Nitrate in Groundwater - A Continuing Issue for Wisconsin Citizens

by

The Nutrient Management Subcommittee of the Nonpoint Source Pollution Abatement Program Redesign

March, 1999

Nutrient Management Workgroup Members

Staff

Jim Vanden Brook	DATCP Groundwater
Richard Wedepohl	DNR Shoreland Zoning
Jennifer Heaton	DATCP Office of the Secretary
Mike Lemcke	DNR Ground Water
Sue Porter	DATCP Land & Water Resources Bureau
Greg Searle	DNR Surface Water
Scott Sturgul	NPM Nutrient Specialist Madison

Members

Larry Bundy	UW-Madison Soil Department
Tom Davies	Winnebago County Land Conservation
Bob Dummer	Farmer - Holmen
Pete Knigge	Farmer - Omro
George Kraft	UW-Stevens Point Groundwater Center
Greg Langer	Cottage Grove Co-op Division Manager
Fred Madison	UW Madison-WGNHS
Pat Murphy	NRCS/DNR Madison
Harriet Pedley	Richland County Zoning Administrator
Jeffrey Polenske	Independent Crop Consultant Appelton
Todd Prill	Chippewa County Land Conservation

Principle Authors:
Laura Chern – DNR
George Kraft - CWGC
Jeff Postle - DATCP

Executive Summary

This paper summarizes the information available concerning nitrate in Wisconsin's groundwater. Previous papers have summarized the sources and concerns related to nitrate in groundwater (Bundy et al, 1994); the occurrence of nitrogen in groundwater and best management practices to reduce nitrate pollution (DATCP, 1989); and nitrogen application rates (Bundy et al, 1994). This paper provides additional information on the extent of nitrate pollution, the costs resulting from nitrate pollution and nitrate pollution sources and trends.

Nitrate is the most widespread groundwater contaminant in Wisconsin. It has a federal Maximum Contaminant Level (MCL) and Wisconsin groundwater enforcement standard (ES) of 10 parts per million as nitrate-nitrogen. The standards are based on the risk of methemoglobenemia in infants.

About 10% of Wisconsin's 800,000 private wells have nitrate-nitrogen concentrations exceeding the ES. Exceedences are not uniform across the state, however. Nitrate is rarely detected in areas with few pollution sources, such as much of northern Wisconsin. It is more frequently detected in wells located in agricultural parts of the state. A DATCP study showed exceedence rates between 17-26% in some agricultural districts. Data collected by researchers at the University of Wisconsin at Stevens Point showed exceedence rates greater than 60% in localized agricultural areas. On a statewide basis, about 90% of the nitrate detected is from agricultural sources (fertilizer, manure, and legumes). Septic systems and other sources contribute 9% and 1% respectively.

Private well owners in Wisconsin have paid an estimated 3 to 5 million dollars to repair or replace private wells, treat nitrate in drinking water or obtain bottled water. Currently, fifteen municipalities are required to treat their source water to reduce nitrate levels in their public water supplies. Installation of nitrate removal systems has cost these communities more than 10 million dollars. Ongoing maintenance and chemicals will cost citizens several thousand dollars per year per system.

There is compelling research that shows the problem is getting worse as older, cleaner groundwater is discharged naturally and replaced by newer groundwater with higher levels of nitrate. Environmental effects that can't be corrected using water treatment devices, such as eutrophication and fish mortality, will get worse. As groundwater quality changes and more wells are affected, costs to private well owners and municipalities will increase.

Introduction

The Department of Natural Resources (DNR) and the Department of Agriculture Trade and Consumer Protection (DATCP) agree that nitrate is the most widespread groundwater contaminant in Wisconsin and that the problem is increasing in extent and severity. Nitrogen is necessary for plant growth, and adding nitrogen fertilizer increases yield for most non-legume crops. This paper presents available information on the extent and potential effects of nitrate contamination of Wisconsin's groundwater.

What is nitrate?

Nitrate (NO_3^-) is one of the chemical forms of nitrogen. It coexists with other forms of nitrogen in a complex cycle. Nitrogen in soil and water originates from atmospheric deposition, applications of fertilizer, manure, waste material and dead plant and animal tissue. Under aerobic conditions, nitrate is a fairly stable form of nitrogen. Ammonium (NH_4^+) and organic nitrogen frequently convert quickly to nitrate.

Most of the nitrogen on earth is in the atmosphere, which consists of 78% N_2 gas. Other forms of nitrogen, originating mainly from power plant emissions, internal combustion engines, fertilizer and manure, also occur in the atmosphere. These include nitrogen oxides (NO_x and N_2O), nitric acid (HNO_3) and ammonia (NH_3). Atmospheric nitrogen interacts with the earth's surface when N_2 is "fixed" (changed chemically) by legumes or lightening, or when pollutants are washed-out in precipitation.

