NITRATE

Key Takeaways

Due to the pervasiveness of ongoing nitrate contamination in groundwater and the seriousness of its human health and environmental impacts, there is urgent need to address Wisconsin's nitrate contamination problem. Nitrate contamination has been negatively impacting Wisconsin waters for over 50 years and is still increasing. The GCC listed nitrate contamination of groundwater as a problem in the first annual report in 1985 and has emphasized nitrate in groundwater as a priority concern since 1994. GCC agencies continue to proactively address nitrate contamination but must be allowed to implement more effective practices in order to protect groundwater sources of drinking water.

GCC member agencies continue to work on multiple initiatives related to reducing the risk of high nitrate levels in groundwater and drinking water (see groundwater management sections – DNR, DATCP, UWS, WGNHS).

For actions to address nitrate contamination in groundwater, see the Recommendations Section.

Sections in this document

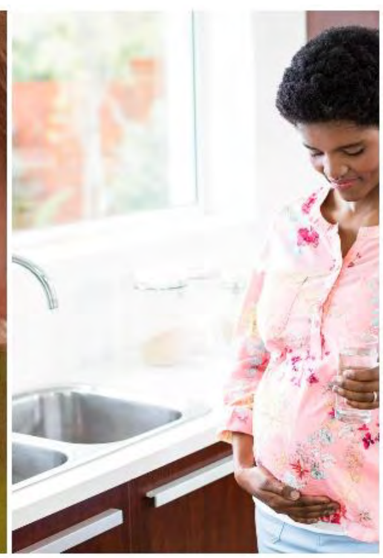
What is nitrate and what are the human health concerns?

Nitrate (NO_3) is a water-soluble molecule that forms when ammonia or other nitrogen rich sources, including nitrogen fertilizers, combine with oxygen. Nitrate levels in groundwater are generally below 2 parts per million where pollution sources are absent. Higher levels indicate a human-caused source of groundwater contamination such as agricultural or turf fertilizers, animal waste, septic systems or wastewater. Nitrate dissolves easily in water and does not adsorb onto the soil. It can easily be carried into the groundwater by rainwater and melting snow as they percolate through the soil and bedrock into the underlying aquifer. While nitrogen fertilizer in agricultural use results in larger crop yields, high concentrations of nitrate in groundwater can harm public health. The health-based groundwater quality enforcement standard (ES) for nitrate-N in groundwater and the maximum contaminant level (MCL) for nitrate-N in public drinking water are both 10 mg/L or 10 ppm (WI NR 140.10, WI NR 809.11). Everyone should avoid long-term consumption of water containing nitrate above this level.

Nitrates are also found naturally in certain vegetables and are added as a preservative in cured meats. Is there a difference in health consequences based on how nitrate is consumed? Nitrate is reduced to nitrite in the body by bacteria in the mouth and gastrointestinal tract. In blood and tissues, nitrite is normally reduced to nitric oxide, which plays an important physiologic role in vascular and immune function. However, under certain conditions in the body, nitrite has the potential to be converted to harmful compounds, notably carcinogenic nitrosamines. The way nitrate is consumed, such as the type of food or in drinking water, may affect how nitrate is processed in the body[1]. While no negative health consequences are attributed to consuming nitrates from vegetables, the Wisconsin Department of Health Services (DHS) concludes, based on the weight of scientific data, that high levels of nitrate in drinking water pose a number of health risks.

Why do we care about nitrate in our groundwater?

Nearly 75% of Wisconsin's drinking water comes from our groundwater. Drinking water with high levels of nitrate is unsafe for everyone! It poses an acute risk to infants and women who are pregnant, a possible risk to the developing fetus during very early stages of pregnancy, and a chronic risk of serious disease in adults, such as thyroid disease and cancer.

Known public health risks:

- Infants below the age of 6 months who drink water containing nitrate in excess of the MCL are especially at risk, and could become seriously ill with a condition called methemoglobinemia or "blue-baby syndrome". This condition deprives the infant of oxygen and in extreme cases can cause death. The DHS has associated at least three cases of suspected blue-baby syndrome in Wisconsin with nitrate contaminated drinking water2. In children, there is also growing evidence of a correlation between nitrate and diabetes[3,4].

- Birth defects have also been linked to nitrate exposure. Several epidemiological studies over the past decade have examined statistical links between nitrate exposure and neural tube birth defects5. Some, but not all, of these studies have concluded there is a statistical correlation between maternal ingestion of nitrates in drinking water and birth defects. Further work, including a clear animal model, would be needed to conclusively demonstrate causation. These studies collectively indicate an ongoing need for caution in addressing consumption of nitrate by pregnant women and support the continuation of private well testing programs.

- In the human body, nitrate can convert to nitrite (NO_2) and then to N-nitroso compounds (NOC's), which are some of the strongest known carcinogens. As a result, additional human health concerns related to nitrate contaminated drinking water include potential associations with non-Hodgkin's lymphoma[6], gastric cancer[7,8], and bladder and ovarian cancer in older women[9].

- DHS also cites thyroid disease and colon cancer as health concerns and states, "When nitrate levels are high, everyone should avoid long-term use of the water for drinking and preparing foods that use a lot of water."

What effect does nitrate contamination have on our wildlife?

Loss of biodiversity and serious health issues, including death in fish and amphibians have been shown to be caused by nitrate contamination.

What are the environmental effects of nitrate contamination?

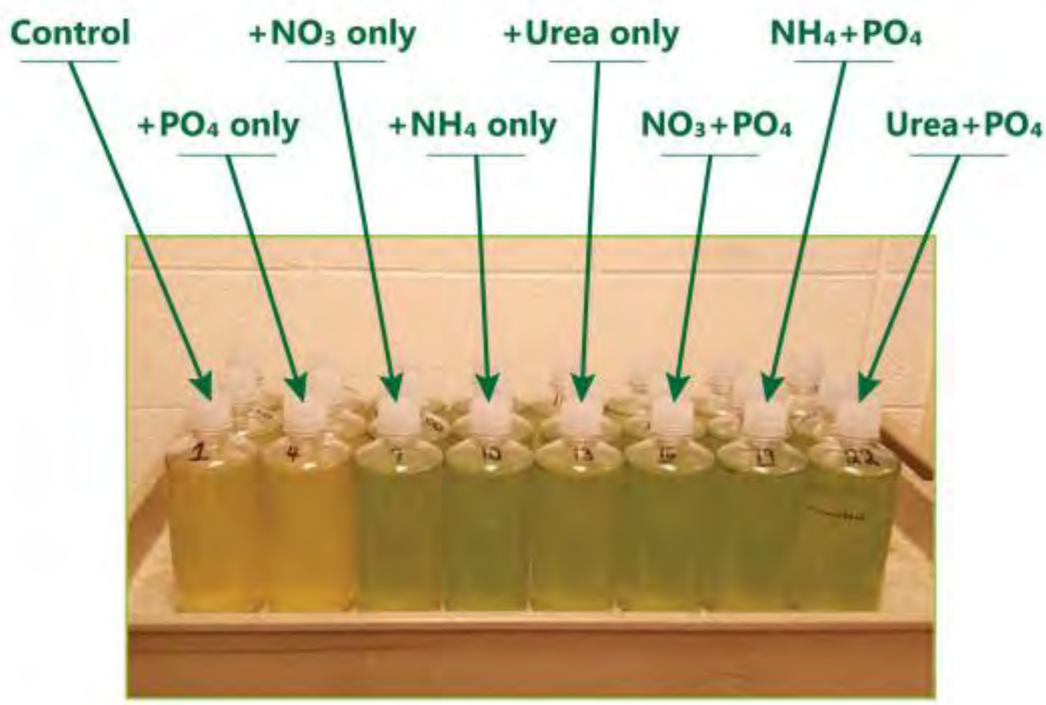
Adverse environmental effects from nitrate contamination are well documented.

