Risk of Nitrate in Groundwaters of the United States—A National Perspective

BERNARD T. NOLAN,*,† BARBARA C. RUDDY,‡ KERIE J. HITT,† AND DENNIS R. HELSEL‡

U.S. Geological Survey, 413 National Center, Reston, Virginia 20192, and U.S. Geological Survey, Denver Federal Center, Mail Stop 415, Box 25046, Lakewood, Colorado 80225

Nitrate contamination of groundwater occurs in predictable patterns, based on findings of the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) Program. The NAWQA Program was begun in 1991 to describe the quality of the Nation's water resources, using nationally consistent methods. Variables affecting nitrate concentration in groundwater were grouped as "input" factors (population density and the amount of nitrogen contributed by fertilizer, manure, and atmospheric sources) and "aquifer vulnerability" factors (soil drainage characteristic and the ratio of woodland acres to cropland acres in agricultural areas) and compiled in a national map that shows patterns of risk for nitrate contamination of groundwater. Areas with high nitrogen input, well-drained soils, and low woodland to cropland ratio have the highest potential for contamination of shallow groundwater by nitrate. Groundwater nitrate data collected through 1992 from wells less than 100 ft deep generally verified the risk patterns shown on the national map. Median nitrate concentration was 0.2 mg/L in wells representing the low-risk group, and the maximum contaminant level (MCL) was exceeded in 3% of the wells. In contrast, median nitrate concentration was 4.8 mg/L in wells representing the high-risk group, and the MCL was exceeded in 25% of the wells.

Introduction

Groundwater provides drinking water for more than one-half the population of the United States (*1*). In 1990, groundwater accounted for 39% of water withdrawn for public supply for cities and towns and 96% of water withdrawn by self-supplied systems for domestic use. Groundwater is the sole source of drinking water for many rural communities and some larger cities.

A variety of chemicals can pass through the soil to the water table. Groundwater in agricultural areas often has a distinct water-quality signature composed of nitrate, potassium, chloride, calcium, and magnesium (*2*). The sources of these compounds frequently are agricultural chemicals such as inorganic fertilizers, animal manure, and lime. Nitrogen not used by plants or returned to the atmosphere is converted to nitrate in the soil, which is soluble in water and can easily leach to the water table. Nitrate can persist in groundwater for decades and can accumulate to high levels as more nitrogen is applied to the land surface every year.

Nitrate in groundwater commonly originates from nonpoint sources such as fields on which inorganic fertilizer and animal manure are applied. Although typically associated with agriculture, inorganic fertilizers also are applied to lawns and golf courses in urban areas. Airborne nitrogen compounds emitted by point sources such as coal- and oil-burning electric utilities, automobiles, and other forms of transportation are regionally deposited on the land in wet and dry forms (*3*, *4*). Once dispersed in the atmosphere, the airborne compounds are considered nonpoint sources of nitrogen.

The magnitude of nonpoint sources of nitrogen has only recently become known. About 11.5 million t of nitrogen is applied yearly as fertilizer in agricultural areas of the United States (*3*). Commercial fertilizer use in the United States increased by a factor of 20 between 1945 and 1985. Manure produced yearly in the United States by farm animals contains an estimated 6.5 million t of nitrogen. Atmospheric deposition contributes an estimated 3.2 million t or more of nitrogen per year to watersheds in the United States. Other nonagricultural sources of nitrate, such as septic systems and leaking sewers, generally are less significant regionally and nationally but can affect groundwater quality locally.

Ingestion of nitrate in drinking water by infants can cause low oxygen levels in the blood, a potentially fatal condition (*5*). For this reason, the U.S. Environmental Protection Agency (U.S. EPA) has established a maximum contaminant level (MCL) of 10 mg/L nitrate as nitrogen (*6*). Additionally, nitrate concentrations of 4 mg/L or more in rural drinking-water supplies have been associated with increased risk of non-Hodgkin's lymphoma (*7*). Nitrate concentration in natural groundwater generally is less than 2 mg/L (*8*).

Knowing where and what type of risks to groundwater exist can alert water-resource managers and private users of the need to protect water supplies. By targeting regions with the highest risk of nitrate contamination, resources can be directed to areas most likely to benefit from pollution-prevention programs and long-term monitoring. Use of risk guidelines to locate areas for prevention of contamination might cost less than simply identifying the most severely contaminated areas. Once groundwater is contaminated, it is expensive and in many cases virtually impossible to clean up (*9*).