In most natural systems, inorganic nitrogen is a scarce nutrient. Plants efficiently use available nitrate and losses to groundwater and surface water are minimal. In agricultural systems, nitrate is added to increase profitability and production of non legume crops. It may be present in amounts exceeding what plants are able to use. As a result, excess nitrate can leach into groundwater or be washed into surface water. Nitrate in soil and water may also eventually cycle to the atmosphere by direct volatilization mainly under anaerobic conditions through a process called "denitrification"

What is groundwater?

Groundwater is the water under the earth's surface that flows freely through tiny pores and cracks in rock and soil and can be pumped from wells. Groundwater supplies 70% of the water used in Wisconsin households and the municipal water used by 608 cities and villages. Groundwater is important not only because it supplies drinking water but also because it provides water to streams, lakes and wetlands.

What is the current status of nitrate in Wisconsin groundwater?

According to a recent study by DATCP, an estimated 10% of Wisconsin wells exceed the groundwater enforcement standard of 10 parts per million (ppm) as nitrate-nitrogen (LeMasters and Baldock, 1997). A Centers for Disease Control (CDC) study showed that 6.5 % of wells in Wisconsin had nitrate-nitrogen levels greater than the standard (CDC, 1998). Databases maintained by DNR, DATCP and other state and federal agencies show 9-14% of wells have nitrate-nitrogen at levels greater than the standards. Concentrations of nitrate in groundwater are not uniform across the state. Nitrate is rarely detected in forested areas while contamination levels are generally higher in agricultural parts of the state. The DATCP study showed that in predominantly agricultural districts, 17-26% of wells had nitrate-nitrogen levels exceeding the

groundwater enforcement standard. Locally, greater than 60% of wells located in some agricultural areas vulnerable to groundwater contamination have nitrate-nitrogen levels greater than the enforcement standard. Septic systems can cause nitrate pollution in high-density unsewered subdivisions.

Why are we concerned about nitrate in groundwater?

Human Health

Nitrate can cause a condition called methemoglobenemia or “blue-baby syndrome” in infants under six months of age. Nitrate in drinking water used to make baby formula is converted to nitrite in the stomach. Nitrite changes hemoglobin in blood (that part of the blood that carries oxygen to the body) to methemoglobin depriving the infant of oxygen. In extreme cases it can cause death. While methemoglobenemia is a serious condition when it occurs, the number of cases treated prior to hospitalization has not been documented and is thought to be low. In 1992, a confirmed non-fatal case of methemoglobenemia due to nitrate contaminated groundwater occurred in Trempeauleau County, Wisconsin (Schubert et. al., 1997). An unconfirmed case of methemoglobenemia due to high nitrate in drinking water was reported in July 1998 in Columbia County (Knobeloch, 1998).

Several investigators have studied the chronic health and reproductive impacts of nitrate contaminated drinking water. Recent studies have implicated nitrate exposure as a possible risk factor associated with lymphoma, gastric cancer, hypertension, thyroid disorder and birth defects. In addition, a recent investigation conducted by local public health officials in La Grange County, Indiana implicated nitrate-contaminated drinking water as the possible cause of several miscarriages (Schubert et.al., 1997).

Livestock Health

Nitrate intake by dairy cattle is related to the levels found in forage and drinking water. According to research conducted on dairy cattle (Crowley, 1974), nitrate-nitrogen in drinking water at levels under 10 ppm is safe for animal and humans. Between 10-20 ppm nitrate-nitrogen, water is safe for livestock unless their feed has high nitrate levels. Problems for livestock can occur between 20-40 ppm nitrate-nitrogen if feed contains more than 1,000 ppm. If well water is between 40-100 ppm nitrate-nitrogen, feed should be low in nitrate, well balanced and fortified with vitamin A. At levels between 100-200 ppm nitrate-nitrogen in water, poor appetite occurs. If nitrate-nitrogen is over 200 ppm in water, acute nitrogen poisoning and death is likely in swine.

Aquatic Life

Nitrate does not appear to be acutely toxic to adult fish except at extremely high concentrations where mortality is due to salinity effects (USEPA, 1977). However, available research indicates that nitrate concentrations lower than the drinking water standard cause substantial egg and fry mortality in some salmonid fish species (Kincheloe et al., 1979). When rearing trout or warm water species, the US Fish and Wildlife Service recommends nitrate levels not exceed 3 ppm (Piper, et. al., 1982). Tadpoles exposed to nitrate at the drinking water standard show decreased appetite, sluggishness and paralysis prior to death (Hecnar, 1995).

Surface Water

Groundwater can carry nitrogen (in the form of nitrate) into surface water bodies. Plant–available nitrogen and phosphorus in surface water promotes excessive growth of weeds and algae. This process is called “eutrophication.” Nitrate supplied by groundwater discharge may cause increases in rooted aquatic plants (Lillie and Barko, 1990, Rodgers, et. al., 1995). Available data

from Wisconsin showed that in 8% of randomly selected lakes, nitrogen was probably the nutrient controlling aquatic weed growth (Lillie and Mason, 1983). Other data from the same study showed that weed growth in up to16% of Wisconsin lakes might be limited by nitrogen in the water.

