NEBRASKA NITRATE IN DRINKING WATER STUDY

Final Report

November 2024

NEBRASKA

DEPT. OF ENVIRONMENT AND ENERGY

SFY 2023-2024 Water Quality Study: Final Project Report

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Nebraska Department of Health and Human Services (NDHHS) Public Health Environmental Laboratory: This lab is sending out all the nitrate test kits associated with the project, providing the laboratory analyses for the kits when they are returned, and sending the results out to the private well owners.

Olsson: Contractor assisting NDEE with outreach, report writing, guidance documents, and the development of an interactive, web-based geographic information system (GIS) tool.

Natural Resources Districts (NRDs): The NRDs have selected representatives from two NRDs, specifically the Upper Niobrara White NRD and the Upper Republican NRD, to serve on the external advisory group to NDEE and Olsson for the project.

University of Nebraska-Lincoln (UNL) Extension: Two representatives from UNL Extension with expertise in water quality and source water protection were selected to serve on the external advisory group to NDEE and Olsson for the project.

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Table of Contents

List of Tables

List of Figures and Maps

Appendices

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Acronyms

Abbreviation	Definition
AO	Administrative Order
ARPA	American Rescue Plan Act
BMP	Best Management Practice
CFR	Code of Federal Regulations
CSD	Conservation and Survey Division
CWS	Community Water System
CWSRF	Clean Water State Revolving Fund
DWSRF	Drinking Water State Revolving Fund
ED/R	Electrodialysis/reversal
GIS	Geographic Information System
IUP	Intended Use Plan
IX	Ion Exchange
MCL	Maximum Contaminant Level
MetHb	Methemoglobinemia
MRLC	Multiresolution Land Characteristics Consortium
MUD	Metropolitan Utility District
NAC	Nebraska Administrative Code
NDEE	Nebraska Department of Environment and Energy
NDHHS	Nebraska Department of Health and Human Services
NDNR	Nebraska Department of Natural Resources
NDOT	Nebraska Department of Transportation
NGIO	Nebraska Geographic Information Office
NLCD	National Land Cover Dataset
NTNCWS	Non-transient Non-community Water System
NRD	Natural Resources District
POE	Point of Entry
POU	Point of Use
PWS	Public Water System
RFP	Request for Proposals
RO	Reverse Osmosis
RWD	Rural Water District
SDWA	Safe Drinking Water Act
SDWIS	Safe Drinking Water Information System
SRF	State Revolving Fund
STC	Space Time Cube
SWP	Source Water Protection
TA	Technical Assistance
TFM	Technical, Financial, and Managerial
TNCWS	Transient Non-community Water System
UNL	University of Nebraska-Lincoln
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WHPA	Wellhead Protection Area
WHPP	Wellhead Protection Plan
WWAC	Water/Wastewater Advisory Committee

NDEE NITRATE STUDY

EXECUTIVE SUMMARY

During the 2023 legislative session, the Nebraska Legislature, at the request of Governor Jim Pillen, appropriated funding for the Nebraska Department of Environment and Energy (NDEE) to conduct a statewide water quality study (LB 814). The focus of the study is limited to nitrate in groundwater being used for drinking water. This document summarizes the findings of the study, gives background information on nitrate in Nebraska groundwater used for drinking water, and provides recommendations to address elevated nitrate concentrations in drinking water.

The overall goal of the water quality study is to provide an analysis and recommend viable solutions for nitrate-affected drinking water, including drinking water not regulated by the Safe Drinking Water Act (SDWA) (i.e. private domestic wells).

OBJECTIVES OF THE STUDY:

- Provide free nitrate test kits to private well owners to collect additional data on nitrate concentrations in private domestic wells.
- Analyze nitrate concentrations in Nebraska groundwater and identify trends and data gaps.
- Develop guidance and tools that prioritize areas of the state for program outreach with the goal of proactively addressing rising nitrate concentrations in community water systems (CWSs), including a guidance document for public water systems (PWSs).
- Develop a guidance document to assist private domestic well owners in evaluating their risk of nitrate in drinking water and provide solutions to mitigate nitrate-affected water.
- Develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies. This includes modeling to identify high-risk areas, and an interactive, web-based geographic information system (GIS) tool for internal NDEE and key agency partner use.

This document is broken into three sections with corresponding border colors:

OVERALL NITRATE STUDY INFORMATION	INFORMATION RELATED TO PUBLIC WATER SYSTEMS	INFORMATION RELATED TO PRIVATE DOMESTIC WELLS

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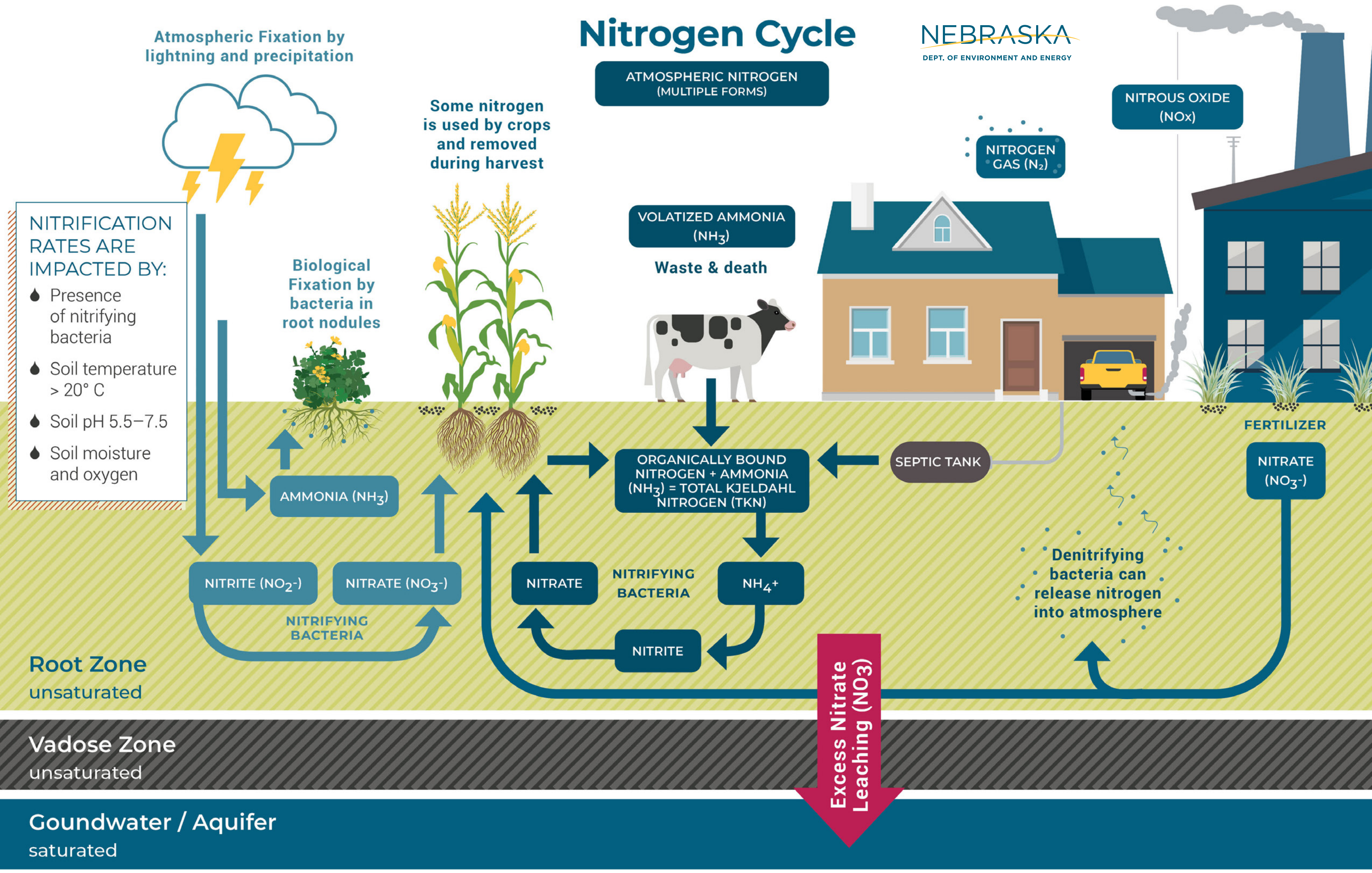
NDEE NITRATE STUDY

WHAT IS NITRATE?

Nitrate is a naturally occurring compound, but **elevated nitrate concentrations in groundwater used for drinking water are a risk to public health.** Excess nitrogen application at the surface impacts groundwater over time.

Depending on local geology, it can take as little as a year or more than 50 years for nitrate to reach groundwater. **Once it reaches groundwater, nitrate can persist for decades.**

Inorganic and organic sources of nitrogen can become nitrate over time. In the soil and water this material combines with oxygen to form nitrate. The figure below shows the pathways nitrogen can take in the environment to become nitrate in the aquifer.



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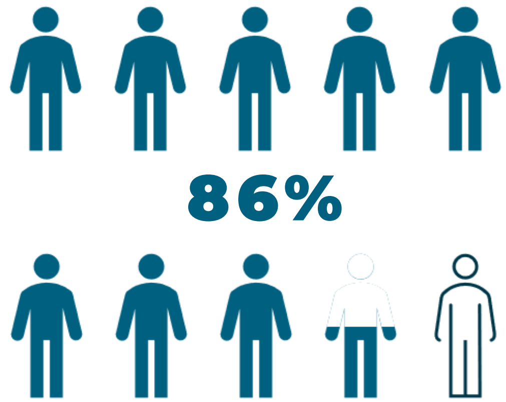
NDEE NITRATE STUDY

NITRATE IN NEBRASKA GROUNDWATER

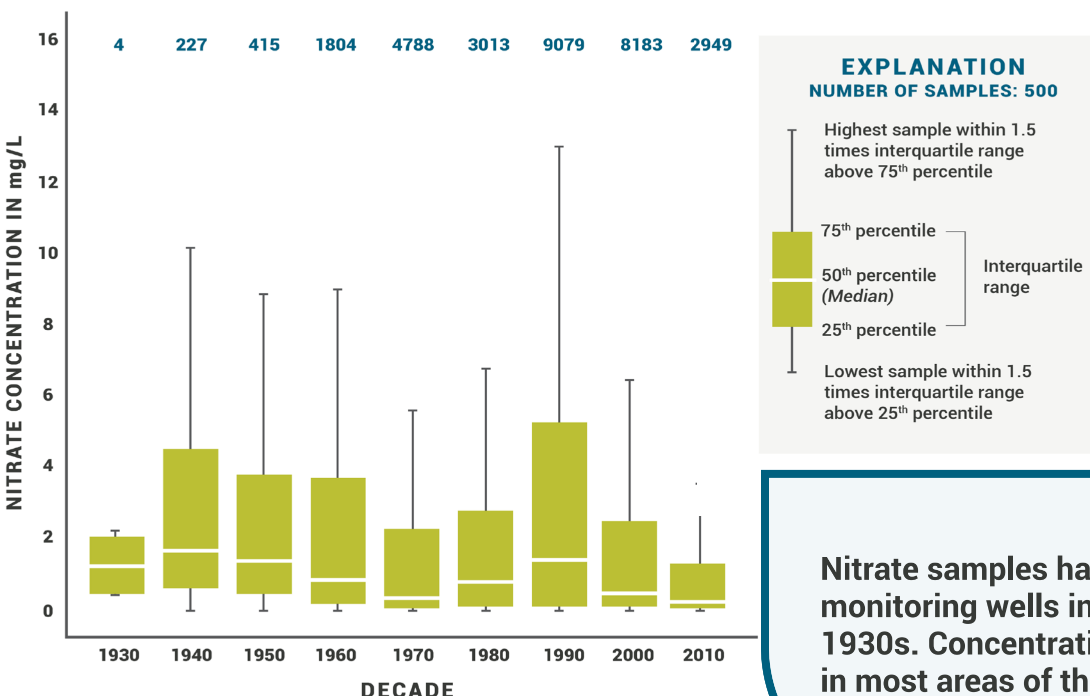
Many Nebraskans rely on groundwater for drinking water. Nitrate contamination in groundwater has been a persistent issue in Nebraska. Increases in nitrate concentration have been reported since the 1930s in areas like the Upper Elkhorn and Central Platte River basins. Because of oxygen levels in groundwater across much of Nebraska, when nitrate leaches past the root zone, it can remain in groundwater for decades. This study largely affirms the existing research into the extent of the problem and seeks to provide viable solutions for nitrate-affected drinking water.

GROUNDWATER IS THE PRIMARY DRINKING WATER SOURCE FOR NEARLY NINE OF EVERY TEN NEBRASKANS.



NEBRASKA NITRATE CONCENTRATIONS BY DECADE

USGS Monitoring Wells 1930-2019



NDEE collaborates with Natural Resource Districts (NRDs) and the University of Nebraska to maintain a Clearinghouse database for water quality data from wells across the state. Data in the Clearinghouse spans 1969 to 2023, however, due to process changes, the record from 2020 to 2024 is incomplete and is a data gap identified by this study.

Nitrate samples have been collected in monitoring wells in Nebraska since the 1930s. Concentrations have increased in most areas of the state since then.

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NDEE NITRATE STUDY

NITRATE STUDY DATA ANALYSIS

The water quality study analyzed available nitrate samples from wells across Nebraska to identify areas of concern, collected additional data on nitrate in private domestic wells, and identified trends in nitrate concentrations in community water systems.

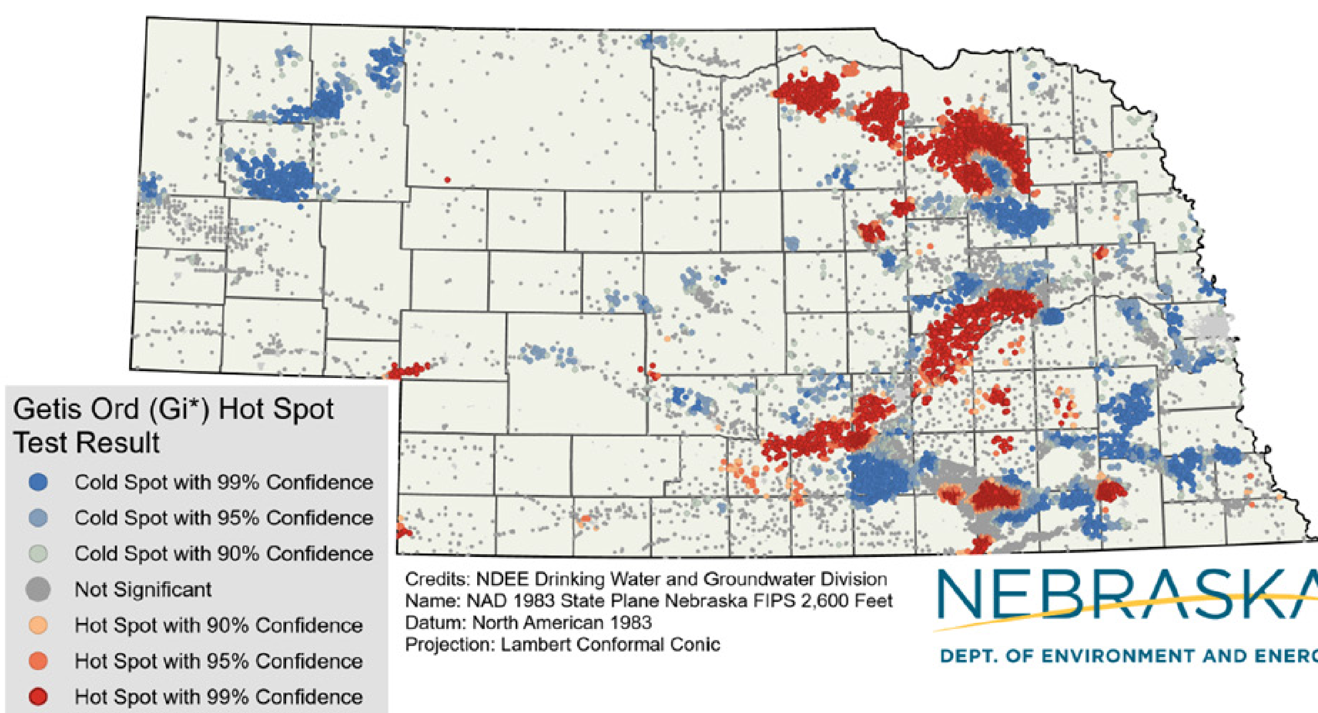
Statistical analysis conducted during the water quality study identified areas with elevated nitrate concentrations consistent with the existing body of research in Nebraska. Relative nitrate hot and cold spots in the state are shown in the figure shown below. Clusters of dots in red represent high concentration nitrate samples taken from wells grouped together based on location and concentration. Blue dots represent low concentration samples taken from wells grouped in the same way. Grey dots represent samples not identified as hot or cold spots by this test.

NITRATE DATA & TREND ANALYSIS

REVIEW BY AGENCY EXPERTS & PARTNERS

DATA-INFORMED RECOMMENDATIONS TO ADDRESS NITRATE-AFFECTED DRINKING WATER

RELATIVE NITRATE HOT & COLD SPOTS IN NEBRASKA



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NDEE NITRATE STUDY

NITRATE IN DRINKING WATER REGULATORY BACKGROUND

- NDEE is the primacy agency responsible for enforcement of the Safe Drinking Water Act (SDWA) in Nebraska.
- Nitrate is a regulated contaminant under the SDWA.
- The SDWA established maximum contaminant level (MCL) for nitrate in Public Water Systems (PWSs) is 10 milligrams per liter.
  - Concentrations of nitrate in drinking water above the MCL are dangerous to infants, who may develop methemoglobinemia, also known as blue baby syndrome.
  - Since the MCL for nitrate was originally established, additional research has examined other potential health effects from consuming nitrate in drinking water, such as cancer.

PRIVATE DOMESTIC WELLS ARE NOT REGULATED BY THE SDWA.

However, they are an important source of drinking water for many Nebraskans, and this study provides information and tools that private domestic well owners can use to evaluate their risk of elevated nitrate concentrations.

PWSs THAT REPEATEDLY VIOLATE THE MCL FOR NITRATE:

- Must notify customers within 24 hours, and provide an alternate source of drinking water for vulnerable populations, including pregnant women and infants.
- Can be legally compelled, by Administrative Order (AO), to provide SDWA compliant drinking water by NDEE. This often requires an engineered solution like a treatment plant or new well.
- Engineered solutions are expensive, particularly for small water systems, which are the majority of systems in Nebraska.

Note: The public can access water quality data for their community at https://drinkingwater.ne.gov.

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INFORMATION RELATED TO PUBLIC WATER SYSTEMS

PUBLIC WATER SYSTEMS (PWSs)

THE WATER QUALITY STUDY ACCOMPLISHED THE FOLLOWING RELATING TO PWSs:

- Analyzed nitrate concentrations in Community Water Systems (CWSs) and summarized these results in an individualized report for each community.
- Identified earlier opportunities for state assistance than the current process.
- Developed a priority system NDEE can use to proactively connect CWSs with voluntary programs to address nitrate and avoid costly engineered solutions.
- Identified key data gaps:
  - Wellhead protection areas, used by communities to proactively address contaminants, are not up-to-date for all PWSs. Updates are ongoing.
  - Service areas for PWSs (where they serve water to customers) are not currently available for the state, which limits the study of regionalization. Regionalization, where two or more PWSs connect to each other, can be a cost-effective solution to address nitrate.

KEY STUDY RECOMMENDATIONS RELATING TO PWSs:

- Conduct a regionalization study on PWS consolidation to address nitrate issues. Larger consolidation efforts have been shown in other states to dramatically reduce the cost of regionalization on a per-service basis i.e., the cost borne by system ratepayers.
- Incorporate the CWS priority system developed during the study into program planning and expand to other PWSs. It is a tool and set of metrics NDEE can use to proactively assist PWSs facing rising or elevated nitrate in drinking water.
- Continue to encourage voluntary BMPs as a way of reducing or preventing elevated nitrate concentrations in groundwater used for drinking water.

STATE PROGRAMS ARE EFFECTIVE AT ADDRESSING NITRATE ON DIFFERENT TIMESCALES

0-3 Years

Short-term engineered solutions like new wells or treatment plants. Low interest rate financing and loan forgiveness are potentially available through the State Revolving Fund (SRF) program and partner agencies like USDA.

3-10 Years

Mid-term technical assistance (TA) and capacity building. Engineering planning grants may be available through the SRF program, and TA providers can work with systems to plan for improvements and upgrades over time.

10+ Years

Long-term source water and wellhead protection planning. Funding and TA are available through the Drinking Water Division to assist communities with long-term planning and voluntary management efforts that can prevent the need to implement expensive, engineered solutions.

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INFORMATION RELATED TO PUBLIC WATER SYSTEMS

COMMUNITY WATER SYSTEM (CWS) NITRATE PRIORITY TOOL

NITRATE DATA & TREND ANALYSIS

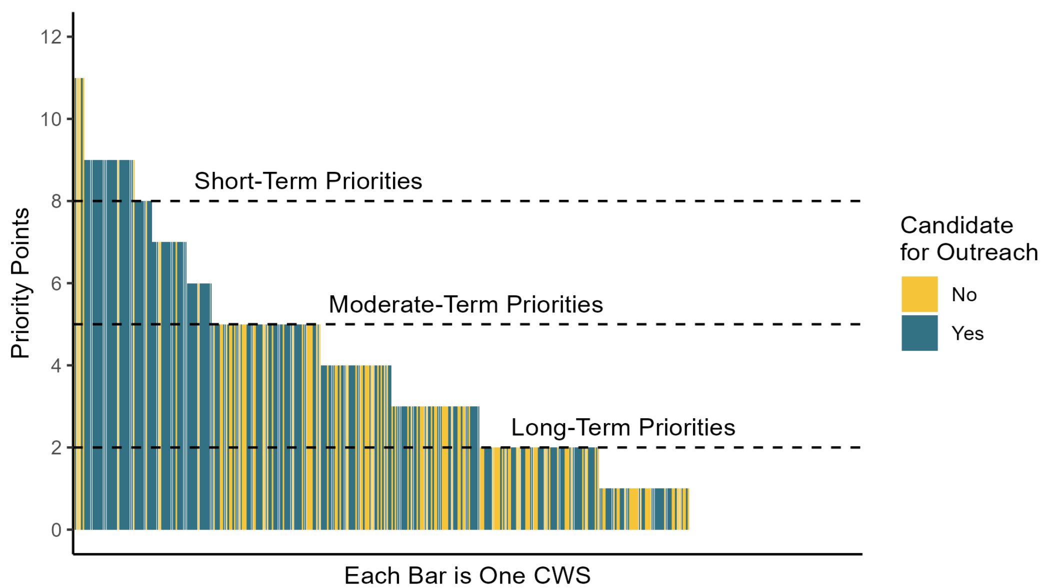
PRIORITY POINTS CALCULATIONS

RANKING BY TOTAL POINTS

1. SHORT-TERM PRIORITIES
2. MID-TERM PRIORITIES
3. LONG-TERM PRIORITIES

The CWS Nitrate Priority Tool is something NDEE can use to identify systems for state program assistance, such as targeted outreach to encourage long-term planning programs to help communities in Nebraska avoid expensive engineered solutions. This metric could also help NDEE track progress on the issue internally.

Nitrate Priority Points Distribution



NDEE analyzed nitrate sample results from CWS to develop a priority score that includes long-term trend analysis and recent water quality data. Higher scores indicate a more immediate-term risk of falling out of compliance with the SDWA.

In conducting the analysis NDEE identified over 170 systems **(in yellow above)** who are working with or have worked with NDEE and partner agencies to address nitrate.

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INFORMATION RELATED TO PRIVATE DOMESTIC WELLS

PRIVATE DOMESTIC WELLS: BACKGROUND

PRIVATE DOMESTIC WELL REGULATIONS:

- Private domestic wells are not regulated by the SDWA and in most counties, there is no requirement to sample them for nitrate. NDEE estimates fewer than 10% of domestic wells are sampled annually for nitrate.
- Prior to 1993, private domestic wells were **not** required to register with the state. Based on population data and registration records, NDEE estimates as many as 110,000 private domestic wells are unregistered in Nebraska.
- NDEE sets well construction standards and certifies well drillers. Natural Resource Districts and counties may set additional rules and requirements for domestic wells.
- Available data suggests around 17% of private domestic wells in the state exceed the SDWA nitrate standard.

ADDRESS NITRATE IN DRINKING WATER:

- Boiling water does not remove nitrate, it concentrates it.
- Home treatment systems, such as reverse osmosis filters, are effective at removing nitrate from drinking water.
- A rebate program provided financial assistance to private domestic well owners for installation of a reverse osmosis treatment system if the nitrate level in their well was above 10 mg/L. The application period opened in January 2023 and closed on June 30, 2024 with installations needing to be completed by September 30, 2024.

Private wells used for drinking water are known as Private Domestic Wells. They are not regulated under the SDWA, but they provide drinking water for nearly 20% of Nebraskans.

ABOUT ONE IN FIVE NEBRASKANS RELY ON A PRIVATE DOMESTIC WELL FOR DRINKING WATER.

NDEE ESTIMATES FEWER THAN 10% OF DOMESTIC WELLS ARE SAMPLED ANNUALLY FOR NITRATE.

PRIVATE DOMESTIC WELL OWNERS can use tools developed during the water quality study to evaluate their risk of elevated nitrate in drinking water. A guidance document was developed by NDEE to assist private domestic well owners.

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INFORMATION RELATED TO PRIVATE DOMESTIC WELLS

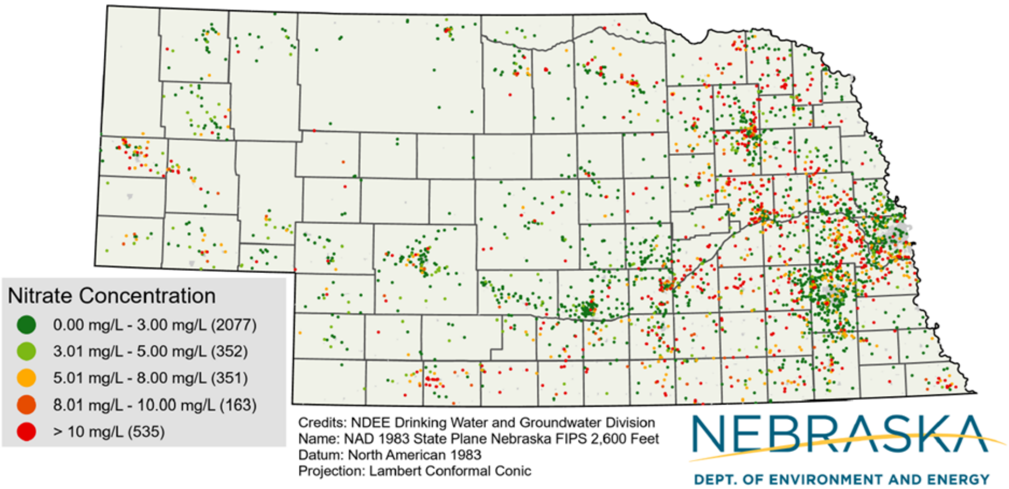
NDEE OVERSAW THE LARGEST PRIVATE DOMESTIC WELL NITRATE SAMPLING EFFORT IN NEBRASKA HISTORY.

Postcards were sent to 29,000 registered private domestic well owners inviting them to request kits. NDEE promoted the effort through press releases and the media to reach unregistered private domestic well owners.

Over 4,500 kits were requested and more than 3,400 were returned for analysis.

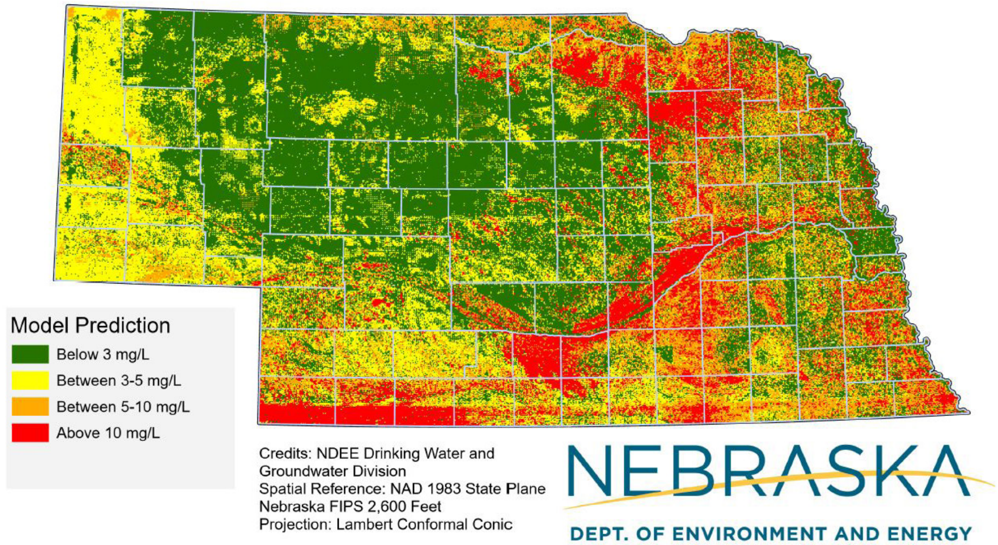
These data provide an invaluable snapshot of nitrate levels in private domestic wells across the state.

3,478 Private Domestic Well Nitrate Samples from the 2023-2024 Free Nitrate Sampling Effort



The average nitrate concentration for the samples collected as part of the free sampling effort was 4.83 mg/L. Around 15% of the samples were above the SDWA standard of 10 mg/L.

Predictive Nitrate Model Results: Composite Layer in Terms of Nitrate Concentration



NDEE conducted modeling to identify high-risk areas in Nebraska and developed a web-based nitrate risk assessment tool as an internal resource for NDEE and key agency partners.

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INFORMATION RELATED TO PRIVATE DOMESTIC WELLS

PRIVATE DOMESTIC WELLS

THE WATER QUALITY STUDY ACCOMPLISHED THE FOLLOWING RELATING TO PRIVATE DOMESTIC WELLS:

- Started a free, statewide sampling program for all private domestic well owners to help fill a needed data gap. Over 4,500 nitrate test kits were requested. NDEE staff fielded over 2,500 calls to discuss nitrate sample results and provide assistance to those who needed it.
- Analyzed nitrate concentrations in Nebraska groundwater and identified key data gaps including a large number of unregistered wells and ongoing updates to the Clearinghouse.
- NDEE and partners developed guidance documents and an outreach toolbox to assist private domestic well owners with sampling, interpreting results, and addressing nitrate contamination in drinking water.
- NDEE conducted modeling to identify high-risk areas where private domestic wells are likely to exceed threshold concentrations like the 10 mg/L SDWA limit and developed a GIS risk assessment tool as an internal resource for NDEE and key agency partners.

KEY STUDY RECOMMENDATIONS RELATING TO PRIVATE DOMESTIC WELLS:

- Updates to the Clearinghouse are ongoing and it is important they be completed. Currently, there is a 3-year backlog in this data, which is used by many stakeholders.
- Historic data for private domestic wells is limited, and many of the samples that have been taken are not currently publicly available. When the Clearinghouse changes are finalized, NDEE should make data collected during this study available. Additionally, work should be continued to increase private domestic well testing.
- Continue to develop and refine risk communication tools developed during the study to provide a clear, unified message from NDEE and its partners on nitrate. Identify funding to continue private well sampling and treatment programs.
- Create a database of likely unregistered well locations and owner contact information.
- Increase well registrations by reducing obstacles for registration.

NDEE encourages private domestic well owners to sample their well annually for nitrate and bacteria.

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1.0 INTRODUCTION/BACKGROUND

During the 2023 legislative session, the Nebraska Legislature, at the request of Governor Jim Pillen, appropriated funding for the Nebraska Department of Environment and Energy (NDEE) to conduct a statewide water quality study (LB 814). The focus of the study is limited to nitrate in groundwater being used for drinking water.

Groundwater is the primary drinking water source for Nebraskans. Groundwater is the source of more than 85 percent of the state's population's drinking water. If the consumers of drinking water provided by the Metropolitan Utilities District (MUD) surface water treatment plant on the Missouri River are excluded, the number jumps to 99 percent. Groundwater is of particular importance to rural Nebraska, where homeowners are likely to rely on private domestic wells. Of the approximately 1,960,000 people living in Nebraska, over 1,600,000 are served their drinking water by community water systems (CWSs). Therefore, it is estimated that approximately 360,000 Nebraskans depend on private domestic wells for their drinking water. Assuming approximately 2.5 people per household, there are approximately 145,000 private domestic wells statewide. Of these, approximately 35,000 are registered and active, leaving approximately 110,000 unregistered private domestic wells in the state (NDEE, 2023a). The NDEE regulates public water systems (PWSs) consistent with the Safe Drinking Water Act (SDWA), but private domestic wells serving less than 25 people and 15 service connections are not regulated by the SDWA. Private domestic well owners are not required by federal or state regulations to report on water quality and, until 1993, were not required by the state to register their private domestic wells (NDNR, 2023). Three kinds of PWSs are regulated by the SDWA: (1) community water systems (CWSs), (2) transient non-community water systems (TNCWSs), and (3) non-transient non-community water systems (NTNCWSs). The flow chart displayed in Figure 1 illustrates how the CWS, TNCWS, and NTNCWS designations are determined and the number of each type in Nebraska.

The SDWA was established in 1974 and authorizes the U.S. Environmental Protection Agency (USEPA) to set minimum standards to protect drinking water quality. The SDWA sets standards for contaminants in drinking water, establishes monitoring and reporting requirements, and requires public notification of water quality issues. Maximum contaminant levels (MCLs) are the highest permissible concentration of a contaminant in drinking water compliant with the SDWA and are a health-based measure. Each PWS must comply with established MCLs to protect public health, and violations may lead to enforcement actions. NDEE is the primacy[1] agency in the state responsible for enforcement of the SDWA. The SDWA MCL for nitrate is 10 milligrams per liter nitrate-nitrogen (mg/L NO_3-N; Title 40 Code of Federal Regulations [CFR] Part 141.62). Nitrate is a serious concern for infants under six months of age, whose bodies do not process nitrate in the same way as adults. Infants who consume water with nitrate concentrations above the MCL risk developing methemoglobinemia, sometimes called blue baby syndrome (USEPA, 2006). Women who are pregnant are advised to contact their doctor if they have questions about health risks from potential nitrate exposure. PWSs that exceed the nitrate MCL are required to notify consumers within 24 hours of a violation and provide an alternate source of drinking water to susceptible populations including infants and pregnant people (40 CFR 141.31). Nitrate is not removed by boiling water or water softening and is not removed by all commercial water filters, such as activated carbon filters or common pitcher-style filters not specifically certified for nitrate removal. There are 1,334 PWSs in Nebraska, including 595 CWSs, 137 NTNCWSs, and 602 TNCWSs (NDEE, 2023a). PWSs sample for nitrate from their

[1] NDEE has primacy which means they have the authority to implement and enforce SDWA regulations. This requires demonstrating that NDEE standards are at least as stringent as the federal standards and that NDEE can ensure that PWSs meet these standards.

compliance point annually at a minimum. The compliance point – also called a point of entry (POE) – represents the water people are drinking and not necessarily source water quality (i.e., treated water). Sampling frequency increases to quarterly if a sample exceeds 5 mg/L during routine monitoring. For a visual breakdown of PWS nitrate sampling requirements, intervention points, and the Administrative Order (AO) process, see the PWS flow chart in Section 8.0.

Public Water System Designation Summary

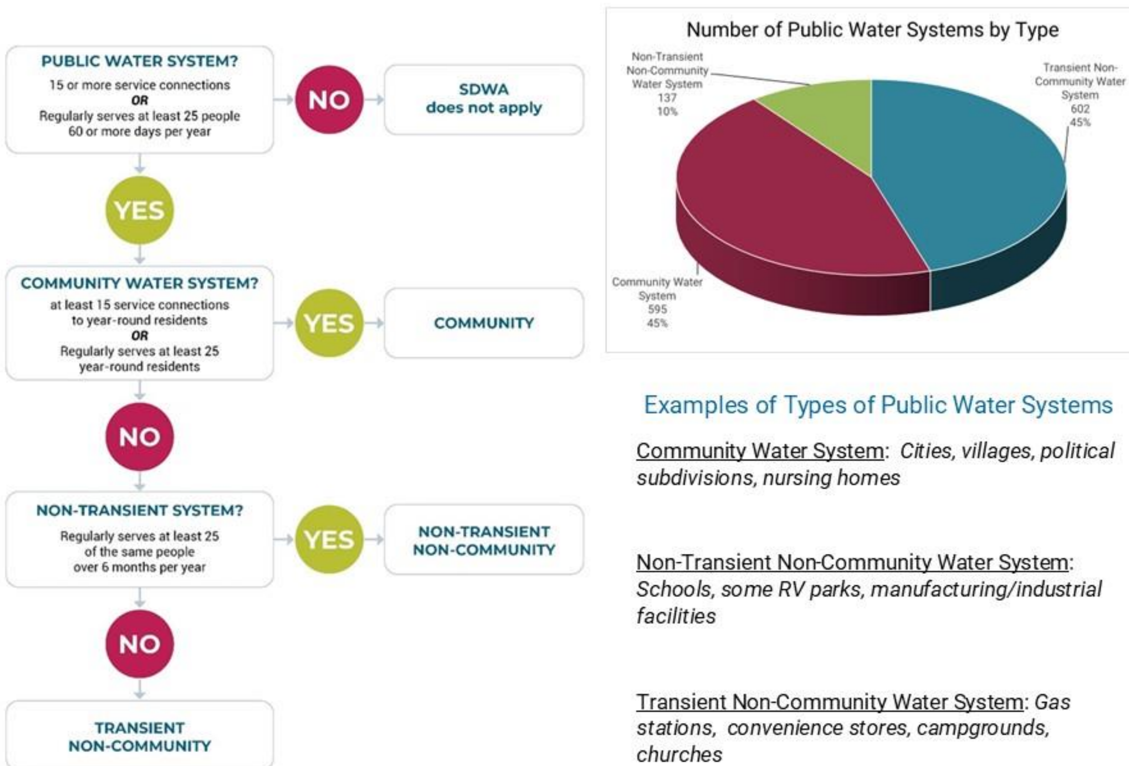

Figure 1. CWS, TNCWS, and NTNCWS Designation Flow Chart and Number of Each Type.

For many villages, cities, and other PWSs, an interconnection project may be the most sustainable and cost-effective solution for high nitrate concentrations in their source water. An example of such a project could involve a situation where one PWS stops using a source high in nitrate and connects to another PWS to purchase water meeting SDWA standards. In addition to regionalization, there are several effective treatment technologies that address elevated nitrate concentrations in drinking water. Reverse osmosis (RO), ion exchange (IX) filtration, and membrane separation processes such as electrodialysis/reversal (ED/R) have been implemented at both the PWS level and the homeowner level to remove nitrate from drinking water (USEPA, 2006). The Water/Wastewater Advisory Committee (WWAC) and the State Revolving Fund (SRF) assist with funding for drinking water treatment projects and regionalization projects in Nebraska that address nitrate issues in PWSs. WWAC is charged with coordinating the financial resources of the U.S. Department of Agriculture (USDA), USEPA, and NDEE to effectively use federal and state funding. Communities can apply to WWAC for funding or directly to the SRF or USDA. Developing new sources (i.e., drilling new wells) in an area that has a lower nitrate concentration is another funding-eligible option for communities to help them provide drinking water meeting SDWA requirements.

NDEE administers funding to provide planning and aid loans to small PWSs serving a population of 10,000 people or fewer. The vast majority of PWSs in Nebraska (1324, 99%) meet the definition of a small PWS, and most serve populations less than 500 (1088, 81%). Some small PWSs in Nebraska may not have the resources to proactively hire consulting engineers to provide technical assistance for their water planning needs. USEPA contracts technical assistance providers and can provide engineering services to small PWSs to help alleviate resource constraints. For the purposes of this report, small PWSs will be defined as those serving 10,000 people or fewer, consistent with EPA's definition.

There are currently seven CWSs and two NTNCWSs in Nebraska under an AO for nitrate as depicted in Figure 2. These PWSs are each subject to a legally enforceable schedule to address the elevated concentrations of nitrate in their drinking water consistent with the SDWA and state regulation. Several of these PWSs are on the SRF Intended Use Plan (IUP), where funding is prioritized for projects that address an AO. For a complete procedure of what happens when PWS samples first indicate elevated nitrate concentrations, see the PWS guidance document (Figure 20) and description in Section 8.0. In addition to treatment, long-term community planning and best management practices (BMPs) by landowners can help to reduce nitrate loading before it enters groundwater supplies, preventing possible MCL violations, AOs, and expensive drinking water infrastructure projects. NDEE administers four programs that help with this kind of planning: (1) 319 program nonpoint source planning and aid, (2) source water protection (SWP) planning and aid, (3) wellhead protection planning (WHPP), and (4) capacity development. SWP funding administered by the SRF has been used for more than 100 projects in Nebraska. Since 1990, NDEE has invested over $8 million to address nitrate contamination. Political subdivisions in Nebraska that operate a small PWS that can show financial hardship are invited to submit proposals for SWP projects each year following NDEE's publication of the SWP grant request for proposals (RFP). In 2023, funds were distributed to two PWSs. SWP works with the 319 program to engage Nebraskans in drinking water protection management plans that proactively address nonpoint sources of contamination. These collaborative efforts have been and continue to be used to address nitrate contamination.

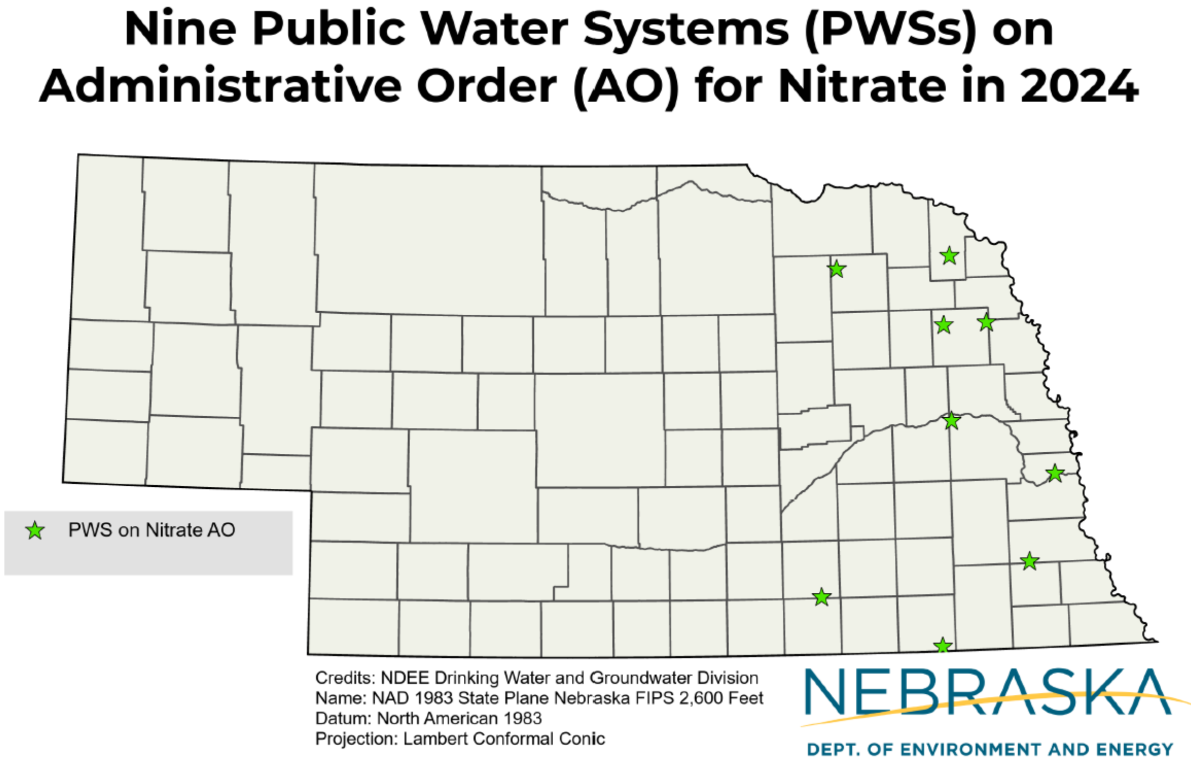

Figure 2. PWSs on an AO for Violating the Nitrate MCL.

NDEE delineates and updates wellhead protection areas (WHPAs) for all PWSs by request at no cost, using hydrogeologic data such as groundwater flow, recharge, and subsurface conditions to delineate a 20-year area of influence. PWSs may now request delineations out to a 50-year area of influence. PWSs can work with a contractor to delineate their WHPA, but the final WHPA must be approved by NDEE. WHPA delineation is always a scientific process, not a political one, though care is taken to align the WHPA with political boundaries for ease of implementation. Encroaching activities are not prohibited within a WHPA until such prohibitions are adopted by local ordinance. The WHPA provides a framework for communities to identify and address sources of contamination, including nitrate.

The SRF includes set-aside funding for technical assistance and capacity development. The Small System Technical Assistance set-aside (up to 2 percent of the capitalization grant) provides technical, managerial, and financial assistance to small PWSs. Capacity development is a proactive approach through which water systems acquire and maintain adequate technical, managerial, and financial capabilities, enabling them to sustainably provide drinking water meeting SDWA standards to Nebraskans. NDEE's activities to bolster water systems' capacities are overseen by the program's Capacity Development Coordinator.

A detailed accounting of the sources of nitrate across the State of Nebraska is outside the scope of this study. Substantial scholarship has been dedicated to the topic and is described briefly in the following section. A graphic description of the nitrogen cycle is provided to visualize common sources of nitrogen and pathways that nitrogen takes to become nitrate in groundwater (see Figure 3).

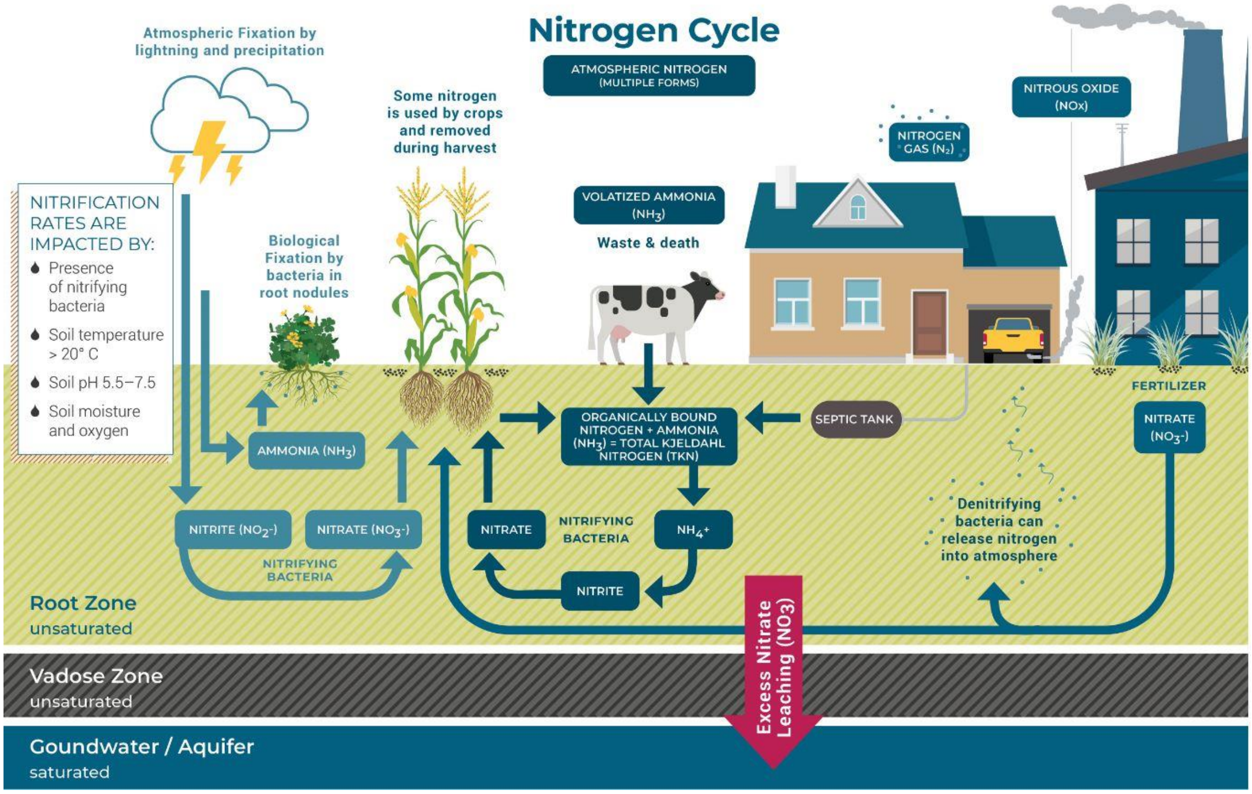

Figure 3. Nitrogen Cycle. (TKN = Total Kjeldahl Nitrogen)

Nitrogen takes multiple forms in the environment and comes from both organic and inorganic sources. Nitrogen typically enters the soil as ammonia where it is converted to nitrate under oxic conditions. Nitrate that occurs naturally in the environment is referred to as “background.” Nolan and Hitt (2003) report that background concentrations of nitrate in rangeland and grassland are between 2 and 3 mg/L. Studies of the High Plains aquifer (McMahon, 2007) have reported that 4 mg/L of nitrate is the highest observed background concentration in the system, with data going back to the 1930s. For this study, a conservative background level of 3 mg/L was assumed based on Nebraska land-use trends (mostly grassland) and to represent the top end of the transitional range between natural background and clear evidence of human contamination.

Nitrate has long been present in Nebraska groundwater. Areas such as the Upper Elkhorn River have reported nitrate concentrations exceeding the MCL since at least the 1970s (Spalding, 1978). Nitrate concentrations across the High Plains aquifer system have generally increased from the 1960s to present (Litke, 2001; McMahon, 2007).

Concentrations of nitrate in groundwater are stratified. The water table varies throughout the year, and upper levels of an aquifer may have different nitrate concentrations than deeper, older groundwater. In areas where groundwater and surface water are interconnected, flows from groundwater to surface water may “flush out” excess nitrate into streams and rivers (Wells, 2018; Malakar, 2023). Seepage from losing reaches and reservoirs may have the opposite impact. Additionally, the varying geology across Nebraska dramatically changes the rate at which nitrate reaches the aquifer (Cherry, 2019). The delay between surface loading and groundwater contamination can vary from years to decades. This means that implementing BMPs, while effective, can take substantial time to reduce nitrate concentrations (Exner, 2014).

While there are numerous studies looking to identify and mitigate nitrate contamination in the environment, this study is focused on ensuring Nebraskans are consuming drinking water that meets SDWA standards for nitrate. Although the SDWA does not regulate private domestic wells, studies have shown the most at-risk populations for exposure to nitrate contamination are those utilizing private domestic wells located in agricultural areas (Ward, 2018). The USEPA set the SDWA MCL for nitrate at 10 mg/L in 1991 based on numerous case studies of infantile methemoglobinemia (MetHb), also known as blue baby syndrome. These case studies were associated with wells containing nitrate concentrations above 10 mg/L, where nearly all the wells were shallow and tested positive for bacterial contamination. High gastric pH (above 5) and the presence of enteric bacteria are conducive to nitrate-to-nitrite conversion in the body.

Nitrate toxicity for humans is due primarily to its conversion to nitrite after ingestion occurs (Figure 4). Nitrite oxidizes iron in hemoglobin, a protein in red blood cells that carries oxygen, resulting in ferric ion or free iron, which is toxic. Oxygen can no longer bind to the hemoglobin because the free iron is already bound in its place, transforming it into methemoglobin. Concentrations of methemoglobin above 10% may lead to cyanosis, resulting in MetHb. In extreme cases of MetHb where the concentrations of methemoglobin exceed 25%, individuals may experience weakness, a rapid pulse, and abnormally rapid and shallow breathing, while concentrations above 50% may result in death (Jones et al., 1973).

The risk of MetHb from ingestion of nitrate depends on both the dose of nitrate consumed and the amount and type of enteric bacteria, as the bacteria is the main factor for mediating the conversion of nitrate to nitrite. Conversion of nitrate to nitrite mainly occurs in the stomach when the pH of gastric fluid is above five, allowing bacterial growth. Infants have naturally high pH levels, putting them at greater risk of MetHb along with adults suffering from gastric diseases that inhibit the production of gastric acid (USEPA, 1991).

Since the MCL for nitrate was originally established, there has been additional research looking at other potential health effects from consuming nitrate in drinking water. A literature review from Ward et al. (2018) of epidemiologic studies involving nitrate intake from drinking water found that the strongest evidence for a relationship between nitrate ingestion from drinking water and negative health outcomes (other than methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. In November 2023, as part of its undertaking of a reassessment of the health effects of nitrate and nitrate, the USEPA released *Protocol for the Nitrate and Nitrite IRIS Assessment (Oral) (Preliminary Assessment Materials)* for a 30-day public review and comment period. The draft protocol presents the methods for conducting the reassessment and states that the systematic review will focus on several health outcome categories, including cancer, that appear to have sufficient information available to support hazard identification based on the availability of animal and human studies identified during an updated literature search and other select resources described in the protocol document (USEPA, 2023). This reassessment could eventually lead to a revised MCL; however, the current MCL for nitrate in the SDWA is still 10 mg/L, which is based on the acute effect of methemoglobinemia in infants and other sensitive populations.

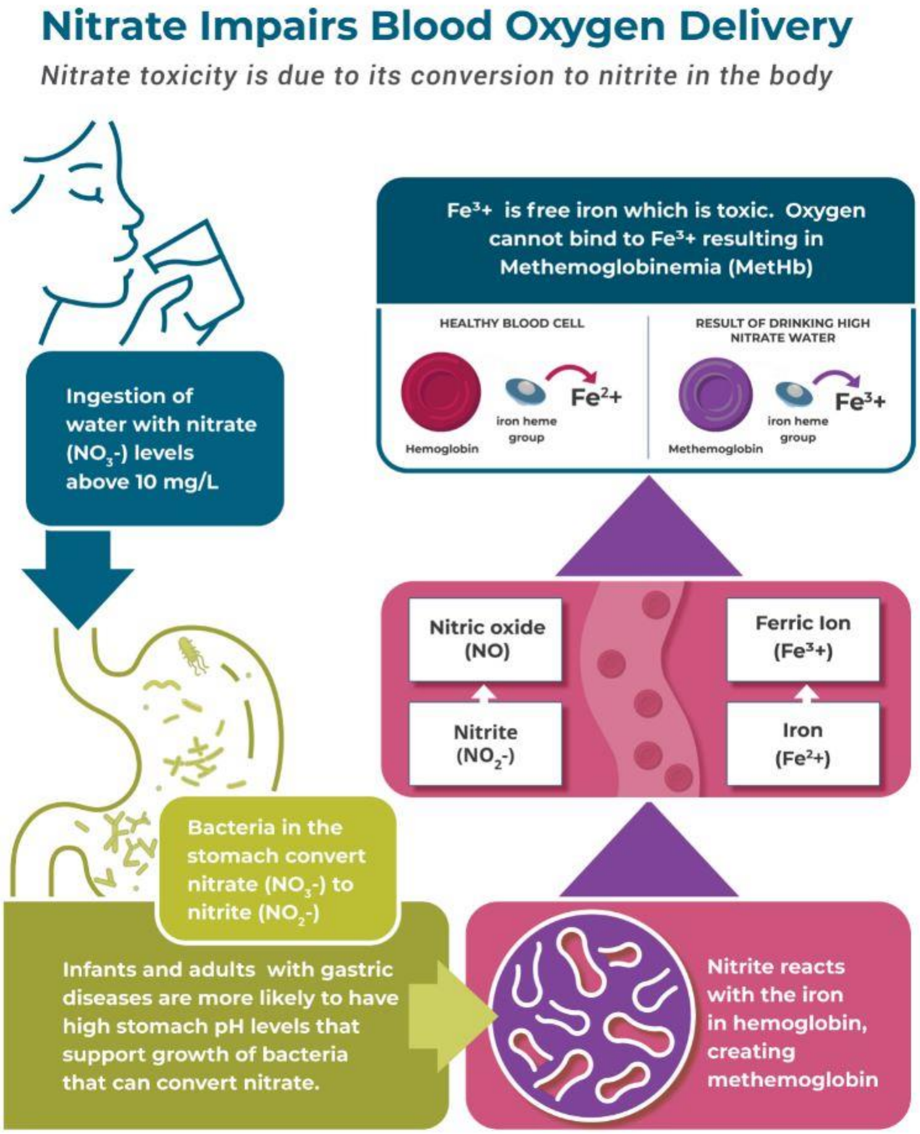

Figure 4. Nitrate Impairs Blood Oxygen Delivery.

2.0 SOURCES OF NITRATE IN GROUNDWATER

Isotope trace studies have been conducted in the state to identify the sources of nitrate in groundwater and to estimate recharge rates for the aquifer systems in Nebraska (Cherry, 2019; Snow, 2018a; Wells, 2018). Nitrate in groundwater can come from both point and nonpoint sources of pollution. A point source is a single identifiable source that directly pollutes water, i.e., typically you can “point” at a point source. Nonpoint source pollution is not from a single source, but instead comes from many sources spread over a large area. Anhydrous fertilizer and livestock manure application to cropland are two primary nonpoint sources of nitrogen in the soil and streams (Exner 2014; Spalding, 1993). Common point sources include improperly managed livestock facility waste, certain industrial facilities, and wastewater treatment facilities (ATSDR, 2017). Other sources of nitrate include fertilizers used on yards, gardens, and golf courses and septic systems, particularly failing septic systems. Modeling efforts across the United States have looked at nitrate in groundwater wells (Black, 2023; Borchardt, 2021; Nolan, 2014; Wellman, 2016). These studies illustrate some of the dynamics and factors influencing nitrate concentrations. They also identify important sources, the relative impact of those sources, and time scales that informed the modeling conducted as a part of this study (Appendix C).

Nitrate is more rapidly transported to groundwater under irrigated lands than non-irrigated lands. Irrigated crops typically receive more fertilizer application than non-irrigated crops and, therefore, have a higher nitrate soil concentration contributing to nitrate leaching (Exner, 2014; Malakar, 2023). Excess water from irrigation not taken up by crops pushes nitrate through the unsaturated vadose zone (Spalding, 2001). Irrigation wells built prior to construction standards were often constructed without a surface seal and have gravel pack along their entire casing. Wells such as these can act as conduits for water high in nitrate to move rapidly into lower levels of the aquifer (Driscoll, 1986). Factors such as soil infiltration and vadose zone thickness also play an important role in the rate of nitrate concentration changes across aquifers in the state (Exner, 2014; Litke, 2001; Malakar, 2023; Wells, 2018). Excessively drained soils and a lack of denitrifying conditions in the local geology are both closely related to the amount of nitrate in groundwater. Much of the state is underlain by the High Plains aquifer system, which has sufficient dissolved oxygen for nitrate to persist for decades (McMahon, 2007).

Land uses such as intensive agriculture and livestock operations have been identified by several studies as a contributor to nitrate contamination in surface water and groundwater (Lombard, 2021; Nolan, 2014; Wheeler, 2015). Garcia et al. (2017) and Wellman (2016) also identified areas with intensive agriculture and livestock operations as being at risk of higher groundwater nitrate concentrations. In a study on the legacy impacts of nitrogen fertilizer in Nebraska, Exner et al. (2014) found that in areas like the Tri-Basin Natural Resources District (NRD) management area south of the Platte River and the Upper Elkhorn River basin, nitrate levels may still be increasing from fertilizer overapplication that occurred decades ago. BMPs have been shown to reduce nitrate concentrations in parts of the central Platte River basin at a rate of around 0.25 mg/L per year (Exner, 2014).

3.0 NITRATE STUDY OBJECTIVES

The overall goal of the water quality study is to provide an analysis and recommend viable solutions for nitrate-affected drinking water, including drinking water not regulated by the SDWA. To achieve this goal, the following objectives were established:

- Provide free nitrate test kits to private domestic well owners to collect additional data on nitrate concentrations in private domestic wells.
- Analyze nitrate concentrations in Nebraska groundwater and identify trends and data gaps.
- Develop guidance and tools that prioritize areas of the state for program outreach with the goal of proactively addressing rising nitrate concentrations in CWSs, including a guidance document for PWSs.
- Develop a guidance document to assist private domestic well owners in evaluating their risk of nitrate in drinking water and provide solutions to mitigate nitrate-affected water.
- Develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies. This includes modeling to identify high-risk areas, and an interactive, web-based geographic information system (GIS) tool for internal NDEE and key agency partner use.

Table 1. Schedule for Implementation of Nitrate Study Tasks.

Task	SFY 2024			
	Q1	Q2	Q3	Q4
Agency Team Kickoff Meeting – Objectives and Goals	X			
Assemble NDEE Data and Analysis	X	X		
Free Sampling for All Private Domestic Well Owners		X	X	
Identify Partners & Stakeholders		X		
Contractor Kickoff Meeting		X		
Partners Engagement Meeting		X	X	
Interim Report			X	
Partners/Stakeholder Review GIS Tool & Offer Feedback				X
Final Report				X
Nitrate in Private Drinking Water Outreach Toolbox				X
GIS Web Tool (Internal NDEE and Key Partners)				X

4.0 FREE DOMESTIC WELL SAMPLING AND TREATMENT

One goal of the study was to provide free nitrate test kits to private domestic well owners to help fill a known data gap. NDEE sent postcards to more than 29,000 registered private domestic well owners to notify them of the free opportunity for analysis of their drinking water. Although there are more than 34,000 active registered private domestic wells, some owners have multiple wells registered to the same mailing address. The free nitrate sample kits and lab analyses were offered to all Nebraskans with a private drinking water well, including both registered and unregistered wells. Although a mass mailing to all registered private domestic well owners was a good way to target private domestic well owners, NDEE wanted to make sure that unregistered private domestic well owners were also aware of the free kits. Therefore, NDEE issued a press release advertising the free kits to help target unregistered private domestic well owners. This release was forwarded to all the NRDs in Nebraska, which helped share the information. Sample kits were available for request from November 29, 2023, through March 1, 2024. Additionally, NDEE fielded over 2,500 calls related to the free nitrate test kit effort. This allowed for direct connections to be made with private domestic well owners across the state and provided a direct method of outreach to better inform private domestic well owners about the risks associated with drinking water with nitrate levels above 10 mg/L, the importance of regularly testing your well, potential sources of nitrate in drinking water, and solutions that exist for addressing nitrate-affected drinking water. More information about the outreach associated with the free nitrate kits and the follow-up that occurred after well owners received their results is available in the outreach toolbox in Appendix D.

The Nebraska Department of Health and Human Services (NDHHS) Public Health Environmental Lab supplied the nitrate test kits for the free sampling effort and provided the analysis for all kits returned to the lab. This lab has been in business for over 100 years and is certified by the USEPA. This ensures the data from this lab is high quality and is both accurate and precise. The analytical method used by the lab for nitrate is *Lachat 10-107-04-1-A NO3 + NO2*. This method analyzes for both nitrate and nitrite and reports the result as nitrate/nitrite-nitrogen in mg/L. The reporting limit for this method is 0.05 mg/L.

The NDHHS Public Health Environmental Lab provided sampling instructions with the nitrate test kits. These instructions were intended for the private domestic well owner to be able to take their own sample without assistance from a technician. The process of collecting a sample is straightforward and not prone to error. Since the focus of the study is for Nebraskans to know what is in their drinking water and not specifically what is in untreated groundwater, well owners with a reverse osmosis system or other treatment system were not instructed to collect a raw water well sample. It was up to the well owner to determine if they wanted to collect a sample of their raw well water or their treated drinking water, if applicable. Because of this, some of the data associated with this sampling effort may not be representative of actual raw groundwater nitrate levels. Therefore, data associated with this study will be flagged as being part of the water quality study prior to being entered into the Clearinghouse to address any data quality concerns associated with uncertainties regarding where the sample was collected. Further discussion of data quality flags and the Clearinghouse is provided in Section 5.

As of May 1, 2024, a total of 4,508 sample kits were requested, and 3,499 kits were returned to the NDHHS Public Health Environmental Lab for analysis. A map displaying these results across the state is shown in Figure 5. Sample results were mapped based on the collection address provided by well owners. Figure 5 includes results from both registered and unregistered private domestic wells. A total of 3,499 samples were collected and 3,478 of were mapped. A total of 542 samples (15.5%) are above 10 mg/L and 535 of these samples are mapped. There are 21 samples not mapped because they fell outside of the state boundary or had an invalid address.

NDEE sent reminder emails to those who did not return their kit to encourage them to collect their sample and send it back as soon as possible. The number of kits returned by May 1, 2024, is more than four times the annual average (748) number of samples collected by private domestic well owners, and more than any year (peak of 882 in 2019) since records began. This volume of sample data obtained in a five-month period is nearly 30% of the amount of all known private domestic well samples collected between 2003 and 2022.

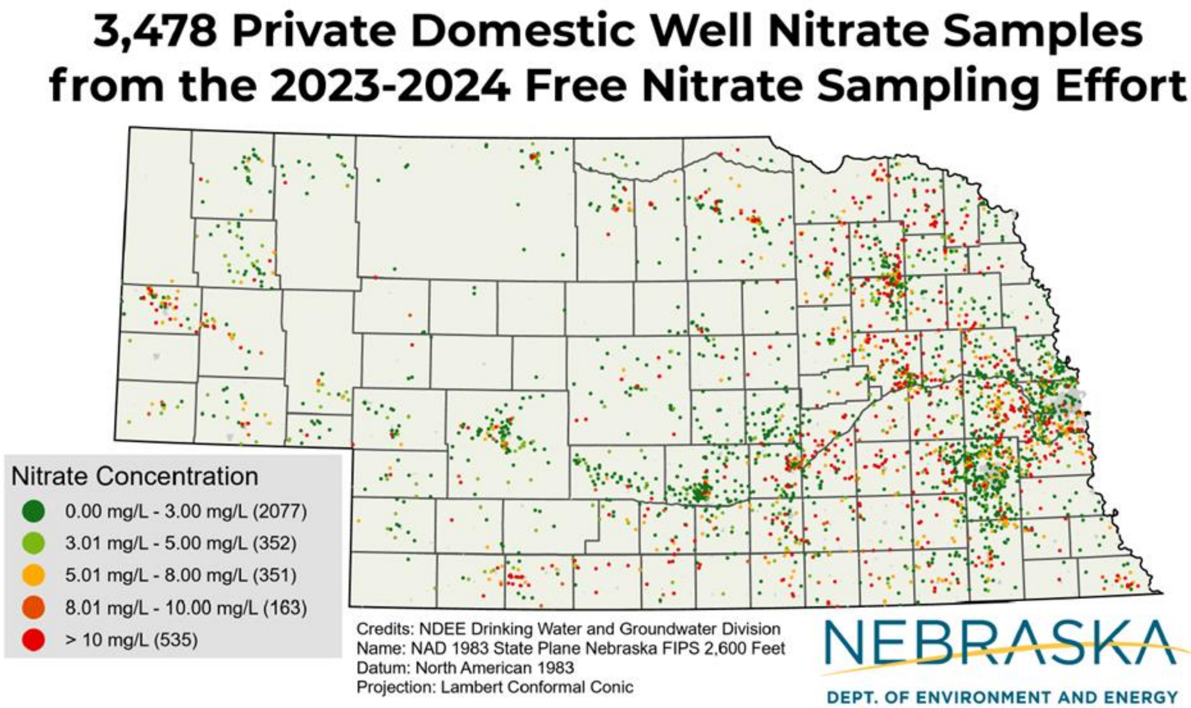

Figure 5. Free Private Domestic Well Sampling Results (as of May 1, 2024).

The median nitrate concentration for all samples collected during the free sampling effort that were returned for analysis by May 1, 2024, is 1.89 mg/L. Summary statistics for the private well sample data from the free sampling effort, NDHHS Public Health Environmental Lab, and the Clearinghouse are shown in Table 2. Of the samples collected for this study,15.5 percent (or 542 samples) are above 10 mg/L. The median concentration for samples collected during the free sampling effort was lower than the median concentration for domestic well samples collected and reported to the Clearinghouse from 2003 to 2019 (2.50 mg/L) and comparable to the median concentration of samples from the NDHHS records from 2010 to 2022 (0.98 mg/L). Data from the study will be incorporated into the Clearinghouse and will increase the available private domestic well samples by nearly 30 percent. The percentage of samples above 10 mg/L in the Clearinghouse from 2003 to 2019 was 24 percent—a larger proportion than the private domestic wells sampled for this study. A total of 866 samples above 10 mg/L (11.8%) were collected by private domestic well owners and analyzed by NDHHS Public Health Environmental Lab from 2010 to 2022.

Table 2. Comparison of Domestic Well Nitrate Data from Free Sampling, Clearinghouse, and NDHHS.

Data Source	Concentration (mg/L)			% of Samples Above 10 mg/L	Sample Count	Wells Sampled
	Mean	Median	Maximum			
Free Nitrate Test Kit Program Domestic Well Samples	4.83	1.89	170	15.5	3,499	3,499
NE Clearinghouse Domestic Well Samples 2003-2019	7.21	2.50	173	24.3	5,676	1,423
NDHHS Public Health Lab Nitrate Sample Records for Samples Requested by Domestic Well Owners 2010-2022	4.02	0.98	143	11.8	7,232	4,085

Two private domestic well owners from the private domestic well sampling effort agreed to follow-up analysis to identify sources of nitrate in private domestic wells used for drinking water. This follow-up analysis was offered to private domestic well owners who collected a nitrate sample exceeding 75 mg/L and to one owner who provided long-term nitrate data from their well that was increasing over time and provided a more typical example. Confirmation samples were collected by NDEE and NRD staff and analyzed at the NDHHS Public Health Environmental Lab. Samples for isotope analysis were collected by NDEE staff and returned on ice to the University of Nebraska-Lincoln (UNL) Water Resources Center within 24 hours of collection for analysis.

Isotope analysis, in combination with other water quality indicators, can help identify sources of nitrate in groundwater. Ratios of nitrogen and oxygen isotopes vary between sources of nitrogen. Figure 6, from Kendall (2008), plots the relative ranges of isotope ratios from common environmental sources of nitrogen. The ratio of nitrate isotopes is measured using the titanium trichloride reduction method (Altabet et al., 2019), which converts nitrate into nitrous oxide. The nitrous oxide is analyzed using a mass spectrometer based on U.S. Geological Survey (USGS) standards. Analyzing the ratio of isotopes for two case studies from the private domestic well sampling effort allows organic and inorganic sources of nitrogen to be identified and, in turn, informs us more about how nitrate is impacting these wells. At the time of this report, the isotope analysis results had not yet been received. NDEE plans to make this data available when analyses are complete.

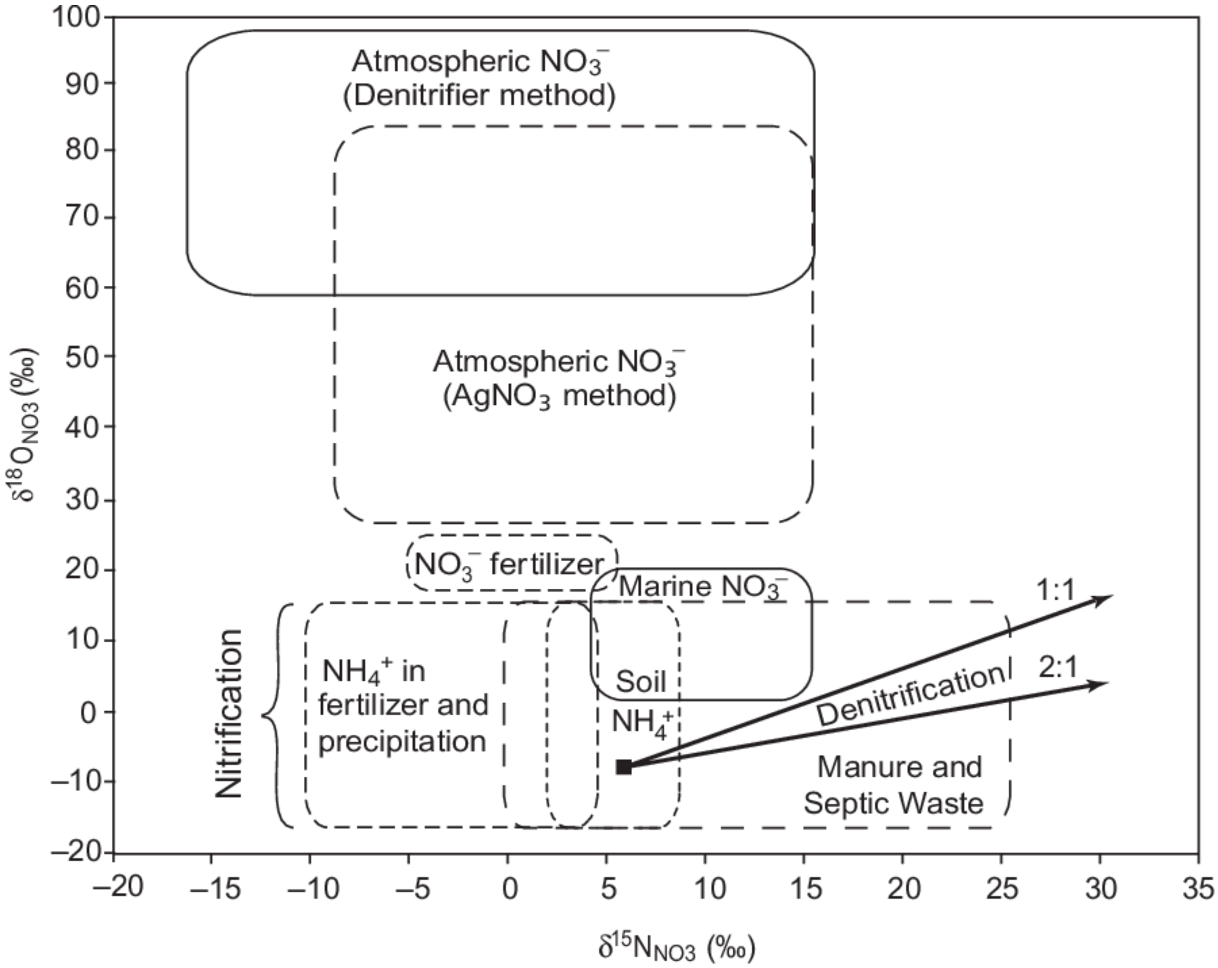

Figure 6. Nitrate Isotope Ratios by Source Type (Kendall, 2008).

A rebate program funded through the American Rescue Plan Act of 2021 (ARPA) provided financial assistance to private domestic well owners for installation of treatment systems for reduction of nitrate concentrations above 10 mg/L. The application period opened in January 2023 and closed on June 30, 2024, with installations needing to be completed by September 30, 2024. NDEE aided private domestic well owners with applications for the program and assisted with well registration, which was a requirement for the program.