Prior investigators have used differing approaches to predict the risk of groundwater contamination by nitrate and other chemicals. In the U.S. EPA's DRASTIC method, factors assumed to influence the vulnerability of groundwater to contaminant sources at the land surface are rated to assess aquifer vulnerability (*10*). To date, DRASTIC predictions have not correlated well with actual water-quality conditions (*11*).

Kellogg and others (*12*) predicted the leaching potential of nitrogen fertilizer for the conterminous United States. Leaching potentials were based on groundwater vulnerability indices calculated from soil variables and estimates of excess nitrogen fertilizer applied. No attempt was made to correlate the vulnerability indices with actual groundwater nitrate concentrations, however.

These methods emphasize hydrogeologic variables and agricultural practices considered to affect groundwater quality but have not compared predicted potentials with actual water-quality data. A benefit of using actual data for calibration is that the relative weights for factors can be checked and adjusted. Some factors might not help explain observed variations in water quality and can be eliminated from consideration.

* Corresponding author's telephone: (703) 648-4000; email address: btnolan@usgs.gov.

† U.S. Geological Survey, Reston, VA.

‡ U.S. Geological Survey, Denver, CO.

S0013-936X(96)00818-8

TABLE 1. Nitrogen Input and Aquifer Vulnerability Factors Used To Create Risk Groups Shown in Table 2 and Mapped at National Scale

magnitude	nitrogen input factors	aquifer vulnerability factors
high	high nitrogen loading[a] or high population density[b]	well-drained soil and low woodland to cropland ratio
low	low nitrogen loading[a] and low population density[b]	poorly drained soil or high woodland to cropland ratio

[a] Nitrogen loading refers to nitrogen inputs from inorganic fertilizer, animal manure, and atmospheric deposition. [b] Population density is assumed to indicate nonagricultural sources of nitrogen such as residential fertilizers, leaking sewers, septic systems, and domestic animals.

TABLE 2. Grouping Scheme Used To Map Risk of Nitrate Contamination of Groundwaters in the United States

risk group[a]	nitrogen input factors	aquifer vulnerability factors
high (red)	nitrogen loading >2100 kg/km^2 or population density > 386 people/km^2	hydrologic group <2.5 and woodland to cropland ratio < 0.3
moderately high (orange)	nitrogen loading >2100 kg/km^2 or population density > 386 people/km^2	hydrologic group ≥2.5 or woodland to cropland ratio ≥ 0.3
moderately low (yellow)	nitrogen loading ≤2100 kg/km^2 and population density ≤ 386 people/km^2	hydrologic group <2.5 and woodland to cropland ratio < 0.3
low (green)	nitrogen loading ≤2100 kg/km^2 and population density ≤ 386 people/km^2	hydrologic group ≥2.5 or woodland to cropland ratio ≥0.3

[a] The color in parentheses refers to Figure 2.

Mueller and others (*13*) compared nitrate concentrations in groundwater across the Nation by land use, well depth, well type, aquifer type, soil drainage characteristic, and geographic region. A hydrologic group variable (*14*), indicating drainage characteristics of soil, was found to relate strongly to the nitrate concentration in wells less than 100 ft deep in agricultural areas.

Nolan and Ruddy (*15*) compiled data for soil hydrologic group and nitrogen loading from fertilizer, animal manure, and atmospheric deposition in a national map that showed patterns of risk for nitrate contamination of groundwater. Four risk groups were presented in order of generally increasing risk: (1) low nitrogen input and poorly drained soils; (2) low nitrogen input and well-drained soils; (3) high nitrogen input and poorly drained soils; and (4) high nitrogen input and well-drained soils. Groundwater nitrate data compiled by Mueller and others (*13*) generally verified risk patterns shown on the national map, except for two areas—the southeastern United States and Long Island, NY. Nitrate concentration was low in the Southeast, despite high nitrogen loading and, in some cases, well-drained soils. Nitrate concentration in groundwater on Long Island was higher than suggested by the map, which did not reflect the influences of urban sources of nitrogen.

The goal of the current study was to improve the accuracy of Nolan and Ruddy's (*15*) risk map by analyzing two additional variables, population density and woodland to cropland ratio. Population density was used as a surrogate for nonagricultural sources of nitrogen such as septic systems, residential fertilizer use, and domestic animal waste in urban areas. The ratio of woodland acres to cropland acres in agricultural areas was used as a surrogate for several attenuation processes in the Southeast, including denitrification, dilution, and vegetative uptake of nitrogen in riparian forests. Specific study objectives were (1) to compile risk factors in a revised national map showing the potential for nitrate contamination of groundwater and (2) to verify the national risk map with historical water-quality data compiled by the National Water Quality Assessment Program (NAWQA).

