NITRATE IN THE NATION'S WATERS: A SUMMARY OF RECENT STUDIES

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Broad patterns in the chemistry of surface or ground waters are the result of regional patterns of human activities and natural features. The relations between these patterns and water chemistry provide insight into cost-effective management methods for improving water quality. They allow prioritization of areas that have the greatest risk of contamination. They also form the context into which studies of local water quality might be fit. Until recently, data collection programs have not often planned to address regional issues. Funding has been driven by the need to examine specific sites, not broader patterns. Identifying regional patterns of water quality and their causes help answer such questions as

- Where are water-quality problems most critical across the United States?
- How does water quality in agricultural areas compare to that downstream of cities and suburbs?
- What effects have 20 years of point-source controls had on water quality?
- Can results of local scientific studies be applied to larger areas?
- How might the Farm Bill or similar legislation ameliorate water-quality problems?

Scope

This article summarizes regional and national studies of nutrients by the U. S. Geological Survey's National Water Quality Assessment (NAWQA) Program, as well as selected other publications. NAWQA's goals include an assessment of the status and trends in water quality of the Nation's streams and aquifers, and an understanding of the human and natural factors that influence those patterns. Consistent sampling and analytical methods are used across the country, making regional interpretations possible. A full description of the Program is given by Leahy and Thompson (1994). Three sets of 20 large watersheds, together representing much of the Nation's water use and population, are being studied in sequence (Figure 1). These 60 areas together cover about 50 percent of the land surface of the United States.

Some of the earliest NAWQA findings come from historical information on nutrient (nitrogen and phosphorus) levels in the first 20 watersheds. Nitrate, a ubiquitous form of nitrogen having both agricultural and urban sources, is discussed here. Most of the results cited below are from three published reports. Puckett (1994) calculated the mass of nitrogen deposited on land surfaces of the United States, based on both national data bases and on information from the first NAWQA studies. Mueller and others (1993) modeled the regional patterns of nitrate in streams of the upper Mississippi River basin, relating nitrate concentrations to variables such as fertilizer use, population, and streamflow within each watershed. Maps were presented showing watersheds where exceedance of the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 10 milligrams per liter (mg/L) was likely. Mueller and others (1995) described nutrient patterns in surface and ground waters throughout the U. S., using data collected by USGS and State and local agencies between 1972 and 1990. Each of these three reports contains far more detailed information than can be presented here. Unreferenced statements in this report are based on these three references.

These three reports are considered to be “national” in scope because they are based on information from large areas across the United States, but not from its entire land surface. Percentages and nitrate concentrations cited here are for the first 20 areas studied rather than national averages. The range of conditions in the first 20 NAWQA studies is sufficiently diverse that estimates for particular categories (urban, agricultural land, etc.) should describe water quality in those categories well. "National" estimates will change as the NAWQA Program sequentially studies 40 additional watersheds and the mix of land types becomes more like the Nation as a whole.

Previous National Descriptions of Nitrate

The possible causes for regional and national patterns in stream-water quality have been addressed in three previous publications. Omernik (1977) related nonpoint sources to stream water quality at several hundred locations across the United States. In particular, he found that nitrate concentrations increased as the percentage of agriculture increased in a watershed. The form of nitrogen was also affected by human activity. Though organic nitrogen was the most abundant form in streams draining forested land, inorganic forms dominated agricultural stream quality. Smith and others (1987) computed the trends in stream water quality on large rivers monitored by the U.S. Geological Survey (USGS) throughout the Nation. They showed that nitrate concentrations increased dramatically during 1974-1981 at numerous locations. Updating this work, Smith and others (1993) reported that nitrate trends generally did not continue to increase from 1981-1989, mirroring the leveling off of fertilizer use throughout the country. Had a similar program been in place for smaller streams within the Nation, a clearer explanation of patterns in relation to human activities could have been made. The NAWQA program is designed to provide some of this additional information for the future.

Less consistent information has been available on which to base summaries of ground-water quality for the Nation. No national programs similar to those reported on by Smith and others (1987) were implemented in the 1970s for ground-water quality. Madison and Brunett (1985) collected all data in USGS files for nitrate in ground water up to the early 1980s, and published a map of color-coded concentrations. As they recognized, their data did not represent any particular area, but rather was a composite of available data that reflected local contamination studies as well as regional surveys.

Power and Schepers (1989) summarized why nitrate concentrations in the Madison and Brunett database were high in certain regions of the Nation. They noted that more than twice the amount of nitrogen was being applied as fertilizer to agricultural land as was being removed by crop harvests. Combining this with the leaching potential of irrigation, they showed that many of the high concentration areas are under irrigated agriculture. Some of the management plans beginning to be used to reduce the amount of excess nitrogen applied to farmland also were surveyed.

