at the state level.

We present results of the disaggregated monotonic trend analysis in figures 4 and 5. The figures show the general trend in the movement of nitrate concentrations and not if it approaches a set threshold. Figure 4 maps the spatial distribution of monotonic trends in nitrate concentrations across counties, categorized by well type from 1992 to 2019. While not all counties exhibit statistically significant trends, those that do, offer insights into regional variations. The analysis reveals that, on average, more counties show statistically significant increases in nitrate levels compared to counties with significant declines. No counties were dropped from the analysis. To further explore spatial patterns, figure 5 presents Kendall's τ values for townships within Nebraska[14]. This finer spatial breakdown results in fewer observations per geographic unit. We required at least 5 years of data

[13] Erroneously rejecting the null hypothesis of 'no trend' in favor of an alternative hypothesis.

[14] A township consists of 36 sections, each measuring approximately one square mile (640 acres). This unit is foundational for land organization and regulation within Nebraska (Neunzert 2010). A township is the smallest geographic unit available for analysis due to data privacy concerns.

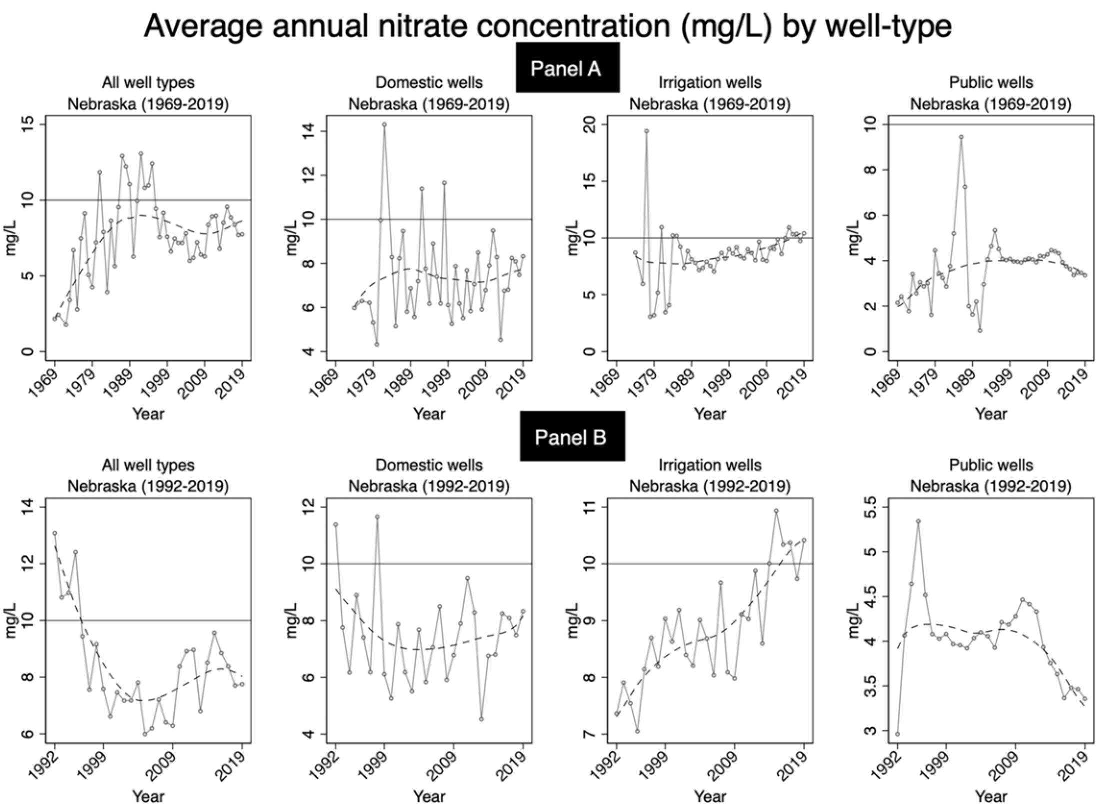

Figure 2. Average annual groundwater nitrate concentration (mg/L) by well-type. Figure describes the average annual nitrate concentration by well-type. The solid line plots the average nitrate concentration. The dash-line is a locally weighted scatter plot smoothing (LOWESS) curve. It locally weights the observations (of average nitrate concentrations) using 80% of the observations around each point (bandwidth = 0.8). This is the default bandwidth chosen by the Stata17 software. Smaller bandwidths use fewer observations around each point, and the subsequent LOWESS lines will, as a result, closely follow the original data. The solid line across 10 mg/L indicates the level of nitrate concentration safe for human consumption asper the SDWA. Nitrate testing was prioritized in Nebraska following the regulation of nitrate as a controlled compound in drinking water in 1992, by the EPA. This increased and regulated nitrate sampling avoiding the likely selection biases from voluntary water quality testing. The top panel (A) depicts average nitrate concentrations between 1969 and 2019, the bottom panel (B) depicts average nitrate concentrations between 1992 and 2019. Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021).