Methods

Nitrogen loading, population density, soil drainage characteristic, and woodland to cropland ratio were segregated into "nitrogen input" and "aquifer vulnerability" factors to create risk groups for mapping in a geographic information system (GIS) (Table 1). Nitrogen input describes nitrogen loading at the land surface, whereas aquifer vulnerability describes land and soil characteristics that can affect transport of nitrogen from the land surface to the water table. Four risk groups were created on the basis of threshold levels of the four variables (Table 2). Threshold levels were obtained by examining scatterplots fitted with LOWESS smooths and determining levels at which nitrate concentration increased above the background concentration of 2 mg/L. The LOWESS smooth is a locally weighted scatterplot smoothing technique (*16*). Nitrate data were stratified by threshold levels and tested for statistical significance using the Wilcoxon rank sum method. The four risk groups were mapped in the GIS to identify areas in the United States at risk of nitrate contamination of shallow groundwater. Areas with well-drained soils, low woodland to cropland ratio, and high nitrogen loading or high population density were designated as high risk.

The GIS overlay approach was used in lieu of a multivariate regression approach because the objective was to produce a map at the national scale. Regression models typically use continuous (rather than categorical) explanatory variables and can yield more accurate predictions at individual locations. Regression predictions at numerous individual locations have high local variability, however, requiring spatial smoothing as a second step. The result of the smoothing is regional categorization, more simply done with the GIS overlay technique. Additionally, error characteristics associated with the historical water-quality data set, compiled from diverse sources, reduce the potential advantages of multivariate regression. Continuous measurements with a lot of scatter are little different from categorical variables. Regression models will be developed when a more uniform and consistent data set is available as a result of the NAWQA program.

National, 1:2 000 000 scale GIS maps were obtained to evaluate nitrogen loading from atmospheric deposition, animal manure, and commercial fertilizer. Nitrogen loading from commercial fertilizer in 1987 was compiled by Battaglin and Goolsby (*17*) from national databases of fertilizer sales (*18*), and loading from animal manure in 1987 was compiled by Smith and others (*19*) from the Census of Agriculture animal population data (*20*) and per animal nitrogen production rates (*21*). Nitrogen loading by atmospheric deposition in 1987 was estimated by Smith and others (*19*) using data from 188 monitoring stations operated by the National Atmospheric Deposition Program/National Trends Network (*22*).

Soil drainage characteristic was determined from soil hydrologic group data in a State Soil Geographic (STATSGO) database (*14*) and was compiled by Ruddy and Battaglin (U.S.