There is compelling evidence that the amount of nitrate entering surface water from groundwater is increasing. A long term study carried out at the Deep Loess Research Station in Iowa showed that after 26 years of fertilizer application, nitrate levels in groundwater entering surface water increased from 5 ppm to 23 ppm. Currently, 16% of the nitrate applied within that study area enters surface water from groundwater as baseflow (Steinheimer et. al., 1998). A similar pattern has been seen in the Little Plover River where nitrate-nitrogen has increased from 1-2 ppm in the 1960s to 8 ppm at present. Figure 1 shows increasing nitrate-nitrogen levels in the Little Plover River since 1966 (Albertson and Shaw, 1998).

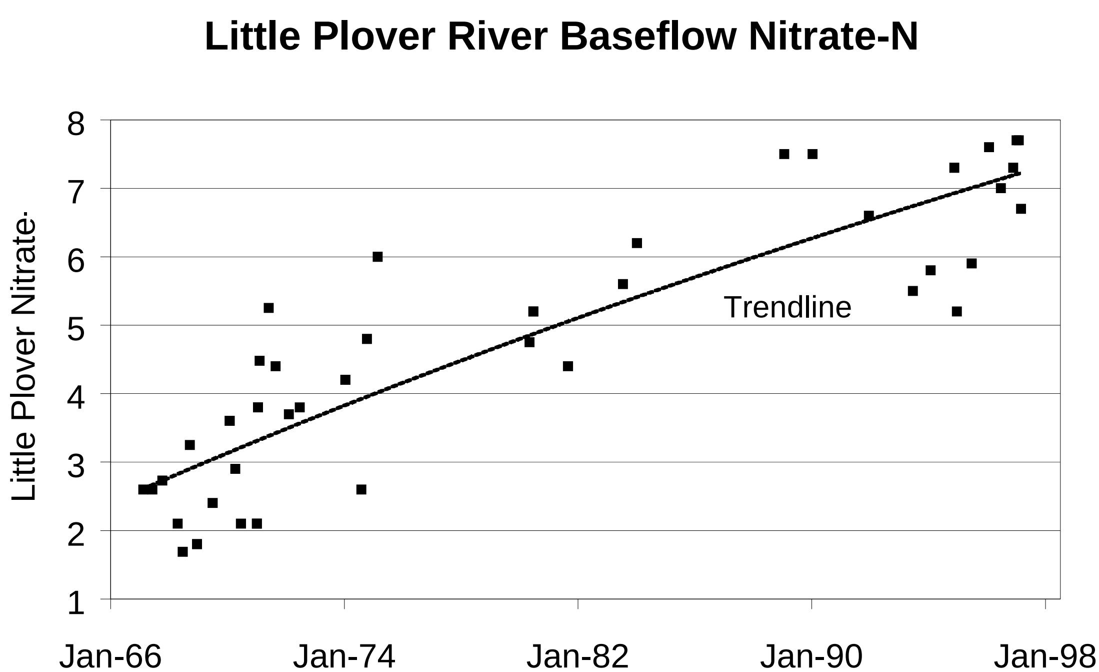

Figure 1. Increasing nitrate-N in Little Plover River baseflow (Albertson and Shaw, 1998).

Nitrate discharge via surface and groundwater has been implicated in the development of a hypoxic (oxygen depleted) area termed the "dead zone" in the Gulf of Mexico. The dead zone is a 6,500 square mile area with oxygen levels too low to support life. Sediment cores from the dead zone show that since the 1950's, nitrogen levels in offshore sediments have doubled with the increased use of fertilizers in the Mississippi Basin.

Atmosphere

Nitric oxide (NO) emissions from soils result from microbial activity. Soil nitric oxide may contribute as much as 15% to the total nitric oxide emissions budget in the United States. Nitric oxide combines with ozone (O_3) causing depletion of the ozone layer.

Nitrous Oxide (N_2O) accounts for less than 1% of all green house gas emissions, however, it has 270 times the warming potential of carbon dioxide (CO_2). In Wisconsin, fertilizer application accounted for 48% of 1990 N_2O emissions, whereas fertilizer use accounted for 32% of 1990 national emissions. Because Wisconsin is an agricultural state, fertilizer use contributes a higher percentage of N_2O emissions than nonagricultural states (USDOE, 1993).

What are the sources of nitrate to groundwater?
An estimated 2040 million pounds of nitrogen are deposited on Wisconsin's surface annually from agriculture, the atmosphere, septic systems and other sources (Shaw, 1994). Approximately 80% of this originates from agricultural sources divided almost equally among legumes, manure and commercial fertilizer (See Figure 2). Another 18% of the nitrogen comes from atmospheric sources including combustion of gasoline in automobiles, the breakdown of nitrogen fertilizers and manure, and lightning. The remaining 2 % comes from septage, sludge disposal and other sources.