availability to be included in the analysis to avoid biased results. As a result, we were unable to estimate private-domestic well water trends for 82.67% of townships, public well water trends for 68.33% of townships, and irrigation well water trends for 55.55% of townships. Figure 5 item A, shows that domestic well observations are concentrated in the Platte River Valley and the Lincoln and Omaha areas, underscoring the need for increased testing in peripheral regions. Figure 5 item B, highlights broader coverage of irrigation wells, likely influenced by the mandatory registration of irrigation wells in 1957 (Jayasekera *et al* 2024), which may have led to more consistent testing. Figure 5 item C, presents mixed results for public water systems, with a higher proportion of statistically significant increasing trends compared to declining trends. Although the coverage of nitrate sampling remains limited[15], the statistically significant upward trends raise concerns, especially for private-domestic wells when coupled with the fact that average private-domestic well nitrate levels are approaching the MCL for safe consumption (see figure 2).

In both figures 4 and 5, counties and townships without the textured overlay represent areas where no statistically significant trend was detected using the methodology adopted in this study. Rather than omitting these units, we present them as naive results—shown as color-coded regions without the textured overlay—to illustrate how failing to account for serial autocorrelation can produce overstated trends. Including these non-significant results highlights the potential for misinterpretation, which can have implications for the effective allocation of resources.

[15] While the limitations in coverage may be due to inadequate data collection both in terms of the unique wells being sampled as well as the number of years samples are collected, we do not expected well coverage to be uniform, as each well type has a different geographic distribution.

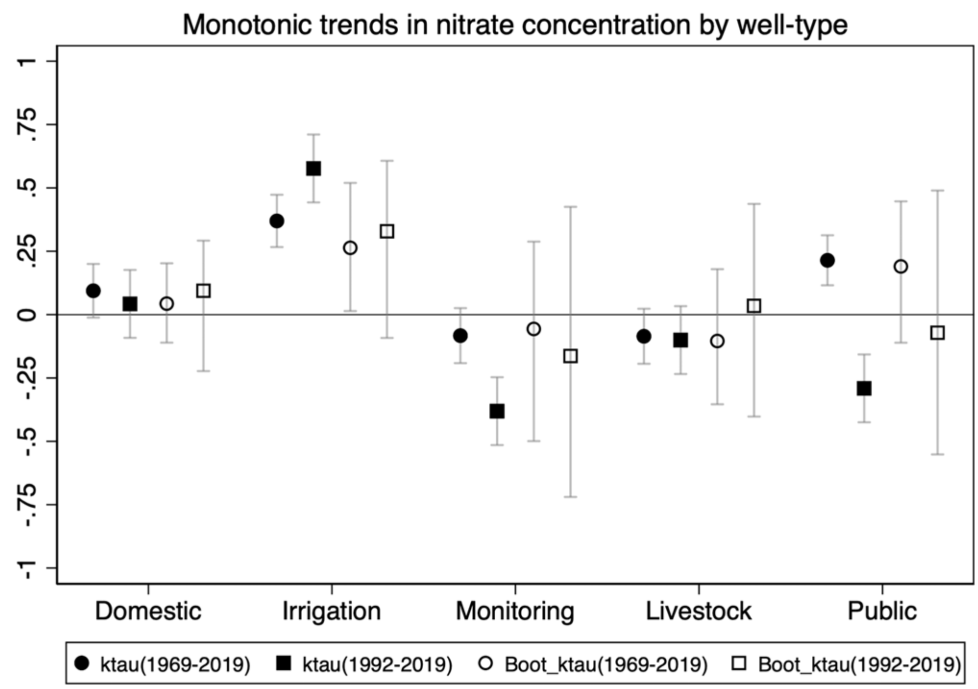

Figure 3. Monotonic trend of nitrate concentration by well-type. Figure depicts the Kendall's τ statistic for two time periods 1969-2019 and 1992-2019. The figure also reports two Kendall's τ calculations for traditional time-series and de-trended time-series using block bootstrapping. The traditional τ calculation is made for time-series that span at least five years. Bootstrapped τ is calculated using 2000 bootstrap iterations. Bootstrapped standard errors are calculated using the percentile method. Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021).