Data from the sampling and analysis program were incorporated into the study as summarized below:

- Two well owners from the private domestic well sampling effort participated in follow-up confirmation sampling and isotope analysis. These results will provide valuable insights into the sources of nitrate likely to impact domestic wells. NDEE plans to make this data available to the public when the analyses are complete.
- Data from the free sampling effort will be uploaded to the Clearinghouse, which will increase the available domestic well data in the Clearinghouse and help fill a data gap.
- Data on the patterns and locations of sampling requests and feedback from the public will be made available to the public for research and future outreach by the agency. This is included in the outreach toolbox in Appendix D.
- Data was used in the development of a predictive model and risk assessment tool for use by NDEE and select agency partners.

5.0 STUDY DATA SOURCES, METHODS, AND DATA GAPS

Nitrate samples taken from wells in Nebraska are collected by the NDEE, the NRDs, landowners, well owners, PWS water operators, and researchers. Data from these samples are compiled in two main repositories. Samples taken by PWSs for compliance with the SDWA are stored in the Safe Drinking Water Information System (SDWIS) and are available to the public on the Drinking Water Watch (http://drinkingwater.nebraska.gov). Although the data is available to the public, locational details are not available as these are confidential for security reasons. The Clearinghouse is a collaborative effort between the NDEE, the NRDs, and the UNL Conservation and Survey Division (CSD) to compile groundwater quality information across the state. Well samples are available for 281 compounds in the Clearinghouse, including nitrate. These samples have been collected from monitoring, irrigation, private domestic, public water supply, commercial/industrial, livestock, and groundwater source heat pump wells since the late 1960s. The Clearinghouse has an interactive map where users can see sample data sorted by analyte, collection date, and responsible agency. Each sample is given a quality flag based on the sampling procedure and the laboratory method used. The flag represents the amount and type of quality assurance/quality control for each sample. Samples taken by PWSs are not available publicly in the Clearinghouse as they include confidential well location details. The Clearinghouse does not include compliance data from permitted point sources of nitrate or facility data.

In addition to nitrate sample data, well construction and registration information from the Nebraska Department of Natural Resources (NDNR) and boundary data from the Nebraska Department of Transportation (NDOT) were used in this report. A summary of the data used are shown in Table 3. Additional data used for the predictive nitrate modeling effort is discussed in the model documentation (Appendix C).

Table 3. Data Sources.

Dataset	Source	Use
CWS Point of Entry (POE) Nitrate Sample Data for Years 2003-2023	SDWIS, NDEE (2023c)	Nitrate samples from CWS POE were used in trend analyses. POE data represents the water that is served to customers and may not reflect the supply well nitrate concentrations. Communities are required to sample at the POE for compliance with the SDWA.
Well Nitrate Sample Data from the Nebraska Groundwater Quality Clearinghouse for Years 2003-2019	CSD, NDEE (2023)	Nitrate samples from the Clearinghouse were analyzed and mapped across the state. Not all samples in the Clearinghouse are from potable water wells.

Dataset	Source	Use
Nebraska Department of Health and Human Services Public Health Lab Domestic Nitrate Sample Data 2010-2022	NDHHS (2023)	Available sample data from samples collected by private domestic well owners and submitted to the NDHHS Public Health Environmental Lab were used as a point of comparison to the private domestic well samples collected as a part of this study. Because of record retention policies, only data since 2010 was available at the time of request.
Nitrate Sample Data Collected from Private Domestic Wells During the Water Quality Study	NDEE (2024)	Nitrate samples from the free sampling effort were compared to previous data and will be made available through the Clearinghouse for future research and analysis. These private domestic well samples were also used as testing data for the predictive nitrate model.
Nebraska WHPA Maps from 2004 to 2023	NDEE (2023b)	WHPAs were used to symbolize maps in this report. The state delineates wellhead protection boundaries for all CWSs. These areas identify the 20-year or 50-year travel time for potential sources of pollution to public water supplies.
State of Nebraska Boundary	NDOT (2023)	Boundary information from NDOT was used to symbolize maps for the report.
Nebraska Municipal and Boundary Data	Census 2020; Nebraska Geographic Information Office (NGIO), 2024	Municipal boundaries in Nebraska are derived from the 2020 census and updated by NGIO using state data from the Department of Revenue and annexation ordinances from cities. These data were used to symbolize maps in the report.

Table 4. Water Quality Study Methods Summary.

Method	Applied to	Description
Lachat 10-107-04-1-A NO3 + NO2	All Nitrate Results Associated with the Free Nitrate Test Kit Program	This is the analytical method that the NDHHS Public Health Environmental lab uses for nitrate + nitrite analysis and was used for analysis of all the private domestic well samples included in the free sampling effort.
Getis Ord (Gi*) Test	All Clearinghouse Nitrate Samples	A statistical test to identify spatially clustered hot and cold spots in the data, where hot spots are significantly above average nitrate concentration and cold spots are significantly below.
Mann-Kendall Test	POE Nitrate Samples from SDWIS for CWSs	A statistical test to identify a monotonic trend in CWS nitrate concentrations over the study period.

Method	Applied to	Description
Log-Linear Model	POE Nitrate Samples from SDWIS for CWSs	A statistical test to identify exponential or seasonally noisy trends in CWS nitrate concentrations over the study period.
Time-Series Clustering	POE Nitrate Samples from SDWIS for CWSs	A statistical method for partitioning data into similar groups, while maximizing the difference between groups. This was applied to the median nitrate concentration in CWS over the study period to group systems with similar nitrate concentrations.
Regional Groundwater Models	Regional Groundwater Elevation and Flow Direction Layers	Regional groundwater models managed by NDNR were used to derive the depth to groundwater and groundwater flow direction across the state. These layers were developed for inclusion with the private domestic well owner risk assessment GIS tool for use by NDEE and key agency partners.
Boosted Regression Trees (BRTs)	Subset of Clearinghouse Nitrate Samples and Contributing Variables	See Appendix C for a complete description of the predictive modeling incorporated into the water quality study.

5.1 Statewide Groundwater Elevation Layer

A statewide GIS layer of the depth to groundwater was developed for this study using the regional groundwater models for incorporation into NDEE internal tools and decision making. The groundwater models were constructed by the NDNR for the purpose of quantifying water budgets across large areas of the state. NRDs across the state use these models for water planning purposes. The seven models used include the Blue Basin model, the Central Nebraska (CENEB) model, the Cooperative Hydrology Study (COHYST) model, the Lower Platte Missouri Tributaries (LPMT) model, the Republican River Compact Administration (RRCA) model, the Upper Niobrara-White (UNW) model, and the Western Water Use Model (WWUM). All the models utilize MODFLOW, a program created by the USGS and the industry standard for groundwater modeling.

Each model has been independently calibrated by the model developers to historical groundwater level measurements. The calibration statistics differ between each model. Each model is discretized into units of time and space. Temporally, model stress periods are typically one month in length and simulate pre-development conditions through the early 2000s. Spatially, the model cells vary in size between the different models (see Table 5). Some models have more than one vertical layer; in the case where more than one model layer is present, the water level in the layer simulating the shallowest aquifer was used. More information about model construction and calibration can be found within each model documentation report on NDNR's website (https://dnr.nebraska.gov/water-planning).

Table 5. Regional Groundwater Model Cell Sizes.

Model Name	Cell Size (ft)
WWUM	1,320 X 1,320
Blue Basin, COHYST, LPMT	2,640 X 2,640
CENEB, RRCA, UNW	5,280 X 5,280

To maintain consistency across all models, the April 2000 stress period was chosen to determine the depth to groundwater layer based on available data in the models. Spring elevations are used by many of the NRDs for water quantity management and represent the seasonal high-water level following winter recharge. April 2000 corresponds to stress period 234 for the Blue Basin model, 220 for the CENEB model, 725 for the COHYST model, 199 for the LPMT model, 989 for the RRCA model, 484 for the UNW model, and 564 for the WWUM. Within each model domain, the calculated heads from April 2000 were subtracted from the surface elevation for each model cell. For areas where model domains overlapped, the following hierarchy was used:

1. COHYST
2. LPMT
3. CENEB
4. Blue Basin
5. UNW
6. WWUM
7. RRCA

The hierarchy was determined based on relative recency of model updates and professional judgment. For example, where the COHYST model and CENEB model overlap, the depth to groundwater calculated from the COHYST model was used in the entire overlapping area.

Some manual adjustment to the depth to groundwater layer was needed. Model cells can go “dry” during the model simulation—meaning calculated heads are below the elevation of the bottom of the cell. In these cases, the model cell was removed from the layer. Model cells can also be flooded—meaning calculated heads are above the land surface elevation. These values were set to zero in the final depth to groundwater layer, indicating groundwater is at ground surface. This layer was incorporated into the GIS tool for use by NDEE and key agency partners.

5.2 Statewide Groundwater Flow Direction

Groundwater flow direction is important to identifying potential sources of nitrate that could impact a given well. To supplement internal NDEE tools and decision making, a statewide groundwater flow direction layer was developed using the same regional groundwater models described in Section 5.1. Flow vectors were calculated using the cell by cell (.cbc) MODFLOW file for each model. The cell-by-cell file contains information on groundwater flow coming into and going out of each model cell. Using the inflows and outflows, a net flow direction and magnitude was assigned to each cell. In overlapping areas, the same model hierarchy described above was applied. This layer was incorporated into the GIS tool for use by NDEE and key agency partners.

5.3 Data Gaps

Additional nitrate groundwater data is known to exist from programs such as the NDEE-required groundwater monitoring for certain permitted facilities and cleanup sites, but the data is in a limited format to facilitate inclusion into GIS maps and predictive modeling efforts. Additional information about data excluded from the model is provided in the modeling documentation (Appendix C).

Wellhead protection area maps are not up to date for some communities in the state. The process of updating these maps is ongoing, as typically, maps are updated as new wells are added to the water system. NDEE is working to complete needed updates.

Service areas for public water systems are not available for the whole state, which limits the scope of regionalization studies and efforts. Service areas are the boundaries where CWSs supply water to customers. As a part of revisions to the USEPA Lead and Copper Rule, this data may become available due to changes in reporting requirements. This data would allow for a more comprehensive study of regionalization to address nitrate-affected drinking water. Efforts in other states have significantly reduced the cost of regionalization to rate-payers by looking at larger interconnections between systems.

Well data in the Clearinghouse for non-PWS wells is not up to date as of May 2024. PWS well samples are checked for quality by the NDHHS Public Health Environmental Lab before they are entered into SDWIS and uploaded automatically to the Clearinghouse. Samples submitted by the NRDs, and landowners are checked for quality in a process coordinated by the CSD and approved manually. Since 2020, a new procedure has been implemented to process large quantities of samples. This change in procedure, in tandem with the COVID-19 pandemic, disrupted Clearinghouse updates. Changes in data management and issues with software vendors have further challenged the process since 2020. Efforts to implement process improvements and close this data gap are ongoing and expected to be complete in 2024. This data gap is not expected to impact the results of the study, as recent sample years are not expected to differ dramatically from previous years.

Discussions and feedback received from project partners indicated that there may be additional domestic well sample data that has been collected by NRDs and private domestic well owners. Some partners felt that many of these samples have been unfairly rejected because of data quality issues. Because private domestic well samples historically were not often approved for inclusion in the Clearinghouse, NRDs were discouraged from submitting additional data. With process improvements and additional data quality flagging options, it may be possible to retroactively submit these samples.

Because many wells are unregistered, the locations of all private domestic wells are not known. Registered well locations and owner contact information are maintained in a database by NDNR, which allows for direct outreach to well owners. NDEE estimates that as many as 110,000 unregistered private domestic wells may be in use in Nebraska. Owner contact information is not available for these wells, and outreach is limited to indirect methods that are less effective. NDEE estimates that fewer than 10% of the private domestic wells in the state are sampled annually for nitrate and bacteria.

6.0 CLEARINGHOUSE AND NDHHS DATA EVALUATION AND TRENDS

6.1 Clearinghouse Data Evaluation and Trends

There are 209,132 nitrate samples in the Clearinghouse collected from 1969 to 2024. Of these, 69,419 samples are from PWS supply wells, and 139,713 samples are from non-PWS wells, including irrigation, monitoring, livestock watering, and private domestic well samples. Data from 2020 to 2024 is incomplete at the time of this report's publication, as discussed in Section 5.3. The period of 2003 to 2019 was selected for analysis because sampling patterns and data quality prior to the 2000s were irregular. Figure 7 shows the number of samples taken by well type from 2003 to 2019, and Figure 8 shows the number of individual well locations sampled from 2003 to 2019. There are 119,683 nitrate samples from 2003 to 2019 in the Clearinghouse included in the analysis in this report. These samples are mapped across the state in Figure 9. Note that higher concentration samples are rendered first but may not be the most recently available data. Figure 10 shows the number of nitrate samples taken each year since 1969 split by PWS and non-PWS wells. Summary statistics for the nitrate sample data queried from the Clearinghouse and used in the analysis, split by well type, are provided in Table 6. Domestic and PWS well data shown in Table 6 only includes samples recorded to the Clearinghouse. Additional data summary tables are available in Appendix A. Additional summary maps showing nitrate concentrations by well type are provided in Appendix B.

Between 2003 and 2019, 5,676 private domestic well samples were reported to the Clearinghouse. A total of 1,380 samples (24.3%) were above 10 mg/L. A map of these samples is provided in Appendix B.

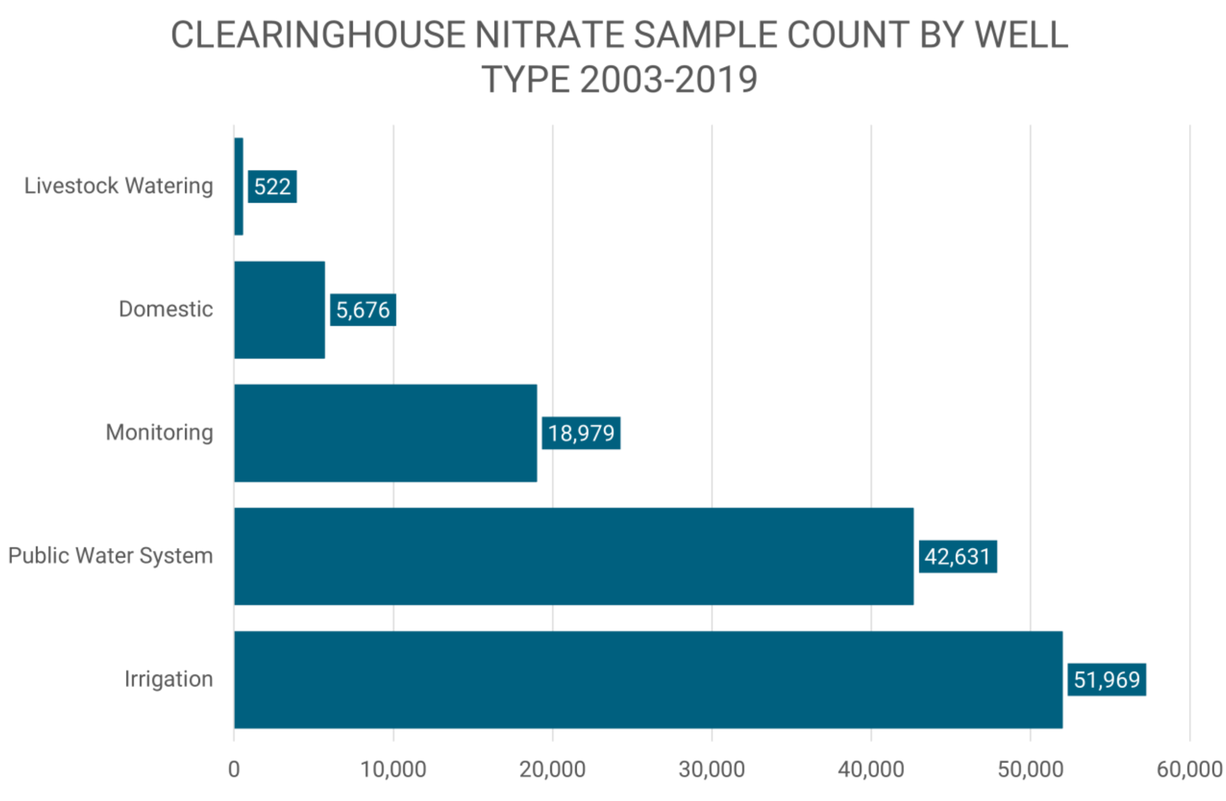

Figure 7. Distribution of Clearinghouse Data by Well Type.

Table 6. Clearinghouse Nitrate Summary Statistics by Well Type.

Clearinghouse Well Type	Mean Nitrate Concentration (mg/L)	Median Nitrate Concentration (mg/L)	Sample Count	Wells Sampled
Livestock Watering	12.43	8.40	522	105
Domestic	7.21	2.50	5,676	1,423
Irrigation	9.35	6.50	51,969	13,504
Monitoring	7.33	4.10	19,021	1,697
Public Water System	4.04	2.94	42,631	3,064
All Wells	7.05	4.5	119,992	19,768

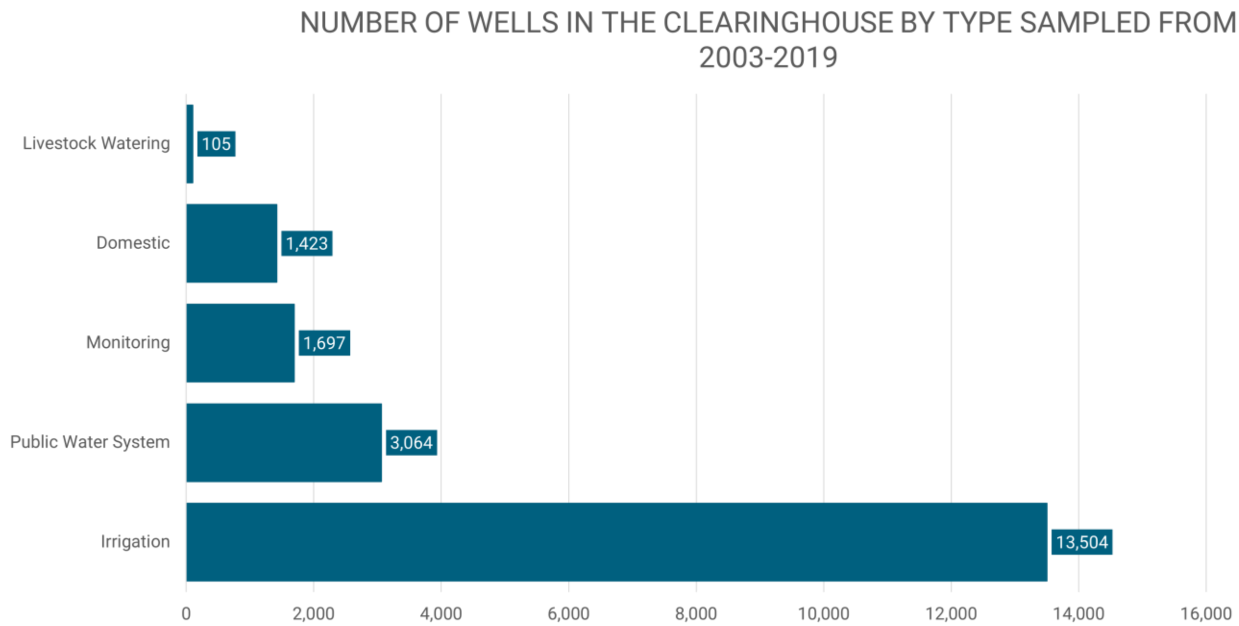

Figure 8. Distribution of Clearinghouse Data by Number of Wells.

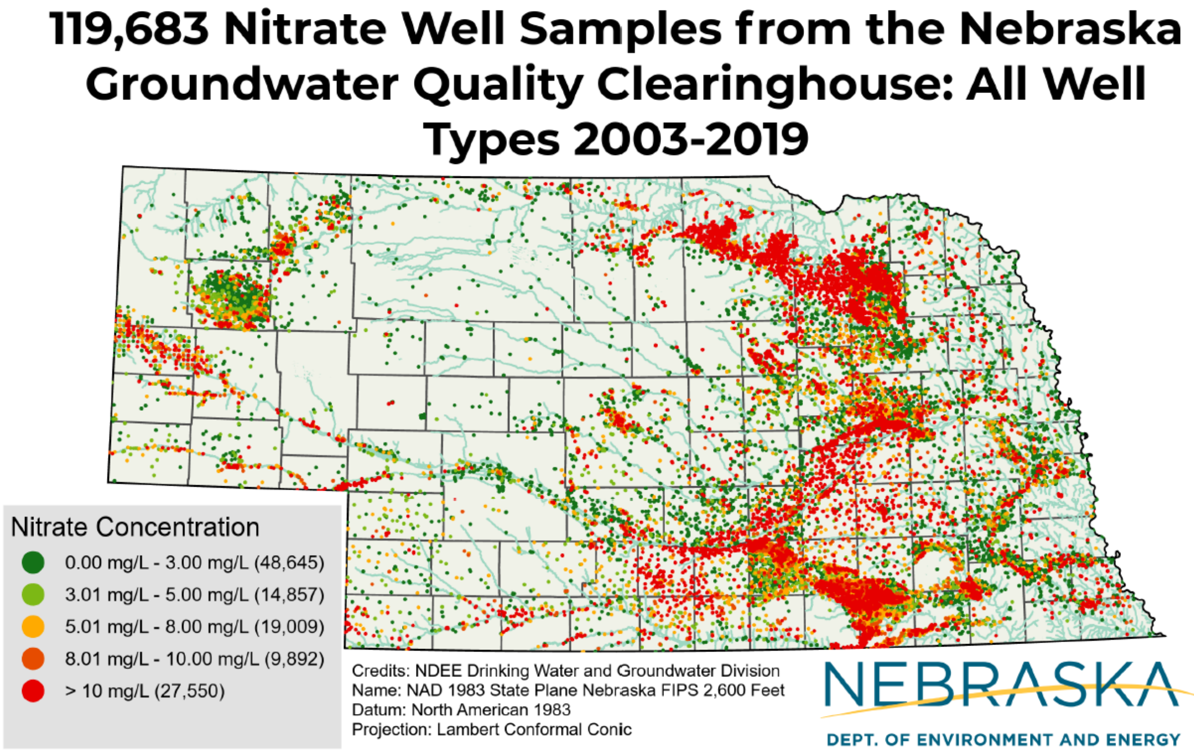

Figure 9. Clearinghouse Nitrate Sample Data Summary.

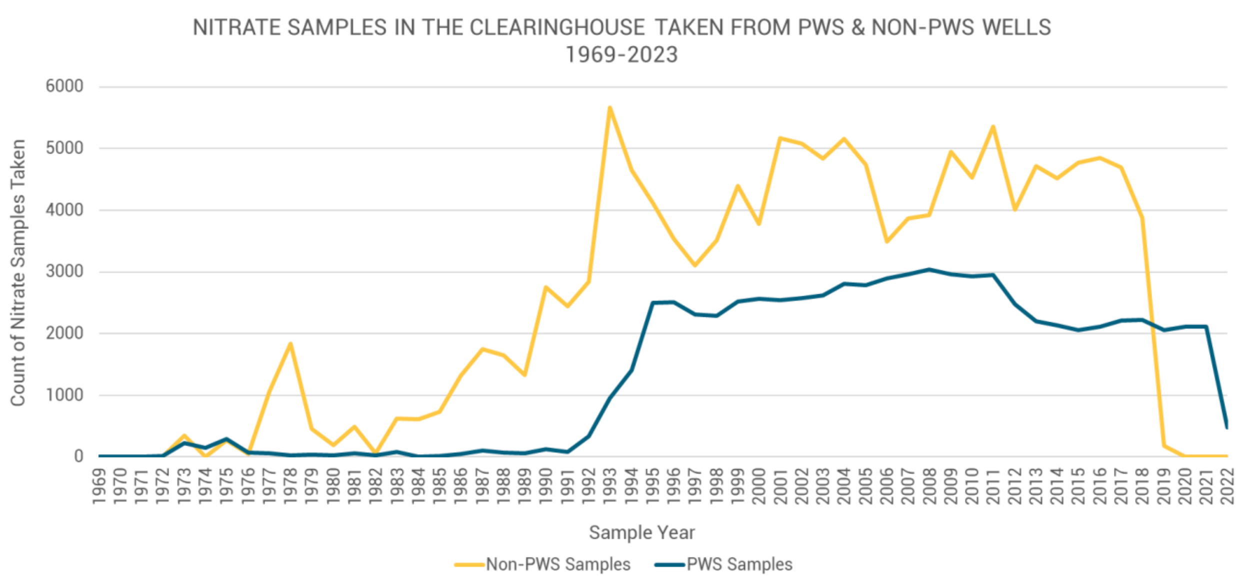

Figure 10. Nitrate Samples Collected by Year in the Nebraska Groundwater Quality Clearinghouse Split by PWS and Non-PWS Wells.

The median nitrate concentration for PWS wells was 2.4 mg/L in 1974 and 2.4 mg/L in 2019. The median nitrate concentration for non-PWS wells was 3.5 mg/L in 1974 and 5.4 mg/L in 2019. Figure 11 summarizes the median nitrate concentration for PWS wells and all other wells from 1974 to 2019. Sample data since 2020 is incomplete and was excluded. Figure 12 shows a distribution of the nitrate sample results recorded to the Clearinghouse from 2003 to 2019. Well samples above 100 mg/L are not plotted for visual clarity.

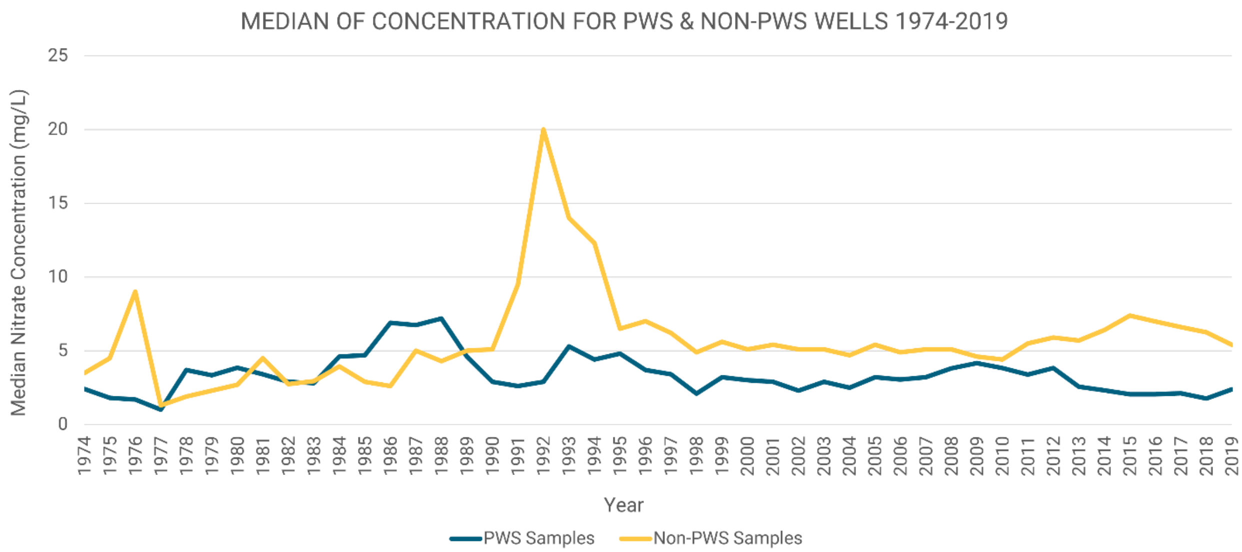

Figure 11. Median Nitrate Concentration by Year for PWS and Non-PWS Wells in the Nebraska Groundwater Quality Clearinghouse, 2003-2019 (mg/L = milligrams per liter).

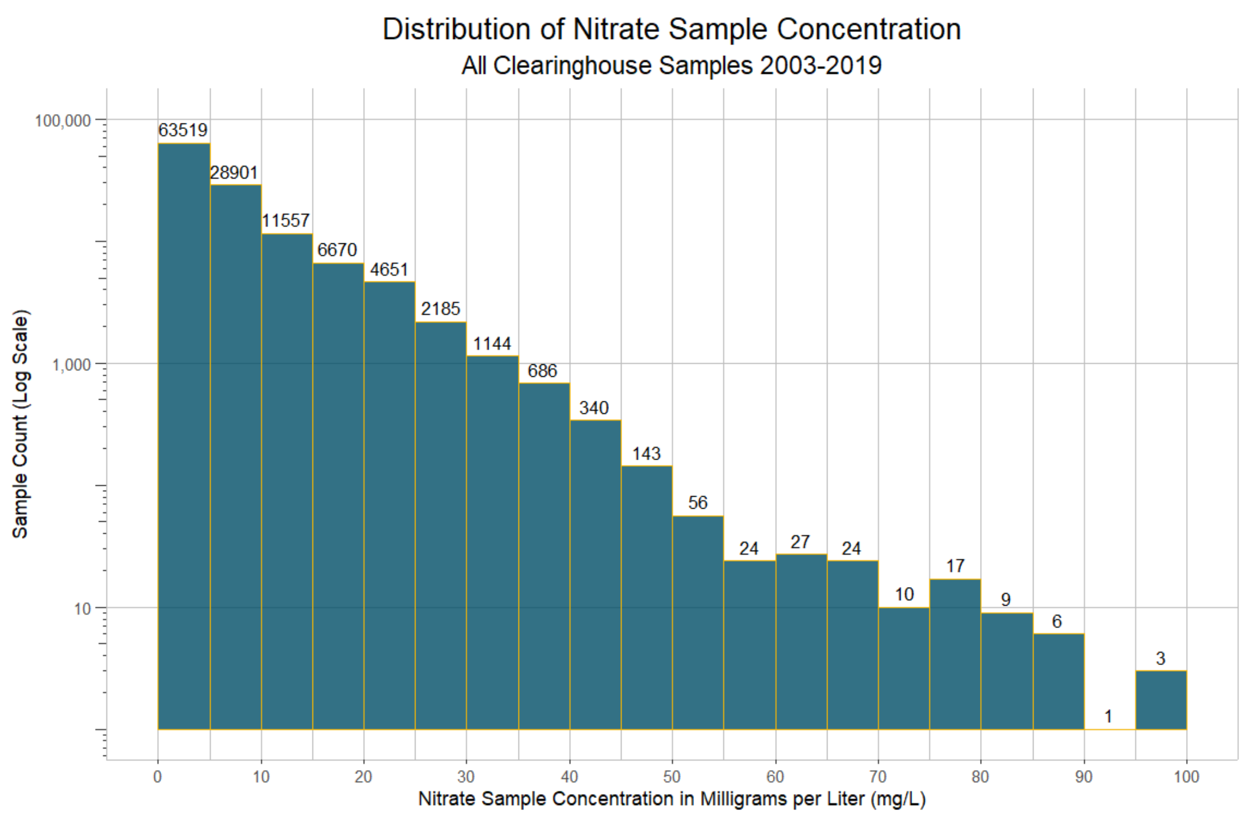

Figure 12. Distribution of Nitrate Concentrations in the Nebraska Groundwater Quality Clearinghouse, 2003-2019.

To identify outliers in the data and look for spatially significant hot spots in nitrate concentrations, a Getis-Ord Gi* test was performed (Ord, 1995). This test identifies outliers in the dataset based on the concentration of nitrate and the spatial grouping of sample data. The test critical values and distance band are adjusted based on the results of multi-distance Global Moran's I test, which helps alleviate the false discovery rate issue common in spatially correlated data. Analysis was performed using ArcGIS Professional (Version 3.1, esri, 2023).

Areas with elevated nitrate concentrations were identified and visualized across the state using a Getis-Ord Gi* test and ArcGIS Professional (Version 3.1). Figure 13 shows the relative hot and cold spots for nitrate for the 2003-2019 data in the Clearinghouse. At wells sampled more than once during the study period, the median concentration was used. Red spots indicate statistically significant hot spots, and blue spots indicate statistically significant cold spots. A hot spot indicates both spatial clustering and high outlier concentrations. Because of the distribution of nitrate concentrations across Nebraska, the relative concentrations of hot and cold spots differ slightly across the state.

This analysis shows areas of elevated nitrate concentrations are largely consistent with other studies of nitrate in Nebraska such as those conducted by Spalding (1993), McMahon (2007), and Exner et al. (2014). Land use in these areas is similar to contributing land use patterns identified in modeling efforts such as Wheeler et al. (2015) and Garcia (2017). The average concentration at a hot spot was 14.42 mg/L. The average concentration at a cold spot was 3.71 mg/L. The average for all data was 7.05 mg/L. Grey dots represent sample locations that are not identified as statistically significant hot or cold spots. Figures 14 and 15 show the distribution of nitrate concentration at points identified as hot spots or cold spots. Table 7 summarizes the average sample concentration for hot or cold spots. It is important to note that this is not a health measure, and some of the cold spot nitrate concentrations are at wells that exceed the SDWA standard because of their location and concentration relative to the area around them. It is possible to be a statistically significant outlier on the low end, in an area where the overall distribution is higher concentrations, such as in the Bazile Groundwater Management Area.

Prominent hot spot clusters include areas along the Upper Elkhorn, Lower Loup, and Central Platte River basins. These areas have historically reported high nitrate concentrations (Spalding, 1978) and have had some success with implementing BMPs to reduce nitrogen loading at the surface. This has led to reductions in nitrate levels of around 0.25 mg/L per year in certain areas (Exner, 2014).

Table 7. Getis Ord (Gi) Nitrate Sample Average Concentration by Grouping.*

Nitrate Sample Group	Average Concentration (mg/L)
All Samples	7.05
Hot Spots	14.42
Cold Spots	3.71

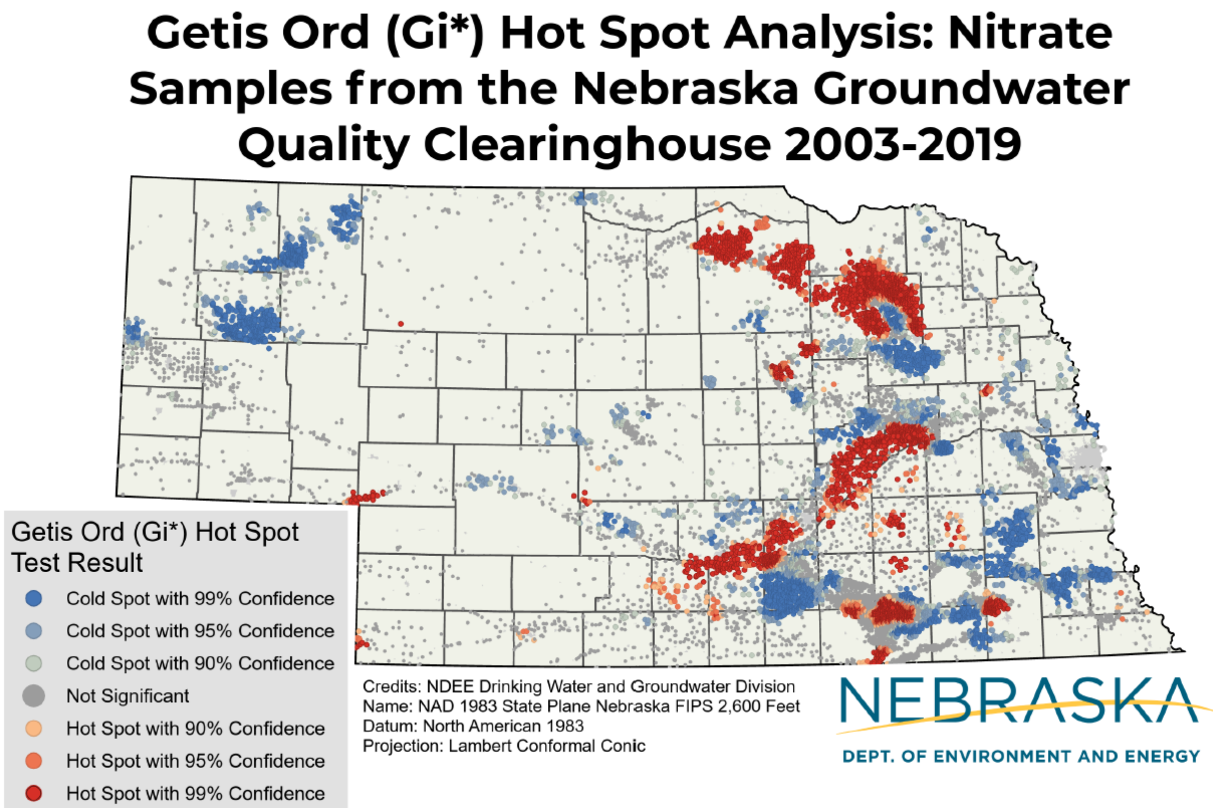

Figure 13. Clearinghouse Hot and Cold Spot Analysis.

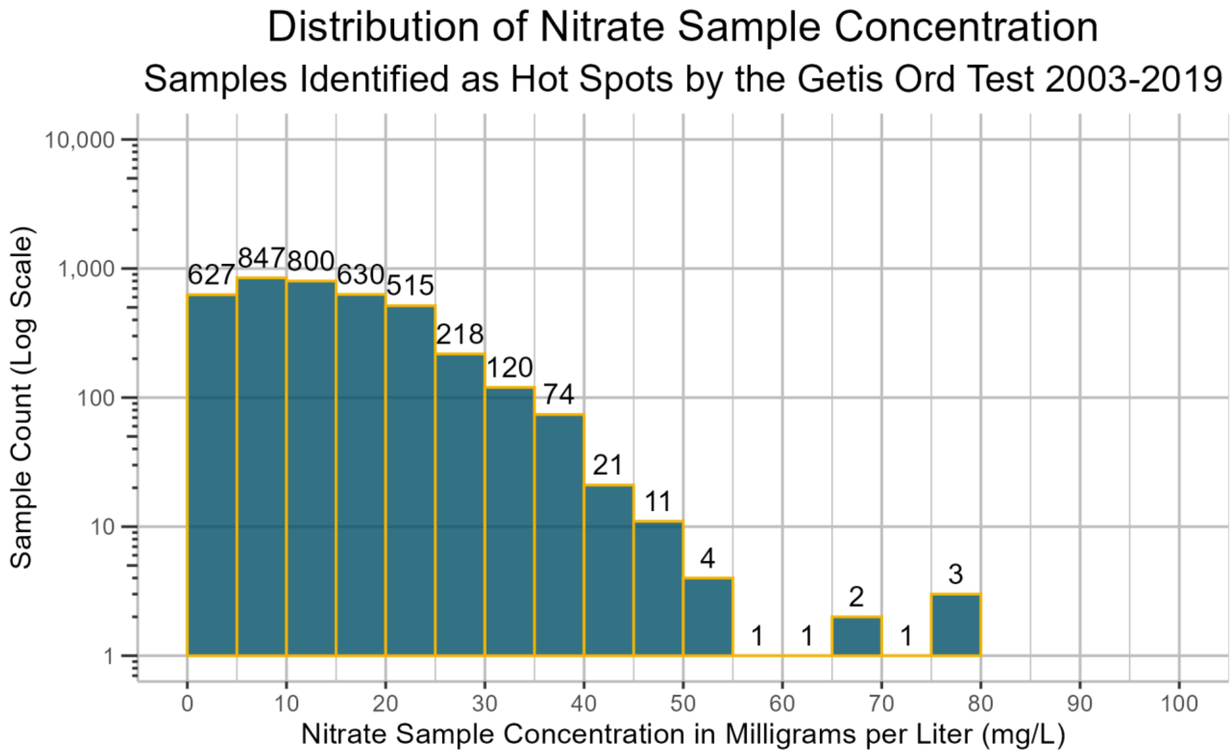

Figure 14. Distribution of Hot Spot Data.

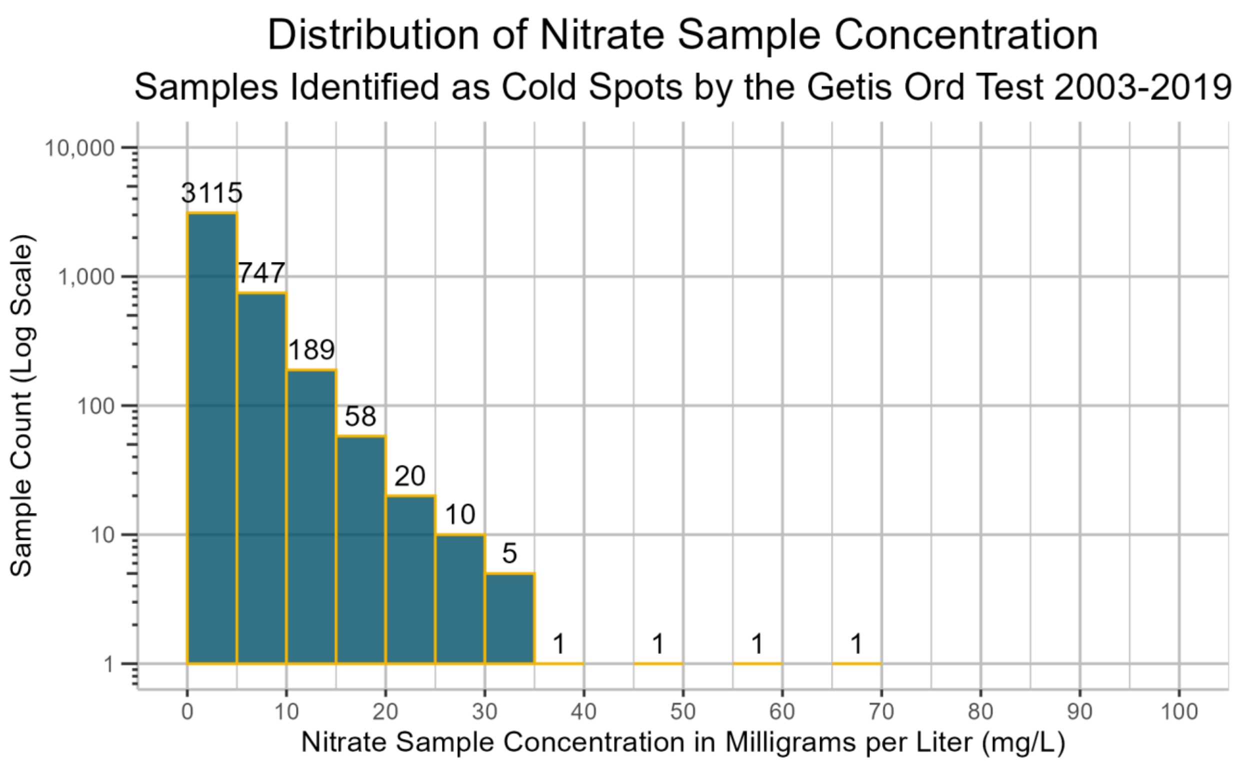

Figure 15. Distribution of Cold Spot Data.

6.2 NDHHS Data Evaluation and Trends

Because they are not subject to SDWA requirements, limited nitrate sample data exists for private domestic wells, and not all private domestic well samples are reported to the Clearinghouse. Between 2010 and 2022, 7,232 nitrate samples were collected by private domestic well owners and analyzed by the NDHHS Public Health Environmental Lab from 4,085 wells (some wells were sampled more than once). A total of 857 (11.8%) of the private domestic wells sampled had nitrate concentrations greater than 10 mg/L. These samples are mapped in Figure 16. There are 46 samples not included in Figure 16 because they did not geocode or fell outside the state boundary. The median nitrate concentration for the private domestic well samples was 0.98 mg/L, and the mean concentration was 4.02 mg/L. The median nitrate concentration was 1.34 mg/L in 2010 and 1.18 mg/L in 2022. Figure 17 summarizes the median concentration for each year of the NDHHS data. At the time of publication of this report, these private domestic well sample data are not available publicly, but efforts are in progress to incorporate these samples into the Clearinghouse. The data start in 2010 because typically only ten years of data are retained by NDHHS consistent with their record retention policy. A majority of this data is from Lancaster County due to property transfer and inspection requirements for this county that are not required in the other 92 counties.

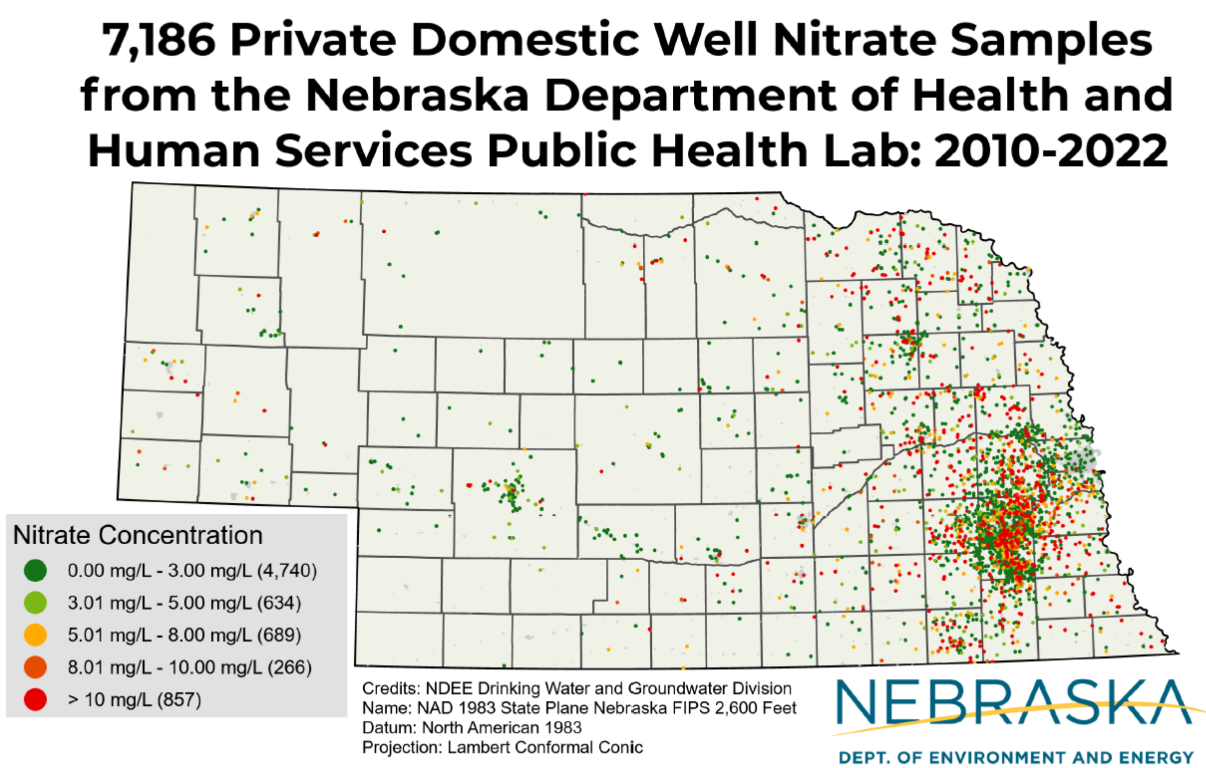

Figure 16. Private Domestic Well Nitrate Samples Analyzed by NDHHS from 2010-2022.

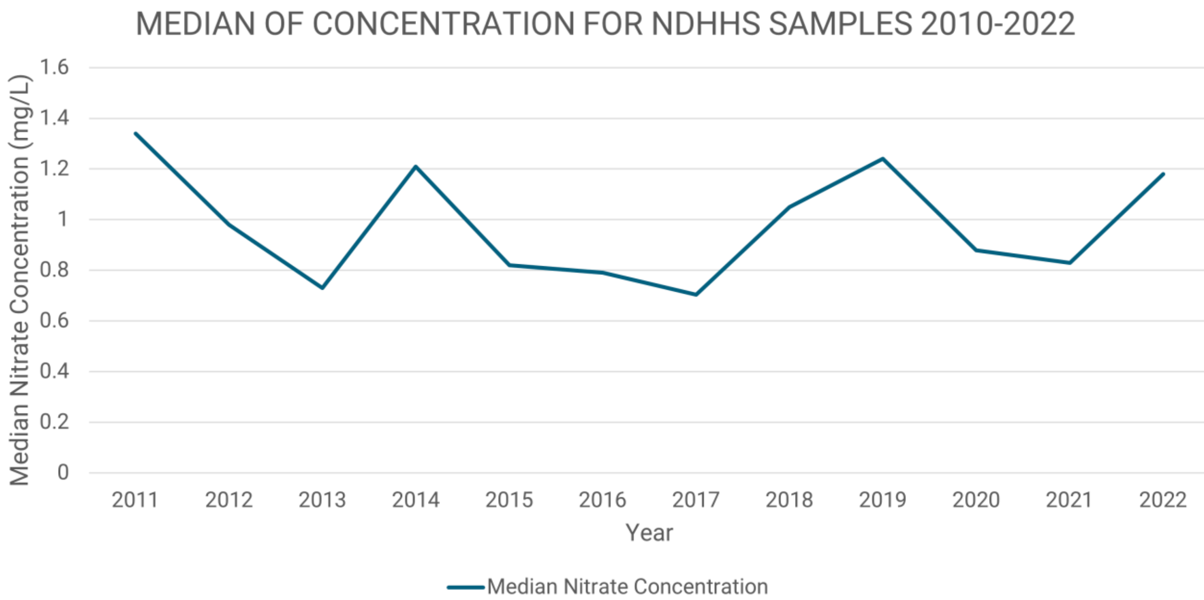

Figure 17. Median Nitrate Concentration by Year for NDHHS Data.

7.0 CWS DATA EVALUATION AND TRENDS

CWSs are required to regularly test their finished water for nitrate in accordance with Title 179, Chapter 3, Section 005.04. At a minimum, POE samples for the CWSs are collected annually. POE sample results reflect the water quality that enters the distribution system for people to drink, but do not necessarily reflect the concentrations of nitrate in supply wells. Because of the regular monitoring, this sample data is well suited to studying trends in CWS drinking water nitrate concentrations. CWS nitrate sample data from POEs in each community were extracted from the SDWIS.

There are 595 CWSs permitted in Nebraska. Of those, 118 CWSs purchase water from other systems and are not expected to sample for nitrate annually unless they are blending purchased water with an existing well, so these CWSs were excluded from analysis. Six CWSs use surface water as a primary source. While surface water systems must sample for nitrate, they have treatment plants and are not using groundwater, which is the focus of this report, so these CWSs were also excluded from analysis. Additionally, while assembling the CWS data, it was determined that at least 19 systems completed an interconnection project during the period of 2003 to 2023, meaning they only had a partial sample record; thus, these CWSs were excluded from analysis as well.

There are at least 446 CWSs that use groundwater as a primary source that must sample annually. See Table 8 for a summary of CWSs included in the analysis. Two systems were excluded from the CWS trend analysis, which included 444 out of the expected 446 CWSs. Errors in SDWIS coding prevented Benedict and Endicott CWSs from inclusion in the trend analysis. Both systems were reviewed by NDEE staff and Benedict was ultimately included in the priority ranking.

The 2018-2023 average nitrate concentration for each CWS from POE samples is shown in Figure 18. The evaluation and trend analyses provided in this section are based on drinking water quality and not the raw water obtained by the CWS. The analyses were used to identify opportunities for earlier state program intervention and develop a priority points system as further discussed in Section 8.

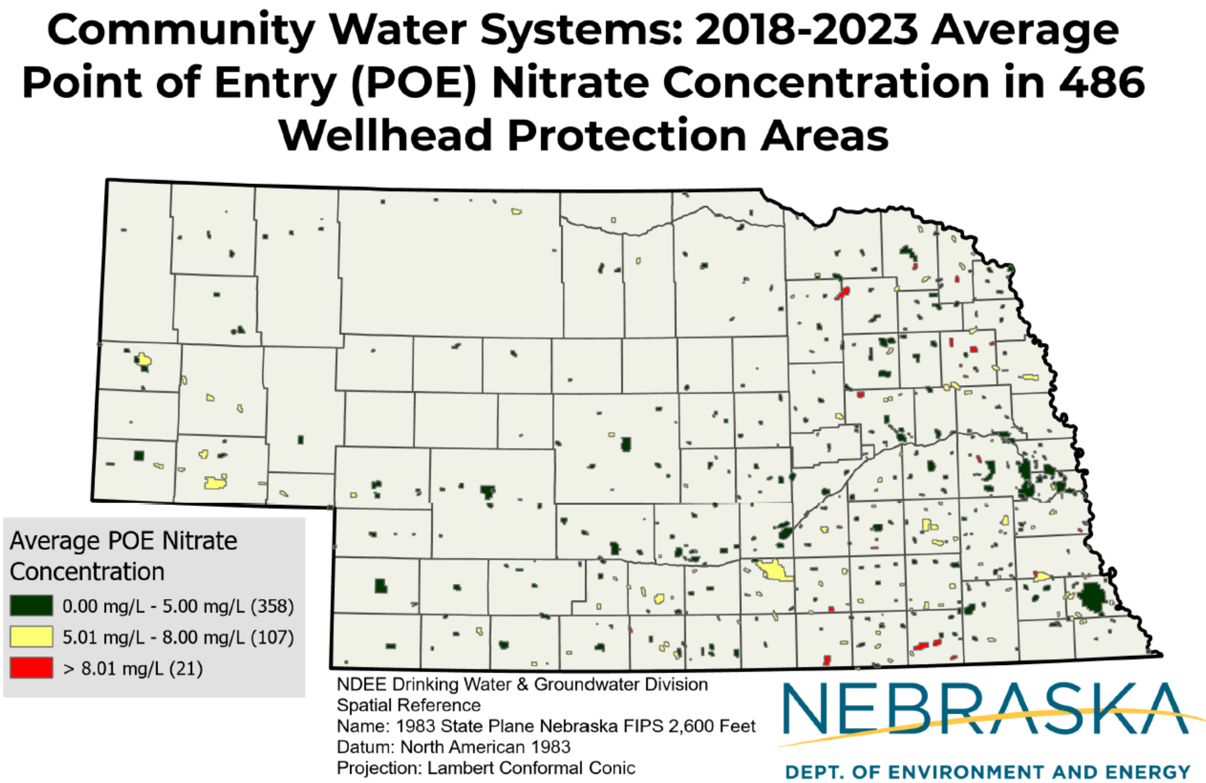

Figure 18. Community Water System (CWS) Average Point of Entry (POE) Nitrate Sample Concentration in Wellhead Protection Areas. In the map, POE samples inside each wellhead protection area (WHPA) were averaged over the last five years and symbolized in each WHPA. POE samples represent water that people are drinking but may not reflect untreated supply well nitrate concentrations.

Over the period from 2003 to 2023, 34,780 nitrate POE samples were collected by CWSs for compliance with the SDWA. These sample results were organized onto timelines, or time series, and evaluated for statistically significant trends over time. The first time-step of one year from 2003 to 2004 in the study period was selected as the reference time. This alignment included the greatest number of CWSs with the fewest estimated time-steps. A total of 8.56 percent (38 CWSs) had at least one time-step with an estimated value. Of the 9,260 bins that comprise the STC, 0.74 percent or 69 were estimated by a fill statistic. The overall trend in mean nitrate concentration was decreasing with a Z-value of -3.29 and a p-value of 0.001. There was no significant trend in sample counts over time.

The fill statistic is the parameter controlling estimates for empty time-steps for a given bin. In this analysis, temporal trend was the selected fill statistic for the mean nitrate concentration and the collection date of the samples was used as the time field. When using the starting time-step and the temporal fill statistic in ArcGIS (Version 3.1, esri, 2023), a minimum number of samples must be present at the first two and last two time-steps for a CWS to be included. This means that CWSs that started after 2005 or those with fewer than 20 samples over the period may not be included. Temporal fill uses a univariate spline algorithm to interpolate between points using a method identical to the one available in the ScyPy package (Version 1.11.2, ScyPy Community, 2023). The length of each time-step was set to one year, based on annual sampling requirements and the relatively slow physical processes that underlie groundwater nitrate concentrations (Wells, 2018). Six CWSs that started in 2005 or later were not included in the evaluation but were reviewed by NDEE staff for nitrate issues. Six surface water treatment facilities and 19 CWSs that completed an interconnection project during the 2003-2023 period were not included in the analysis as discussed above. Several time series were created and compared before settling on one that was most representative of the data underlying it.

Table 8. Community Water System (CWS) Point of Entry (POE) nCDF Data Organization Summary.

CWS POE nCDF Creation Results	
CWSs in Nebraska	595
CWSs with purchase agreements	118
CWSs with completed interconnection over study period	19
CWSs that started after 2005	6
CWSs with Surface Water Treatment Plant	6
Minimum number of CWSs on groundwater that must sample annually	446
CWSs in nCDF Cube	444
Percent of CWSs Included / Expected (Cube Count / >=20 Sample Count x 100%)	98.2%

7.1 CWS Time-Series Clustering

Time-series analysis is the process of comparing the nitrate sample data over time for each CWS. Sample data were organized on a timeline covering 2003-2023 for each CWS included in the analysis, and then the timelines were analyzed for trends and clustering. Time-series clustering was performed to classify systems based on the nitrate level over time. Clustering compares timelines to each other by taking the difference in nitrate concentration at each time-step. These differences populate a dissimilarity matrix, which is partitioned into mathematically similar submatrices based on Euclidean distance so that locations with similar time series are in the same block groups (Montero, 2014). Based on a pseudo f-statistic, the number of blocks is minimized while maximizing the difference between blocks (Calinski 1974). Time series were clustered based on nitrate sample values over time. Value clustering looks for functions with similar magnitudes (i.e., nitrate concentrations) across the study period.

Value clustering of the CWS POE nitrate sample data was conducted to compare groups of systems with similar nitrate concentrations over the study period. The median nitrate concentration in each cluster of CWSs is displayed in Figure 19. The POE samples were divided into three clusters based on the value of the f-statistic.

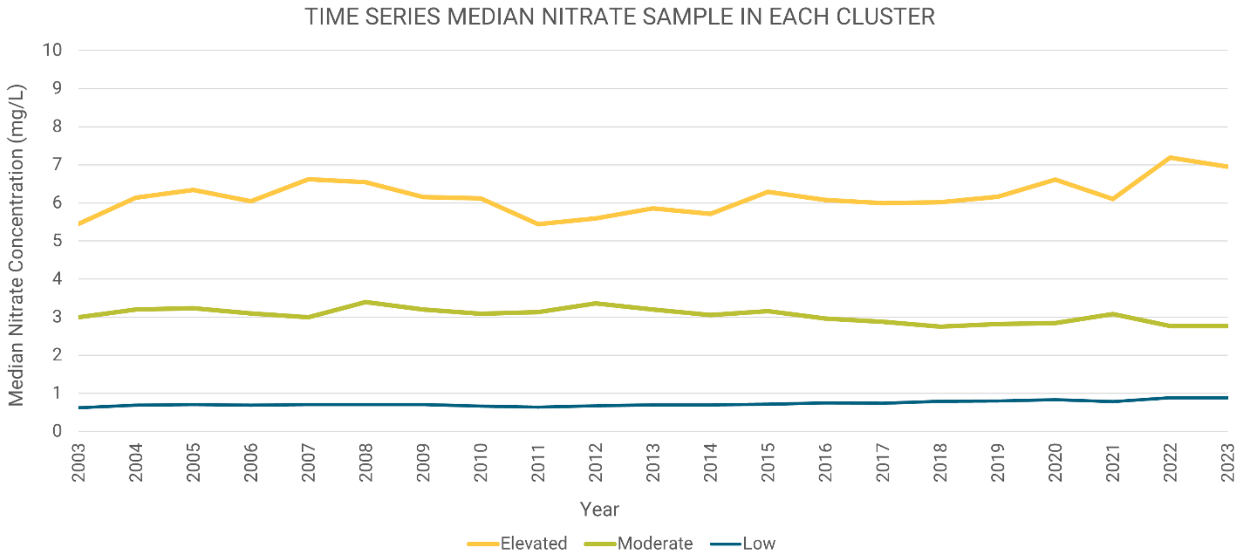

Figure 19. Value Clustering of Community Water System Drinking Water Nitrate Concentrations.

7.2 Mann Kendall

A Mann-Kendall statistic for each CWS included in the analysis was calculated based on the change in mean nitrate concentration in that CWS over the study period. In short, CWS data was binned for each system, a yearly average concentration was calculated for the period from 2003 to 2023, averages were placed on a timeline, and each timeline (time series) was analyzed for an upward or downward trend.

The Mann-Kendall statistic is a straightforward way to detect trends over time in nitrate sample data that is not strongly seasonal (Sokal, 1969; ITRC, 2013). At the time scale studied, nitrate data does not exhibit strongly seasonal behavior, though yearly loading at the surface varies greatly over the season. For further reading about the behavior of nitrate in the vadose zone as it relates to nitrate loading in Nebraska, see Malakar et al. (2023) and Snow et al. (2018).

Important notes about Mann-Kendall analysis are as follows:

- The test does not comment on function shape.
- Seasonal variability can mask increasing trends.
- More confidence in a trend does not indicate a faster change - 99 percent confidence and 90 percent confidence could be increasing at the same rate.
- High confidence does not mean high concentration.
- Sample data was averaged by year, so if 10 samples were taken one year and only one sample was taken the following year, there would be no difference in the weight of those averages.

There were 137 systems identified with an increasing trend in average concentration, 117 systems with a decreasing trend, and 190 without a statistically significant trend based on the results of the Mann-Kendall analysis.

Table 9. Mann-Kendall Trend Analysis Results for CWS POE Nitrate Data. Sample data are from the SDWIS.

Sample Set	No. of Nitrate Samples	No. of Systems Included in Time Series	No. of Systems Trending Up in Nitrate	Expected Number of Systems	Number of CWS Wellhead Protection Area (WHPA)	Overall Trend in Mean N-Concentration
CWS Point of Entry (POE) Nitrate Data	34,780	444	137	446	505*	Decreasing

*Some CWSs have a WHPA but purchase water from another system and no longer regularly use supply wells in the delineated area. These WHPAs and associated WHPPs are currently under review by NDEE to ensure they are still necessary and accurate.

7.3 Log-Linear

Log-linear models were fit to the CWS time-series data in R (Core R, 2024) and evaluated for statistically significant trends. Model fits were tested for statistical significance and the slope term was used to determine the direction of the trend in nitrate concentration. A log-linear relationship is more likely to detect seasonal and exponential trends than the Mann-Kendall analysis (Sokal, 1969).

All CWSs that collected one or more nitrate samples over the study period were included in this analysis. However, no more than 446 are expected to have significant trends because of monitoring requirements. A total of 535 CWSs were analyzed, and 245 statistically significant trends were identified in the data. There were 120 trends that were positive and significant, indicating an increasing nitrate concentration in the CWS. There were 125 CWSs with a negative trend, indicating a decreasing nitrate concentration in CWS. The slope for each model represents the rate of change of nitrate concentration for each CWS. It is important to note that not all significant trends have similar magnitudes, and that some systems are increasing or decreasing faster than others.

It should also be noted that when a CWS dramatically trends down in nitrate concentration, this is often the result of decommissioning a well high in nitrate, drilling a new well, implementing a blending scheme, implementing treatment, or interconnecting to another system.

7.4 Value Analysis

Recent sample data from each CWS was analyzed by taking the five-year average nitrate concentration in POE samples from each CWS included in the analysis (Figure 18). This "value analysis" of CWS POE nitrate data was used in conjunction with Mann-Kendall and linear models to rank systems for different state program interventions. Recent sample data helps to filter systems that have both an increasing trend in nitrate concentration and elevated concentrations of nitrate. Water quality data is a more reliable indicator than statistical measures. Including value analysis in the priority system helps to eliminate spurious trends identified by the Mann-Kendall analysis or small changes identified by simple log-linear models.

8.0 PUBLIC WATER SYSTEM OUTREACH AND GUIDANCE

A guidance document showing the current procedure that a PWS follows under the SDWA when sampling drinking water for nitrate—including violations and AO trigger points—is shown in Figure 20. Additionally, it identifies opportunities for state outreach for SWP, wellhead protection, capacity development, and infrastructure projects funded by the WWAC and the SRF. The results of the water quality study have identified earlier opportunities for program intervention than those shown in the flowchart. Using the CWS analysis presented in the previous section, a priority ranking system was developed to identify systems for different kinds of assistance based on the amount of time it takes for each program to effectively address nitrate in drinking water. While this report focuses on CWSs, NDEE encourages any PWS that is concerned about nitrate to reach out to the NDEE for assistance.

The diagram (Figure 20) starts in the upper left with routine annual sampling by a PWS for nitrate. If a routine sample for nitrate is greater than 5 mg/L, then the PWS increases its nitrate sampling frequency from annually to quarterly. If a PWS is required to conduct quarterly sampling and all sample results in four consecutive quarters are below 8 mg/L and are not trending upwards (defined as reliably and consistently less than the MCL), the PWS may return to annual sampling. At this point, the new trigger point for returning to quarterly monitoring is 8 mg/L instead of 5 mg/L. If a PWS collects a nitrate sample greater than 10 mg/L, then a confirmation sample is required. If the average of the two samples is greater than 10 mg/L, the system is issued a Letter of Noncompliance. PWSs that exceed the nitrate MCL are required to issue a public notice notifying consumers within 24 hours of a violation and provide an alternate source of drinking water to susceptible populations, including infants and pregnant people (40 CFR 141.31). After an MCL violation, if a PWS system has an additional MCL violation in the following two quarters (i.e., MCL violations in two out of three quarters), it will be issued an AO by NDEE. At this point, the PWS is required to hire an engineer and draft a preliminary engineering report and final implementation plan to achieve SDWA compliance within three years. Often this means drilling a new well, building treatment facilities, or developing interconnection projects. Once construction of the engineered solution is completed, the PWS conducts follow-up sampling for a minimum of one year to ensure nitrate concentrations are reduced below the MCL before being returned to compliance.

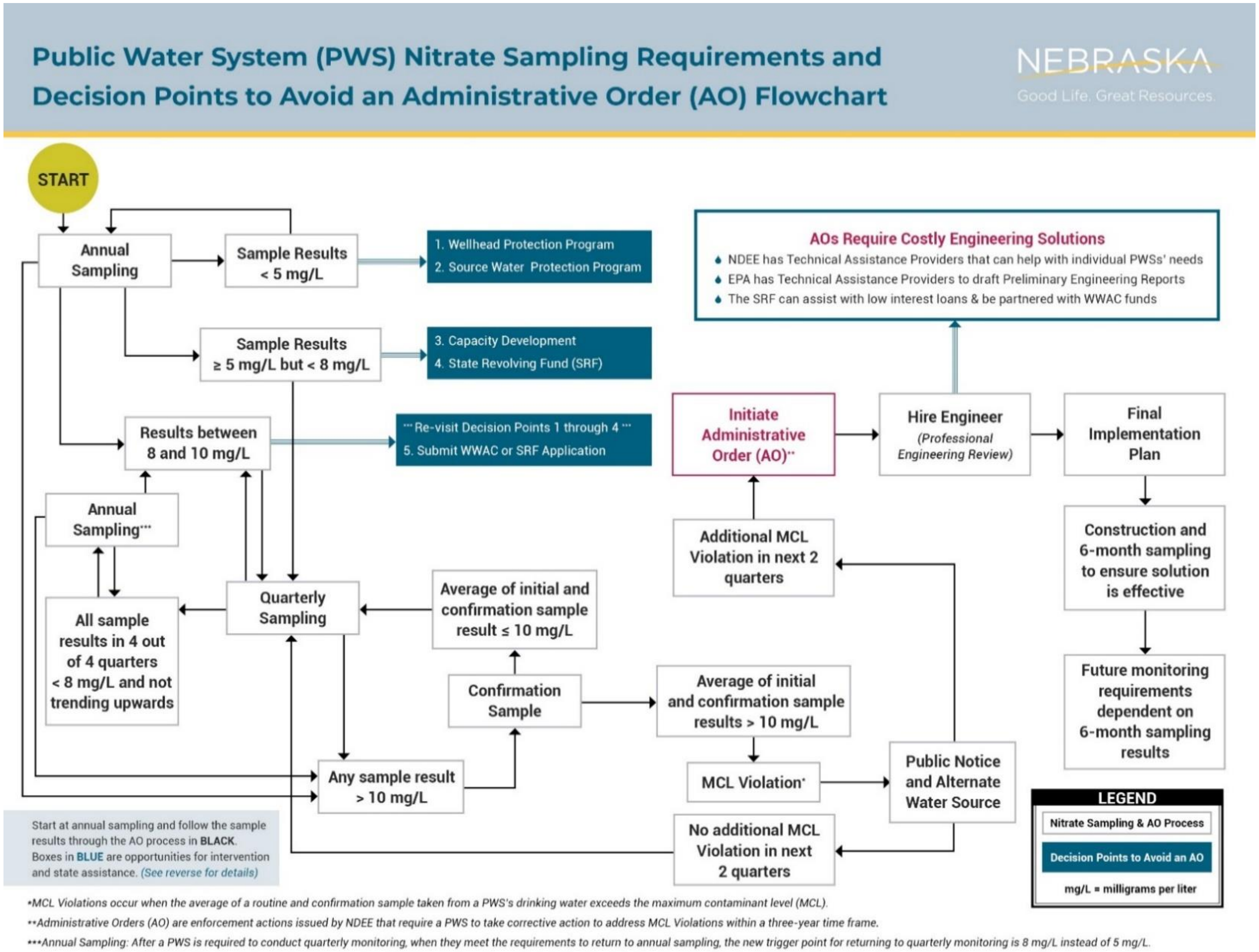

Figure 20. Guidance for PWS Nitrate Sampling Requirements and Decision Points to Avoid an AO.

The results of the CWS analysis will improve NDEE's ability to reach out to systems before they violate SDWA standards or are issued an AO. By analyzing trends in CWS data, earlier opportunities for outreach have been identified. The priority ranking system described in this report is a framework to improve outreach for different state-administered programs that operate on different time scales. The analysis identified 42 systems for short-term planning outreach, 77 systems for mid-term outreach, and 103 systems identified for long-term wellhead and source water protection planning. Priority rankings give NDEE a tool to break down the 595 CWSs into groups for targeted program intervention. A complete list of the priority rankings is available in Appendix A.

Analysis conducted during the study supplements existing procedures to communicate early and often with systems that may face nitrate issues. Currently, NDEE tracks nitrate levels as they exceed certain regulatory thresholds that require increased monitoring. Conducting the CWS trend analysis creates a basis for intervening earlier in the process and improving outreach to communities. Communication tools like the system summaries (Figure 23) can help CWSs understand what the nitrate study results mean for their system. In combination with routine sampling, the trend analysis can assist systems in evaluating the long-term efficacy of different solutions to elevated nitrate concentrations such as blending, treatment, long-term planning, or alternate sources of drinking water. Creating a flow chart helps owners and operators understand what their responsibilities are in the event of nitrate MCL violations.

Several methods were used to identify trends and score systems for different kinds of program assistance. A matrix describing each line of evidence was organized to summarize the priority scoring system. Scores were assigned to CWSs based on threshold values for each line of evidence. Threshold values were determined based on what the results of each method indicate about the likelihood a system will exceed the SDWA nitrate MCL in the near future. See Table 10 for a summary of how each part of the analysis was weighted, where the data came from, and how the data was interpreted. The goal of this scoring is to rank systems based on short-term, medium-term, and long-term priorities for outreach. Short-term priorities are systems that would benefit from outreach for WWAC or SRF funding but may not have time to implement a source water protection plan to reduce nitrate loading. Medium-term and long-term priorities are systems that would benefit from targeted WHPP, 319, SWP, and capacity development outreach.

In the priority system, nitrate sample results were given the highest weighting because they are the most reliable source of water quality information. Points were assigned based on what ranges the 5-year sample average fell into for each community. Higher concentrations are given more points to represent targets for more immediate-term outreach. Lower nitrate sample results are still awarded points so systems that are good candidates for SWP or WHPP are not excluded from the ranking. Point values were not determined based on health measures.

Table 10. Community Water System Supply Well Analysis Methods Matrix & Priority Scoring.

Method/Line of Evidence	Five-Year Sample Average	Trend Analysis (Mann-Kendall)	Time-Series Clustering	Log-Linear Models
Description	The 5-year average sample concentration for the CWS Points of Entry (POE) from 2018-2023 was calculated.	CWS POE samples were analyzed for trends during the 2003-2023 period using the Mann-Kendall statistic.	CWS time series were compared based on the average nitrate concentration in POE samples over the study period.	CWS POE trends were analyzed using log-linear models. Positive slope values indicate increasing nitrate concentration over the study period.
Data Source	**2018-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**
Tier	**Tier 1**	**Tier 2**	**Tier 2**	**Tier 2**
Threshold Values	**< 1 mg/L: 0 points** **1-3 mg/L: 1 point** **3-5 mg/L: 2 points** **5-8 mg/L: 3 points** **>8 mg/L: 5 points**	**90% Confidence: 1 point** **95% Confidence: 2 points** **99% Confidence: 2 points**	**Low Cluster: 0 points** **Moderate Cluster: 1 point** **Elevated Cluster: 2 points**	**Positive slope and significant: 2 points**
Points (11 Maximum)	**5**	**2**	**2**	**2**

Mann-Kendall threshold values were based on the confidence level of the trend detected by the test. Points were awarded to systems that detected a statistically significant, increasing trend; one point was awarded for systems trending up with 90 percent confidence and two points for those trending up with 95 or 99 percent confidence. All other trend results were awarded 0 points.

Value clustering thresholds were based on group membership. This analysis groups systems based on the median nitrate concentration over the whole 20-year period. Systems in the elevated cluster were awarded 2 points, systems in the moderate cluster were awarded 1 point, and systems in the low cluster were not awarded points. See Figure 19 which visualizes the nitrate concentration over time in each cluster. In combination with sample data, this measure helps delineate between systems that should be prioritized for shorter-term and longer-term outreach.

Linear model threshold values were based on two criteria. A positive slope for the model indicates an increasing trend in nitrate over the study period and if that trend was statistically significant, then 2 points were awarded to the system. These linear models detect functions that are shaped differently than the Mann-Kendall statistic and are more robust to seasonally noisy data.

After scoring, the priority list was reviewed by NDEE program managers to identify systems already working with NDEE to address nitrate issues, those that have implemented solutions, inactive water systems, and those with capacity to address issues. These systems were excluded from the final ranking, but Figure 21 shows the distribution of scores from all systems for illustrative purposes. Bars in yellow represent systems excluded from the final list, and bars in blue are systems the study identified as potential outreach targets. The distribution of points for systems included in the priority list for outreach is shown in Figure 21. A map summarizing the priority ranking is shown in Figure 22.