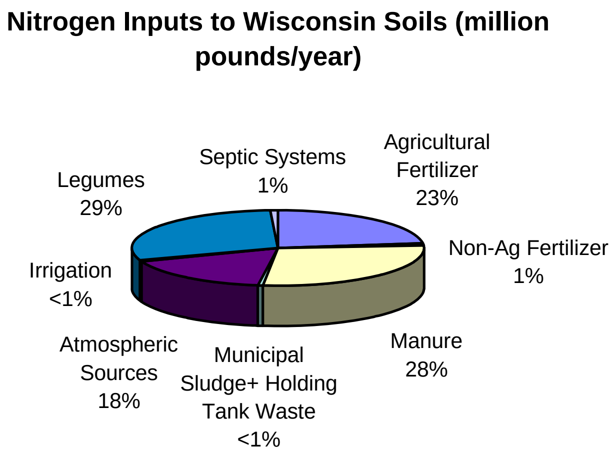

Figure 2. Nitrogen inputs to Wisconsin soils total 2040 million pounds per year from various sources (after Shaw, 1994).

Roughly 10% of the total nitrogen added to Wisconsin soils each year leaches to groundwater as nitrate. Ninety percent of this is from agriculture, 9% from septic systems and 1% from other

sources (See Figure 3). Though agriculture is the largest source on a statewide basis, other sources can be locally important. Nitrate loading from septic systems in dense, unsewered subdivisions can be as high as some of the most intensive farming operations (Shaw, 1994).

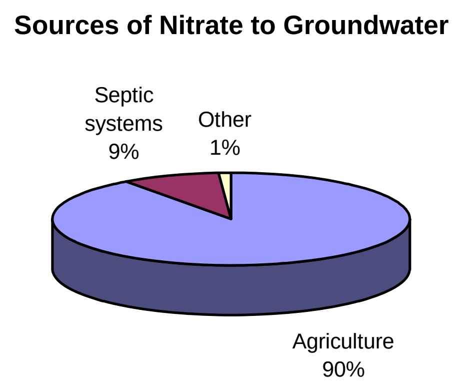

Figure 3. Sources of nitrate to groundwater (Shaw, 1994).

Between 1960 and 1978 fertilizer sales increased dramatically in Wisconsin and the US. In 1960, approximately 27,600 tons of nitrogen were sold in Wisconsin. Annual consumption rose to 220,000 tons in 1978 and has remained fairly constant between 225 - 250 thousand tons applied per year. This was almost a ten-fold increase over twenty years (See Figure 4).

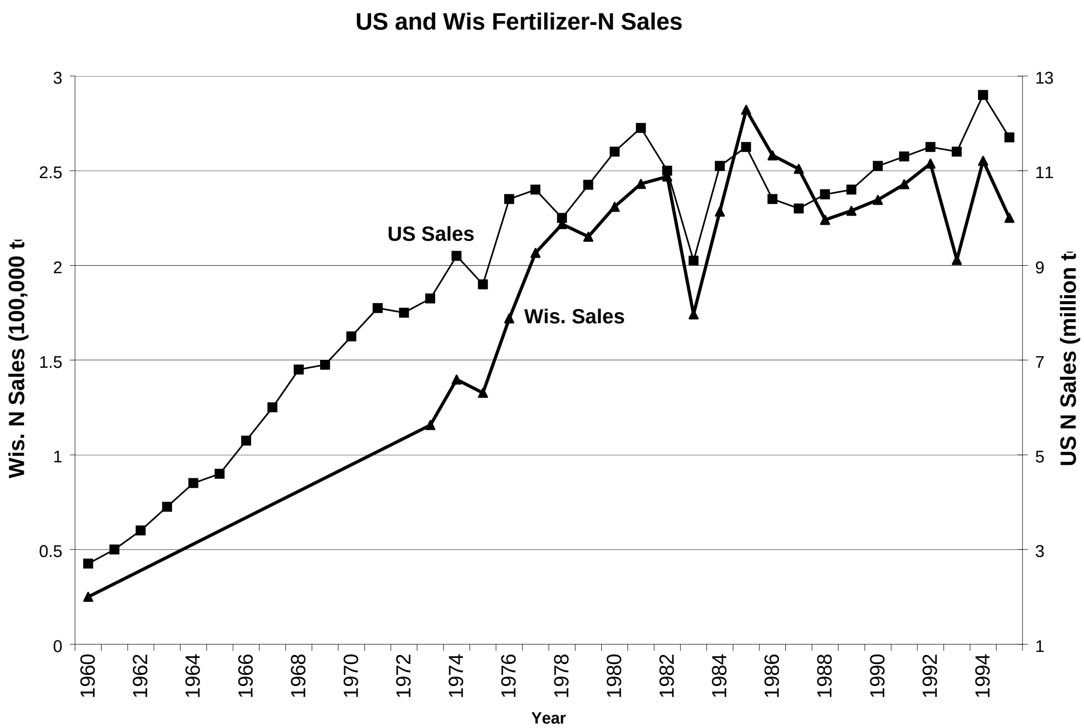

Figure 4. Increasing US and Wisconsin fertilizer-N sales over time.