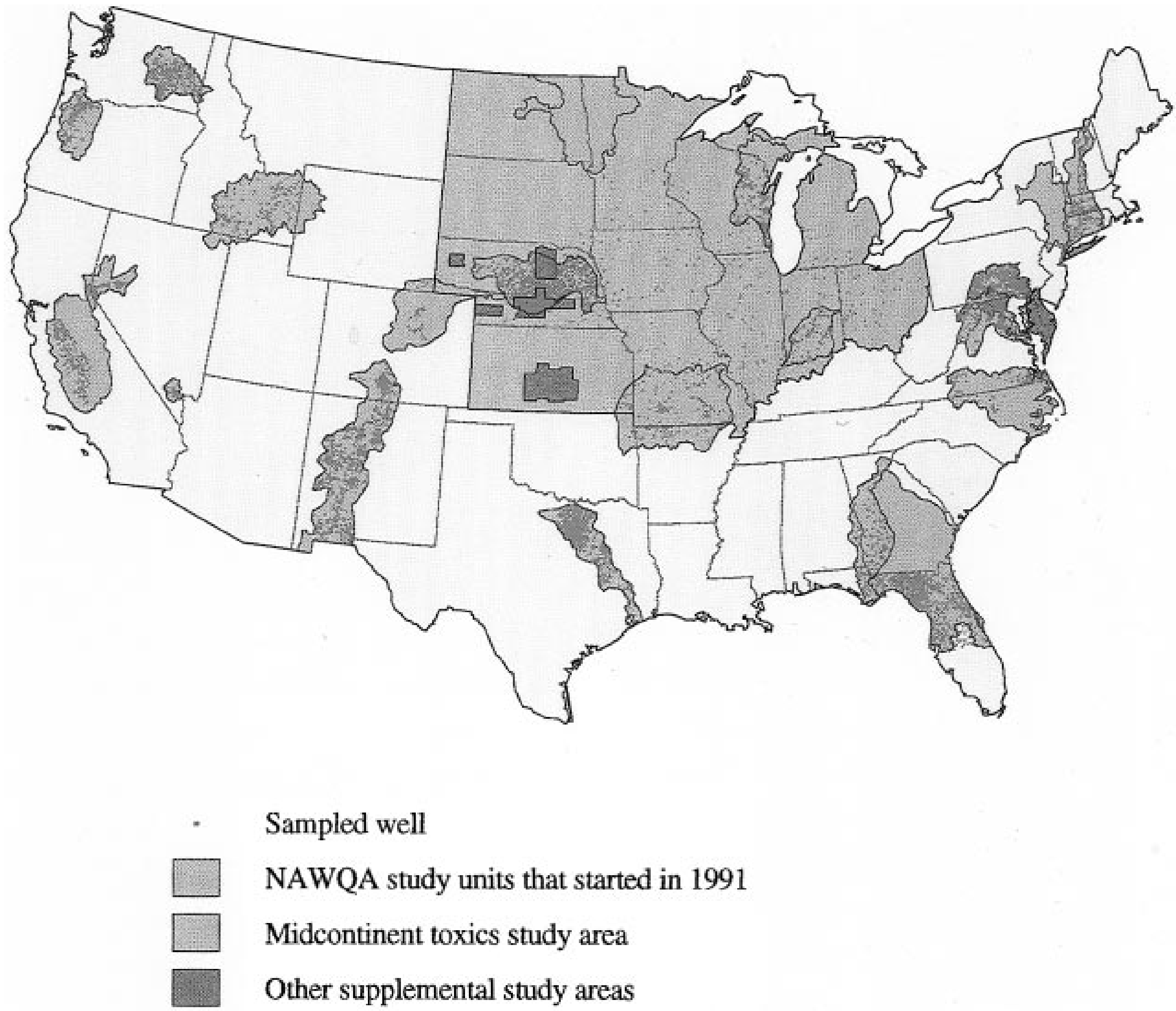

FIGURE 1. Locations of well sites compiled in the national retrospective database.

Geological Survey, unpublished data, 1997) in 1:250 000 scale GIS maps. The soil hydrologic group variable has four categories ranging from well-drained soils (groups A and B) to poorly drained soils (groups C and D). The categorical variable was converted to a number (A = 1, B = 2, C = 3, D = 4) to permit aggregation from soil associations into mapping units (*13*). Area-weighted hydrologic group means were calculated for each soil mapping unit, and groundwater sampling sites were assigned the mean hydrologic group value of the mapping unit in which they were located.

The extent of woodland and cropland in agricultural areas was compiled in a 1:2 000 000 scale GIS map (Gail P. Thelin, U.S. Geological Survey, unpublished data) from 1992 Census of Agriculture data describing acres in woodland and cropland for each county in the Nation (*23*). Woodland includes natural and planted timber, deforested land with young growth, land planted for Christmas tree production, and pastured woodland. Cropland includes crops, hayfields, orchards, citrus groves, vineyards, pastures, and grazed land. Woodland to cropland ratio was calculated by dividing the acres in woodland by those in cropland. The ratio represents the extent of woodland in relation to cropland in agricultural areas of the Southeast, where dilution, denitrification, and vegetative uptake likely attenuate nitrate concentration in groundwater.

Population density was determined from 1990 population data compiled by census block group in 1:100 000 scale GIS maps (*24*). Population density was calculated for each census block group by dividing the number of people in the block group by the land area of the block group.

A national water-quality data set was used to verify the risk map using statistical methods. This retrospective data set consists of historical water-quality and ancillary data compiled to determine preexisting water-quality conditions in the first 20 NAWQA study units that began in 1991 (*13*). The data set was augmented with data from the Delmarva Peninsula NAWQA pilot study and from the USGS Toxic Substances Hydrology Program. Water-quality data were obtained by study-unit personnel from the USGS National Water Information System (NWIS), from State water-resource agencies, and from STORET, the U.S. EPA's national database. Mueller and others (*13*) discuss assumptions and limitations associated with the national retrospective data set, which currently holds more than 10 000 groundwater nitrate records from sampled wells dispersed across the Nation (Figure 1).