- Loss of biodiversity in terrestrial and aquatic systems has been documented with increasing nitrate[10].

- A number of studies have shown that nitrate can cause harm or death in fishes, amphibians and aquatic invertebrates[11-17]. This is significant because many baseflow-dominated streams (springs, groundwater-fed low-order streams) in agricultural watersheds in Wisconsin exhibit elevated nitrate concentrations, at times exceeding 30 ppm.

- In addition to phosphorus, nitrogen contributes significantly to nutrient-related water quality degradation of lakes and streams in Wisconsin. Groundwater and drain tile transported nitrate, along with urea and ammonium play a significant role in the over-enrichment of water bodies, driving excessive algae and cyanobacteria growth, along with increasing the potential for harmful algal bloom toxin formation[18,19]

How Does Nitrogen Affect Harmful Algal Blooms?



Nutrient additions to Planktothrix bloom samples from Sandusky Bay show that nitrogen affects algae growth (Davis et al. 2015). Water samples that appear green indicate more algal growth than samples that appear yellow. The type of nutrient addition, if any, is shown above each column of water samples: the yellow bottle on the far left is the control (i.e., no nutrient addition), the second yellow bottle was spiked with phosphorus only, and the six green bottles on the right are spiked with either nitrogen or both nitrogen and phosphorus. Source: Great Lakes HABs Collaborative.

How widespread is elevated nitrate in **Wisconsin's** groundwater?

Nitrate is Wisconsin's most widespread groundwater contaminant and nitrate is increasing in extent and severity in the state[20-23].

Nitrate in public water systems

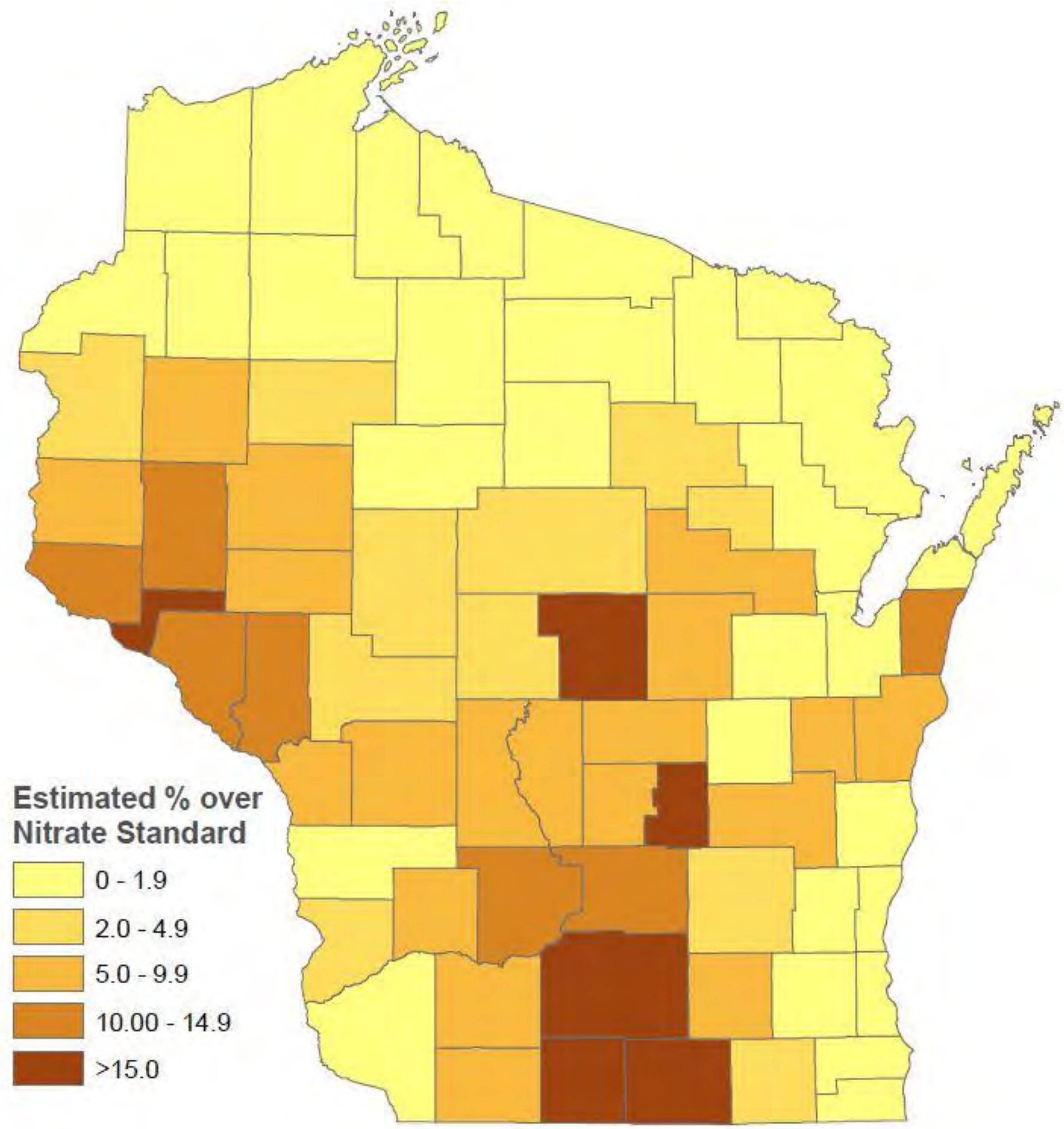
A 2012 survey of Wisconsin municipal water-supply systems found that 47 systems had raw water samples that exceeded the nitrate-N MCL, up from just 14 systems in 1999. Increasing nitrate levels have been observed in an additional 74 municipal systems. In FY 22, more than 200 public water supply systems (many of which were small businesses) exceeded the nitrate drinking water standard of 10 mg/L requiring them to post notices, provide bottled water, replace wells, install treatment or take other corrective actions.

Nitrate in private water systems

Private water wells, which serve about one third of Wisconsin families, are at continued risk of nitrate contamination. Statewide, about 10% of private well samples exceed the MCL for nitrate-N, although one third of private well owners have never had their water tested for nitrate[24,25]. In agricultural areas, such as the highly cultivated regions in south-central Wisconsin, around 20%-30% of private well samples exceed the MCL[26]. Nitrate concentrations affect deeper wells over time as nitrate pollution penetrates aquifers and migrates farther from original source areas[21].

In 2014, in response to the DHS revised health recommendation that long-term use of water over the standard by anyone poses a significant health risk, ch. NR 812 Wis. Admin code (Well Construction and Pump Installation) was changed to require sampling for nitrate in both newly constructed wells and existing wells that had pump work done. To date, the pump work and new well dataset has over 200,000 samples, providing one of the least biased large data sets in Wisconsin.

Data from Jan. 2022 – June 2023 for new well and pump work showed that of the 23,126 samples taken, 1,379 or 6.0% were greater than 10 ppm and 7,299 or 31.5% were above the preventative action limit (PAL) of 2 ppm. Unfortunately, some counties have a much greater percentage of wells testing above the 10 ppm standard for nitrate. See map below for individual county results.



Map of Estimated Percentage of Private Wells over Nitrate Standard by County (Jan. 2022 through June 2023).