While nitrogen is needed to increase plant productivity and farm profitability, Wisconsin farmers frequently apply more nitrogen to crops than is necessary to optimize yields. A survey of more than 1500 Wisconsin farmers found that two out of three farmers purchased more nitrogen fertilizer than their crops needed (Shepard et al, 1997). Farmers on average used an excess of 40 pounds per acre of nitrogen beyond University of Wisconsin recommendations for growing corn. This average number is conservative in that it doesn't account for residual soil nitrate, it only accounts for first-year legume and manure nitrogen credits, it assumes no incorporation of manure and the lowest value was used when a range was presented for manure or legume credits. At a cost of approximately $.23 per pound, Wisconsin farmers are spending $9.20 per acre on nitrogen beyond University of Wisconsin Extension recommendations.

How long has the problem been around?

Nitrate pollution at very low levels has probably existed in Wisconsin waters since settlement times. However, both in Wisconsin and other agricultural states, increasing nitrate pollution is a relatively recent phenomenon and is correlated with the increasing use of nitrogen fertilizers over the last 30-40 years (Hallberg, 1989; Hallberg et al 1989). Figure 5 shows a direct link between increasing nitrogen inputs on agricultural lands and water quality in the Big Springs, Iowa watershed.

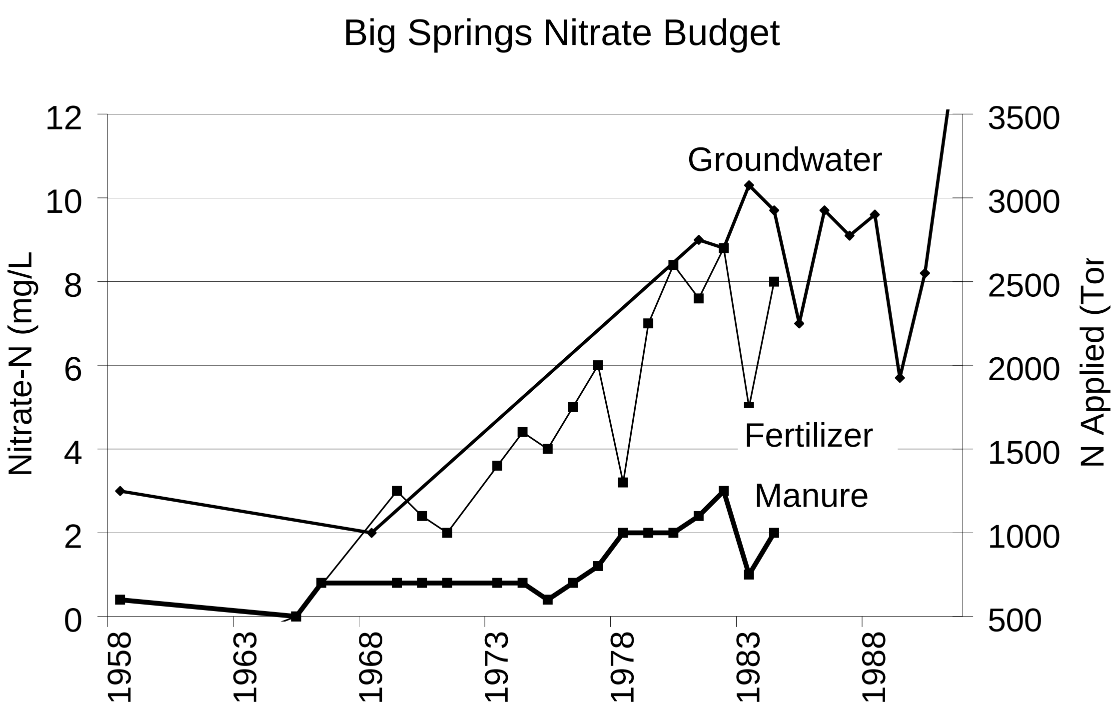

Figure 5. Data from the Big Springs Watershed in Iowa showing a correlation between increasing nitrate-nitrogen concentration in groundwater and increased fertilizer and manure application (Hallberg, 1989).

Similar patterns have since been observed in Wisconsin and Iowa in stream baseflow (Mason et al, 1990; Alberson and Shaw, 1998; Steinheimer et al,1998) and in some wells with long-term records such as the Village of Whitings municipal well located in Central Wisconsin (See Figure 6).