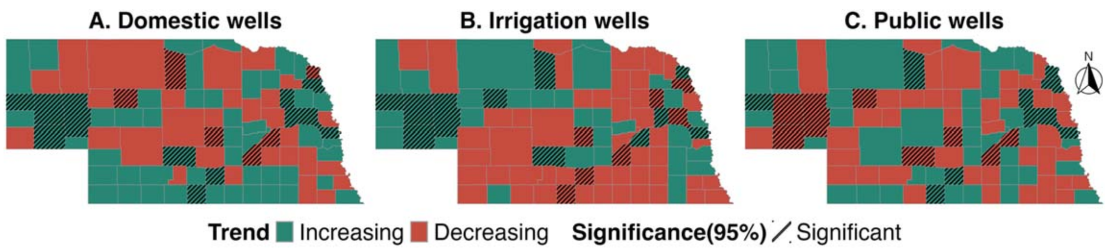

Figure 4. County-wide monotonic trends in nitrate concentration. Figure depicts the Kendall's τ statistic for each county in Nebraska for the time period 1992-2019. The τ statistic is corrected for autocorrelation using 2000 bootstrap iterations. Bootstrapped standard errors are calculated using the percentile method. *Green* color depicts decreasing monotonic trends, *red* color depicts increasing monotonic trends, and the textured overlay depicts statistical significance at 95%. The non-significant counties exhibit Kendall's τ statistics that are statistically indistinguishable from zero (null trend) under the block bootstrap method. Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021). Further details on the breakdown of geographies included in the analysis, as well as the number of units that exhibit meaningful trends over this period, are provided in the Appendix.

5. Discussion

This study aims to analyze temporal trends in groundwater nitrate contamination in Nebraska and explore the implications for communities affected by elevated nitrate levels. Our analysis reveals two key findings: (1) nitrate levels in Nebraska have generally increased over time, and (2) long-term trends in nitrate concentrations exhibit significant spatial heterogeneity.

The state-wide descriptive analysis may provide some insight into how nitrate concentrations have responded to policy interventions. Notably, nitrate concentrations declined across all well types from 1992 to 2005, followed by an increase from 2005 onward. The Energy Policy Act of 2005 (Energy Policy Act 2005) and its subsequent revision under the Energy Independence and Security Act of 2007 (Energy Independence and Security Act 2007) have significantly impacted agricultural land use by incentivizing the conversion of previously uncultivated and expiring Conservation Reserve Program (CRP) land into commodity production (Sainju *et al*

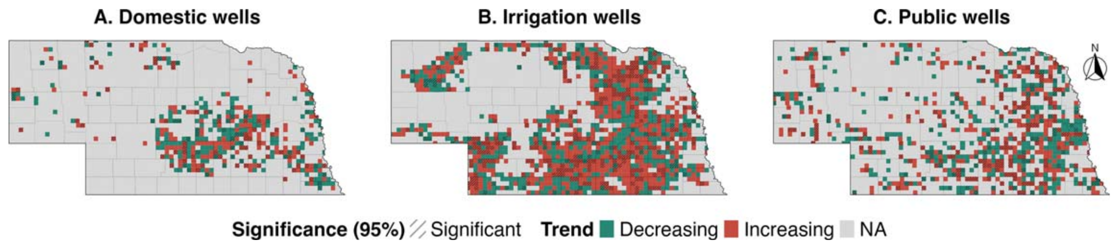

Figure 5. Township-wide monotonic trends in nitrate concentration. Figure depicts the Kendall's τ statistic for each township (approximately 36 mil^2) in Nebraska for the time period 1992-2019. The τ statistic is corrected for autocorrelation using 2000 bootstrap iterations. Bootstrapped standard errors are calculated using the percentile method. *Green* color depicts decreasing monotonic trends, *red* depicts increasing monotonic trends, and the textured overlay depicts statistical significance at 95%. The *gray* spaces in the visualization are missing values due to the lack of sufficient observations. The non-significant townships exhibit Kendall's τ statistics that are statistically indistinguishable from zero (null trend) under the block bootstrap method. Data sourced from Nebraska Groundwater Quality Clearinghouse published by DWEE (Nebraska Department of Water, Energy, and Environment 2021). Further details on the breakdown of geographies included in the analysis, as well as the number that exhibit meaningful trends over this period, are provided in the Appendix.

2014, Yin *et al* 2021). These legislative acts have played a central role in shaping crop choices, particularly by promoting the cultivation of commodity crops.

As the linkage between agricultural practices and groundwater quality is mediated by a complex policy landscape, agriculture and energy policies in the United States are closely linked to the intensity of nitrate inputs that can, if not managed well, eventually contaminate water sources (Randall *et al* 1997, Hoffpauir 2009, Sainju *et al* 2014, Hanson *et al* 2016, Yin *et al* 2021, Spor Leal *et al* 2024). For example, researchers have found that agriculture policy may crowd-out on-farm conservation (Schoengold *et al* 2015), may hinder diversification of farm operations (Horowitz and Lichtenberg 1993, Roll 2019), and increase input usage (Horowitz and Lichtenberg 1993)[16].