Hallberg (1989) summarized published reports concerning nitrate in ground water for numerous locations throughout the United States. He reported that water from 20-30% of the private wells in Iowa and Kansas analyzed by State laboratories exceeded the drinking water standard of 10 mg/L, a much higher percentage than in the USGS data compilation. Many of these samples were voluntary submissions, and therefore may overemphasize those most worried that contamination has occurred. The amount of this "self-selection" bias is unknown. Even so, his work pointed to significant regional contamination of shallow aquifers used for rural supplies. Hallberg also reviewed reports investigating many of the important factors influencing nitrate concentrations, including well depth and land use.

Spalding and Exner (1993) summarized and compared results from statewide and countywide surveys of ground water. They noted the lower nitrate concentrations under agricultural land of the Southeast in comparison to other regions, a high proportion of exceedances of the MCL in the Midwest, and frequent exceedances in other agricultural areas with well-drained soils.

Nitrate In Surface Waters Of The United States

Nitrogen can be supplied to streams by ground-water discharges, washed from the surface of the watershed, discharged from point sources such as wastewater treatment plants, and deposited from the atmosphere. Puckett (1994) found that agriculture was the primary source of nitrogen on the land surface over much of the United States. Manure applied to land was the single largest source of nitrogen in the Southeast. Commercial fertilizers were the largest source in the central and western United States. Only in parts of the Northeast was a non-agricultural source, atmospheric deposition, the major provider of nitrogen to watersheds. Therefore it is not surprising that throughout the country, regional patterns in stream nitrate are related, in part, to patterns and intensities of agricultural activities.

Commercial fertilizer use increased twenty-fold between 1945 and 1981 in the United States. Since 1981, use has remained relatively constant (Alexander and Smith, 1990). However, some of the nitrogen applied is taken up by crops and removed from the watershed. Not all applied nitrogen reaches streams, unlike nitrogen in point-source discharges of industrial or sewage effluents. Puckett (1994) found that point sources directly discharged 1.3 million tons per year of nitrogen to U.S. streams between 1978 and 1981. In comparison, 21.4 million tons per year of nitrogen was applied to agricultural land (nonpoint sources) during the same period, most of which did not reach streamwaters. For sites directly downstream from cities and towns, point sources remain a major source of nitrogen to streams. However, it is nonpoint sources that determine nitrogen levels in most of the stream miles of the Nation.

Nitrate concentrations are highest in streams below agricultural or urban areas. Concentrations are consistently lower downstream from forested areas and rangeland. This is strong evidence that nitrate concentrations have been artificially elevated in streams due to human influence.

Streams in agricultural areas with poorly-drained soils, such as much of the corn-growing region of the Midwest, have some of the highest nitrate concentrations in the Nation. Field drainage practices such as tile drains are common in the region, quickly collecting and delivering soil water to streams in order to improve the land's ability to grow crops. Nitrogen fertilizer is heavily applied to corn, and the resulting soil water is a major influence on stream quality.

Mueller and others (1993) developed equations that fit observed nitrate concentrations to upstream basin characteristics throughout the corn-growing region of the Midwest. The most important variable in accounting for high or low nitrate concentrations was the percent of land upstream used for growing corn and soybeans. High nitrate concentrations were found in streams with the highest percentages of corn and soybeans. Probabilities of exceeding the 10 mg/L MCL increased dramatically as the percentage of corn increased. Nitrate concentrations also generally were high in basins with high cattle densities. A third important influence was soil permeability. Basins with tighter (less permeable) soils generally had higher stream nitrate concentrations than those with more permeable soils.

Urban areas also influenced stream nitrate concentrations. Probabilities of observing moderate nitrate concentrations (between 3 and 10 mg/L as nitrogen) increased as population densities increased. But the likelihood of exceeding the 10 mg/L MCL was not increased by higher population densities. Exceedances were not generally found in populated areas, but near farmland.

Nitrogen yields (in tons carried by the stream per square mile) were determined by Smith and others (1993) to be twice as high in streams draining corn and soybean agriculture as yields in streams draining urban areas. Streams draining forests, rangeland, or wheat agriculture carried much less nitrogen than either of these. This is not surprising, as Puckett (1994) has shown that the major center of commercial fertilizer application in the Nation is the corn-growing region of the Midwest.