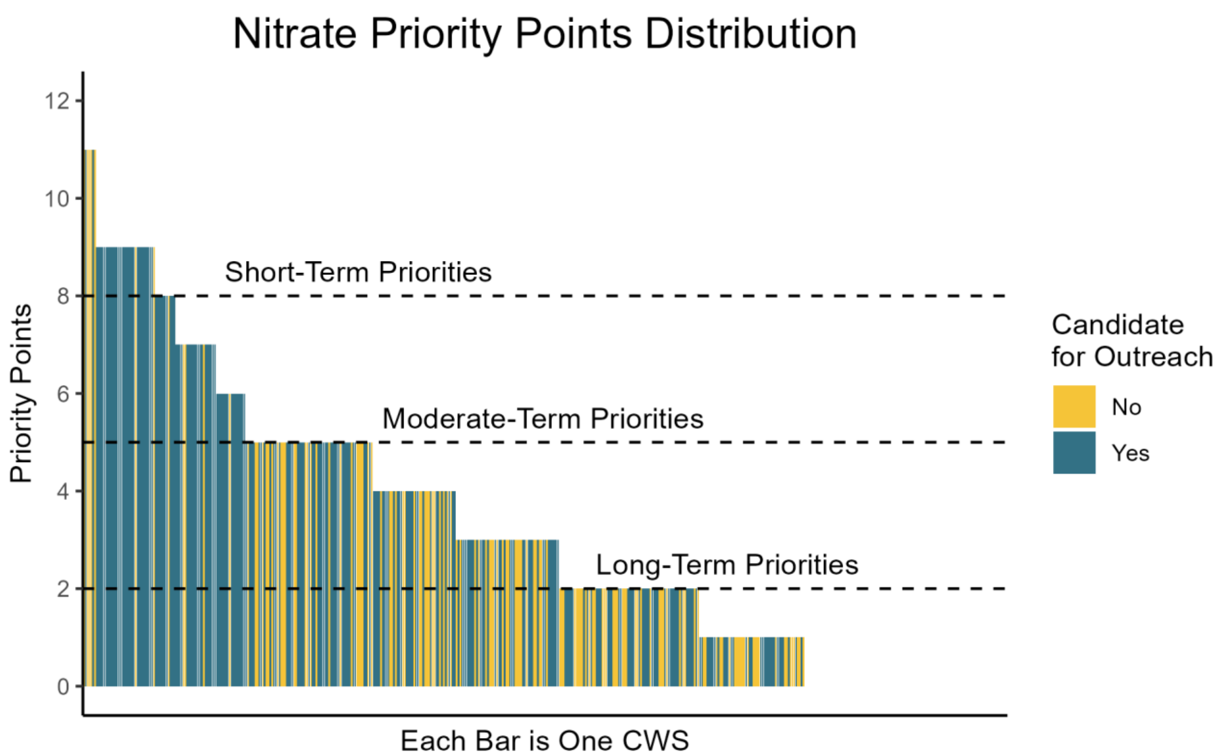

Figure 21. Distribution of Priority Scores for Systems on the Priority Outreach List.

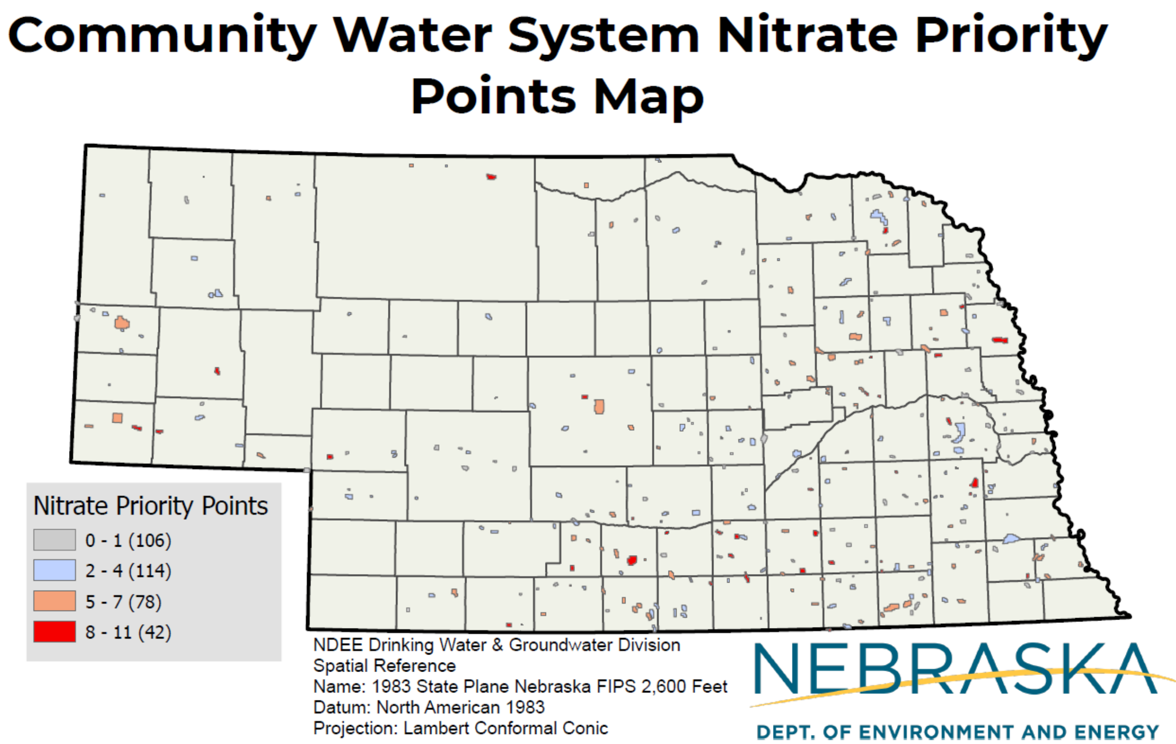

Figure 22. Community Water System Nitrate Priority Points Map.

System summaries were prepared for each CWS to communicate the results of the nitrate study in a simple one-page report. An example of a system summary is shown in Figure 23 for the hypothetical “Nebraskaville” CWS. CWS summaries are not available to the public but help NDEE to communicate the results of the study to CWS owners in an easy-to-parse format. In the upper portion of the document, a map frame shows the WHPA for the CWS and the locations of nitrate samples from wells in the map. Below the map, a table summarizes the measures from the priority system and the total points for the CWS. The figure at the bottom plots nitrate samples in the area from PWS and non-PWS wells. The reverse side of the document provides context for each measure. NDEE can use these documents for outreach to communities, and to assist owners and operators in understanding how nitrate concentrations are changing in their community.

Water System: Nebraskaville, Village of

The map frame shows the WHPA boundary, aerial imagery, and the locations of all recorded nitrate samples nearby. These samples are plotted on the chart below separated by CWS and non-CWS samples. Study results are summarized by the table – which shows the total priority points and top-line results of the analysis. The reverse page of this map briefly summarizes each measure to help CWS understand what the water quality study findings mean for their system. CWS GPS information is not publicly available.

NE_ID	NRD	Mean Nitrate Supply Well C	Priority Points	Trend MK Score	Value Cluster Score	Linear Trend Score
		10.5 mg/L	9	0	1	2

Groundwater Nitrate Samples 2003-2023 Inside the Map Frame

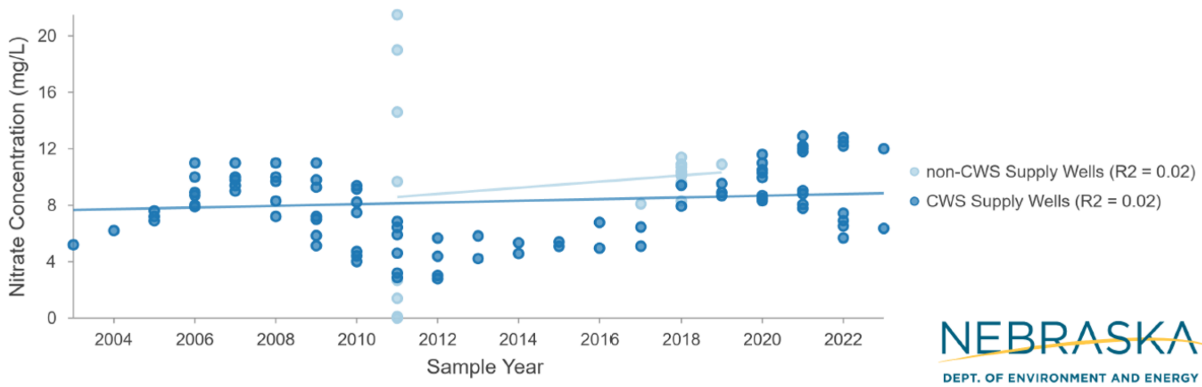

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Figure 23. Example System Summary for the Hypothetical Village of Nebraskaville.

9.0 PRIVATE DOMESTIC WELL OWNER OUTREACH AND GUIDANCE

One objective of the study was to develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies. A risk communication-based outreach toolbox has been developed with outside project partners as an independent document that can be updated regularly and utilized by organizations completing nitrate-related outreach. The toolbox provides guidance and instruction on options for a course of action that NDEE and others can utilize to communicate nitrate risk and solutions as well as additional information for homeowners and businesses that have private domestic wells that may be used for drinking water. The outreach toolbox identifies the target audience(s) affected by nitrate-affected groundwater used for drinking water, provides methods to reach them, and identifies resources for current and future outreach partners to use. The outreach toolbox is provided in Appendix D.

NDEE worked with their external advisory group to develop written guidance about nitrate in drinking water geared primarily towards private domestic well owners to help them evaluate and address nitrate risk in drinking water. The guidance document that was developed for private domestic well owners is available in this section and Appendix D.

NDEE recommends that all private domestic well owners sample their wells for nitrate annually because it is the most reliable way to assess their level of risk. A tri-fold mailer was developed and mailed to private domestic well owners that participated in the free sampling effort with information on nitrate sources and health effects, how to interpret sample results, and next steps to address potentially elevated concentrations of nitrate in their drinking water. This tri-fold mailer is also available in Appendix D.

NITRATE IN DRINKING WATER Nitrate is a compound that occurs naturally and has many human-made sources. Nitrate is in some lakes, rivers, and groundwater in Nebraska. You cannot taste, smell, or see nitrate in water. Consuming too much nitrate can be harmful—especially for babies.

Background Information

Nitrate occurs naturally and at safe and healthy levels in some foods (e.g., spinach and carrots) and comes from natural processes, like plant decay. The primary source of inorganic nitrate is from fertilizers used on yards, gardens, golf courses, and crops. Certain industrial processes and leaks from fertilizer storage can also be a source of inorganic nitrate. Common sources of organic nitrate are human and animal waste.

Nitrate in Nebraska Water

Nitrate has been found in groundwater across Nebraska. While nitrate occurs naturally, levels in groundwater above 3 mg/L are considered an indicator of human-driven contamination.

Based on available data, there were 16,403 domestic well nitrate samples collected from 2003-2024. Of all the domestic wells sampled over this period, 6,468 (39.4%) of them were above 3 mg/L for nitrate and 2,775 (16.9%) of them were above 10 mg/L for nitrate. For more information about nitrate in Nebraska surface water and groundwater, see the Nebraska Department of Environment and Energy's (NDEE's) annual water program publications included in the Resources section.

Health Effects

HUMANS: The U.S. Environmental Protection Agency (EPA) established the Maximum Contaminant Level (MCL) for nitrate in drinking water at 10 milligrams of nitrate (measured as nitrogen) per liter of drinking water (mg/L NO3-N).

Drinking water with nitrate above the MCL can affect how blood carries oxygen and may cause methemoglobinemia (also known as blue baby syndrome). Bottle-fed babies under six months old are at the highest risk of getting methemoglobinemia. This illness can cause the skin to turn a bluish color and result in serious illness or death. Other symptoms connected to methemoglobinemia include decreased blood pressure, increased heart rate, headaches, stomach cramps, and vomiting.[1] Pregnant women are also a high-risk group and should not consume water with nitrate above the MCL.[2] The following conditions may also put people at higher risk of developing nitrate-induced methemoglobinemia: anemia, cardiovascular disease, sepsis, glucose-6- sepsis, glucose-6-phosphate-dehydrogenase deficiency, gastrointestinal diseases and other metabolic problems.[2, 3]

The EPA standard was set based on immediate health effects of consuming nitrate above 10 mg/L. There is additional research being done by others, including the University of Nebraska-Lincoln (UNL), on other potential health effects, including chronic health effects. Chronic health effects occur from ingesting a contaminant over a long period of time. For more information about other potential health effects, visit the UNL websites located in the Resources section.

LIVESTOCK: It is recommended to not allow livestock to drink water with a nitrate level above 100 mg/L. Nitrate can affect livestock similarly to how it affects humans.[4] Additionally, nitrate levels above 100 mg/L may cause reproductive problems in adult cattle and reduce growth rates in replacement heifers.[5] It is recommended that you consult with a veterinarian if you have questions about an acceptable nitrate level in drinking water for other species of animals.

How to Protect Yourself and Your Family

IF YOU ARE ON A PUBLIC WATER SYSTEM: Your public water system regularly tests for nitrate and makes sure levels meet the EPA standard. You can find the level of nitrate detected in your public water system by reading the system's Consumer Confidence Report (CCR) which is a water quality report that is required to be provided to water customers annually. Call your water system to get a paper copy of your community's most recent report or find drinking water quality information about your system online at the Drinking Water Watch website listed in the Resources section.

IF YOU HAVE A PRIVATE WELL: The following types of wells are the most vulnerable to nitrate contamination, especially if they are near or downgradient of septic tanks and absorption/leach fields, certain industrial areas, areas with agricultural activities, or areas with known high concentrations of nitrate in groundwater:

- Shallow wells 50 feet or less in depth.
- Wells in sand aquifers.
- Dug wells or wells with casings that are not watertight due to damage or construction materials used.
- Wells in a pit.
- Wells constructed prior to the 1988 construction standards.

[1] Agency for Toxic Substances and Disease Registry (ATSDR). 2015: ToxFAQs™ for Nitrate and Nitrite (https://www.atsdr.cdc.gov/toxfaqs/tfacts204.pdf). Accessed April 2024.

[2] ATSDR. 2013. ATSDR Case Studies in Environmental Medicine Nitrate/Nitrite Toxicity (https://www.atsdr.cdc.gov/csem/nitrate_2013/docs/nitrite.pdf). Page 37. Accessed April 2024

[3] U.S. Environmental Protection Agency. 1991. Integrated Risk Information System (IRIS) Chemical Assessment Summary (https://iris.epa.gov/static/pdfs/0076_summary.pdf). Accessed April 2024.

[4] Rasby, R. & Walz, T. 2011. Water Requirements for Beef Cattle. University of Nebraska-Lincoln Extension. (https://extensionpubs.unl.edu/publication/g2060/html/view). Accessed May 2024.

[5] Kononoff, P. & Clark, K. 2017. Water Quality and Requirements for Dairy Cattle. University of Nebraska-Lincoln Extension. (https://extensionpubs.unl.edu/publication/g2292/html/view). Accessed May 2024.

Prevent Contamination

- **Construct your well in a safe spot.** Domestic wells constructed in Nebraska are required to adhere to setback distances and construction standards set in Nebraska Administrative Code (NAC) Title 178, Chapter 12. Ensure your installer is a licensed Water Well Professional using the NDEE website listed in the Resources section or by calling 402-471-0546.
- **Keep nitrate sources away from your well.** Sources may include fertilizer application and storage, fuel storage, septic systems, wastewater treatment facilities, and livestock facilities. See NAC Title 178, Chapter 12, Chart 1 for setback distances from common sources of well contamination. Consult with a Certified Onsite Wastewater Treatment (OWT) Professional if you have concerns about the location or condition of your septic system in relation to your well. A link to find a Certified OWT Professional is listed in the Resources section.
- **Get your well inspected.** Work with a licensed professional to take any corrective actions that may be needed. Water Well Professionals with a current license are listed on the NDEE website listed in the Resources section.
- **Test for nitrate and bacteria every year.** You are responsible for regularly testing your well water. NDEE recommends using an accredited laboratory to test your well water. Well owners can request sample kits from the Nebraska Department of Health and Human Services (NDHHS) online at the website listed in the Resources section or by calling 402-471-3935. Additionally, the NDHHS's website has a list of other accredited laboratories. Contact the laboratory to get sample containers and instructions or ask your local Natural Resources District (NRD) or public health services if they provide well water testing services. If you need help finding your local NRD, visit the website in the Resources section.

Address Contamination

If nitrate is detected in your water at levels above 10 mg/L, follow these steps:

- **Get your drinking water from a safe source**, such as bottled water, or a public water system including rural water districts. This is especially important if babies under six months old drink the water or formula is made with the water. Pregnant or nursing mothers should consult with their doctor about how elevated nitrate levels in drinking water may affect them. Boiling water is not a solution for elevated nitrate levels as it causes evaporation and concentrates the nitrate in the water.
- **Consider testing the well for other contaminants that commonly occur with nitrate such as bacteria and uranium.** Sample test kits for other contaminants, such as bacteria and uranium may be requested from the Nebraska Department of Health and Human Services online at the website listed in the Resources section or by calling 402-471-3935. For more information about other potential contaminants in your well, visit the NebGuides link under the UNL Resources section.
- **Contact a local rural water district.** Connection to the rural water district-supplied water may be an option in your area.
- **Consider your well construction.** If your existing well is poorly constructed or is located near a contamination source such as a septic system, drilling a new well or rehabilitating your well may be an option. However, this can be costly and is not a guarantee that the new or modified well will have nitrate below 10 mg/L. Water Well Professionals with a current license that can help drill a new well or rehabilitate an existing well are listed on the NDEE website listed in the Resources section.
- **Consider a Point of Use (POU) or Point of Entry (POE) treatment system to remove nitrate from drinking water.** POU treatment systems treat water at one tap while POE treatment systems treat all the water that enters your home. Reverse osmosis, ion exchange, or distillation filtration systems are the typical types of treatment systems used to remove nitrate from drinking water. These systems require regular maintenance and testing to ensure they are working correctly and must be properly installed, operated, and maintained to be effective. You may be able to purchase a basic system from your local home improvement store. Consult with a licensed plumber for help installing a more sophisticated system. Additionally, your local NRD may have assistance available to help fund the installation of a treatment system. If you need help finding your local NRD, visit the website located in the Resources section.

Resources

- Drinking Water Watch
  https://drinkingwater.ne.gov
- Find Your NRD
  https://www.nrdnet.org/
- NDEE Annual Report to the Legislature
  https://dee.nebraska.gov/forms/publications-grants-forms/ndee034
- Groundwater Quality Monitoring Report
  https://dee.nebraska.gov/forms/publications-grants-forms/24-026
- NDEE Water Quality Integrated Report
  https://dee.nebraska.gov/forms/publications-grants-forms/23-012
- NDEE Certified Onsite Wastewater Treatment Professionals Lookup
  https://dee.nebraska.gov/water/wastewater/onsite-wastewater-program/certified-installers-mound-endorsement-and-professional-engineers
- NDEE Water Well Professionals Licensee Lookup
  https://deq-iis.ne.gov/zs/wwp/main_pro.php
- NAC Title 178 (Chapter 12 Setback Distances)
  https://rules.nebraska.gov/rules?agencyId=37&titleId=107
- NDHHS Water Sampling Test Kit Request
  https://www.nebraska.gov/dhhs/water-test-kits/private.html
- NDHHS Certified Labs
  https://dhhs.ne.gov/Pages/Lab-Certification-Requirements.aspx
- EPA Fact Sheet
  https://archive.epa.gov/water/archive/web/pdf/archived-consumer-fact-sheet-on-nitrates-and-or-nitrites.pdf
- UNL Resources:
  https://water.unl.edu/category/water-and-health/
  https://water.unl.edu/water-and-health-resources/
  https://water.unl.edu/article/drinking-water/nebguides/

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10.0 CONCLUSIONS AND RECOMMENDATIONS

The overall goal of the water quality study was to provide an analysis and recommend viable solutions for nitrate-affected drinking water, including drinking water not regulated by the SDWA (i.e. private domestic wells). NDEE will continue to work closely with project partners on nitrate and other water quality issues to help provide Nebraskans across the state with access to drinking water meeting SDWA standards. The five objectives identified to accomplish during this study and a summary of the actions completed to achieve these objectives are provided below, separated into sections related to PWS and private domestic wells, each followed by key recommendations for future activities to reduce public consumption of nitrate impacted drinking water above the MCL.

Nitrate in groundwater, which many Nebraskans rely on for drinking water, has been a persistent issue in the state. Increases in nitrate concentration have been reported since the 1930s in areas like the Upper Elkhorn and Central Platte River basins (Spalding, 1993; Litke, 2001; Wells, 2018). Because of the aquifer characteristics in much of the state, when nitrate leaches past the root zone, it can remain in groundwater for decades (McMahon, 2007). This study largely affirms the existing research regarding the extent of the problem and seeks to provide viable solutions for nitrate-affected drinking water.

PUBLIC WATER SYSTEMS

Objective: Analyze nitrate concentrations in Nebraska groundwater and identify trends and data gaps. The water quality study accomplished the following tasks for PWSs associated with this objective:

- Available CWS nitrate data was analyzed for trends using multiple statistical methods. Of the 444 systems analyzed, 120 to 137 systems were found to have an increasing trend of nitrate concentrations in drinking water supplied to residents.
- Analysis affirmed that BMPs are effective at lowering the nitrate concentrations in groundwater in the long-term. Reducing surface loading through BMPs has been connected to a reduction in nitrate levels in certain basins in the state by around 0.25 mg/L per year (Exner, 2014). Wellhead and source water protection programs are a tool for communities to encourage these BMPs to protect drinking water supplies.
- Several data gaps were identified while preparing this report:
    - WHPAs for some communities need to be updated or digitized for systems in the state. These updates are an ongoing process and maps are typically updated when new wells are added to the water system.
    - Customer service areas for PWSs are not available for the whole state, which limits potential regionalization studies. Changes to reporting rules in 2024 may close this data gap, which would benefit future regionalization efforts to address nitrate in drinking water.

Objective: Develop guidance and tools that prioritize areas of the state for program outreach with the goal of proactively addressing rising nitrate concentrations in CWSs, including a guidance document for PWSs. The water quality study accomplished the following tasks associated with this objective:

- A guidance document explaining nitrate monitoring requirements and intervention points to avoid an AO with available state and federal program assistance was developed for PWS owners and operators.
- Study results summarized in an individualized, one-page report were prepared for each CWS.
- A priority system was developed to identify CWSs that could benefit from short-term, moderate-term, and long-term assistance based on the amount of time it takes for each funding program to effectively address nitrate in drinking water. Out of 594 CWSs, there were 42, 77, and 103 systems identified for short-, moderate-, and long-term prioritization, respectively.

Key Recommendations relating to PWSs:

- Conduct a regionalization study on PWS consolidation to address nitrate issues using newly available CWS service connection information from the updated Lead and Copper Rule. Larger consolidation efforts have been shown in other states to dramatically reduce the cost of regionalization on a per-service basis i.e., the cost borne by system ratepayers.
- Incorporate the CWSs priority system described in this report into program planning. It's a tool NDEE can use to identify opportunities for medium and long-term planning efforts that can help communities prepare to address or avoid elevated nitrate in drinking water. By calculating the index annually, the Department could track progress on the issue over time. Adding technical, financial, and managerial (TFM) variables to this index could improve the ability to identify systems where organizational barriers to providing SDWA compliant water may exist. The nitrate priority system described herein could be a basis for incorporating water quality indicators into the SRF ranking process. This system could be expanded to cover all PWSs.
- NDEE should continue to partner with stakeholders and encourage voluntary BMPs as a means of reducing or preventing drinking water nitrate contamination.

PRIVATE DOMESTIC WELLS

Objective: Provide free nitrate test kits to private domestic well owners to collect needed data on nitrate concentrations in private domestic wells. The water quality study accomplished the following tasks associated with this objective:

- During the water quality study, over 4,500 nitrate test kids were requested, and as of May 1, 2024, results were reported for 3,499 of these. This is the most nitrate samples collected for private domestic wells in any single year on record for the state. This data provides an invaluable snapshot of water quality in private domestic wells across the state, and collecting the data has raised public awareness of nitrate in drinking water.
- As described in the outreach toolbox in Appendix D, NDEE fielded over 2,500 calls related to the free nitrate test kit effort. This allowed for direct connections to be made with private domestic well owners across the state and helped to inform them about the risks associated with drinking water with nitrate concentrations above 10 mg/L, the importance of regularly testing your well, potential sources of nitrate in drinking water, and solutions that exist for addressing nitrate-affected drinking water.

Objective: Analyze nitrate concentrations in Nebraska groundwater and identify trends and data gaps. The water quality study accomplished the following tasks for private domestic wells associated with this objective:

- Analyzed historic nitrate data and identified areas with elevated nitrate concentrations.
- Compared new private domestic well data collected during the study to historic trends.
- Several data gaps were identified while preparing this report:
    - As many as 110,000 private domestic wells in the state are unregistered. Unknown locations of unregistered private domestic wells and contact information for owners is a significant data gap hindering direct outreach.
    - NDEE estimates that fewer than 10% of private domestic wells are sampled annually for nitrate.
    - There is a three-year backlog in publicly available water quality data in the Groundwater Clearinghouse, a major data gap identified by this report. Changes to the upload process since 2020 are ongoing and expected to resolve in 2024. Additionally, based on feedback from project partners, there is a perception that private domestic well nitrate samples will always be rejected due to data quality concerns. This discourages NRDs from submitting the samples. With process improvements and additional data quality flagging options, it may be possible to retroactively submit these samples.

Objective: Develop a guidance document to assist private domestic well owners in evaluating their risk of nitrate in drinking water and provide solutions to mitigate nitrate-affected water. The water quality study accomplished the following tasks associated with this objective:

- A nitrate in drinking water guidance document was developed to summarize nitrate issues in the state, common health effects, sources, methods to prevent and address contaminated drinking water, and links to additional existing resources.

Objective: Develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies. This includes modeling to identify high-risk areas, and an interactive, web-based geographic information system (GIS) tool for internal NDEE and key agency partner use. The water quality study accomplished the following tasks associated with this objective:

- NDEE and its partners developed an outreach toolbox and identified private domestic well owners, the medical community, well drillers, septic system installers, realtors, and mortgage lenders as target audiences to promote awareness of nitrate issues in private domestic drinking water supplies. This toolbox can be used by NDEE and its project partners to help deliver consistent messaging related to nitrate in drinking water.
- A predictive model was developed to identify high-risk areas where private domestic wells are likely to exceed 3, 5 or 10 mg/L of nitrate. This modeling was incorporated into the internal NDEE GIS tool.
- An interactive, web-based risk assessment GIS tool was developed for internal NDEE and key agency partner use to identify high risk areas for future outreach efforts.

Key recommendations identified by the study relating to private domestic wells:

- Updates to the Clearinghouse data are ongoing. At time of reporting, there is a 3-year backlog in this data, a major gap identified by the study. This database is important to water quality managers across the state, and every effort should be made to update and continue to maintain these data.
- Historic data for private domestic wells is limited, and many of the samples that have been taken are not currently publicly available. When the Clearinghouse changes are finalized, NDEE should make data collected during this study available. Additionally, work should be continued to increase private domestic well testing.

- NDEE and its partners should continue to develop and refine risk communication resources developed during the study to provide a clear, unified message on nitrate in drinking water. As funding allows, NDEE and its partners could continue private well sampling and treatment programs. Coordination with partner agencies could improve the visibility of these programs for private domestic well owners.
- Create a database of likely unregistered well locations and owner contact information by implementing the methodology discussed in the outreach toolbox. This would allow for direct and more cost-effective outreach to unregistered well owners.
- Increase well registrations by reducing obstacles for registration. This could potentially include temporarily waiving the fee for the registration of old wells that predated the well registration requirement (pre-1993). Additionally, creating a simplified registration form for old wells or modifying the existing form may help prevent discouraging owners from registering wells due to lack of detailed information currently required to register a well.

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Appendix A – Summary Tables

SUMMARY TABLES

Table A 1. Community Water System ((CWS) Point of Entry (POE) Nitrate Sample Summary 2003-2023. Data from the State Drinking Water Information System (SDWIS) 2003-2023.

Number of Compliance Samples	Mean Nitrate Concentration (milligrams per liter [mg/L])	Median Nitrate Concentration (mg/L)	Maximum Nitrate Concentration (mg/L)	Unique CWS Count
34,780	**4.44**	**4.16**	**34.3**	**535**

*Table A 2. All Nebraska Groundwater Quality Clearinghouse Nitrate Sample Summary 2003-2019. *Domestic and PWS well data shown in this table only includes samples recorded to the Clearinghouse.*

Clearinghouse Well Type	Mean Nitrate Concentration (mg/L)	Median Nitrate Concentration (mg/L)	Sample Count	Wells Sampled
Livestock Watering	12.43	8.40	522	105
Domestic	7.21	2.50	5,676	1,423
Irrigation	9.35	6.50	51,969	13,504
Monitoring	7.33	4.10	19,021	1,697
Public Water System	4.04	2.94	42,631	3,064
All Wells	7.05	4.5	119,992	19,768

Table A 3. Community Water System Log-linear Model Results 2003-2023.

Number of Well Samples	Number of Significant Models	Wells with an Increasing Trend in Nitrate C	Wells with a Decreasing Trend in Nitrate C	Number of Communities Modeled
34,780	**245**	**120**	**125**	**535**

*Table A 4. Community Water System (CWS) Supply Well Analysis Methods Matrix & Priority Scoring.**

Method/Line of Evidence	Five-year Sample Average	Trend Analysis (Mann-Kendall)	Time Series Clustering	Log-Linear Models
Description	The 5-year average sample concentration for the CWS Points of Entry (POE) from 2018-2023	CWS POE samples were analyzed for trends during the 2003-2023 period using the Mann-Kendall statistic.	CWS time series were compared based on the average nitrate concentration in POE samples over the study period.	CWS POE trends were analyzed using log-linear models. Positive slope values indicate increasing nitrate concentration over the study period.
Data Source	**2018-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**	**2003-2023 SDWIS POE Nitrate Samples by CWS**
Tier	**Tier 1**	**Tier 2**	**Tier 2**	**Tier 2**
Threshold Values	**< 1 mg/L: 0 points 1-3 mg/L: 1 points 3-5 mg/L: 2 point 5-8 mg/L: 3 points >8 mg/L: 5 points**	**90% Confidence: 1 point 95% Confidence: 2 points 99% Confidence: 2 points**	**Low Cluster: 0 points Moderate Cluster: 1 point Elevated Cluster: 2 points**	**Positive slope and significant: 2 points**
Points (11 Maximum)	**5**	**2**	**2**	**2**

*** For a complete description of the methods and threshold values – see section 8.0.**

Table A 5. Community Water System (CWS) Preliminary Priority Results Table.

Grouping	Number of Systems	Point Cutoff (of 11)
Short-term Planning Priorities	**42**	**9**
Medium-term Planning Priorities	**77**	**5**
Long-term Planning Priorities	**103**	**3**
Not Prioritized at this Time	**373**	**2**
Total CWS	**594**	

Table A 6. 2024 Priority Ranking for CWS Nitrate Assistance (POE Data).

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
11	NE3114107	SILVER TRAILER PARK	Lower Loup	9.02
11	NE3103901	BANCROFT, VILLAGE OF	Lower Elkhorn	9.73
9	NE3115510	MALMO, VILLAGE OF	Lower Platte North	8.24
9	NE3102706	COLERIDGE, VILLAGE OF	Lewis & Clark	7.89
9	NE3130003	ROSELAND, VILLAGE OF	Little Blue	5.82
9	NE3113705	HOLDREGE, CITY OF	Tri-Basin	7.27
9	NE3103507	SUTTON, CITY OF	Upper Big Blue	6.63
9	NE3114303	STROMSBURG, CITY OF	Upper Big Blue	5.9
9	NE3115914	STAPLEHURST, VILLAGE OF	Upper Big Blue	5.9
9	NE3115508	MEMPHIS, VILLAGE OF	Lower Platte North	8.31
9	NE3114114	CRESTON, VILLAGE OF	Lower Elkhorn	6.85
9	NE3115504	CEDAR BLUFFS, VILLAGE OF	Lower Platte North	5.68
9	NE3110905	WAVERLY, CITY OF	Lower Platte South	7.05
9	NE3106107	CAMPBELL, VILLAGE OF	Lower Republican	6.98
9	NE3110505	DIX, VILLAGE OF	South Platte	7.21
9	NE3103106	VALENTINE, CITY OF	Middle Niobrara	7.7
9	NE3115108	TOBIAS, VILLAGE OF	Lower Big Blue	6.44
9	NE3101908	ELM CREEK, VILLAGE OF	Central Platte	6.84
9	NE3110903	CATHOLIC CENTER	Lower Platte South	6.94
9	NE3108102	HAMPTON, VILLAGE OF	Upper Big Blue	7.97
9	NE3116907	BYRON, VILLAGE OF	Little Blue	6.2
9	NE3102102	TEKAMAH, CITY OF	Papio-Missouri River	6.7
9	NE3110911	DAVEY, VILLAGE OF	Lower Platte South	8.28
9	NE3100106	KENESAW, VILLAGE OF	Little Blue	6.85
9	NE3114501	DANBURY, VILLAGE OF	Middle Republican	7.12
9	NE3104108	MERNA, VILLAGE OF	Lower Loup	7.13
9	NE3100107	JUNIATA, VILLAGE OF	Little Blue	5.78
9	NE3105303	SNYDER, VILLAGE OF	Lower Elkhorn	6.37
9	NE3110103	BRULE, VILLAGE OF	Twin Platte	7.37
9	NE3106506	ARAPAHOE, CITY OF	Lower Republican	5.82
9	NE3112301	BROADWATER, VILLAGE OF	North Platte	6.98
8	NE3110915	SKY RANCH ACRES	Lower Platte South	5.27
8	NE3108104	HORDVILLE, VILLAGE OF	Central Platte	6.66
8	NE3105909	SHICKLEY, VILLAGE OF	Little Blue	5.49
8	NE3118302	BLUE HILL, CITY OF	Little Blue	6.93
8	NE3109703	ELK CREEK, VILLAGE OF	Nemaha	6.22
8	NE3101914	RIVERSIDE MOBILE HOME PARK	Tri-Basin	6.81
8	NE3102517	GREENWOOD, VILLAGE OF	Lower Platte South	7.72
8	NE3120840	EAGLES NEST ESTATES	Upper Niobrara White	6.52
8	NE3114106	COLLEGE VIEW PARK	Lower Loup	10.16
8	NE3103302	POTTER, VILLAGE OF	South Platte	5.21
7	NE3112707	NEMAHA COUNTY RWD #2	Nemaha	6.52

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
7	NE3150471	COVIDIEN	Lower Elkhorn	6.52
7	NE3110301	SPRINGVIEW, VILLAGE OF	Lower Niobrara	7.19
7	NE3111905	NEWMAN GROVE, CITY OF	Lower Platte North	4.58
7	NE3110504	BUSHNELL, VILLAGE OF	South Platte	4.71
7	NE3100305	NELIGH, CITY OF	Upper Elkhorn	3
7	NE3103101	CODY, VILLAGE OF	Middle Niobrara	4.5
7	NE3102309	BAY MEADOWS TRAILER COURT	Central Platte	5.79
7	NE3108306	ORLEANS, VILLAGE OF	Lower Republican	3.45
7	NE3113501	VENANGO, VILLAGE OF	Upper Republican	4.22
7	NE3107308	ELWOOD, VILLAGE OF	Tri-Basin	4.13
7	NE3112708	JOHNSON, VILLAGE OF	Nemaha	5.1
7	NE3106502	OXFORD, VILLAGE OF	Lower Republican	8.18
7	NE3115716	SCOTTSBLUFF, CITY OF	North Platte	8.06
7	NE3115507	MORSE BLUFF, VILLAGE OF	Lower Platte North	4.16
7	NE3104710	OVERTON, VILLAGE OF	Central Platte	3.25
7	NE3102522	CUMING COUNTY RWD #1	Lower Elkhorn	8.58
7	NE3101102	ALBION, CITY OF	Lower Loup	3.2
7	NE3109507	FAIRBURY, CITY OF	Little Blue	8.39
6	NE3115305	SARPY COUNTY SID #24 - THOUS	Papio-Missouri River	6.53
6	NE3116302	LITCHFIELD, VILLAGE OF	Lower Loup	6.56
6	NE3101105	ST. EDWARD, VILLAGE OF	Lower Loup	5.83
6	NE3102708	WYNOT, VILLAGE OF	Lewis & Clark	7.94
6	NE3101101	CEDAR RAPIDS, VILLAGE OF	Lower Loup	2.87
6	NE3120372	PROSSER, VILLAGE OF	Little Blue	4.25
6	NE3103502	HARVARD, CITY OF	Upper Big Blue	4.02
6	NE3114505	LEBANON, VILLAGE OF	Middle Republican	2.94
6	NE3114111	CIRCLE H MOBILE HOME PARK	Lower Platte North	4.38
6	NE3113702	LOOMIS, VILLAGE OF	Tri-Basin	7.4
6	NE3112903	NELSON, CITY OF	Little Blue	2.92
6	NE3110501	KIMBALL, CITY OF	South Platte	2.74
6	NE3107703	SCOTIA, VILLAGE OF	Lower Loup	2.46
6	NE3104104	ANSLEY, VILLAGE OF	Lower Loup	2.3
6	NE3114104	LINDSAY, VILLAGE OF	Lower Platte North	7.99
5	NE3106501	WILSONVILLE, VILLAGE OF	Lower Republican	7.35
5	NE3106304	MOOREFIELD, VILLAGE OF	Middle Republican	5.28
5	NE3106105	HILDRETH, VILLAGE OF	Tri Basin	8.31
5	NE3118703	BENEDICT, VILLAGE OF	Upper Big Blue	8.07
5	NE3112905	RUSKIN, VILLAGE OF	Little Blue	5.65
5	NE3108307	ALMA, CITY OF	Lower Republican	5.74
5	NE3106712	ADAMS, VILLAGE OF	Nemaha	6.7
5	NE3112701	NEMAHA COUNTY RWD #1	Nemaha	6.8
5	NE3114113	DUNCAN, VILLAGE OF	Lower Loup	5.08

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
5	NE3108702	CULBERTSON, VILLAGE OF	Middle Republican	6.94
5	NE3114902	BASSETT, CITY OF	Upper Elkhorn	5.21
5	NE3107704	WOLBACH, VILLAGE OF	Lower Loup	1.73
5	NE3102705	LAUREL, CITY OF	Lower Elkhorn	7.38
5	NE3111916	MADISON, CITY OF	Lower Elkhorn	2.29
5	NE3108908	CHRISTENSENS COUNTRY COUF	Upper Elkhorn	7.39
5	NE3113701	FUNK, VILLAGE OF	Tri-Basin	6.78
5	NE3100304	ORCHARD, VILLAGE OF	Upper Elkhorn	7.4
5	NE3107313	SMITHFIELD, VILLAGE OF	Tri-Basin	6.03
5	NE3106710	WYMORE, CITY OF	Lower Big Blue	6.5
5	NE3116903	HUBBELL, VILLAGE OF	Little Blue	6.21
5	NE3120483	WOODCLIFF WATER SYSTEM	Lower Platte North	5.18
5	NE3115106	SWANTON, VILLAGE OF	Lower Big Blue	6.78
5	NE3110707	CENTER, VILLAGE OF	Lewis & Clark	2.38
5	NE3113707	BERTRAND, VILLAGE OF	Tri-Basin	6.34
5	NE3112706	NEMAHA, VILLAGE OF	Nemaha	6.21
5	NE3116101	RUSHVILLE, CITY OF	Upper Niobrara White	4.66
5	NE3104901	CHAPPELL, CITY OF	South Platte	6.53
5	NE3116908	DAVENPORT, VILLAGE OF	Little Blue	3.34
5	NE3108303	TAYLORS MANOR	Lower Republican	6.4
5	NE3115711	NORTHSIDE MOBILE HOME RAN(	North Platte	6.95
5	NE3115906	PLEASANT DALE, VILLAGE OF	Lower Platte South	5.94
5	NE3105907	MILLIGAN, VILLAGE OF	Upper Big Blue	6.21
5	NE3102709	RANDOLPH, CITY OF	Lower Elkhorn	5.92
5	NE3120030	DEWEESE, VILLAGE OF	Little Blue	5.25
5	NE3109501	REYNOLDS, VILLAGE OF	Little Blue	5.35
5	NE3105307	DODGE, VILLAGE OF	Lower Elkhorn	7.69
5	NE3110904	SPRAGUE, VILLAGE OF	Lower Platte South	5.27
5	NE3114103	HUMPHREY, CITY OF	Lower Elkhorn	6.22
5	NE3112502	GENOA, CITY OF	Lower Loup	5.17
5	NE3105105	NEWCASTLE, VILLAGE OF	Lewis & Clark	5.61
5	NE3109510	HARBINE, VILLAGE OF	Lower Big Blue	2.15
5	NE3106711	PICKRELL, VILLAGE OF	Lower Big Blue	2.66
5	NE3120157	SARPY COUNTY SID #38 - HIGHL/	Papio-Missouri River	4.05
4	NE3101907	GIBBON, CITY OF	Central Platte	3.33
4	NE3120305	SCOTTSBLUFF COUNTY SID #10	North Platte	3.18
4	NE3106503	EDISON, VILLAGE OF	Lower Republican	6.36
4	NE3102702	HARTINGTON, CITY OF	Lewis & Clark	5.15
4	NE3101904	SHEENS MOBILE HOME PARK	Central Platte	2.73
4	NE3116501	HARRISON, VILLAGE OF	Upper Niobrara White	4.51
4	NE3107702	SPALDING, VILLAGE OF	Lower Loup	1
4	NE3113502	MADRID, VILLAGE OF	Upper Republican	4.68

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
4	NE3113104	SYRACUSE, CITY OF	Nemaha	5.89
4	NE3100303	ROYAL, VILLAGE OF	Upper Elkhorn	0.92
4	NE3120819	CHAPMAN, VILLAGE OF	Central Platte	0.55
4	NE3118303	BLADEN, VILLAGE OF	Little Blue	4.43
4	NE3103504	GLENVIL, VILLAGE OF	Little Blue	3.43
4	NE3108304	REPUBLICAN CITY, VILLAGE OF	Lower Republican	4.79
4	NE3115503	CERESCO, VILLAGE OF	Lower Platte South	0.63
4	NE3102103	LYONS, CITY OF	Lower Elkhorn	0.47
4	NE3111917	MEADOW GROVE, VILLAGE OF	Lower Elkhorn	0.97
4	NE3104103	ANSELMO, VILLAGE OF	Lower Loup	0.84
4	NE3108503	TRENTON, VILLAGE OF	Middle Republican	3.15
4	NE3114102	MONROE, VILLAGE OF	Lower Loup	4.67
4	NE3118704	BRADSHAW, VILLAGE OF	Upper Big Blue	4.85
4	NE3111915	BATTLE CREEK, CITY OF	Lower Elkhorn	3.69
4	NE3116909	BELVIDERE, VILLAGE OF	Little Blue	2.7
4	NE3106706	CORTLAND, VILLAGE OF	Lower Big Blue	0.44
4	NE3113903	OSMOND, CITY OF	Lower Elkhorn	4.08
4	NE3103306	GURLEY, VILLAGE OF	South Platte	2.18
4	NE3115512	WAHOO, CITY OF	Lower Platte North	4.34
3	NE3120446	ITHACA, VILLAGE OF	Lower Platte North	5.33
3	NE3103304	LODGEPOLE, VILLAGE OF	South Platte	6.15
3	NE3112102	CENTRAL CITY, CITY OF	Central Platte	4.25
3	NE3120712	SOUTHFORK ESTATES	Lower Platte South	1.55
3	NE3102519	CASS COUNTY SID #1 - LAKE WA	Lower Platte South	1.29
3	NE3120658	LOGAN EAST RURAL WATER SYS	Lower Elkhorn	5.51
3	NE3115107	WESTERN, VILLAGE OF	Lower Big Blue	5.31
3	NE3101505	NAPER, VILLAGE OF	Lower Niobrara	3.21
3	NE3115101	DEWITT, VILLAGE OF	Lower Big Blue	4.51
3	NE3114301	POLK, VILLAGE OF	Upper Big Blue	3.79
3	NE3104703	FARNAM, VILLAGE OF	Central Platte	3.53
3	NE3105317	SCHULZLAND MOBILE HOME PAI	Lower Platte North	1.79
3	NE3116902	DESHLER, CITY OF	Little Blue	4.12
3	NE3106104	FRANKLIN, CITY OF	Lower Republican	4.1
3	NE3120014	HITCH N RAIL MOBILE HOME COI	Central Platte	0.87
3	NE3115703	MITCHELL, CITY OF	North Platte	4.08
3	NE3118701	HENDERSON, CITY OF	Upper Big Blue	3.07
3	NE3106102	UPLAND, VILLAGE OF	Lower Republican	4.22
3	NE3106303	MAYWOOD, VILLAGE OF	Middle Republican	4.01
3	NE3108310	B AND R TRAILER COURT	Lower Republican	5.02
3	NE3116702	STANTON, CITY OF	Lower Elkhorn	1.31
3	NE3111112	WALLACE, VILLAGE OF	Middle Republican	3.31
3	NE3120306	BOYD COUNTY RWD #1	Lower Niobrara	4.33

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
3	NE3120304	CASS COUNTY RWD #2	Lower Platte South	1.56
3	NE3113706	ATLANTA, VILLAGE OF	Tri-Basin	4
3	NE3108905	ATKINSON, CITY OF	Upper Elkhorn	2.87
3	NE3101302	ALLIANCE, CITY OF	Upper Niobrara White	3.61
3	NE3102508	ALVO, VILLAGE OF	Lower Platte South	1.2
3	NE3101905	WOOD RIVER VALLEY MOBILE H	Central Platte	1.05
3	NE3130031	WATERBURY, VILLAGE OF	Lewis & Clark	2.78
3	NE3112501	BELGRADE, VILLAGE OF	Lower Loup	2.93
3	NE3101303	HEMINGFORD, VILLAGE OF	Upper Niobrara White	3.52
3	NE3120348	WEST KNOX RWD	Lower Niobrara	6.28
3	NE3120037	BUFFALO COUNTY SID #3 - GLEN	Central Platte	1.04
2	NE3108904	ONEILL, CITY OF	Upper Elkhorn	0.34
2	NE3102510	EAGLE, VILLAGE OF	Lower Platte South	0.53
2	NE3112901	LAWRENCE, VILLAGE OF	Little Blue	4.88
2	NE3120757	LANCASTER COUNTY SID #6 - VII	Lower Platte South	3.15
2	NE3115511	VALPARAISO, VILLAGE OF	Lower Platte South	3.52
2	NE3112702	BROCK, VILLAGE OF	Nemaha	4.75
2	NE3105104	MASKELL, VILLAGE OF	Lewis & Clark	2.08
2	NE3107501	HYANNIS, VILLAGE OF	Upper Loup	2.87
2	NE3107905	DONIPHAN, VILLAGE OF	Central Platte	1.98
2	NE3106301	EUSTIS, VILLAGE OF	Central Platte	2.52
2	NE3104102	ARNOLD, VILLAGE OF	Lower Loup	2.45
2	NE3116303	LOUP CITY, CITY OF	Lower Loup	2.27
2	NE3109304	ELBA, VILLAGE OF	Lower Loup	2.7
2	NE3109302	FARWELL, VILLAGE OF	Lower Loup	0.45
2	NE3101903	MILLER, VILLAGE OF	Central Platte	2.28
2	NE3103104	KILGORE, VILLAGE OF	Middle Niobrara	2.84
2	NE3106302	CURTIS, CITY OF	Middle Republican	2.64
2	NE3104110	COMSTOCK, VILLAGE OF	Lower Loup	2.31
2	NE3107311	LAKESIDE TRAILER COURT	Tri-Basin	0.09
2	NE3107101	BURWELL, CITY OF	Lower Loup	2.72
2	NE3118501	BARTLETT, VILLAGE OF	Lower Loup	2.21
2	NE3113503	GRANT, CITY OF	Upper Republican	2.59
2	NE3110907	RAYMOND, VILLAGE OF	Lower Platte South	3.97
2	NE3102509	EAGLE LAKE SUBDIVISION	Nemaha	1.83
2	NE3120824	CROOKED CREEK WATER SYSTE	Lower Platte South	0.23
2	NE3117901	ARLINGTON, VILLAGE OF	Papio-Missouri River	0.16
2	NE3110708	BLOOMFIELD, CITY OF	Lewis & Clark	2.12
2	NE3101103	PRIMROSE, VILLAGE OF	Lower Loup	2.38
2	NE3106106	BLOOMINGTON, VILLAGE OF	Lower Republican	2.4
2	NE3107303	BULLHEAD POINT	Tri-Basin	0
2	NE3104107	OCONTO, VILLAGE OF	Central Platte	2.87

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

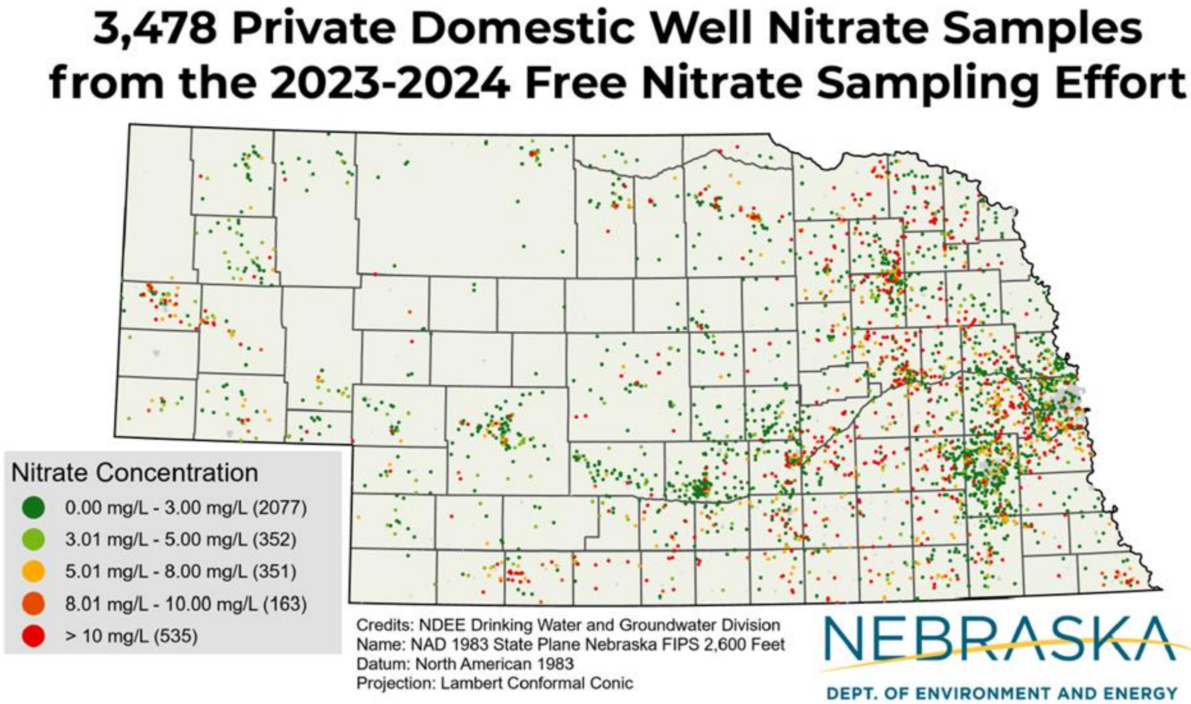
Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
2	NE3120068	BUFFALO BILL MOBILE HOME PA	Twin Platte	1.99
2	NE3120354	COUNTRY ACRES SUBDIVISION	Lower Platte South	0.47
2	NE3104701	COZAD, CITY OF	Central Platte	1.81
2	NE3102308	RISING CITY, VILLAGE OF	Upper Big Blue	0.79
2	NE3117101	THEDFORD, VILLAGE OF	Upper Loup	2.22
2	NE3116104	GORDON, CITY OF	Upper Niobrara White	2.32
2	NE3104101	SARGENT, CITY OF	Lower Loup	2.45
2	NE3106708	ODELL, VILLAGE OF	Lower Big Blue	2.86
2	NE3104111	CALLAWAY, VILLAGE OF	Lower Loup	2.46
2	NE3120954	HARRISBURG, VILLAGE OF	North Platte	1.97
2	NE3109306	ST. PAUL, CITY OF	Lower Loup	2.41
1	NE3108701	STRATTON, VILLAGE OF	Middle Republican	1.76
1	NE3120818	ROCKVILLE, VILLAGE OF	Lower Loup	1.3
1	NE3101701	LONG PINE, CITY OF	Middle Niobrara	1.36
1	NE3120041	AMHERST, VILLAGE OF	Central Platte	1.91
1	NE3105904	GRAFTON, VILLAGE OF	Upper Big Blue	0.67
1	NE3115516	WESTON, VILLAGE OF	Lower Platte North	1.35
1	NE3116905	BRUNING, VILLAGE OF	Little Blue	0.95
1	NE3120293	MAXWELL, VILLAGE OF	Twin Platte	1.39
1	NE3108105	MARQUETTE, VILLAGE OF	Upper Big Blue	2.22
1	NE3116904	CARLETON, VILLAGE OF	Little Blue	1.43
1	NE3103305	DALTON, VILLAGE OF	South Platte	1.64
1	NE3109301	BOELUS, VILLAGE OF	Lower Loup	1.13
1	NE3111301	STAPLETON, VILLAGE OF	Upper Loup	1.48
1	NE3108901	CHAMBERS, VILLAGE OF	Upper Elkhorn	1.4
1	NE3108906	STUART, VILLAGE OF	Upper Elkhorn	1.77
1	NE3115515	YUTAN, CITY OF	Lower Platte North	0.62
1	NE3120443	BOW VALLEY WATER WORKS	Lewis & Clark	1.09
1	NE3120700	SHERMAN LAKE HOMES	Lower Loup	2.3
1	NE3104502	DAWES COUNTY RWD #1	Upper Niobrara White	1.64
1	NE3120220	SUMNER, VILLAGE OF	Central Platte	1.93
1	NE3112103	PALMER, VILLAGE OF	Lower Loup	0.89
1	NE3116301	ASHTON, VILLAGE OF	Lower Loup	1.31
1	NE3111907	COUNTRY VILLAGE MOBILE HOM	Lower Elkhorn	1.35
1	NE3108903	PAGE, VILLAGE OF	Upper Elkhorn	1.23
1	NE3104712	RICH MOBILE HOME COURT	Central Platte	0.76
1	NE3107908	PRAIRIE WEST MOBILE HOME PA	Central Platte	2.58
1	NE3104713	RIVERSIDE TRAILER PARK	Central Platte	0.66
1	NE3109503	PLYMOUTH, VILLAGE OF	Lower Big Blue	1.21
1	NE3104902	BIG SPRINGS, VILLAGE OF	South Platte	1.55
1	NE3120162	CLAY COUNTY DISTRICT 1-C - SA	Little Blue	2.67
1	NE3130005	DOUGLAS COUNTY SID #277 - TH	Papio-Missouri River	2.5

2024 Priority Ranking for CWS NITRATE ASSISTANCE (POE DATA)
(Orange = Immediate-term priorities, Yellow = mid-term priorities, Green = long-term priorities)

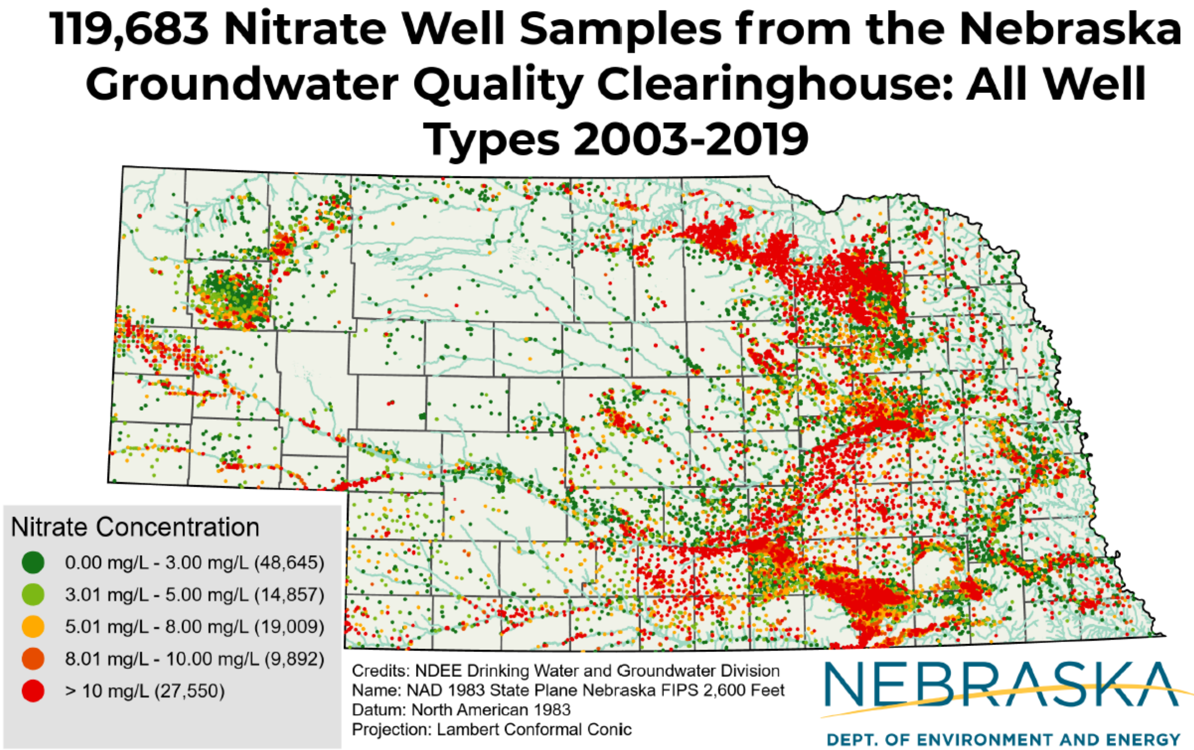
Priority Points	SDWIS NEID	Community Water System Name	NRD	5-Year Mean Nitrate Concentration in CWS Points of Entry (mg/L)
0	NE3111107	EAST MALONEY HOME ASSOCIA	Twin Platte	0.37
0	NE3102104	DECATUR, VILLAGE OF	Papio-Missouri River	0.12
0	NE3101104	PETERSBURG, VILLAGE OF	Lower Loup	0.84
0	NE3113308	TABLE ROCK, VILLAGE OF	Nemaha	0.61
0	NE3105308	DODGE COUNTY SID #3 - LAKE V	Lower Platte North	0
0	NE3105310	HOOPER, CITY OF	Lower Elkhorn	0
0	NE3120514	SAUNDERS COUNTY SID #4 - PA\	Lower Platte North	0.94
0	NE3103703	CLARKSON, CITY OF	Lower Elkhorn	0.48
0	NE3111102	BRADY, VILLAGE OF	Twin Platte	0.8
0	NE3105905	GENEVA, CITY OF	Upper Big Blue	0.38
0	NE3120623	MIDDLE ISLAND LAKE ASSOCIAT	Lower Platte South	0
0	NE3102307	ULYSSES, VILLAGE OF	Upper Big Blue	0
0	NE3117304	OMAHA TRIBAL UTILITIES - MAC\	Papio-Missouri River	0.28
0	NE3104304	HOMER, VILLAGE OF	Papio-Missouri River	0.49
0	NE3120942	CAMP OASIS	Nemaha	0.04
0	NE3102305	ABIE, VILLAGE OF	Lower Platte North	0.6
0	NE3111101	HERSHEY, VILLAGE OF	Twin Platte	0.71
0	NE3100307	ELGIN, CITY OF	Upper Elkhorn	0.16
0	NE3115909	SUNRISE COUNTRY MANOR	Upper Big Blue	0
0	NE3107301	NORTH POINT (JOHNSON LAKE)	Central Platte	0.02
0	NE3120312	LAKEVIEW ACRES LOT OWNERS	Central Platte	0.11
0	NE3114901	NEWPORT, VILLAGE OF	Upper Elkhorn	0.78
0	NE3107906	CAIRO, VILLAGE OF	Central Platte	0.92
0	NE3109706	STERLING, VILLAGE OF	Nemaha	0
0	NE3115901	GARLAND, VILLAGE OF	Lower Platte South	0.01
0	NE3120833	ROCK CREEK STATION SHP - NG	Little Blue	0
0	NE3120682	TRADEWINDS MOBILE HOME CO	Lower Loup	0.01
0	NE3118101	HOSKINS, VILLAGE OF	Lower Elkhorn	0.01
0	NE3110922	HALLAM, VILLAGE OF	Lower Platte South	0
0	NE3100103	HOLSTEIN, VILLAGE OF	Little Blue	0
0	NE3100308	CLEARWATER, VILLAGE OF	Upper Elkhorn	0.21
0	NE3105906	EXETER, VILLAGE OF	Upper Big Blue	0
0	NE3120031	SANTEE UTILITY COMMISSION	Lewis & Clark	0.16
0	NE3118502	ERICSON, VILLAGE OF	Lower Loup	0.2
0	NE3117503	ARCADIA, VILLAGE OF	Lower Loup	0.16
0	NE3115911	BEAVER CROSSING, VILLAGE OF	Upper Big Blue	0
0	NE3109902	AXTELL, VILLAGE OF	Tri-Basin	0
0	NE3108902	EWING, VILLAGE OF	Upper Elkhorn	0.72
0	NE3121214	DISMAL RIVER CLUB	Upper Loup	0
0	NE3121353	LAKE ALLURE SUBDIVISION	Lower Platte North	0

Appendix B – Summary Maps

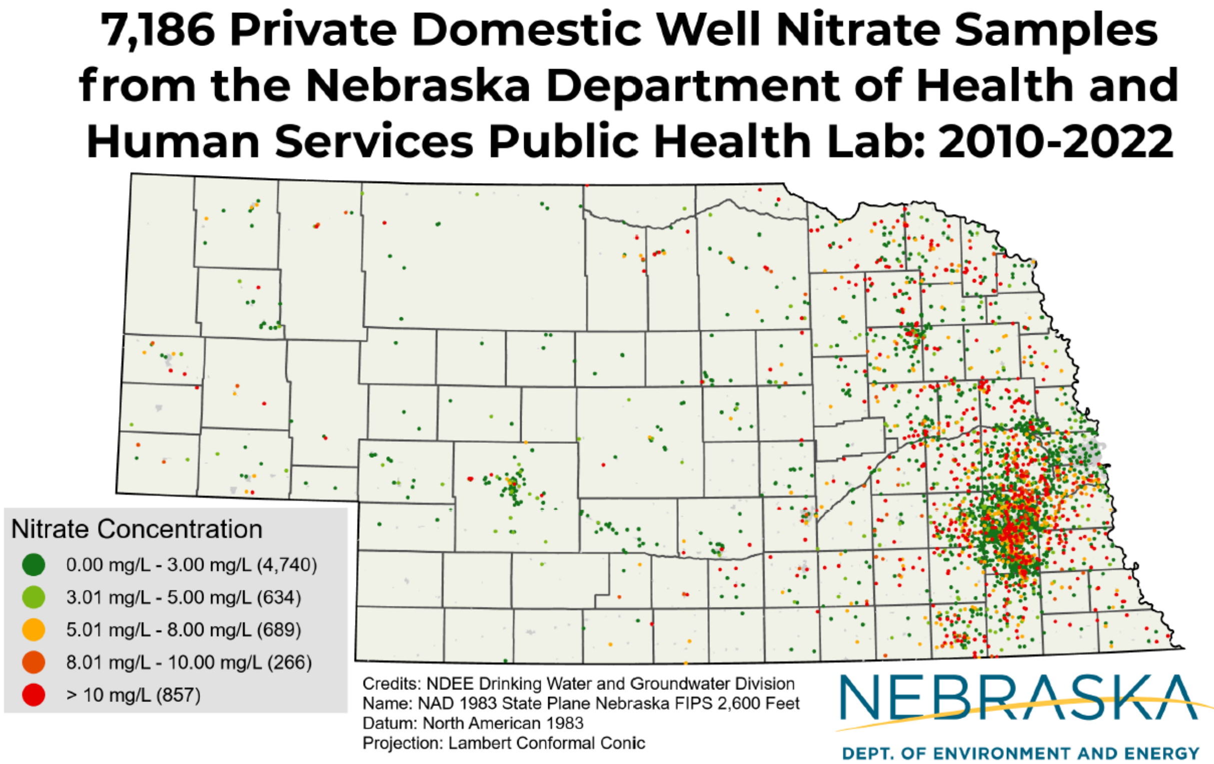
SUMMARY MAPS



Map B 1. Nitrate Free Domestic Well Sampling Results (as of May 1, 2024).

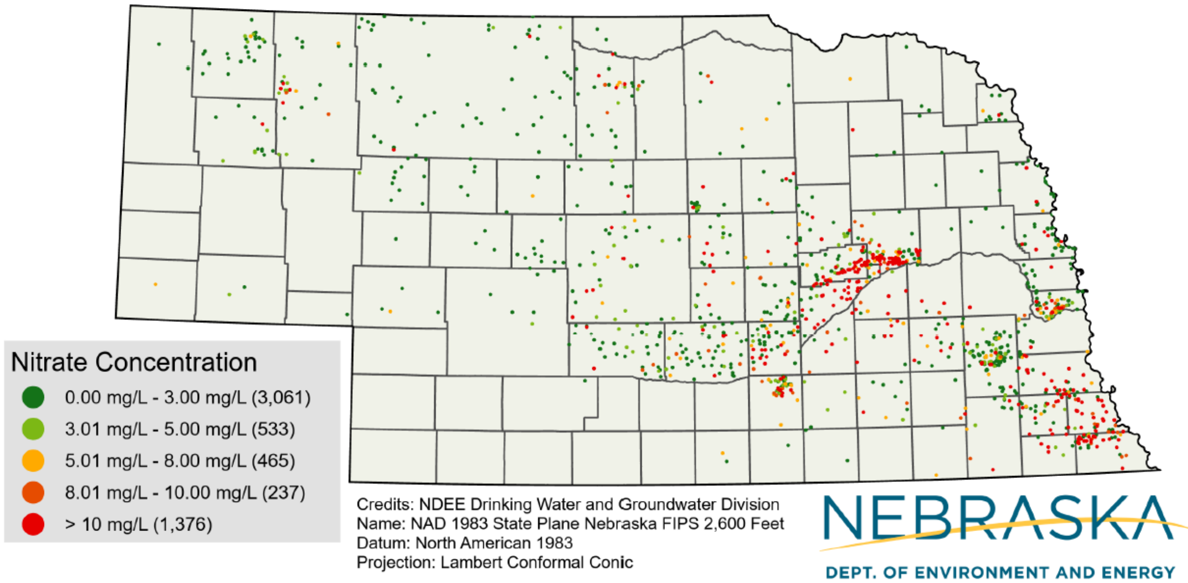


Map B 2. Nitrate Sample Data from All Well Types from the Nebraska Groundwater Quality Clearinghouse. Sample data covers the study period of 2003 to 2019. Each dot represents one nitrate sample from a groundwater well. Many samples are from non-potable water wells.

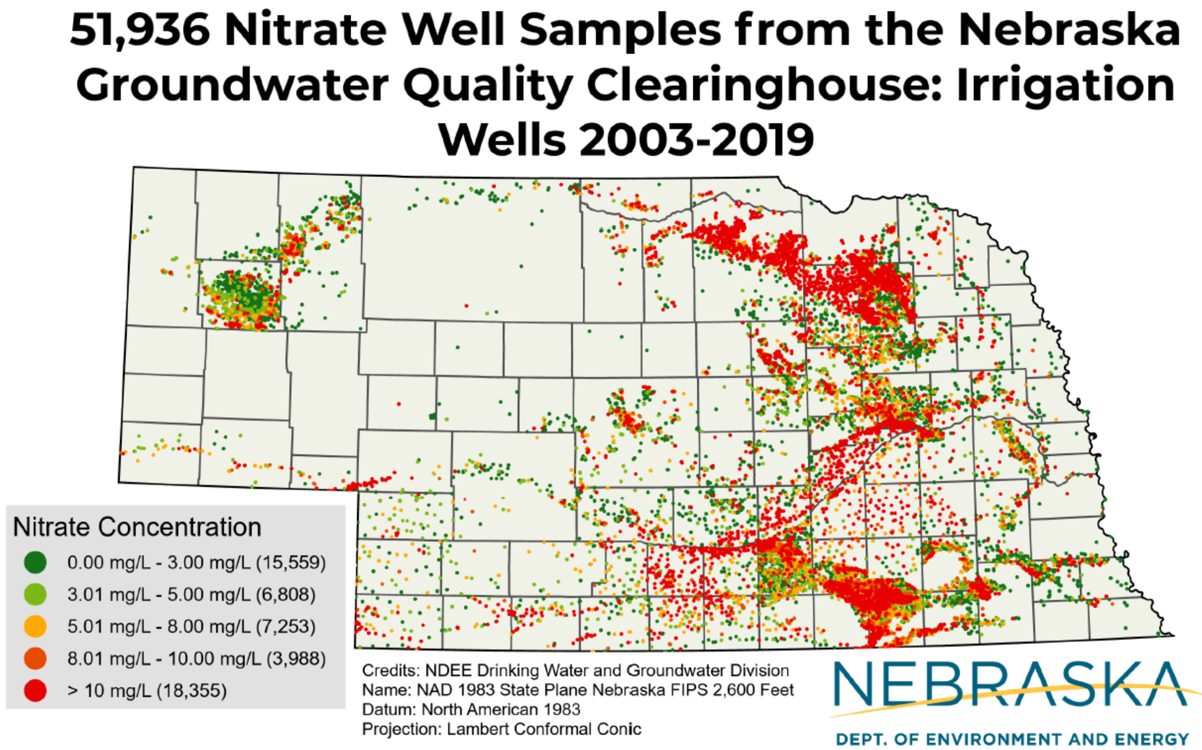


Map B 3. Nitrate Sample Data from Private Domestic Wells Analyzed by the Nebraska Department of Health and Human Services from 2010 to 2022. Sample results were mapped based on the collection address provided by well owners. The figure includes registered and unregistered wells. Nitrate concentrations are reported in milligrams per liter (mg/L). A total of 7,232 samples were collected, 7,186 were mapped, and 857 samples (11.8%) were above 10 mg/L.

5,672 Nitrate Well Samples from the Nebraska Groundwater Quality Clearinghouse: Domestic Wells 2003-2019

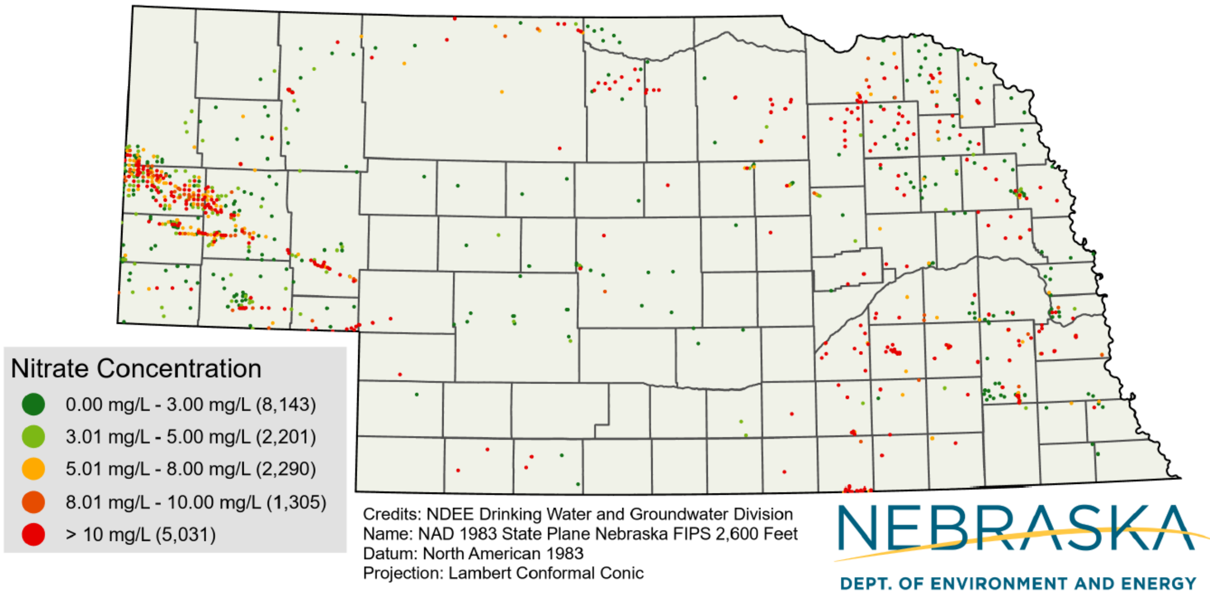


Map B 4. Nitrate Sample Data from Domestic Wells from the Nebraska Groundwater Quality Clearinghouse. Sample data covers the study period of 2003 to 2019. Each dot represents one nitrate sample from a private domestic well.

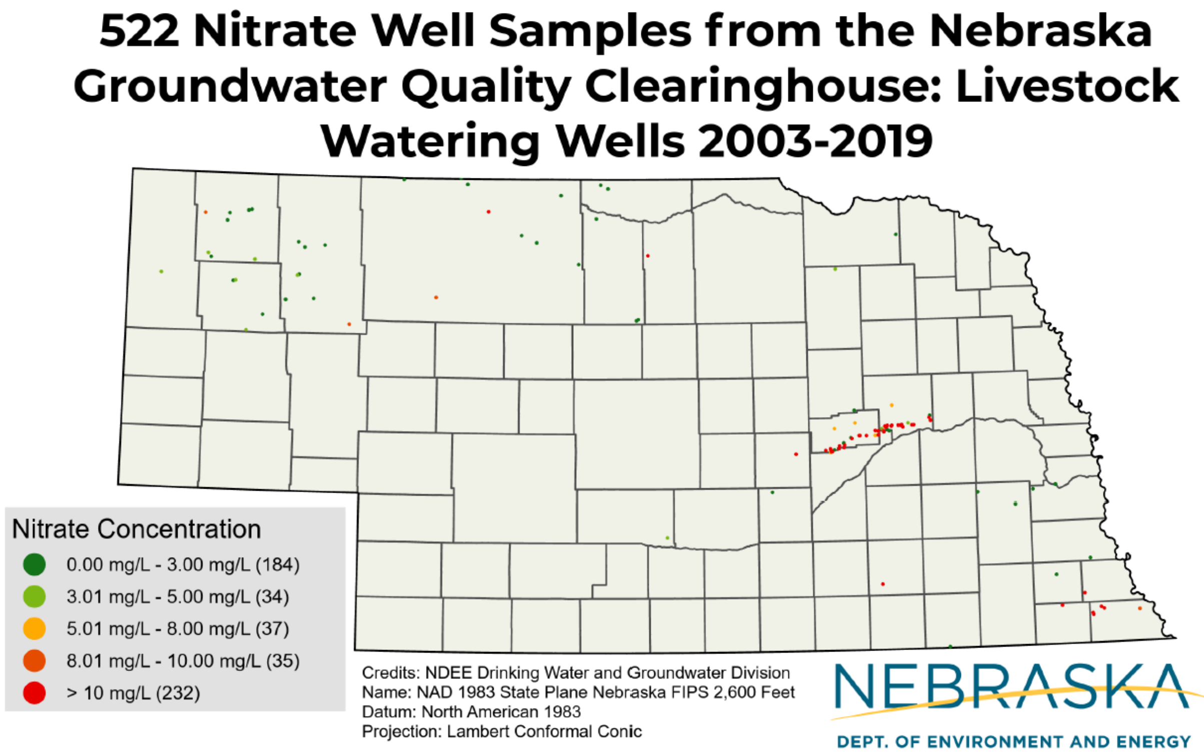


Map B 5. Nitrate Sample Data from Irrigation Wells from the Nebraska Groundwater Quality Clearinghouse. Sample data covers the study period from 2003 to 2019. Each dot represents one nitrate sample from an irrigation well. Samples are from non-potable water wells.