While agricultural policies continue to incentivize increased farm production, they do not account for associated negative externalities (Hoffpauir 2009, Schoengold *et al* 2015). This is in part due to the difficulties of attributing responsibility in non-point source pollution, and partly because environmental policies often exclude the agricultural sector from stricter regulations (Hanson *et al* 2016, United States Environmental Protection Agency 2024a).

While we recognize these relationships, this study does not attempt to establish causal links between the policy landscape and nitrate levels in groundwater.

Our geographically explicit findings show that there are more counties and townships exhibiting statistically significantly increasing trends in nitrate concentrations compared to those with decreasing trends. While an increasing trends does not necessarily point to groundwater nitrate concentrations reaching the MCL (see figure 2 for average nitrate concentrations), the consistent increase could lead to compounding effects, and affect the longer-term dynamics of nitrate observations in groundwater. Notably, areas exhibiting rising nitrate levels are likely to continue experiencing elevated concentrations over time, reflecting the persistent, longer-term impacts of historical practices and other contributing factors.

The financial burden of nitrate clean-up—ranging from decommissioning contaminated wells and drilling new ones, to purchasing water from alternative sources, and installing advanced filtration systems—are often passed onto public water utility customers through higher water rates. Such costs can range from hundreds to thousands of dollars, depending on the severity of contamination (Fargen 2020, Xu 2022). Larger utilities may be able to absorb these expenses, but smaller utilities, particularly those serving rural, and low-income households, may struggle to bear such financial costs. Even modest increases in water rates disproportionately affect low-income and fixed-income households (Regnier 2014, Cory and Taylor 2017, Belzer 2020). Rural counties in Nebraska, which tend to have higher poverty rates (Daily *et al* 2017) and are closer in proximity to agricultural areas, are especially vulnerable to these economic pressures.

Private-domestic well owners face unique challenges when addressing rising nitrate levels. These residents are typically ineligible for financial assistance programs, as private-domestic wells are not subject to routine nitrate testing or treatment regulations. This creates significant disparities in access to safe drinking water,

[16] However, other studies have challenged these findings, arguing that the availability of insurance can create a moral hazard, leading to reduced reliance on farm inputs such as fertilizers (Smith and Goodwin 1996, Goodwin and Smith 2013). These conflicting perspectives underscore the complex and sometimes unintended effects of policy interventions on farm management decisions.

especially considering that many private-domestic well owners may lack awareness of the health risks associated with nitrate contamination (Vogt et al 2022)[17].

The distributional implications associated with nitrate contamination highlight a critical intersection between economic hardship and health risk, disproportionately affecting vulnerable populations. Infrastructure improvements to address rising nitrate levels necessitate substantial investments, leading to higher water rates and property taxes, which in turn burden disadvantaged communities, including rural and low-income populations, as well as aging residents (Vogt et al 2022). Simultaneously, these groups are at greater risk of the adverse health effects from elevated nitrate concentrations in drinking water, which have been linked to adverse health outcomes and the mobilization of geogenic contaminants (Joshi et al 2013, Migeot et al 2013, Nolan and Weber 2015). This dynamic creates a cycle that exacerbates socio-economic disparities, compounding the vulnerabilities of these communities.

6. Conclusion

This study provides a statewide assessment of long-term trends in nitrate concentrations in Nebraska's groundwater, with an emphasis on differences across well types and land use contexts. Using a robust non-parametric trend analysis on an extensive historical dataset, we find that nitrate concentrations have increased significantly over time in many parts of the state, particularly in areas of intensive agriculture.

These findings highlight both environmental and public health concerns. In rural regions where private-domestic wells are common and where agricultural land use dominates, residents may be unknowingly exposed to elevated nitrate levels, which are linked to a range of health risks. The spatial heterogeneity of these trends suggests the need for localized management approaches to target areas at highest risk.

Some interventions targeting groundwater contamination have been tested. For instance, several NRDs in Nebraska have implemented localized controls on nitrogen application and developed educational initiatives to raise awareness and promote available cost-share tools (e.g., discounts on reverse osmosis systems). Strengthening the alignment between agricultural subsidies and incentives with environmental outcomes is needed to enhance sustainable groundwater governance. To that end, one recent policy-driven initiative in Nebraska was developed to encourage better nitrogen management through incentives. In 2024, Nebraska lawmakers passed the Nitrogen Reduction Incentive Act (Nebraska Legislature 2024), which provides financial rewards ($10-15/acre) to growers who cut back their commercial nitrogen use by either 40 pounds per acre or 15% from their usual rate. Another initiative focuses on creating opportunities for producers to learn new practices from peers without risking economic losses. For example, Testing Ag Performance Solutions (TAPS) is a collaborative program developed at the University of Nebraska in 2017, which has now spread to multiple other states. The program allows farmers to compete based on the outcomes of different decision-making scenarios, which includes testing different nitrogen management approaches, like fertigation (Burr et al 2024).