Land use and nitrate contamination

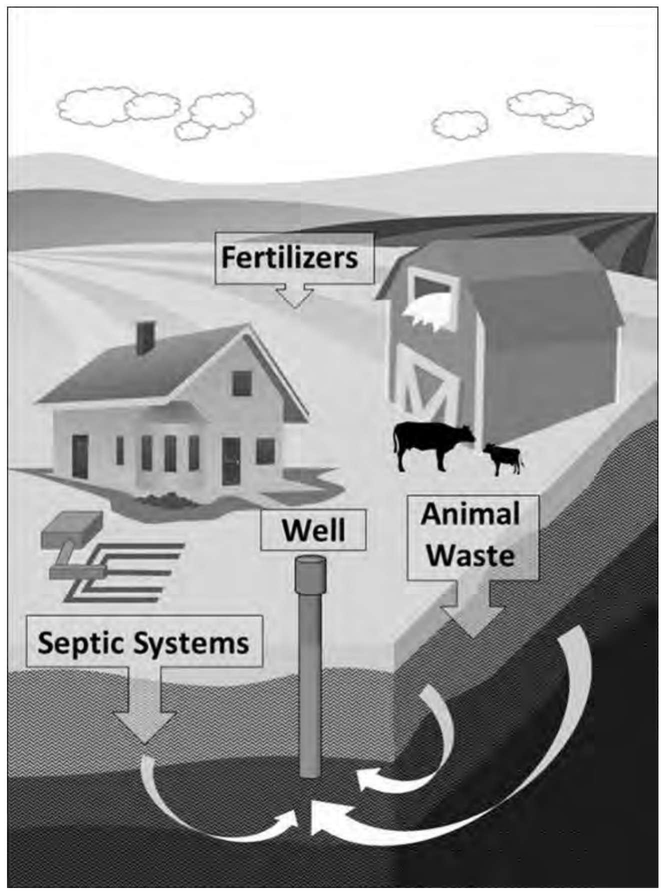
The vulnerability of groundwater to contamination depends on aquifer sensitivity in combination with a source of naturally occurring or human-caused contamination. An analysis completed in 1994 of relative source contributions concluded that about

90% of nitrogen inputs to groundwater in Wisconsin can be traced to agricultural sources including manure spreading and fertilizer application[27].

The Wisconsin Department of Agriculture, Trade and Consumer Protection (DATCP) and the Wisconsin Field Office of the National Agricultural Statistics Service (NASS) surveyed private wells and placed them into categories based on how intensively the surrounding land was cultivated for agricultural production. The survey found that overall, 8.2% of private wells in Wisconsin exceeded 10 mg/L for nitrate. However, marked differences in the percentage of wells over 10 mg/L were noted when grouping the data by surrounding agricultural intensity; the percentage increased from 1.7% when surrounding land was lightly cultivated to 20% of wells exceeding the health based standard when the surrounding land was greater than 75% cultivated.

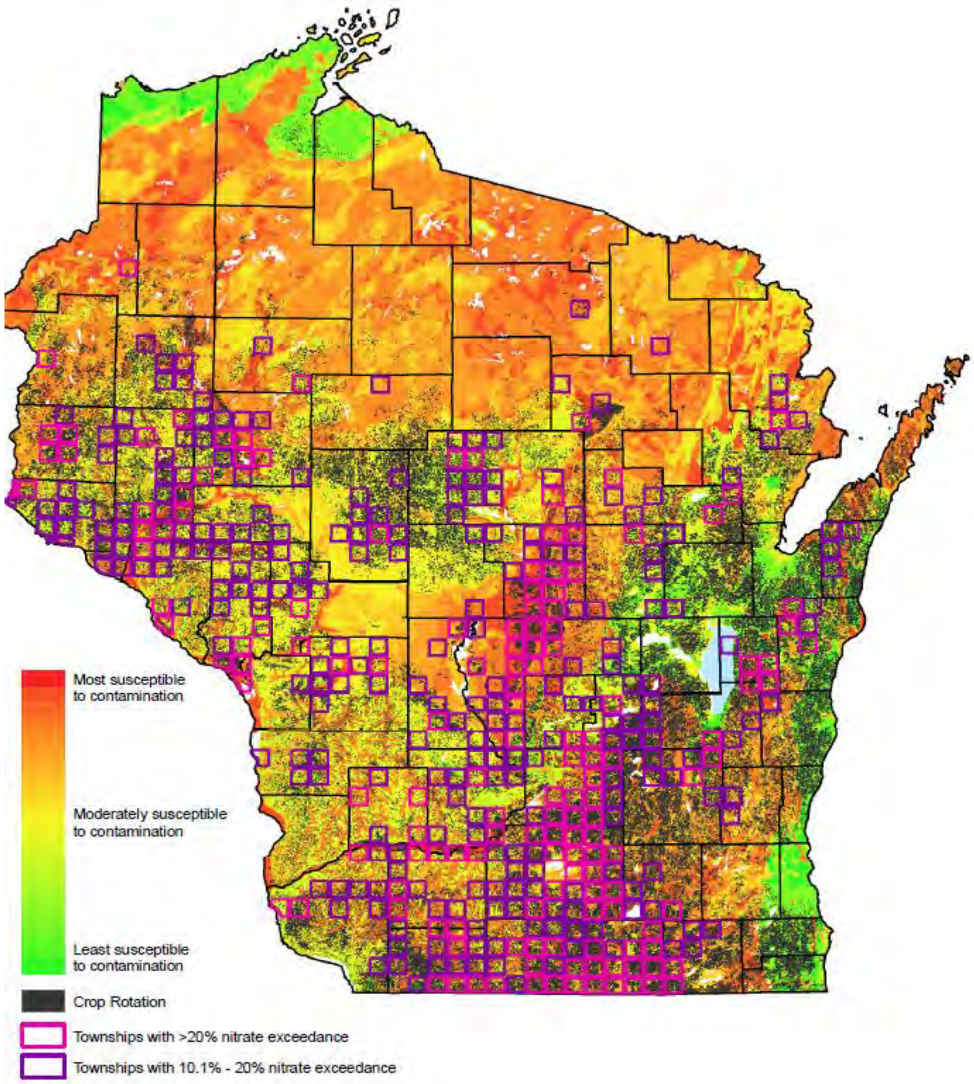
How does nitrate get into our drinking water?

Nitrate can enter our groundwater (and then our drinking water) from fertilizer, animal and human waste runoff. *Graphic created by Minnesota Department of Health. Used with permission.*