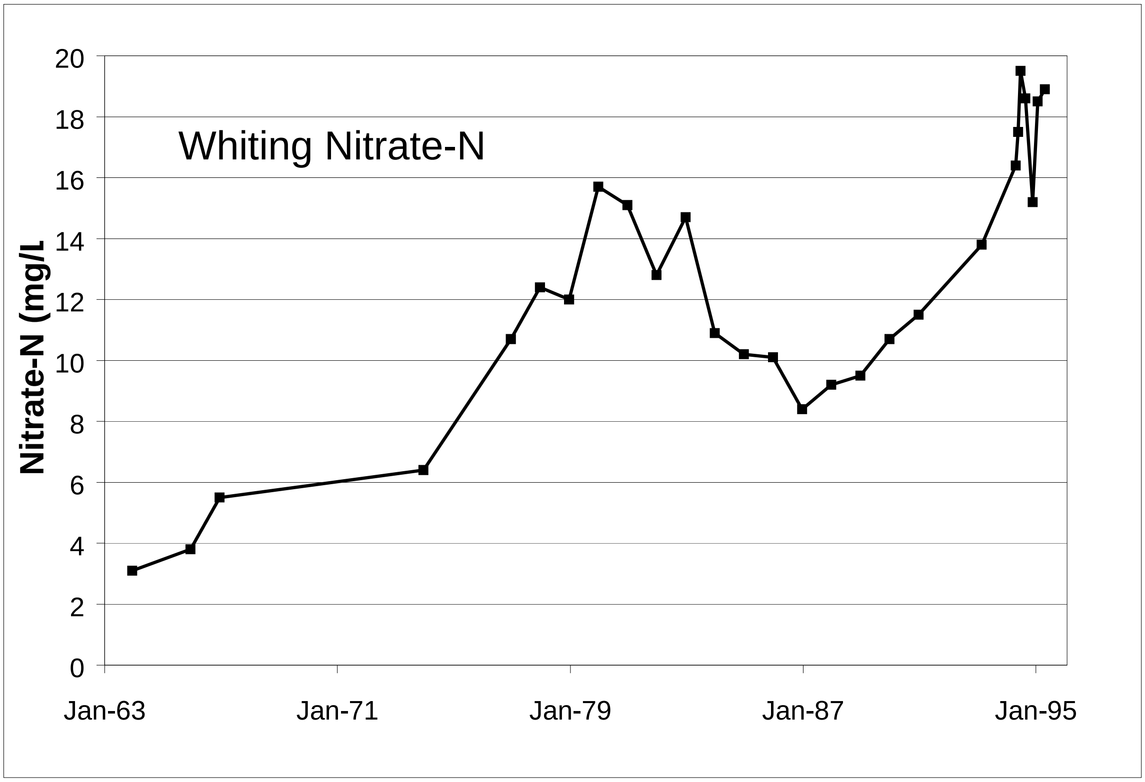

Figure 6. Increasing nitrate-nitrogen in the Village of Whiting's public water supply well.

What's the future for nitrate in groundwater?

Without a reduction in nitrate loading to groundwater, nitrate concentration in Wisconsin groundwater will likely increase and nitrate pollution will likely affect larger areas and larger volumes of groundwater and surface water. This is because, in many parts of Wisconsin, older groundwater originating before the use of chemical fertilizers and having low levels of nitrate is being discharged. It is being replenished with newer, high nitrate, groundwater. The net effect is that the average nitrate concentration in Wisconsin groundwater will likely continue to increase.

What are the tangible costs of nitrate pollution and who bears them?

The tangible cost of nitrate contamination of groundwater can be measured as the cost of water treatment for public, noncommunity (waysides and schools for example) and private well systems. These costs are borne by taxpayers, utility customers and well owners. Groundwater is the source of water for most of the 608 public water supply well systems in Wisconsin. Municipal wells are regulated under the Safe Drinking Water Act, which requires nitrate-nitrogen levels to be below the maximum contaminant level of 10 ppm. At least fifteen of these systems have been

required to install nitrate removal systems or drill new wells at a total cost to municipal taxpayers in excess of 10 million dollars. This amount does not include the annual cost of maintaining the systems. For example, the Village of Whiting's anion exchange treatment system cost over $630,000 to install and an additional $9,400 per year for salt. In addition, 1.2 million gallons of water are needed for regeneration of the system. This water is wasted as it is not potable after regenerating the system.

Wells used by schools, churches and businesses are called noncommunity wells. Noncommunity wells are classified as non-transient, meaning the well serves the same people everyday, and transient, meaning the well is used by different people everyday. Fifty-four of the approximately 1,000 non-transient wells in Wisconsin have nitrate levels greater than 10 ppm and 118 of 10,000 transient wells exceed 10 ppm. The cost of water treatment for these systems ranges from $600-$2,500 per well. A conservative estimate of the cost ($600 per well) to well owners is over 1 million dollars. This doesn't include the cost of operation. These wells are regulated under the Safe Drinking Water Act and must have nitrate levels below the MCL of 10 ppm nitrate-nitrogen. Wells are sampled for nitrate annually or quarterly, depending on the population served.