Statistical verification of the national risk map involved grouping nitrate values in the retrospective data set by the four risk groups in Table 2 and testing the risk groups for statistical significance. Regardless of the how the data were grouped, nitrate concentrations were generally positively skewed, requiring a log transformation and subsequent check for normality prior to performing parametric tests such as analysis of variance. Tests between the means of log-transformed data are actually tests for differences in the medians of groups if the groups are log-normally distributed (*16*). Medians were used to measure central tendency because they are resistant to the effects of outliers and represent "typical" values for skewed data sets. When the results of the Kruskal-Wallis test, a nonparametric test equivalent in purpose to analysis of variance (ANOVA), agreed with ANOVA on the log-transformed data, it confirmed that no assumptions required by the parametric test were violated. Where differences were found by ANOVA, Tukey's multiple-comparison test was performed (also on log-transformed nitrate concentrations) to determine which groups were different. Kruskal-Wallis, ANOVA, and Tukey's multiple-comparison tests were performed at the 0.05 level of significance.

Limitations of National-Scale Risk Analysis

The GIS overlay analysis that was used to infer risk of nitrate contamination of groundwater has several limitations. First, areas shown as high risk on the national map have contamination *potential*, but do not necessarily depict areas with actual contamination. Second, the map describes the contamination potential of groundwater near the land surface (less than 100 ft deep). Groundwater from deeper wells completed in confined aquifers is less likely to be contaminated by nitrate. Thus, people who drink groundwater from deep confined aquifers are less likely to ingest nitrate, even in areas shown as high risk on the national map. Third, the map was "calibrated" to nitrate data from the first 20 NAWQA study units (Figure 1). Future versions of the map based on additional data might yield different risk patterns. Fourth, the use of county-based nitrogen loading data likely underestimates the risk of groundwater contamination in counties with small areas of cropland. The amount of nitrogen is divided by the total area of the county to determine loading in mass per unit area. If only a portion of the county is cropland, then the calculated nitrogen loading from agricultural sources is smaller than if the amount of nitrogen had been divided by the actual cropped area. Fifth, local hydrogeologic conditions can cause variations in local groundwater quality not evident at the national scale. For example, karst aquifers can have high nitrate concentration because of rapid infiltration through sinkholes. Because small, local features such as sinkholes were not mapped at the national scale, the risk of groundwater contamination can be greater in karst areas than indicated by the map. Finally, map anomalies can result from discrepancies between the soil hydrologic group variable and actual soil drainage characteristics. Deposits containing clay-size material can be classified as poorly drained, yet result in high groundwater nitrate concentration. Clay layers that are thin and discontinuous or that contain fractures from desiccation and plant and animal activity might not effectively restrict contaminant migration.

Results and Discussion

The four risk groups in Table 2 were superimposed in a GIS to create a national map showing the potential for nitrate contamination of groundwater (Figure 2). Figure 2 shows four groups in order of increasing risk: (1) low input, low vulnerability (green area on the map); (2) low input, high vulnerability (yellow area); (3) high input, low vulnerability (orange area); and (4) high input, high vulnerability (red area).

The Risk of Nitrate Contamination Varies across the United States. Figure 2 indicates that parts of the western, midwestern, and northeastern United States have a high risk of nitrate contamination of shallow groundwater. These areas—shown in red on the map—generally have well-drained soils, high nitrogen input, and low woodland to cropland ratios. Well-drained soils generally are coarse-grained and can easily transmit water and nitrate to groundwater. In contrast, the other three groups have a lower risk of nitrate contamination because of low nitrogen input from agricultural and nonagricultural sources, poorly drained soils, and/or high woodland to cropland ratio. Poorly drained soils commonly are fine-grained and transmit water and nitrate at a slower rate than well-drained soils (*13*). Poorly drained soils also can lack oxygen, which promotes conversion of nitrate to nitrogen gas and limits conversion of ammonia to nitrate. Tile drains and ditches often are used to remove excess water from poorly drained agricultural fields, thereby diverting nitrate to nearby streams. High woodland to cropland ratios indicate areas receiving smaller amounts of fertilizer and manure, decreasing the risk of nitrate contamination of groundwater.

The revised risk map yielded improved statistical separation of risk groups as compared with the previous version (*15*). Both maps have four risk groups and the same degrees of freedom. Kruskal-Wallis and ANOVA test statistics were used to determine the degree of separation of risk-group medians resulting from Nolan and Ruddy's (*15*) scheme and the revised grouping scheme. Higher values of these statistics indicate better separation of risk group medians and, hence, more accurate prediction by the risk map. The Kruskal-Wallis and ANOVA test statistics increased by more than 20% under the revised grouping scheme (Table 3). The p value was the same (0.0001) for both types of tests under both grouping schemes.