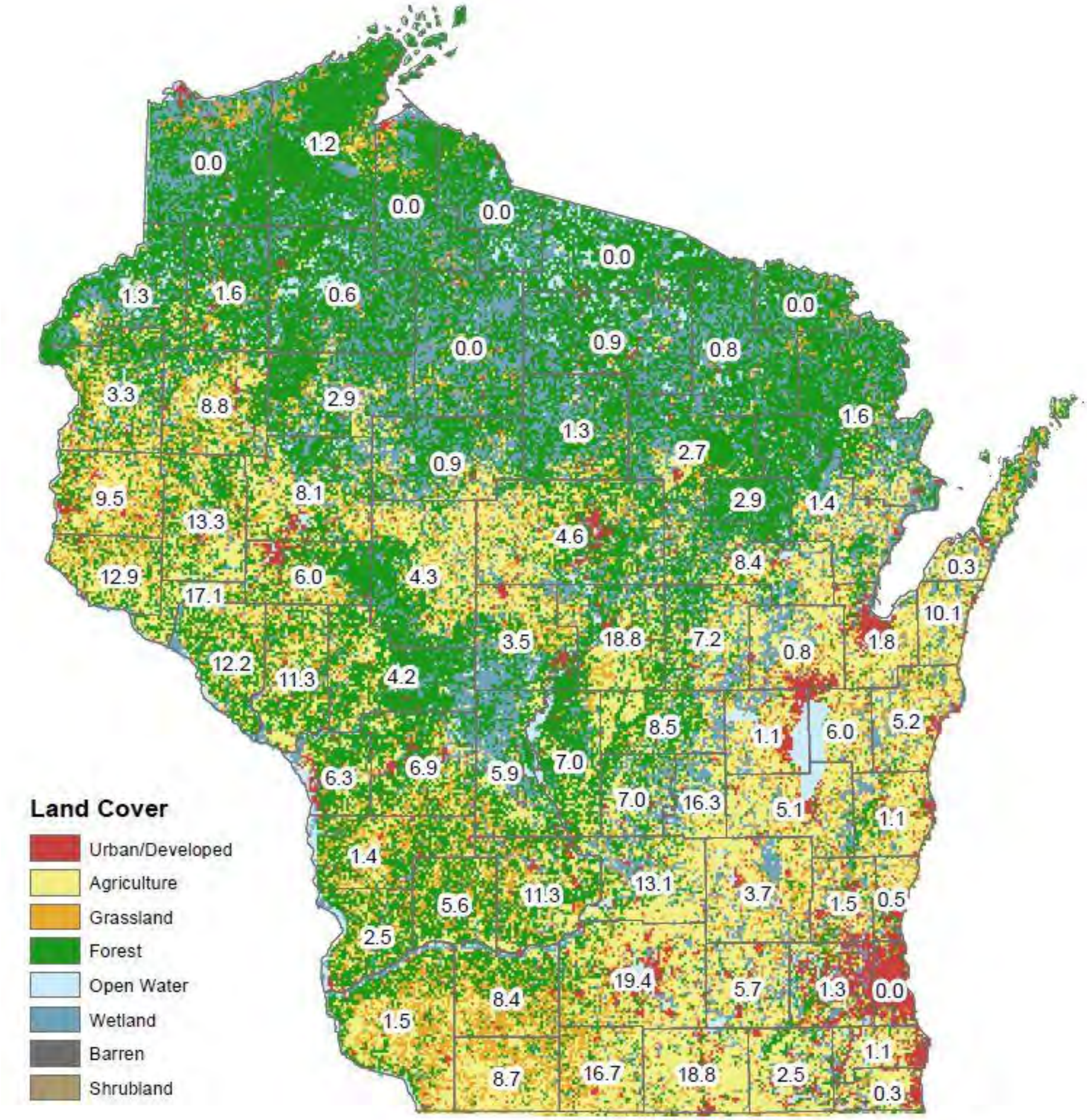


At a statewide scale, a mapping of broad land use categories overlayed with the estimated percentage of private wells exceeding the health-based standard by individual counties also illustrates that more wells are impacted in agriculturally intensive areas of the state.

The dominant effect of land use in comparison to aquifer sensitivity is also illustrated when overlaying township level private well nitrate data and agricultural land use with the Groundwater Contamination Susceptibility Model (GCSM). The GCSM for Wisconsin was developed by WGNHS, DNR, and the USGS and is intended to be used at broad scales. Five physical resource characteristics - type of bedrock, depth to bedrock, depth to water table, soil characteristics, and characteristics of surficial deposits (geologic materials lying between the soil and the top of the bedrock)—for which information was available were identified as important in determining how easily a contaminant can be carried through overlying materials to the groundwater. Areas with sand and gravel are considered more sensitive to groundwater contamination; areas with silt and clay are considered less susceptible. When viewed at a statewide scale, even parts of the state with only moderate aquifer sensitivity have townships where greater than 10% and frequently greater than 20% of private wells exceed the health-based standard for nitrate in drinking water.



Sensitivity of Wisconsin's groundwater versus agricultural land use and nitrate impacts to private wells.



Map of Estimated Percentage of Private Wells over Nitrate Standard by County with Land Cover (Jan. 2022 - June 2023).

Is groundwater nitrate increasing or decreasing?

Evidence indicates that nitrate contamination of our groundwater resources has increased in more locations over time rather than decreased. Upward nitrate trends over time are frequently observed when reviewing regional or local trends in well water quality, particularly where wells are vulnerable to nitrate contamination.

At a statewide scale, evaluation of overall nitrate trends using existing private and public well data is challenging for several reasons. Private wells are not typically sampled consistently over time, and not all private well data is reported to DNR. Public water system sampling, on the other hand, is to ensure water is safe at the tap. Once a public well exceeds the nitrate MCL, the system is required to come back into compliance and the preferred action is to replace the well. Wells with increasing trends are thereby removed, biasing the public water data set towards wells without increasing nitrate concentrations.

Both new private and public wells tend to be sited, drilled and cased to avoid known water quality issues such as nitrate contaminated groundwater. To help evaluate aquifer depths where lower nitrate levels may be found, the DNR provides assessment tools to evaluate the depth of penetration of nitrate in the aquifer based on historical well sampling and well construction data within a Township. The result of these factors is that both private and public wells are not consistently sampling the "same" water or depths over time and are biased toward utilizing groundwater without contamination, making an analysis of the groundwater resource, comparisons over time and trend analysis difficult using these data sets.

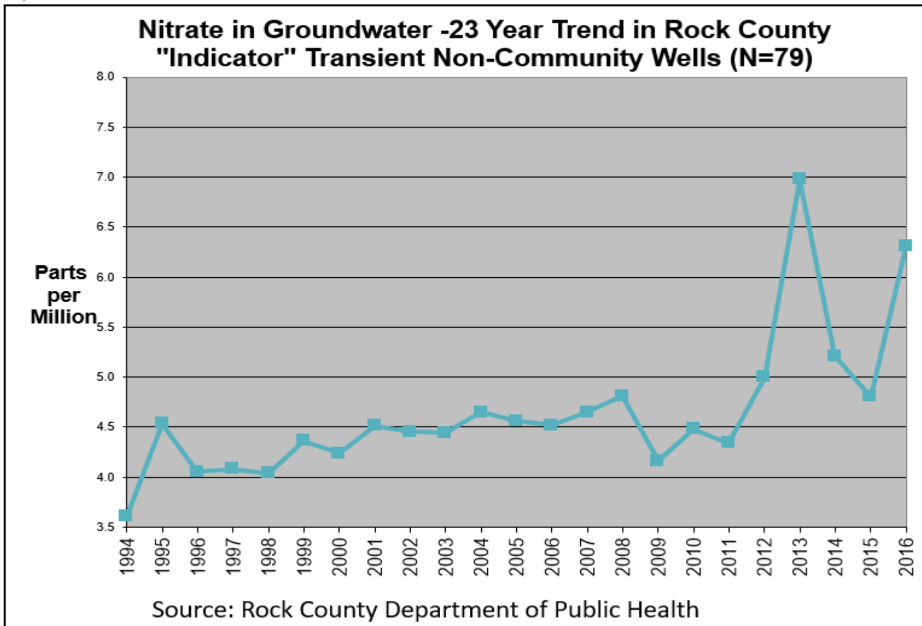
Year	MC	OC	NN	TN
2015	3	6	12	18
2016	0	2	3	8
2017	3	4	15	27
2018	2	4	12	17
2019	3	2	8	22
2020	3	5	6	19

MCL violations for nitrate in recent years by public well type – Municipal Community (MC), Other than Municipal Community (OC), Non-Transient, Non-community (NN) and Transient, Non-community (TN). *Note: the numbers for TN systems do not include the approximately 200 wells on continuing operation (sampling between 10 ppm and 20 ppm).* DNR has initiated a work plan that will bring all TN public water systems back into compliance with the nitrate standard of 10 mg/L.