Continued research is needed to assess the effectiveness of existing policy interventions, identify opportunities for collaboration, and examine the influence of socio-economic and institutional factors on groundwater quality. As nitrate contamination increases in many agricultural regions globally, Nebraska provides a relevant case for understanding the challenges of maintaining both agricultural productivity and safe water resources. This study also underscores the need for more consistent and frequent data collection. Greater consistency in monitoring would allow for improved detection of trends and a stronger empirical basis for designing targeted and timely responses to groundwater contamination.

Data availability statement

Portions of the data that support the findings of this study are openly available at https://clearinghouse.nebraska.gov and can also be accessed via DOI https://doi.org/10.71964/119 for users outside the United States. Data related to public supply wells are restricted and not openly accessible. To request access, please contact ndee.clearinghouse@nebraska.gov. You will be asked to register with the State of Nebraska before being granted access to the complete dataset.

[17] The responsibility to monitor and treat water quality often falls entirely on the well owner, further exacerbating the financial, and information burdens. In response, there have been several efforts to address this disparity. For example, NDHHS launched the Low-Income Household Water Assistance Program (LIHWAP) in 2022, providing lump sum payments to households below 150% of the federal poverty line to assist with water utility costs (Nebraska Department of Health and Human Services 2021). Additionally, small water systems can access low-interest loans to fund infrastructure improvements, allowing for more gradual repayment (United States Environmental Protection Agency 2023).

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Appendix

Figures 4 and 5 present nitrate trends in Nebraska from 1992 to 2019. Each figure displays the naive Kendall's τ statistic, with a textured overlay indicating statistical significance. To provide additional context, the following table summarizes the number of geographies included in the analysis and how many exhibit meaningful trends over this period.

Figure	Well type	Number of geographies			
		Total calculated	Increasing	Decreasing	Null trend
Figure 4	Domestic	93	6	12	75
Counties	Irrigation	93	14	5	74
n=93	Public	93	9	10	74
Figure 5	Domestic	389	64	47	278
Townships	Irrigation	1,118	219	77	822
n=2,245	Public	296	148	87	61

References

Almasri M N and Kaluarachchi J J 2004 Assessment and management of longterm nitrate pollution of ground water in agriculture-dominated watersheds *J. Hydrol.* **295** 225–45

Ayers J R, Villarini G, Jones C and Schilling K 2019 Changes in monthly baseflow across the US Midwest *Hydrol. Processes* **33** 748–58

Belzer R B 2020 Achieving economically feasible drinking water regulation *Journal of Benefit-Cost Analysis* **11** 294–318

Blain G C 2013 The Mann-Kendall test: the need to consider the interaction between serial correlation and trend *Acta Scientiarum. Agronomy* **35** 393–402

Bleed A and Babbitt C H 2015 *Nebraska's Natural Resources Districts: an assessment of a large-scale locally controlled water governance framework* Policy Report 1 of the Robert B. Daugherty Water for Food Institute. URL: https://digitalcommons.unl.edu/wffdocs/79/

Burow K R, Nolan B T, Rupert M G and Dubrovsky N M 2010 Nitrate in groundwater of the United States, 1991- 2003 *Environmental Science & Technology* **44** 4988–97

Burr C, Proctor C, Rhoades K, Nakabuye H, Rudnick D, Stockton M and Dorr T 2024 *Testing Ag Performance Solutions (TAPS)-2023 farm management competitions report* UNL-TAPS report archive. URL: https://taps.unl.edu/unl-taps-report-archive/

Centers for Disease Control and Prevention. 1996 Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water-LaGrange county, Indiana, 1991-1994 *Morbidity and mortality weekly report* 569–72 URL: https://pubmed.ncbi.nlm.nih.gov/9132576/

Chen S, Ghadami A and Epureanu B I 2022 Practical guide to using Kendall's τ in the context of forecasting critical transitions *Royal Society Open Science* **9** 211346

Coppess J 2016 Dead zones & drinking water, part 4: the Des Moines Water Works lawsuit *farmdocDAILY* Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign 58 URL: https://farmdocdaily.illinois.edu/2016/03/dead-zones-drinking-water-part4.html

Cory D C and Taylor L D 2017 On the distributional implications of safe drinking water standards *Journal of Benefit-Cost Analysis* **8** 49–90

Daily G, Cantarero R, de Guzman M R, Hong S-Y, Taylor S, Garcia A and Xia Y R 2017 The geographic distribution of poverty *Mapping Quality of Life in Nebraska* URL: https://digitalcommons.unl.edu/mapquallifene/1