Nitrate in Groundwater Generally Follows the Risk Map. Groundwater nitrate data from across the Nation (Figure 1) were analyzed to verify the four risk groups shown on the national map. Figure 3 shows boxplots of nitrate in water from wells less than 100 ft deep and the percent of wells in which nitrate exceeds the MCL (10 mg/L nitrate as nitrogen) for each of the four risk groups. Nitrate concentration in groundwater generally increased with high nitrogen input, more well-drained soils, and low woodland to cropland ratio. Median nitrate concentration and percent of wells from which water exceeded the MCL for nitrate were lowest in samples from the low-risk group (green color) and highest in samples from the high-risk group (red color). Median concentration of nitrate was 0.2 mg/L in wells representing the low-risk group, and the nitrate MCL was exceeded in 3% of the wells. In contrast, median concentration of nitrate was 4.8 mg/L in wells representing the high-risk group, and the nitrate MCL was exceeded in 25% of the wells.

An ANOVA test performed with log-transformed nitrate data yielded an F statistic of 182.69 ($p = 0.0001$), indicating that the risk groups were significantly different at the 0.05 level. Tukey's multiple-comparison test indicated that the low- and high-risk groups differed significantly from each of the other risk groups at the 0.05 level (Figure 3). The moderately low- and moderately high-risk groups were not significantly different, however. Boxes with the same letter (B in Figure 3) have medians that are not significantly different.

Data for specific locations give examples of the difference in risk. Groundwater in the red area in southeastern Washington State had a median nitrate concentration of 6.5 mg/L. Soils in this part of the West generally are well-drained, permeable, and underlain by unconsolidated sand and gravel (*13*). Large amounts of fertilizer are applied to maintain conditions adequate for crop growth. Woodland to cropland ratio typically is low in these areas. The combination of high fertilizer loading, well-drained soils, irrigation, and extensive acreage under cultivation create a large potential for movement of nitrate to groundwater.

In contrast, groundwater in the green and yellow areas in western New Mexico, where nitrogen input is low, had a median nitrate concentration of 0.3 mg/L. About half the land area in mountainous western states is rangeland, and about one-fourth of the land area is forested (*25*). Only about 5% of the region is cultivated.

Poorly drained soils can reduce the risk of groundwater contamination, even in areas with high nitrogen input.