However, we do have a large number of public wells distributed across the state that are required to submit nitrate sample results to the DNR at least annually. On average, there are approximately 11,0000 non-community public wells (e.g. small businesses, schools, churches) active at any given time. A review of the historical record of these well data since 1975, shows a relatively consistent number of wells exceed the 5 mg/L and 10 mg/L nitrate thresholds within any single decade (i.e. about 18.3% of non-community water systems exceed 5 mg/L and about 6.5% exceed 10 mg/L). However, when looking at these wells over the full period of record, there is a much larger set of wells represented (>20,000 individual wells) and the total number of wells exceeding these thresholds at any point in time is greater than in any discrete decade. Over the full record of the DNR Public Water System database, approximately 21% of these wells exceeded 5 mg/L and approximately 8.3% exceeded 10 mg/L. Many of the nitrate impacted wells have dropped out of the data set over time as corrective actions are implemented to meet drinking water standards. The table below lists MCL violations for nitrate in recent years by public well type – Municipal Community (MC), Other than Municipal Community (OC), Non-Transient, Non-community (NN) and Transient, Non-community (TN).

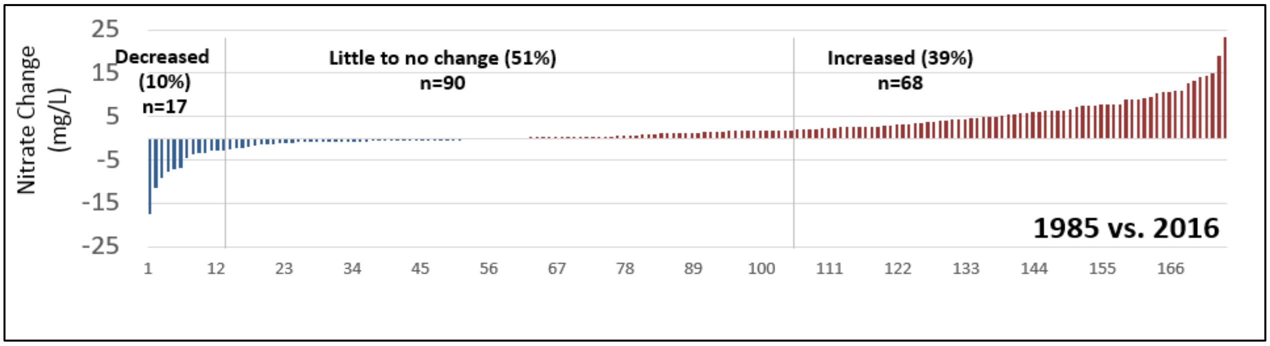
Regional and local nitrate trends

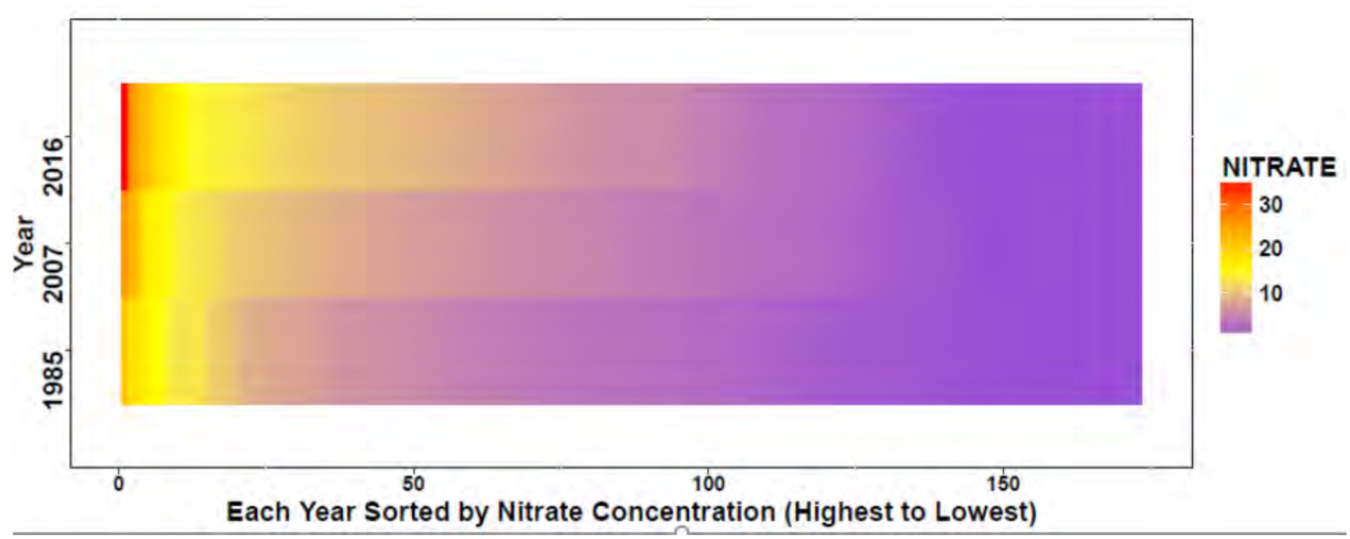
Wisconsin counties have conducted their own studies using consistent sets of well data that reveal local trends in aquifer nitrate levels. The Rock County Health department has been sampling and maintaining a data set based on a consistent set of transient non-community (TN) public wells over approximately 25 years. A group of 79 wells located throughout the county has shown an increasing average concentration since 1994, with a marked increase in the last decade (see figure below).



These consistently sampled TN wells show an increasing nitrate trend since 1994.