18,970 Nitrate Well Samples from the Nebraska Groundwater Quality Clearinghouse: Monitoring Wells 2003-2019

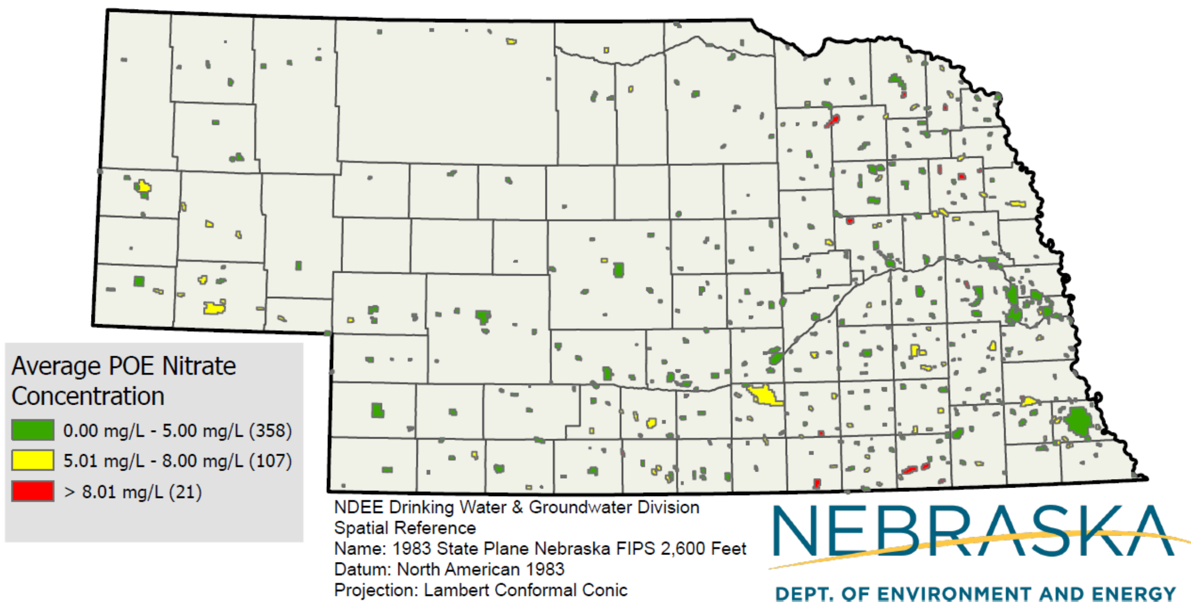


Map B 6. Nitrate Sample Data from Monitoring Wells from the Nebraska Groundwater Quality Clearinghouse. Sample data covers the study period of 2003 to 2019. Each dot represents one nitrate sample from a groundwater well. Samples are from non-potable water wells.

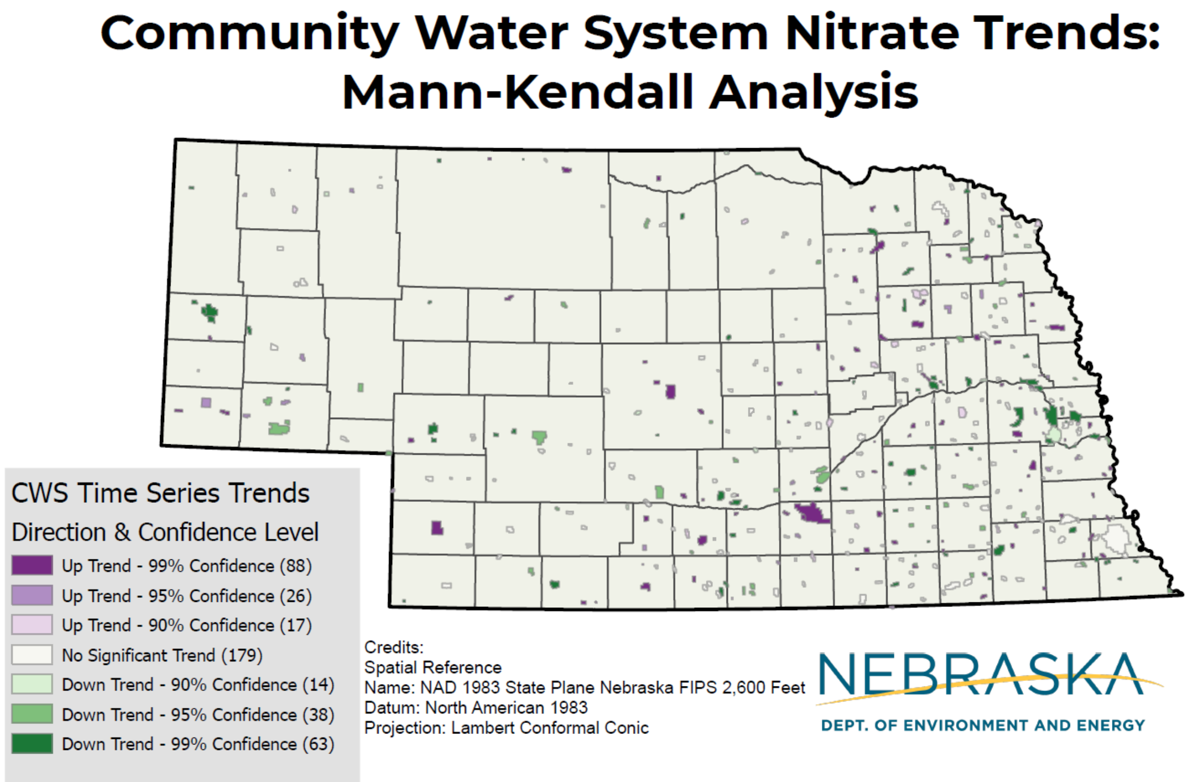


Map B 7. Nitrate Sample Data from Livestock Wells from the Nebraska Groundwater Quality Clearinghouse. Sample data covers the study period of 2003 to 2019. Each dot represents one nitrate sample from a groundwater well. Samples are from non-potable water wells.

Community Water Systems: 2018-2023 Average Point of Entry (POE) Nitrate Concentration in 486 Wellhead Protection Areas

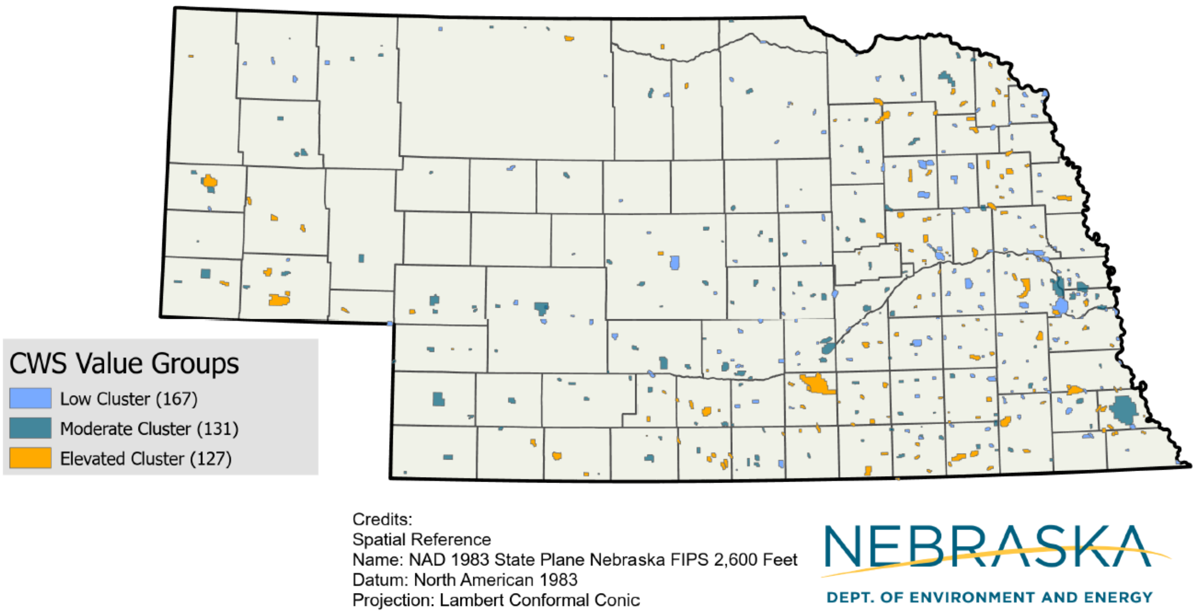


Map B 8. Community Water System (CWS) Average Point of Entry (POE) Nitrate Sample Concentration in Wellhead Protection Areas (WHPAs). In the map, POE samples inside each WHPA were averaged over the last five years and symbolized in each WHPA. POE samples are representative of water that people are drinking but may not reflect untreated supply well nitrate concentrations.



Map B 9. Community Water System (CWS) Supply Wells Mann-Kendall Trend Analysis Results. Trend analysis for CWS based on the Wellhead Protection Area (WHPA) for the period 2003 to 2023. CWS point of entry (POE) nitrate sample results were averaged year over year to build timelines and compare trends in nitrate concentration over time. These timelines were analyzed for trends using several methods. Map B8 shows trends based on a Mann-Kendall statistic, which is a test to detect monotonic trends (up or down) over time. Systems in purple are identified as having a statistically significant upward trend over time. Systems in green are identified as having a statistically significant downward trend. There are important limits to interpreting this test as discussed in Section 7.2. These trend analyses were combined with other methods to identify and prioritize source water protection and wellhead protection funding and outreach opportunities as described in Section 8.0.

Community Water System Nitrate Levels: Time Series Value Clustering



Map B 10. Community Water System (CWS) Nitrate Levels: Time Series Value Clustering. Time series for CWS were compared and classified based on their nitrate sample values from 2003 to 2023.The "value" refers to the overall average nitrate concentration in the WHPA over the study period. The analysis identified three clusters in the data. For a full description of the time-series clustering, see Section 7.1. Systems with a median nitrate concentration in the WHPA of approximately 6 mg/L are symbolized in orange. Systems in dark blue had a median nitrate concentration of around 3 mg/L over the study period (2003-2023). Systems in light blue had a median nitrate concentration around or below 1 mg/L. See Section 6.0 for a description of how the clustering analysis was used in priority ranking.

Appendix C – Predictive Model

Summary

This document provides the technical underpinnings of the modeling approach taken to predict areas likely to have high nitrate concentrations across the State of Nebraska for the 2023-2024 Nebraska Department of Environment and Energy (NDEE) Water Quality Study. The model predictions represent the probability that nitrate concentrations will exceed certain threshold values in private domestic wells based solely on the model inputs listed in Table 1. In this study, threshold values of 3 mg/L, 5 mg/L, and 10 mg/L were modeled as representative of the background, elevated, and maximum contaminant level for nitrate in groundwater, respectively. Ultimately, this estimate is just one factor used in the web-based Geographic Information System (GIS) risk assessment tool for use by NDEE and agency partners. Regardless of the predicted risk, private domestic well owners are strongly encouraged to sample their well annually to properly assess their specific risk. Model construction and results offer valuable insights into the relationship between nitrate concentrations in Nebraska, common sources, hydrogeological factors, and land-use trends. Exploratory analyses and literature review were first conducted to identify potentially influential factors, then Boosted Regression Trees (BRTs) were trained to classify wells likely to exceed each threshold value. Finally, the BRTs were generalized for the internal NDEE GIS tool and evaluated against private domestic well samples from the free NDEE sampling effort. Model performance was strong for the testing and training data, and the model surfaces had acceptable performance compared to the fully independent private domestic well samples. However, additional work on the model is recommended to incorporate additional variables known to impact nitrate concentrations and reduce the false negative predictions (under prediction of nitrate concentration). A Model Card (based on the one proposed by Mitchell et al, 2019) is provided in Model Card

Table 1.

Outline

List of Figures

List of Tables

Model Card

Table 1.Model Card.

Model Owner	Nebraska Department of Environment and Energy (NDEE)
Model Date	November 2024
Model Version	1.0
Model Type	Boosted Regression Trees (Classification)
Spatial References	Datum: North American Datum 1983 State Plane Projection: Lambert Conformal Conic
Model Goals	• Evaluate the relationship between nitrate concentrations, common point sources (limited to registered onsite wastewater treatment (OWT) facilities and animal feeding operations (AFO)), contributing land-use patterns, well construction, and hydrogeological factors. • Predict the probability that nitrate in a domestic well will exceed three values: a background concentration, an elevated concentration, and the Maximum Contaminant Level (MCL). Identify high-risk areas of nitrate in groundwater. • Incorporate model results into a private domestic well risk assessment GIS tool to be used by NDEE and select agency partners.
Model Inputs	
Nitrate Well Samples	The median nitrate sample from the Nebraska Groundwater Clearinghouse database for the period 2003-2019 was calculated at each well modeled. These median values were converted to binary variables at three threshold values: 3 mg/L, 5 mg/L, and 10 mg/L. Concentrations above each threshold were assigned 1 and below were assigned 0. Around each well, a 1500-meter buffer was generated and used to aggregate predictor variables that were not defined at the well level (such as nitrate concentration or well construction details).
Well Construction	Well construction variables were derived from the Nebraska Department of Natural Resources (NDNR) registered wells database. One-half screened interval depth, pumping water level, static water level, the presence or absence of a well seal, and well depth variables were included in the model. Location for each well was represented in the model using latitude and longitude as numeric variables.
Land Use	USDA Cropland Data Layer (CDL). Pixel counts and class percentages were calculated for each well buffer. The percentage of cultivated soybeans and corn were included in the model. USGS 30-meter irrigated acres (LGRIP30) 2023 Release. The percentage of irrigated and rainfed crops in each well buffer were included in the model. Historic fertilizer data assembled by the USGS, derived from USDA National Agricultural census, were used to estimate application rates at the county-scale and joined to wells included in the model. Municipal boundary information from Nebraska Map, a census derived product, was used to represent the potential impacts of municipal wastewater collection systems and other potential urban sources of nitrate, such as lawn fertilizer. Nebraska Map is managed by the Nebraska Geographic Information Office (GIO).

Hydrogeological	Soil infiltration data from Soil Survey Geographic Database (SSURGO) was sampled at 30-meter resolution and aggregated by mean value inside each well buffer. The mean vertical soil infiltration (ksat) for each well was used in the analysis. Streams have an impact on nitrate concentrations where surface and groundwater are interconnected. The distance to the nearest stream was calculated for each well buffer. Stream data came from the NDEE Title 117 waterbodies database. Reservoirs and lakes can also impact nitrate concentrations much like streams. Similarly, the distance to the nearest Title 117 lake was calculated for each well buffer.
Model Inputs	
Point Sources	Registered OWT facilities from the NDEE integrated information system (IIS) were aggregated into well buffers as a per square mile density and as a distance measured from the buffer edge for each well. Animal Feeding Operation (AFO) facilities from the NDEE IIS were aggregated into well buffers in the same manner as OWT facilities, with the addition of a facility count metric for AFOs in each well buffer. Animal facilities were also represented by livestock watering wells data from the NDNR registered wells database. Watering wells may capture areas where animals graze and smaller operations not permitted under Title 130.
Model Outputs	Probability that the median nitrate concentration will exceed a background concentration, elevated concentration, and the MCL (based on model inputs within a 1500-meter radius of each well), confusion matrix, variable influence, partial dependence, variable interaction, evaluation statistics, and associated plots. Predictor variables were aggregated to a half-mile grid surface across Nebraska and passed to the trained models to generalize the predictions for use in a GIS tool for use by NDEE and key partners.
Model Evaluation	Models were optimized to maximize Matthew's Correlation Coefficient (MCC), Sensitivity, Specificity, and Overall Accuracy calculated from the Confusion Matrix for each model. Values are reported for testing data. MCC values were between 0.5 – 0.51. Sensitivity was from 55 – 88%. Specificity was from 59 – 92%. Overall Accuracy was from 78 – 81%. Model surfaces were compared to an independent set of domestic well samples collected in 2023-2024. Evaluation metrics were lower across the board for the model surfaces, but MCC (0.20 – 0.28), sensitivity (34 – 60%), specificity (68 – 87%), and overall accuracy were acceptable (65 – 79%) to recommend model results for incorporation into an internal tool for NDEE and key partners.
Credits	Author: Bridger Corkill Year: 2024 Affiliation: Nebraska Department of Environment and Energy
Intended Use	This model is intended to supplement a risk assessment tool for private domestic wells. The model considers many factors that may influence the nitrate level around a private domestic well. Estimating the probability that nitrate will exceed the modeled threshold concentrations can help assess risk for private domestic wells located in areas where nitrate samples are unavailable. Nitrate concentrations were modeled based on a range of threshold concentrations that reflect a low, medium, or high-risk potential to private domestic well owners. The model is not intended to predict the exact concentration at any one well location. Rather, the goal is to provide a reasonable baseline assessment of risk potential given the available data and model inputs. Additional risk factors will be included in the GIS tool. This model is not intended as a primary decision-making tool, and will be used exclusively by NDEE and select agency partners.

Introduction

One objective of the water quality study, conducted by the NDEE, was to develop a model identifying high-risk areas of nitrate in groundwater. Results of this modeling effort are intended to supplement a risk assessment Geographic Information System (GIS) tool that was developed during the water quality study. This tool assists NDEE and select agency partners in evaluating the potential risk of elevated nitrate in a domestic well. In the GIS tool, the user will enter a well location, and the tool queries information for that location to calculate a risk index and create a report for the user. Predictive model results are one part of this risk index and are intended to provide an estimate of how likely a private domestic well owner is to find elevated nitrate concentrations in their well, based on contributing factors and existing nitrate sample data. Ultimately, the only way to ensure a safe supply of drinking water is to have it tested.

Previous studies conducted in coordination with the U.S. Geological Survey (USGS), such as Nolan et al. (2014) and Wheeler et al. (2015), have employed machine learning (ML) methods to predict nitrate concentrations, including the probability that N as Nitrate will exceed several thresholds, in private domestic wells. Similar studies conducted by USGS in Wisconsin (Wellman and Rupert, 2016; Borchardt et al., 2021) use logistic regression analysis to predict the risk of domestic well contamination by several contaminants, including nitrate. Traditional regression methods were not used in this study because the nitrate data used to train the models does not meet many of the underlying assumptions for a regression model, such as Gaussian distribution of model residuals and a homogenous relationship between nitrate and predictor variables across the model space, i.e., the state of Nebraska. ML algorithms do not require a particular distribution or assume the data has a homogenous relationship across the model space. They also benefit from large, multi-dimensional datasets (Breiman et al., 1984). Because of these advantages, this study uses a forest-based classification algorithm, BRTs, to predict whether a well is likely to exceed several threshold values for nitrate concentration based on well characteristics, geologic conditions, land-use, and some common potential sources of nitrate. Predictions were made for wells considered representative of domestic well construction in Nebraska. Figure 1 shows the nitrogen cycle.

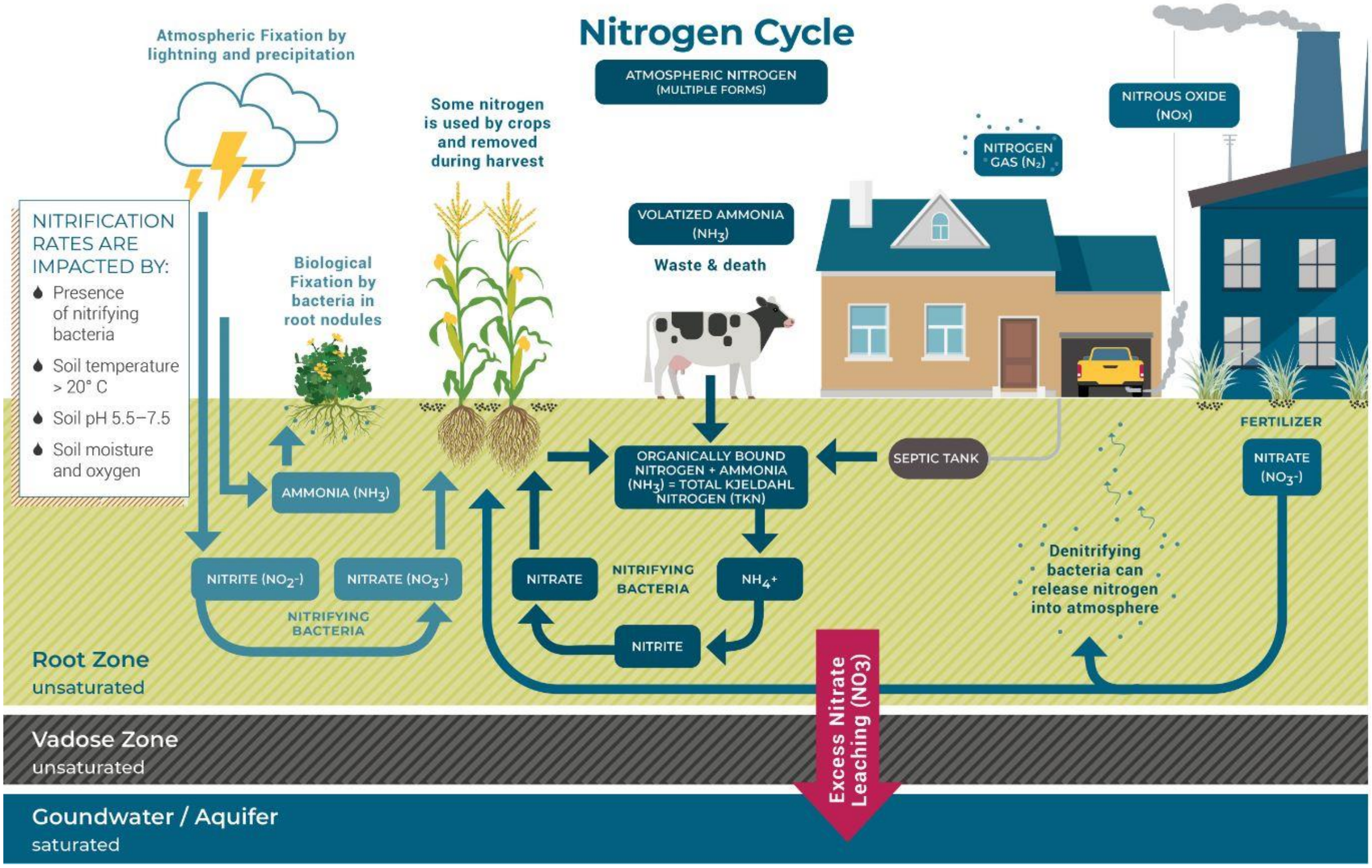


Figure 1. Nitrogen Cycle Conceptual Diagram.

Nitrogen takes multiple forms in the environment and comes from both organic and inorganic sources. Nitrogen typically enters the soil as ammonia where it is nitrified to nitrate under oxic conditions. Nolan and Hitt (2002) report that background concentrations in undeveloped forested areas of the United States are around 1 mg/L. Levels measured slightly higher in rangeland and grassland, between 2 and 3 mg/L. Further studies of the High Plains Aquifer (McMahon, 2007) have generally agreed that 4 mg/L is the highest observed “relative” background concentration in the system. Background and relative background concentrations of nitrate are an area of debate in literature. Nitrate concentrations between 0.5 and 3 mg/L are considered a transitional range between natural background and anthropogenic contamination (McMahon et al., 2007). For this study, a conservative background level of 3 mg/L was assumed based on Nebraska land-use trends. Anhydrous fertilizer and livestock manure application to cropland are two primary sources of nitrogen in the soil and streams (Spalding and Exner, 1993). Additional sources include human and livestock waste, certain industrial facilities, and wastewater treatment facilities (ATSDR, 2017).

Inorganic and organic nitrogen (as ammonia) are nitrified in the soil to nitrite and then nitrate under oxic conditions. In the High Plains system, dissolved oxygen levels are such that nitrate can persist for decades (Spalding and Exner,1993; McMahon et al., 2007). Nitrate management practices can reduce levels over time, but in Nebraska levels may still be rising (Exner, 2014). When nitrate is not biologically fixed—by plants or microorganisms—it leaches through the unsaturated root and vadose zone eventually reaching groundwater (Malakar et al., 2023). The time it takes for nitrate to reach groundwater is related to the thickness of the vadose zone, the depth to groundwater, soil characteristics, precipitation, and irrigation (Wells et al., 2018; Malakar et al., 2023). In areas where groundwater and surface water are interconnected, groundwater can be a source of nitrate in streams or vice versa (Green et al. 2018). Domestic wells are more likely to tap shallower formations and are often constructed near onsite wastewater treatment systems, cropland, and animal feed operations which can all contribute to contamination (Wheeler et al., 2015; Wellman et al., 2016; Borchardt et al., 2021). In addition to permitted animal feed operations and onsite facilities, livestock watering wells registered with the NDNR were incorporated into the model to represent areas where animals may graze that are not captured by a single facility location.

The water table varies throughout the year and upper levels of an aquifer may have different nitrate concentrations than deeper, older groundwater. In areas where groundwater and surface water are interconnected, flows from groundwater to surface water may act to 'flush out' excess nitrate into streams and rivers (Snow and Miller, 2018; Malakar et al., 2023). Seepage from losing reaches and reservoirs may have the opposite impact. Additionally, the varying geology across Nebraska dramatically changes the rate at which nitrate reaches groundwater (Spalding, 2001; Wells, 2018; Cherry, 2019).

Nitrate is more rapidly transported to groundwater under irrigated lands than non-irrigated lands. Irrigated crops typically receive more fertilizer application than non-irrigated crops and therefore have a higher nitrate soil concentration contributing to nitrate leaching (Spalding 2001; Exner 2014; Malakar et al., 2023). Excess water from irrigation not taken up by crops pushes nitrate through the unsaturated vadose zone. Irrigation wells, which may be constructed with gravel pack along their entire casing, can act as conduits for water high in nitrate to move rapidly into lower levels of the aquifer. Wells that are screened or gravel packed through multiple formations can cause aquifer comingling (Driscoll, 1986). The impact of agriculture was captured in this study using percentage of irrigated cropland, crop-percentages, cumulative nitrogen application estimates, and livestock facility data. The 30-meter irrigated acres (LGRIP30) product produced by the USGS was used to estimate the percentage of irrigated area around each well. It is nominally a 2015 product (Teluguntla, 2023); however, because of the permitting requirements and water management by the Nebraska Natural Resources Districts, the total irrigated acres over the study period should be relatively constant. Additionally, investigation of the cropland data layer (CDL) in Nebraska showed little change over time in the dominant crop classes.

Well samples for 281 water quality indicators, including nitrate, are available to the public in Nebraska via the Nebraska Quality Assessed Agrichemical Clearinghouse (the Clearinghouse). The Clearinghouse is a collaborative effort between the NDEE, the University of Nebraska-Lincoln Conservation Survey Division (UNL CSD), and the Natural Resources Districts of Nebraska (NRDs). Nitrate samples in this study were all sourced from and are publicly available on the Clearinghouse. Samples have been collected from monitoring, irrigation, domestic, public water supply, commercial/industrial, livestock, and groundwater source heat pump wells since mid-1974 to present. Each sample is given a quality flag based on the methodologies used for sampling and the laboratory method. The flag depends on the amount and type of quality assurance/quality control that was identified in obtaining each sample. At the time of the study, data for the years 2020 to present is incomplete. No data quality filter was applied to nitrate samples used to train and test the models.

Point sources of nitrate, such as failing onsite treatment systems, are an important source to consider for estimating the nitrate risk in a domestic well (Nolan et al., 2014; Wheeler et al., 2015). OWT facility data from Title 124 permit records were used to calculate the impact of OWTs on nitrate. There are important limits to this record. Title 124 Onsite Wastewater Systems requires registration of any OWT constructed, reconstructed, altered, modified, or otherwise changed by a certified professional, professional engineer, or registered environmental health specialist since January 1, 2004. There are currently approximately 29,600 registered OWT, but many OWTs are not registered, and some OWTs are exempt from registration. Data considered for inclusion in the predictive model are summarized in Table 2. Other point sources, such as those regulated by NDEE's release assessment program, did not have the data quality needed for inclusion in the model.

Table 2. Datasets Considered for the Predictive Nitrate Model.

Dataset	Agency & Year	Description
Clearinghouse Well Samples	NDEE, UNL CSD, 2024	Nitrate samples from the Clearinghouse from Non-Public Water Supply wells for the years 2003 to 2023 were used as model inputs. Because of data gaps in the Clearinghouse, this is nominally a 2003-2019 product. The median nitrate concentration from all samples taken over the study period was calculated at each well.
Domestic Well Samples from the Free Sampling Effort	NDEE, 2024	Results from the NDEE free sampling effort were used as an independent testing set to evaluate model performance. These results are from samples collected by private well owners, per instructions they received with their nitrate test kit from the Nebraska Department of Health and Human Services (NDHHS) Public Health Environmental Lab. Some of these samples may have been collected following reverse osmosis or other treatment units and they may not all be representative of raw well water.
National Land Cover Dataset (NLCD)	USGS, 2022	Land-use trends and data were analyzed for relationships to nitrate levels in Nebraska. Data were aggregated to well buffers by pixel counts, and percentages for each land use type were compared to nitrate levels. In the models, LGRIP30 and the CDL were used instead of NLCD data.
Depth to Groundwater	NDEE, 2024	Groundwater elevations, based on the regional Nebraska hydrologic models, were calculated for the spring season and generalized across the state. These elevations were not incorporated into the modeling but may benefit future efforts.
Well Construction Information	NDNR, 2024	Well construction information (e.g., well depth and construction year) for wells in the Clearinghouse, provided by NDNR, was evaluated for relationships to nitrate levels. Well construction variables were derived from the NDNR registered wells database. Location, one-half-screened interval depth, pumping water level, static water level, presence or absence of a well seal, and well depth variables were included in the model. Location for each well was represented by latitude and longitude as numeric variables
Soil Survey Geographic Database (SSURGO) Soil Properties	NRCS, 2023	The SSURGO database was used to generate representative saturated soil infiltration rates (ksat) for each well buffer distance. Other SSURGO variables recommended for future modeling are discussed in the conclusions and recommendations section.
Cropland Data Layer (CDL)	USDA, 2022	The CDL was analyzed for relationships to nitrate levels and change over time. The percentage of corn and percentage of soybeans was calculated inside each well buffer and included in the modeling. Other notable classes, such as alfalfa and winter wheat were considered but ultimately excluded and covered by LGRIP30 data.

Dataset	Agency & Year	Description
LGRIP30	USGS, 2023	USGS 30-meter irrigated acres (LGRIP30) product was used as a model input. The percentage of irrigated and rainfed crops in each well buffer were included in the model.
Nebraska Permitted Irrigated Acres	NDNR, 2023	The irrigated acres from groundwater were queried from the Permitted Irrigated Acres data layer maintained by the NDNR. LGRIP30 was selected to represent irrigated acres in the dataset instead of this product.
Registered Onsite Wastewater Treatment (OWT) Systems	NDEE, 2023	Title 124 registered OWT facilities were aggregated by well buffer as count, distance, and density values. Domestic, industrial, and commercial facilities were included.
Registered Animal Feed Operations (AFOs)	NDEE, 2023	Animal feed operations (AFOs), as defined by Title 130, were aggregated into well buffers by facility count, distance, and density values. Facility data were retrieved from the NDEE IIS.
Livestock Watering Wells	NDNR, 2023	Stock wells were aggregated by count into well buffers and as a per square mile density value inside each buffer.
Historic Fertilizer Application Rates	USGS, 2006	County level fertilizer application data from USGS for the years 1987 to 2006 was normalized over the land area in each county and then joined to wells as a kg/land-acre rate value.
Groundwater Release Assessments	NDEE, 2024	Release assessment data is collected by NDEE but was not in a form that could be reliably included in the modeling.
Permitted Nitrate Precursor Storage Facilities	NDEE, EPA CAMEO, 2024	Tier two storage facilities are required to report through NDEE to the EPA on chemical storage facilities. These data were ultimately excluded from the model.
Nebraska Municipal Boundary Data	Census 2020; NE Geographic Information Office (GIO), 2024	Municipal boundaries in Nebraska are derived from the 2020 census and updated by NGIO using state data from the Department of Revenue and annexation ordinances from cities. Municipal boundaries were used in the models to represent urban sources of nitrate, such as fertilizer runoff and wastewater collection systems.
Title 117 Waterbodies Database	NDEE, 2024	NDEE maintains a database of regulated surface waters under Title 117. Streams, lakes, and reservoirs can all impact nitrate in groundwater when they are hydrologically connected. Data on Title 117 defined streams and lakes that were incorporated into the models as distance variables.
Title 123 Wastewater Treatment Facilities	NDEE, 2024	Permitted wastewater facilities defined by Title 123 were considered for inclusion in the model but were ultimately excluded and the impact of municipal treatment and collection systems was represented using the municipal boundary data.

Methods

Variable Aggregation

Nitrate well sample data from the Clearinghouse for the period 2003 to 2019 from non-PWS wells 300 feet or less in depth were used in the analysis. Because some wells have been sampled multiple times, the median concentration at each well was calculated prior to analysis. 1500-meter radius buffers around each well were created using ArcGIS Pro (Arc version 3.1) and used to aggregate variables. Buffer distances in this study were comparable to those used in previous studies (Tesoriero and Voss, 1997; Nolan et al., 2014; Borchardt et al., 2021). Variables can be broadly categorized as either aggregated at the well level or buffer level. Well construction information and nitrate sample data were joined to each well, while land-use variables, potential sources, distance features, and hydrogeologic features were aggregated in each well buffer.

Preliminary variables were assembled based on related modeling studies (Nolan et al., 2014; Wheeler et al., 2014; Wellman et al., 2016), potential sources of nitrate (ATSDR, 2015), historic information on nitrate in Nebraska (Spalding and Exner, 1993; Litke, 2001; McMahon, 2007), data availability, and consultation with modeling, hydrology, and engineering experts. A list of all datasets considered for inclusion is presented in Table 2. Notable exclusions from the model are discussed in the recommendations section for future work.

Well construction information, including well depth, static water level (SWL), pumping water level (PWL), drawdown (the difference between SWL and PWL), depth to the mid-point of the screened interval, length of gravel pack, presence of a seal, and pump rate were derived from the NDNR Registered Wells Database. Construction data are collected when the well is registered and may not reflect changes to water level, well depth, or pump level. Where information on well construction was unavailable, the variable was set to Null. Except for drawdown, gravel pack length, and pump rate, all available construction data was used in the modeling.

Hydrogeologic variables including vertical soil infiltration rate (Ksat), aquifer boundary data, stream location, and depth to bedrock geology were considered for inclusion in the model. Ksat was calculated from the USGS SSURGO dataset by first resampling the 10-m product to 30-m resolution and then zonal statistics were calculated inside each well buffer. The mean Ksat value was selected as the representative statistic and included in the model. Additional variables from the SSURGO database, such as hydric rating, drainage class, and soil geochemical properties were considered for inclusion. However, these data were not in a format that was usable in the modeling effort at time of writing. A discussion of additional SSURGO factors for the model is presented in the conclusions and recommendations. The distance to the nearest stream and nearest lake, as defined by Title 117, was calculated for each well buffer and included in the model. Aquifer boundary data were ultimately excluded from the model but may be a good option to divide the state into regions for future groundwater modeling efforts.

Distances between each well buffer and potential point-source datasets were calculated and used as explanatory variables. Models include only onsite wastewater treatment facilities, livestock watering wells, and permitted livestock facilities as listed in Model Card

Table 1. A discussion of missing facilities data for potential nitrate sources is provided in the conclusions and recommendations section. No maximum distance was established. Facilities inside the buffer had distance equal to zero. Facility counts by type inside each buffer were also calculated for livestock facilities and livestock watering wells. Density for these point facilities was calculated as a facility per square mile value using the focal statistics tool in ArcGIS Pro (Version 3.1) using a 6-mile moving window. Mean facility density values were aggregated into each well buffer distance using the Zonal Statistics tool in ArcGIS Pro 3.1. Livestock watering well data from the NDNR registered wells database was also used to calculate a well per square mile value across the state to represent areas where livestock may be moved to that are not captured by permitted facility data.

Land-use data from the National Land Cover Dataset (NLCD), an irrigated acres product derived from NLCD called LGRIP30 (Teluguntla et al., 2023), and the CDL (USDA NASS, 2023) were evaluated for inclusion in the model. The NLCD land-cover dataset did not have adequate variance to include as a model input, a vast majority of the land in Nebraska is either grassland or cropland. For each land use dataset, the 30-m products were aggregated into the 1500-meter well buffer and pixel statistics were calculated summarizing the land use percentages. LGRIP30, including irrigated and rainfed cropland data, and the CDL, including only the two largest classes, corn, and soybeans, were included in the models. The CDL from 2008 was used in the modeling. Analysis of the CDL in Nebraska showed little change in major crop classes over time.

Nitrogen application rates were estimated by USGS at the county level for the years 1988 to 2006 (Spahr et al., 2010). Previous studies discussed the impact of legacy fertilizer application on present-day nitrate levels (Exner, 2014). This study seeks to empirically account for this legacy nitrogen input based on the 2006 USGS county level estimates. A cumulative nitrogen application rate was calculated as follows: farm and non-farm tonnage was summed across years, then the sum of nitrogen applied in kilograms (kg) was divided by the total land area in each county (in acres) to estimate the cumulative application per acre. These county level values were joined to each well. As with the CDL, using values from 2006 is reflective of the lag-time between nitrogen application at the surface and elevated groundwater nitrate levels (Wheeler et al., 2015; Cherry et al., 2019).

Prior to modeling the wells with nitrate sample data from the Clearinghouse, data were randomly divided into testing and training groups. Training data are used in the model training. Testing data are not used in model training and are instead used to evaluate model performance (Breiman et al., 1984). Two-thirds of the sample data were set aside for training and one-third for testing. To ensure a repeatable split, wells were sampled in R (Kuhn, 2020) using a fixed seed. The same seed was used across models.

During the 2023-2024 water quality study, NDEE offered free nitrate test kits to private domestic well owners. Results from the NDEE free sampling effort were used as an independent testing set to evaluate model performance. These results are from samples collected by private domestic well owners per the instructions they received with their nitrate test kit from the Nebraska Department of Health and Human Services (NDHHS) Public Health Environmental Lab. Some of these samples may have been collected following reverse osmosis or other treatment units and they may not all be representative of raw well water. Because not all construction variables were known for these wells, they were used to evaluate the performance of generalized model results discussed later in this section. Samples were geocoded using ArcGIS Professional (Version 3.1, 2023) To alleviate data quality issues, duplicate addresses, P.O. boxes, points of interest, and street centerlines were removed from the set of geocoded points to calculate model evaluation metrics.

Boosted Regression Trees (BRTs)

Previous water quality investigations have used regression (Hirsch et al., 2010; Garcia et al., 2017), logistic regression (Black et al., 2023; Wellman and Rupert, 2016; Gross and Low, 2013; Lombard, et al. 2021), and machine learning methods like those employed in this study (Nolan et al., 2014; Nolan, 2015 et al.; Lombard et al., 2021; Knierim et al., 2022) to predict water quality in surface and groundwater. Logistic regression and regression were explored for predicting nitrate concentrations in this study, but the nitrate data available violate several important assumptions of traditional regression methods such as a Gaussian distribution of the model residuals and a uniform relationship between predictor variables and response variable across the model space. Additionally, machine learning methods had stronger predictive power during testing.

Random forest models use a set of tree predictors to classify data or fit regression coefficients to predict a continuous variable (Breiman et al., 1984). Forest-based models have been applied to water quality predictions in nitrate investigations (Nolan et al., 2014; Wheeler et al., 2015), and to predict other regulated contaminants like arsenic and manganese (Lombard et al., 2021; Knierim et al., 2022). Variables were aggregated in ArcGIS Professional (Version 3.1, 2023) and models were tuned in R using the dismo and gbm packages (Friedman, 2002; Hijmans, 2023). In this study, classification was chosen over continuous prediction. For the purposes of this investigation priority was placed on predicting whether a private domestic well is likely to exceed threshold concentrations and pose a health risk rather than predicting specific concentrations at a given well.

Forest-based classification uses combinations of input variables and an element of randomness to predict class membership (Breiman et al., 1984). Decision 'trees' based on a random sampling of predictor variables, vote on the most popular class for a given input vector. BRTs are a type of forest-based regression model that has been employed in species distribution modeling (Elith et al., 2008; Yu et al., 2020) and water quality analysis. Two studies with similar hydrology and investigation goals looked at relatively shallow, unconfined aquifers in the California Central Valley (Nolan et al., 2014) and the State of Iowa (Nolan et al., 2015) using forest-based classification and/or BRTs. Contaminants like arsenic (Lombard, et al. 2021) have also been modeled using BRTs. In this study, nitrate well samples were classified into binary variables at three concentration thresholds: 3 mg/L, 5 mg/L, and 10 mg/L. These values represent the upper-end background concentration in unpopulated grassland areas (Nolan and Hitt, 2003), an elevated level of nitrate, and the Safe Drinking Water Act (SDWA) Maximum Contaminant Level (MCL), respectively (US EPA, 1991). The BRT models in this study were trained to predict the probability that nitrate would exceed each concentration threshold.

BRTs are made up of many simple tree-predictors, which in aggregate, are optimized for predictive accuracy. This can be analogously thought of as many rules of thumb may be more practical than a single, complex rule to describe every situation (Elith et al, 2008). In the classification case, trees predict the most likely class instead of fitting a continuous response. Boosting, in BRT, is the combination of tree-predictor models which 'boosts' the strength of the constituent trees (Friedman, 2003). BRTs are well suited to modeling various predictor variables (continuous, categorical) and are robust to missing data (Breiman et al., 1984).

Each tree's contribution to the overall model is governed by the learning (shrinkage) rate. Generally, model performance is more robust using a low (slow) value, because of the optimization procedure. "Boosting is a form of functional gradient descent," where the unexplained deviance in the model is minimized at each stepwise addition of trees to the forest (Elith et al., 2008). A smooth descent along the curve leads to more stable model behavior (Friedman, 2003). Variable influence is calculated for the predictors in BRT models in the gbm package (Friedman, 2002) and is a measure of how frequently a variable is selected for splitting. Variables that contribute to a greater reduction in error are weighted more heavily by the measure. Relative variable influence for the model sums to 100%. Higher variable influence indicates that the variable is strongly influential to model predictions (Friedman, 2002). Percentage of relative influence does not equal percentage contribution to response variable. That is to say, the percentage influences reported by the BRT models do not correspond to percent contribution to nitrate levels in groundwater. Rather, they indicate how strongly each contributing variable is related to *predicting* the nitrate risk. Collinear factors, while largely unproblematic for BRT efficacy, do impact the calculations for variable influence and should be considered when interpreting the results (Dormann et al., 2013; Belitz and Stackelberg, 2021).

Tree complexity refers to the number of variable interactions possible in each decision tree constituent of the model. A complexity of 1 would be a "stump" with one variable and two terminal nodes. The addition of all these stumps would make up the BRT, where each stump casts its vote for the most likely class. A complexity of two allows for two-way interaction, and so forth (Elith et al., 2008; Breiman et al., 1984). Variable interaction can be tabulated and plotted from BRT models because interactions are inherent to the structures of decision trees. As splits in the tree progress, later predictor variables are dependent on the branches of earlier predictors. In this way, variable interaction is a part of the method (Breiman et al., 1984). By holding other predictors to mean values, partial variable influence plots can be developed for the response variable in the gbm package (Friedman, 2002). These partial influence plots offer insight into the shape and relative relationships between the predictor variables and the response. Because of the method for their creation, partial dependence plots should not be interpreted as individual models or used to interpolate specific values (Friedman, 2002).

Interaction can also be calculated and visualized between variables in the BRT ensemble. Variable interaction plots, created using the same principle as partial influence plots, can be created to show the interactions between influential factors in the model (Friedman, 2002). Like partial dependence, these plots are not intended to perfectly represent the relationship between nitrate and each predictor variable, but they do offer insights into how model variables interact with each other. For instance, it is expected that irrigation and soil infiltration rate will impact the rate at which nitrate reaches groundwater (Exner, 2014; Wells et al., 2018; Malakar et al., 2023), and the interaction between these factors in the model may shed additional light on that relationship.

Evaluation Metrics

Models were evaluated using Matthew's Correlation Coefficient (MCC), sensitivity, specificity, and total accuracy. A confusion matrix, with associated statistics, was calculated for each classification model using the R package caret (Kuhn, 2023). MCC was the primary evaluation metric, and all measures used to evaluate model performance are summarized in Table 3. There are four possible outcomes for binary classification in confusion matrix calculations: true positive (TP), true negative (TN), false positive (FP), and false negative (FN). True positives refer to the samples that were above the threshold concentration accurately classified by the model. True negatives are the samples that were below the threshold concentration accurately classified by the model. False positives indicate a model prediction of above the threshold, but an actual value below. False negatives are the samples that were above the threshold concentration incorrectly classified as below. False negatives are more problematic to this study than false positives because a false positive may encourage someone to test their well, while a false negative may engender a false sense of safety.

In binary classification, MCC provides a measure of how model predictions compare to the performance of random predictions (Matthews, 1975, Chicco, 2021). MCC ranges between -1 and 1 where -1 indicates discord between predictions and actual values, 0 indicates predictions no better than random, and 1 indicates perfect agreement between model and observation. Positive MCC values can be interpreted on the same scale as Pearson's R (Chicco, 2021, Sokal et al., 1969). Sensitivity is the percentage of samples above the threshold concentration correctly classified by the model. Specificity is the percentage of true negatives predicted by the model out of total negative samples (Sokal et al., 1969). Accuracy, sometimes called overall accuracy, is a measure of sensitivity and specificity. Evaluation metrics were calculated using the following equations:

$$MCC = \frac{TP * TN - FP * FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}}$$

$$Sensitivity = \frac{TP}{P}$$

$$Specificity = \frac{TN}{N}$$

$$Accuracy = \frac{TP + TN}{P + N}$$

Where TP stands for true positive, TN stands for true negative, FP stands for false positive, and FN stands for false negative. MCC was selected as the primary evaluation metric because it is robust to lopsided datasets and appropriate for binary classification problems (Chicco, 2021).

Table 3. Evaluation Metrics Used to Evaluate Models.

Diagnostic	Type of Model	Description
Accuracy	Binary Classification	Accuracy is a measure of Sensitivity for all classes, in the case of binary classification, accuracy is the same across classes (Sokal et al., 1969).
Sensitivity	Binary Classification	Sensitivity is the percentage of samples that fall above the threshold value correctly classified by the model (Sokal et al., 1969).
Specificity	Binary Classification	Specificity is the percentage of samples that fall below the threshold value correctly classified by the model (Sokal et al., 1969).
Matthews Correlation Coefficient (MCC)	Binary Classification	Also known as the mean square contingency value or phi statistic, the MCC is a measure of agreement between predicted and actual values. In binary classification, it is akin to comparing the model to a coin flip. Interpretation of MCC on the order of Pearson's R correlation, where 1 indicates perfect agreement between model and observation, -1 is disagreement, and 0 is no better than a random prediction (Matthews, 1975 and Chicco, 2021).

Generalizing Model Results for the GIS Tool

A key goal of this modeling investigation is to supplement a web-based GIS tool for NDEE and select agency partners to help evaluate the risk of elevated nitrate concentrations. In the ideal case, this tool would host the model weights and predictor datasets and predict to the user-entered well location based on the local factors. Because of technical limitations, this is not possible in the near term and an alternate product covering all possible input locations for the tool, i.e., a statewide product, is highly desirable.

Model results from each BRT were generalized across the state to form a smooth prediction surface by first aggregating the predictor variables to an arbitrary half-mile grid surface in the ArcGIS Professional (Version 3.1) software suite, then importing the data into R where trained model files predicted to the surface, and finally mapping the results. Variable aggregation followed the same procedure as the wells data with one notable exception. All available well construction data from the NDNR for active, registered wells was used to create the grid surface, including wells that were not sampled for nitrate or included in the model data.

Data Exploration

Nitrate samples from the Clearinghouse and variables summarized in Table 2 were explored prior to final aggregation strategy and modeling. This section summarizes the important elements of the data exploration. Because some wells have been sampled multiple times during the period 2003-2019, median nitrate concentration was calculated for each well and is mapped in Figure 2. Observed concentrations were converted to binary responses as described in the methods section. Training wells are shown in Figure 3, symbolized based on the 10 mg/L MCL threshold. GBM-MCL stands for Gradient Boosted Model – Maximum Contaminant Level. Each model is named following this convention which is used in figures throughout the text. Wells below that value are symbolized in navy and wells above the MCL are symbolized in yellow. Figure 4 shows the wells used to test the model symbolized in the same fashion.

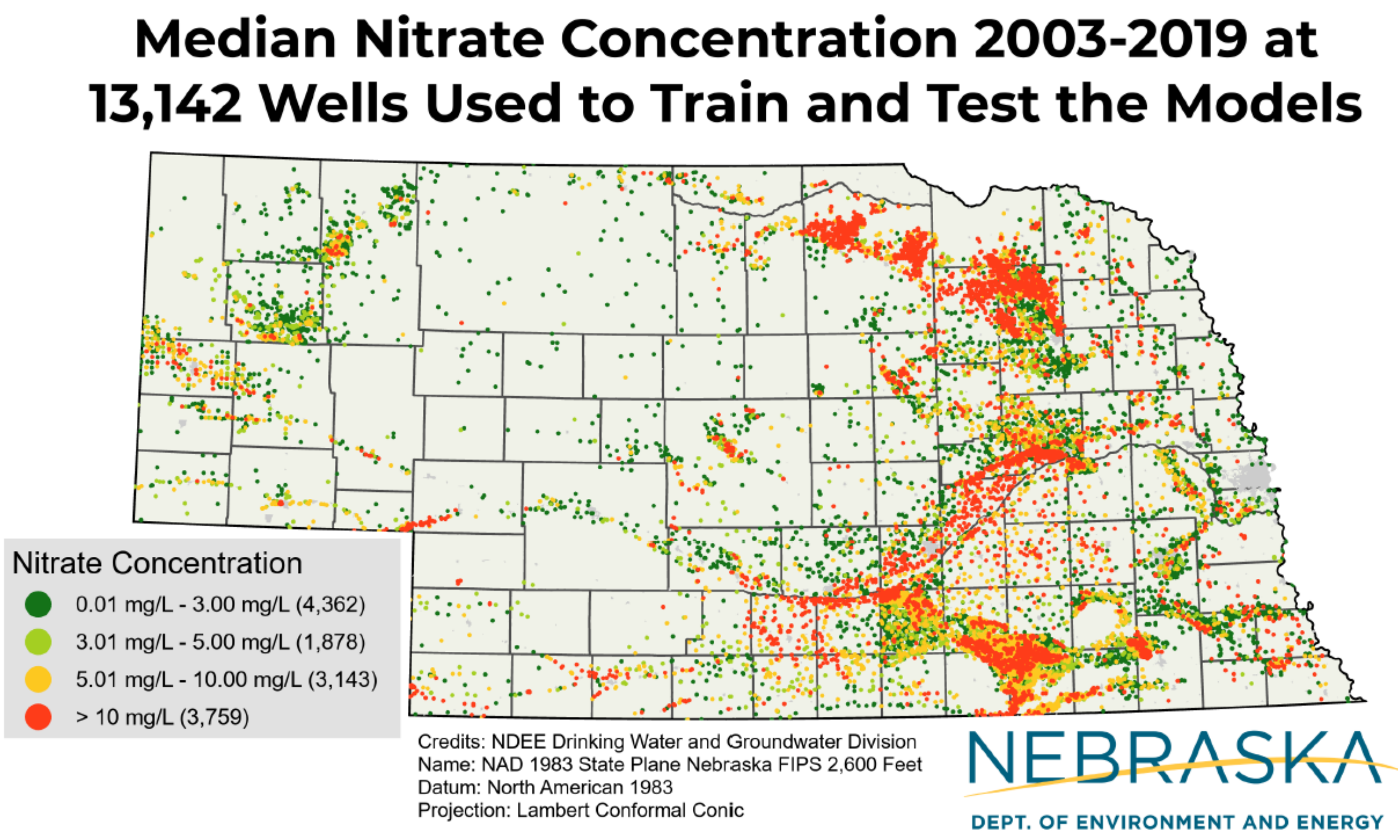


Figure 2. Predictive Nitrate Model Input: All Well Locations Used to Train and Test Each Model by Median Nitrate Concentration.

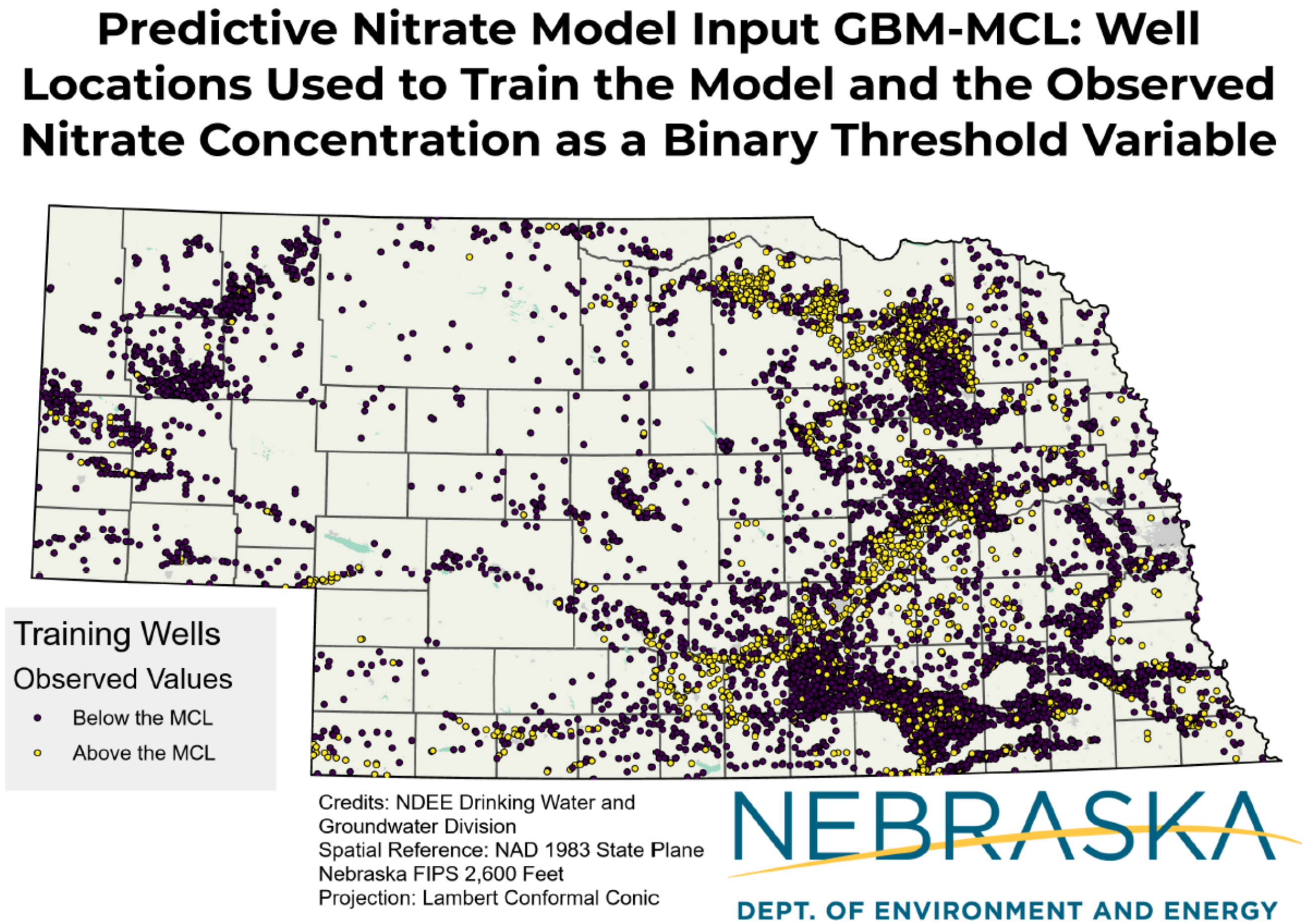


Figure 3. Predictive Nitrate Model Input GBM-MCL Well Locations Used to Train the Model and the Observed Nitrate Concentration as a Binary Threshold Variable.

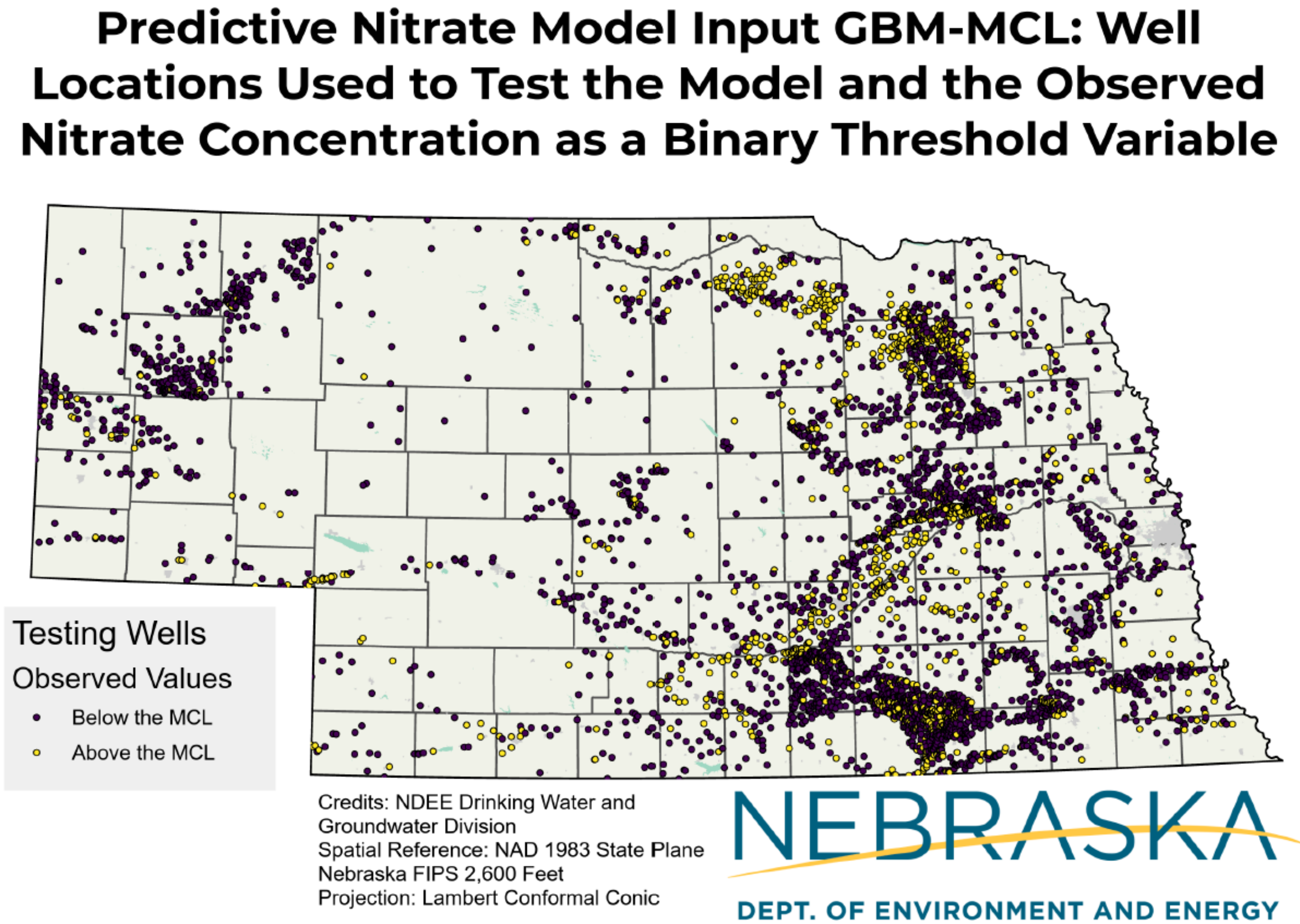


Figure 4. Predictive Nitrate Model Input GBM-MCL Well Locations Used to Test the Model and the Observed Nitrate Concentration as a Binary Threshold Variable.

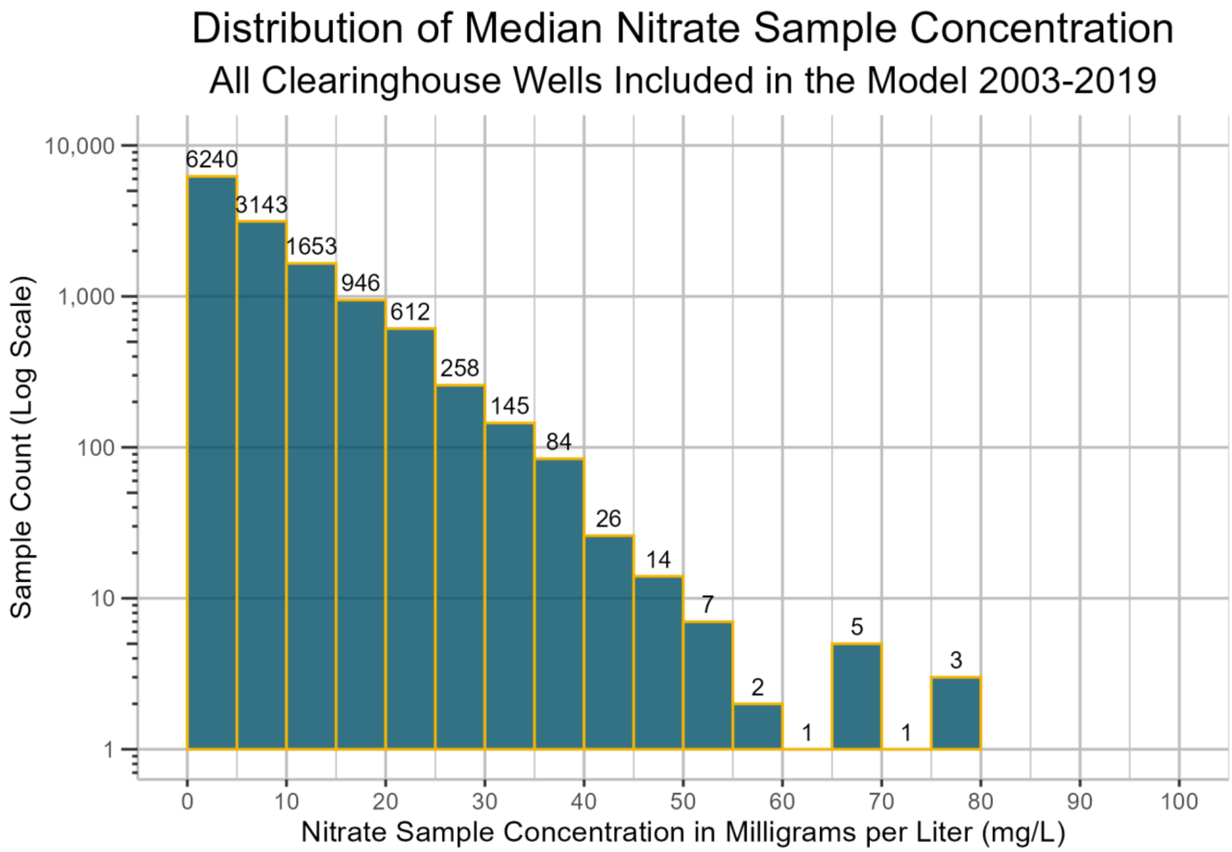


Figure 5. Median Nitrate Concentration Distribution at Wells Included in the Model.

Because of siting, design, and sampling requirements, Public Water Supply (PWS) wells are biased to lower nitrate levels and were excluded from modeling. See Table 4 for a summary of the well sample data in the Clearinghouse organized by well type. It shows the wide range in sampling patterns and concentrations between well classes. This range in concentrations between well types shown in Table 4 can be explained in part by the more stringent construction standards for PWS wells than other types of wells. Additionally, PWS wells must meet SDWA standards and those that do not are typically decommissioned, blended, or treated. This biases the PWS data toward lower nitrate concentrations overall. Sample data from PWS wells were excluded from training and testing data because it is not representative of nitrate levels in private domestic wells, the target of this modeling effort.

Table 4. Summary statistics for nitrate samples in the clearinghouse by well type from 2003 to 2019.

Clearinghouse Well Type	Mean Nitrate Concentration (mg/L)	Median Nitrate Concentration (mg/L)	Sample Count	Wells Sampled
Livestock Watering	12.43	8.40	522	105
Domestic	7.21	2.50	5,676	1,423
Irrigation	9.35	6.50	51,969	13,504
Monitoring	7.33	4.10	19,021	1,697
Public Water System	4.04	2.94	42,631	3,064
All Wells	7.05	4.5	119,992	19,768

Well Construction

Well depth, pumping water level (PWL), static water level (SWL), half the distance to the screened interval, the presence or absence of a surface seal, the length of gravel pack, and construction year were factors evaluated against the nitrate concentration in all sampled wells. Construction year was assigned a binary variable corresponding to wells built before or after state construction standards were established in 1988 and was ultimately insignificant in modeling. Only wells 300 feet or shallower were modeled. Domestic wells in Nebraska do not typically exceed 300 feet in depth. Figure 6 shows the depth of active, registered domestic wells in the state. All Clearinghouse samples included in the model are plotted against half the depth to the screened interval in Figure 7. Well depth, depth of the screened interval, PWL, and SWL, are all proxy measures for an important nitrate predictor: groundwater age (Nolan et al., 2015; Wells et al., 2018; Malakar et al., 2023). Depth to the screened interval shows a negative relationship with nitrate concentration.

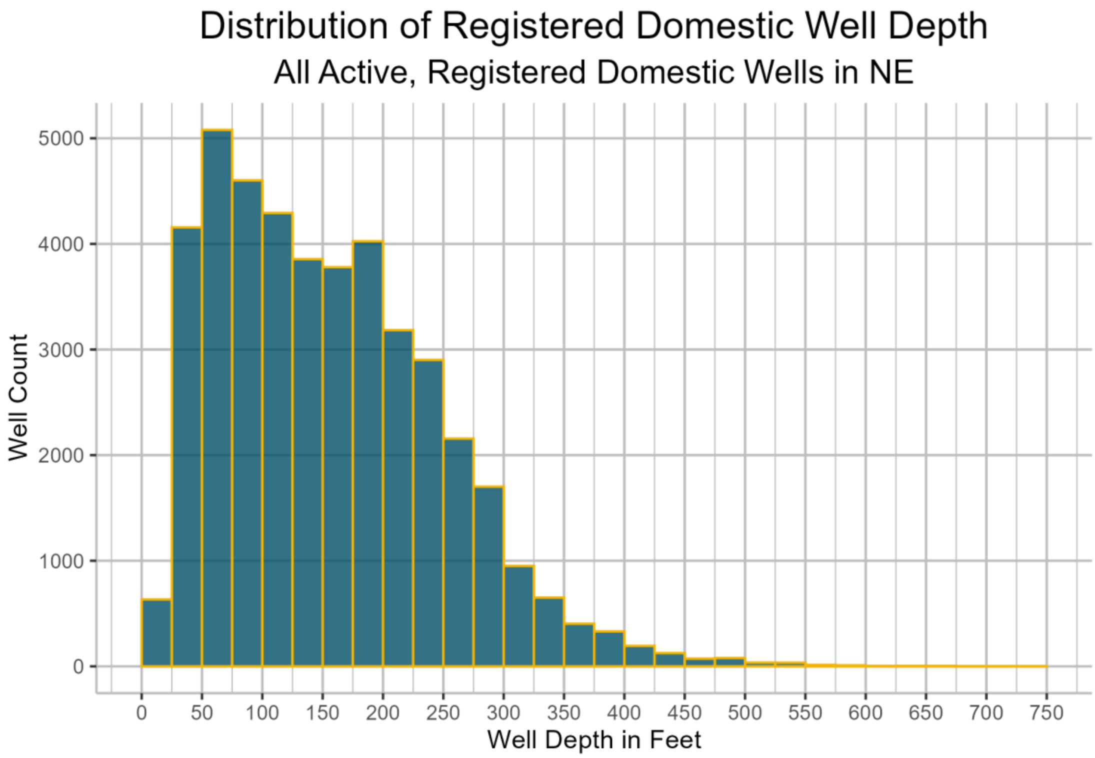


Figure 6. Distribution of Domestic Well Depth Among Active, Registered Wells in Nebraska.

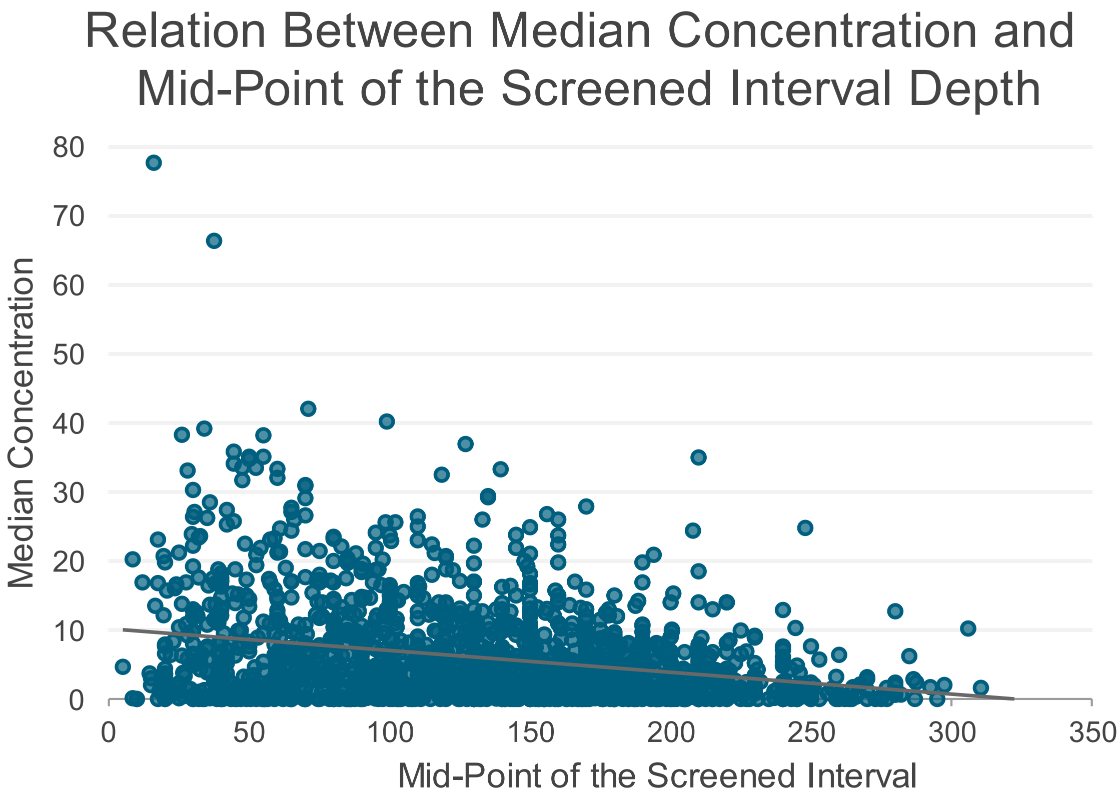


Figure 7. Nitrate Concentration in Milligrams per Liter (mg/L) and Depth to the Mid-Point of the Screened Interval in Feet (ft).

Land-Use

The CDL was evaluated for changes over time at the Township scale across the state (Figure 8) using the R package ggplot2 (Wickham, 2016). Significant changes were not seen between the major classes (grassland, corn, soy) over the study area since the initial release of the 2008 product. Additionally, around 80% of corn and soy acres appear to be in rotation with each other over the study period and these two should be considered a linked class. Corn shows similar correlation with the percentage of irrigated land and the historic fertilizer application rate. See a correlation matrix of the land use inputs in Figure 9 where Pearson's R values are plotted on the right diagonal (Sokal et al., 1969). A combined CornSoy class is shown illustrating the close relationship between the two factors. While factor independence is not a required assumption of BRTs (Elith et al., 2008), collinear factors do influence the variable influence and interactions in the model (Dormann et al., 2013).