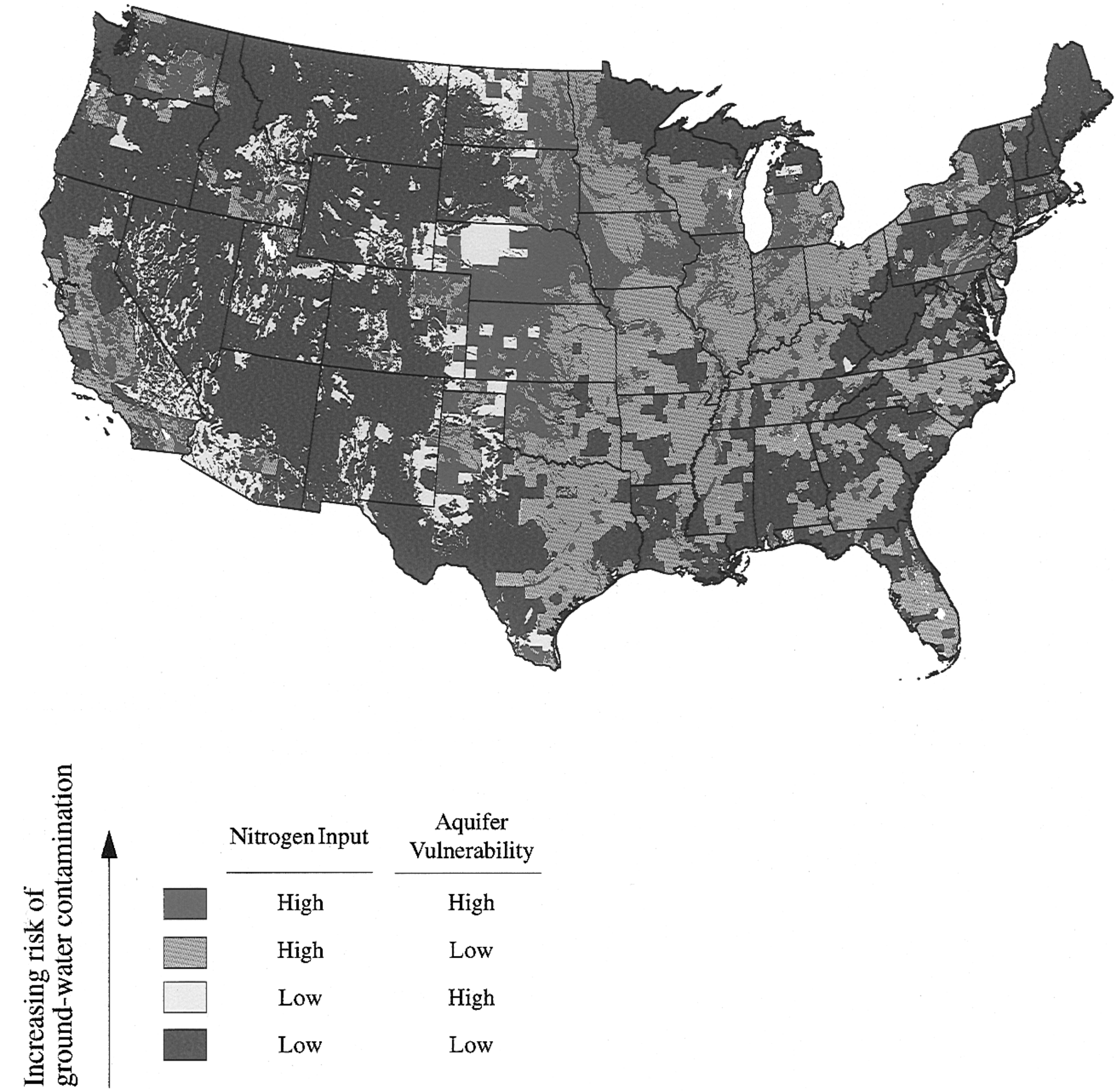

FIGURE 2. Risk of nitrate contamination of groundwaters in the United States.

TABLE 3. Results of Analysis of Variance on Log-Transformed Nitrate Data and Kruskal-Wallis Test To Determine Degree of Separation between Medians of Risk Groups Under Original and Revised Grouping Schemes[a]

grouping scheme	Kruskal-Wallis test statistic[b]	analysis of variance *F* statistic[c]
original four risk groups based on nitrogen input and soil-drainage characteristic[d]	426.77	146.40
revised four risk groups based on nitrogen loading, population density, soil-drainage characteristic, and woodland to cropland ratio	529.00	182.69

[a] *p* values were the same (0.0001) for both types of tests under both grouping schemes. [b] $\chi^2_{.95,3} = 7.815$. [c] $F_{.95,3\infty} = 2.60$. [d] Nolan and Ruddy (*15*).

Groundwater in orange areas in southern Indiana had a median nitrate concentration of only 0.5 mg/L. Although nitrogen input is high, soils in this part of the Midwest commonly contain fine-grained glacial deposits that are poorly drained and that transmit water through the unsaturated zone at a slower rate than coarser sands and gravels (*13*). The low permeability of glacial deposits restricts the downward movement of water and nitrate. Additionally, tiling and ditching of agricultural fields is a common practice in the Midwest. Soil water is intercepted by tile drains and, instead of seeping to the water table, is carried to surface water (*26*). High nitrogen input in these areas is more likely to affect surface water than groundwater.

High woodland to cropland ratios indicate a lower risk of groundwater contamination, even in areas with high nitrogen input and, in some cases, well-drained soils. Orange-colored areas in southern Georgia, northern Florida, and North Carolina have high nitrogen input, well-drained soils, but high woodland to cropland ratio. The median nitrate concentration in groundwater in this area was only 0.05 mg/L. Nitrate levels in shallow groundwaters of the Southeast can be decreased by dilution, denitrification, and uptake by

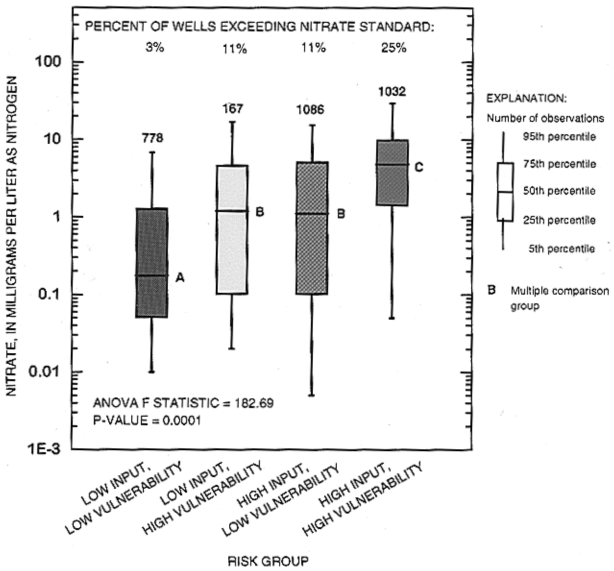

FIGURE 3. Relation of risk group to nitrate concentration in groundwater for samples in the national retrospective data set (well depths less than 100 ft deep).