Ducci D, Della Morte R, Mottola A, Onorati G and Pugliano G 2020 Evaluating upward trends in groundwater nitrate concentrations: an example in an alluvial plain of the Campania region (Southern Italy) *Environmental Earth Sciences* **79** 1–10

Exner M E, Hirsh A J and Spalding R F 2014 Nebraska's groundwater legacy: nitrate contamination beneath irrigated cropland. *Water Resour. Res.* **50** 4474–89

Fargen J 2020 Nebraska towns pay millions to fight nitrates as water bills go up *OmahaWorld-Herald* URL:https://www.omaha.com/news/state_and_regional/nebraska-towns-pay-millions-to-ght-nitrates-as-water-bills-go-up/article_5a810bb0-1437-5538-aab9-e50546672f60.html (Accessed 26-Jun-2023)

Fazal A, Imaizumi M, Ishida S, Kawachi T, Tsuchihara T, Takeuchi J and Badiul H A A 2003 Review on groundwater nitrate contamination: causes, effects and remedies: a guideline for efficient management strategies *Journal of Rainwater Catchment Systems* **8** 15–33

Goodwin B K and Smith V H 2013 What harm is done by subsidizing crop insurance? *American Journal of Agricultural Economics* **95** 489–97

Hanson M J, Keller A, Boland M A and Lazarus W F 2016 The debate about farm nitrates and drinking water *Choices.* 1–7 URL: http://www.choicesmagazine.org