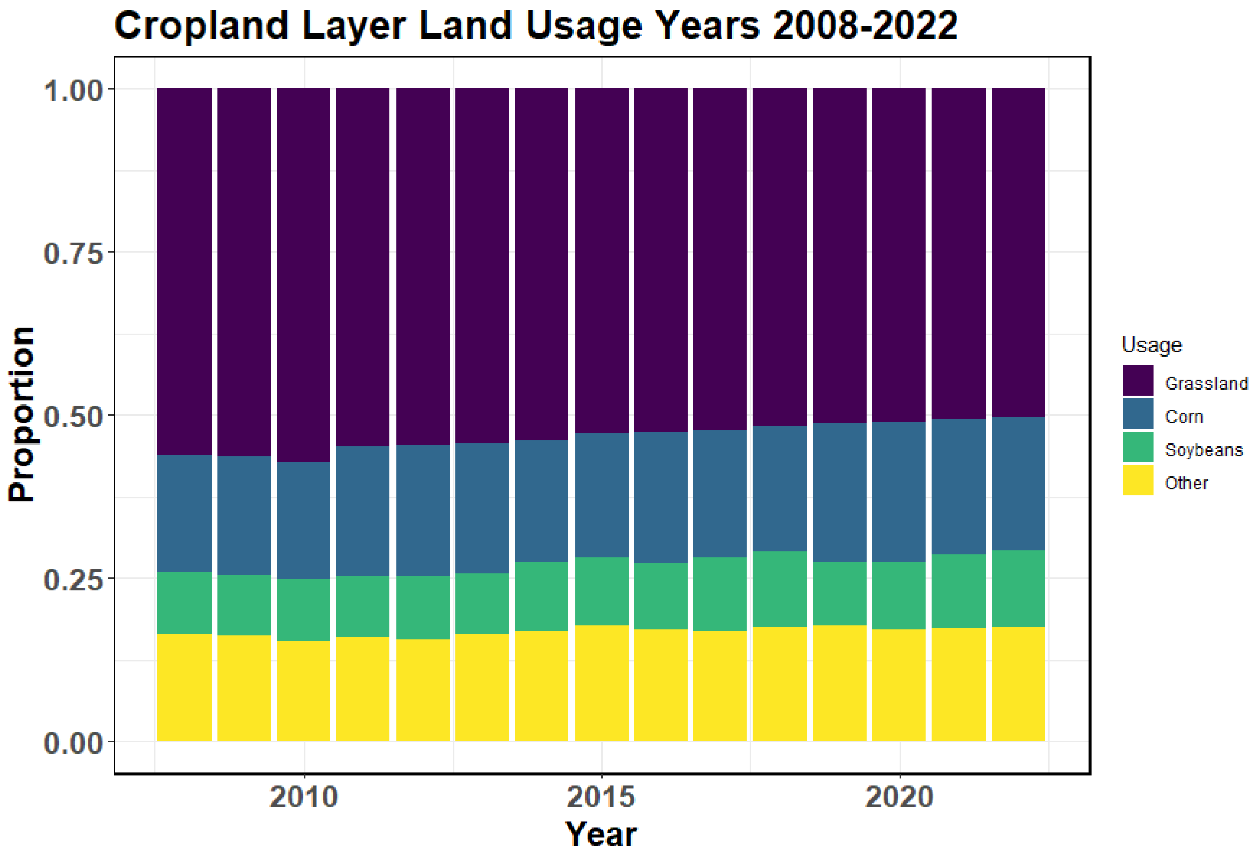


Figure 8. Cropland Data Layer Largest Land-Use Classes.

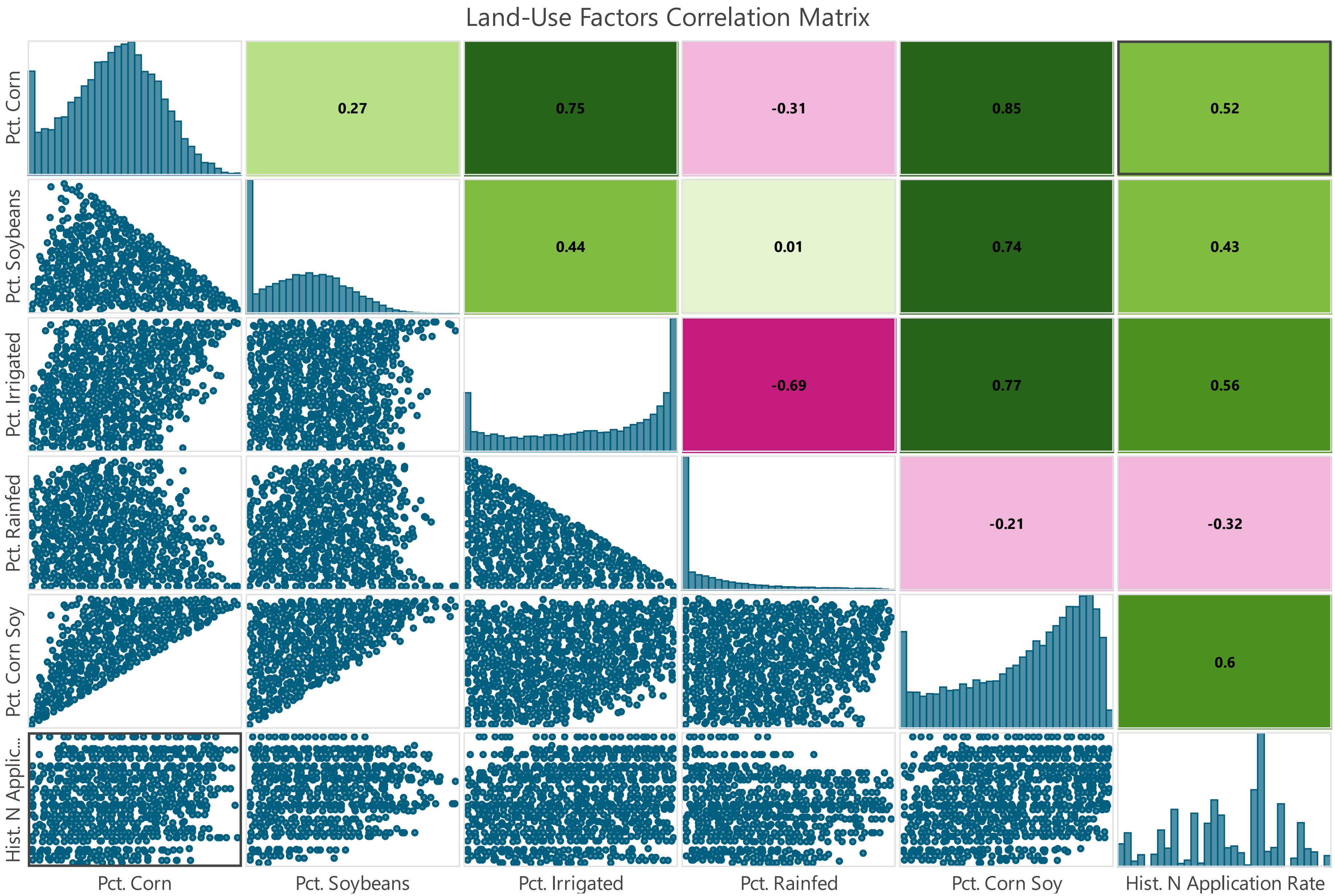


Figure 9. Correlation Matrix for Land Use Variables Considered for or Included in the Model.

Results & Discussion

Model predictions in probability terms were converted to binary values and compared with the training and testing data. Probability values of above 0.5 were treated as a prediction of one and equal to or below 0.5 as zero for mapping and confusion matrix calculations.

Models were tuned by varying the learning rate (from 0.001 to 0.1), tree complexity (from 3-5), and number of trees (from 100-15,000). Once a rough number of trees was established, values of complexity and learning rate were optimized. As a rule of thumb, when the complexity was increased by one, the learning rate was reduced by approximately one-half. Complexity was varied between three and five. A complexity of five was found to optimize all models. Unsurprisingly, optimal complexity was near the square root of the number of predictor variables (22). See table 5 for a summary of the model parameters after tuning.

Table 5. Model Parameters Used in each Tuned BRT Model.

Model	Number of Trees	Tree Complexity	Learning Rate
GBM-MCL (MCL)	8600	5	0.008
GBM10.18 (Elevated)	12100	5	0.005
GBM10.19 (Background)	13600	5	0.007

Table 6 summarizes diagnostic statistics for the models separated by training and testing data. Model sensitivity for the training data ranged between 76-97% with the highest sensitivity for classifying wells above the background level. For the testing data, sensitivity ranged from 55-88%. Again, the highest sensitivity was achieved classifying wells above the 3 mg/L background. Overall accuracy was high across the board, ranging from 75-91% in the testing and training data.

MCC values evaluated from the training data ranged between 0.74 and 0.82 indicating very strong (0.7 – 1.0) agreement between predictions and observations. In the testing data, MCC values ranged from 0.50 – 0.51 indicating strong agreement (0.4 – 0.69) between testing data and model predictions.

Table 6. Model Diagnostic Statistics.

Model Diagnostic Statistics Model	Specificity (0)	Sensitivity (1)	Accuracy	MCC
	Training Data			
GBM-MCL (MCL)	97%	76%	91%	0.78
GBM10.18 (Elevated)	86%	88%	87%	0.74
GBM10.19 (Background)	82%	97%	92%	0.82
	Testing Data			
GBM-MCL (MCL)	92%	55%	81%	0.51
GBM10.18 (Elevated)	72%	78%	75%	0.51
GBM10.19 (Background)	59%	88%	78%	0.50

Variable influence is plotted in Figure 10 for the GBM-MCL model. Variable influence, partial dependence, and variable interaction plots were roughly equivalent across models, results are reported for GBM-MCL and are representative of the other models. Across models the most influential factors were well location (lat/long) and soil infiltration rate (ksat). Variables with many null values – like depth to the midpoint of the screened interval (Half_ScreenDepth) – have lower influence. Partial dependence plots for the eight most influential factors in the GBM-MCL model are shown in Figure 11.

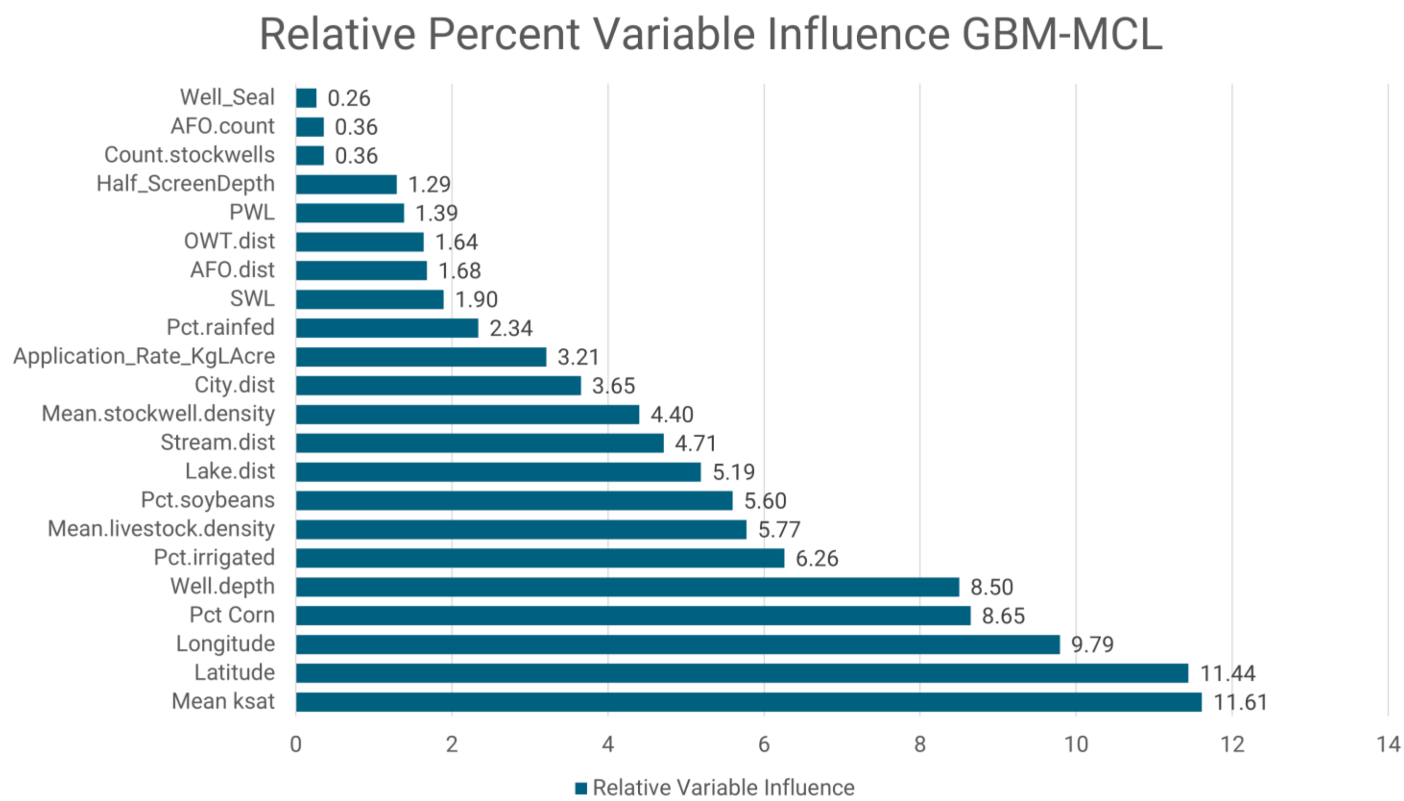


Figure 10. Relative Percent Variable Influence for the 22 Predictor Variables in the GBM-MCL Model.

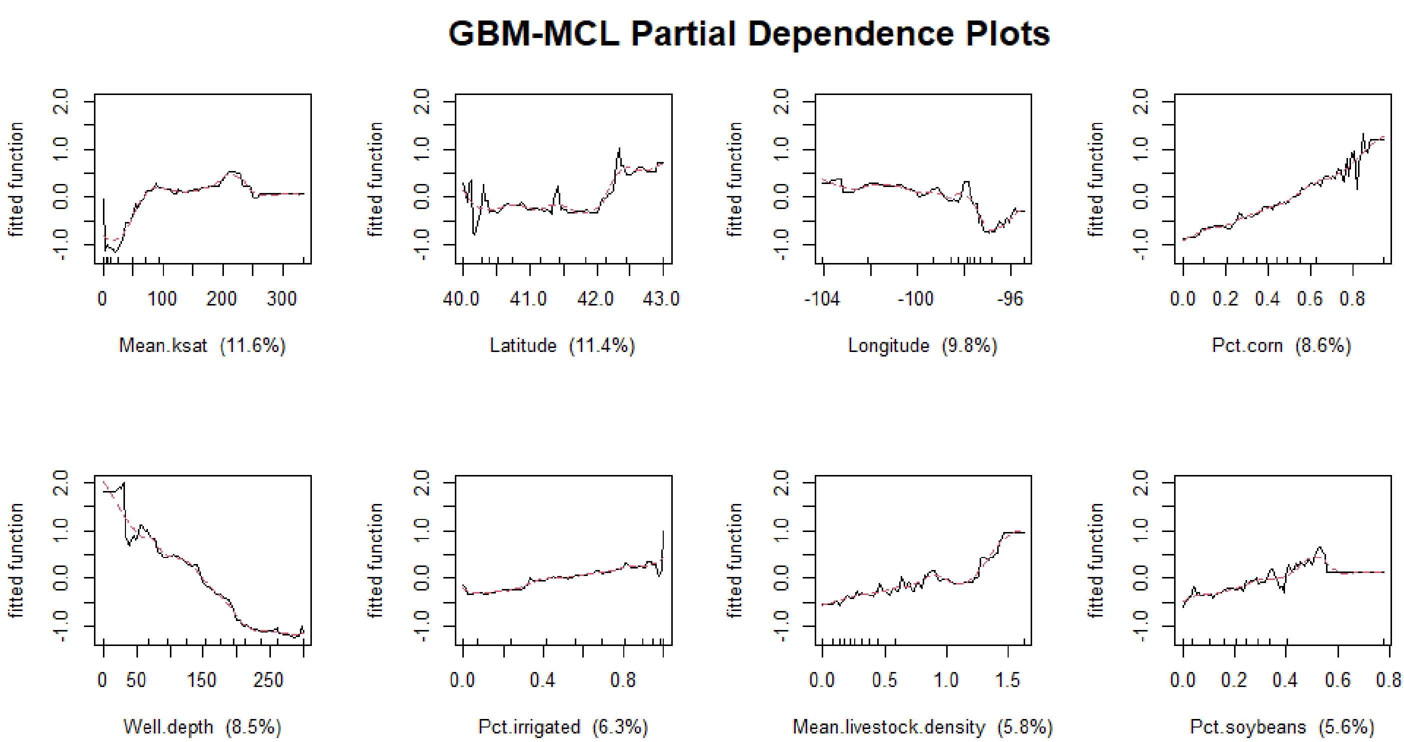


Figure 11. Partial Dependence Plots for the Eight Most Influential Variables in GBM-MCL.

Based on the variable influence and partial dependence plots, intensive agricultural land-use is a strong predictor of nitrate risk. Corn and soy should be considered a linked class based on crop rotation patterns in

Nebraska and the shape of their response supports this. Location, as measured by latitude and longitude, was consistently identified across models as a strong predictor with about 20% variable influence. This is unsurprising, given historic land-use patterns are strongly linked to nitrate levels in groundwater. Soil infiltration was another factor closely linked to estimated nitrate risk as expected. In general, nitrate risk increases with increasing ksat, but plateaus after a steep increase between 50 – 100 micrometers/second. Well depth had a negative relationship with nitrate risk. Shallower wells were more likely to be classified as high-risk, with the highest risk estimated in wells 50 feet or less in depth.

Variable interactions between land use trends and soil infiltration rate appear strong in the GBM-MCL model predicting against the MCL. Figure 12 shows the surface plot of predicted probability (z-axis) based on ksat and the percentage of irrigated land around each well. Figure 13 shows this interaction in two-dimensions, where more intense color indicates a higher predicted probability.

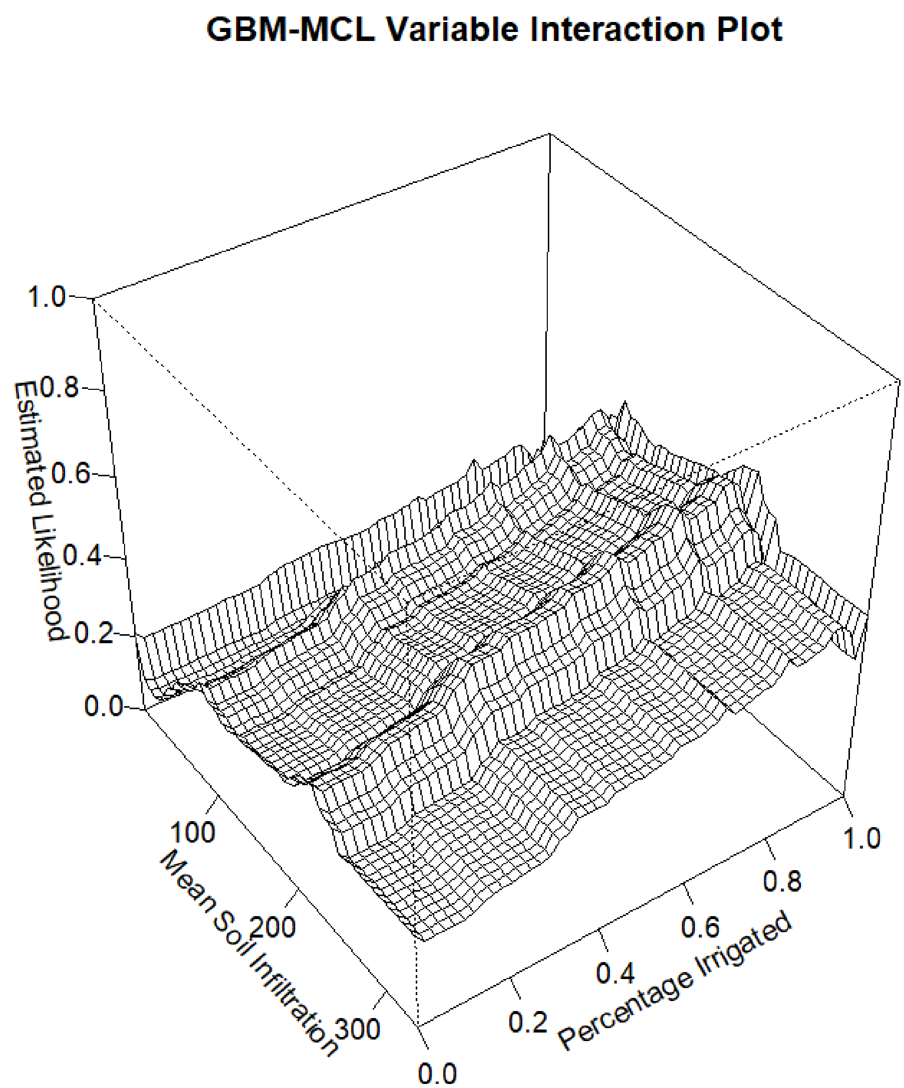


Figure 12. GBM-MCL Variable Interaction Surface Plot for Mean Soil Infiltration Rate and Percentage Irrigated Land.

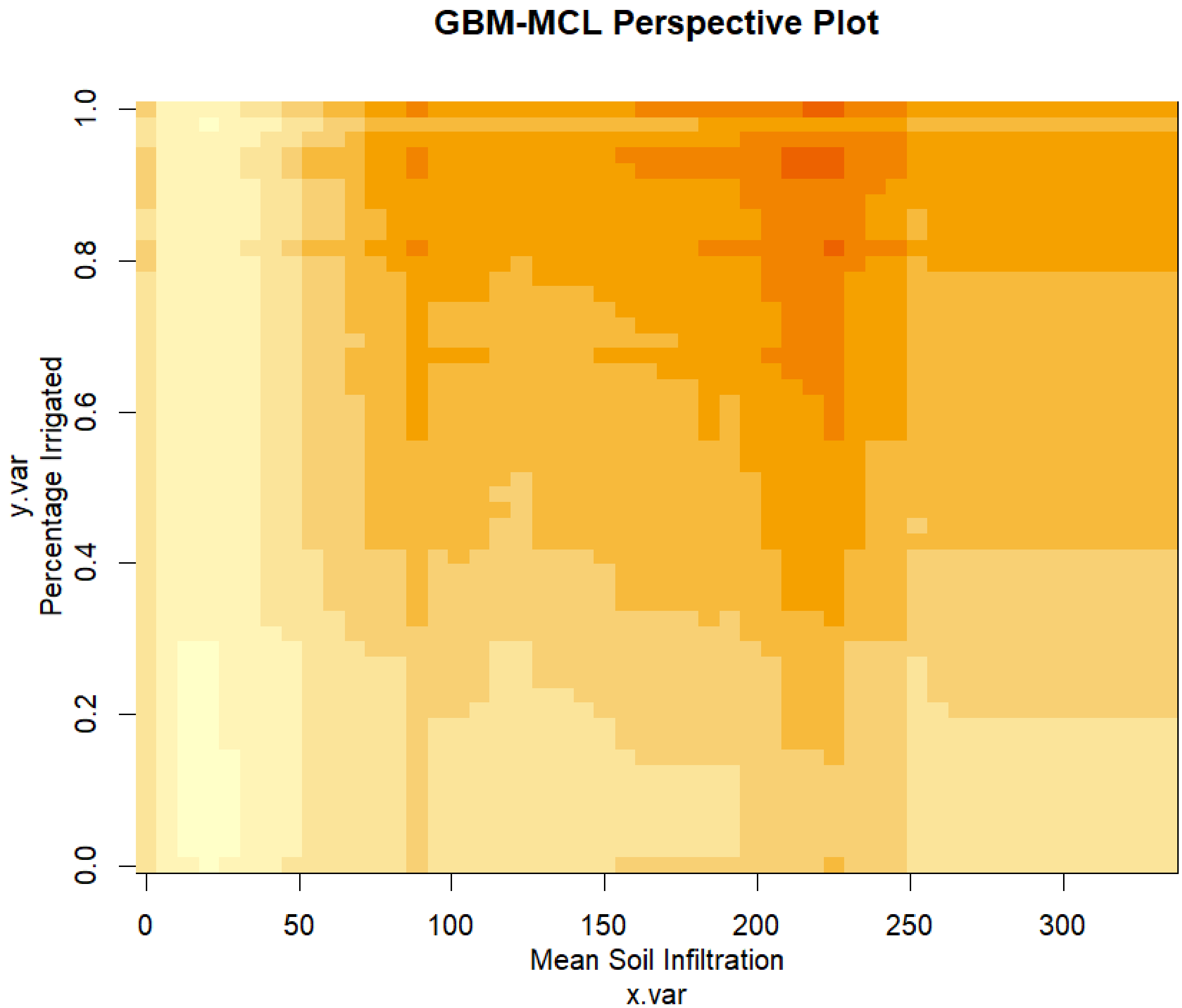


Figure 13. GBM-MCL Perspective Plot.

Physically, this interaction suggests that wells in heavily irrigated areas are at a higher risk of elevated nitrate levels if the soil infiltration rate is also above 50 micrometers per second. This relationship dips at high soil infiltration rates, suggesting soils that are unproductive for farming. It may also suggest that marginal soils on either end of the drainage spectrum receive comparably more inputs. Figure 14 plots the interaction between historic fertilizer rate and soil infiltration which supports this assertion. Correlation between other crop predictors such as corn, soy, historic fertilizer application, and irrigated land may be muting this relationship.

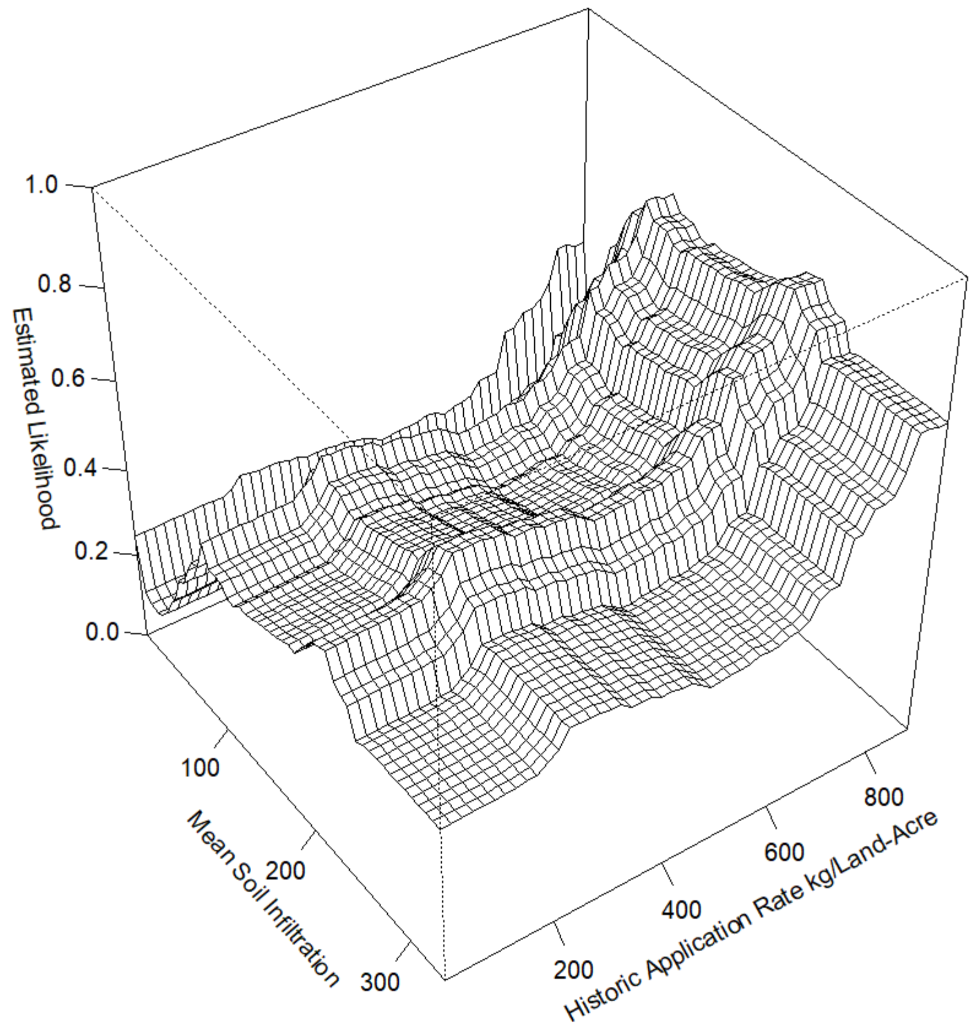


Figure 14. GBM-MCL Variable Interaction Plot Between Estimated Likelihood Soil Infiltration Rate and Historic Application Rate.

Model predictions were exported from R and mapped using ArcGIS Pro. Figure 15 plots the predicted and observed results from the GBM-MCL testing data. Light blue triangles are true positives, dark blue triangles are true negatives, orange x's are false positives, and red x's are false negatives. False negatives are rendered first in the figure, and it should be noted that at this scale the wells appear much closer together than they are. Mapping the results reveals that the model generalizes wells across Nebraska with the apparent exception of the Paleo Valley Aquifer systems.

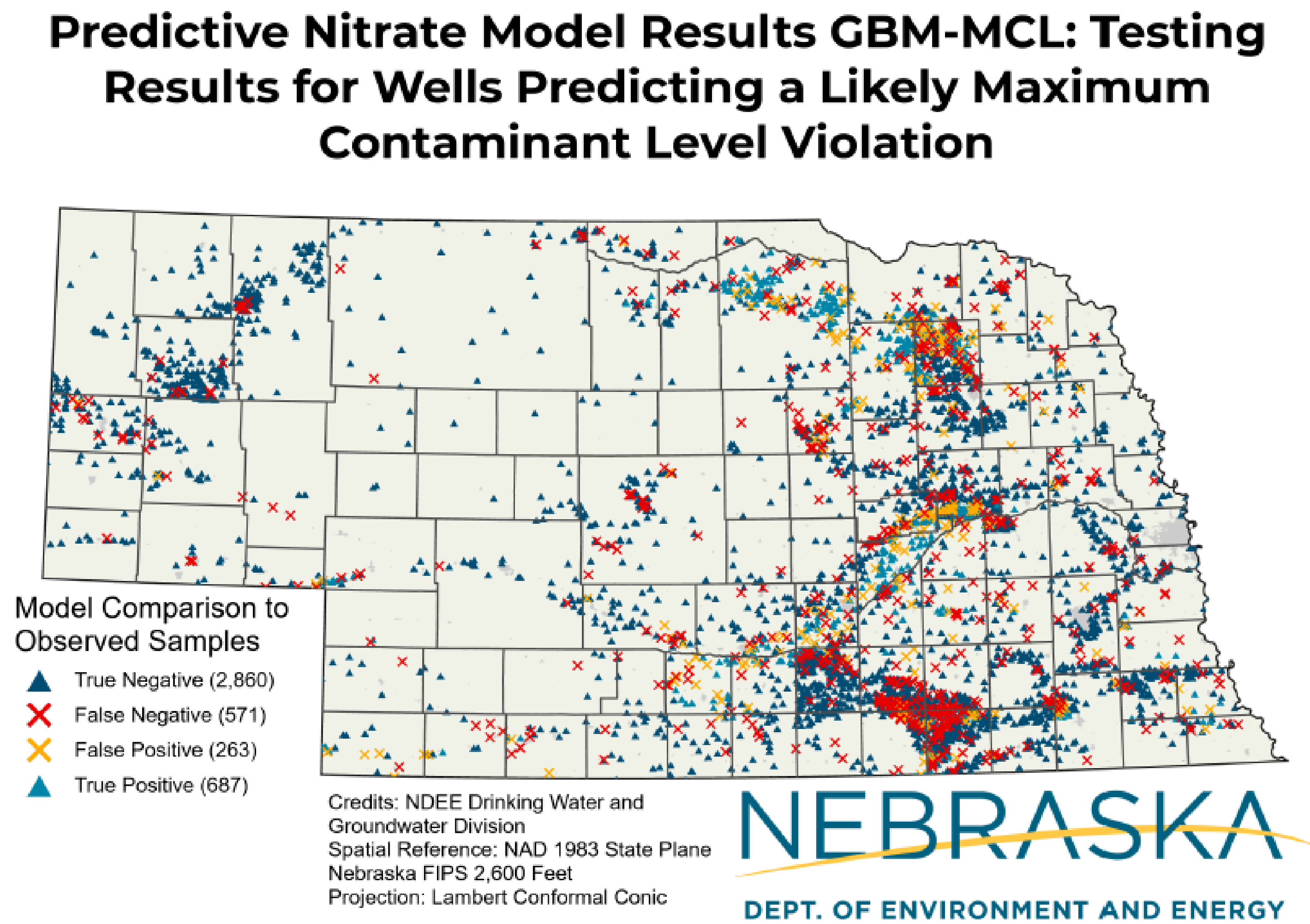


Figure 15. GBM-MCL Testing Results.

Generalizing Model Results for the NDEE Domestic Well Risk Assessment Tool

Results from the three trained models were generalized across the state. First, predictor variables were aggregated into a half-mile grid surface covering the State of Nebraska, then the trained models were used to predict to that surface, and finally the predictions were mapped for incorporation into the tool. Figure 16 shows the composite model results as they are queried by the GIS tool. Areas in red are more likely than not to exceed the MCL, areas in orange are more likely than not to exceed the elevated concentration, areas in yellow are more likely than not to exceed the background concentration, and areas in green are more likely than not to fall below the background concentration. A fully independent set of testing data from the NDEE free private domestic well sampling effort was used to evaluate the performance of the gridded model predictions.

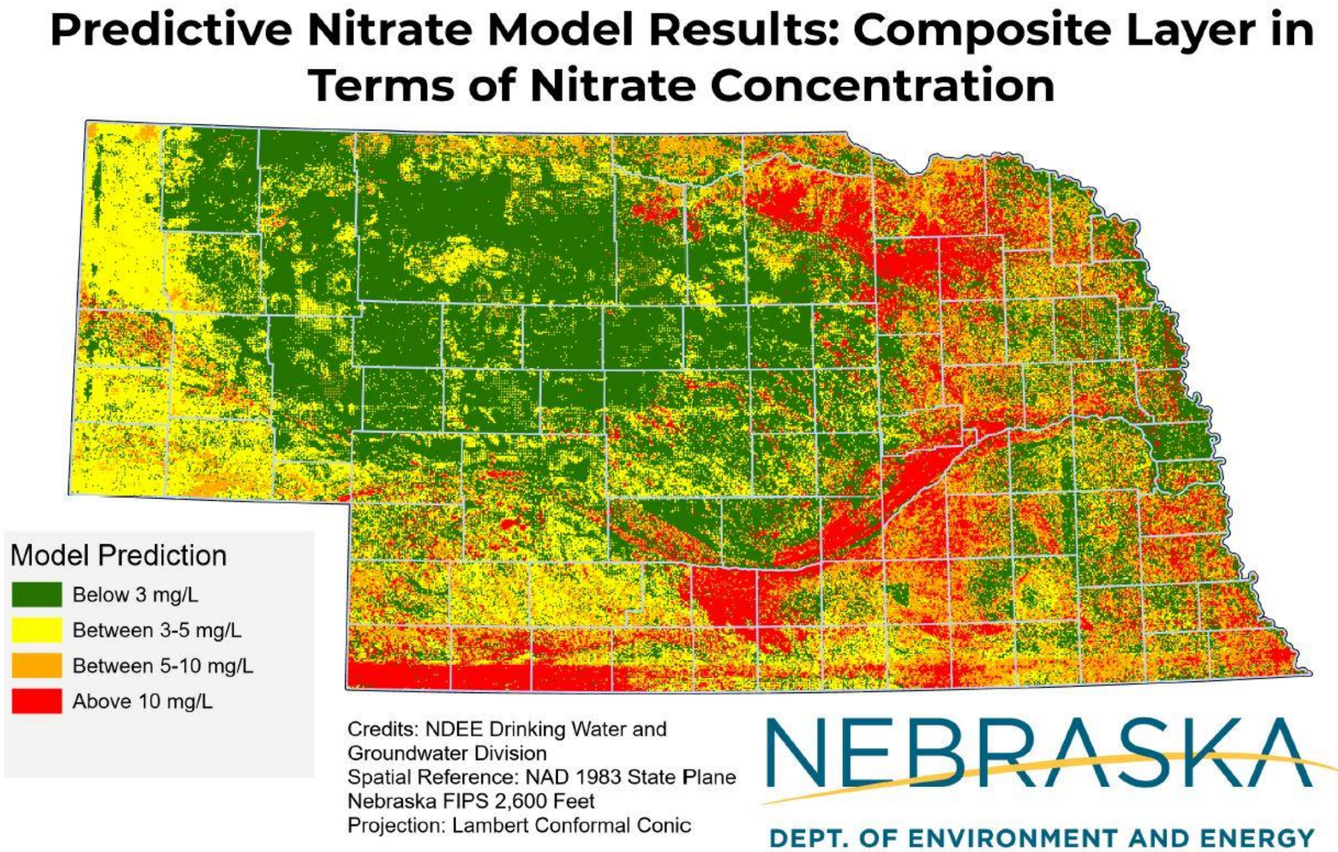


Figure 16. Predictive Nitrate Model Results: Composite Layer in Terms of Nitrate Concentration.

Model Predictions Compared to NDEE Private Domestic Sampling Effort Results

In addition to testing data (data not used in model training), model performance was evaluated against samples collected by private domestic well owners as a part of the 2023-2024 NDEE water quality study free private domestic well nitrate sampling effort. Because these were not used to train the models, they represent a fully independent testing set. This test estimates how well the model predictions generalized to the half-mile grid surface will perform in the GIS tool. Table 7 summarizes the metrics for each surface. Results are also plotted in Figure 17 to visualize how the model results compare to the independent dataset.

Based on testing, it was found that aggregating the variables into an arbitrary grid ‘weakened’ model efficacy by generally under-estimating probability of exceeding each threshold concentration when compared to the fully independent private domestic well data (MCC=0.13 – 0.28). Classification thresholds were systematically reduced (in increments of 0.05) on the grid surface to optimize predictive accuracy and provide a conservative estimate of risk. By adjusting the cutoff value from 0.5 to 0.25 for the MCL model, from 0.5 to 0.35 for the elevated model, and from 0.5 to 0.45 for the background model, comparison to the private domestic well samples were acceptable (MCC=0.20 – 0.28) and more in line with a comparison between the gridded surface and the testing data (MCC=0.40 – 0.44).

Figure 17 shows a comparison between the MCL predictions and the private domestic samples by outcome. Location information for these wells is based on the street address provided by well owners and then geocoded using ArcGIS Pro (Version 3.1). Addresses matching P.O. boxes, Points of Interest, and Street centerlines were removed for evaluation metric calculations. Addresses that requested more than one sample kit were also removed as some owners tested before and after treatment units or for multiple properties. Areas in darker blue on Figure 17 correspond to higher probability of exceeding the MCL. Figure 18 summarizes the results of the MCL comparison with the domestic samples by classification category. Figures for the elevated and background surfaces are available in the supplemental model material.

Table 7. Diagnostic Statistics based on Comparing the Gridded Model Predictions to the Domestic Samples from the 2023-2024 Domestic Well Sampling Effort.

Metric → Model-Surface ↓	Specificity (0)	Sensitivity (1)	Accuracy	MCC
	2024 Domestic Well Testing Data			
GBM-MCL (MCL)	87%	34%	79%	0.20
GBM10.18 (Elevated)	75%	52%	68%	0.26
GBM10.19 (Background)	68%	60%	65%	0.28

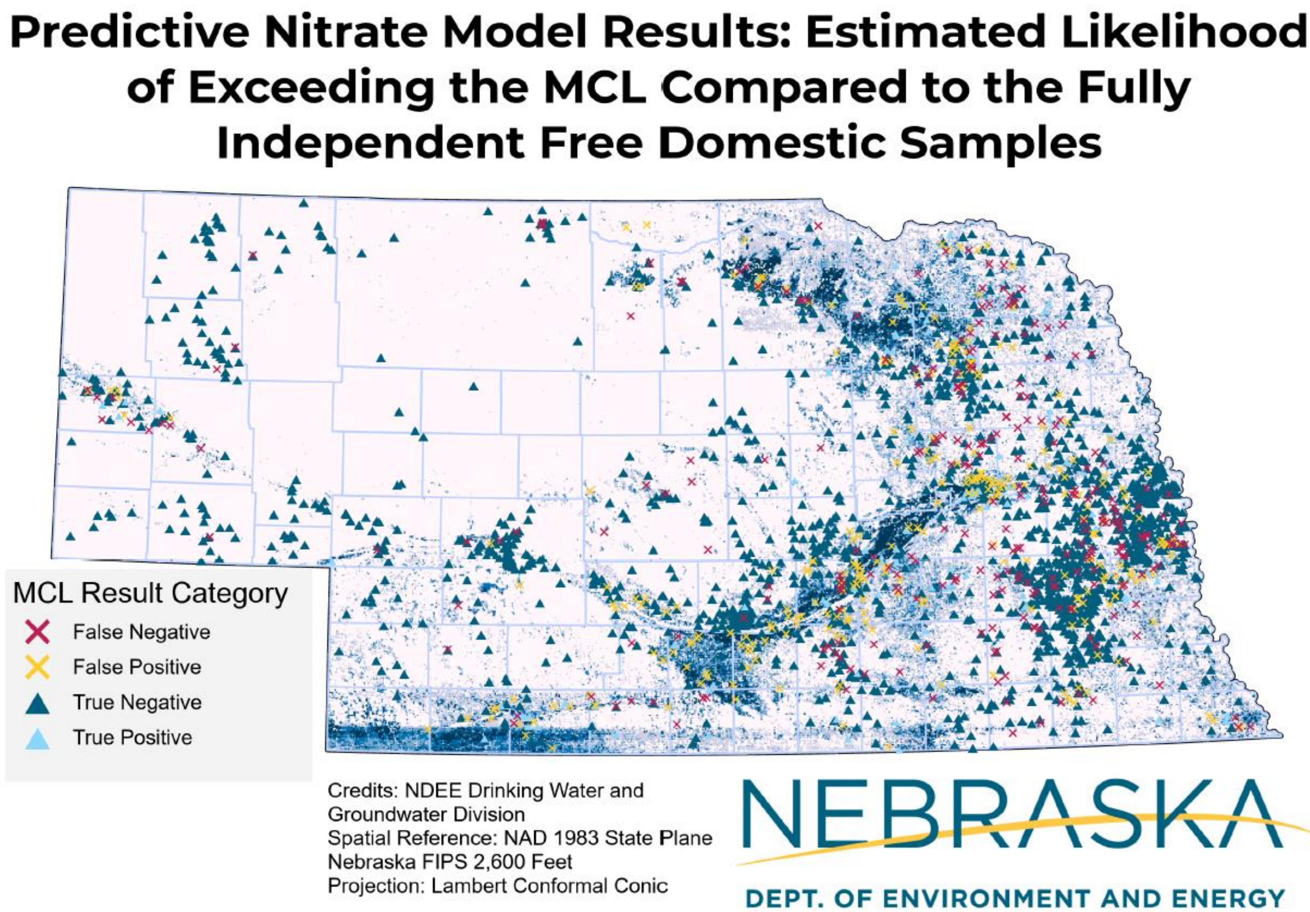


Figure 17. Predictive Nitrate Model Results: Half-Mile Grid Surface for GIS tool.

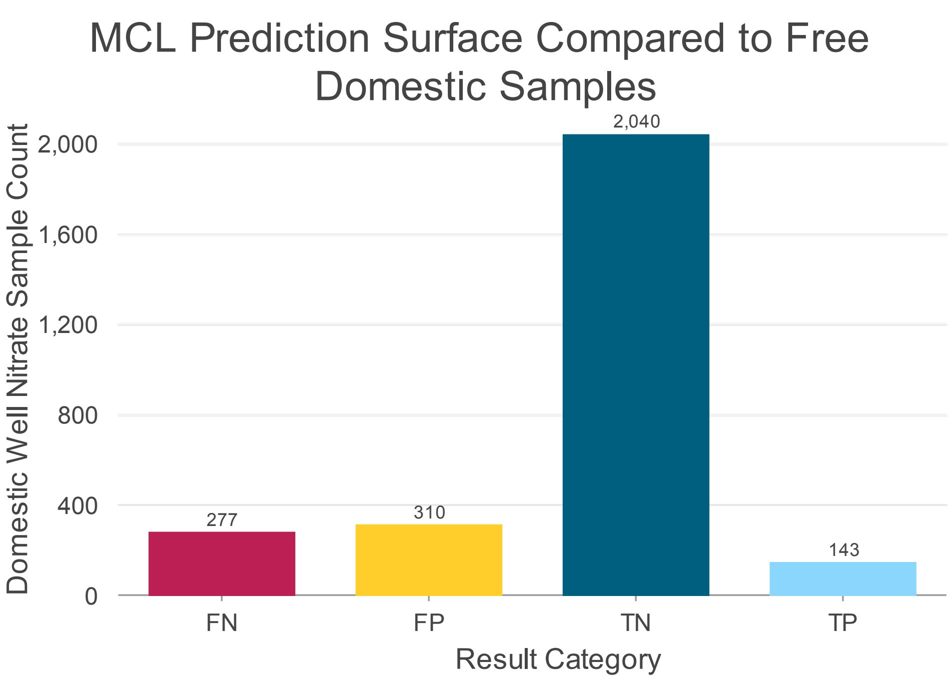


Figure 18. MCL Prediction Surface Compared to Domestic Well Samples by Result Classification.

Limiting Training Data

While BRTs are robust to null values for predictor variables and strongly related predictors, the influence of variables with missing values is systemically lowered. Preliminary testing that limited the dataset to only complete records and a limited number of collinear factors yielded interesting results (Figure 19). Depth to the midpoint of the screened interval became much more influential to the model predictions. Land-use influence was distributed mostly to the percentage of irrigated lands and the historic application rate. Ksat and well location were still key factors.

Modeling was repeated on a subset of the training data (n=1,559) where no factor contained null values. The results were overall in line with the models, with some differences in variable influence and interactions. For instance, in GBM-MCL no-NULL, the depth to the mid-point of the screened interval increased 900% in variable influence (Figure 19). This would indicate that screen depth is a stronger predictor than well depth, as expected, because it better estimates groundwater age. Figure 19 also illustrates the way that null values mute the variable influence measure. Low influence does not equal low impact. It may just indicate low coverage of a given predictor. Static water level and pumping water level increased by 200-250% by removing wells with null values from the training data.

Reducing the training set reduced the ability of the models to generalize, which was reflected in lower MCC values (0.41-0.45) when compared with the BRTs (0.5-0.51). Accuracy and sensitivity were also around 5% lower across the board for the testing data when using the limited training set. This is not particularly surprising given the data-hungry nature of ML methods and the steep reduction in class examples (from more than 13,000 to 1,559).

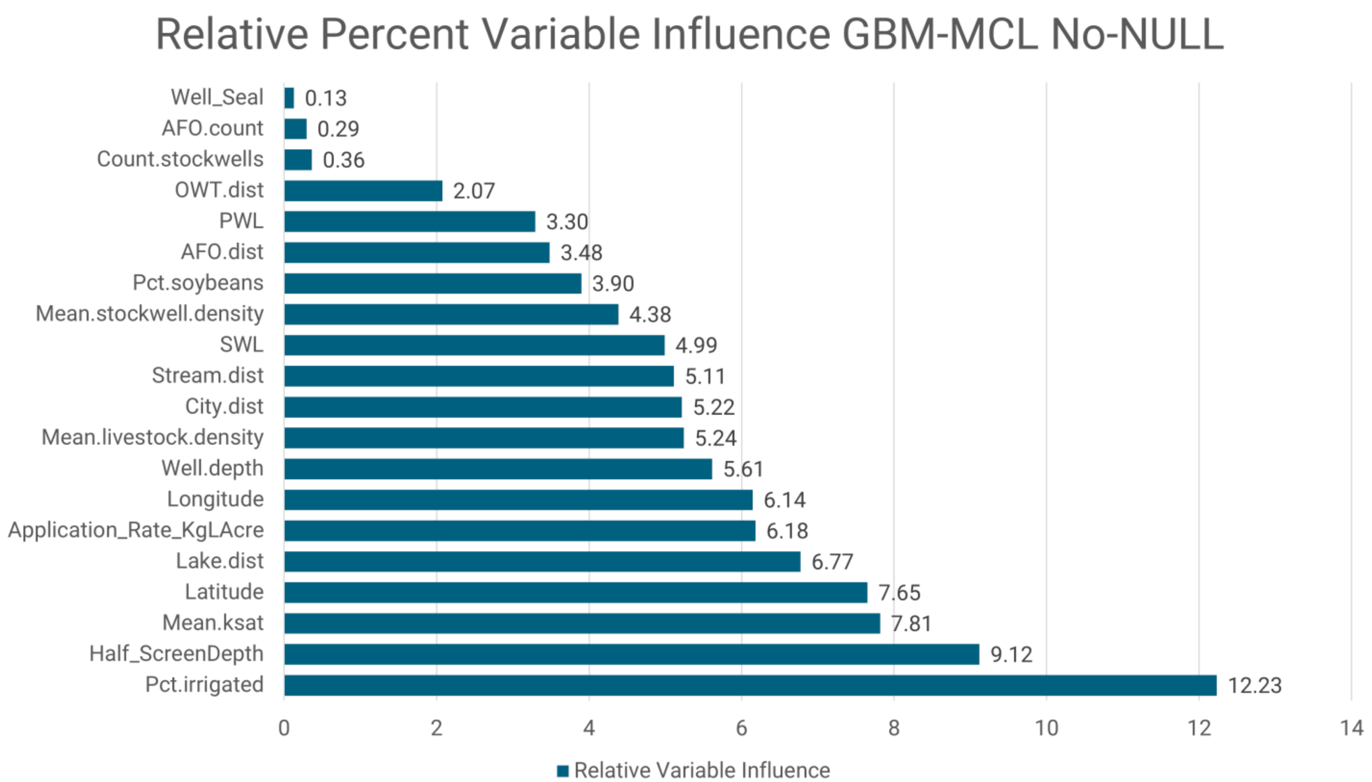


Figure 19. Relative Percent Variable Influence in the GBM-MCL Model with no NULL Factors.

Conclusions & Recommendations

In this study, three BRT models were trained to predict the probability that median nitrate concentration in a private domestic well would exceed water quality thresholds based on the available model inputs aggregated within 1500-meters of each well modeled. Input variables representing land-use, hydrogeologic factors, point sources, well construction details, and nitrate samples collected from 2003-2019 were used to train the model. Threshold values of 3 mg/L, 5 mg/L, and 10 mg/L were modeled to represent the background, elevated, and the SDWA MCL for nitrate, respectively.

Predictor variables used to train the BRTs were aggregated into a half-mile grid surface across Nebraska and model predictions were made for each grid cell to generalize models for the internal NDEE GIS tool. Predictions were only based on the input data listed in the model card, and it is important to note that this is not a complete accounting of the variables that could impact nitrate concentrations in a given well. Overall, the evaluation statistics for the models were strong, with MCC values between 0.5 and 0.51 for the testing data, and acceptable (MCC=0.20 – 0.28) when the gridded predictions were compared to the fully independent private domestic well sample set for use in the GIS tool. Overall model accuracy was high in the training and testing data (71 – 91%), and the estimates generalized acceptably to the private domestic well data collected during the 2023-2024 NDEE free private domestic well sampling effort (68 – 87% overall accuracy). Evaluation metrics from the training data indicate that models were well optimized, though additional predictor data, more complete predictor data coverage, and additional nitrate samples will almost certainly improve future modeling efforts.

False negatives (underprediction of nitrate concentration) are of greater concern than false positives for this study. NDEE intends to use the model internally and with key partners. Decision makers should note that a high false negative rate suggests the model generally underestimates risk of exceeding the MCL. GBM-MCL model sensitivity was 55%, with an overall accuracy of 81%. The testing specificity was very high – 92%, however the false negative rate of 45% could be improved with future work. Values compare favorably to those reported by Nolan (2014) and Wheeler and Nolan (2015) for nitrate prediction. GBM-MCL performance was comparable to Lombard (2021) in a similar study exploring arsenic MCL exceedances. From a regulatory perspective, it can be argued that predicting where nitrate is not likely to exceed the MCL is just as important as predicting where it is likely to exceed the MCL. Ultimately, testing the water is the only way to know the concentration for certain. When the predicted surface for the GBM-MCL model was compared to the private domestic well data collected during the water quality study (a fully independent test set) the results were acceptable, with 47% sensitivity and an overall accuracy of 73%.

Several insights about the relationship between nitrate and contributing factors can be taken away from the model. Variable influence and partial dependence plots show that well location, intensive agricultural land-use, irrigation, and high soil infiltration rates are strongly related to the level of nitrate in groundwater. This is consistent with other research demonstrating that shallow wells in high infiltration soils sited in areas where there is significant nitrogen surface loading are at the highest risk of nitrate contamination (Spalding and Exner, 1993; Spalding, 2001; Litke, 2001; Exner, 2014; Nolan et al., 2014; Davis et al., 2015; Wheeler et al., 2015; Garcia et al., 2017). At the scale of this modeling, point source impacts from nitrate were less influential to the nitrate risk of a given private domestic well than expected. However, it is nearly certain that variable aggregation, missing point source data, and data coverage issues play a large role in muting the signal from these sources. This modeling does not support the assertion that point sources do not impact nitrate levels in private domestic wells. Until recent decades, OWT systems like septic tanks were not permitted by the state or tracked. Like private domestic wells, there are likely thousands of unregistered OWT systems. Livestock operations data used to train the model only covers facilities regulated by Title 130, and as such is not a complete record of animal operations in the state. Smaller facilities, which are not permitted, are not included in the AFO data used to train the model. Livestock watering-well data may partially capture these facilities but is a proxy measure. Animal units, a common measure to generalize livestock counts across species, could be incorporated into future modeling to better reflect the size differences between operations, which directly impacts the loading rate.

Livestock operation density, nearby onsite treatment systems, and municipal boundaries were all significant factors, but were not as strongly predictive as crop variables or well location. The significance of well location to nitrate predictions is unsurprising, considering areas like the Upper Elkhorn River Basin have reported elevated nitrate concentrations since at least the 1970s (Spalding and Engberg, 1978), and increasing concentrations have been reported across the state as far back as 1930 (Litke, 2001; McMahon et al., 2007). Location reflects history, and the legacy nature of the nitrate issue in Nebraska. Location is also reflective of local geology and site conditions that likely boost its significance as a factor.

Future modeling efforts could better incorporate additional point source datasets which may more fully capture these impacts. Limited data on unregistered facilities discussed above, or facilities that do not require permitting, are likely reducing the impact of point source data in the model. This data gap could also be a contributor to the relatively high false negative rate (45%) of the GBM-MCL model. Data on release assessments and storage facilities for nitrogen precursors such as ammonia and fertilizer tier two facilities regulated by NDEE could be incorporated into future modeling efforts and may more completely capture the potential sources around each well.

Since 2010, an additional million acres of corn have been cultivated in the state and there is evidence that trends in fertilizer efficiency have plateaued (Ferguson, 2024). Future modeling could incorporate more classes from the CDL and explore other years to see what potential differences may arise in the data. Fertilizer and irrigation vary based on crop, and it is possible additional classes would improve the modeling. Across the state, the time it takes for this surface loading to reach groundwater varies from years to decades (Wells et al., 2018; Malakar et al., 2023). Future modeling efforts could better address the differences in transport time by broadly grouping wells based on soil characteristics as in Exner 2014. Another option would be to model wells in distinct groundwater regions, such as major aquifer units delineated by USGS or UNL CSD.

At time of the analysis – the public Clearinghouse for nitrate sample data does not have a complete sample record for the years 2020 to 2023. These models should be re-evaluated and trained when that data becomes available. BRTs, like other machine learning methods, benefit from large datasets (Breiman et al., 1984). While it is not expected that these data would change the variable influence or conclusions of this report, they would likely improve accuracy by virtue of providing more class examples to train models.

Well construction information was not available for all nitrate samples included in the analysis. While BRTs are robust to missing data, the variable influence is strongly impacted by missing values as seen in the discussion section. Future modeling could incorporate more of this well data. Variables representing meteorological factors, such as average annual precipitation, soil geochemical variables, and vadose zone transport rates have been valuable to other studies predicting water quality in domestic wells (Wheeler et al., 2015, Lombard et al., 2021). Additional SSURGO variables that could benefit the models include available water capacity, clay, sand, and silt content, soil organic matter, hydrologic group, drainage class, depth to bedrock geology, water table depths, conductivity, and pH value. Further work should incorporate this data into predicting nitrate levels in Nebraska. Annual precipitation data could come from the High Plains Regional Climate Center or NOAA. These data would improve model results and in turn the efficacy of the internal NDEE GIS tool.

Groundwater elevation was another variable not directly included in the model. However, variables such as well depth, static water level, pumping water level, and ½ the screened interval depth, indirectly capture the groundwater elevation. A groundwater elevation product, based on the regional groundwater models managed by NDNR, was developed as a part of the water quality study. Future modeling could incorporate this product directly. A more up-to-date accounting of fertilizer application rates and land-application sites could improve future modeling results. The Lower Loup Natural Resources District produced a GIS product that linked

Confined Animal Feed Operations (CAFOs) to their land application sites as permitted by NDEE. NDEE could explore developing a statewide product which could improve modeling efforts and management.

Vertical flow rates within each aquifer are influential to the stratification of nitrate concentrations in groundwater (Snow and Miller, 2018; Malakar et al., 2023). Transport rates could be derived from each of the regional groundwater models (as they are updated and improved) and have been valuable to other modeling efforts like Nolan 2015. As a model input, vertical transport rate through the aquifer would more directly capture the varying timescales it takes for nitrate to reach deeper groundwater across the state. Another option to reflect the varying transport rates would be group wells by hydrologic region or by aquifer and train regional models. This should be explored when the BRTs from this study are updated as additional data becomes available.

The state should consider developing regional groundwater models that incorporate a nitrogen cycle balance such as the one proposed by Garcia et al. (2019), using the coupled Community Multiscale Air Quality Bidirectional modeling system developed by USEPA and USDA Environmental Policy Integrated Climate (EPIC) agroecosystem model (Pleim and Ran, 2023). Such a system would allow for a much more detailed accounting of nitrogen at the surface for management efforts. This could help target efforts to lower concentrations in areas where groundwater is a primary source of drinking water.

Model accuracy is generally highest where there is more available data, such as in the river valleys and northeastern portions of the state. In areas with fewer nitrate samples, there are relatively fewer class examples to train the model on those locally relevant variables. The next section discusses recommendations for how model results should be incorporated into the internal NDEE GIS tool.

Determining Threshold Values and Risk Level

Based on the model performance, it is recommended to incorporate the results into the internal NDEE risk assessment GIS tool, with important caveats about the limits of these predictions. Each factor in the GIS tool is assigned points which are added together to determine an overall risk index. More points correspond with a higher risk. Recommended threshold values for incorporating the model into the tool are show in in Table 8. Points were assigned to the threshold values shown in Table 9 based on how model predictions relate to potential nitrate risk. Each model predicts where nitrate concentrations are likely to exceed the values in the table, and points are assigned based on each prediction. Threshold values reported in table 9 were determined based on: literature, model performance review, data from the free private domestic well sampling effort, and quality assurance procedures conducted by NDEE and project partners. As more data become available, the BRTs in this report should be updated and using the recommendations provided in the previous section. Updated models could improve the gridded surfaces in the GIS tool and reduce false negative rates.

Table 8. Threshold Values for the Predictive Nitrate Model Results Incorporated into the GIS Risk-Assessment Tool.

Predicted Nitrate Concentration Range (mg/L)	Points Assigned	Minimum Probability Predicted	Description
<3 mg/L	0	0.00	If the model predicts the input location has a probability of 0.25 or less of exceeding the MCL, a probability of 0.35 or less of exceeding 5 mg/L, and a probability of 0.45 or less of exceeding 3 mg/L, then the tool assigns zero points for this indicator. Language is provided to the user based on the model; it is likely that the nitrate level in their well is below background (less than 3 mg/L).
>3 mg/L	1	0.45	If the model predicts the input location has a probability of 0.25 or less of exceeding the MCL, a probability of 0.35 or less of exceeding 5 mg/L, but a probability greater than 0.45 of exceeding 3 mg/L, then the tool assigns one point for this

Predicted Nitrate Concentration Range (mg/L)	Points Assigned	Minimum Probability Predicted	Description
			indicator. Language is provided to the user that based on the model, it is likely that the nitrate level in their well is above background but below elevated (between 3 and 5 mg/L).
>5 mg/L	2	0.35	If the model predicts the input location has a probability of 0.25 or less of exceeding the MCL, but a probability greater than 0.35 of exceeding 5 mg/L, then the tool assigns two points for this indicator. Language is provided to the user that based on the model, it is likely that the nitrate level in their well is elevated (between 5 and 10 mg/L).
> 10 mg/L	3	0.25	If the model predicts the input location has a probability greater than 0.25 of exceeding the MCL, then the tool assigns the maximum number of points (three) for this indicator. In the GIS tool, language is provided to the user that based on the model, it is likely that nitrate level in their well exceeds the MCL (10 mg/L).

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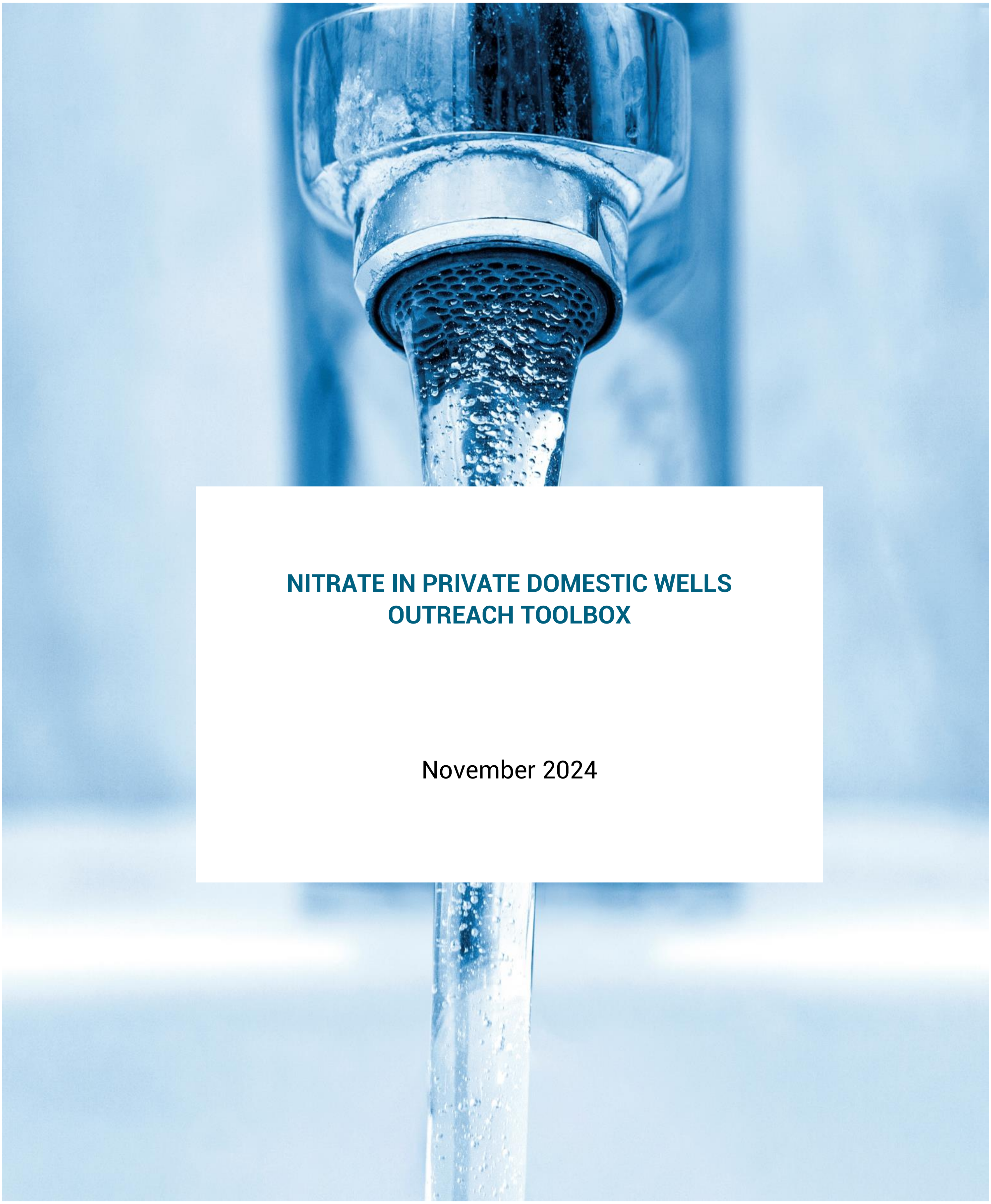
Appendix D – Nitrate in Private Domestic Wells Outreach Toolbox



NITRATE IN PRIVATE DOMESTIC WELLS OUTREACH TOOLBOX

November 2024

NEBRASKA

DEPT. OF ENVIRONMENT AND ENERGY

Table of Contents

List of Figures

Appendices

EXECUTIVE SUMMARY

This Nitrate in Private Domestic Wells Outreach Toolbox covers background information related to nitrate in groundwater in Nebraska. It also includes information related to past, current, and future efforts to address drinking water quality nitrate problems for private domestic well owners. While the Nebraska Department of Environment and Energy (NDEE) is the lead conjoiner of the effort to produce this toolbox, it must be emphasized that other agencies such as the Natural Resource Districts (NRDs), University of Nebraska (e.g. Nebraska Extension, Nebraska Water Center, and University of Nebraska Medical Center- Climate and Health Program), and state and local public health departments, have been facilitating many education and outreach efforts for the public related to water sampling, testing, and potential solutions in order to mitigate potential acute and chronic health implications related to high nitrate levels in private domestic wells. Therefore, this preliminary outreach toolbox is a first step in an ongoing process to compile as much information related to these efforts as possible to assist the public and various stakeholders in the essential first step resources to help address the nitrate issue both locally and personally. The full list of resources by agency and applicable topic are in the Appendix of this outreach toolbox document.

One of the objectives of the water quality study was to develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies. The water quality study accomplished the following tasks associated with this objective:

> NDEE and its partners developed an outreach toolbox and identified private domestic well owners, the medical community, well drillers, septic system installers, realtors, and mortgage lenders as target audiences to promote awareness of nitrate issues in private domestic drinking water supplies. This toolbox can be used by NDEE and its project partners to help deliver consistent messaging related to nitrate in drinking water.

Key recommendations for future nitrate related outreach in private domestic drinking water include:

- NDEE and its partners should continue to develop and refine risk communication resources developed during the study to provide a clear, unified message on nitrate in drinking water. As funding allows, NDEE and its partners could continue private well sampling and treatment programs. Coordination with partner agencies could improve the visibility of these programs for private domestic well owners.
- Continue work to increase private domestic well testing.
- Create a database of unregistered well locations and owner contact information by implementing the methodology discussed in the Outreach Toolbox. This would allow for direct and more cost-effective outreach to unregistered well owners.
- Increase well registrations by reducing obstacles for registration. This could potentially include temporarily waiving the fee for the registration of old wells that predated the well registration requirement (pre-1993). Additionally, creating a simplified registration form for old wells or modifying the existing form may help avoid discouraging owners from registering wells due to lack of detailed information currently required to register a well.

1.0 PURPOSE, SCOPE, AND BACKGROUND

During the 2023 legislative session, the Nebraska Legislature, at the request of Governor Jim Pillen, appropriated funding for the Nebraska Department of Environment and Energy (NDEE) to conduct a statewide water quality study (LB 814). The overall goal of the water quality study is to provide an analysis and recommend viable solutions for nitrate-affected drinking water, including drinking water not regulated by the Safe Drinking Water Act (SDWA) (i.e. private domestic wells). This outreach toolbox fulfills the study objective to develop a risk communication-based outreach toolbox that NDEE and other partners can use to promote awareness of nitrate in private domestic drinking water supplies.

The outreach toolbox must identify the target audience(s) impacted by nitrate-affected groundwater used for drinking water, provide methods to reach them, and resources for current and future outreach partners to use. The resources must be engaging and provide related background/summary information on the concerns with drinking nitrate-affected water. The toolbox must also have specific recommendations for proactively reaching the target audiences, risk communication-based options and templates for engaging with the target audience and contact information for NDEE and others if they choose to contact representatives from local, county, state, and/or federal environmental and health related departments/agencies.

Nitrate (NO_3^-) is a compound that occurs naturally and has many anthropogenic sources. Nitrate is in some lakes, rivers, and groundwater in Nebraska. Because nitrate is highly soluble, contamination occurs primarily through leaching of nitrate-nitrogen through the soil profile. Primary sources of organic nitrate include human sewage and livestock manure. The primary source of inorganic nitrate is agricultural and domestic fertilizer. Protection of groundwater sources from leaching nitrate is a complex issue because leaching depends on several factors including precipitation amount and timing, soil type and depth, biological fixation of nitrate, and uptake rates and timing of nitrate by plants (Shaver, 2014).

Of the approximately 1,960,000 people (about twice the population of South Dakota) living in Nebraska, over 1,600,000 Nebraskans are served their drinking water by community water systems (CWS), including rural water districts (RWDs), leaving an estimated 360,000 Nebraskans that rely on private domestic wells for their drinking water supply (NDEE, 2023). Before September 1993, private domestic wells were not required to be registered with Nebraska. Since then, private domestic wells have been required to be registered and are listed in the Nebraska Department of Natural Resources (NDNR) Registered Well Database. The NDNR Registered Well Database listed over 34,600 active private domestic wells in the state as of November 2023. NDEE has estimated there are approximately 145,000 private domestic wells across the state, meaning over 110,000 private domestic wells are unregistered (2023).

Addressing water quality concerns regarding nitrate contamination in groundwater used for drinking water must be a collaborative and iterative process that involves public and private entities, spanning across all sectors because drinking water quality affects more than just environmental quality, it affects public health and economies at various scales. Therefore, this outreach toolbox seeks to unify the entities already working across Nebraska to inform, manage, and address water quality concerns regarding nitrate contamination in drinking water as well as to identify the challenges in providing effective outreach to the owners of registered and unregistered private domestic wells. Locally, there may be other drinking water quality concerns, but this effort is focused solely on nitrate.

1.1 Existing Partners, Resources, and Ongoing Outreach

There are multiple entities and resources that are working to inform the public, specifically private domestic well owners, about the causes, threats, and actions to take when facing nitrate contamination in groundwater used for drinking water. One outcome of this outreach toolbox is to identify those partners and existing resources available to the public.

1.1.1 NDEE

NDEE is the lead agency behind the development of the statewide water quality study and subsequential risk assessment and outreach tools. NDEE is also one of the leading governing bodies regarding surface water and groundwater quality in the State of Nebraska and regularly provides education and outreach to the public. That said, this toolbox's intent is to summarize available resources that NDEE and its partners can use for outreach related to nitrate in drinking water, specifically private domestic wells. NDEE has some existing resources tailored for outreach to private domestic well owners and has developed new resources as part of the water quality study such as a "Nitrate in Drinking Water Fact Sheet" with input from several project partners. These resources will be coupled with the outreach materials that NDEE's partners have available to present a unified and consistent message using risk-communication techniques to present the information on what nitrate is, why knowing exposure to high concentrations is important, and what a well owner can do to address these issues. Resources such as a "Nitrate in Drinking Water Fact Sheet" and information related to "Nitrate Test Kits and Treatment Units" can be found in Appendix A.

1.1.2 Natural Resources Districts

Nebraska's 23 Natural Resources Districts (NRDs) were established to provide locally led management of resource concerns. The Nebraska Legislature has identified 12 areas of responsibilities for the NRDs with programs and priorities then being established by a locally elected board of directors. This unique resource management approach has been tailored to match Nebraska's climatic, geologic, soil type, topographical, land use and hydrologic variation. Regarding groundwater quality, each NRD has developed a State-approved management plan that lays out the process for monitoring and evaluation of groundwater in a region and the steps to be taken to address declines in quantity or quality. As a result of this process, the Nebraska Legislature has found that Nebraska NRDs have the legal authority to regulate certain activities and, as local entities, are the preferred regulators of activities which may contribute to groundwater contamination in both urban and rural areas. Additionally, the Legislature has found that the powers given to the NRDs and the NDEE should be used to stabilize, reduce, and prevent the increase or spread of groundwater contamination.

As stated above, the unique nature of Nebraska allows for cropping practices and types that include corn, soybeans, alfalfa, wheat, dry edible beans, sorghum, sugar beets, potatoes, and others. In some areas, production requires supplemental irrigation where precipitation may not consistently meet the targeted crop's needs.

Annual monitoring and assessment are conducted to track groundwater quality conditions within each district to identify concerns. When concerns are detected, NRDs will delineate control areas and initiate regulatory actions. While areas of nitrate contamination have been identified, not all groundwater supplies are a health concern.

While similarities do exist in each NRD's management approach, the difference from district to district requires that management be tailored for the local conditions, and, therefore, a one-size-fits-all nitrate management approach is not practical. Each NRD provides information where patrons can navigate through and find out more information on groundwater monitoring, assessment, regulatory and cost share programs.

To find out more about your NRD go to www.nrdnet.org/nrds/find-your-nrd.

1.1.3 University of Nebraska

The University of Nebraska (NU) system is at the forefront of research and education on the nitrate contamination issue facing the State of Nebraska. Many entities and partners are nested under the NU umbrella. The roles and resources of each of those entities are described below. NDEE worked with two liaisons from the NU system who were on the Advisory Group for this project and helped provide information about existing resources available under the NU umbrella.

1.1.3.1 Nebraska Extension

Nebraska Extension is an organization that aims to strengthen Nebraska's agriculture and food systems, provide outreach to Nebraskans and their communities, and enhance the health and wellbeing of all Nebraskans with the resources, research, and innovation of the University of Nebraska. One of Nebraska Extension's primary focus areas is "Water and Cropping Systems". Extension employees who work within the Water and Cropping Systems focus area aim to assist all Nebraskans with issues related to water and crops, including drinking water quality, nitrate, and nitrogen fertilizer applications. Extension employees are in every county throughout the entire state, giving them the opportunity to build strong relationships with the people they serve. Nebraska Extension is closely aligned with outreach as a primary driver of operations, thus their involvement as a partner in outreach to private domestic well owners are paramount. A few resources available through Nebraska Extension that would be most pertinent to this outreach toolbox include various extension/education documents, also known as "NebGuides", a "Water Quality Network Mapping Resource" and a recent 2024 YouTube Video dedicated to private domestic well owners in Nebraska can be found in Appendix A.

Lastly, below (Figure 1) is a link and map version to the directory of all Extension employees who work within water and crops.