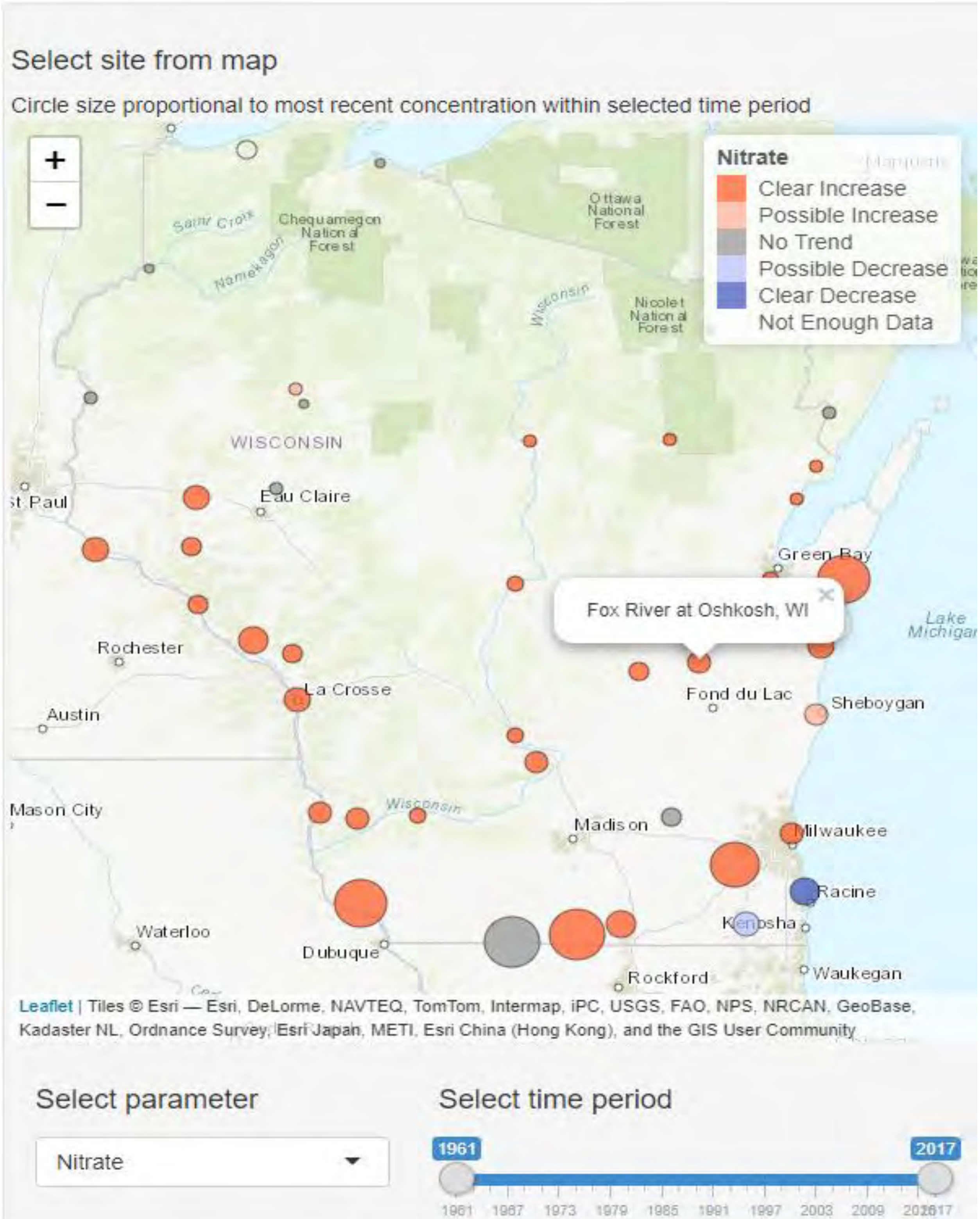
Chippewa County provides another example where a consistent set of private wells (175) were sampled multiple times over thirty years. This data set shows the importance of location: most wells saw little or no change over the 30 years (51%) and some wells showed a decrease (10%), while 39% showed an increase in nitrate concentrations (see figure below).



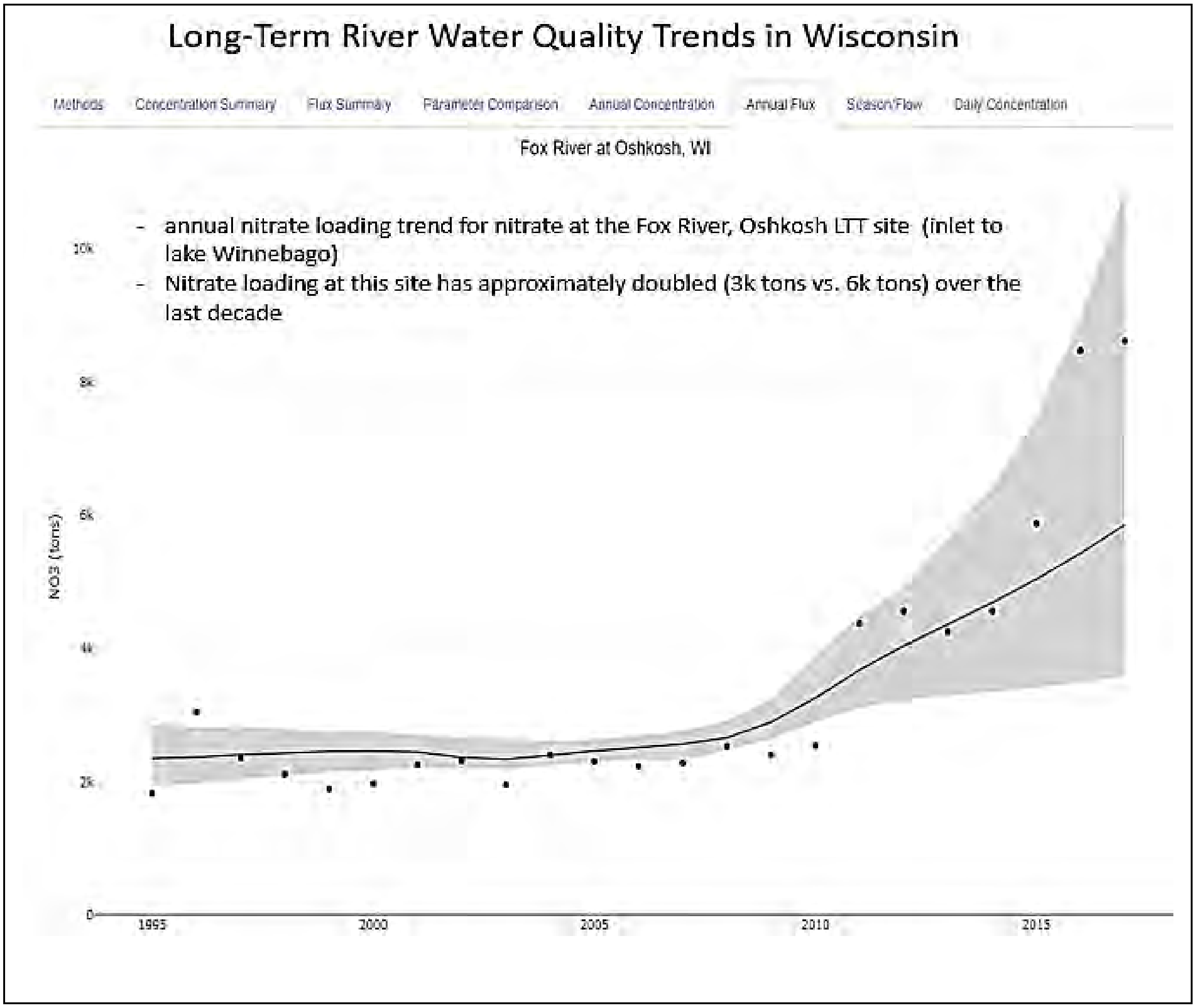


Chippewa study: old, mid and late era sample data. Masarik et al., 2016 In preparation.

Another useful method to assess long-term groundwater nitrate trends throughout the state is to evaluate data from groundwater baseflow dominated streams. A large portion of the state is covered by "groundwater dominated" watersheds (i.e. the ratio of groundwater baseflow to total streamflow is greater than 50%). Long term trend monitoring sites maintained by DNR and USGS in these watersheds provide information about the aggregate water quality yielded by these watersheds over time for groundwater transported contaminants such as nitrate. Wisconsin has some large basins where the baseflow contribution at the monitoring station is estimated to be as high as 90%[28]. Data from DNR's Long Term Trend Network for streams shows increases in nitrate concentration for most locations throughout the state.



DNR Long Term Trend (LTT) Data Viewer: https://wisconsindnr.shinyapps.io/riverwq/



Estimated costs in Wisconsin to mitigate Nitrate

To obtain a safe water supply, private well owners may opt to replace an existing well with a deeper, better cased well or, if available, connect to a nearby public water supply. Owners of nitrate-contaminated private wells can qualify for the state well compensation grant program if the nitrate-N level in their well exceeds 10 ppm.

Alternatively, well owners may choose to install a water treatment system or use bottled water. In a survey of 1,500 families in 1999, the DHS found that few took any action to reduce nitrate exposure[29]. Of the families who took actions, most purchased bottled water for use by an infant or pregnant woman. It appears that some private well owners in rural Wisconsin are installing reverse osmosis filter systems at considerable cost to obtain safe drinking water[23].