Härdle W, Horowitz J and Kreiss J-P 2003 Bootstrap methods for time series *International Statistical Review* **71** 435–59
Helsel D R and Hirsch R M 1993 *Statistical Methods in Water Resources* 49 (Elsevier) (https://doi.org/10.3133/tm4A3)
Hirsch R M, Slack J R and Smith R A 1982 Techniques of trend analysis for monthly water quality data. *Water Resour. Res.* **18** 107–21
Hoffpauir J 2009 The environmental impact of commodity subsidies: NEPA and the Farm Bill *Fordham Environmental Law Review* **20** 233–65 http://www.jstor.org/stable/44175148
Horowitz J K and Lichtenberg E 1993 Insurance, moral hazard, and chemical use in agriculture *American Journal of Agricultural Economics* **75** 926–35
Jansen J and Stokes J 2020 *Nebraska farm real estate market highlights 2019-2020* (https://doi.org/10.13014/frm00018)
Jayasekera D H, Powers C, Aiken J D, Schoengold K and Rimšaitė K 2024 Nitrate contamination in Nebraska's drinking water *The Water Report TWR #247* 1–11 URL: https://www.thewaterreport.com/water-report/twr-247/
Joshi N, Rhoades M G, Bennett G D, Wells S M, Mirvish S S, Breitbach M J and Shea P J 2013 Developmental abnormalities in chicken embryos exposed to N-nitrosoatrazine *Journal of Toxicology and Environmental Health, Part A* **76** 1015–22
Juntakut P, Haacker E M, Snow D D and Ray C 2020 Risk and cost assessment of nitrate contamination in domestic wells *Water* **12** 428
Juntakut P, Snow D D, Haacker E M and Ray C 2019 The long term effect of agricultural, vadose zone and climatic factors on nitrate contamination in Nebraska's groundwater system *J. Contam. Hydrol.* **220** 33–48
Keeler B L, Gourevitch J D, Polasky S, Isbell F, Tessum C W, Hill J D and Marshall J D 2016 The social costs of nitrogen *Science Advances* **2** e1600219
Keeler B L and Polasky S 2014 Land-use change and costs to rural households: a case study in groundwater nitrate contamination *Environ. Res. Lett.* **9** 074002
Killpack S C and Buchholz D 1993 Nitrogen in the environment: leaching *WQ - Water Quality Initiative 0262* University of Missouri–Columbia. Extension. URL: https://hdl.handle.net/10355/71821
Knobeloch L, Salna B, Hogan A, Postle J and Anderson H 2000 Blue babies and nitrate-contaminated well water *Environ. Health Perspect.* **108** 675–8
Kross B C, Hallberg G R, Bruner D R, Cherryholmes K and Johnson J K 1993 The nitrate contamination of private well water in Iowa *American Journal of Public Health* **83** 270–2
Liu A, Ming J and Ankumah R O 2005 Nitrate contamination in private wells in rural Alabama, United States *Sci. Total Environ.* **346** 112–20
Locke M, Knight S, Smith S, Cullum R, Zablotowicz R, Yuan Y and Bingner R 2008 Environmental quality research in the Beasley Lake watershed, 1995 to 2007: succession from conventional to conservation practices *J. Soil Water Conserv.* **63** 430–42
Loftis J C 1996 Trends in groundwater quality *Hydrol. Process.* **10** 335–55
Mamun S, Castillo-Castillo A, Swedberg K, Zhang J, Boyle K J, Cardoso D, Kling C L, Nolte C, Papenfus M, Phaneuf D and Polasky S 2023 Valuing water quality in the United States using a national dataset on property values. *Proc. Natl Acad. Sci.* **120** e2210417120
Mann H B 1945 Nonparametric tests against trend *Econometrica: Journal of the Econometric Society* **13** 245–59
Meals D W, Spooner J, Dressing S A and Harcum J B 2011 Statistical analysis for monotonic trends *Tech Notes 6* 1–23 URL: https://www.epa.gov/nps/nonpoint-source-monitoring-technotes
Migeot V, Albouy-Llaty M, Carles C, Limousi F, Strezlec S, Dupuis A and Rabouan S 2013 Drinking-water exposure to a mixture of nitrate and low-dose atrazine metabolites and small-for-gestational age (SGA) babies: a historic cohort study *Environ. Res.* **122** 58–64
Moore E, Matalon E, Balazs C, Clary J, Firestone L, De Anda S and Luu P 2011 *The human costs of nitrate-contaminated drinking water in the San Joaquin Valley* ISBN:1-893790-31-2
Nebraska Association of Resources Districts 2025 NRD groundwater quantity and quality regulations *Groundwater quality regulations across Nebraska* URL: https://www.nrdnet.org/programs/water
Nebraska Department of Water, Energy, and Environment 2021 *Nebraska Groundwater Quality Clearinghouse* URL: https://clearinghouse.nebraska.gov (Accessed 25-Aug-2022)
Nebraska Department of Water, Energy, and Environment 2021 *DWEE launches the Nebraska Groundwater Quality Clearinghouse* URL: https://dee.nebraska.gov/news-events/press-releases/dwee-launches-nebraska-groundwater-quality-clearinghouse (Accessed 25-Aug-2022)
Nebraska Department of Health and Human Services 2018 *Nebraska public water supply program summary report*
Nebraska Department of Health and Human Services 2021 *DHHS launches low income household water assistance program* URL:https://dhhs.ne.gov/Pages/DHHS-Launches-Low-Income-Household-Water-Assistance-Program.aspx (Accessed 4-Apr-2024)
Nebraska Legislature 2024 Adopt the Nitrogen Reduction Incentive Act and provide for a transfer from the Water Resources Cash Fund *LB1368* URL:https://nebraskalegislature.gov/bills/view_bill.php?DocumentID=55603 (Accessed 10-Jun-2025)
Neunzert Gaby M 2010 *Subdividing the land: metes and bounds and rectangular survey systems* (CRC Press) ISBN: 978-1439827475
Noguchi K, Gel Y R and Duguay C R 2011 Bootstrap-based tests for trends in hydrological time series, with application to ice phenology data *J. Hydrol.* **410** 150–61
Nolan B T, Ruddy B C, Hitt K J and Helsel D R 1998 A national look at nitrate contamination of ground water *Nutrients National Synthesis Project* 76–9 URL:https://pubs.usgs.gov/publication/70046294
Nolan J and Weber K A 2015 Natural uranium contamination in major US aquifers linked to nitrate *Environmental Science & Technology Letters* **2** 215–20
Önöz B and Bayazit M 2012 Block bootstrap for Mann-Kendall trend test of serially dependent data *Hydrol. Process.* **26** 3552–60
Pennino M J, Compton J E and Leibowitz S G 2017 Trends in drinking water nitrate violations across the United States *Environmental Science & Technology* **51** 13450–60
Randall G W, Huggins D R, Russelle M, Fuchs D, Nelson W and Anderson J 1997 Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop systems *J. Environ. Qual.* **26** 1240–7
Rauh E and Hughes S 2024 Collaboration for source water protection in the United States: community water systems engagement in nitrate pollution reduction *Wiley Interdisciplinary Reviews: Water* **11** e1682
Regnier J E 2014 The roles and effects of safety factors in small system water regulation *Journal-American Water Works Association* **106** 50–3
Ribaudo M O 1989 Targeting the Conservation Reserve Program to maximize water quality benefits *Land Economics* **65** 320–32
Richards J, Chambers T, Hales S, Joy M, Radu T, Woodward A and Baker M G 2022 Nitrate contamination in drinking water and colorectal cancer: exposure assessment and estimated health burden in New Zealand *Environ. Res.* **204** 112322
Roll K H 2019 Moral hazard: the effect of insurance on risk and efficiency *Agricultural Economics* **50** 367–75
Sainju U M, Stevens W B, Caesar-TonThat T and Montagne C 2014 Nitrogen dynamics affected by management practices in croplands transitioning from Conservation Reserve Program *Agron. J.* **106** 1677–89
Saint-Fort R, Schepers J and Spalding R 1991 Potentially mineralizable nitrogen and nitrate leaching under different land-use conditions in western Nebraska *Journal of Environmental Science & Health Part A* **26** 335–45