Approximately 800,000 households in Wisconsin use private well water. The groundwater standards for private wells are set under Chapter NR 140 Wis. Adm. Code and regulated under Chapter NR 812 Wis. Adm. Code. The Department of Health and Family Services investigated the cost to families with high nitrate concentrations in private wells (Schubert et. al., 1997) Of 562 well owners who responded to the survey, 70% took no action to reduce their exposure to nitrate contaminated groundwater. Nearly everyone who took action did so because of the presence of a pregnant woman or infant in the household. The most common action taken was the purchase of bottled water at an annual cost of roughly $200. Several families installed nitrate removal systems at an average cost of $850. One family repaired their existing well at a cost of $750. Two families installed new wells. Their costs averaged $7800. Assuming that between 10% and 6.5% of the 800,000 private wells in the state have nitrate concentrations greater than the enforcement standard for nitrate, private citizens have paid between $5.7 and $3.7 million for the cost of mitigating high nitrate levels in groundwater. Between $626,000 and $407,000 of that is spent annually by well owners purchasing bottled water.

What's the current legal framework for addressing nitrate in groundwater?

The Groundwater Law

The Groundwater Law (1983, Wis. Act 410) is the overriding Wisconsin statute which establishes authority for groundwater protection and numerical enforcement standards applicable to all Wisconsin agencies and programs. The enforcement standard is the health-based concentration of a substance at which a facility regulated by state agencies must take action to reduce the level of the substance in groundwater. Once enforcement standards are established, all state agencies must manage their regulatory programs to comply. Private wells are regulated under Chapter 160, Wis. Stats. However, nitrate is handled differently than other substances of

public health concern. Under sec. 160.25(3), Wis. Stats., a regulatory agency in not required to impose a prohibition or close a facility when nitrate-nitrogen levels attain or exceed the enforcement standard if the agency determines that this occurred in whole or in part because (a) high background levels of nitrate or (b) the additional concentration does not represent a public welfare concern.

The Safe Drinking Water Act
The maximum contaminant level (MCLs), set by USEPA, is the level of a contaminant at which no known or anticipated adverse effects on the health of persons occur and which allows an adequate margin of safety. The MCL for nitrate-nitrogen is 10 ppm - the same as Wisconsin's enforcement standard. Public water supplies, transient and non-transient noncommunity wells monitor for nitrate and must meet the MCL

What are current management strategies for nitrate pollution?
There are four entities involved in agricultural nitrogen management efforts in Wisconsin:

- The University of Wisconsin-Madison and the University of Wisconsin-Extension provide research information and educational programs on nutrient management largely through the Department of Soil Science in College of Agriculture and Life Sciences. The University of Wisconsin's Nutrient and Pest Management program is an educational effort based on soil testing programs and University of Wisconsin Extension Soil fertility recommendations by soil type and crop.
- The Nonpoint Source Water Pollution Abatement Program cost shares the use of best management practices to protect water quality by reducing the amount of nutrients from urban and rural sources.
- The Agricultural Conservation Program is a federal program administered to restore and protect land and water resources and preserve the environment. This program uses cost sharing of best management practices and outreach efforts to reduce nutrient loads from agriculture.
- County land conservation departments provide nutrient management planning funded by DATCP's Land and Water Resource Management grants.

The DNR wastewater program regulates the discharge of nitrogen containing wastewater and biosolids to the land surface and potentially to groundwater. The wastewater program regulates:

- Discharge of municipal and industrial wastewater to land treatment systems such as spray irrigation systems, seepage cells and ridge and furrow systems.
- Discharge of municipal and industrial sludges, biosolids and industrial liquid wastes through land application.
- Discharge of septage through land application.
- Impacts on groundwater from wastewater treatment and storage lagoons leaking in excess of groundwater standards.

Disposal of animal waste (manure) from concentrated animal facilities is also regulated. Facilities with over one thousand animal units must have a Wisconsin Pollutant Discharge Elimination permit as required under chapter NR 243 Wis. Adm. Code. Chapter NR 243 does the following:

- Establishes design standards and accepted animal waste management practices for the large animal feeding operations category of point sources.
- Establishes the criteria under which the DNR issues a permit to other animal feeding operations, which discharge pollutants to waters of the state.

The Department of Commerce under COMM 83 Wis. Stats regulates private septic systems. Currently COMM 83 is under revision. The private septic system program does the following:

- Establishes design standards and accepted waste management practices for private septic systems.
- Establishes the criteria under which sanitary permits are issued to build private septic systems, which discharge pollutants to waters of the state.
- Establishes soil site evaluation standards for placement of septic systems.

References

Albertson, P.N. and B. Shaw. 1998. Little Plover River study. Pesticide research contract #95-03 to Wisconsin Department of Agriculture, Trade and Consumer Protection. University of Wisconsin - Stevens Point, Stevens Point, WI

Bundy, L.G., L. Knobeloch, B. Webendorfer, G. Jackson and B.H. Shaw, 1994. Nitrate in Wisconsin Groundwater: Sources and Concerns, UW-Extension publication number G3054, 8 pages.

Bundy, L. G., K.A. Kelling, E.E. Schulte, S. Combs, R.P. Wolkowski, S.J. Sturgel, 1994. Practices for Wisconsin corn Production and Water Quality Protection, UW-Extension publication A3557, 27 pages.

Centers for Disease Control, September 1998. A survey of the Quality of Water Drawn from Domestic Wells in Nine Midwest States, Centers for Disease Control and Prevention National Center for Environmental Health.