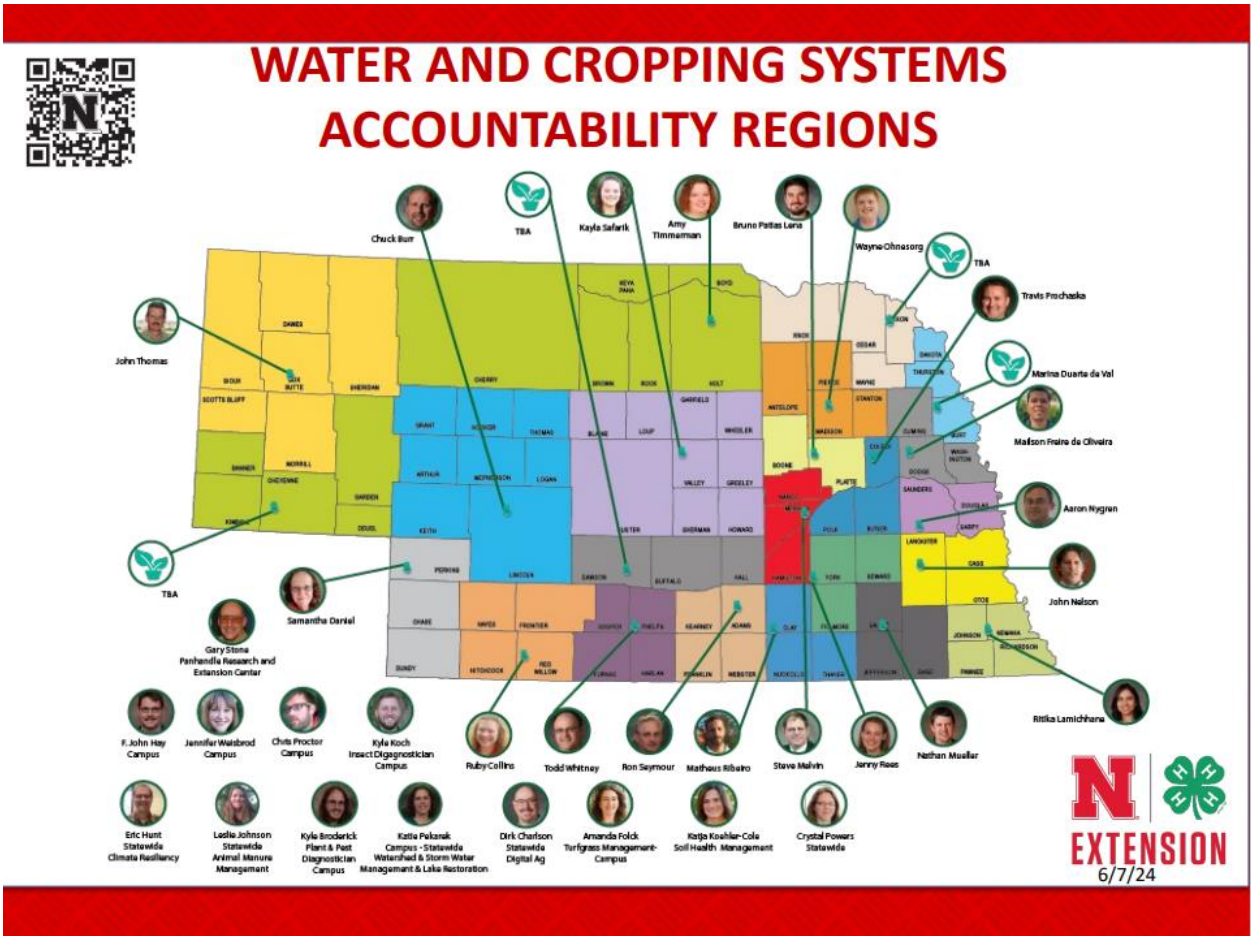


Figure 1. Extension Employee Map. https://epd.unl.edu/program-area/water-integrated-cropping-systems.

Additionally, Extension provides information called "CropWatch" which is a central resource that houses an article relating to crops, water, and pests. CropWatch | University of Nebraska–Lincoln (unl.edu)

1.1.3.2 University of Nebraska Medical Center

The University of Nebraska Medical Center (UNMC) is one of four campuses in the NU system and stands as the only public academic health science center in the state. UNMC plays a crucial role in educational outreach and engagement, leveraging its strong public relationships and integrating cutting-edge research.

Nitrate concentrations in drinking water are regulated to protect infants from methemoglobinemia (blue baby syndrome), but research suggests that ingestion of nitrate in drinking water may have other adverse health effects on both adults and children (Ward et al., 2018). Because of this, having a strong partnership with the UNMC adds credibility to the public health dimension of the outreach described in this toolbox. UNMC's deep ties with Nebraska Medicine, Children's Hospital, the Buffet Cancer Center, and the Water, Climate, and Health Program amplify its impact on public health outreach.

Nebraska Medicine and Children's Hospital, as clinical partners, bridge research with patient care, enhancing the credibility and effectiveness of public health initiatives. The Buffet Cancer Center's pioneering work in cancer research and treatment offers vital resources for community health education. UNMC's Water, Climate, and Health Program, located within the College of Public Health, conducts interdisciplinary research and disseminates information on environmental issues related to water and health.

1.1.3.3 Nebraska Water Center

The Nebraska Water Center and its Water Sciences Laboratory are part of the Daughtery Water for Food Global Institute at the University of Nebraska. The Nebraska Water Center is a water research institution that focuses on helping the University of Nebraska become an international leader in water research, teaching, extension, and outreach. The Water Sciences Laboratory is an incredible resource for private domestic well owners as it provides additional academic resources and a resource for these well owners to test their drinking water for contaminants. A few resources available through the Nebraska Water Center that are most pertinent to this outreach toolbox are located in Appendix A and include a "Nitrogen Timeline" and "Water Facts" informational flyer.

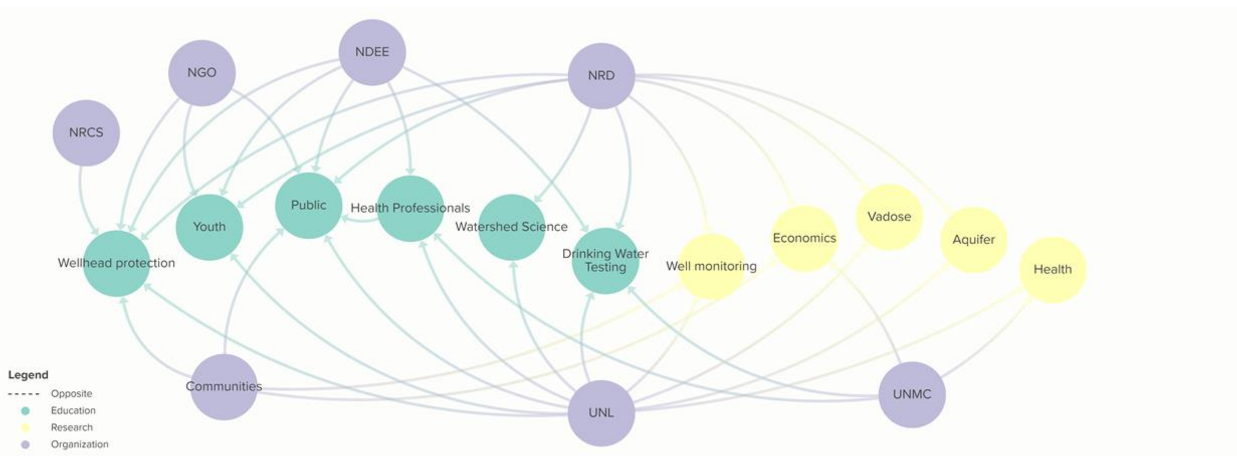


Figure 2. Nebraska Nitrate Network • nitrate related programs / Topic • Kumu (created by UNL Water Center).

Figure 2 displays an ongoing effort to map who is doing what in Nebraska regarding water work, specifically drinking water. Network mapping is a way to visualize the connections in complex systems. With the number of academic, governmental, private, and non-governmental organization (NGO) partners involved in education, research, and incentive programs to help address nitrate, the Water Center wanted to visualize the network. This map includes the high-level categories specific to nitrate in drinking water. A project level map is under development: https://kumu.io/crystalwater/nebraska-nitrate-network.

If you have projects you want to add to the map, please contact the Nebraska Water Center.

Isotope analysis, in combination with other water quality indicators, can help identify sources of nitrate in groundwater. Ratios of nitrogen and oxygen isotopes vary between sources of nitrogen. Figure 3, from Kendall (2008), plots the relative ranges of isotope ratios from common environmental sources of nitrogen. Analyzing the ratio of isotopes allows organic and inorganic sources of nitrogen to be identified and, in turn, informs us more about potential sources impacting a specific well. Isotope testing is a valuable tool in determining the source of the nitrate impacts.

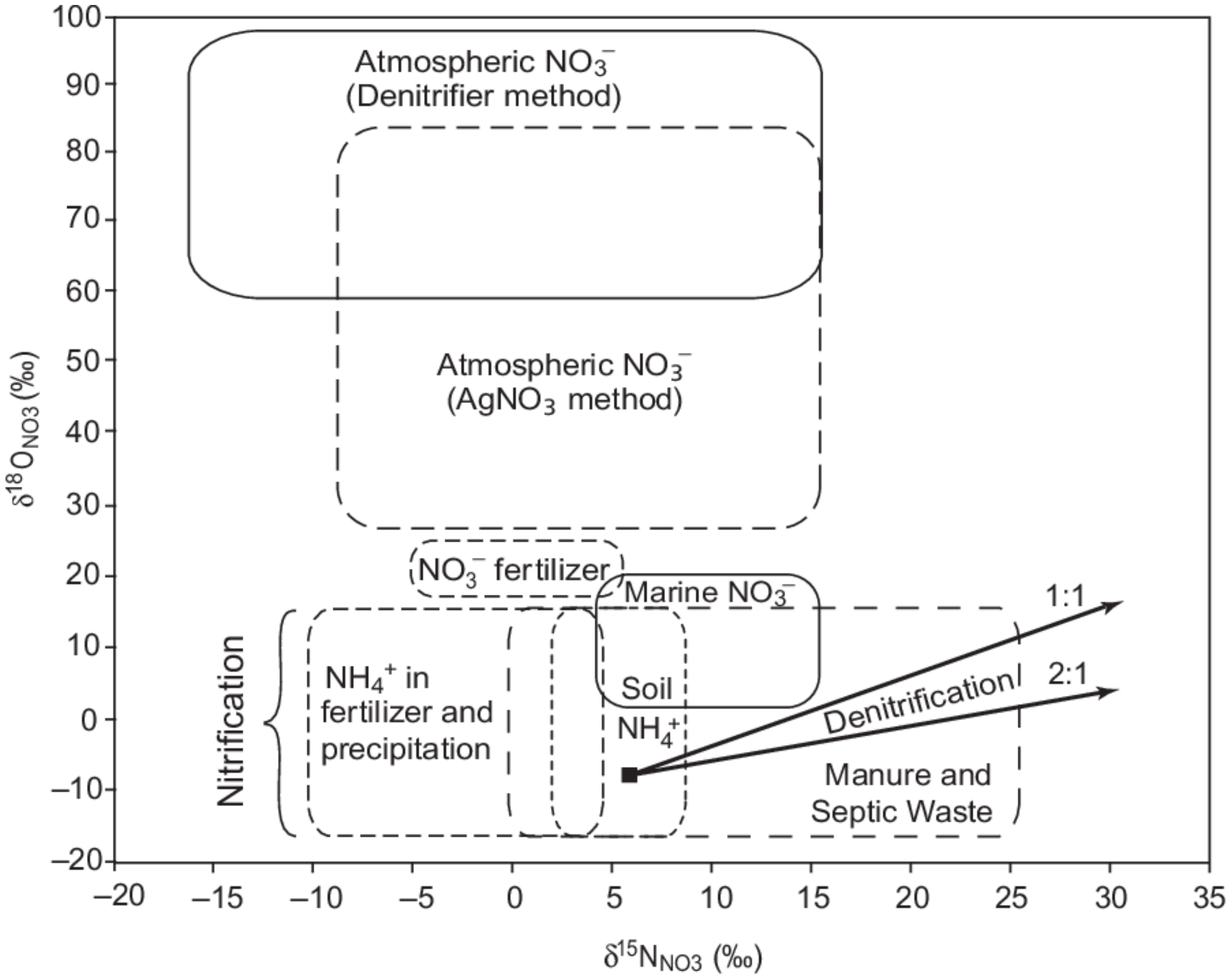


Figure 3. Nitrate Isotope Ratios by Source Type (Kendall, 2008).

1.1.4 NDHHS Public Health Environmental Lab

The Nebraska Department of Health and Human Services (NDHHS) Public Health Environmental Lab can supply nitrate test kits with instructions for the well owner to collect and return the sample for analysis. The NDHHS Lab generally calls customers if their nitrate result is over 10 mg/L to educate them about the health risks associated with drinking water with a nitrate concentration above the MCL. The NDHHS Public Health Environmental Lab is an important partner in nitrate outreach since they provide test kits and follow-up information, and often have direct communication with both registered and unregistered private domestic well owners.

1.1.5 Local Health Departments

Local Health Departments (LHDs) play an important role in raising awareness for the connection between drinking water quality and adverse health effects. To engage with the owners of private domestic wells, LHDs provide a valuable avenue to reach the primary audience. All LHDs are working on water quality, primarily focusing on encouraging private domestic well testing. Many are collaborating with NRDs in their efforts. One thing to keep in mind is that LHDs typically have different community connections than NRDs, such as with the medical community, hospitals, and underserved populations. Therefore, a continued partnership with the LHDs is very important in addressing nitrate in private domestic wells. Additionally, by partnering with

LHDs, the research and expertise of other partners like UNMC can provide guidance to these LHDs to proactively address these public health concerns, have more informed diagnoses, and provide specific guidance on addressing the public health component of drinking water quality concerns.

Some current resources include efforts by the North Central District Health Department, the Upper Elkhorn NRD, and the Lower Niobrara NRD who invited NDEE to help with a radio show in February 2024. NDEE provided them with information about the free nitrate test kits and the reverse osmosis rebate program to share during the radio show. A recording of this show is included in Appendix A. Also, as part of Appendix A, is a list of LHD contacts that can help clients who are concerned about their private domestic well drinking water quality.

1.1.6 Nebraska Department of Natural Resources

The NDNR and the NRDs are responsible for surface water and groundwater integrated management planning. The NDNR is responsible for well registrations in the state and maintains the Registered Well Database. They provided NDEE the list of mailing addresses for all registered well owners that was used to mail out the postcards as part of the free nitrate test kit effort. Because of this, they are an important partner in communicating with registered well owners. Additionally, since they manage all well registrations in the state, any potential changes in registration processes to help facilitate well registration must be done in coordination with them.

1.2 Existing Challenges

There are many existing challenges in the effort to engage and provide outreach to the owners of the estimated 110,000 unregistered private domestic wells and the 34,600 registered private domestic wells in the state. The following list of challenges is not exhaustive, but it does include a few of the principal challenges expected to be encountered during engagement of the target audiences.

1.2.1 Effective Communication Channels

The principal difficulty in outreach to the owners of private, unregistered domestic wells is the absence of any of these wells or owners being listed within the NDNR Registered Well Database. Due to this, there is no clear way to locate, contact, and inform these individuals of drinking water quality concerns regarding nitrate contamination. Many challenges facing this effort stem from the inability to effectively communicate with these well owners. Options exist for tracking these well locations such as the creation of a statewide unregistered well database or providing an opportunity for these wells to be registered in a simplified manner to help encourage the adoption of registration. However, to complicate the matter further, the parcel owner listed with the local county assessor’s office for a specific parcel does not necessitate the owner of the well on a parcel to be identical to the listed parcel owner’s name. Thus, directly contacting an unregistered private domestic well owner becomes even less feasible as there may be no way to digitally connect a potential unregistered private domestic well location to a specific individual. Thus, other avenues of engagement will be needed to reach the target audience aside from direct communication with the owners of these unregistered private domestic wells. Direct communication channels exist for private domestic wells registered with NDNR and listed in the Registered Well Database. When available, this channel could be and has been used. Outreach partners must understand and work to mitigate the difference in the effectiveness of communication between those with registered and unregistered private domestic wells.

1.2.2 Consistent Messaging

One issue in addressing a problem as complex as nitrate-affected groundwater used for drinking water is that each of the entities affected by nitrate contamination has their own mission, goals, and vision, as well as authority and messaging regarding the situation. NDEE is working with its partners to create consistent messaging, informed by risk-communication techniques that will provide information, solutions, and resources to owners of private domestic wells and other key stakeholders. The messages will be crafted as a coordinated and collective message from all the partners involved and create a unified stance for entities across the state to refer to when they work to address the complex issue of nitrate-affected groundwater used for drinking water.

1.2.3 Well Registration

As discussed in Section 1.0, there are an estimated 110,000 unregistered wells in Nebraska. Relative to outreach methods, this means the owners, locations and contact information are unknown which is a significant limiting factor in communicating risk to an unregistered well owner. Although having these wells registered allows for a more direct line of communication, the engagement with these individuals must transcend simply asking the unregistered private domestic well owners to register their wells. Nevertheless, providing outreach to private domestic well owners about nitrate in drinking water also provides an opportunity for NDEE and its partners to educate private domestic well owners about the benefits of registering their well. For example, if there is no formal documentation of the presence of a well in the NDNR Registered Well Database, the State is unable to protect the well when evaluating setbacks for a wastewater construction or onsite septic system permit or land application of wastewater. Additionally, any other entity, such as a well driller or septic system installer, that does a desktop review to ensure they meet well setback distances will only be aware of the presence of registered wells. The benefits of well registration and guidance on the process of well registration, although not the main priority of this outreach toolbox, is still an important message for NDEE and its partners to communicate. The benefits of registering a well extend beyond those issues associated with nitrate.

1.2.4 Cost to Target Audience

Many of the recommendations provided to the owners of private domestic wells come at some cost to the owner, and depending on the recommendation, sometimes a significant cost. One difficulty NDEE has already faced and will continue to face is apprehension to changes in private domestic well management purely from a cost-aversion stance. NDEE and its partners should strive to provide clear estimates of cost to the private domestic well owners for each of the different recommendations for addressing nitrate contamination in drinking water and, equally important, cost-share opportunities for these recommendations. NDEE and its partners occasionally have limited funding available through programs, grants, and funding sources that provide some level of financial support to private domestic well owners, but many individuals are not as aware of these financial assistance programs as those in the agencies that provide them. Pointing individuals to financial assistance opportunities, when available, will work to overcome the cost-aversion that could prevent a private domestic well owner from testing, treating, or protecting their drinking water.

1.3 Important Feedback from 2024 Well Testing

From November 29, 2023, through March 1, 2024, NDEE offered free nitrate test kits to all private domestic well owners in Nebraska regardless of well registration status. Over 29,000 postcards advertising the free kits were mailed out to all registered private domestic well owners in the state. Although there are more than 34,000 active registered domestic wells, some owners have multiple wells registered to the same mailing address. Press releases were published by Nebraska news outlets to encourage private domestic well owners to have their well tested (See Appendix A). As of May 1, 2024, 4,508 sample kits were requested, and 3,499 were returned to the NDHHS Public Health Environmental Lab for analysis. Figure 4 shows the ranges of nitrate concentrations, and the locations of wells tested during this sampling effort. As of May 2024, NDEE had called 13.7% of well owners that opted to test their wells or over 480 well owners with a nitrate level above 10 mg/L. NDEE fielded over 2,500 calls related to the free nitrate test kit effort (Figure 5). During these calls, NDEE and NRDs helped many private domestic well owners with the well registration process and the application process for the reverse osmosis rebate program. NDEE also mailed a nitrate brochure out to every well owner that participated in the free sampling effort when their results were mailed out. These phone calls and mailings have provided NDEE an avenue to provide direct, personal outreach to many Nebraskans who were previously unaware of the importance of regularly sampling their well for nitrate or the health risks associated with drinking water with a nitrate level above 10 mg/L.

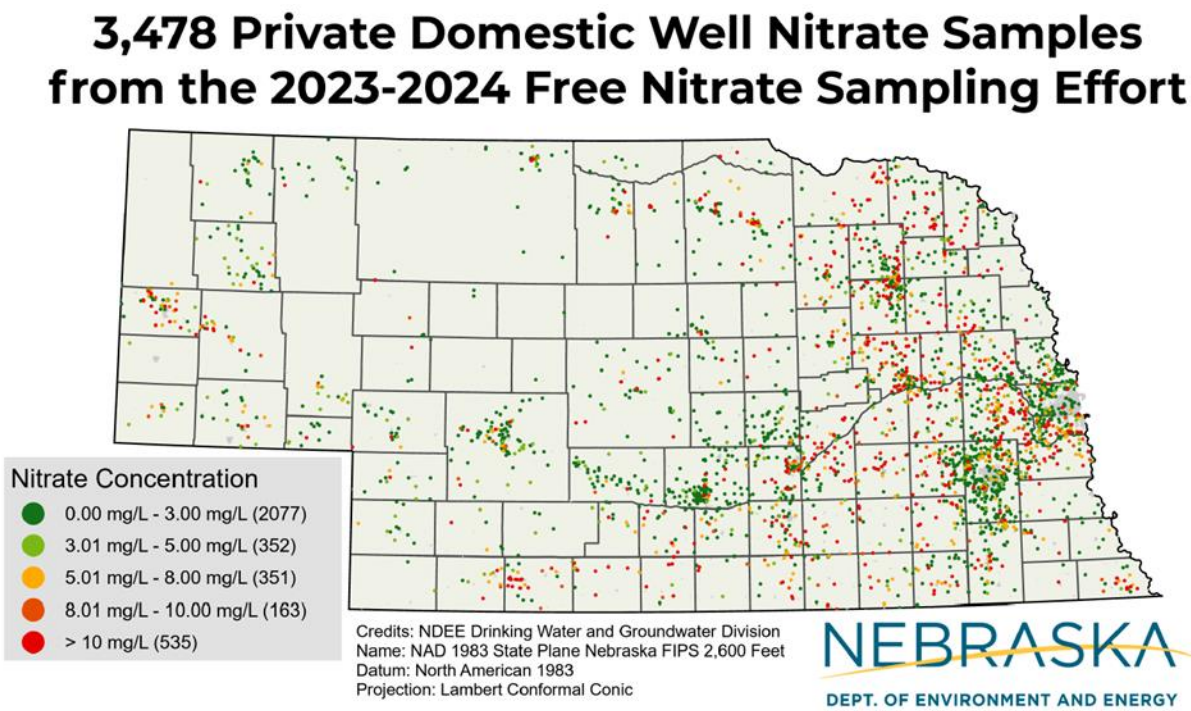


Figure 4. Free Private Domestic Well Sampling Results (as of May 1, 2024).

Figure 5. Number of Overall Calls Regarding the Testing, Results, and Well Registration. Calls received were only tracked formally through March 1, 2024. These total numbers are as of May 2024 and also include calls made by NDEE to private domestic well owners.

The feedback received from the public, lessons learned by NDEE staff engaging with the public, and questions asked by the public have all been incorporated to tailor outreach tools to address these curiosities, fears, and questions and align with providing the target audiences with the information they need. Some of the topics informed by this feedback include explaining sample analysis results to the general public and communicating to a non-scientific community, being able to provide private domestic well owners an immediate recommendation to address high nitrate concentrations in their well, walking individuals through the well registration process, and the necessity for a clear and consistent message from all outreach partners. Appendix A includes the nitrate informational brochure and postcard, various press releases, and other resources related to the sampling effort including sampling instructions and how to interpret the results (both of which are products from NDHHS).

HEALTH QUESTIONS/CONCERNS:

- A caller reported that she recently had an infant that had to stay in the hospital after birth due to hemoglobin issues. They are renters and had not previously tested their drinking water. The nitrate concentration for their well was 19.2 mg/L. The doctors treating the infant never mentioned the possibility of nitrate-contaminated drinking water as a potential cause of the infant's health problems. This same NDEE employee talked to at least two other women that are currently pregnant and have been drinking water over 10 mg/L and were not aware of the risks prior to sampling.
- Many questions about potential health effects in addition to methemoglobinemia or for adults. UNL has resources that these private domestic well owners can be directed to if they want to know more about potential health effects in adults.
- Doctors may not know to talk about nitrate in drinking water or consider nitrate in drinking water as a potential cause of certain health effects.
- Concern regarding how nitrate in drinking water can affect pets and livestock.
- What they can and cannot use high nitrate water for (bathing, washing dishes, etc.)

QUESTIONS/CONCERNS RELATED TO REGISTRATION, TESTING, AND SOLUTIONS:

- Hesitation to connect to a RWD even when the nitrate concentration in their well is above 10 mg/L. Some private domestic well owners indicated they think their well water would be of higher quality than water supplied by the RWD. Others have indicated they prefer to have their own well or like the taste of their well water. For others, connecting to a RWD is cost prohibitive.
- Emotional responses if an immediate solution is not available (treatment or bottled drinking water). It is important to provide recommendations to private domestic well owners, so they know how to properly address a nitrate level above the MCL, such as bottled water for drinking and the installation of an RO unit (or other treatment device) and retesting after installation.
- Hesitation to test wells if not registered due to concerns of getting in trouble. A fear of the government having additional information about their well.
- Questions about what other contaminants they should test for in private domestic wells.
- How to find out if well is registered and how to register a well if it is not registered.
- Questions about what technologies remove nitrate from water. Many wondered if carbon filters or water softeners are effective at removing nitrate from their water, both of which are not.

2.0 TARGET AUDIENCES

The issue of nitrate contamination in drinking water is so vast, outreach could not reasonably be tailored to address every entity affected by the issue. Instead, outreach tools and materials have been specifically designed for the primary audience of homeowners and businesses that have private domestic wells which may be used for drinking water. The toolbox also includes secondary audiences, the larger medical community outside of the UNMC system, licensed well drillers, septic system installers, realtors, and mortgage lenders. The method to engage and desired outcome for each of these audiences differs, consequently this section will outline the method of which to reach each target audience along with the desired outcome for said audience.

2.1 Private Domestic Well Owners

The primary audience is individuals and businesses that have private domestic wells which may be used for drinking water, regardless of well registration. The desired outcomes for this audience are to engage the private domestic well owners so they are aware of the issue of nitrate in the groundwater they rely on for drinking water and inform these owners of the resources available to them regarding the identification of potential localized risks to their well, potential management practices to protect their source water and/or treat their drinking water, and funding sources.

The methodology to reach this population widely varies with the status of a private domestic well's registration. Those who are registered are much simpler to engage as their information is listed in NDNR's Registered Wells Database. These well owners can be contacted in direct communication (i.e. direct mailing) through the information provided to NDNR. Conversely, the owners of unregistered private domestic wells will need to be addressed through indirect channels of communication without the development of a tool to allow for a more direct channel of communication. One method to reach these unregistered private domestic well owners include the education of secondary target audiences with the outlook that these secondary audiences may have direct contact with the unregistered private well owners and would be able to communicate the resources or direct the owners to the resources that have been created or will be created. Additionally, public events such as the State Fair, public meetings, education events at local schools, and broadcasting over local news outlets or radio provide opportunities for these individuals to be engaged.

2.2 Medical Community

UNMC is a partner in the development of this outreach toolbox and is critical in communication to one of the secondary audiences: the larger medical community outside of the NU system. Extending this outreach to the broader medical community is important because drinking water quality has a direct impact on the health of those drinking it. The desired outcomes for the engagement with the larger medical community are to equip and empower LHDs and subsequently local health care providers with the knowledge and resources to have conversations with patients about the importance of drinking water quality and the effects it can have on one's health, as well as be able to identify health issues that may be an outcome of drinking high nitrate water and direct those with water quality issues to the resources available through NDEE and its partners.

To reach this sector, all partners could build on their connection with NDHHS and past work with LHDs as well as encourage partners such as UNMC to supply information to medical professionals through newsletters, education events, and continuing education credits. There are numerous associations for medical professionals that NDEE and other partners have worked with in the past and could utilize to pass along information regarding new resources and tools available and seek to get approval for new continuing education credit opportunities related to nitrate.

2.3 Licensed Well Drillers and Septic System Installers

Licensed well drillers and septic system installers across the state play a crucial role in educating private domestic well owners about how to properly maintain their well, the basics of hydrogeology and groundwater movement, and how contamination of a private domestic well can occur. Most septic systems and private domestic wells are installed in similar areas where individuals are outside of a public water system and are not served by a sanitary sewer, thus these audiences are paired as one because these professionals engage with private domestic well owners in similar fashions. The desired outcome for these professionals is to create and provide resources to assist them with having conversations and passing along materials and tools to private domestic well and septic system owners when these professionals are hired to replace, repair, inspect, or install their respective systems.

To reach these two groups of individuals, NDEE can make direct engagement by utilizing the license numbers of licensed well drillers and septic system installers as both licensure programs reside within NDEE. These professionals must complete continuing education, and NDEE, along with other organizations, provides educational courses, workshops, and conferences. Education materials can be incorporated into these training sessions to help inform owners and minimize potential impacts to private domestic wells. NDEE could also send these individuals direct information through mail and email. Furthermore, there are professional associations that NDEE engages with that could pass information along in a newsletter such as the Nebraska Well Drillers Association.

2.4 Realtors and Mortgage Lenders

Realtors and mortgage lenders are commonly involved with private domestic well owners during property transactions. Additional outreach with realtors and mortgage lenders could increase private domestic well sampling and treatment if warranted and increase awareness of the NDEE Well and Septic Loan Evaluation program (http://dee.ne.gov/NDEQProg.nsf/OnWeb/WSLE). Realtors and mortgage lenders are familiar with radon issues and processes for testing indoor air and mitigation. General awareness outreach efforts to inform realtors and mortgage lenders of nitrate issues faced by Nebraska private domestic well owners could increase well testing, registration, and treatment. Realtor and mortgage lender associations should be targeted for additional indirect outreach and to provide education on available tools and resources.

3.0 LONG-TERM PLANNING AND PREPAREDNESS

Addressing complex issues such as nitrate-affected groundwater used for drinking water must be an iterative and ongoing process, therefore communication with the target audiences mentioned in **Section 2** must also be similarly viewed as a long-term process that continues to evolve as the situation changes, new findings arise, and as progress is made. Establishing an expectation of coordination and a framework for actions that make progress towards the outreach goals will ensure that progress is made, and efforts remain consistent and unified.

3.1 Future Coordination and Management

Although the list of existing partners is significant and casts a wide net regarding sectors involved, there are countless additional partnerships to be developed. These partnerships include furthering the relationship between NDEE, its partners and other organizations that play a role in the use and management of nitrate across all sectors of the economy of the State of Nebraska. This section aims to outline the partnerships that should be developed or enhanced. As UNMC and others continue to research the health implications of nitrate in drinking water, consistent guidance on having conversations about drinking water sources, identifying when water quality concerns are present, and being able to point patients in the direction of resources are all actions local health officials should be empowered to do. Furthermore, incorporating additional programs within the NDHHS, the entity in charge of licensing Health Care Professionals and the program for the prevention of waterborne illnesses, into the list of partners to ensure the messages provided are consistent with the other main partners. Aligning the message coming from separate state agencies would add to the credibility and confidence with which the public may perceive this issue.

The education sector provides excellent opportunities for NDEE to leverage existing relationships such as Nebraska Extension to reach Nebraska's youth and educate young generations on nitrate in drinking water. High schools, middle schools, and elementary schools all offer opportunities for NDEE and its partners to engage with the public, including both students and parents or guardians of students, and inform, educate, and provide resources to this population. For instance, the "Know Your Well" program is a joint citizen science training program that involves mostly high school students on how to sample and test well water quality. This project began in 2017 with up to at least four schools and, to date, has worked with over 30 schools and hundreds of students across Nebraska (https//:knowyourwell.unl.edu).

Two groups of professionals that directly encounter private domestic well owners are well drillers and septic system installers. These two groups of people are pivotal in protecting the drinking water sources; for example, septic system installers can protect drinking water by siting new septic systems downgradient (in terms of groundwater flow) of existing private domestic wells and well drillers by siting new private domestic wells upgradient (in terms of groundwater flow) of existing septic systems. Furthermore, these two groups of people can educate members of the public on proper usage and maintenance of their wells and septic systems. These individuals can be reached by NDEE through their respective license numbers.

Other partnerships to enhance include RWDs and associations, agronomists, and elected officials such as members of the Corn Board or Cattleman's Association. The above list of potential partnerships to develop or enhance is not exhaustive nor should the development of partnerships be limited to this list. Different entities provide various opportunities to engage with the public through different channels and using different mechanisms. The channels, mechanisms, and entities not listed in this toolbox should be considered as viable outreach partners.

3.2 Other Potential Considerations and Activities

Addressing the challenges outlined in **Section 1.2** will require not only future coordination and partnerships between entities, but also the development of tools to close the gap in communication between the partnering entities of this outreach toolbox and the target audiences described in **Section 2**. Some of these tools include the possible creation of a potential unregistered well database. The development of this database could incorporate existing resources such as using Microsoft Building Footprints to identify potential residences anticipated to have private domestic wells while eliminating locations with registered wells.

4.0 OUTREACH IMPLEMENTATION

Engagement and outreach regarding nitrate-affected groundwater used for drinking water has been ongoing, thus, materials and tools developed for this effort are not geared towards pioneering outreach, but to reinforce the ongoing efforts of NDEE's programs and partners and unify efforts under a common message. Implementation of renewed outreach efforts begins with the development of new materials that are tailored to the primary and secondary audiences while carrying the unified message regarding nitrate contamination in drinking water. Figure 6 provides an overview of the numerous agencies contributing to outreach and the target audiences.

4.1 NDEE

NDEE has a multi-faceted team of professionals across the water quality realm. This team was charged with reaching a consensus on what new materials, tools, resources, and steps to develop to meet the objective of the outreach toolbox. All materials and tools follow risk-communication techniques and adhere to the best available science regarding nitrate in drinking water and the implications of such. NDEE staff from various programs will utilize outreach materials through the course of normal business and will identify additional opportunities to collaborate with new and existing partners to conduct outreach to broader audiences.

4.1.1 Nitrate in Drinking Water Fact Sheet

This resource provides a high-level understanding of nitrate in drinking water and was developed to target private domestic well owners. This fact sheet provides background information about nitrate and sources of nitrate; health effects of consuming drinking water contaminated with nitrate; information on prevention, protection, and potential actions for private domestic well owners to take if their drinking water has nitrate concentrations above the 10 mg/L MCL; and additional resources to learn more or contact professionals. This fact sheet should be provided to all private domestic well owners. This fact sheet can be mailed directly to those private domestic well owners in the NDNR Registered Well Database and should be dispersed to the secondary audiences to provide to the public in their storefronts, waiting rooms, or while they are on the job at the site of a private domestic well in an effort to get this resource to unregistered private domestic well owners.

4.1.2 Frequently Asked Questions

The following questions were frequently asked by well owners during calls associated with the free nitrate test kit program, and the resources in Appendix A were compiled and developed to assist in answering these in the future:

Q: ***What could be causing high nitrate in my well?***
A: See the Nitrate in Drinking Water fact sheet for common nitrate sources that may contributing to nitrate in your well, and the isotope testing discussed in Section 2.1.3.3. Isotope testing would need to be completed to determine the specific cause of high nitrate in your well.

Q: ***Are there any other contaminants I should be concerned about in my well water?***
A: Yes, see the Nitrate in Drinking Water fact sheet. There are numerous other contaminants that could be in your well water. The NDHHS laboratory can assist with nitrate analysis and other contaminant analysis. At a minimum, you should test for nitrate and bacteria annually.

Q: ***Are there any health concerns associated with drinking water with a nitrate level above 10 mg/L for adults or just infants?***

A: Yes, see the Nitrate in Drinking Water fact sheet. Adults with certain health conditions may be at a higher risk of developing methemoglobinemia from drinking water with a nitrate level above 10 mg/L. These health conditions include anemia, cardiovascular disease, sepsis, and certain gastric diseases. Additionally, research is ongoing and suggests a link between drinking nitrate-contaminated water and colorectal cancer, thyroid disease, and neural tube defects in adults.

Q: ***How can I address high nitrate in my well?***
A: There are multiple options, see the Nitrate in Drinking Water fact sheet. The quickest and most common option is to install a reverse osmosis, ion exchange or distillation filtration system to remove nitrate from your drinking water. Additionally, you can use bottled water for drinking and cooking.

Q: ***Can my pets/livestock drink my well water with nitrate above 10 mg/L?***
A: See the Nitrate in Drinking Water fact sheet. It is recommended to not allow livestock to drink water with a nitrate level above 100 mg/L. Please consult with your veterinarian if you have concerns about an acceptable nitrate level for pets, such as dogs and cats.

Q: ***I heard that drinking water with high nitrate levels can cause cancer. Can you tell me more about that?***
A: See the Nitrate in Drinking Water fact sheet. This document includes information about potential health effects of drinking water with nitrate above the MCL of 10 mg/L. Additionally, this document includes links from the University of Nebraska-Lincoln with more information about potential health effects.

Q: ***Can I wash dishes or bathe in high nitrate water?***
A: Nitrate does not easily absorb through the skin, so it is safe to use water with nitrate levels above 10 mg/L for bathing and laundry, as long as the water is not swallowed while bathing. Very little water clings to smooth surfaces so washing dishes with water with nitrate levels above 10 mg/L is also acceptable.

Q: ***Will my fridge filter remove nitrate?***
A: No. See the Nitrate in Drinking Water fact sheet for types of treatment processes that will remove nitrate from your water. You should test your water after installation of a treatment process to confirm adequate removal of nitrate. Additionally, treatment systems require ongoing maintenance to remain effective.

Q: ***Will a water distiller remove nitrate?***
A: Yes, see the Nitrate in Drinking Water fact sheet.

Q: ***Why isn't my well registered?***
A: Wells constructed prior to September 1993 were not required to be registered. If you have questions about well registration, please contact the Nebraska Department of Natural Resources.

4.1.3 Predictive Nitrate Model

One goal of the water quality study was to evaluate the relative risk of elevated nitrate concentrations in private domestic wells. To this end, models based on available regional nitrate sample data, well construction, land use trends, soils, and geology were developed to estimate the probability that nitrate concentrations across Nebraska will exceed threshold concentrations. Model predictions were used to estimate a low, medium, or high-risk level and supplement the GIS tool for use by NDEE and key partners, which is described in the following section. Figure 5 maps these results, where green and yellow areas represent low to medium risk and orange and red areas represent medium to high risk. It is important to note these are estimated probabilities and not field-confirmed data. Although outreach should occur throughout the state, these model results help target higher risk areas for nitrate where outreach implementation is particularly important.

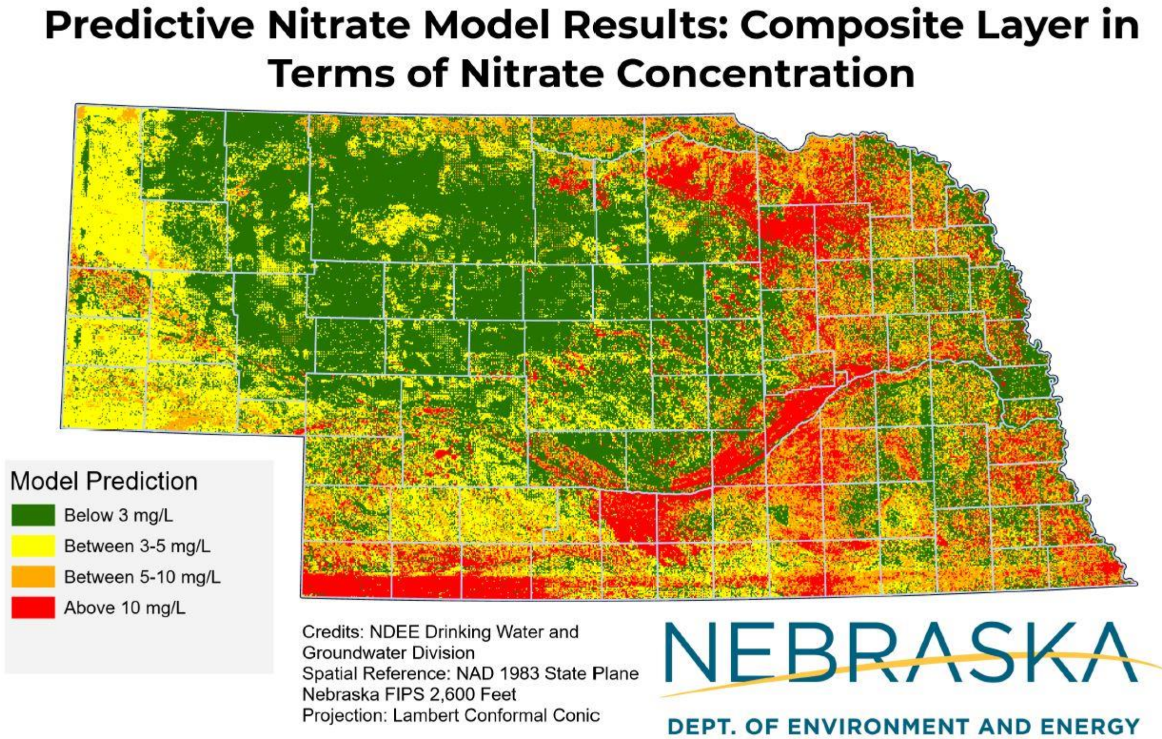


Figure 6. Predictive Model Risk Levels. Green and yellow areas represent low to medium risk and orange and red areas represent medium to high risk.

4.1.4 Geographic Information System Groundwater Tool

NDEE and project partners coordinated during the study to develop an interactive, online GIS risk assessment tool for use by NDEE or agency partners. Users of the tool can enter the address of a well or drop a pin on the map at a well location. Then, the tool queries available information for the well location and calculates a risk index for that point. There are four different indicators included in the tool to calculate the overall risk index: predictive model results, nearby nitrate sample results, possible nearby sources of nitrate, and estimated depth to groundwater. A personalized report is created for the user detailing the overall risk for that point.

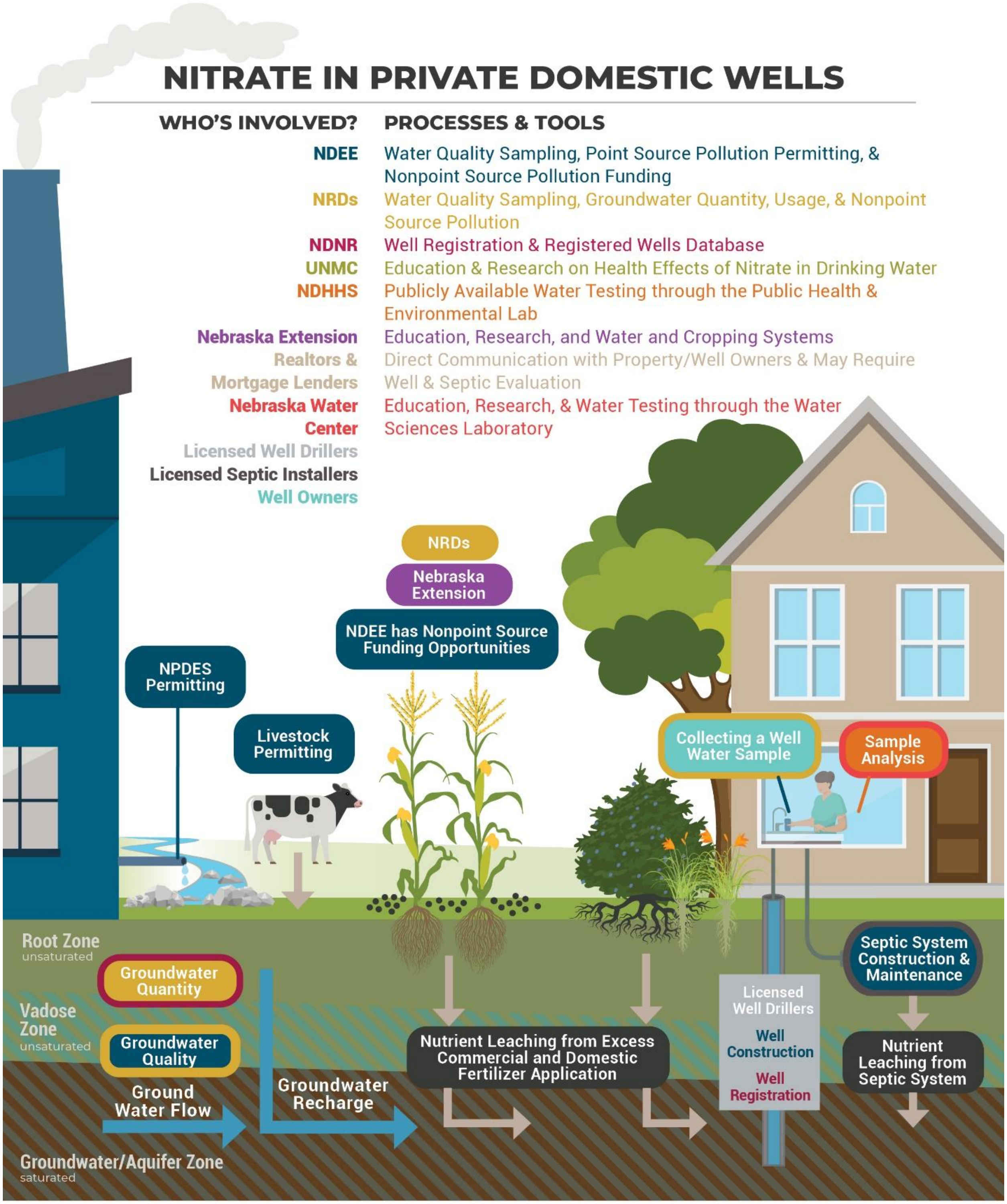


Figure 7. Nitrate in Private Domestic Wells – Outreach Agencies and Target Audiences

5.0 CONCLUSIONS AND RECOMMENDATIONS

The effort to address nitrate-affected groundwater used for drinking water is a continuous, statewide, multi-faceted, and multi-agency endeavor. Outreach tools and materials compiled and developed out of the nitrate study are available (Appendix A) to partners to adopt and apply locally in the context of their sphere of influence. This outreach effort has:

- Compiled and modified existing resources for future outreach activities,
- Developed new tools for future outreach activities,
- Identified opportunities and methods for engaging private domestic well owners and other audiences to promote awareness and options for addressing nitrate-affected groundwater used for drinking water.

Key recommendations for future nitrate-related outreach for private domestic wells used for drinking water include:

- NDEE and its partners should continue to develop and refine risk communication resources developed during the study to provide a clear, unified message on nitrate in drinking water. As funding allows, NDEE and its partners could continue private well sampling and treatment programs. Coordination with partner agencies could improve the visibility of these programs for private domestic well owners.
- Continue work to increase private domestic well testing. Regularly testing private domestic wells for nitrate and bacteria is an important part of continued outreach to protect public health. Although 4,508 kits were requested as part of the free sampling effort, only 3,499 (74%) had been returned as of May 1, 2024. This indicates that some owners may have initially been interested in requesting the kit since it was free but lacked urgency to collect the sample and return it to the lab. Continued outreach to educate private domestic well owners of the importance of regularly testing their well for nitrate and bacteria is crucial to increase the amount of people that test their well.
- Create a database of likely unregistered well locations and owner contact information by implementing the methodology discussed in the Outreach Toolbox. This would allow for direct and more cost-effective outreach to unregistered well owners.
- Increase well registrations by reducing obstacles for registration. This could potentially include temporarily waiving the fee for the registration of old wells that predated the well registration requirement (pre-1993). Additionally, creating a simplified registration form for old wells or modifying the existing form may help avoid discouraging owners from registering wells due to lack of detailed information currently required to register a well.

6.0 REFERENCES

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Shaver, T., R. Khosla, and D. Westfall. (2014) Evaluation of Two Crop Canopy Sensors for Nitrogen Recommendations in Irrigates Maize, Journal of Plant Nutrition, 37:3, 406-419.

Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking Water Nitrate and Human Health: An Updated Review. International journal of environmental research and public health, 15(7), 1557. https://doi.org/10.3390/ijerph15071557

Appendix A – Tools and Resources

Web-Based Resources

Nebraska Department of Environment and Energy (NDEE)

Well and Septic Loan Evaluation
http://dee.ne.gov/NDEQProg.nsf/%24%24OpenDominoDocument.xsp?documentId=5A8EB80D6AB5B906862583AE005AB4D3&action=OpenDocument

Natural Resources Districts (NRD)

Natural Resources Districts
http://www.nrdnet.org/nrds/find-your-nrd

University of Nebraska-Lincoln School of Natural Resources

CropWatch
https://cropwatch.unl.edu/

Water and Health Resources
https://water.unl.edu/category/water-and-health

Water and Cropping Systems Personnel
https://epd.unl.edu/program-area/water-integrated-cropping-systems

NebGuides
https://water.unl.edu/article/drinking-water/nebguides

Call to Action Nebraska Nitrate Conference
https://water.unl.edu/article/nitrate/nebraska-nitrate-working-groups-summary-and-call-action

UNL Extension YouTube Nitrate Videos
https://www.youtube.com/@nebraskawaves6405.com

Nebraska Water Center (Daugherty Water for Food Global Institute)

Nebraska Statewide Nitrate Network Graphic (real time)
https://kumu.io/crystalwater/nebraska-nitrate-network#nitrate-related-programs/topic

Nitrate Network Map for Nebraska
https://knowyourwell.unl.edu

Nebraska WAVES YouTube Channel

Private Well Testing
https://www.youtube.com/watch?v=3KzHU2d_u6o

KBRX Podcast

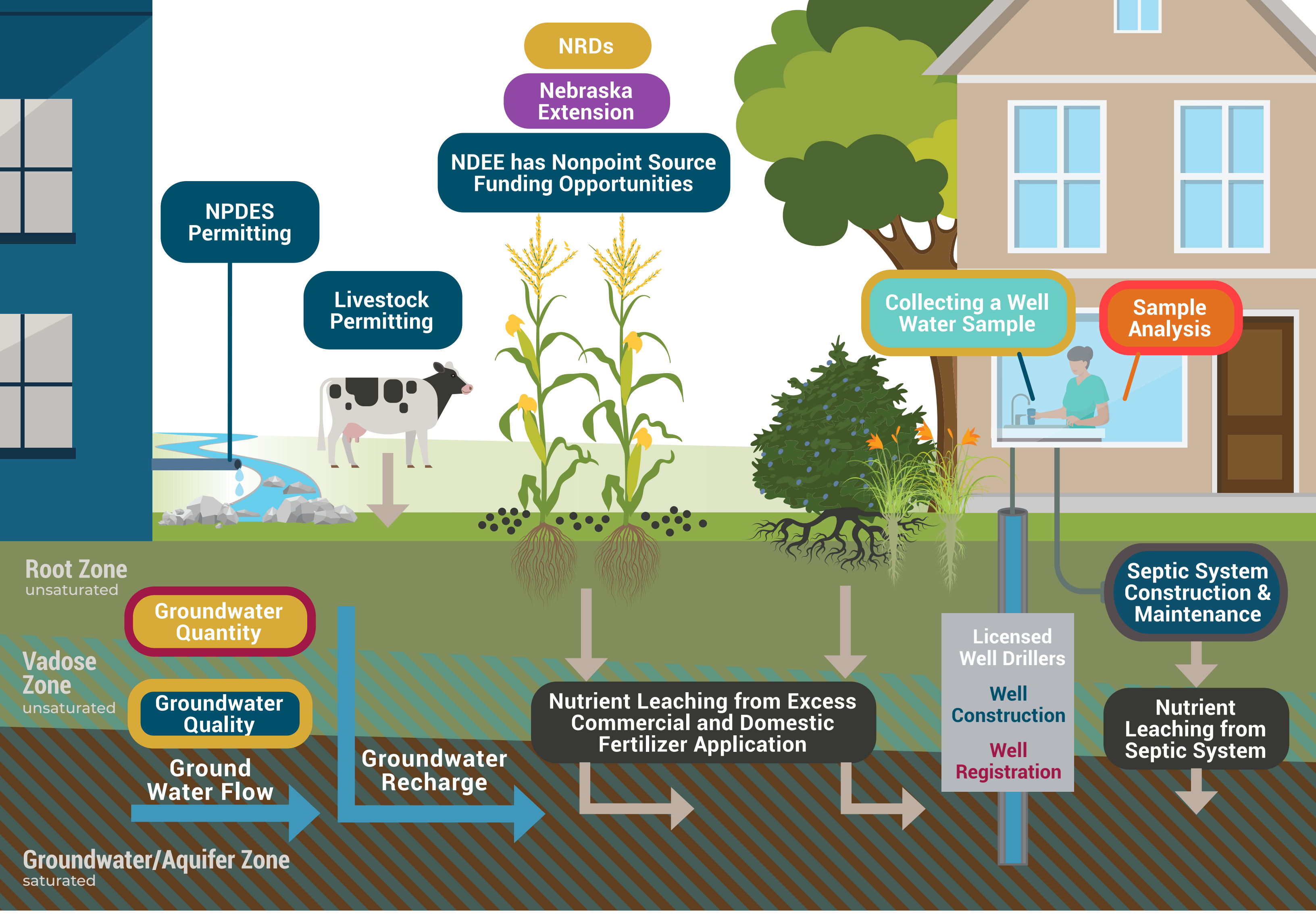
Water Nitrate Testing Information
https://www.kbrx.com/episode/water-nitrate-testing-information-from-ncdhd-uenrd-lnnrd/

Social Media Links

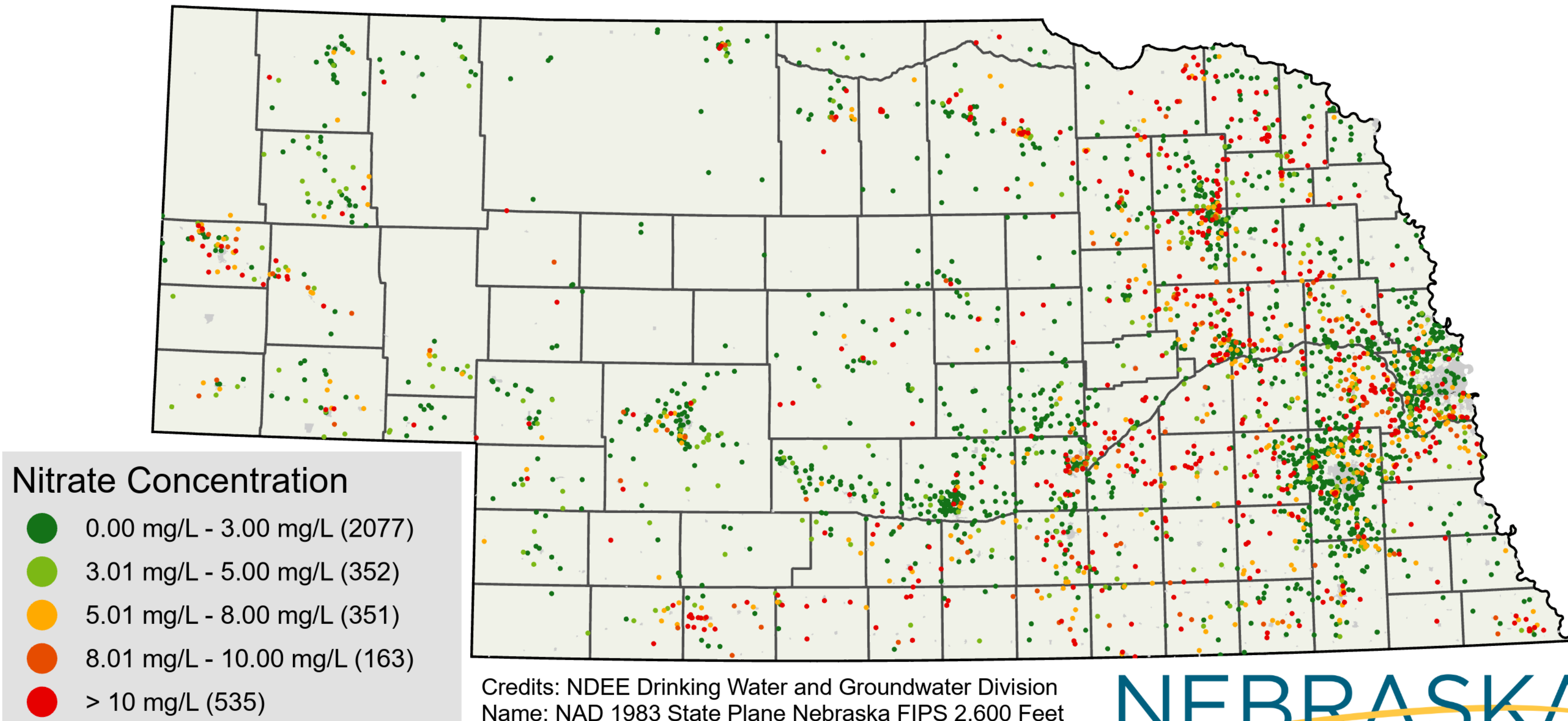
NDEE Twitter: @NebraskaDEE
DHHS Twitter: @NEDHHS
NE Water Center Twitter: @NebrWaterCenter
UNMC Twitter: @unmc
UNMC's Water, Climate, and Health Program Twitter: @UNMC_WCHP
DNR Facebook: https://www.facebook.com/nebraskadnr/

NITRATE IN PRIVATE DOMESTIC WELLS

WHO'S INVOLVED?	PROCESSES & TOOLS
NDEE	Water Quality Sampling, Point Source Pollution Permitting, & Nonpoint Source Pollution Funding
NRDs	Water Quality Sampling, Groundwater Quantity, Usage, & Nonpoint Source Pollution
NDNR	Well Registration & Registered Wells Database
UNMC	Education & Research on Health Effects of Nitrate in Drinking Water
NDHHS	Publicly Available Water Testing through the Public Health & Environmental Lab
Nebraska Extension	Education, Research, and Water and Cropping Systems
Realtors & Mortgage Lenders	Direct Communication with Property/Well Owners & May Require Well & Septic Evaluation
Nebraska Water Center	Education, Research, & Water Testing through the Water Sciences Laboratory
Licensed Well Drillers	
Licensed Septic Installers	
Well Owners	



3,478 Private Domestic Well Nitrate Samples from the 2023-2024 Free Nitrate Sampling Effort



Credits: NDEE Drinking Water and Groundwater Division
Name: NAD 1983 State Plane Nebraska FIPS 2,600 Feet
Datum: North American 1983
Projection: Lambert Conformal Conic

NEBRASKA
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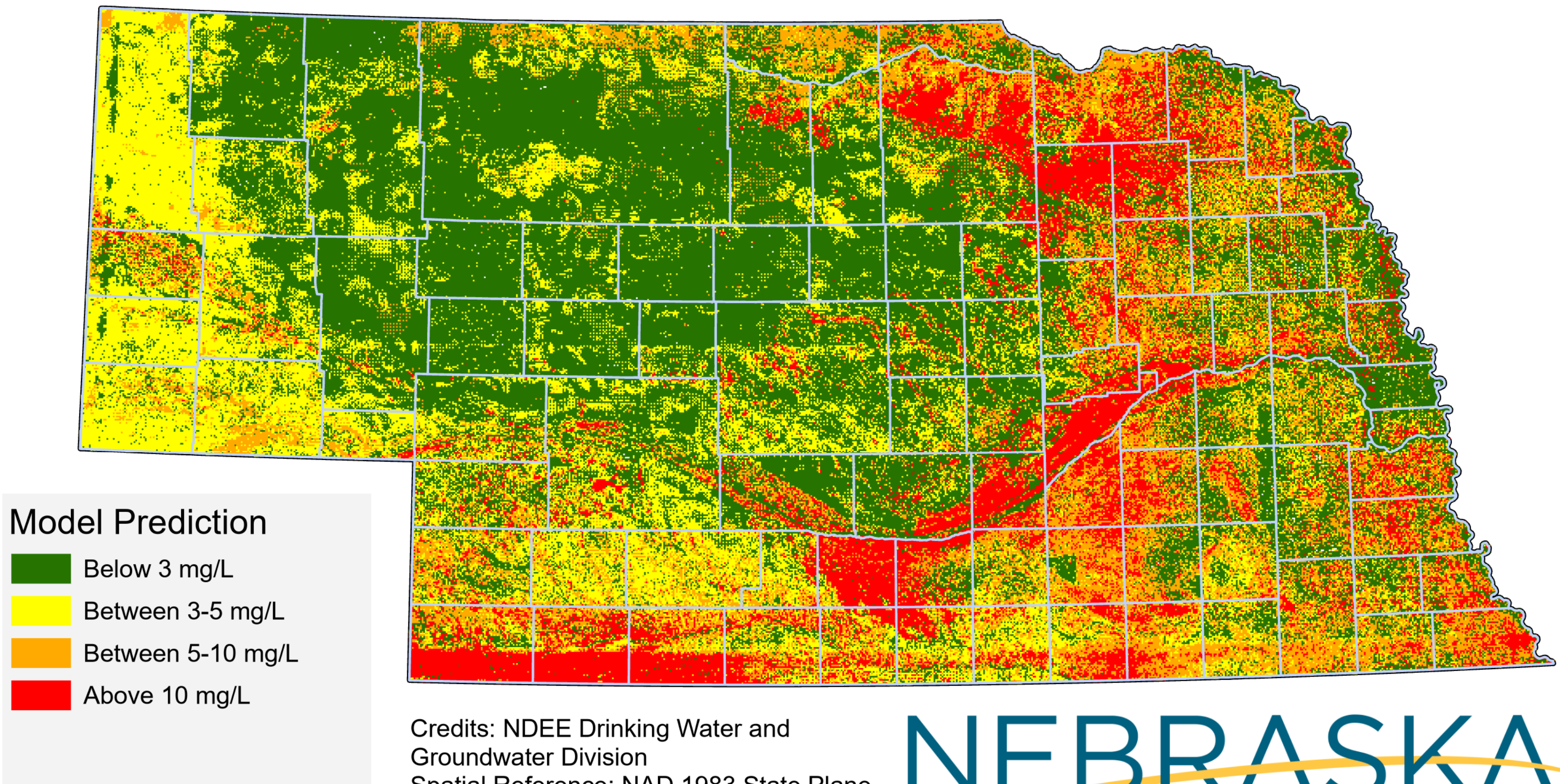
Predictive Nitrate Model Results: Composite Layer in Terms of Nitrate Concentration



Credits: NDEE Drinking Water and Groundwater Division
Spatial Reference: NAD 1983 State Plane Nebraska FIPS 2,600 Feet
Projection: Lambert Conformal Conic

NEBRASKA
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FREE
DRINKING WATER
NITRATE TESTING
Learn more about how to request your free private domestic well sample kit
NEBRASKA
DEPT. OF ENVIRONMENT AND ENERGY

Greetings,

You are receiving this postcard because you are listed as the owner of a registered domestic well in Nebraska. If your domestic well is used for drinking water, the Nebraska Department of Environment and Energy is offering to provide a free sample kit and lab analysis to test your well for nitrate for a limited time. To request a sample kit, scan the QR code on the front of this postcard, go to the website listed below, or call our office at (402) 471-2186. A sample kit, sampling instructions, and prepaid return postage will be sent to you. You will receive your sample results and the data will be used in a statewide nitrate study that NDEE is currently conducting.

Sincerely,

Jim Macy, NDEE Director

To request a sample kit, visit:
https://dhhs.ne.gov/Pages/Lab-Price-List.aspx

The maximum contaminant level (MCL) for nitrate in drinking water is

10 mg/L

If your water sample is above this level, see the RO rebate information inside this brochure.

Contact information

Nebraska Department of Environment and Energy

Front desk — 402-471-2186
Email — ndee.moreinfo@nebraska.gov
website — dee.ne.gov

P.O. Box 98922
Lincoln, Nebraska 68509-8922

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Nebraska Department of
Environment and Energy
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84001097

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Understanding your well sample results

Provided by NDEE's free nitrate sample kit program

You are receiving this brochure because your private drinking water well has been tested for nitrate recently. This brochure is intended to help you understand the sample results.

It is recommended that private well owners regularly test their wells to know the quality of their water. Regardless of your result, it is recommended that you test your well for nitrate each year in case your water quality changes.

What is nitrate?

Nitrate and nitrite are forms of nitrogen in the environment from both natural and man-made causes. They are used for fertilizer in agriculture and residential applications; are present near certain industrial sites, septic, and livestock waste systems; and are also found naturally occurring in the soil. Additionally, shallow wells, wells in sand aquifers, or poorly constructed wells are more vulnerable to nitrate contamination. Large amounts of nitrate in drinking water can be harmful to a person's health.

Health Concerns Associated with Nitrate
The Safe Drinking Water Act requires the Environmental Protection Agency to determine safe levels of chemicals in drinking water. The maximum contaminant level of nitrate in drinking water set by the EPA is 10 mg/L. Although private wells are not regulated by the Safe Drinking Water Act, there are safety concerns associated with consuming water with a nitrate concentration above 10 mg/L. Consuming high levels of nitrate has been linked to methemoglobinemia, or blue baby syndrome. Babies that are under six months old and are bottle fed are at risk for this disease that can cause the skin to turn a bluish color and, if left untreated, could result in serious illness or death.

Nitrate and private wells

Approximately 84% of Nebraskans get their water from community water systems that are regulated by the Safe Drinking Water Act and are protected from harmful nitrate exposure. However, private wells are not regulated by the Safe Drinking Water Act and are not required to be tested for nitrate under state or federal law. Only a portion of the private drinking water wells in Nebraska have been tested, and those that have often have a higher nitrate level than community water systems. It is imperative for Nebraskans on private drinking water wells to know if their drinking water is safe. Elevated nitrate levels are a particular concern in Nebraska.

What should I do if my test results are above 10 mg/L?
You should not use water from this well to prepare formula for a bottle-fed infant or for cooking. Do not boil the water. Boiling causes evaporation and concentrates the nitrate in the water. It is okay to bathe with this water, however, the Department recommends that you locate an alternate drinking water source or install an in-home treatment system.

Resources to treat nitrate in drinking water

If your well tested over 10 mg/L of nitrate, you may be eligible for NDEE's Reverse Osmosis (RO) Rebate Program to treat your water. This program offers up to $4000 in rebates to well owners whose wells are registered through the Nebraska Department of Natural Resources and whose water sample is above 10 mg/L of nitrate.

Learn more about the RO Rebate Program by scanning the QR code, or visiting the website listed below:

http://dee.ne.gov/Publica.nsf/pages/22-051

IT IS IMPORTANT TO KNOW IF YOUR DRINKING WATER PUTS YOU AT RISK. NDEE CAN HELP.

NEBRASKA
DEPT. OF ENVIRONMENT AND ENERGY

NITRATE IN DRINKING WATER

Nitrate is a compound that occurs naturally and has many human-made sources. Nitrate is in some lakes, rivers, and groundwater in Nebraska. You cannot taste, smell, or see nitrate in water. Consuming too much nitrate can be harmful—especially for babies.

Background Information

Nitrate occurs naturally and at safe and healthy levels in some foods (e.g., spinach and carrots) and comes from natural processes, like plant decay. The primary source of inorganic nitrate is from fertilizers used on yards, gardens, golf courses, and crops. Certain industrial processes and leaks from fertilizer storage can also be a source of inorganic nitrate. Common sources of organic nitrate are human and animal waste.

Nitrate in Nebraska Water

Nitrate has been found in groundwater across Nebraska. While nitrate occurs naturally, levels in groundwater above 3 mg/L are considered an indicator of human-driven contamination.

Based on available data, there were 16,403 domestic well nitrate samples collected from 2003-2024. Of all the domestic wells sampled over this period, 6,468 (39.4%) of them were above 3 mg/L for nitrate and 2,775 (16.9%) of them were above 10 mg/L for nitrate. For more information about nitrate in Nebraska surface water and groundwater, see the Nebraska Department of Environment and Energy's (NDEE's) annual water program publications included in the Resources section.

Health Effects

HUMANS: The U.S. Environmental Protection Agency (EPA) established the Maximum Contaminant Level (MCL) for nitrate in drinking water at 10 milligrams of nitrate (measured as nitrogen) per liter of drinking water (mg/L NO_3-N).

Drinking water with nitrate above the MCL can affect how blood carries oxygen and may cause methemoglobinemia (also known as blue baby syndrome). Bottle-fed babies under six months old are at the highest risk of getting methemoglobinemia. This illness can cause the skin to turn a bluish color and result in serious illness or death. Other symptoms connected to methemoglobinemia include decreased blood pressure, increased heart rate, headaches, stomach cramps, and vomiting.[1] Pregnant women are also a high-risk group and should not consume water with nitrate above the MCL.[2] The following conditions may also put people at higher risk of developing nitrate-induced methemoglobinemia: anemia, cardiovascular disease, sepsis, glucose-6-phosphate- dehydrogenase deficiency, gastrointestinal diseases and other metabolic problems.[2, 3]

The EPA standard was set based on immediate health effects of consuming nitrate above 10 mg/L. There is additional research being done by others, including the University of Nebraska-Lincoln (UNL), on other potential health effects, including chronic health effects. Chronic health effects occur from ingesting a contaminant over a long period of time.

For more information about other potential health effects, visit the UNL websites located in the Resources section.

LIVESTOCK: It is recommended to not allow livestock to drink water with a nitrate level above 100 mg/L. Nitrate can affect livestock similarly to how it affects humans.[4] Additionally, nitrate levels above 100 mg/L may cause reproductive problems in adult cattle and reduce growth rates in replacement heifers.[5] It is recommended that you consult with a veterinarian if you have questions about an acceptable nitrate level in drinking water for other species of animals.

How to Protect Yourself and Your Family

IF YOU ARE ON A PUBLIC WATER SYSTEM: Your public water system regularly tests for nitrate and makes sure levels meet the EPA standard. You can find the level of nitrate detected in your public water system by reading the system's Consumer Confidence Report (CCR) which is a water quality report that is required to be provided to water customers annually. Call your water system to get a paper copy of your community's most recent report or find drinking water quality information about your system online at the Drinking Water Watch website listed in the Resources section.

IF YOU HAVE A PRIVATE WELL: The following types of wells are the most vulnerable to nitrate contamination, especially if they are near or downgradient of septic tanks and absorption/leach fields, certain industrial areas, areas with agricultural activities, or areas with known high concentrations of nitrate in groundwater:

- Shallow wells 50 feet or less in depth.
- Wells in sand aquifers.
- Dug wells or wells with casings that are not watertight due to damage or construction materials used.
- Wells in a pit.
- Improperly constructed wells.
- Wells constructed prior to the 1988 construction standards.

[1] Agency for Toxic Substances and Disease Registry (ATSDR). 2015: ToxFAQs™ for Nitrate and Nitrite (https://www.atsdr.cdc.gov/toxfaqs/tfacts204.pdf). Accessed April 2024.

[2] ATSDR. 2013. ATSDR Case Studies in Environmental Medicine Nitrate/Nitrite Toxicity (https://www.atsdr.cdc.gov/csem/nitrate_2013/docs/nitrite.pdf). Page 37. Accessed April 2024

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[4] Rasby, R. & Walz, T. 2011. Water Requirements for Beef Cattle. University of Nebraska-Lincoln Extension. (https://extensionpubs.unl.edu/publication/g2060/html/view). Accessed May 2024.

[5] Kononoff, P. & Clark, K. 2017. Water Quality and Requirements for Dairy Cattle. University of Nebraska-Lincoln Extension. (https://extensionpubs.unl.edu/publication/g2292/html/view). Accessed May 2024.

Prevent Contamination

- **Construct your well in a safe spot.** Domestic wells constructed in Nebraska are required to adhere to setback distances and construction standards set in Nebraska Administrative Code (NAC) Title 178, Chapter 12. Ensure your installer is a licensed Water Well Professional using the NDEE website listed in the Resources section or by calling 402-471-0546
- **Keep nitrate sources away from your well**. Sources may include fertilizer application and storage, fuel storage, septic systems, wastewater treatment facilities, and livestock facilities. See NAC Title 178, Chapter 12, Chart 1 for setback distances from common sources of well contamination. Consult with a Certified Onsite Wastewater Treatment (OWT) Professional if you have concerns about the location or condition of your septic system in relation to your well. A link to find a Certified OWT Professional is listed in the Resources section.
- **Get your well inspected.** Work with a licensed professional to take any corrective actions that may be needed. Water Well Professionals with a current license are listed on the NDEE website listed in the Resources section.
- **Test for nitrate and bacteria every year.** You are responsible for regularly testing your well water. NDEE recommends using an accredited laboratory to test your well water. Well owners can request sample kits from the Nebraska Department of Health and Human Services (NDHHS) online at the website listed in the Resources section or by calling 402-471-3935. Additionally, the NDHHS's website has a list of other accredited laboratories. Contact the laboratory to get sample containers and instructions or ask your local Natural Resources District (NRD) or public health services if they provide well water testing services. If you need help finding your local NRD, visit the website in the Resources section.

Address Contamination

If nitrate is detected in your water at levels above 10 mg/L, follow these steps:

- **Get your drinking water from a safe source**, such as bottled water, or a public water system including rural water districts. This is especially important if babies under six months old drink the water or formula is made with the water. Pregnant or nursing mothers should consult with their doctor about how elevated nitrate levels in drinking water may affect them. Boiling water is not a solution for elevated nitrate levels as it causes evaporation and concentrates the nitrate in the water.
- **Consider testing the well for other contaminants that commonly occur with nitrate such as bacteria and uranium.** Sample test kits for other contaminants, such as bacteria and uranium may be requested from the Nebraska Department of Health and Human Services online at the website listed in the Resources section or by calling 402-471-3935. For more information about other potential contaminants in your well, visit the NebGuides link under the UNL Resources section.
- **Contact a local rural water district.** Connection to the rural water district-supplied water may be an option in your area.
- **Consider your well construction.** If your existing well is poorly constructed or is located near a contamination source such as a septic system, drilling a new well or rehabilitating your well may be an option. However, this can be costly and is not a guarantee that the new or modified well will have nitrate below 10 mg/L. Water Well Professionals with a current license that can help drill a new well or rehabilitate an existing well are listed on the NDEE website listed in the Resources section.
- **Consider a Point of Use (POU) or Point of Entry (POE) treatment system to remove nitrate from drinking water.** POU treatment systems treat water at one tap while POE treatment systems treat all the water that enters your home. Reverse osmosis, ion exchange, or distillation filtration systems are the typical types of treatment systems used to remove nitrate from drinking water. These systems require regular maintenance and testing to ensure they are working correctly and must be properly installed, operated, and maintained to be effective. You may be able to purchase a basic system from your local home improvement store. Consult with a licensed plumber for help installing a more sophisticated system. Additionally, your local NRD may have assistance available to help fund the installation of a treatment system. If you need help finding your local NRD, visit the website located in the Resources section.