Schoengold K, Ding Y and Headlee R 2015 The impact of ad hoc disaster and crop insurance programs on the use of risk-reducing conservation tillage practices *American Journal of Agricultural Economics* **97** 897–919

State of Nebraska 2025 Municipal Boundaries *NebraskaMap* URL:https://www.nebraskamap.gov/datasets/nebraska::municipal-boundaries-1/about (Accessed 10-Jun-2025)

Schullehner J, Hansen B, Thygesen M, Pedersen C B and Sigsgaard T 2018 Nitrate in drinking water and colorectal cancer risk: a nationwide population-based cohort study *International Journal of Cancer* **143** 73–9

Smith V H and Goodwin B K 1996 Crop insurance, moral hazard, and agricultural chemical use *American Journal of Agricultural Economics* **78** 428–38

Spalding R F and Exner M E 1993 Occurrence of nitrate in groundwater—a review *J. Environ. Qual.* **22** 392–402

Spor Leal L B, Roy T, Uden D R and Schoengold K 2024 Hydrological impacts of the Conservation Reserve Program—a mini review *Frontiers in Water* **6** 1506255

Syswerda S, Basso B, Hamilton S, Tausig J and Robertson G 2012 Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA *Agriculture, Ecosystems & Environment* **149** 10–9

Temkin A, Evans S, Manidis T, Campbell C and Naidenko O V 2019 Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water *Environ. Res.* **176** 108442

United States Environmental Protection Agency 2024 Commercial fertilizer purchased URL: https://www.epa.gov/nutrientpollution/commercial-fertilizer-purchased (Accessed 01-Jan-2024)

United States Environmental Protection Agency 2025 USDA water grants and loans available to water and wastewater utilities *Federal funding for water and wastewater utilities in national disasters* URL: https://www.epa.gov/fedfunds/usda-water-grants-and-loans-available-water-and-wastewater-utilities (Accessed 26-Jun-2023)

United States Congress 2005 *Energy Policy Act of 2005* 1–27 Public Law 109-58. URL: https://www.govinfo.gov/app/details/PLAW-109publ58

United States Environmental Protection Agency 2022 *National primary drinking water regulations* URL:https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations (Accessed 26-Jun-2023)

United States Environmental Protection Agency 2024a *Clean Water Act section 404 and agriculture* URL:https://www.epa.gov/cwa-404/clean-water-act-section-404-and-agriculture (Accessed 26-Jun-2023)

United States Environmental Protection Agency 2024b *Potential well water contaminants and their impacts* URL:https://www.epa.gov/privatewells/potential-well-water-contaminants-and-their-impacts (Accessed 26-Jun-2023)

United States Congress 2007 *Energy Independence and Security Act of 2007* Public Law 110-140. URL: https://www.govinfo.gov/app/details/PLAW-110publ140 (Accessed 23-Jul- 2023)

Vedachalam S, Mandelia A and Heath E 2018 *Source water quality and the cost of nitrate treatment in the Mississippi River Basin* The Northeast-Midwest Institute URL:http://www.nemw.org/

Vedachalam S, Mandelia A J and Heath E A 2019 The impact of source water quality on the cost of nitrate treatment *AWWA Water Science* **1** e1011

Vogt R J, Akin H, Burkhart-Kriesel C A, Lubben B, McElravy L, Meyer T L and Tupper A 2022 *Nonmetropolitan Nebraskans' opinions about water, climate, and energy: 2022 Nebraska Rural Poll results* URL: https://digitalcommons.unl.edu/ruralpoll/2/

Weyer P J, Cerhan J R, Kross B C, Hallberg G R, Kantamneni J, Breuer G and Lynch C F 2001 Municipal drinking water nitrate level and cancer risk in older women: the Iowa women's health study *Epidemiology* **12** 327–38

Xu Y 2022 Clean water doesn't come cheap: Nebraska towns are shelling out millions to treat nitrate-laced drinking water *Flatwater Free Press* URL: https://flatwaterfreepress.org/nitrates-costly/ (Accessed 26-Jun-2023)

Yin D, Wang L, Zhu Z, Clark S S, Cao Y, Besek J and Dai N 2021 Water quality related to Conservation Reserve Program (CRP) and cropland areas: evidence from multi-temporal remote sensing *Int. J. Appl. Earth Obs. Geoinf.* **96** 102272

Zhang Y, Cabilio P and Nadeem K 2016 Improved seasonal Mann–Kendall tests for trend analysis in water resources time series *Fields Institute Communications* **78** 215