Nitrate concentrations in streams draining undeveloped (forested) watersheds were highest in the Northeastern United States. Concentrations in forested Northeast streams have increased by a factor of 3 or 4 since 1970, though they still hover around 1 mg/L. Atmospheric deposition of nitrate, as part of "acid rain", is known to be higher in the Northeast than in the rest of the country. Most forested streams in the U. S. exhibited nitrate concentrations which did not exceed 0.7 mg/L as nitrogen. Concentrations higher than this can be considered elevated. Nitrate concentrations of 0.7 mg/L or lower can be considered "background" for streams.

Improvements in wastewater treatment since passage of the first Clean Water Act in 1972 have resulted in decreased ammonia concentrations in many urban streams. Treatment plants are designed to convert ammonia to nitrate before it is discharged, avoiding fish toxicity from either low dissolved oxygen or from ammonia itself. However, these improvements have not decreased total nitrogen concentrations, but merely changed their form. Although not toxic to fish, nitrogen in the form of nitrate remains a concern for enhancing eutrophication in many reservoirs and estuaries downstream of urban areas.

In general, nitrate concentrations in streams rarely exceed the MCL, and are predictable over space and time. They occur most often downstream of agricultural land following storms during the active growing season, and immediately below waste treatment plants during low flows. Exceedances of the nitrate MCL are far more common in ground water than surface water.

Nitrate In Ground Waters Of The United States

Mueller and others (1995) found that nitrate concentrations were generally twice as high in ground water under agricultural lands than under other areas. Concentrations of 10 mg/L or greater were exceeded in about 21 percent of the ground-water samples collected in agricultural areas. However, these data included shallow irrigation and stock wells not used for human consumption. Focusing only on domestic supply wells providing drinking water in agricultural areas, the nitrate MCL was exceeded in 12 percent of wells. This compares to only 1 percent of samples collected from public-supply wells used for drinking water by towns and cities. Thus water being consumed in rural areas is considerably higher in nitrate than water consumed in more developed locations of the Nation.

Nitrate concentrations in ground water beneath agricultural areas were highest in wells less than 100 feet deep. Exceptions to this were areas of wet soils, where low dissolved oxygen conditions favor the retention of ammonia or denitrification of nitrate to various nitrogen gases. These gases are then lost to the atmosphere, so that areas of wet soils inhibit nitrate from entering the ground-water system.

Nitrate concentrations were high in areas where geologic characteristics promoted rapid movement of water to the

aquifer. Examples are carbonate bedrock, where fractures allow water to quickly infiltrate, or unconsolidated sands and gravels that drain rapidly. Nitrate was also consistently high in areas of well-drained soils. Concentrations in shallow rural wells were higher in areas with sandy soils than in those with poorer drainage, for example.
Certain regions of the United States seemed more vulnerable to nitrate contamination of ground water in agricultural areas. Regions of high vulnerability included parts of the Northeast, Midwest, and West Coast. The well-drained soils typical to these regions have little capacity to hold water and nutrients; therefore, these soils receive some of the largest applications of fertilizer and irrigation in the Nation. The agricultural land is intensively cultivated for row crops, with little intermixing of pasture and woodland.

The southeastern United States has consistently low nitrate concentrations in ground water, even under well-drained soils. Higher percentages of organic carbon in soils, and warm temperatures year-round, provide ideal conditions in the Southeast for microbial processes such as denitrification, which can remove nitrogen from soil water (Jacobs and Gilliam, 1985). In addition, the Southeast has the greatest percentage of intermixed pasture and woodlands. Lower nitrate concentrations occurred where pasture and woodlands were intermixed with cropland in agricultural areas. In addition to receiving less intensive fertilizer applications, these intermixed areas also provide a location for low-nitrogen water to recharge the aquifer, and for denitrification to occur in organic-rich forest soils..

Isotopic ratios can indicate whether inorganic fertilizer or animal waste is the primary source for nitrogen contained in a ground-water system. Isotopic signatures have documented fertilizer as the predominant source of nitrogen in ground water at several locations. For example, Böhlke and Denver (1995) used isotopes to reconstruct a 40-year record of nitrate concentrations in ground water of the Eastern Shore in Maryland. Concentrations increased from 3 to 6 times over the period, most rapidly during the 1970s coincident with a rapid increase in fertilizer use. In other locations, animal manure applied to cropland can be the dominant source, as found by McMahon and Böhlke (in press) for base flow and shallow ground water under agricultural fields draining to the South Platte River in Colorado.