Private well owners cost analysis

In 2019, the data from new wells and pump work from 2014 through 2018 was used in an analysis to develop a cost estimate for private wells to address nitrate over the 10 ppm health standard. The estimate is based on private well owners who are over the nitrate standard choosing to drill a new well to a depth where water below the standard can be obtained (the preferred safe at the source method).

The analysis involved estimating the number of private wells in each county and multiplying that by the percentage of wells over 10 ppm for each county. A cost for individual well replacement was developed using Groundwater Retrieval Network (GRN) nitrate data to determine the depth of penetration of nitrate into the aquifer. This depth was used as the estimated depth to construct a well reaching safe water at the source.

The data analysis from 2019 shows that the estimated number of private wells exceeding the health standard for nitrate in Wisconsin is over 42,000, with a total cost estimate of abandoning the contaminated well and replacing it with a new safe water supply exceeding 446 million dollars. Results by county are shown in the table below. These costs are now about double due to the increased cost of steel, cement and drilling being driven by supply chain issues during and after Covid-19.

An estimate of the cost to well owners who have already replaced their well due to elevated nitrate was calculated by reviewing well construction reports submitted to the department where nitrate was listed as the reason for the new well. This likely underestimates the number of wells replaced for nitrate, because no reason was listed on the report. Using the same methodology, it is estimated that private well owners have spent more than 9 million dollars to replace wells with elevated nitrate levels.

Table 1: Estimated percent/number of private wells exceeding the health standard for nitrate and the total cost estimate to abandon the contaminated well and replace it with a new safe water supply by county.

County	Estimated # of private wells	Estimated % of wells over 10 ppm Nitrate Standard	Estimated # of private wells over Nitrate Standard	Estimated Replacement Cost (millions)
Adams	9959	12.4%	1232	$10.82
Ashland	2290	0.0%	0	$0.00
Barron	9336	9.3%	872	$8.69
Bayfield	5679	0.0%	0	$0.00
Brown	14077	2.9%	414	$4.93
Buffalo	3158	7.1%	224	$1.67
Burnett	6689	1.2%	82	$0.41
Calumet	3932	10.5%	413	$5.25

Table 1 continued:

County	Estimated # of private wells	Estimated % of wells over 10 ppm Nitrate Standard	Estimated # of private wells over Nitrate Standard	Estimated Replacement Cost (millions)
Chippewa	13242	13.5%	1788	$15.99
Clark	6581	5.4%	357	$1.80
Columbia	8762	17.9%	1564	$19.22
Crawford	2485	0.9%	24	$0.28
Dane	23506	18.3%	4313	$65.61
Dodge	11112	5.0%	553	$7.44
Door	11797	1.3%	153	$2.04
Douglas	5165	0.0%	0	$0.00
Dunn	7501	12.1%	906	$6.65
Eau Claire	9153	5.3%	483	$3.89
Florence	2423	1.6%	39	$0.18
Fond du Lac	12190	5.3%	649	$8.41
Forest	4073	1.3%	54	$0.19
Grant	5895	6.6%	389	$6.05
Green	5474	20.2%	1106	$15.22
Green Lake	4957	19.5%	968	$14.60
Iowa	3511	12.5%	438	$7.13
Iron	749	0.7%	6	$0.02
Jackson	4688	6.7%	312	$1.63
Jefferson	9491	8.3%	792	$8.16
Juneau	5166	11.6%	600	$3.85
Kenosha	15570	0.8%	132	$1.21
Kewaunee	3741	3.3%	122	$0.90
La Crosse	7216	13.4%	965	$8.99
Lafayette	2628	15.3%	402	$5.74
Langlade	6387	4.7%	298	$2.41
Lincoln	7396	3.7%	277	$1.55
Manitowoc	8693	6.2%	539	$6.87
Marathon	22195	7.1%	1578	$11.36
Marinette	10295	2.3%	239	$1.41
Marquette	5951	9.4%	559	$5.90
Menominee	1287	0.0%	0	$0.00
Milwaukee	23534	0.3%	80	$0.48
Monroe	6561	10.1%	662	$4.63
Oconto	13336	2.4%	321	$2.54
Oneida	15788	1.7%	274	$1.31
Outagamie	13997	0.8%	117	$1.91
Ozaukee	11940	0.7%	80	$0.69
Pepin	1593	20.1%	320	$2.48

Table 1 continued:				
County	Estimated # of private wells	Estimated % of wells over 10 ppm Nitrate Standard	Estimated # of private wells over Nitrate Standard	Estimated Replacement Cost (millions)
Pierce	4678	14.7%	689	$9.98
Polk	8907	4.7%	422	$3.75
Portage	8658	17.7%	1536	$13.13
Price	4868	1.9%	94	$0.38
Racine	16892	0.6%	99	$0.84
Richland	3262	8.8%	286	$2.47
Rock	12275	24.4%	2999	$32.45
Rusk	4857	3.6%	175	$1.00
Saint Croix	13362	12.2%	1624	$15.97
Sauk	7775	13.4%	1042	$9.33
Sawyer	9796	1.0%	99	$0.48
Shawano	7604	8.0%	606	$5.14
Sheboygan	11561	3.0%	344	$3.03
Taylor	5255	2.7%	144	$0.91
Trempealeau	5044	18.2%	917	$10.05
Vernon	4350	3.3%	142	$2.11
Vilas	12718	1.6%	201	$0.95
Walworth	17916	4.0%	715	$6.31
Washburn	6395	0.8%	53	$0.34
Washington	19541	3.8%	735	$10.52
Waukesha	57361	1.8%	1041	$14.38
Waupaca	10389	7.1%	736	$6.15
Waushara	9254	10.4%	964	$9.08
Winnebago	14271	1.9%	266	$4.27
Wood	8099	4.9%	394	$2.75
Totals	676,237		42,019	$446M

Public water systems costs

Because nitrate is both an acute and chronic health issue, community Public Water Systems cannot serve water over the nitrate Enforcement Standard (ES), and therefore must either replace the well or install approved treatment if they exceed it. In 2019, the city of Colby in Marathon County spent $769,000 to install a nitrate mitigation system. In 2018, the village of Junction City in Portage County replaced a public water supply well due to high nitrate concentrations at a cost of $1,128,000. That same year, the village of Fall Creek spent $1,074,000 to replace a well due to high nitrate. While complete information on the costs have not been confirmed, the current estimate is over 40 million dollars have been spent by municipal public systems to deal with nitrate. Theses cost estimates do not include increased sampling or investigative costs, nor operational costs to maintain treatment systems.

The Safe Drinking Water Act allows transient non-community (TN) systems to continue to operate with nitrate above the health standard of 10 mg/L but below 20 mg/L if the nitrate level warning is posted and bottled water is provided. TN systems include motels, restaurants, taverns, campgrounds, parks and gas stations. In recent years, there have been up to 300 TN systems in operation in this situation. WDNR has recently initiated a plan that will bring all TN public water systems back into compliance with the nitrate standard of 10 mg/L. Using the same process for developing costs as for the private well replacement, the total cost for TN well mitigation of the currently existing systems over 10 ppm is 3.2 million dollars. Each year about 20 new TN systems go over the nitrate standard.

Over the past 10 years 61 Non-transient Non-community systems (NN) (such as wells serving schools, day care centers and factories) have gone over the standard. Using a similar cost estimate method as above, the cost to those systems is estimated at 747,000 dollars.