Resources

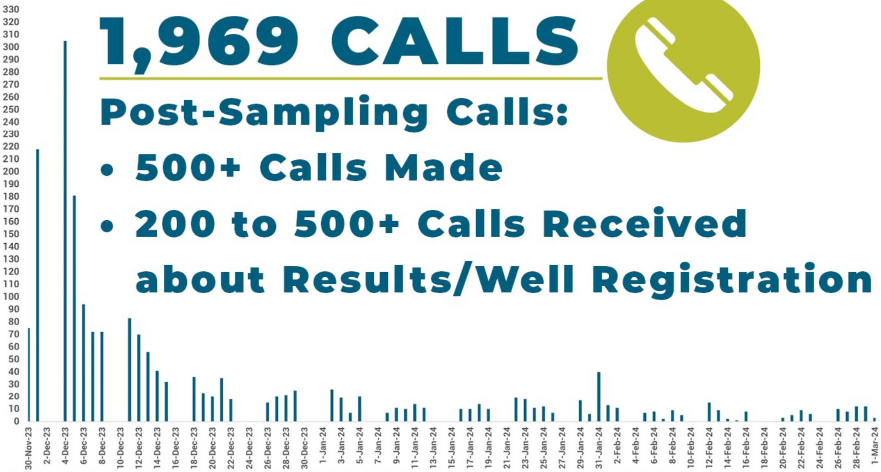
- Drinking Water Watch
  https://drinkingwater.ne.gov
- Find Your NRD
  https://www.nrdnet.org/
- NDEE Annual Report to the Legislature
  https://dee.nebraska.gov/forms/publications-grants-forms/ndee034
- Groundwater Quality Monitoring Report
  https://dee.nebraska.gov/forms/publications-grants-forms/24-026
- NDEE Water Quality Integrated Report
  https://dee.nebraska.gov/forms/publications-grants-forms/23-012
- NDEE Certified Onsite Wastewater Treatment Professionals Lookup
  https://dee.nebraska.gov/water/wastewater/onsite-wastewater-program/certified-installers-mound-endorsement-and-professional-engineers
- NDEE Water Well Professionals Licensee Lookup
  https://deq-iis.ne.gov/zs/wwp/main_pro.php
- NAC Title 178 (Chapter 12 Setback Distances)
  https://rules.nebraska.gov/rules?agencyId=37&titleId=107
- NDHHS Water Sampling Test Kit Request
  https://www.nebraska.gov/dhhs/water-test-kits/private.html
- NDHHS Certified Labs
  https://dhhs.ne.gov/Pages/Lab-Certification-Requirements.aspx
- EPA Fact Sheet
  https://archive.epa.gov/water/archive/web/pdf/archived-consumer-fact-sheet-on-nitrates-and-or-nitrites.pdf
- UNL Resources:
  https://water.unl.edu/category/water-and-health
  https://water.unl.edu/category/water-and-health/resources
  https://water.unl.edu/article/drinking-water/nebguides

Nebraska Department of Environment and Energy
402-471-2186
ndee.moreinfo@nebraska.gov

1,969 CALLS

Post-Sampling Calls:

- 500+ Calls Made
- 200 to 500+ Calls Received about Results/Well Registration



NOVEMBER 30, 2023 TO MARCH 1, 2024

Department of Environment and Energy

News Release

NEBRASKA Good Life. Great Resources.

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FOR IMMEDIATE RELEASE
July 28, 2023

NDEE Releases Report on Nitrate and Drinking Water

LINCOLN, NE – Today, the Nebraska Department of Environment and Energy (NDEE) released a mid-year report on nitrate and water quality which includes nitrate data on private drinking water along with an update regarding the agency's continued effort to protect Nebraskans and the state's drinking water supply. NDEE Director Jim Macy said the new report shows that Nebraska's drinking water quality remains high, and that Nebraska has the necessary tools to continue improving drinking water quality.

"This report highlights that the vast majority of Nebraskans are protected from high nitrate levels in their drinking water," said Macy. "Because private wells are not covered under the Safe Drinking Water Act, private wells have a higher risk of exposure to high nitrate in drinking water. I encourage Nebraskans, who own a private well and are concerned about high nitrate in their drinking water, to get their well tested. A test costs around $20 and the state has a grant program to help reimburse costs for qualifying treatment systems for private wells that have high nitrate levels."

The report highlighted some of the following points:

- *1.65 million Nebraskans (or over 85% of Nebraska's population) get their water from public water systems that are protected from nitrate and other pollutants under the Safe Drinking Water Act (SDWA). The SDWA requires that public drinking water be at or below 10 mg/l or be properly treated. Nebraska drinking water quality remains high with 98% of public water systems in full compliance with nitrate requirements.*
- *Private wells service 300,000 Nebraskans and are not covered by the SDWA. These well owners can be at risk for nitrate. Updated data reveals that the vast majority of private wells that have been tested are at or below the recommended safe nitrate standard.*
- *The state of Nebraska has $1.2 million in grant money available for qualifying private well owners to install a reverse osmosis system that will help protect them from nitrate exposure through their drinking water. Most private wells with nitrate levels of at least 10 mg/L (the EPA safety limit) are eligible for these grants.*

A copy of the report can be found here: https://deq-iis.ne.gov/zs/publications/

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Department of Environment and Energy

News Release

NEBRASKA Good Life. Great Resources.

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FOR IMMEDIATE RELEASE
November 29, 2023

NDEE offers free nitrate sample kits for private drinking water wells

LINCOLN, Neb. – The Nebraska Department of Environment and Energy (NDEE) is offering free nitrate sample kits and lab analyses to private drinking water well owners across the state. These kits are only available for a limited time until Jan. 31, 2024.

Well owners who participate will receive their sample results, and NDEE will use the data from this sampling effort in a statewide nitrate study that the agency is currently conducting. The study will include nitrate sampling data from public water systems and from private drinking water well owners who agree to participate. Well owners' identifying information will not be used in the study.

Nebraska's private drinking water well owners can request a free nitrate sample kit, which comes with sampling instructions and pre-paid return postage, online on the Nebraska Department of Health and Human Services website: https://dhhs.ne.gov/Pages/Lab-Price-List.aspx. Those without access to the internet who need help requesting a free sample kit may call NDEE at 402-471-2186.

The state does not regularly conduct sampling in private drinking water wells because they are not regulated under the Safe Drinking Water Act. Public participation in this free sampling event is key to ensuring the nitrate study accurately encompasses private drinking water wells in Nebraska.

NDEE has sent postcards to more than 29,000 registered domestic well owners in Nebraska inviting them to participate in this study. The free sample kits and lab analyses are offered to all Nebraskans with a private drinking water well - not just those who received a postcard or have a registered well.

Collecting the sample is easy. Allow the cold water tap to run for three minutes, then fill the plastic container provided in the sample kit, being careful not to overfill. More detailed instructions will be provided with the sample kit.

If a private well owner's results are above 10 parts per million (ppm) of nitrate, they may be eligible for NDEE's Reverse Osmosis (RO) Rebate Program to treat their water. This program offers up to $4,000 in rebates to well owners whose wells are registered through the Nebraska Department of Natural Resources and whose wells sample above 10 ppm of nitrate.

Applications for the RO system rebates must be submitted by June 30, 2024. NDEE accepts and reviews RO rebate applications on a month-to-month basis. Learn more about the RO Rebate Program on NDEE's website: http://dee.ne.gov/Publica.nsf/pages/22-051.

245 Fallbrook Blvd Suite 100, Lincoln, NE 68521 -- PO Box 98922, Lincoln, NE 68509 -- phone (402) 471-2186, toll-free (877) 253-2603

Department of Environment and Energy

News Release

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FOR IMMEDIATE RELEASE
January 22, 2024

NDEE extends deadline to request free nitrate sample kits

LINCOLN, Neb. – The Nebraska Department of Environment and Energy (NDEE) is extending the deadline for Nebraskans to request a free nitrate sample kit and lab analysis.

Sample kits can now be requested through March 1, 2024, or until funds are expended. The free nitrate sample kits and lab analyses are offered to all Nebraskans with a private drinking water well.

Nebraska's private drinking water well owners can request a free kit, which comes with sampling instructions and pre-paid return postage, online on the Nebraska Department of Health and Human Services website: https://dhhs.ne.gov/Pages/Lab-Price-List.aspx. At this link, there is a box for this project titled "Nitrate Project Kit Request." Please fill out the PDF form in this box and email it to the address provided in the box. Those without access to the internet who need help requesting a free sample kit may call NDEE at 402-471-2186.

Due to high demand, it may take several weeks or more to receive your kit in the mail. After receiving the kit, NDEE encourages requestors to collect their sample and return it to the Public Health Environmental Lab as soon as possible.

Well owners who participate will receive their sample results, and NDEE will use the data from this sampling effort in a statewide nitrate study that the agency is currently conducting. The study will include nitrate sampling data from public water systems and from private drinking water well owners who agree to participate. Well owners' identifying information will not be used in the study.

The state does not regularly conduct sampling in private drinking water wells because they are not regulated under the Safe Drinking Water Act. Public participation in this free sampling event is key to ensuring the nitrate study accurately encompasses private drinking water wells in Nebraska.

For more information, see NDEE's previous press release announcing the availability of the test kits: http://dee.ne.gov/Press.nsf/pages/PR112923.

Department of Environment and Energy

News Release

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FOR IMMEDIATE RELEASE
March 8, 2024

NDEE encourages private well owners to return sample kits

LINCOLN, Neb. – The Nebraska Department of Environment and Energy urges those who requested free nitrate sample kits to sample their drinking water and return the kits to the Public Health Environmental Lab for processing.

Returning the test kit is a proactive way private well owners can learn their wells' nitrate concentration and can make informed decisions about their drinking water.

From November 29, 2023, through March 1, 2024, NDEE offered free nitrate sample kits to all private well owners in Nebraska. More than 4,500 well owners requested kits. The kits expire after 90 days.

Data from this sampling effort will be used in a statewide nitrate study NDEE is conducting. Sample kits must be received by the lab as soon as possible to ensure the data is included in the study and to give the state a clearer picture of nitrate impacts on groundwater.

While the free sample kits are no longer available, nitrate sample kits are available any time through the Department of Health and Human Services Public Health Environmental lab for a $16 fee, plus postage. NDEE recommends private well owners sample their drinking water on an annual basis.

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PUBLIC HEALTH ENVIRONMENTAL LAB

Kits not returned within 90 days will be charged the cost of the kit plus shipping

SAMPLING INSTRUCTIONS FOR PRIVATE DRINKING WATER NITRATE TESTING

******PLEASE READ ALL INSTRUCTIONS BEFORE COLLECTING SAMPLES******

The enclosed sample kit(s) are being sent to you to collect for a drinking water nitrate. **Please contact the Private Well Water Program at (402) 471-0930, if you have questions about this sample collection.**

Prior to Sample Collection

The enclosed sample container(s) is for nitrate analysis. The sample container should be used within 90 days. Sample containers not used within this time frame should be returned to the laboratory. Do not use this container to collect samples for tests other than nitrate analysis.

Each kit contains the following items. If you did not get all of the items, please call 402-471-3935.

1. A plastic 4-ounce bottle, with a small amount of **sulfuric acid** added as a preservative
2. A laboratory sample submission form with return mailing label
3. Re-sealable bag
4. Sampling instructions

Caution: Sulfuric acid is highly toxic by digestion and inhalation: and a strong irritant to eyes and skin. Please wash hands thoroughly and use protective gloves to prevent chemical burns.

Sampling Instructions

1. Before handling the sampling container, make sure your hands are clean of dirt, grease, and oil.

2. Allow the cold water tap to run approximately 3 minutes.

3. Carefully remove the lid from the 4oz plastic container and fill with water up to the shoulder area. Avoid contamination by not touching the containers inside, lip, or inside cap surface. **Do not overfill**, as the sulfuric acid preservative would be lost and the results may then be invalid.

4. Be sure to recap the container securely. Place one sample barcode sticker on the bottle and one on the lid. Place the sample bottle into the re-sealable bag and seal it. Per USPS requirements the contents must be leak proof. Place this in the Styrofoam packaging.

5. Complete the collector, sample date, sample time, and sampling location on the submission form as well as a phone number where you can be reached if we have questions. Keep one barcode sticker for your records.

6. If you received multiple sampling kits, repeat steps 1 through 6 to collect the remaining samples.

(Continued on reverse side)

7. Place the completed laboratory submission form and the Styrofoam containing the bagged sample back into the box. Multiple sample kits can then be packed into a larger cardboard box if desired. USPS return mailing labels are part of the submission form for your convenience. Samples may be shipped by U.S. Mail, Federal Express or United Parcel Service. **The sample should be shipped within a business day of collection.** Avoid sending samples on Friday. Return postage is at the client's expense.

USPS Mailing Address for the sample
Nebraska Health and Human Services,
Public Health Environmental Laboratory
3701 S 14th St
PO Box 22790
Lincoln, NE 68542-2790

Physical Address if using other delivery Service
Nebraska Public Health Environmental Laboratory
3701 S 14th St
Lincoln, NE 68502

Test Results Interpretation

If you have results that concern you, first consult the link below for more information.
Nitrate - http://extensionpubs.unl.edu/publication/9000016365631/drinking-water/
If you still need further consultation, call Dave Miesbach at 402-471-4982.
For sample interpretation, call 402-471-0930.

Understanding My Drinking Water Test Results

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Coliform Results

Example Lab Report:

Parameters	Results	Units	Qual	Report Limit	MCL or AL	Analyzed	By
Analytical Method: SM 9223B - Colilert Quantitray							
Total Coliform	0	MPN/100mL		0		7/2/2019	TSW
E.coli	0	MPN/100mL		0		7/2/2019	TSW

If your results column has 0 Total Coliform and 0 *E. coli* then your water is safe!

What is Coliform and *E. coli*?

Coliform is a group of bacteria found in plant material, water, and soil. Coliform bacteria is also present in the digestive tracts and feces of humans and animals. Most of the time, these bacteria are not harmful. Finding coliform bacteria in a drinking water sample however, can indicate potential contamination. *E. coli* is a type of coliform bacteria. Most strains of *E. coli* are harmless, but some can cause serious illness in humans.

What should I do if Coliform is present but is *E.coli* absent?

The Department recommends conducting further testing to determine the extent of bacterial infiltration. Results less than 5 MPN/100mL indicate a potential sampling error. Flush the line and re-collect a sample. If your results are higher than 5 MPN/100mL, the Department recommends chlorination of the well by a certified well contractor.

What should I do if my test results are *E.coli* positive?

You should not drink, bathe, or cook with water from this well. We also recommend that the well be treated by shock chlorination by a certified well contractor. If the water must be used before the well is treated, you should boil it for a minimum of 1 minute before using it for cooking or drinking. Allow for cooling prior to consumption.

Guidance on treating a well using shock chlorination can be found at the link below:
http://extensionpublications.unl.edu/assets/pdf/g1761.pdf

The Nebraska Department of Environment and Energy recommends you contact a licensed water well contractor to shock chlorinate a well. Click this link (https://deq-iis.ne.gov/zs/wwp/main_pro.php) to search for a licensed water well contractor.

Nitrate Results

Example Lab Report:

Parameters	Results	Units	Qual	Report Limit	MCL or AL	Analyzed	By
Analytical Method: EPA 353.2-Nitrate/Nitrite							
Nitrate + Nitrite (As N)	6.02	mg/L		0.05	10	5/15/2019	SKH

If the results column has a result less than 10 mg/L then your water is safe!

What is Nitrate/Nitrite?

Nitrates are used as fertilizers for agriculture but are also present in livestock waste. They can easily contaminate both surface and groundwater when used in excess or due to runoff. Infants, pregnant women, and nursing mothers are especially vulnerable when exposed to nitrate levels above 10 mg/L.

What should I do if my test results are above 10 mg/L?

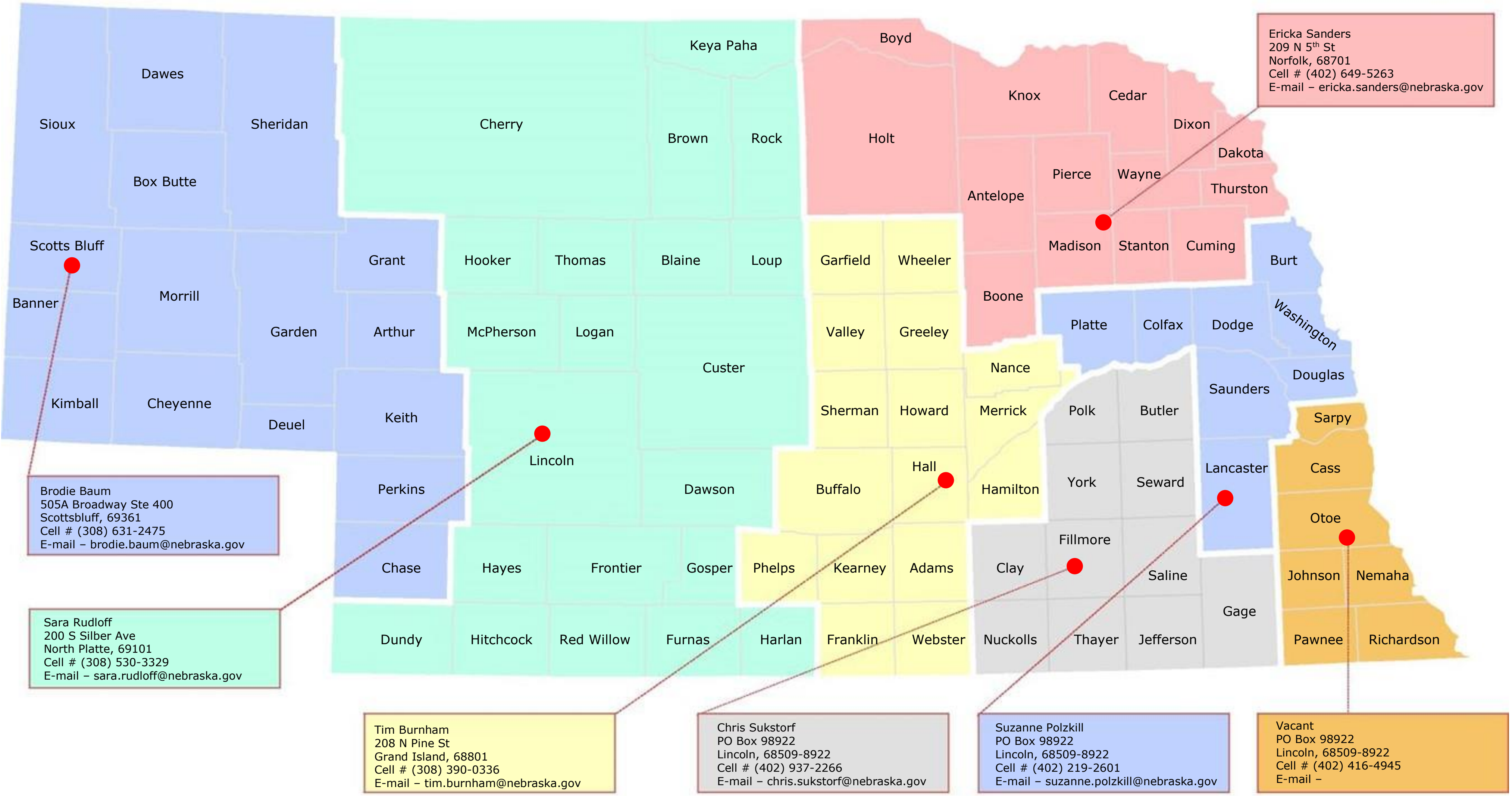
You should not use water from this well to prepare formula for a bottle-fed infant or for cooking. The Department recommends that you locate an alternate drinking water source or install in-home treatment. Do not boil the water. Boiling causes evaporation and concentrates the nitrate in the water. It is okay to bathe with this water.

For coliform or nitrate questions, please see the back side of this paper if you need further assistance. Locate your county of residence and contact the representative in your area.

If you need to order a sample kit, contact the Nebraska Environmental Health Lab at 402-471-3935.

WAT295
Rev. 9/2022

Environmental Safety Programs



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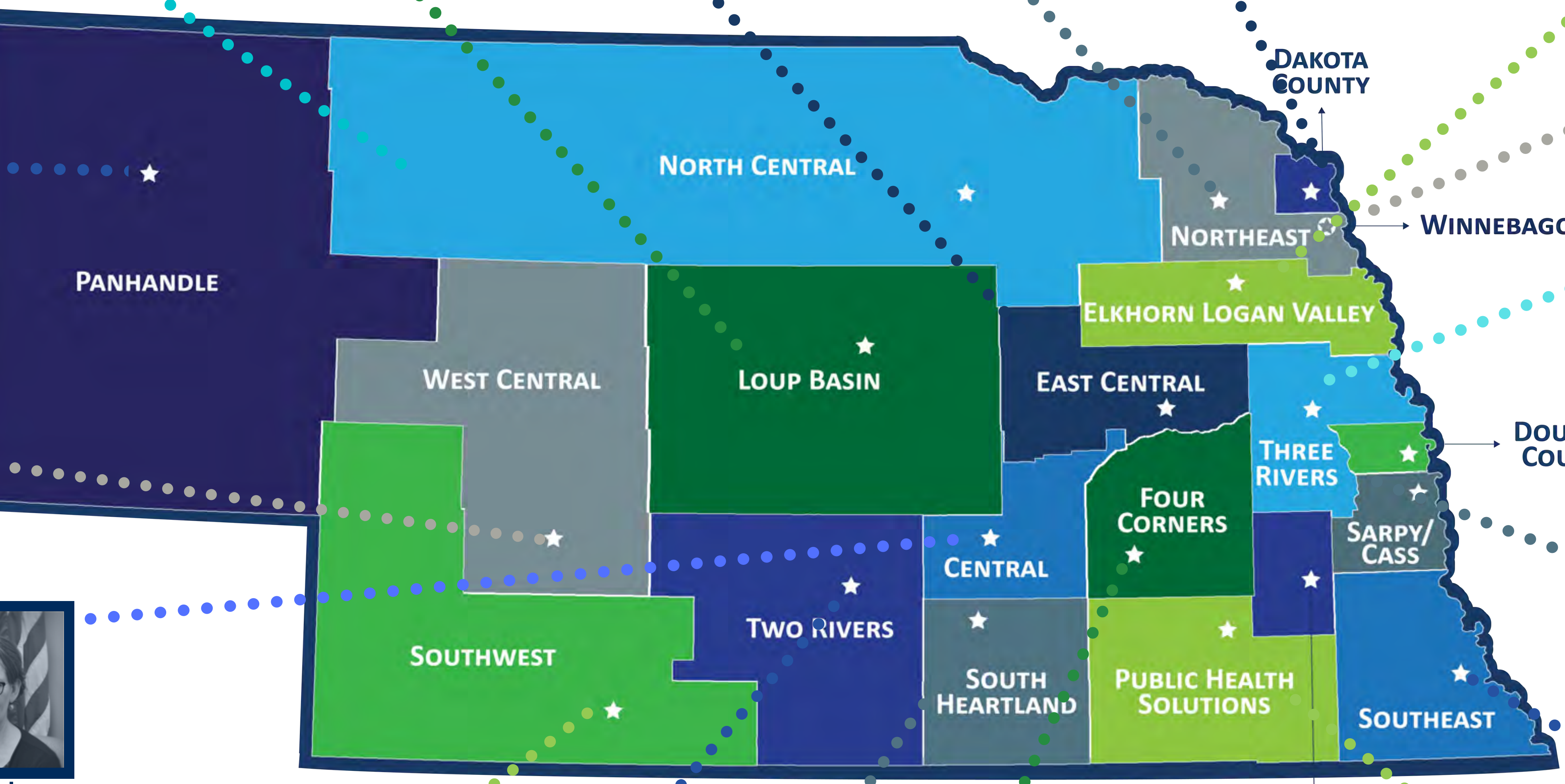


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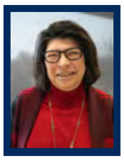

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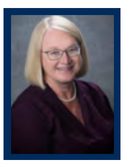

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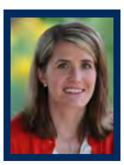

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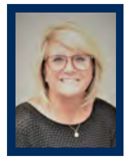

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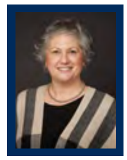

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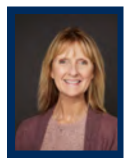

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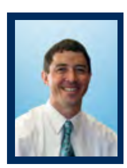

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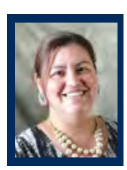

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NebGuide

Nebraska Extension

Research-Based Information That You Can Use

G1784

Drinking Water

Nitrate-Nitrogen

Becky Schuerman, Extension Associate Domestic Water/Wastewater Management

Bruce I. Dvorak, Extension Environmental Engineering Specialist

Nitrate-nitrogen is sometimes present in drinking water. At certain levels it can present a health risk. Properly locating and constructing wells along with regularly testing water can help to manage the risk.

Many Nebraskans have questions about the impact of nitrate in their drinking water. Water quality monitoring shows that nitrate is present in groundwater throughout much of Nebraska and concentrations are increasing in some areas.

Nitrogen is essential for all living things, as it is an essential component of protein. Nitrogen exists in the environment in many forms and changes forms as it moves through the nitrogen cycle. However, excessive concentrations of nitrate-nitrogen in drinking water can be hazardous to health, especially for infants, nursing mothers, and pregnant women.

Sources of Nitrate in Drinking Water

Nitrogen is a nutrient applied for lawn and garden care and crop production to increase productivity. Feedlots, animal yards, septic systems, and other waste treatment systems are additional sources of nitrogen that is carried in waste. Nitrogen occurs naturally in the soil in organic forms from decaying plant and animal residues.

Bacteria in the soil convert various forms of nitrogen to nitrate, a form of nitrogen and oxygen. This is desirable since the majority of the nitrogen used by plants is absorbed in the nitrate form. However, nitrate is highly soluble and readily moves with water through the soil profile. If there is excessive rainfall or over-irrigation, nitrate will drain below the plant's root zone and may eventually reach groundwater.

Nitrate in groundwater may result from point sources such as sewage disposal systems and livestock facilities, from nonpoint sources such as fertilized cropland, parks, golf courses, lawns, and gardens, or from naturally occurring sources of nitrogen. Proper site selection for the location of domestic water wells can reduce potential nitrate contamination of drinking water. Important considerations include a sufficient well depth, an adequate distance from possible contamination sources, and a location upslope from possible contamination sources. Proper well construction and maintenance also reduces the risk of drinking water contamination. See NebGuide G2050 "Protecting Private Drinking Water Supplies: Water Well Location, Construction, Condition, and Management" for additional information.

Indications of Nitrate

Nitrate in water is colorless, odorless, and tasteless, which makes it undetectable without testing.

Potential Health Effects

The U.S. Environmental Protection Agency (EPA) Maximum Contaminant Level (MCL) for nitrate-nitrogen in a public water supply is 10 milligrams per liter (mg/L), sometimes expressed as 10 parts per million (ppm) measured as nitrate-nitrogen (NO_3-N.) It is based on acute health effects, specifically the risk of methemoglobinemia (explained below.) Acute health effects are those that result from ingestion of a contaminant over a short period of time.

The acute health hazard associated with drinking water with elevated levels of nitrate occurs when bacteria in the digestive system transform nitrate to nitrite. The nitrite reacts with iron in the hemoglobin of red blood cells to form methemoglobin, which lacks the oxygen-carrying ability of hemoglobin. This creates the condition known as methemoglobinemia (sometimes referred to as "blue baby syndrome"), in which blood lacks the ability to carry sufficient oxygen to the individual body cells.

Infants under one year of age have the highest risk of developing methemoglobinemia from consuming water with elevated levels of nitrate. Contributing risk factors include digestive and enzyme systems that are not fully developed. Older persons who have a gastrointestinal system disorder resulting in increased bacteria growth may be at greater risk than the general population. In addition, individuals who have a genetically impaired enzyme system for metabolizing methemoglobin may be at greater risk. The general population has a low risk of developing methemoglobinemia, even when ingesting relatively high levels of nitrate/nitrite.

Historical information on infants with methemoglobinemia suggests that a number of infants with the condition also showed signs of diarrhea, inflammation, and infection of the gastrointestinal track, or protein intolerance. The significance of these factors in regard to methemoglobinemia risk, if any, is not known.

Definitive guidelines for determining susceptibility to methemoglobinemia have not been developed. The EPA has established the regulatory threshold for acute health effects based on best available science. The intake from food, drugs, and other sources also is important and must be considered.

Although the EPA standard was set at 10 mg/L based on acute health effects, questions have been raised regarding possible chronic health effects from consuming water with nitrate at various concentrations. Chronic health effects are those that can occur when a contaminant has been ingested over long periods of time. Research is limited regarding the possibility of chronic health effects due to long-term ingestion of drinking water with nitrate at various concentrations. However, studies have shown a correlation between long-term ingestion of water with nitrate, both above and below 10mg/L, and increased incidence of certain diseases and cancers, particularly pediatric brain tumors, and colorectal and thyroid cancers in adults. Based on the available scientific evidence, the World Health Organization International Agency for Research on Cancer has stated that nitrate and nitrite are probably carcinogenic to humans when ingested under conditions favorable for endogenous nitrosation. Endogenous nitrosation is the process by which nitrate is consumed and converted by the human body into nitrite, which can morph into nitrosamines—compounds that can cause cancer. Other studies have shown a correlation between increased birth defects and consumption of drinking water with elevated nitrate while pregnant. While correlations may not prove cause and effect, the possibility of chronic health risk resulting from ingestion of nitrate-nitrogen must be considered. The connections between the level of nitrate in drinking water, volume ingested, duration of exposure, and possible chronic risks are not fully understood.

Livestock, especially cattle and hogs, are also susceptible to nitrate poisoning. In cattle, it results in lower milk production and loss of calves; in hogs, it results in loss of piglets. Dogs are also known to be susceptible to nitrate poisoning, resulting in loss of litters and decreased milk production.

Note: This publication is not a substitute for professional medical advice. If you have questions or concerns related to potential health effects from consuming water containing nitrate, consult your physician.

Testing

Testing Public Water Supplies

Public water supplies classified as either community or non-community are required to test for nitrate concentration. If water comes from a public water supply, users can contact the water utility to learn about the nitrate level in their water.

Testing Private Water Supplies

Water quality in private wells is not currently regulated by federal or state statutes; thus, the regular testing of a private water supply is not required under state or federal law. If users want to know the concentration of nitrate in a private water supply, they will need to have the water tested for a fee and on a confidential basis.

An initial test of a new water supply is recommended to determine the baseline nitrate concentration in the water source. Activities near a well potentially can contaminate the water supply, changing the nitrate concentration over time. Private drinking water wells should be tested annually to monitor changes in nitrate concentration. In addition, private drinking water wells should be tested any time an infant, pregnant woman, nursing mother, or elderly person begins to use the water supply. These groups are believed to be the most susceptible to nitrate health effects.

Tests to determine the presence of nitrate in drinking water should be done by a laboratory certified for nitrate testing. The Nebraska Department of Health and Human Services Public Health Environmental Laboratory) certifies laboratories to conduct tests for drinking water supplies. This approval means that recognized, standard test and quality control procedures are used. See *Drinking Water: Certified Water Testing Laboratories in Nebraska* (G1614) for a list of certified laboratories and contact information for each.

Some Nebraska Natural Resources Districts (NRDs) may offer assistance or cost-sharing to help well owners with water testing. Individuals can contact their NRD to find out if testing assistance is provided.

Laboratories not specifically certified to test for nitrate may use the same equipment and procedures as certified laboratories. Such laboratories may provide accurate analysis, but there is no independent information about the laboratory's ability to obtain reliable nitrate concentration results.

In addition, a variety of test kits and dip strips are available for nitrate testing outside of a laboratory environment. These might be used for preliminary "screening" and to raise awareness of nitrate issues. When using these tests, users should understand the nature of the test and the accuracy of the test results. While an estimate of nitrate concentration level might be obtained, laboratory analysis is needed for an accurate and reliable nitrate measurement.

To have water tested, private water well owners or users must select a laboratory and obtain a drinking water nitrate test kit from the laboratory. The kit will usually include a pre-preserved sample bottle, an information form, and sampling instructions. The sample bottle for nitrate testing may contain a preservative to prevent any loss of nitrate in the sample. This sample bottle should not be rinsed before filling and should only be used for samples intended for nitrate analysis. It must be used within 90 days to ensure validity of the analysis. The sampling instructions provide information on how to collect the sample. These instructions must be followed carefully to avoid contamination and to obtain a representative sample. The sample must be promptly mailed or delivered to the laboratory along with the completed information form.

Interpreting Test Results

Public Water Supply Test Results

The quality of water supplied by Public Water Systems is regulated by the EPA and the Nebraska Department of Environment and Energy(NDEE). This includes any well with 15 or more service connections or that serves 25 or more people on a regular basis.

Public drinking water standards established by EPA fall into two categories—Secondary Standards and Primary Standards. Secondary Standards are based on aesthetic factors such as taste, odor, color, corrosivity, foaming, and staining properties of water that may affect the suitability of a water supply for drinking and other domestic uses. Primary Standards are based on health considerations and are designed to protect human health. The EPA has established an enforceable Primary Standard for nitrate in public drinking water supplies.

The EPA Maximum Contaminant Level (MCL) is measured and reported as nitrate-nitrogen, (NO_3-N), which is the amount of nitrogen in the nitrate form. The MCL for nitrate-nitrogen in a public water supply is 10 milligrams per liter (mg/L) which can also be expressed as 10 parts per million (ppm). This drinking water standard was established to protect the health of infants and is based on risk assessment using the best knowledge available.

It is worth noting that the European standard is measured and reported as total nitrate ($NO_{3,}$) with a maximum allowable level of 40 mg/L or 40 ppm. The two reporting systems can be compared as follows:

$$1 \text{ mg/L nitrate-nitrogen } (NO_3\text{-N}) = 4.4 \text{ mg/L nitrate } (NO_{3.})$$

Therefore, the U.S. standard of 10 mg/L nitrate-nitrogen would be reported as 44 mg/L nitrate if the European reporting method was used, or the European standard of 40 mg/L nitrate would be reported as 9 mg/L nitrate-nitrogen if the U.S. reporting method was used.

Although not common, a few U.S. laboratories report total nitrate ($NO_{3.}$) rather than the more commonly used nitrate-nitrogen (NO_3-N) quantity. Because potential health risks are often unknown or hard to predict, many drinking water standards are set at some fraction of the level of "no observed adverse health effects." In general, the greater the uncertainty about potential health effects, the greater the margin of safety built into the standard. In the case of nitrate, there may not be a large safety factor.

Private Water Supply Test Results

While EPA and Nebraska regulations do not apply to private drinking water wells, users of private drinking water should consider the EPA guideline of 10 ppm nitrate-nitrogen when considering the risk associated with their water supply. If nitrate-nitrogen concentrations are found to be above 10 ppm, private drinking water users might voluntarily try to reduce the nitrate-nitrogen concentration in the water, taking into account health risks, cost, and benefits.

Options

Options for Public Water Supplies

If a test indicates that the nitrate-nitrogen concentration of public water exceeds the standard, the public must be notified and steps must be taken by the water supplier to bring the water into compliance. Often, the treatment may be as simple as blending the water that exceeds the standard with water that has a nitrate-nitrogen concentration less than 10 mg/L such that the average concentration of the delivered water is below the EPA standard. Another option for achieving compliance is water treatment, such as with ion exchange or reverse osmosis, to reduce the nitrate-nitrogen concentration. Biological filtration to remove nitrate has been successfully applied by public water systems in other states that have the managerial capacity to operate and monitor this advanced system. In some cases, compliance may be achieved by offering bottled water to vulnerable consumers in conjunction with developing a source water protection plan designed to eliminate or reduce the source of contamination, which should result in the reduction of nitrate-nitrogen concentration in the water supply over time. Public water systems cannot achieve compliance by supplying bottled water as the only means of addressing high nitrate levels.

The NDEE has the responsibility for implementing the federal requirements and can take action toward public water supplies that are not in compliance. This action includes Administrative Orders, a precursor to legal action. NDEE issues a Nitrate Administrative Order to public water systems exceeding 10 ppm twice in a three quarter period. At any given time, a very small percentage of public water supplies in Nebraska may have a nitrate concentration above 10 ppm, and some systems may be under Administrative Order for noncompliance with the MCL. NDEE requires any public water system exceeding 20 ppm in any sample to discontinue the use of the well and provide alternate safe water to all consumers until the concentration of nitrate is less than 20 ppm for two consecutive quarters.

Options for Private Water Supplies

If nitrate-nitrogen exceeds 10 ppm, users should consider that their water exceeds the EPA MCL for nitrate-nitrogen in drinking water. Also, users might consider that NDEE takes immediate action toward public water suppliers exceeding this concentration, and voluntarily consider an alternative drinking water source or water treatment. Decisions should be based on a nitrate analysis by a certified laboratory, and after consulting with a physician to help evaluate the level of risk.

It may be possible to obtain a satisfactory alternate water supply by drilling a new well in a different location or a deeper well in a different aquifer, especially if the nitrate contamination is from a point source such as livestock or human waste. If the water supply with high nitrate is coming from a shallow aquifer, there may be an uncontaminated, deeper aquifer protected by a clay layer that prevents the downward movement of the nitrate-contaminated water. A new well should be constructed so surface contamination cannot enter the well. It should be located away from any potential sources of contamination, such as septic systems or feedlots. Consult a Nebraska-licensed water well professional regarding this option. Another alternate source of water is bottled water that can be purchased in stores or direct from bottling companies. This alternative especially might be considered if the primary concern is water for infant food and drinking.

Drinking water can be treated for nitrate-nitrogen by three treatment methods: distillation, reverse osmosis, and ion exchange. Home treatment equipment using these processes is available from several manufacturers. **Carbon filters and standard water softeners do not remove nitrate-nitrogen. Merely boiling water does not remove nitrate-nitrogen. The act of boiling water for an extended period of time results in evaporation, and a decrease in water volume. The nitrate does not evaporate with the water, resulting in an increased nitrate-nitrogen concentration in the remaining volume of water**.

The distillation process involves heating the water to boiling and collecting and condensing the steam by means of a coil. This process can remove nearly 100 percent of the nitrate-nitrogen, since the nitrate-nitrogen does not volatilize with the steam. For information on this treatment method see NebGuide 1493, *Drinking Water Treatment: Distillation*.

In the reverse osmosis process, pressure is applied to water to force it through a semipermeable membrane. As the water passes through, the membrane filters out most of the impurities. This process can remove approximately 85 percent to 95 percent of the nitrate-nitrogen. Actual removal rates may vary, depending on the initial quality of the water, the system pressure, membrane technology, and water temperature. For information on this treatment method see NebGuide 1490, *Drinking Water Treatment: Reverse Osmosis*.

Ion exchange for nitrate-nitrogen removal operates on the same principle as a household water softener. However, for the nitrate-nitrogen removal process, special anion exchange resins are used that exchange chloride ions for nitrate and sulfate ions in the water as it passes through the resin. Since most anion exchange resins have a higher selectivity for sulfate than nitrate, the level of sulfate in the water is an important factor in the efficiency of an ion exchange system for removing nitrate-nitrogen.

Summary

Nitrate can be present in some water sources, most often as a result of point or nonpoint source pollution from fertilizer or human or animal waste. Proper well location and construction are key practices to avoiding nitrate contamination of drinking water. Management practices to reduce the risk of contamination from fertilizers and manure/sewage help keep the water supply safe. Ingesting drinking water containing nitrate-nitrogen can present an acute health risk, especially for infants. Public water supplies must comply with the EPA standard for nitrate-nitrogen of 10 ppm. Management of a private drinking water well for nitrate-nitrogen is a decision made by the well owner and/or water user. A water test is the only way to determine the nitrate-nitrogen concentration. If public drinking water exceeds the EPA nitrate-nitrogen standard, the utility must inform water users and must take steps to reduce the nitrate-nitrogen concentration. If private drinking water exceeds an acceptable nitrate-nitrogen concentration, choices are to use an alternate water supply or treat the water. An alternate supply may be bottled water or a new well in a different location or aquifer. Water treatment options include distillation, reverse osmosis, or ion exchange.

ACKNOWLEDGMENT

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Private Drinking Water Wells: Planning for Water Use

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This publication is one of six in a series designed to help rural families understand and manage their private drinking water supplies.

When planning for a private drinking water supply, it is important to determine if the well capacity will meet water demands. The well capacity — the amount of water that can be produced — must be accurately determined. A Nebraska-licensed water well professional can help determine the appropriate well flow rate — a measure of the gallons of water that can be produced per minute. The flow rate must be capable of providing the total quantity of water needed every day — the total daily demand. In addition, the flow rate should be sufficient to meet temporary large demands that occur throughout the day — the peak use demand. If the amount of water produced by the well is greater than the total daily demand, but the flow rate is insufficient to meet the peak use demand, intermediate storage can be used to supplement the water supply during peak use periods.

In addition, it is important to determine if the well water quality is adequate for its intended use. Drinking water does not need to be pure to be safe for consumption, hygiene, and other domestic uses. Whether drinking water is safe will depend on which substances are present and in what amounts. Water quality can be determined by having a sample tested by a certified laboratory. If water quality does not meet the minimum standard desired, water treatment may be an option.

Determining Well Capacity

A Nebraska-licensed water well professional can determine the yield of a well. The professional will pump the well continuously for an extended period. During the pumping period, measurements will be taken to determine the water level drop in the well relative to the rate at which water is being pumped out. The balance point will occur when the water level stops dropping as a given amount is pumped, providing the well yield in gallons per minute. Quantities of water produced by marginal aquifers are difficult to estimate by the contractor and sometimes wells do not yield as desired. There are several variables that cannot be easily accounted for when dealing with marginal aquifers. It is important to have realistic expectations when dealing with marginal aquifers.

Determining Water Quantity Needs

The quantity of water supplied by a private water supply must meet the total daily demand and all peak use demands. Both demands can be minimized with wise water use.

Total Daily Demand

The average American uses from 60 to 100 gallons of water per day. You can estimate the total daily domestic water demand by multiplying use (100 gallons per day) by the number of people that might reasonably be expected to live in the rural home. This gives an estimate of the total gallons per day that will be needed for domestic use. A more specific total daily demand can be calculated by using the water use estimates in *Table I*. Amounts are based on long-term national averages; actual water use may vary significantly.

The well flow rate (gallons per minute, or gpm) multiplied by the number of minutes in a day that the well pump will operate provides an estimate of the total gallons of water that will be produced each day. This amount must be equal to or greater than the total daily demand. Minimizing water use will reduce the total daily demand. To reduce demand, start with the fixtures and activities that use the largest volumes of water. The toilet, shower/bath, and clothes washer account for two-thirds of the water used in an average household.

Toilets installed after 1993 are water efficient. Toilet dams or water-filled plastic containers can be installed in older toilet tanks but the reduced flow can affect the effectiveness of a flush; you may have to flush two or three times to remove the waste. In older toilets, about 3 gallons of water may be needed in the tank to flush properly. Avoid placing bricks that crumble in the tank; they may affect operation. Reduce the number of toilet flushes by not using the toilet as a waste paper basket.

Table I. Water use estimates for household appliances and fixtures

Appliance or Fixture	*Typical Water Use*
Clothes washer — standard	40 to 50 gallons per load
Clothes washer — high efficiency	18 to 28 gallons per load
Dishwasher — standard	7 to 14 gallons per load
Dishwasher — high efficiency	4.5 to 7 gallons per load
Sink faucet — standard	3 to 5 gallons per minute of use
Sink faucet — low flow	2 gallons per minute of use
Toilet — standard	3.5 to 5 gallons per flush
Toilet — low-flush (Required Jan. 1, 1994)	1.6 gallons per flush
Shower — standard	6 to 8 gallons per minute of use
Shower — low-flow (Required Jan. 1, 1994)	2.5 gallons per minute of use
Garbage disposal	4 gallons per minute of use
Water softener regeneration	50 to 100 gallons per cycle
Backwash filters	100 to 200 gallons per backwash
Reverse osmosis filter	3 to 5 gallons per 1 gallon of treated water

eaks acco for a g eat volume of water usage. Abou 20 percent of toilets leak. To test for a leak, put a few drops of food dye in the tank. If, after 15 minutes, color appears in the bowl, there is a leak that should be repaired. Typically, the toilet flapper needs replacing or the water level needs adjusting.

The rate that water flows through fixtures will affect the amount of water used. Showerheads manufactured after 1993 have flow rates of no more than 2.5 gpm. Faucet aerators at sinks restrict the water going through the faucet by about 50 percent, adding air to make the flow appear the same. Faucet aerators with flow rates of 1.5 gpm or lower (½ - 1 gpm) are available.

Water-saving clothes washers use about ⅓ as much water as traditional washers. When purchasing a new washer, check the label to determine water efficiency. Try to narrow your options to those that are most efficient. Features to look for include the option of reusing water from one wash cycle for another wash cycle, and the ability to adjust water levels to accommodate different size loads or different degree of washing needed. When laundering, adjust water levels to the laundry load size and degree of soil. Typically, fewer full loads use less total water than several small loads.

Peak Use Demand

Water use will not be the same over the course of a day; it will fluctuate. Water systems must meet the needs of many uses during short periods of time. These times, called peak use periods, usually occur near mealtimes, during laundry periods, and when occupants are showering or bathing. The water system should be able to produce enough water to meet the peak demand for a period of two hours. If it cannot, intermediate storage can be used to supplement the water supply during peak use periods.

The *Private Water Systems Handbook*, developed by Midwest Plan Services[1], recommends the following minimum flow rates for homes to meet peak demand.

A minimum of 10 gpm is recomme ded for a 2-bedroom, 2-bath home. The minimum flow rate increases with additional bedrooms and/or baths since larger homes will be likely to have more residents using more fixtures and appliances at the same time. Other recommended minimum flow rates include:

3 bedrooms, 2 baths — 12 gpm
4 bedrooms, 3 baths — 16 gpm
5 bedrooms, 3 baths — 17 gpm

In general, add 2 gpm for each additional bedroom and 2 gpm for each additional bath.

Ideally, the yield of the well should exceed the recommended minimum flow rate. This is because the recommended minimum flow rate may not support the operation of multiple water-using devices at the same time, and some devices may require greater flow rates to operate properly. The *Private Water Systems Handbook* lists flow rate requirements for typical devices (*Table II*).

Table II. Typical flow rate requirements for household water-using devices. MWPS (Midwest Plan Service), Iowa State University, Ames, IA, *www.mwps.org*. Used with permission: Jones, D. *Private Water Systems Handbook.*

Device	*Typical Flow Rate Required for Operation*
Automatic washer	5 gpm
Dishwasher	2 gpm
Garbage disposal	3 gpm
Kitchen sink	3 gpm
Shower or tub	5 gpm
Toilet flush	3 gpm
Bathroom sink	2 gpm
Water softener regeneration	5 gpm
Backwash filters	10 gpm
Outside hose faucet	5 gpm
Outdoor lawn sprinkler system	12 gpm
Fire protection	10 gpm — preferred 20 gpm

[1]©MWPS (MidWest Plan Service), Iowa Sta e Universi y, Ames, IA., *www.mwps.org*. Used with permission: Jones, D., *Private Water Systems Handbook*.

awn sprinkler s stems place add onal demands on the system. Typical lawn sprinkler irrigation systems may require a 12-gpm flow rate to operate properly. This is in addition to that required to meet normal household needs.

Peak use demand can be reduced by changing the timing of water-using activities and spreading out water use. Spread out laundry, doing only one or two loads per day. Have some family members shower at night while others shower in the morning. Install low-flow water fixtures, and encourage short showers. Run the dishwasher at night after family members have gone to bed. Compost food wastes and avoid using a garbage disposal.

Conserving water and distributing water use over an extended period has the additional benefit of extending the life of a septic system. Wastewater generated by a household should remain in the septic tank long enough — at least 24 hours — for heavy solids to settle out, forming sludge, and light solids to float to the top, forming scum. Except for the period immediately after pumping, a septic tank contains wastewater to its full capacity at all times. As a gallon of wastewater flows into the tank from the house, a gallon of effluent flows out of the tank into the drainfield. If wastewater moves in and out of the tank too rapidly, due to constant flow for extended periods, or heavy water flow at any time, solids remain suspended in the wastewater. This means they may move with the effluent out of the tank and into the drainfield. Solids can clog a drainfield, decreasing its ability to treat wastewater. This can lead to costly repairs or even the need for replacement.

Determining and Protecting Water Quality

Drinking water is never pure. Water naturally contains minerals and microorganisms from the rocks, soil, and air with which it comes in contact. Human activities can add many more substances to water. Drinking water does not need to be pure to be safe, however. In fact, some dissolved minerals in water can be beneficial to health. For example, the National Research Council states that drinking water containing dissolved calcium and magnesium generally contributes a small amount toward human dietary needs. Naturally occurring fluoride in groundwater can help protect against tooth decay. Whether or not drinking water is safe will depend on which substances are present and in what amounts.

An ounce of protection is worth a pound of cure when it comes to the drinking water source. If wells are poorly located, constructed, or maintained, they can allow bacteria, nitrate, or other pollutants to contaminate the groundwater serving as the drinking water source.

Most acreages, farms, and ranches with private wells use septic systems or other onsite wastewater treatment systems for treating wastewater and returning it to the environment. If systems are poorly designed, located, constructed, or maintained, they can contribute to groundwater contamination.

Runoff is the water from rain, melting snow, or excess irrigation that moves across property. As it flows, runoff can collect and transport soil, pet waste, livestock manure, salt, pesticides, fertilizer, oil and grease, leaves, litter, and many other potential pollutants. Polluted runoff can flow down a poorly sealed or an unplugged well where it can con am nate groundwater. In areas with porous, sandy soi s, pollutants carried by runoff may percolate through the soil into groundwater.

Pesticides (herbicides, insecticides, fungicides, and rodenticides) and fertilizers (nitrate and phosphorus) play an important role in the management of rural property. If pesticides and fertilizers are not stored, handled, and applied correctly, they can seep through soil into groundwater.

Consider the variety of products used in households and on rural property — paints, solvents, oils, cleaners, wood preservatives, batteries, and adhesives. Also, consider the amount of these products that goes unused or is thrown away. Minimizing usage of these substances, along with practicing proper disposal procedures can protect groundwater, the source of drinking water.

For additional information on drinking water protection, see:

Protecting Private Drinking Water Supplies: An Introduction, *www.ianrpubs.unl.edu/sendIt/g2049.pdf*

Protecting Private Drinking Water Supplies: Water Well Location, Construction, Condition, and Management, *www.ianrpubs.unl.edu/sendIt/g2050.pdf*

Protecting Private Drinking Water Supplies: Household Wastewater (Sewage) Treatment System Management, *www.ianrpubs.unl.edu/sendIt/g2051.pdf*

Protecting Private Drinking Water Supplies: Hazardous Materials and Waste Management, *www.ianrpubs.unl.edu/sendIt/g2053.pdf*

Protecting Private Drinking Water Supplies: Pesticide and Fertilizer Storage and Handling, *www.ianrpubs.unl.edu/sendIt/g2054.pdf*

Protecting Private Drinking Water Supplies: Runoff Management. *www.ianrpubs.unl.edu/sendIt/g2052.pdf*

Testing Private Drinking Water

The quality of water provided by a private drinking water well can be determined through laboratory analysis. Several Nebraska laboratories offer testing services that include drinking water analysis. Some are operated by government agencies and others are private commercial laboratories.

Since there are many potential water contaminants, it would be very costly — and in most cases unnecessary — to test a private water supply for all of them. Tests for nitrate and bacteria often are used as general indicators of the safety of private well water. Generally, private water supplies should be checked annually for these contaminants. Tests for nitrate and bacteria do not guarantee the water is safe, however, as other contaminants could be present. Tests should be done for other substances when specific contamination is suspected. Contamination might be the result of a spill, backflow, use of product near the well, the presence of industrial or commercial activities in the vicinity of the well, the presence of a contaminant in neighboring wells, or other similar situations.

The safety and quality of private drinking water in Nebraska is not subject to any federal or state regulation. It is at the discretion of the water user except in cases where water quality is regulated at the local level or when state licensing may be required for a specific activity. Alt oug not required by federal or state regulations, the quality of private well water can be evaluated by com aring test results to water quality standards enforced for ublic drinking water sup lies.

The Federal Safe rinking Water Act directs the U.S. Environmental Protection Agency (EPA) to establis minimum national drinking water standards for public water supplies. These standards set limits on the amounts of various substances allowed in public drinking water. EPA regulations currently cover about 100 potential contaminants. Drinking water regulations established by EPA reflect the best available scientific and technical judgment. The number of contaminants regulated is increasing, and standards are re-evaluated as new data and information become available.

The maximum concentration of nitrate-nitrogen allowed in public water su plies is 10 milligrams er liter, which also can be reported as 10 parts per million. Public water supplies must be free of bacteria. While not required, users of private water supplies might strive to meet these standards.

For additional information on water qu lity, see:

An Introduction to Drinking Water, *www.ianrpubs.unl.edu/sendIt/g1539.pdf*

Drinking Water: Arsenic, *www.ianrpubs.unl.edu/sendIt/g1552.pdf*

Drinking Water: B cteria, *www.ianrpubs.unl.edu/sendIt/g1826.pdf*

Drinking Water: Copper, *www.ianrpubs.unl.edu/sendIt/g1360.pdf*

Drinking Water: Fluoride, *www.ianrpubs.unl.edu/sendIt/g1376.pdf*

Drinking Water: H rd Water (C lcium nd Magnesium), *www.ianrpubs.unl.edu/sendIt/g1274.pdf*

Drinking Water: Iron nd Manganese, *www.ianrpubs.unl.edu/sendIt/g1714.pdf*

Drinking Water: Lead, *www.ianrpubs.unl.edu/sendIt/g1333.pdf*

Drinking Water: Nitrate-Nitrogen, *www.ianrpubs.unl.edu/sendIt/g1784.pdf*

Drinking Water: Sulfur (Sulfates and Hydrogen Sulfide), *www.ianrpubs.unl.edu/sendIt/g1275.pdf*

Drinking Water: Uranium, *www.ianrpubs.unl.edu/sendIt/g1569.pdf*

If water quality does not meet the desired minimum standard, water treatment may be an o tion. No single piece of treatment equi ment manages all contaminants. All treatment methods have limitations and a situation may require a combination of treatment processes to effectively achieve the desired water quality.

For additional information on water tre tment, see:

Drinking Water Treatment: An Overview, *www.ianrpubs.unl.edu/sendIt/ec703.pdf*

Drinking Water Treatment: W at You Need to Know When Selecting Water Treatment Equipment, *www.ianrpubs.unl.edu/sendIt/g1488.pdf*

Drinking Water Tre tment: Sediment Filtration, *www.ianrpubs.unl.edu/sendIt/g1492.pdf*

Drinking Water Treatment: Carbon Filtration, *www.ianrpubs.unl.edu/sendIt/g1489.pdf*

Drinking Water Treatment: Water Softening (Ion Exchange), *www.ianrpubs.unl.edu/sendIt/g1491.pdf*

Drinking Water Treatment: Reverse Osmosis, *www.ianrpubs.unl.edu/sendIt/g1490.pdf*

Drinking Water Treatment: Distillation, *www.ianrpubs.unl.edu/sendIt/g1493.pdf*

Drinking Water Treatment: Continuous Chlorination, *www.ianrpubs.unl.edu/sendIt/g1496.pdf*

Drinking Water Tre tment: Shock Chlorination, *www.ianrpubs.unl.edu/sendIt/g1761.pdf*

Summary

When planning for a private drinking water supply, consider the quantity and quality of water that will be needed. The quantity of water supplied by a private water supply must meet the total daily demand and all peak use demands. Both total daily demand and peak use demands can be reduced with wise water use. The quality of a private drinking water supply is at the discretion of the user, and drinking water does not need to be pure to be safe. The quality of water can be evaluated by testing the water and com aring laboratory results to guidelines established for public water sup lies. If the water quality is less than desired, treatment may be an option.

Acknowledgments

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The Midwest Plan Service publication *Private Water Systems Handbook* provides additional information on private drinking water systems. The publication can be purchased from Midwest Plan Service, 122 Davidson Hall, Iowa State University, Ames, Iowa, 50011-3080; phone 800-562-3618; website *www.mwps.org*.

This publication has been peer reviewed.

UNL Extension public tions are available online at *http://extension.unl.edu/publications*.

Index: Water Management
Drinking Water

Issued May 2012

ONE HUNDRED YEARS OF

NEBRASKA NITROGEN

NITROGEN IS AN ESSENTIAL PLANT NUTRIENT BUT INCREASINGLY FOUND IN OUR WATER. HERE IS A BRIEF HISTORY

	GROUNDWATER	FERTILIZER
	Background levels of groundwater nitrate are <1 mg/L nitrate-N	Historically, nitrogen fertilizer only came from plant or animal sources
1909		Haber Bosch process developed for turning atmospheric nitrogen into inorganic ammonia
1920s	1921 - UNL Conservation and Survey established to study Nebraska water	Nebr. corn: 26 bushels/acre UNL Agricultural Experiment Station begins inorganic N research
1940s	1940 - Nitrate identified by State of Nebr. Dept. of Health as a problem in poorly built wells 1947 - Methemoglobinemia (blue baby) in infants investigated in Nebr. Medical Journal. First nitrate compound carcinogen research	Nebr. Corn: 26 bu/ac 1944 - UNL Extension's first inorganic N fertilizer soil fertility recommendations 1946 - UNL Soil Testing Lab opened 1947 - UNL recommends minimizing leaching loss with in-season N and efficient irrigation 1949 - Adding N through irrigation water begins
1950s	1951 - Research review suggests 10-20 mg/L nitrate-N limit in water used for infant formula	Nebr. irrigated corn: 60 bu/ac; 0.5 mill acres 1952 - Center pivot manufacturing begins
1960s	1962 - U.S. Public Health Service adopts 10 mg/L nitrate-N drinking water standard 1965 - Nebraska Water Quality Survey by UNL CSD finds pockets above 10 mg/L, attributed to coarse soils, irrigation, inorganic N fertilizer, shallow groundwater, and livestock manure	Nebr. irrigated corn: 80 bu/ac; 1.5 mill acres 1964 - UNL cautions "mounting evidence that many farmers are using more fertilizer nitrogen than necessary for best economic return." Water meters and soil moisture sensors recommended for irrigation scheduling
1970s	1971 -NE Dept of Environmental Control (now NDEE) 1972 - Nebr. Natural Resource Districts established and widespread nitrate testing begins 1974 - Safe Drinking Water Act adopts 10 mg/L nitrate-N maximum contaminant level	Nebr. irrigated corn: 110 bu/ac; 1.6 lb N/bu; 2.5 mill acres; about 10% irrigated by pivot 1979 - Inorganic N fertilizer identified as main nitrate source in Central Platte. First NRD irrigation water allocations
1980s	1981 - UNL Extension Nitrate Task Force 1984 - First adverse birth outcomes research 1985 - Nebraska Natural Resources Commission study identifies growing regions impacted. Groundwater Foundation established 1988 - Children's Groundwater Festivals begin	Nebr. irrigated corn: 125 bu/ac; 1.3 lb N/bu; 5 mill acres; about a third irrigated with center pivots 1985 - Groundwater Management & Protection Act 1987 - Central Platte NRD first quality policies 1989 - Bazile Triangle established in Northeast NE
1990s	1991 - Nitrate travel timing and amount estimated 1993 - Public Water Supplies required to provide drinking water below 10mg/L nitrate-N Creighton builds first reverse osmosis filtration 1996 - CDC Report on miscarriages from nitrate	Nebr. irrigated corn: 145 bu/ac; 1.2 lb N/bu; 0.15 inches water/bu; 5 mill acres 1992 - On-Farm Research program started 1994 - UNL Corn Nitrogen calculator 1993 - crop nitrogen sensors recommended 1999 - nitrate leaving corn rootzone 24-42 mg/L
2000s	2004 - International workgroup review of nitrate and health (updated 2018)	Nebr. irrigated corn: 165 bu/ac; 71% pivot 1.0 lb N/bu; 0.14" water/bu; 4.8 mill acres 2005 - Renewable Fuel Standard for ethanol
2010s	2010 - Int. Agency for Research on Cancer determines nitrate is probably carcinogenic 2013 - More than 1 out of 3 Nebr. irrigated acres have groundwater exceeding 10 mg/L	Nebr. irrigated corn: 190 bu/ac; 86% pivot 0.9 lb N/bu; 0.13" water/bu; 5.3 mill acres 2015 - Project SENSE, sensor-based N 2017 - UNL TAPS competition for N & irrigation
2020s	2023 - Nitrate shown to release uranium. EPA reopens evaluation of chronic health effects	Nebr. irrigated corn: 205 bu/ac; 91% pivot 2023 - nitrate leaving corn rootzone 17-22 mg/L

Author: Crystal Powers Reviewers: Dan Snow, Richard Ferguson Sources:

Nebraska Water Center
Daugherty Water for Food Global Institute
THE DAUGHERTY WATER for FOOD GLOBAL INSTITUTE at the University of Nebraska
N EXTENSION

NEBRASKA WATER FACTS

from the NEBRASKA WATER CENTER

Nebraska means "flat water" from the Omaha Sioux "ni braska" and Oto "ni brathge" describing the Platte River. The Platte River was named by early French explorers, also meaning "flat."

SURFACE WATER

- Nearly 80,000 miles of rivers and streams drain to the Missouri River in the East.
  - Along the Niobrara and Missouri Rivers, 197 miles are designated as National Wild and Scenic.
- Tallest waterfall is Smith Falls, spilling 63 feet into the Niobrara River.
- Largest storage reservoir: Lake McConaughy
  - When full is 1.74 million acre-feet of storage
  - Covers 30,500 acres
  - Created by the state's largest dam, Kingsley Dam
  - Supplies irrigation directly & indirectly for 530,000 ac
- More than 2,900 dams, >25 ft tall or 50 ac-ft storage

GROUNDWATER

Total groundwater state #1

- Mostly from the Ogallala Aquifer, part of the High Plains Aquifer.
  - Water among mostly sand and gravel.
  - From 1 to 1000+ feet thick.
  - Poured over the surface of the state, the water would be 38 feet deep.
- Groundwater and surface water are connected. For example:
  - More than 90% of the Loup Rivers' streamflow started as groundwater.
- Nebraska has more than 192,000 registered groundwater wells.

WATER USE

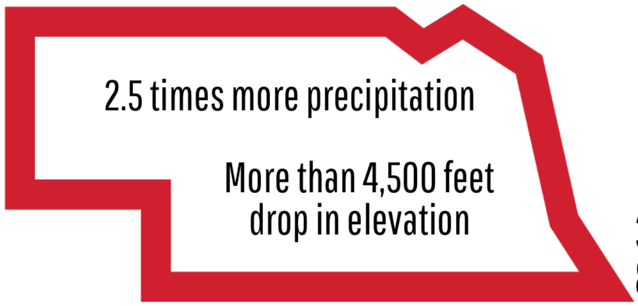
#1 Irrigated acres: 9.1 million

- Annual average additional crop value of $1.5 billion statewide. Added property valuation of $13-24 billion.
- Agriculture irrigation is 91% of Nebraska's total consumptive water use.
- From 1990 to 2014, Nebraska now grows 1.7 times more corn and 1.8 times more soybeans per gallon of water.
- From 1960 to 2016, Nebraska raises 1.8 times the amount of beef per gallon of water and 5.1 times more milk.
- Other uses of Nebraska's water:
  - home 5%; industrial 1%; thermoelectric 1%; livestock 1%
- 85% of Nebraskans get their home water from groundwater.
- 594 public water supply systems serve 1.69 million residents. EPA requires testing for 90 contaminants.
- More than 360,000 residents use private wells. Exempt from testing.
- Each person uses an average of 122 gallons of water each day.
  - Home water use has dropped by 1/3 in the last 20 years.

Center pivot irrigating soybeans. Photo: UNL

Changes West to East

13 inches precipitation
5,424 feet above sea level



33 inches precipitation
840 feet above sea level

Smith Falls. Photo: Nebraskaland Magazine.

RECREATION

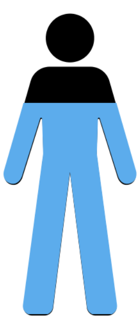
Lake McConaughy with >2 million visitors #1

- 7 out of top 10 Nebraska attractions involve water.
- Crane migration annual visitors' impact: $17.2 mill.

LAND USE

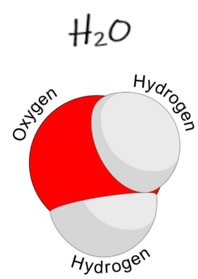
- Nebraska's farms and ranches utilize 44.8 million acres, 92% of the state's total land area.
- 22 million acres of rangeland and pastureland in Nebraska, half of which are in the Sandhills.
- 1/3 of Nebraska land is annual crops.
- Nebraska's cities and town cover about 1% of the land, less than wetlands and forest.

WATER SCIENCE



A person's body is 66% water

A corn plant is 80% water



Only substance found naturally as

liquid, solid, and gas

Author: Crystal A. Powers | Reviewers: Katie Pekarek, Gary Stone | Sources:

Nebraska Water Center
Daugherty Water for Food Global Institute
THE DAUGHERTY WATER for FOOD GLOBAL INSTITUTE at the University of Nebraska
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Review

Drinking Water Nitrate and Human Health: An Updated Review

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Abstract: Nitrate levels in our water resources have increased in many areas of the world largely due to applications of inorganic fertilizer and animal manure in agricultural areas. The regulatory limit for nitrate in public drinking water supplies was set to protect against infant methemoglobinemia, but other health effects were not considered. Risk of specific cancers and birth defects may be increased when nitrate is ingested under conditions that increase formation of *N*-nitroso compounds. We previously reviewed epidemiologic studies before 2005 of nitrate intake from drinking water and cancer, adverse reproductive outcomes and other health effects. Since that review, more than 30 epidemiologic studies have evaluated drinking water nitrate and these outcomes. The most common endpoints studied were colorectal cancer, bladder, and breast cancer (three studies each), and thyroid disease (four studies). Considering all studies, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Many studies observed increased risk with ingestion of water nitrate levels that were below regulatory limits. Future studies of these and other health outcomes should include improved exposure assessment and accurate characterization of individual factors that affect endogenous nitrosation.

Keywords: drinking water; nitrate; cancer; adverse reproductive outcomes; methemoglobinemia; thyroid disease; endogenous nitrosation; *N*-nitroso compounds

1. Introduction

Since the mid-1920s, humans have doubled the natural rate at which nitrogen is deposited onto land through the production and application of nitrogen fertilizers (inorganic and manure), the combustion of fossil fuels, and replacement of natural vegetation with nitrogen-fixing crops such as soybeans [1,2]. The major anthropogenic source of nitrogen in the environment is nitrogen fertilizer, the application of which increased exponentially after the development of the Haber–Bosch process in the 1920s. Most synthetic fertilizer applications to agricultural land occurred after 1980 [3]. Since approximately half of all applied nitrogen drains from agricultural fields to contaminate surface and groundwater, nitrate concentrations in our water resources have also increased [1].

The maximum contaminant level (MCL) for nitrate in public drinking water supplies in the United States (U.S.) is 10 mg/L as nitrate-nitrogen (NO_3-N). This concentration is approximately equivalent to the World Health Organization (WHO) guideline of 50 mg/L as NO_3 or 11.3 mg/L NO_3-N (multiply NO_3 mg/L by 0.2258). The MCL was set to protect against infant methemoglobinemia; however other health effects including cancer and adverse reproductive outcomes were not considered [4]. Through endogenous nitrosation, nitrate is a precursor in the formation of *N*-nitroso compounds (NOC); most NOC are carcinogens and teratogens. Thus, exposure to NOC formed after ingestion of nitrate from drinking water and dietary sources may result in cancer, birth defects, or other adverse health effects. Nitrate is found in many foods, with the highest levels occurring in some green leafy and root vegetables [5,6]. Average daily intakes from food are in the range of 30–130 mg/day as NO_3 (7–29 mg/day NO_3-N) [5]. Because NOC formation is inhibited by ascorbic acid, polyphenols, and other compounds present at high levels in most vegetables, dietary nitrate intake may not result in substantial endogenous NOC formation [5,7].

Studies of health effects related to nitrate exposure from drinking water were previously reviewed through early 2004 [8]. Further, an International Agency for Research on Cancer (IARC) Working Group reviewed human, animal, and mechanistic studies of cancer through mid-2006 and concluded that ingested nitrate and nitrite, under conditions that result in endogenous nitrosation, are probably carcinogenic [5]. Here, our objective is to provide updated information on human exposure and to review mechanistic and health effects studies since 2004. We summarize how the additional studies contribute to the overall evidence for health effects and we discuss what future research may be most informative.

2. Drinking Water Nitrate Exposures in the United States and Europe

Approximately 45 million people in the U.S. (about 14% of the population) had self-supplied water at their residence in 2010 [9]. Almost all (98%) were private wells, which are not regulated by the U.S. Environmental Protection Agency (EPA). The rest of the population was served by public water supplies, which use groundwater, surface water, or both. The U.S. Geological Survey's National Water Quality Assessment (USGS-NAWQA) Project [10] sampled principal groundwater aquifers used as U.S. public and private drinking water supplies in 1988–2015. Nitrate levels in groundwater under agricultural land were about three times the national background level of 1 mg/L NO_3-N (Figure 1) [11]. The mixed land use category mostly had nitrate concentrations below background levels reflecting levels in deeper private and public water supply wells. Based on the NAWQA study, it was estimated that 2% of public-supply wells and 6% of private wells exceeded the MCL; whereas, in agricultural areas, 21% of private wells exceeded the MCL [10]. The USGS-NAWQA study also revealed significant decadal-scale changes in groundwater nitrate concentrations among wells sampled first in 1988–2000 and again in 2001–2010 for agricultural, urban, and mixed land uses [12]. More sampling networks had increases in median nitrate concentration than had decreases.

A study of U.S. public water supplies (PWS) using data from EPA's Safe Drinking Water Information System estimated that the percentage of PWS violating the MCL increased from 0.28 to 0.42% during 1994–2009; most increases were for small to medium PWS (<10,000 population served) using groundwater [13]. As a result of increasing nitrate levels, some PWS have incurred expensive upgrades to their treatment systems to comply with the regulatory level [14–16].

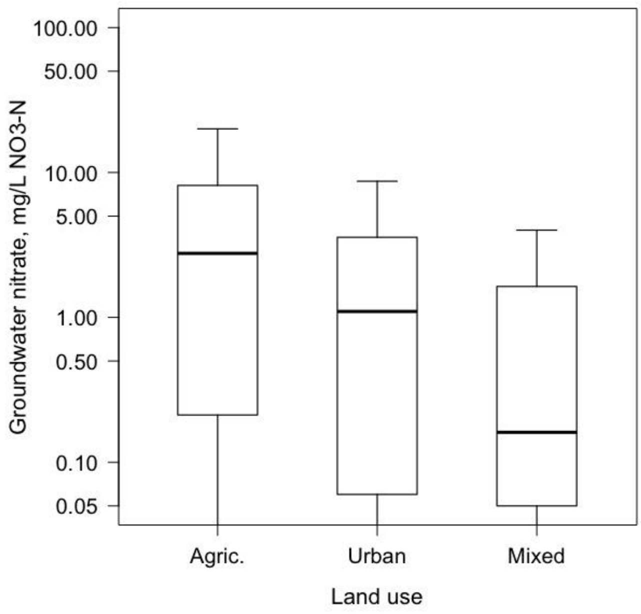

Figure 1. Boxplots of nitrate concentrations in shallow groundwater beneath agricultural and urban land uses, and at depths of private and public drinking water supplies beneath mixed land use. The number of sampled wells were 1573 (agricultural land), 1054 (urban), and 3417 (mixed). The agricultural and urban wells were sampled to assess land use effects, whereas the mixed category wells were sampled at depths of private and public supplies. Median depths of wells in the agricultural, urban, and mixed categories were 34, 32, and 200 feet, respectively. The height of the upper bar is 1.5 times the length of the box, and the lower bound was truncated at the nitrate detection limit of 0.05 mg/L NO_3-N.

In Europe, the Nitrates Directive was set in 1991 [17,18] to reduce or prevent nitrate pollution from agriculture. Areas most affected by nitrate pollution are designated as 'nitrate vulnerable zones' and are subject to mandatory Codes of Good Agricultural Practice [18]. The results of compliance with this directive have been reflected in the time trends of nitrate in some countries. For example, nitrate levels in groundwater in Denmark increased in 1950–1980 and decreased since the 1990s [19]. Average nitrate levels in groundwater in most other European countries have been stable at around 17.5 mg/L NO_3 (4 mg/L NO_3-N) across Europe over a 20-year period (1992–2012), with some differences between countries both in trends and concentrations. Average concentrations are lowest in Finland (around 1 mg/L NO_3 in 1992–2012) and highest in Malta (58.1 mg/L in 2000–2012) [20]. Average annual nitrate concentrations at river monitoring stations in Europe showed a steady decline from 2.7 NO_3-N in 1992 to 2.1 mg/L in 2012 [20], with the lowest average levels in Norway (0.2 mg/L NO_3-N in 2012) and highest in Greece (6.6 mg/L NO_3-N in 2012).

Levels in finished public drinking water have been published only for a few European countries. Trends of nitrate in drinking water supplies from 1976 to 2012 in Denmark showed a decline in public supplies but not in private wells [21]. In Spain, median concentrations were 3.5 mg/L NO_3 (range: 0.4−66.8) in 108 municipalities in 2012 [22], and 4.2 mg/L (range: <1−29) in 11 provinces in 2010 [23]. Levels in other countries included a median of 0.18 mg/L (range: <0.02−7.9) in Iceland in 2001−2012 [24], a mean of 16.1 mg/L (range: 0.05−296 mg/L) in Sicily, Italy in 2004−2005 [25] and a range from undetected to 63.3 mg/L in Deux-Sèvres, France in in 2005−2009 [26].

Nitrate levels in bottled water have been measured in a few areas of the EU and the U.S. and have been found to be below the MCL. In Sicily, the mean level was 15.2 mg/L NO_3(range: 1.2−31.8 mg/L) in 16 brands [25] and in Spain, the median level was 5.2 mg/L NO_3 (range: <1.0−29.0 mg/L) in 9 brands [23]. In the U.S., a survey of bottle water sold in 42 Iowa and 32 Texas communities found varying but generally low nitrate levels. Nitrate concentrations ranged from below the limit of detection (0.1 mg/L NO_3-N) to 4.9 mg/L NO_3-N for U.S. domestic spring water purchased in Texas.

There are few published studies of nitrate concentrations in drinking water outside the U.S. and Europe. Nitrate concentrations in groundwater were reported for Morocco, Niger, Nigeria, Senegal, India-Pakistan, Japan, Lebanon, Philippines and Turkey with maximum levels in Senegal (median 42.9 mg/L NO_3-N) [5]. In India, nitrate in drinking water supplies is particularly high in rural areas, where average levels have been reported to be 45.7 mg/L NO_3 [27,28] and 66.6 mg/L NO_3 [28]; maximum levels in drinking water exceeded 100 mg/L NO_3 in several regions [27,29]. Extremely high levels of nitrate have been reported in The Gaza Strip, where nitrate reached concentrations of 500 mg/L NO_3 in some areas, and more than 50% of public-supply wells had nitrate concentrations above 45 mg/L NO_3 [30].