Unfortunately, little information exists about trends over time in the quality of ground water. Fedkiw (1991) cites instances in which nitrate trends have been seen over decades in Iowa and Nebraska. Nitrate concentrations increased as fertilizer use increased. Only recently have monitoring programs begun to sample wells at regular time intervals. Trends in nitrate concentrations can be determined for a few locations, but information on trends of other nutrients in ground water are generally lacking. Clearly, additional information on trends in ground-water quality is needed across the Nation. One way this might be met is to use the aquifer as a natural 'archive' of water quality. Ground water that has entered the aquifer over time will be found at differing depths. If samples collected at different depths are age-dated (Plummer and others 1993) and their quality measured, a history can be developed on changes in concentrations of the water entering through the soil horizon. Nitrate concentrations must be adjusted for any nitrate which has undergone denitrification once it reaches the aquifer (Böhlke and Denver, 1995). These samples not only provide a record of nitrate trends, but an understanding of residence times in the system, and the
quality of base flow from ground water that will be discharging to streams in the future.

Implications Of These Findings

<u>These Findings Can Identify Where Nutrient Problems Are Most Severe</u>

Determining where water-quality problems are most likely to occur is the key to devising cost-effective watershed-management strategies. These findings imply that management strategies need to incorporate some flexibility among different regions of the Nation in order to provide the greatest benefit for the lowest cost. For example, soil drainage characteristics are a useful guide to where ground water or surface water is most at risk to contamination from nutrients applied at the land surface. Ground water in areas of well-drained soils is vulnerable to surface application of chemicals, and warrants more complete protection strategies than in areas of poorly-drained soils. Nitrate concentrations are generally low in ground water under poorly-drained soils, even in NAWQA study areas where fertilizer was heavily applied at the surface. Watershed management of surface water, rather than ground water, might be a priority in these areas.

Without an understanding of where water quality is most at risk, monitoring may be evenly implemented across a State or protection area. This may not be the most efficient way to spend scare monitoring dollars. With even limited amounts of data, relations between water quality and basin characteristics can be used to locate areas most likely to exceed human health or aquatic life standards. The sampling efforts needed to verify this information are smaller than those required to establish it had nothing been known from the outset. Limited dollars for pollution prevention can be targeted to areas which are most at risk. Ground-water protection strategies also can vary with the depth of wells and geologic characteristics of the area. Areas where domestic-supply wells are prevalent, and whose geologic characteristics allow easy transmittal of chemicals to ground water, may warrant protection measures not necessary for other parts of the Nation.

These Findings Can Identify When Nutrient Problems Require Special Management

Nutrients have a distinct seasonal pattern in streams. Concentrations commonly are highest during storm events after application of fertilizers upstream. Other agricultural chemicals in streams usually follow similar patterns. Protection strategies in areas where these chemicals are of concern might need to be in force only during certain seasons, such as during the spring runoff period, to fully meet drinking water standards at much lower costs than year-round implementation.

Future Findings Can Quantify Improvements Due to Pollution Control Programs

Reducing the amount of nutrients applied to land could improve the local quality of water. Agricultural scientists are currently considering such methods as varying the timing of fertilizer applications to avoid storm runoff into streams, and pumping high-nutrient, shallow ground water for use as a fertilizer source. Fertilizer management plans are becoming more common as farmers better account for the many sources of nutrients present in soils, including nitrogen fixation by legumes, and manure application to cropland. Accounting for these additional sources of nitrogen when determining fertilizer application rates decreases the excess nitrogen in soil, and the amount available to streams and ground water. The effectiveness of these strategies needs to be measured by the resulting improvements in stream and ground-water quality. Without such data, an accurate analysis of benefits versus costs is not possible.

Conclusions

Nitrate concentrations in streams have responded in the past to both increases and decreases of nitrogen inputs to the land surface. Improved nutrient management is likely to lower peak stream nitrate concentrations during storm runoff within years of its implementation. However, no "quick fixes" of long-term nitrogen excesses should be expected in ground water. Ground water moves slowly, and waters of improved quality may take 30 years or more to move through the ground-water system into nearby streams or wells. A long-term view must be taken.

What is the value of scientific water-quality information to the public? Most obvious are answers to simple questions such as "Is my water safe to drink?", and "Is water quality getting better or worse?" More complex is information answering "Where are problems most severe?", and "Why is water in one area worse than another?" Yet today's questions go beyond these to "Were the improvements we realized in water quality worth the costs incurred?" Only with performance data on changes in water quality can we hope to assess costs versus benefits. Only by understanding the causative factors of changing quality can we tailor lowest-cost protection strategies to fit the need. Only by understanding how aquatic ecosystems function can we determine how much change is allowable. Yet very little systematic monitoring of water quality is occurring in the United States at present, and the trend for funding of scientific studies of aquatic systems appears to be going sharply downward. Understanding the regional distribution and key scientific factors that affect water quality in ground and surface waters is critical to implementing and evaluating cost-effective programs to manage and protect our water resources.

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