Further Reading

- DNR overview of nitrate in drinking water
- DNR overview of nutrient management planning
- DATCP overview of nutrient management
- DHS overview of nitrate health effects
- DNR, DATCP, and DHS water quality recommendations
- NR 151 rule changes for nitrate

References

1. Hord NG, Tang Y, Bryan NS. Food sources of nitrates and nitrites: the physiologic context for potential health benefits. Am J Clin Nutr. 2009 Jul;90(1):1-10. doi: 10.3945/ajcn.2008.27131. Epub 2009 May 13. PMID: 19439460.
2. Knobeloch, L., B. Salna, A .Hogan, J. Postle, H. Anderson. 2000. Blue babies and nitrate contaminated well water. Environmental Health Perspectives, 108(7):675-678. Available at *http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1638204/*
3. Moltchanova E., M. Rytkonen, A. Kousa, O. Taskinen, J. Tuomilehto, M. Kavonen. 2004. Zinc and nitrate in the ground water and the incidence of Tye 1 diabetes in Finland. Diabetic Medicine, 21(3):256-261.

4. Parslow, R.C., P.A. McKinney, G.R. Law, A. Staines, R. Williams, H.J. Bodansky. 1997. Incidence of childhood diabetes mellitus in Yorkshire, northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40(5):550-556.

5. Brender, J.D. et al. 2013. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the National Birth Defects Prevention Study. Environmental Health Perspectives, 121(9):1083-1089. Available at *http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3764078/*

6. Ward, M.H., S.D. Mark, K.P. Cantor, D.D. Weisenburger, A. Correa-Villasenor, S.H. Zahm. 1996. Drinking water nitrate and the risk of non-Hodgkin's lymphoma. Epidemiology 7(5):465-471.

7. Xu, G., P. Song, P.I. Reed. 1992. The relationship between gastric mucosal changes and nitrate intake via drinking water in a high-risk population for gastric cancer in Moping county, China. European Journal of Cancer Prevention, 1(6):437-443.

8. Yang, C.Y., M.F. Chen, S.S. Tsai, Y.L. Hsieh. 1998. Calcium, magnesium, and nitrate in drinking water and gastric cancer mortality. Japanese Journal of Cancer Research, 89(2):124-130.

9. Weyer, P.J., J.R. Cerhan, B.C. Kross , G.R. Hallberb, J. Kantamneni, G. Breuer, M.P. Jones, W. Zheng, C.F. Lynch. 2001. Municipal drinking water nitrate level and cancer risk in older women: The Iowa Women's Health Study. Epidemiology, 11(3):327-338.

10. Vitousek, P. M., et al. 1997. Human alteration of the global nitrogen cycle: causes and consequences. Ecological Society of America *Volume7, Issue3* *https://esajournals.onlinelibrary.wiley.com/doi/full/10.1890/1051-0761%281997%29007%5B0737%3AHAOTGN%5D2.0.CO%3B2*

11. Camargo J.A. and J.V. Ward. 1995. Nitrate toxicity to aquatic life: a proposal of safe concentrations for two species of near arctic freshwater invertebrates. Chemosphere, 31(5):3211-3216.

12. Marco A., C. Quilchano, A.R. Blaustein. 1999. Sensitivity to nitrate and nitrite in pond-breeding amphibians from the Pacific Northwest, USA. Environmental Toxicology and Chemistry, 18(12):2836- 2839.

13. Crunkilton, R.L. and T. Johnson. 2000. Acute and chronic toxicity of nitrate to brook trout (Salvelinus fontinalis). Wisconsin groundwater management practice monitoring project, DNR-140. Available at *http://digital.library.wisc.edu/1711.dl/EcoNatRes.CrunkiltonAcute*

14. Camargo J.A., A. Alonso, A. Salamanca. 2005. Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. Chemosphere, 58:1255-1267.

15. Smith, G.R., K.G. Temple, D.A. Vaala, H.A. Dingfelder. 2005. Effects of nitrate on the tadpoles of two ranids (Rana catesbeiana and R. clamitans). Archives of Environmental Contamination and Toxicology, 49(4):559-562.

16. McGurk M.D., F. Landry, A. Tang, C.C. Hanks. 2006. Acute and chronic toxicity of nitrate to early life stages of lake trout (Salvelinus namaycush) and lake whitefish (Coregonus clupeaformis). Environmental Toxicology and Chemistry, 25(8):2187-2196.

17. Stelzer, R.S. and B.L. Joachim. 2010. Effects of elevated nitrate concentration on mortality, growth, and egestion rates of Gammarus pseudolimnaeus amphipods. Archives of Environmental Contamination and Toxicology, 58(3): 694-699.

18. Davis, T.W., Bullerjahn, G.S., Tuttle, T., McKay, R.M., and Watson, S.B. (2015). Effects of Increasing Nitrogen and Phosphorous Concentrations on Phytoplankton Community Growth and Toxicity During Planktothrix Blooms in Sandusky Bay, Lake Erie. Environmental Science & Technology, 49(12), 7197-7207

19. Harke, M.J., Steffen, M.M., Gobler, C.J., Pttem. T.G., Wilhelm, S.W., Wood, S.A., and Paerl, H.Q. (2016). A review of the global ecology, genomics, and biogeography of the toxic cyanobacterium, Microcystis spp. Harmful Algae, 54, 4-20.

20. Kraft, G.J. and W. Stites. 2003. Nitrate impacts on groundwater from irrigated vegetable systems in a humid north-central US sand plain. Agriculture, Ecosystems & Environment, 100(1):63-74.

21. Kraft, G.J., B.A. Browne, W.M. DeVita, D.J. Mechenich. 2004. Nitrate and pesticide penetration into a Wisconsin central sand plain aquifer. Wisconsin groundwater management practice monitoring project, DNR-171. Available at http://digital.library.wisc.edu/1711.dl/EcoNatRes.KraftNitrate

22. Kraft, G.J., B.A. Browne, W.D. DeVita, D.J. Mechenich. 2008. Agricultural pollutant penetration and steady-state in thick aquifers. Ground Water Journal, 46(1):41-50.

23. Saad, D.A. 2008. Agriculture-Related Trends in Groundwater Quality of the Glacial Deposits Aquifer, Central Wisconsin. Journal of Environmental Quality, 37(5-S):S209-S225.

24. Knobeloch, L., P. Gorski, M. Christenson, H. Anderson. 2013. Private drinking water quality in rural Wisconsin. Journal of Environmental Health, 75(7):16-20

25. Schultz, A. and K.C. Malecki. 2015. Reducing human health risks from groundwater: private well testing behaviors and barriers among Wisconsin adults. Wisconsin groundwater management practice monitoring project, DNR-221.

26. Mechenich, D. 2015. Interactive Well Water Quality Viewer 1.0. University of Wisconsin-Stevens Point, Center for Watershed Science and Education. Available at *http://www.uwsp.edu/cnr-ap/watershed/Pages/WellWaterViewer.aspx*

27. Shaw B. 1994. Nitrogen Contamination Sources: A Look at Relative Contribution. Conference proceedings: Nitrate in Wisconsin's Groundwater – Strategies and Challenges. May 10, 1994. Central Wisconsin Groundwater Center, University of Wisconsin-Stevens Point, WI. Available at *http://www.uwsp.edu/cnr-ap/watershed/Documents/nitrogen_conferenceproceedings.pdf*

28. Gebert, W.A., Walker, J.F., and Kennedy, J.L., 2011, Estimating 1970–99 average annual groundwater recharge in Wisconsin using streamflow data: U.S. Geological Survey Open-File Report 2009–1210 *https://pubs.usgs.gov/of/2009/1210/*

29. Schubert, C., L. Knobeloch, M.S. Kanarek, H.A. Anderson. 1999. Public response to elevated nitrate in drinking water wells in Wisconsin. Archives of Environmental Health, 54(4):242-247.