3. Exposure Assessment in Epidemiologic Studies

With the implementation of the Safe Drinking Water Act in 1974, more than 40 years of monitoring data for public water supplies in the U.S. provide a framework of measurements to support exposure assessments. Historical data for Europe are more limited, but a quadrennial nitrate reporting requirement was implemented as part of the EU Nitrates Directive [17,18]. In the U.S., the frequency of sampling for nitrate in community water systems is stipulated by their sources (ground versus surface waters) and whether concentrations are below the MCL, and historically, by the size of the population served and vulnerability to nitrate contamination. Therefore, the exposure assessment for study participants who report using a public drinking water source may be based on a variable number of measurements, raising concerns about exposure misclassification. In a study of bladder cancer risk in Iowa, associations were stronger in sensitivity analyses based on more comprehensive measurement data [31]. Other studies have restricted analyses to subgroups with more complete or recent measurements [32–35], with implications for study power and possible selection biases. Sampling frequency also limits the extent to which temporal variation in exposure can be represented within a study population, such as the monthly or trimester-based estimates of exposure most relevant for etiologic investigations of adverse reproductive outcomes. In Denmark, limited seasonal variation in nitrate monitoring data suggested these data would sufficiently capture temporal variation for long-term exposure estimates [36]. Studies have often combined regulatory measurements with questionnaire and ancillary data to better characterize individual variation in nitrate exposure, such as to capture changes in water supply characteristics over time or a participant's duration at a drinking water source [31,33,37,38]. Most case-control studies of drinking water nitrate and cancer obtained lifetime residence and drinking water source histories, whereas cohort studies typically have collected only the current water source. Many studies lacked information about study participants' water consumption, which may be an important determinant of exposure to drinking water contaminants [39].

Due to sparse measurement data, exposures for individuals served by private wells are more difficult to estimate than exposures for those on public water supplies. However, advances in geographic-based modeling efforts that incorporate available measurements, nitrogen inputs, aquifer characteristics, and other data hold promise for this purpose. These models include predictor variables describing land use, nitrogen inputs (fertilizer applications, animal feeding operations), soils, geology, climate, management practices, and other factors at the scale of interest. Nolan and Hitt [40] and Messier et al. [41] used nonlinear regression models with terms representing nitrogen inputs at the land surface, transport in soils and groundwater, and nitrate removal by processes such as denitrification, to predict groundwater nitrate concentration at the national scale and for North Carolina, respectively. Predictor variables in the models included N fertilizer and manure, agricultural or forested land use, soils, and, in Nolan and Hitt [40], water-use practices and major geology. Nolan and Hitt [40] reported a training R^2 values of 0.77 for a model of groundwater used mainly for private supplies and Messier, Kane, Bolich and Serre [41] reported a cross-validation testing R^2 value of 0.33 for a point-level private well model. These and earlier regression approaches for groundwater nitrate [42–46] relied on predictor variables describing surficial soils and activities at the land surface, because conditions at depth in the aquifer typically are unknown. Redox conditions in the aquifer and the time since water entered the subsurface (i.e., groundwater age) are two of the most important factors affecting groundwater nitrate, but redox constituents typically are not analyzed, and age is difficult to measure. Even if a well has sufficient data to estimate these conditions, the data must be available for all wells in order to predict water quality in unsampled areas. In most of the above studies, well depth was used as a proxy for age and redox and set to average private or public-supply well depth for prediction.

Recent advances in groundwater nitrate exposure modeling have involved machine-learning methods such as random forest (RF) and boosted regression trees (BRT), along with improved characterization of aquifer conditions at the depth of the well screen (the perforated portion of the well where groundwater intake occurs). Tree-based models do not require data transformation, can fit nonlinear relations, and automatically incorporate interactions among predictors [47]. Wheeler et al. [48] used RF to estimate private well nitrate levels in Iowa. In addition to land use and soil variables, predictor variables included aquifer characteristics at the depth of the well screen, such as total thickness of fine-grained glacial deposits above the well screen, average and minimum thicknesses of glacial deposits near sampled wells, and horizontal and vertical hydraulic conductivities near the wells. Well depth, landscape features, nitrogen sources, and aquifer characteristics ranked highly in the final model, which explained 77% and 38% of the variation in training and hold-out nitrate data, respectively.

Ransom et al. [49] used BRT to predict nitrate concentration at the depths of private and public-supply wells for the Central Valley, California. The model used as input estimates of groundwater age at the depth of the well screen (from MODFLOW/MODPATH models) and depth-related reducing conditions in the groundwater. These estimates were generated by separate models and were available throughout the aquifer. Other MODFLOW-based predictor variables comprised depth to groundwater, and vertical water fluxes and the percent coarse material in the uppermost part of the aquifer where groundwater flow was simulated by MODFLOW. Redox variables were top-ranked in the final BRT model, which also included land use-based N leaching flux, precipitation, soil characteristics, and the MODFLOW-based variables described above. The final model retained 25 of an initial 145 predictor variables considered, had training and hold-out R^2 values of 0.83 and 0.44 respectively, and was used to produce a 3D visualization of nitrate in the aquifer. These studies show that modeling advances and improved characterization of aquifer conditions at depth are increasing our ability to predict nitrate exposure from drinking water supplied by private wells.

4. Nitrate Intake and Endogenous Formation of *N*-Nitroso Compounds

Drinking water nitrate is readily absorbed in the upper gastrointestinal tract and distributed in the human body. When it reaches the salivary glands, it is actively transported from blood into saliva and levels may be up to 20 times higher than in the plasma [50–53]. In the oral cavity 6–7% of the total nitrate can be reduced to nitrite, predominantly by nitrate-reducing bacteria [52,54,55]. The secreted nitrate as well as the nitrite generated in the oral cavity re-enter the gastrointestinal tract when swallowed.

Under acidic conditions in the stomach, nitrite can be protonated to nitrous acid (HNO_2), and subsequently yield dinitrogen trioxide (N_2O_3), nitric oxide (NO), and nitrogen dioxide (NO_2). Since the discovery of endogenous NO formation, it has become clear that NO is involved in a wide range of NO-mediated physiological effects. These comprise the regulation of blood pressure and blood flow by mediating vasodilation [56–58], the maintenance of blood vessel tonus [59], the inhibition of platelet adhesion and aggregation [60,61], modulation of mitochondrial function [62] and several other processes [63–66].

On the other hand, various nitrate and nitrite derived metabolites such as nitrous acid (HNO_2) are powerful nitrosating agents and known to drive the formation of NOC, which are suggested to be the causal agents in many of the nitrate-associated adverse health outcomes. NOC comprise *N*-nitrosamines and *N*-nitrosamides, and may be formed when nitrosating agents encounter *N*-nitrosatable amino acids, which are also from dietary origin. The nitrosation process depends on the reaction mechanisms involved, on the concentration of the compounds involved, the pH of the reaction environment, and further modifying factors, including the presence of catalysts or inhibitors of *N*-nitrosation [66–69].

Endogenous nitrosation can also be inhibited, for instance by dietary compounds like vitamin C, which has the capacity to reduce HNO_2 to NO; and alpha-tocopherol or polyphenols, which can reduce nitrite to NO [54,70–72]. Inhibitory effects on nitrosation have also been described for dietary flavonoids such as quercetin, ferulic and caffeic acid, betel nut extracts, garlic, coffee, and green tea polyphenols [73,74]. Earlier studies showed that the intake of 250 mg or 1 g ascorbic acid per day substantially inhibited *N*-nitrosodimethylamine (NDMA) excretion in 25 women consuming a fish meal rich in amines (nitrosatable precursors) for seven days, in combination with drinking water containing nitrate at the acceptable daily intake (ADI) [75]. In addition, strawberries, garlic juice, and kale juice were shown to inhibit NDMA excretion in humans [76]. The effect of these fruits and vegetables is unlikely to be due solely to ascorbic acid. Using the *N*-nitrosoproline (NPRO) test, Helser et al. [77] found that ascorbic acid only inhibited nitrosamine formation by 24% compared with 41–63% following ingestion of juices (100 mL) made of green pepper, pineapple, strawberry or carrot containing an equal total amount of ascorbic acid.

The protective potential of such dietary inhibitors depends not only on the reaction rates of *N*-nitrosatable precursors and nitrosation inhibitors, but also on their biokinetics, since an effective inhibitor needs to follow gastrointestinal circulation kinetics similar to nitrate [78]. It has been argued that consumption of some vegetables with high nitrate content, can at least partially inhibit the formation of NOC [79–81]. This might apply for green leafy vegetables such as spinach and rocket salad, celery or kale [77] as well as other vegetables rich in both nitrate and natural nitrosation inhibitors. Preliminary data show that daily consumption of one bottle of beetroot juice containing 400 mg nitrate (the minimal amount advised for athletes to increase their sports performances) for one day and seven days by 29 young individuals results in an increased urinary excretion of apparent total nitroso compounds (ATNC), an effect that can only be partially inhibited by vitamin C supplements (1 g per day) [82].

Also, the amount of nitrosatable precursors is a key factor in the formation of NOC. Dietary intakes of red and processed meat are of particular importance [83–87] as increased consumption of red meat (600 vs. 60 g/day), but not white meat, was found to cause a three-fold increase in fecal NOC levels [85]. It was demonstrated that heme iron stimulated endogenous nitrosation [84], thereby providing a possible explanation for the differences in colon cancer risk between red and white meat consumption [88]. The link between meat consumption and colon cancer risk is even stronger for nitrite-preserved processed meat than for fresh meat leading an IARC review to conclude that processed meat is carcinogenic to humans [89].

In a human feeding study [90], the replacement of nitrite in processed meat products by natural antioxidants and the impact of drinking water nitrate ingestion is being evaluated in relation to fecal excretion of NOC, accounting for intakes of meat and dietary vitamin C. A pilot study demonstrated that fecal excretion of ATNC increased after participants switched from ingesting drinking water with low nitrate levels to drinking water with nitrate levels at the acceptable daily intake level of 3.7 mg/kg. The 20 volunteers were assigned to a group consuming either 3.75 g/kg body weight (maximum 300 g per day) red processed meat or fresh (unprocessed) white meat. Comparison of the two dietary groups showed that the most pronounced effect of drinking water nitrate was observed in the red processed meat group. No inhibitory effect of vitamin C intake on ATNC levels in feces was found (unpublished results).

5. Methemoglobinemia

The physiologic processes that can lead to methemoglobinemia in infants under six months of age have been described in detail previously [8,91]. Ingested nitrate is reduced to nitrite by bacteria in the mouth and in the infant stomach, which is less acidic than adults. Nitrite binds to hemoglobin to form methemoglobin, which interferes with the oxygen carrying capacity of the blood. Methemoglobinemia is a life-threatening condition that occurs when methemoglobin levels exceed about 10% [8,91]. Risk factors for infant methemoglobinemia include formula made with water containing high nitrate levels, foods and medications that have high nitrate levels [91,92], and enteric infections [93]. Methemoglobinemia related to high nitrate levels in drinking water used to make infant formula was first reported in 1945 [94]. The U.S. EPA limit of 10 mg/L NO_3-N was set as about one-half the level at which there were no observed cases [95]. The most recent U.S. cases related to nitrate in drinking water were reported by Knobeloch and colleagues in the late 1990s in Wisconsin [96] and were not described in our prior review. Nitrate concentrations in the private wells were about two-times the MCL and bacterial contamination was not a factor. They also summarize another U.S. case in 1999 related to nitrate contamination of a private well and six infant deaths attributed to methemoglobinemia in the U.S. between 1979–1999 only one of which was reported in the literature [96,97]. High incidence of infant methemoglobinemia in eastern Europe has also been described previously [98,99]. A 2002 WHO report on water and health [100] noted that there were 41 cases in Hungary annually, 2913 cases in Romania from 1985–1996 and 46 cases in Albania in 1996.

Results of several epidemiologic studies conducted before 2005 that examined the relationship between nitrate in drinking water and levels of methemoglobin or methemoglobinemia in infants have been described previously [8]. Briefly, nitrate levels >10 mg/L NO_3-N were usually associated with increased methemoglobin levels but clinical methemoglobinemia was not always present. Since our last review, a cross-sectional study conducted in Gaza found elevated methemoglobin levels in infants on supplemental feeding with formula made from well water in an area with the highest mean nitrate concentration of 195 mg/L NO_3 (range: 18–440) compared to an area with lower nitrate concentration (mean: 119 mg/L NO_3; range 18–244) [101]. A cross-sectional study in Morocco found a 22% increased risk of methemoglobinemia in infants in an area with drinking water nitrate >50 mg/L (>11 as NO_3-N) compared to infants in an area with nitrate levels <50 mg/L nitrate [102]. A retrospective cohort study in Iowa of persons (aged 1–60 years) consuming private well water with nitrate levels <10 mg/L NO_3-N found a positive relationship between methemoglobin levels in the blood and the amount of nitrate ingestion [103]. Among pregnant women in rural Minnesota with drinking water supplies that were mostly $\leq$3 mg/L NO_3-N, there was no relationship between water nitrate intake and women's methemoglobin levels around 36 weeks' gestation [104].

6. Adverse Pregnancy Outcomes

Maternal drinking water nitrate intake during pregnancy has been investigated as a risk factor for a range of pregnancy outcomes, including spontaneous abortion, fetal deaths, prematurity, intrauterine growth retardation, low birth weight, congenital malformations, and neonatal deaths. The relation between drinking water nitrate and congenital malformations in offspring has been the most extensively studied, most likely because of the availability of birth defect surveillance systems around the world.

Our earlier review focused on studies of drinking water nitrate and adverse pregnancy outcomes published before 2005 [8]. In that review, we cited several studies on the relation between maternal exposure to drinking water nitrate and spontaneous abortion including a cluster investigation that suggested a positive association [105] and a case-control study that found no association [106]. These studies were published over 20 years ago. In the present review, we were unable to identify any recently published studies on this outcome. In Table 1, we describe the findings of studies published since 2004 on the relation between drinking water nitrate and prematurity, low birthweight, and congenital malformations. We report results for nitrate in the units (mg/L NO_3 or NO_3-N) that were reported in the publications. In a historic cohort study conducted in the Deux-Sèvres district (France), Migeot et al. [26] linked maternal addresses from birth records to community water system measurements of nitrate, atrazine, and other pesticides. Exposure to the second tertile of nitrate (14–27 mg/L NO_3) without detectable atrazine metabolites was associated with small-for-gestational age births (Odds Ratio (OR) 1.74, 95% CI 1.1, 2.8), but without a monotonic increase in risk with exposures. There was no association with nitrate among those with atrazine detected in their drinking water supplies. Within the same cohort, Albouy-Llaty and colleagues did not observe any association between higher water nitrate concentrations (with or without the presence of atrazine) and preterm birth [107].

Stayner and colleagues also investigated the relation between atrazine and nitrate in drinking water and rates of low birth weight and preterm birth in 46 counties in four Midwestern U.S. states that were required by EPA to measure nitrate and atrazine monthly due to prior atrazine MCL violations [108]. The investigators developed county-level population-weighted metrics of average monthly nitrate concentrations in public drinking water supplies. When analyses were restricted to counties with less than 20% private well usage (to reduce misclassification due to unknown nitrate levels), average nitrate concentrations during the pregnancy were associated with increased rates of very low birth weight (<1.5 kg Rate Ratio $(RR)_{\text{per 1 ppm}}$ = 1.17, 95% CI 1.08, 1.25) and very preterm births (<32 weeks $RR_{\text{per 1 ppm}}$ = 1.08, 95% CI 1.02, 1.15) but not with low birth weight or preterm birth overall.

In record-based prevalence study in Perth Australia, Joyce et al. mapped births to their water distribution zone and noted positive associations between increasing tertiles of nitrate levels and prevalence of term premature rupture of membranes (PROM) adjusted for smoking and socioeconomic status [109]. Nitrate concentrations were low; the upper tertile cut point was 0.350 mg/L and the maximum concentration was 1.80 mg/L NO_3-N. Preterm PROM was not associated with nitrate concentrations.

Among studies of drinking water nitrate and congenital malformations, few before 2005 included birth defects other than central nervous system defects [8]. More recently, Mattix et al. [110] noted higher rates of abdominal wall defects (AWD) in Indiana compared to U.S. rates for specific years during the period 1990–2002. They observed a positive correlation between monthly AWD rates and monthly atrazine concentrations in surface waters but no correlation with nitrate levels. Water quality data were obtained from the USGS-NAWQA project that monitors agricultural chemicals in streams and shallow groundwater that are mostly not used as drinking water sources. A case-control study of gastroschisis (one of the two major types of AWD), in Washington State [111] also used USGS-NAWQA measurements of nitrate and pesticides in surface water and determined the distance between maternal residences (zip code centroids) and the closest monitoring site with concentrations above the MCL for nitrate, nitrite, and atrazine. Gastrochisis was not associated with maternal proximity to surface water above the MCL for nitrate (>10 mg/L NO_3-N) or nitrite (>1 mg/L NO_2-N) but there was a positive relationship with proximity to sites with atrazine concentrations above the MCL. In a USA-wide study, Winchester et al. [112] linked the USGS-NAWQA monthly surface water nitrate and pesticide concentrations computed for the month of the last menstrual period with monthly rates of 22 types of birth defects in 1996–2002. Rates of birth defects among women who were estimated to have conceived during April through July were higher than rates among women conceiving in other months. In multivariable models that included nitrate, atrazine, and other pesticides, atrazine (but not nitrate or other pesticides) was associated with several types of anomalies. Nitrate was associated with birth defects in the category of "other congenital anomalies" (OR 1.18, 95% CI 1.14, 1.21); the authors did not specify what defects were included in this category. None of these three studies included local or regional data to support the assumption that surface water nitrate and pesticide concentrations correlated with drinking water exposures to these contaminants.

Using a more refined exposure assessment than the aforementioned studies, Holtby et al. [113] conducted a case-control study of congenital anomalies in an agricultural county in Nova Scotia, Canada. They linked maternal addresses at delivery to municipal water supply median nitrate concentrations and used kriging of monthly measurements from a network of 140 private wells to estimate drinking water nitrate concentrations in private wells. They observed no associations between drinking water nitrate and all birth defects combined for conceptions during 1987–1997. However, the prevalence of all birth defects occurring during 1998–2006 was associated with drinking water nitrate concentrations of 1–5.56 mg/L NO_3-N (OR 2.44, 95% CI 1.05, 5.66) and $\geq$5.56 mg/L (OR 2.25, 95% CI 0.92, 5.52).

None of the studies of congenital anomalies accounted for maternal consumption of bottled water or the quantity of water consumed during the first trimester, the most critical period of organ/structural morphogenesis. Attempting to overcome some of these limitations, Brender, Weyer, and colleagues [38,114] conducted a population-based, case-control study in the states of Iowa and Texas where they: (1) linked maternal addresses during the first trimester to public water utilities and respective nitrate measurements; (2) estimated nitrate intake from bottled water based on a survey of products consumed and measurement of nitrate in the major products; (3) predicted drinking water nitrate from private wells through modeling (Texas only); and (4) estimated daily nitrate ingestion from women's drinking water sources and daily consumption of water. The study populations were participants of the U.S. National Birth Defects Prevention Study [115]. Compared to the lowest tertile of nitrate ingestion from drinking water (<0.91 mg/day NO_3), mothers of babies with spina bifida were twice as likely (95% CI 1.3, 3.2) to ingest $\geq$5 mg/day NO_3 from drinking water than control mothers. Mothers of babies with limb deficiencies, cleft palate, and cleft lip were, respectively, 1.8 (95% CI 1.1, 3.1), 1.9 (95% CI 1.2, 3.1), and 1.8 (95% CI 1.1, 3.1) times more likely to ingest $\geq$5.4 mg/day of water NO_3 than controls. Women were also classified by their nitrosatable drug exposure during the first trimester [116] and by their daily nitrate and nitrite intake based on a food frequency questionnaire [117]. Higher ingestion of drinking water nitrate did not strengthen associations between maternal nitrosatable drug exposure and birth defects in offspring [38]. However, a pattern was observed of stronger associations between nitrosatable drug exposure and selected birth defects for women in the upper two tertiles of total nitrite ingestion that included contributions from drinking water nitrate and dietary intakes of nitrate and nitrite compared to women in the lowest tertile. Higher intake of food nitrate/nitrite was found to also modify the associations of nitrosatable drug exposure and birth defects in this study [118,119] as well as in an earlier study of neural tube defects conducted in south Texas [120]. Multiplicative interactions were observed between higher food nitrate/nitrite and nitrosatable drug exposures for conotruncal heart, limb deficiency, and oral cleft defects [118].

In summary, five out of six studies, conducted since the 1980s of drinking water nitrate and central nervous system defects, found positive associations between higher drinking water nitrate exposure during pregnancy and neural tube defects or central nervous system defects combined [38,120–123]. The sixth study, which did not find a relationship, did not include measures of association, but compared average drinking water nitrate concentrations between mothers with and without neural tube defect-affected births, which were comparable [124].

Table 1. Studies of drinking water nitrate [a] and adverse pregnancy outcomes published January 2005–March 2018.

First Author, Year, Country	Study Design Regional Description	Years of Outcome Ascertainment	Exposure Description	Pregnancy Outcome	Summary of Findings
Albouy-Llaty, 2016 France [107]	Historic cohort study Deux-Sèvres	2005–2010	Measurements of atrazine metabolites and NO_3 in community water systems (263 municipalities) were linked to birth addresses	Preterm birth	No association for >26.99 mg/L vs. <14.13 mg/L NO_3 in community water systems with or without atrazine detections, adjusted for neighborhood deprivation
Brender, 2013 Weyer, 2014 USA [38]	Population-based case-control study Iowa and Texas	1997–2005	Maternal addresses during the first trimester linked to public water utility nitrate measurements; nitrate intake from bottled water estimated with survey and laboratory testing; nitrate from private wells predicted through modeling; nitrate ingestion (NO_3) estimated from reported water consumption	Congenital heart defects Limb deficiencies Neural tube defects Oral cleft defects	$\geq$5 vs. <0.91 mg/day NO_3 from drinking water spina bifida OR = 2.0 (95% CI: 1.3, 3.2) $\geq$5.42 vs. <1.0 mg/day NO_3 from water: limb deficiencies OR = 1.8 (CI: 1.1, 3.1); cleft palate OR = 1.9 (CI: 1.2, 3.1) cleft lip OR = 1.8 (CI: 1.1, 3.1)
Holtby, 2014 Canada [113]	Population-based case-control study Kings County, Nova Scotia	1988–2006	Maternal addresses at delivery linked to municipal water supply median nitrate (NO_3-N) concentrations; nitrate in rural private wells estimated from historic sampling and kriging	Congenital malformations combined into one group	Conceptions in 1987–1997: no association with nitrate concentrations Conceptions in 1998–2006: 1–5.56 mg/L NO_3-N (vs. <1 mg/L) OR = 2.44 (CI: 1.05, 5.66); $\geq$5.56 mg/L OR = 2.25 (CI: 0.92, 5.52)
Joyce, 2008 Australia [109]	Record-based prevalence study Perth	2002–2004	Linked birth residences to 24 water distribution zones; computed average NO_3-N mg/L from historical measurements; independent sampling conducted for 6 zones as part of exposure validation; also evaluated trihalomethanes (THM)	Premature rupture of membranes at term (PROM) (37 weeks' gestation or later)	ORs for tertiles (vs. <0.125 mg/L NO_3-N): 0.125–0.350 mg/L OR = 1.23 (CI: 1.03, 1.52); >0.350 mg/L OR = 1.47 (CI: 1.20, 1.79) No association with THM levels
Mattix, 2007 USA [110]	Ecologic study Indiana	1990–2002	Monthly abdominal wall defect rates linked to monthly surface water nitrate and atrazine concentrations (USGS-NAWQA monitoring data [b])	Abdominal wall birth defects	No correlation observed between nitrate levels in surface water and monthly abdominal wall defects Positive correlation with atrazine levels

Table 1. *Cont.*

First Author, Year, Country	Study Design Regional Description	Years of Outcome Ascertainment	Exposure Description	Pregnancy Outcome	Summary of Findings
Migeot, 2013 France [26]	Historic cohort study Deux-Sèvres	2005–2009	Measurements of atrazine metabolites and NO_3 in community water systems (263 municipalities) were linked to birth addresses	Small-for-gestational age (SGA) births	ORs for tertiles (vs. <14.13 mg/L NO_3) in community water systems with no atrazine detections: 14–27 mg/L OR = 1.74 (CI: 1.10, 2.75); >27 mg/L OR = OR 1.51 (CI: 0.96, 2.4); no association with nitrate when atrazine was detected
Stayner, 2017 USA [108]	Ecologic study 46 counties in Indiana, Iowa, Missouri, and Ohio	2004–2008	Counties had one or more water utility in EPA's atrazine monitoring program; excluded counties with >20% of population on private wells and >300,000 population. Computed county-specific monthly weighted averages of NO_3-N in finished drinking water; exposure metric was average 9 months prior to birth	Preterm birth Low birth weight	Average nitrate not associated with low birth weight and preterm birth Very low birth weight: RR for 1 ppm increase in NO_3-N = 1.17 (CI: 1.08, 1.25); Very preterm birth RR for 1 ppm increase = 1.08 (CI: 1.02, 1.15)
Waller, 2010 USA [111]	Population-based case-control study Washington State	1987–2006	Calculated distance between maternal residence and closest stream monitoring site with concentrations >MCL for NO_3-N, NO_2-N, or atrazine in surface water (USGS-NAWQA data [b])	Gastroschisis	Gastroschisis was not associated with maternal residential proximity to surface water with elevated nitrate (>10 mg/L) or nitrite (>1 mg/L)
Winchester, 2009 USA [112]	Ecologic study USA-wide	1996–2002	Rates of combined and specific birth defects (computed by month of last menstrual period) linked to monthly surface water nitrate concentrations (USGS-NAWQA data [b]); also evaluated atrazine and other pesticides (combined)	Birth defects categorized into 22 groups	Birth defect category "other congenital anomalies": OR for continuous log nitrate = 1.15 (CI: 1.12, 1.18); adjusted for atrazine and other pesticides: OR = 1.18, CI: 1.14, 1.21); No association with other birth defects

Abbreviations: CI, 95% CI confidence interval; OR, odds ratio; RR, rate ratio; USGS-NAWQA, U. S. Geological Survey National Water Quality Assessment; [a] nitrate units are specified as reported in publications. NO_3 can be converted to NO_3-N by multiplying by 0.2258; [b] USGS-NAWQA data for 186 streams in 51 hydrological study areas; streams were not drinking water sources.

7. Cancer

Most early epidemiologic studies of cancer were ecologic studies of stomach cancer mortality that used exposure estimates concurrent with the time of death. Results were mixed, with some studies showing positive associations, many showing no association, and a few showing inverse associations. The results of ecologic studies through 1995 were reviewed by Cantor [125]. Our previous review included ecologic studies of the brain, esophagus, stomach, kidney, ovary, and non-Hodgkin lymphoma (NHL) published between 1999 and 2003 that were largely null [8]. We did not include ecologic studies or mortality case-control studies in this review due to the limitations of these study designs, especially their inability to assess individual-level exposure and dietary factors that influence the endogenous formation of NOC.

Since our review of drinking water nitrate and health in 2005 [8], eight case-control studies and eight analyses in three cohorts have evaluated historical nitrate levels in PWS in relation to several cancers. Nitrate levels were largely below 10 mg/L NO_3-N. Most of these studies evaluated potential confounders and factors affecting nitrosation. Table 2 shows the study designs and results of studies published from 2005 through 2018, including findings from periodic follow-ups of a cohort study of postmenopausal women in Iowa (USA) [31,37,126–129]. In the first analysis of drinking water nitrate in the Iowa cohort with follow-up through 1998, Weyer and colleagues [130] reported that ovarian and bladder cancers were positively associated with the long-term average PWS nitrate levels prior to enrollment (highest quartile average 1955–1988: >2.46 mg/L NO_3-N). They observed inverse associations for uterine and rectal cancer, but no associations with cancers of the breast, colon, rectum, pancreas, kidney, lung, melanoma, non-Hodgkin lymphoma (NHL), or leukemia. Analyses of PWS nitrate concentrations and cancers of the thyroid, breast, ovary, bladder, and kidney were published after additional follow-up of the cohort. The exposure assessment was improved by: (a) the computation of average nitrate levels and years of exposure at or above 5 mg/L NO_3-N, based on time in residence (vs. one long-term PWS average nitrate estimate used by Weyer and colleagues); and (b) by estimation of total trihalomethanes (TTHM) and dietary nitrite intake.

Thyroid cancer was evaluated for the first time after follow-up of the cohort through 2004. A total of 40 cases were identified [37]. Among women with >10 years on PWS with levels exceeding 5 mg/L NO_3-N for five years or more, thyroid cancer risk was 2.6 times higher than that of women whose supplies never exceeded 5 mg/L. With follow-up through 2010, the risk of ovarian cancer remained increased among women in the highest quartile of average nitrate in PWS [129]. Ovarian cancer risk among private well users was also elevated compared to the lowest PWS nitrate quartile. Associations were stronger when vitamin C intake was below median levels with a significant interaction for users of private wells. Overall, breast cancer risk was not associated with water nitrate levels with follow-up through 2008 [128]. Among women with folate intake $\geq$ 400 μg/day, risk was increased for those in the highest average nitrate quintile (Hazard Ratio (HR) = 1.40; 95% CI: = 1.05–1.87) and among private well users (HR = 1.38; 95% CI: = 1.05–1.82), compared to those with the lowest average nitrate quintile. There was no association with nitrate exposure among women with lower folate intake. With follow-up through 2010, there were 130 bladder cancer cases among women who had used PWS >10 years. Risk remained elevated among women with the highest average nitrate levels and was 1.6 times higher among women whose drinking water concentration exceeded 5 mg/L NO_3-N for at least four years [31]. Risk estimates were not changed by adjustment for TTHM, which are suspected bladder cancer risk factors. Smoking, but not vitamin C intake, modified the association with nitrate in water; increased risk was apparent only in current smokers (p-interaction <0.03). With follow-up through 2010, there were 125 kidney cancer cases among women using PWS; risk was increased among those in the 95th percentile of average nitrate (>5.0 mg/L NO_3-N) compared with the lowest quartile (HR = 2.2, 95% CI: 1.2–4.2) [127]. There was no positive trend with the average nitrate level and no increased risk for women using private wells, compared to those with low average nitrate in their public supply. An investigation of pancreatic cancer in the same population (follow-up through 2011) found no association with average water nitrate levels in public supplies and no association among women on private wells [126].

In contrast to the positive findings for bladder cancer among the cohort of Iowa women, a cohort study of men and women aged 55–69 in the Netherlands with lower nitrate levels in PWS found no association between water nitrate ingestion (median in top quintile = 2.4 mg/day NO_3-N) and bladder cancer risk [131]. Dietary intake of vitamins C and E and history of cigarette smoking did not modify the association. A hospital-based case-control study of bladder cancer in multiple areas of Spain [33] assessed lifetime water sources and usual intake of tap water. Nitrate levels in PWS were low, with almost all average levels below 2 mg/L NO_3-N. Risk of bladder cancer was not associated with the nitrate level in drinking water or with estimated nitrate ingestion from drinking water, and there was no evidence of interaction with factors affecting endogenous nitrosation.

Several case-control studies conducted in the Midwestern U.S. obtained lifetime histories of drinking water sources and estimated exposure for PWS users. In contrast to findings of an increased risk of NHL associated with nitrate levels in Nebraska PWS in an earlier study [132], there was no association with similar concentrations in public water sources in a case-control study of NHL in Iowa [35]. A study of renal cell carcinoma in Iowa [34] found no association with the level of nitrate in PWS, including the number of years that levels exceeded 5 or 10 mg/L NO_3-N. However, higher nitrate levels in PWS increased risk among subgroups who reported above the median intake of red meat intake or below the median intake of vitamin C (p-interaction <0.05). A small case-control study of adenocarcinoma of the stomach and esophagus among men and women in Nebraska [133] estimated nitrate levels among long-term users of PWS and found no association between average nitrate levels and risk.

A case-control study of colorectal cancer among rural women in Wisconsin estimated nitrate levels in private wells using spatial interpolation of nitrate concentrations from a 1994 water quality survey and found increased risk of proximal colon cancer among women estimated to have nitrate levels >10 mg/L NO_3-N compared to levels < 0.5 mg/L. Risk of distal colon cancer and rectal cancer were not associated with nitrate levels [134]. Water nitrate ingestion from public supplies, bottled water, and private wells and springs over the adult lifetime was estimated in analyses that pooled case-control studies of colorectal cancer in Spain and Italy [135]. Risk of colorectal cancer was increased among those with >2.3 mg/day NO_3-N (vs. <1.1 mg/day). There were no interactions with red meat, vitamins C and E, and fiber except for a borderline interaction (p-interaction = 0.07) for rectum cancer with fiber intake. A small hospital-based case-control study in Indonesia found that drinking water nitrate levels above the WHO standard (>11.3 mg/L as NO_3-N) was associated with colorectal cancer [136]. A national registry-based cohort study in Denmark [32] evaluated average nitrate concentrations in PWS and private wells in relation to colorectal cancer incidence among those whose 35th birthday occurred during 1978–2011. The average nitrate level was computed over residential water supplies from age 20 to 35. Increased risks for colon and rectum cancer were observed in association with average nitrate levels $\geq$9.25 mg/L NO_3 ($\geq$2.1 as NO_3-N) and $\geq$3.87 mg/L NO_3 (>0.87 as NO_3-N), respectively, with a significant positive trend. Because the study did not interview individuals, it could not evaluate individual-level risk factors that might influence endogenous nitrosation.

A case-control study of breast cancer in Cape Cod, Massachusetts (US) [137] estimated nitrate concentrations in PWS over approximately 20 years as an historical proxy for wastewater contamination and potential exposure to endocrine disruption compounds. Average exposures >1.2 mg/L NO_3-N (vs. <0.3 mg/L) were not associated with risk. A hospital-based case-control study in Spain found no association between water nitrate ingestion and pre- and post-menopausal breast cancers [138].

Table 2. Case-control and cohort studies of drinking water nitrate and cancer (January 2004–March 2018) by cancer site.

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Zeegers, 2006 Netherlands [131]	Cohort Incidence, 1986–1995 204 municipal registries across the Netherlands	1986 nitrate level in 364 pumping stations, exposure data available for 871 cases, 4359 members of the subcohort	Bladder	Highest vs. lowest quintile intake from water ($\geq$1.7 mg/day NO_3-N [median 2.4 mg/day] vs. <0.20) RR = 1.11 (CI: 0.87–1.41; *p*-trend = 0.14)	No interaction with vitamin C, E, smoking
Espejo-Herrera, 2015 Spain [33]	Hospital-based multi-center case-control Incidence, 1998–2001 Asturias, Alicante, Barcelona, Vallès-Bages, Tenerife provinces	Nitrate levels in PWS (1979–2010) and bottled water (measurements of brands with highest consumption based on a Spanish survey); analyses limited to those with $\geq$70% of residential history with nitrate estimate (531 cases, 556 controls)	Bladder	Highest vs. lowest quartile average level (age 18-interview) ($\geq$2.26 vs. 1.13 mg/L NO_3-N) OR = 1.04 (CI: 0.60–1.81) Years >2.15 mg/L NO_3-N (75th percentile) (>20 vs. 0 years) OR = 1.41 (CI: 0.89–2.24)	No interaction with vitamin C, E, red meat, processed meat, average THM level
Jones, 2016 USA [31]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence with nitrate and trihalomethane estimates (20,945 women; 170 bladder cases); no measurements for private wells Adjusted for total trihalomethanes (TTHM)	Bladder	Highest vs. lowest quartile PWS average ($\geq$2.98 vs. <0.47 mg/L NO_3-N) HR = 1.47 (CI: 0.91–2.38; *p*-trend = 0.11) Years >5 mg/L ($\geq$4 years vs. 0) HR = 1.61 (CI: 1.05–2.47; *p*-trend = 0.03) Private well users (vs. <0.47 mg/L NO_3-N on PWS) HR = 1.53 (CI: 0.93–2.54)	Interaction with smoking (*p*-interaction = 0.03); HR = 3.67 (CI: 1.43–9.38) among current smokers/$\geq$2.98 mg/L vs. non-smokers/<0.47 mg/L NO_3-N); No interaction with vitamin C, TTHM levels
Mueller, 2004 USA, Canada, France, Italy, Spain [139]	Pooled case-control studies Incidence among children <15 years (USA <20 years) 7 regions of 5 countries	Water source during pregnancy and first year of child's life (836 cases, 1485 controls); nitrate test strip measurements of nitrate and nitrite for pregnancy home (except Italy) (283 cases, 537 controls; excluding bottled water users: 207 cases, 400 controls)	Brain, childhood	Private well use versus PWS associated with increased risk in 2 regions and decreased risk in one; No association with nitrate levels in water supplies Astrocytomas (excludes bottled water users): $\geq$1.5 vs. <0.3 mg/L NO_2-N OR = 5.7 (CI: 1.2–27.2)	Not described
Brody, 2006 USA [137]	Case-control Incidence, 1988–1995 Cape Cod, Massachusetts	Nitrate levels in public water supplies (PWS) since 1972 was used as an indicator of wastewater contamination and potential mammary carcinogens and endocrine disrupting compounds; excluded women on private wells	Breast	Average $\geq$1.2 mg/L NO_3-N vs. <0.3 OR = 1.8, (CI: 0.6–5.0); summed annual NO_3-N $\geq$ 10 vs. 1–< 10 mg/L OR = 0.9, CI: 0.6–1.5); number of years >1 mg/L NO_3-N $\geq$8 vs. 0 years OR = 0.9 (CI: 0.5–1.5)	Not described

Table 2. *Cont.*

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Inoue-Choi, 2012 USA [128]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2008 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence (20,147 women; 1751 breast cases); no measurements for private wells	Breast	Highest vs. lowest quintile PWS average (≥3.8 vs. ≤0.32 mg/L NO_3-N) HR = 1.14 (CI: 0.95–1.36; *p*-trend = 0.11); Private well (vs. ≤ 0.32 mg/L NO_3-N) HR = 1.14 (CI: 0.97–1.34); Private well (vs. ≤0.32 mg/L NO_3-N on PWS) HR = 1.38 (CI: 1.05–1.82); No association among those with low folate <400 µg/day	Interaction with folate for PWS (*p*-interaction = 0.06). Folate ≥400 µg/d: (≥3.8 vs. ≤0.32 mg/L NO_3-N) HR = 1.40 (CI: 1.05–1.87; *p*-trend = 0.04)
Espejo-Herrera, 2016 Spain [138]	Hospital-based multi-center case-control Incidence, 2008–2013 Spain (8 provinces)	Nitrate levels in PWS (2004–2010), bottled water measurements and private wells and springs (2013 measurements in 21 municipalities in León, Spain, the area with highest non-PWS use) Analyses include women with ≥70% of period from age 18 to 2 years before interview (1245 cases, 1520 controls)	Breast	Water nitrate intake based on average nitrate levels (age 18 to 2 years prior to interview) and water intake (L/day). Post-menopausal women: >2.0 vs. 0.5 mg/day NO_3-N OR = 1.32 (0.93–1.86); Premenopausal women: >1.4 vs. 0.4 mg/day NO_3-N OR = 1.14 (0.67–1.94)	No interaction with red meat, processed meat, vitamin C, E, smoking for pre- and post-menopausal women
McElroy, 2008 USA [134]	Population-based case-control, women Incidence, 1990–1992 and 1999–2001 Wisconsin	Limited to women in rural areas with no public water system (475 cases, 1447 controls); nitrate levels at residence (presumed to be private wells) estimated by kriging using data from a 1994 representative sample of 289 private wells	Colorectal	All colon cancers: Private wells ≥10.0 mg/L NO_3-N vs. <0.5 OR = 1.52 (CI: 0.95–2.44); Proximal colon cancer: OR = 2.91 (CI: 1.52–5.56)	Not described
Espejo-Herrera, 2016 Spain, Italy [135]	Multi-center case-control study Incidence, 2008–2013 Spain (9 provinces) and population-based controls; Italy (two provinces) and hospital-based controls	Nitrate levels in PWS (2004–2010) for 349 water supply zones, bottled water (measured brands with highest consumption), and private wells and springs (measurements in 2013 in 21 municipalities in León, Spain, the area with highest non-PWS use) Analyses include those with nitrate estimates for ≥70% of period 30 years before interview (1869 cases, 3530 controls)	Colorectal	Water nitrate intake based on average nitrate levels (estimated 30 to 2 years prior to interview) and water intake (L/day) Highest vs. lowest exposure quintiles (≥2.3 vs. <1.1 mg /day NO_3-N) OR = 1.49 (CI:1.24–1.78); Colon OR = 1.52 (CI: 1.24–1.86), Rectum OR = 1.62 (CI: 1.23–2.14)	Interaction with fiber for rectum (*p*-interaction = 0.07); >20 g/day fiber + >1.0 mg/L NO_3-N vs. <20 g/day + ≤1.0 mg/L HR = 0.72 (CI: 0.52–1.00). No interaction with red meat, vitamin C, E

Table 2. *Cont*.

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Fathmawati, 2017 Indonesia [136]	Hospital-based case-control Incidence, 2014–2016 Indonesia (3 provinces)	Nitrate levels in well water collected during the raining season (Feb-March 2016) and classified based on >11.3 or ≤11.3 mg/L as NO_3-N and duration of exposure >10 and ≤10 years Analyses included participants who reported drinking well water (75 cases, 75 controls)	Colorectal	Water nitrate > WHO standard vs. below (> 11.3 vs. ≤11.3 mg/L NO_3-N) OR = 2.82 (CI: 1.08–7.40); > 10 years: 4.31 (CI: 11.32–14.10); ≤10 years: 1.41 (CI: 0.14–13.68)	Not described
Schullehner, 2018 Denmark [32]	Population-based record-linkage cohort of men and women ages 35 and older, 1978–2011 Denmark	Nitrate levels in PWS and private wells among 1,742,321 who met exposure assessment criteria (5944 colorectal cancer cases, including 3700 with colon and 2308 with rectal cancer)	Colorectal	Annual average nitrate exposure between ages 20–35 among those who lived ≥75% of study period at homes with a water sample within 1 year (61% of Danish population). Highest vs. lowest exposure quintile (≥2.1 vs. 0.16 mg/L NO_3-N); Colorectal: HR = 1.16 (CI: 1.08–1.25); colon: 1.15 (CI: 1.05–1.26); rectum: 1.17 (CI: 1.04–1.32)	No information on dietary intakes or smoking
Ward, 2007 USA [34]	Population-based case control Incidence, 1986–1989 Iowa	Nitrate levels in PWS among those with nitrate estimates for ≥70% of person-years ≥1960 (201 cases, 1244 controls)	Kidney (renal cell carcinomas)	Highest vs. lowest quartile PWS average (≥2.8 mg/L NO_3-N vs. <0.62) OR = 0.89 (CI 0.57–1.39); Years >5mg/L NO_3-N 11+ vs. 0 OR = 1.03 (CI: 0.66–1.60)	Interaction with red meat intake (*p*-interaction = 0.01); OR = 1.91 (CI 1.04–3.51) among 11+ years >5 mg/L NO_3-N and red meat ≥1.2 servings/day. Interaction with vitamin C showed similar pattern (*p*-interaction = 0.13)
Jones, 2017 USA [127]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence. PWS measurements for nitrate and TTHM; no measurements for private wells (20,945 women; 163 kidney cases)	Kidney	Nitrate and TTHM metrics computed for duration at water source (11+ years) 95th percentile vs. lowest quartile PWS average (≥5.00 vs. <0.47 mg/L NO_3-N) HR = 2.23 (CI: 1.19–4.17; *p*-trend = 0.35) Years >5 mg/L (≥4 years vs. 0) HR = 1.54 (CI: 0.97–2.44; *p*-trend = 0.09) Private well users (vs. <0.47 mg/L NO_3-N in PWS) HR = 0.96 (CI: 0.59–1.58)	No interaction with smoking, vitamin C
Ward, 2006 USA [35]	Population-based case-control Incidence, 1998–2000 Iowa	Nitrate levels in PWS among those with nitrate estimates for ≥70% of person-years ≥1960 (181 case, 142 controls); nitrate measurements for private well users at time of interviews (1998–2000; 54 cases, 44 controls)	Non-Hodgkin lymphoma	Private wells: >5.0 mg/L NO_3-N vs. ND OR = 0.8 (CI 0.2–2.5) PWS average: ≥2.9 mg/L NO_3-N vs. <0.63 OR = 1.2 (CI 0.6–2.2) Years ≥5mg/L NO3-N: 10+ vs. 0 OR = 1.4 (CI: 0.7–2.9)	No interaction with vitamin C, smoking

Table 2. *Cont.*

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Inoue-Choi, 2015 USA [129]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence; PWS measurements for nitrate and TTHM; no measurements for private wells (17,216 women; 190 ovarian cases)	Ovary	Nitrate and TTHM metrics computed for reported duration at water source (11+ years) Highest vs. lowest quartile PWS average ($\geq$2.98 mg/L vs. <0.47 mg/L NO_3-N) HR = 2.03 (CI = 1.22–3.38; *p*-trend = 0.003) Years >5 mg/L ($\geq$4 years vs. 0) HR = 1.52 (CI: 1.00–2.31; *p*-trend = 0.05) Private well users (vs. <0.47 mg/L NO_3-N in PWS) HR = 1.53 (CI: 0.93–2.54)	No interaction with vitamin C, red meat intake, smoking for PWS nitrate Interaction with private well use and vitamin C intake (*p*-interaction = 0.01)
Quist, 2018 USA [126]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2011 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence; nitrate and TTHM estimates for PWS (20,945 women; 189 pancreas cases); no measurements for private wells Adjusted for TTHM (1955–1988), measured levels in 1980s, prior year levels estimated by expert)	Pancreas	Nitrate and TTHM metrics computed for reported duration at water source (11+ years) 95th percentile vs. lowest quartile PWS average ($\geq$5.69 vs. <0.47 mg/L NO_3-N) HR = 1.16 (CI: 0.51–2.64; *p*-trend = 0.97) Years >5 mg/L ($\geq$4 years vs. 0) HR = 0.90 (CI: 0.55–1.48; *p*-trend = 0.62) Private well users (vs. <0.47 mg/L NO_3-N) HR = 0.92 (CI: 0.55–1.52)	No interaction with smoking, vitamin C
Ward, 2008 USA [133]	Population-based case control Incidence, 1988–1993 Nebraska	Controls from prior study of lymphohematopoetic cases and controls interviewed in 1992–1994; Proxy interviews for 80%, 76%, 61% of stomach, esophagus, controls, respectively. Nitrate levels (1965–1985) in PWS for $\geq$70% of person-years (79 distal stomach, 84, esophagus, 321 controls); Private well users sampling at interview (15 stomach, 22 esophagus, 44 controls)	Stomach and esophagus (adenocarcinomas)	Highest vs. lowest quartile PWS average (>4.32 vs. <2.45 mg/L NO_3-N): stomach OR = 1.2 (CI 0.5–2.7); esophagus OR = 1.3 (CI: 0.6–3.1); Years >10 mg/L NO_3-N (9+ vs. 0): stomach OR = 1.1 (CI: 0.5–2.3); esophagus OR = 1.2 (CI: 0.6–2.7) Private well users (>4.5 mg/L NO_3-N vs. <0.5) stomach OR = 5.1 (CI: 0.5–52; 4 cases, 13 controls); esophagus OR = 0.5 (CI: 0.1–2.9; 8 cases; 13 controls)	No interaction with vitamin C, processed meat, or red meat for either cancer
Ward, 2010 USA [37]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2004 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence (21,977 women; 40 thyroid cases); no measurements for private wells	Thyroid	Highest vs. lowest quartile PWS average (>2.46 vs. <0.36 mg/L NO_3-N) HR = 2.18 (CI: 0.83–5.76; *p*-trend = 0.02) Years >5 mg/L ($\geq$5 years vs. 0) HR = 2.59 (CI: 1.09–6.19; *p*-trend = 0.04); Private well (vs. <0.36 mg/L NO_3-N on PWS) HR = 1.13 (CI: 0.83–3.66) Dietary nitrate intake quartiles positively associated with risk (*p*-trend = 0.05)	No interaction with smoking, vitamin C, body mass index, education, residence location (farm/rural vs. urban)

ND = not detected; PWS = public water supplies; [a] nitrate or nitrite levels presented in the publications as mg/L of the ion were converted to mg/L as NO_3-N or NO_2-N; [b] Odds ratios (OR) for case-control studies, incidence rate ratios (RR) and hazard ratios (HR) for cohort studies, and 95% confidence intervals (CI); [c] Factors evaluated are noted. Interaction refers to reported $p \leq 0.10$ from test of heterogeneity.

Animal studies demonstrate that in utero exposure to nitrosamides can cause brain tumors in the exposed offspring. Water nitrate and nitrite intake during pregnancy was estimated in a multi-center case-control study of childhood brain tumors in five countries based on the maternal residential water source [139]. Results for the California and Washington State sites were reported in our previous review [8,140]. Nitrate/nitrite levels in water supplies were measured using a nitrate test strip method in four countries including these U.S. sites; most of these measurements occurred many years after the pregnancy. Measured nitrate concentrations were not associated with risk of childhood brain tumors. However, higher nitrite levels (>1.5 mg/L NO_2-N) in the drinking water were associated with increased risk of astrocytomas.

8. Thyroid Disease

Animal studies demonstrate that ingestion of nitrate at high doses can competitively inhibit iodine uptake and induce hypertrophy of the thyroid gland [141]. An early study of women in the Netherlands consuming water with nitrate levels at or above the MCL, found increased prevalence of thyroid hypertrophy [142]. Since the last review, five studies have evaluated nitrate ingestion from drinking water (the Iowa cohort study also assessed diet) and prevalence of thyroid disease. A study of school-age children in Slovakia found increased prevalence of subclinical hypothyroidism among children in an area with high nitrate levels (51–274 mg/L NO_3) in water supplies compared with children ingesting water with nitrate ≤50 mg/L (11 mg/L NO_3-N). In Bulgarian villages with high nitrate levels (75 mg/L NO_3) and low nitrate levels (8 mg/L), clinical examinations of the thyroids of pregnant women and school children revealed an approximately four- and three-fold increased prevalence of goiter, respectively, in the high nitrate village [143,144]. The iodine status of the populations in both studies was adequate. Self-reported hypothyroidism and hyperthyroidism among a cohort of post-menopausal women in Iowa was not associated with average nitrate concentrations in PWS [37]. However, dietary nitrate, the predominant source of intake, was associated with increased prevalence of hypothyroidism but not hyperthyroidism. Modeled estimates of nitrate concentrations in private wells among a cohort of Old Order Amish in Pennsylvania (USA) were associated with increased prevalence of subclinical hypothyroidism as determined by thyroid stimulating hormone measurements, among women but not men [145].

9. Other Health Effects

Associations between nitrate in drinking water and other non-cancer health effects, including type 1 childhood diabetes (T1D), blood pressure, and acute respiratory tract infections in children were previously reviewed [8]. Since 2004, a small number of studies have contributed additional mixed evidence for these associations. Animal studies indicate that NOC may play a role in the pathology of T1D through damage to pancreatic beta cells [146]. A registry-based study in Finland [147] found a positive trend in T1D incidence with levels of nitrate in drinking water. In contrast, an ecological analysis in Italy showed an inverse correlation with water nitrate levels and T1D rates [148]. A small T1D case-control study in Canada with 57 cases showed no association between T1D and estimated intake of nitrate from drinking water (highest quartile >2.7 mg/day NO_3-N) [149]. Concentrations of nitrate in drinking water (median ~2.1 mg/L NO_3-N) were not associated with progression to T1D in a German nested case-control study of islet autoantibody-positive children, who may be at increased risk of the disease [150].

In a prospective, population-based cohort study in Wisconsin (USA), increased incidence of early and late age-related macular degeneration was positively associated with higher nitrate levels (≥5 mg/L vs. <5 mg/L NO_3-N) in rural private drinking water supplies [151]. The authors suggested several possible mechanisms, including methemoglobin-induced lipid peroxidation in the retina.

Potential benefits of nitrate ingestion include lowering of blood pressure due to production of nitric oxide in the acidic stomach and subsequent vasodilation, antithrombotic, and immunoregulatory effects [152]. Experimental studies in animals and controlled feeding studies in humans have demonstrated mixed evidence of these effects and on other cardiovascular endpoints such as vascular hypertrophy, heart failure, and myocardial infarction (e.g., [152–154]). Ingested nitrite from diet has also been associated with increased blood flow in certain parts of the brain [155]. Epidemiologic studies of these effects are limited to estimation of dietary exposures or biomarkers that integrate exposures from nitrate from diet and drinking water. Recent findings in the Framingham Offspring Study suggested that plasma nitrate was associated with increased overall risk of death that attenuated when adjusted for glomerular function (HR: 1.16, 95% CI: 1.0–1.35) but no association was observed for incident cardiovascular disease [156]. No epidemiologic studies have specifically evaluated nitrate ingested from drinking water in relation to these outcomes. Another potential beneficial effect of nitrate is protection against bacterial infections via its reduction to nitrite by enteric bacteria. In an experimental inflammatory bowel disease mouse model, nitrite in drinking water was associated with both preventive and therapeutic effects [157]. However, there is limited epidemiologic evidence for a reduced risk of gastrointestinal disease in populations with high drinking water nitrate intake. One small, cross-sectional study in Iran found no association between nitrate levels in public water supplies with mean levels of ~5.6 mg/L NO_3-N and gastrointestinal disease [158].

10. Discussion

Since our last review of studies through 2004 [8], more than 30 epidemiologic studies have evaluated drinking water nitrate and risk of cancer, adverse reproductive outcomes, or thyroid disease. However, the number of studies of any one outcome was not large and there are still too few studies to allow firm conclusions about risk. The most common endpoints studied were colorectal cancer, bladder, and breast cancer (three studies each) and thyroid disease (four studies). Considering all studies to date, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Four of the five published studies of colorectal cancer found evidence of an increased risk of colorectal cancer or colon cancer associated with water nitrate levels that were mostly below the respective regulatory limits [32,134,135,159]. In one of the four positive studies [159], increased risk was only observed in subgroups likely to have increased nitrosation. Four of the five studies of thyroid disease found evidence for an increased prevalence of subclinical hypothyroidism with higher ingestion of drinking water nitrate among children, pregnant women, or women only [37,144,145,160]. Positive associations with drinking water nitrate were observed at nitrate concentrations close to or above the MCL. The fifth study, a cohort of post-menopausal women in Iowa, had lower drinking water nitrate exposure but observed a positive association with dietary nitrate [37]. To date, five of six studies of neural tube defects showed increased risk with exposure to drinking water nitrate below the MCL. Thus, the evidence continues to accumulate that higher nitrate intake during the pregnancy is a risk factor for this group of birth defects.

All but one of the 17 cancer studies conducted since 2004 were in the U.S. or Europe, the majority of which were investigations of nitrate in regulated public drinking water. Thyroid cancer was studied for the first time [37] with a positive finding that should be evaluated in future studies. Bladder cancer, a site for which other drinking water contaminants (arsenic, disinfection by-products [DBPs]) are established or suspected risk factors, was not associated with drinking water nitrate in three of the four studies. Most of the cancer studies since 2004 evaluated effect modification by factors known to influence endogenous nitrosation, although few observed evidence for these effects. Several studies of adverse reproductive outcomes since 2004 have indicated a positive association between maternal prenatal exposure to nitrate concentrations below the MCL and low birth weight and small for gestational age births. However, most studies did not account for co-exposure to other water contaminants, nor did they adjust for potential risk factors. The relation between drinking water nitrate and spontaneous abortion continues to be understudied. Few cases of methemoglobinemia, the health concern that lead to the regulation of nitrate in public water supplies, have been reported in the U.S. since the 1990s. However, as described by Knobeloch et al. [96], cases may be underreported and only a small proportion of cases are thoroughly investigated and described in the literature. Based on published reports, [100] areas of the world of particular concern include several eastern European countries, Gaza, and Morocco, where high nitrate concentrations in water supplies have been linked to high levels of methemoglobin in children. Therefore, continued surveillance and education of physicians and parents will be important. Biological plausibility exists for relationships between nitrate ingestion from drinking water and a few other health outcomes including diabetes and beneficial effects on the cardiovascular system, but there have been only a limited number of epidemiologic studies.

Assessment of drinking water nitrate exposures in future studies should be improved by obtaining drinking water sources at home and at work, estimating the amount of water consumed from each source, and collecting information on water filtration systems that may impact exposure. These efforts are important for reducing misclassification of exposure. Since our last review, an additional decade of PWS monitoring data are available in the U.S. and European countries, which has allowed assessment of exposure over a substantial proportion of participants' lifetimes in recent studies. Future studies should estimate exposure to multiple water contaminants as has been done in recent cancer studies [31,33,127,129]. For instance, nitrate and atrazine frequently occur together in drinking water in agricultural areas [161] and animal studies have found this mixture to be teratogenic [162]. Regulatory monitoring data for pesticides in PWS has been available for over 20 years in the U.S.; therefore, it is now feasible to evaluate co-exposure to these contaminants. Additionally, water supplies in agricultural areas that rely on alluvial aquifers or surface water often have elevated levels of both DBPs and nitrate. Under this exposure scenario, there is the possibility of formation of the nitrogenated DBPs including the carcinogenic NDMA, especially if chloramination treatment is used for disinfection [163,164]. Studies of health effects in countries outside the U.S. and Europe are also needed.

A comprehensive assessment of nitrate and nitrite from drinking water and dietary sources as well as estimation of intakes of antioxidants and other inhibitors of endogenous nitrosation including dietary polyphenols and flavonoids is needed in future studies. Heme iron from red meat, which increases fecal NOC in human feeding studies, should also be assessed as a potential effect modifier of risk from nitrate ingestion. More research is needed on the potential interaction of nitrate ingestion and nitrosatable drugs (those with secondary and tertiary amines or amides). Evidence from several studies of birth defects [38,118–120] implicates nitrosatable drug intake during pregnancy as a risk factor for specific congenital anomalies especially in combination with nitrate. Drugs with nitrosatable groups include many over-the-counter and prescription drugs. Future studies with electronic medical records and record-linkage studies in countries like Denmark with national pharmacy data may provide opportunities for evaluation of these exposures.

Populations with the highest exposure to nitrate from their drinking water are those living in agricultural regions, especially those drinking water from shallow wells near nitrogen sources (e.g., crop fields, animal feeding operations). Estimating exposure for private well users is important because it allows assessment of risk over a greater range of nitrate exposures compared to studies focusing solely on populations using PWS. Future health studies should focus on these populations, many of which may have been exposed to elevated nitrate in drinking water from early childhood into adulthood. A major challenge in conducting studies in these regions is the high prevalence of private well use with limited nitrate measurement data for exposure assessment. Recent efforts to model nitrate concentrations in private wells have shown that it is feasible to develop predictive models where sufficient measurement data are available [41,48,49]. However, predictive models from one area are not likely to be directly translatable to other geographic regions with different aquifers, soils, and nitrogen inputs.

Controlled human feeding studies have demonstrated that endogenous nitrosation occurs after ingestion of drinking water with nitrate concentrations above the MCL of 10 mg/L NO_3-N (~44 mg/L as NO_3). However, the extent of NOC formation after ingestion of drinking water with nitrate concentrations below the MCL has not been well characterized. Increased risks of specific cancers and central nervous system birth defects in study populations consuming nitrate below the MCL is indirect evidence that nitrate ingestion at these levels may be a risk factor under some conditions. However, confounding by other exposures or risk factors can be difficult to rule out in many studies. Controlled human studies to evaluate endogenous nitrosation at levels below the MCL are needed to understand interindividual variability and factors that affect endogenous nitrosation at drinking water nitrate levels below the MCL.

A key step in the endogenous formation of NOC is the reduction of nitrate, which has been transported from the bloodstream into the saliva, to nitrite by the nitrate-reducing bacteria that are located primarily in the crypts on the back of the tongue [165–167]. Tools for measuring bacterial DNA and characterizing the oral microbiome are now available and are currently being incorporated into epidemiologic studies [168,169]. Buccal cell samples that have been collected in epidemiologic studies can be used to characterize the oral microbiome and to determine the relative abundance of the nitrate-reducing bacteria. Studies are needed to characterize the stability of the nitrate-reducing capacity of the oral microbiome over time and to determine factors that may modify this capacity such as diet, oral hygiene, and periodontal disease. Interindividual variability in the oral nitrate-reducing bacteria may play an important role in modifying endogenous NOC formation. The quantification of an individual's nitrate-reducing bacteria in future epidemiologic studies is likely to improve our ability to classify participants by their intrinsic capacity for endogenous nitrosation.

In addition to characterizing the oral microbiome, future epidemiologic studies should incorporate biomarkers of NOC (e.g., urinary or fecal NOC), markers of genetic damage, and determine genetic variability in NOC metabolism. As many NOC require α-hydroxylation by CYP2E1 for bioactivation and for formation of DNA adducts, it is important to investigate the influence of polymorphisms in the gene encoding for this enzyme. Studies are also needed among populations with medical conditions that increase nitrosation such as patients with inflammatory bowel disease and periodontal disease [8]. Because NOC exposures induce characteristic gene expression profiles [170,171], further studies linking drinking water intake to NOC excretion and gene expression responses are relevant to our understanding of health risks associated with drinking water nitrate. The field of 'Exposome-research' [172,173] generates large numbers of genomics profiles in human population studies for which dietary exposures and biobank materials are also available. These studies provide opportunities to measure urinary levels of nitrate and NOC that could be associated with molecular markers of exposure and disease risk.

Nitrate concentrations in global water supplies are likely to increase in the future due to population growth, increases in nitrogen fertilizer use, and increasing intensity and concentration of animal agriculture. Even with increased inputs, mitigation of nitrate concentrations in water resources is possible through local, national, and global efforts. Examples of the latter are the International Nitrogen Initiative [174] and the EU Nitrates Directive [17,18], which aim to quantify human effects on the nitrogen cycle and to validate and promote methods for sustainable nitrogen management. Evidence for the effectiveness of these efforts, which include the identification of vulnerable areas, establishment of codes of good agricultural practices, and national monitoring and reporting are indicated by decreasing trends in groundwater nitrate concentrations in some European countries after the implementation of the EU Nitrates Directive [19]. However, the effect of this initiative was variable across the EU. In the U.S., nitrogen applications to crop fields are not regulated and efforts to reduce nitrogen runoff are voluntary. Although strategies such as appropriate timing of fertilizer applications, diversified crop rotations, planting of cover crops, and reduced tillage can be effective [175], concentrations in U.S. ground and surface water have continued to increase in most areas [10]. Climate change is expected to affect nitrogen in aquatic ecosystems and groundwater through alterations of the hydrological cycle [176]. Climatic factors that affect nitrate in groundwater include the amount, intensity, and timing of precipitation. Increasing rainfall intensity, especially in the winter and spring, can lead to increases in nitrogen runoff from agricultural fields and leaching to groundwater.

11. Conclusions

In summary, most adverse health effects related to drinking water nitrate are likely due to a combination of high nitrate ingestion and factors that increase endogenous nitrosation. Some of the recent studies of cancer and some birth defects have been able to identify subgroups of the population likely to have greater potential for endogenous nitrosation. However, direct methods of assessing these individuals are needed. New methods for quantifying the nitrate-reducing bacteria in the oral microbiome and characterizing genetic variation in NOC metabolism hold promise for identifying high risk groups in epidemiologic studies.

To date, the number of well-designed studies of individual health outcomes is still too few to draw firm conclusions about risk from drinking water nitrate ingestion. Additional studies that incorporate improved exposure assessment for populations on PWS, measured or predicted exposure for private well users, quantification of nitrate-reducing bacteria, and estimates of dietary and other factors affecting nitrosation are needed. Studies of colorectal cancer, thyroid disease, and central nervous system birth defects, which show the most consistent associations with water nitrate ingestion, will be particularly useful for clarifying these risks. Future studies of other health effects with more limited evidence of increased risk are also needed including cancers of the thyroid, ovary, and kidney, and the adverse reproductive outcomes of spontaneous abortion, preterm birth, and small for gestational age births.

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NITRATE AND HEALTH

PROTECT THE HEALTH OF YOU AND YOUR LOVED ONES BY KNOWING WHAT IS IN YOUR DRINKING WATER!

WHERE AND WHAT IS NITRATE?

Nitrate is a form of nitrogen that can sometimes be found in our drinking water. Nitrogen fertilizers used for growing crops are the largest contributor to nitrate in our drinking water. Therefore, if you live in an area where there is a lot of agricultural production, you are at risk of drinking nitrate-contaminated water.

WHAT CAN I DO TO PROTECT MYSELF AND MY FAMILY?

If you drink water from a private well, it is up to you to ensure you are drinking safe water. There are no requirements for private well owners to test or treat their water. Nitrate is colorless, odorless and tasteless. **The only way to know if you have nitrate in your drinking water is to test for it.**

Private well users should test their drinking water annually. You can order a test kit from a certified laboratory or do-it-yourself test kits are available as well. The do-it-yourself kits should be used as a screening tool only. An analysis by an approved lab is recommended for the most accurate, reliable and precise measurement.

If you find nitrate above the safe drinking water level (10 ppm) in your water, the quickest and easiest solution is to install a reverse osmosis water filtration system in your house. For more information, go to https://water.unl.edu/

EXTENSION

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HOW CAN CONSUMING NITRATE IMPACT HUMAN HEALTH?

Children and Infants

- A result in infants consuming nitrate-contaminated water is methemoglobinemia (blue-baby syndrome); bottle-fed babies under six months old are at the highest risk. This illness can cause the skin to turn a bluish color and result in serious illness or death.
- There are studies suggesting potential linkages between nitrate consumption and pediatric cancers. Nebraska has the highest rate of pediatric cancer in the Midwest and 7th highest in the entire United States. More research needs to be conducted before we can draw sure conclusions.

Pregnant Women

- During pregnancy, it is common for a woman's methemoglobin levels to increase from normal. Therefore, pregnant women are particularly susceptible to methemoglobinemia as well.
- Pregnant women exposed to too much nitrate are at greater risk of giving birth prematurely
- Maternal exposure to nitrate through drinking water has been linked to birth defects. Nebraska has double the national average rate of birth defects.

Other Adults

- The University of Nebraska Medical Center, along with researchers across the globe, continue to study linkages between consuming nitrate and human health impacts
- A growing body of studies indicate potential associations between nitrate and...

  increased heart rate, nausea, headaches, thyroid disease, and other cancers such as colorectal, bladder, ovarian and kidney

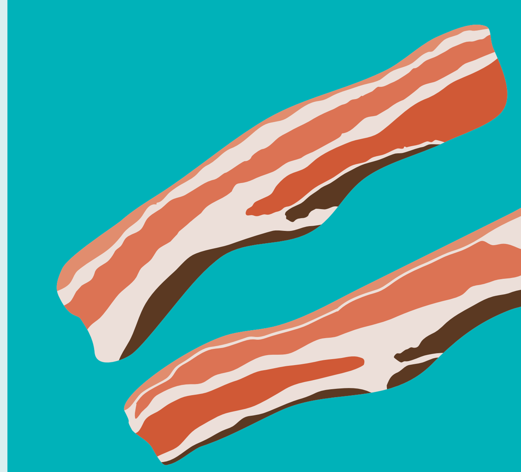
  *Please consult your doctor if you are experiencing any of these symptoms

NITRATE AWARENESS

What is in Your Water?

WHAT IS NITRATE?

Nitrate occurs naturally as part of the nitrogen cycle, but it also is generated through human activity, often times through agricultural practices. Nitrogen fertilizers can breakdown into nitrate and then seep into our groundwater. The United States Enviornmental Protection Agency (EPA) mandates that public water systems keep nitrate contamination levels under 10 mg/L due to its associated health risks.



PROCCESSED MEATS

Nitrate can be found in highly processed meats such as bacon, ham and sausage. It is often used as a preservative and can improve the color of the raw meat. A diet high in processed meats can lead to high nitrate consumption, and put you at risk for certain health effects.

DRINKING WATER

A common way you might consume nitrate is through drinking water, as nitrate can infiltrate the groundwater we rely on for drinking. While public water is tested and treated for nitrate contamination, private well owners are responsible to test their water and make sure it is safe.

INFANTS

Consuming too much nitrate can interfere with the ability of blood to carry oxygen. The result in infants is methemoglobinemia, also called blue baby syndrome. Bottle-fed babies under six months old are at the highest risk of getting methemoglobinemia. This illness can cause the skin to turn a bluish color from a lack of oxygen, and result in serious illness or death.

PREGNANT WOMEN

During pregnancy, it is common for a woman's methemoglobin levels to be thigher than normal. Therefore, pregnant women are particularly susceptible to methemoglobinemia. Additionally, pregnant women exposed to high nitrate concentrations in their drinking water are at greater risk of pre-term births, birth defects, and miscarriages.

WHAT ARE THE HEALTH IMPACTS?

There are certain populations that are more susceptible to negative health outcomes. These include pregnant women, infants, children, and individuals with oxygen transport issues. Scientific research, including studies carried out at the University of Nebraska Medical Center, is ongoing regarding the health effects of nitrate consumption. These studies include research on the effects of nitrate consumption on thyroid disease and cancer, specifically colorectal, bladder, ovarian, and kidney cancers. Further research is needed to fully understand these potential health impacts.

WHAT CAN YOU DO?

First and foremost, know what you're consuming. Check labels for nitrate preservatives and TEST YOUR WATER. Nitrate is odorless, tasteless and colorless. If you find high nitrate concentrations in your water (over 10 mg/L), you need to immediately switch to a safe source of drinking water, such as bottled water. Next, take the necessary steps to ensure your home has clean water. This may include installing a reverse osmosis system or digging a new well.

WANT TO LEARN MORE?

Talk to your doctor if you have questions or concerns about the health impacts related to consuming nitrate. Additionally, visit the University of Nebraska's website on this topic for more information.

https://water.unl.edu/category/water-and-health

EXTENSION

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NEBRASKA WATER FACTS

from the
NEBRASKA WATER CENTER

Nebraska means "flat water" from the Omaha Sioux "ni braska" and Oto "ni brathge" describing the Platte River. The Platte River was named by early French explorers, also meaning "flat."

SURFACE WATER

- Nearly 80,000 miles of rivers and streams drain to the Missouri River in the East.
  - Along the Niobrara and Missouri Rivers, 197 miles are designated as National Wild and Scenic.
- Tallest waterfall is Smith Falls, spilling 63 feet into the Niobrara River.
- Largest storage reservoir: Lake McConaughy
  - When full is 1.74 million acre-feet of storage
  - Covers 30,500 acres
  - Created by the state's largest dam, Kingsley Dam
  - Supplies irrigation directly & indirectly for 530,000 ac
- More than 2,900 dams, >25 ft tall or 50 ac-ft storage

GROUNDWATER

Total groundwater state #1

- Mostly from the Ogallala Aquifer, part of the High Plains Aquifer.
  - Water among mostly sand and gravel.
  - From 1 to 1000+ feet thick.
  - Poured over the surface of the state, the water would be 38 feet deep.
- Groundwater and surface water are connected. For example:
  - More than 90% of the Loup Rivers' streamflow started as groundwater.
- Nebraska has more than 192,000 registered groundwater wells.

WATER USE

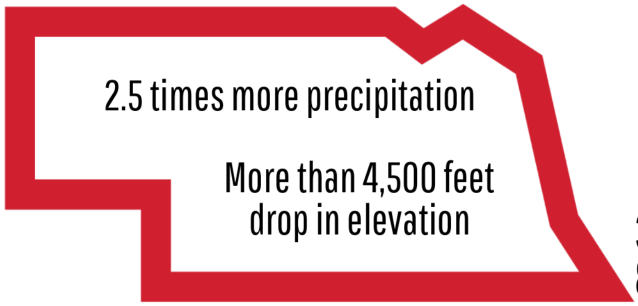
#1 Irrigated acres: 9.1 million

- Annual average additional crop value of $1.5 billion statewide. Added property valuation of $13-24 billion.
- Agriculture irrigation is 91% of Nebraska's total consumptive water use.
- From 1990 to 2014, Nebraska now grows 1.7 times more corn and 1.8 times more soybeans per gallon of water.
- From 1960 to 2016, Nebraska raises 1.8 times the amount of beef per gallon of water and 5.1 times more milk.
- Other uses of Nebraska's water:
  - home 5%; industrial 1%; thermoelectric 1%; livestock 1%
- 85% of Nebraskans get their home water from groundwater.
- 594 public water supply systems serve 1.69 million residents. EPA requires testing for 90 contaminants.
- More than 360,000 residents use private wells. Exempt from testing.
- Each person uses an average of 122 gallons of water each day.
  - Home water use has dropped by 1/3 in the last 20 years.

Center pivot irrigating soybeans. Photo: UNL

Changes West to East

13 inches precipitation
5,424 feet above sea level



33 inches precipitation
840 feet above sea level

Smith Falls. Photo: Nebraskaland Magazine.

RECREATION

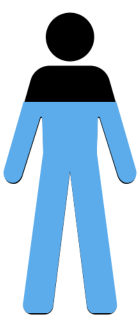
Lake McConaughy with >2 million visitors #1

- 7 out of top 10 Nebraska attractions involve water.
- Crane migration annual visitors' impact: $17.2 mill.

LAND USE

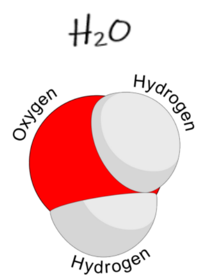
- Nebraska's farms and ranches utilize 44.8 million acres, 92% of the state's total land area.
- 22 million acres of rangeland and pastureland in Nebraska, half of which are in the Sandhills.
- 1/3 of Nebraska land is annual crops.
- Nebraska's cities and town cover about 1% of the land, less than wetlands and forest.

WATER SCIENCE



A person's body is 66% water

A corn plant is 80% water



Only substance found naturally as

liquid, solid, and gas

Author: Crystal A. Powers | Reviewers: Katie Pekarek, Gary Stone | Sources:

Nebraska Water Center
Daugherty Water for Food Global Institute

THE DAUGHERTY WATER for FOOD GLOBAL INSTITUTE at the University of Nebraska

N EXTENSION

Agua Potable y Salud

1. Agua potable en Nebraska

¿Sabía que no es un requerimiento analizar ni tratar el agua de pozos privados? Por lo tanto, la única manera de saber si su agua es segura para beber es hacer pruebas para averiguarlo usted mismo.

2. Contaminantes comunes del agua

En gran parte de Nebraska, el monitoreo del agua muestra varios contaminantes dañinos. El contaminante más común es el nitrato el cual está relacionado con el uso de fertilizantes nitrogenados.

3. Impactos de por vida en la salud

Hay impactos conocidos en la salud por beber agua contaminada con nitratos. Los vínculos más fuertes son: síndrome del bebé azul, problemas de parto prematuro, defectos de nacimiento, cáncer infantil y cáncer en adultos.

4. ¿Quién está en mayor riesgo?

Las poblaciones más vulnerables son las mujeres embarazadas y sus fetos, los bebés pequeños, los niños y las personas con condiciones de transporte/entrega de oxígeno.

5. ¡Hágale un análisis a su agua de pozo!

¡La única manera de estar seguro de lo que hay en su agua potable es analizándola! La forma recomendada de realizar el análisis es pedir un kit de prueba de un laboratorio oficial de Nebraska. Después de saber qué hay en su agua, puede empezar a construir un plan de tratamiento si es necesario.

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o ¡Escanee aquí!