Crowley, J.W., N.A. Jorgensen, L.W. Kahler, L.D. Satter, W.J. Tyler, M.F. Finner, 1974. Effect of Nitrate in Drinking Water on Reproductive and Produ tive Efficiency of Dairy Cattle, Water Resources Center, University of Wisconsin Technical Report WIS WRC 74-06.

Hall, S.J., P.A. Matson, and P.M. Roth, 1996. NO_x Emissions from Soil: a review and analysis of current knowledge, Prepared for: American Petroleum Institute, Wash. D.C.

Hallberg, G.R. 1989. Nitrate in groundwater in the United States. IN: Nitrogen Management and Groundwater Protection. Elsevier, Amsterdam, pp. 35-74.

Hallberg, G.R., R.D. Libra, D.J. Quade, J.P. Littke, and B.K. Nations. 1989. Groundwater Monitoring in the Big Springs basin 1984-1987: a Summary Review: Iowa Department of Natural Resources, Geological Survey Bureau, Technical Information Series 16. 68 p.

Hecnar, S.J., 1995. Acute and Chronic Toxicity of Ammonium Nitrate Fertilizer to Amphibians from Southern Ontario, Environmental Toxicology and Chemistry, vol. 14 no. 12, pgs 2131-2137.

Kincheloe, J.W., G.A. Wedemeyer, and D.L. Koch, 1979. Tolerance of Developing Salmonid Eggs and Fry to Nitrate Exposure, Bulletin of Environmental Contamination and Toxicology, vol. 3, pgs. 575-578.

Knobeloch, L., 1998. Department of Health and Family Services, Personal Communication.

LeMasters, G. and J. Baldock, 1997. A Survey of Atrazine in Wisconsin Groundwater, Final Report, WI Departement of Agriculture, Trade and Consumer Protection.

Lillie, R.A. and J.W. Mason, 1983. Limnological Characteristics of Wisconsin Lakes, Technical Bulletin No. 138, Wisconsin Department of Natural Resources.

Lillie, R.A., and J.W. Barko, 1990. Influence of Sediment and Groundwater on the Distribution and Biomass of Myriophyllum spicatum L. in Devil's Lake, Wisconsin, Journal of Freshwater Ecology, vol. 5, no. 4, pgs 417-426.

Mason, J.W., G.D. Wegner, G.I. Quinn and E.L. Lange, 1990. Nutrient Loss Via Groundwater Discharge from Small Watersheds in Southwestern And South Central Wisconsin, Journal of Soil and Water Conservation, vol.45, no.2 pgs. 327-331.

Piper, R., I.B. McElwain, L.E. Orme, J.P. McCraren, L.G. Fowler, and J.R. Leanard, 1982. Fish Hatchery Management, U.S. Fish and Wildlife Service, Washington, D.C., 517 pages.

Robertson, D.M., and D.A. Saad, 1996. Water-Quality Assessment of the Western Lake Michigan Drainages-Analysis of Available Information on Nutrients and Suspended Sediment, Water Years 1971-90, USGS Water Resources Investigations Report 96-4012.

Rogers, S.J., D.G. McFarland and J.W. Barko, 1995. Evaluation of the Growth of Vallisneria americana Michx. In Relation to Sediment Nutrient Availability, Lake and Reservoir Management, vol. 11, no.1, pgs 57-66.

Schubert, C., L. Knobeloch, H. Anderson, C. Warzecha, and M. Kanarek, 1997. Nitrate-Contaminated Drinking Water Followback Study, Submitted to the WI Dept. of Natural Resources and the WI Groundwater Coordinating Council. Department of Preventive Medicine, University of Wisconsin-Madison and the WI Department of Health and Family Services. 17 pages.

Shaw, Byron, 1994. Nitrogen Contamination sources: A Look at Relative Contributions, IN: Conference Proceedings: Nitrate in Wisconsin's Groundwater: Strategies and Challenges, May 10, 1994, Central Wisconsin Groundwater Center (UWEX), Golden Sands RC&D, WI Dept of Natural Resources and WI Dept. of Health and Social Services.

Shepard, R., F. Madison, P. Nowak, and G. O'Keefe, 1997. Watershed/Source Water Protection Programs Targeting Mixed Farming Systems in The Upper Midwest, for: American Water Works Association Annual Conference, August, 1997, Seattle Washington.

Steinheimer, T.R., K.D. Scoggin and L.A. Kramer, 1998. Agricultural Chemical Movement through a Field-Size Watershed in Iowa: Surface Hydrology and Nitrate Losses in Discharge, Environmental Science and Technology, vol. 32, pgs. 1048-1052.

USEPA, 1977. Quality Criteria for Water, US Government Printing Office, Washington DC, 20402, Stock No. 055-001-01049-4.

UW-Extension, 1989. Nutrient and Pesticide Best Management Practices for Wisconsin Farms, UW-Extension publication A-3466, 174 pages.