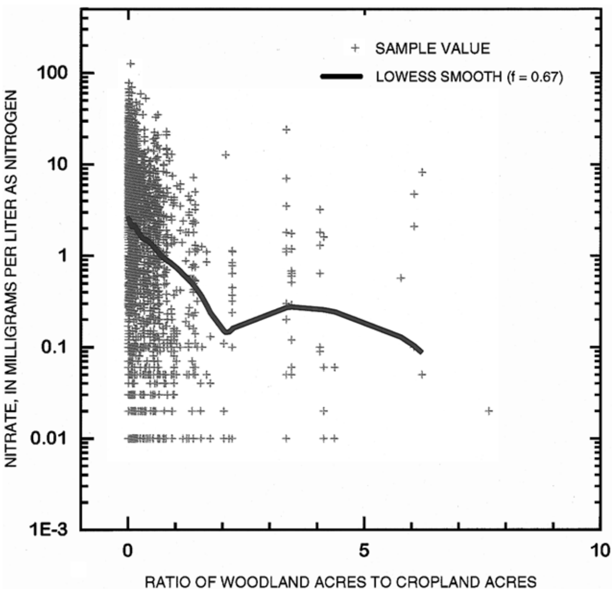

FIGURE 4. Relation of woodland to cropland ratio to nitrate concentration in groundwater for samples in the national retrospective data set (well depths less than 100 ft deep).

plants (*27*). The amount of woodland interspersed with cropland was used to represent all three of these processes. As the woodland to cropland ratio increased, nitrate concentration in groundwater samples from the national retrospective database decreased (Figure 4). Dilution of high-nitrate water recharged in cropped areas by low-nitrate water recharged through forest soils can occur in areas where large amounts of woodland are interspersed with cropland (*28*). Fertilizers and manure generally are applied less extensively in agricultural areas with large amounts of interspersed woodland. Denitrification, a process that converts nitrate to nitrogen gas, can occur in forested areas separating agricultural fields from streams. In a study of a riparian forest in the Georgia Coastal Plain, high denitrification potential of surface soil at a field−forest interface might have contributed to nitrate removal from shallow groundwater moving beneath the forest to a stream (*29*). Nitrogen and carbon from fine roots and leaf litter enhanced denitrification in upper soil layers. Direct denitrification in the saturated zone was negligible, however, unless the saturated zone was within 0.6 m of the land surface, which occurred closer to the stream. These investigators concluded that nitrate was removed from shallow groundwater primarily through uptake by living, fine root biomass associated with riparian vegetation such as *Pinus* species and selected hardwoods. Besides denitrification and plant uptake, the ratio of woodland to cropland might indicate other factors that affect nitrate concentration, including soil characteristics, hydrology, and geomorphology (*28*).

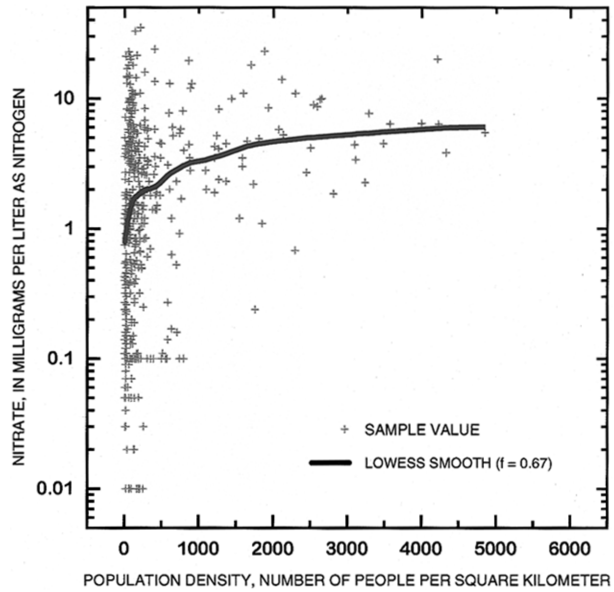

FIGURE 5. Relation of population density to nitrate concentration in groundwater for samples in the national retrospective data set from the northeastern United States (well depths less than 100 ft deep).

Urban land-use activities can increase the risk of groundwater contamination, even when agricultural sources of nitrogen are lacking. Groundwater nitrate concentration was high (median of 8.9 mg/L) in heavily populated (greater than 386 people/km^2) areas of Long Island, NY, even though nitrogen loadings from commercial fertilizer, manure, and atmospheric sources were low. LOWESS smooths indicated that urban effects were most pronounced in the northeastern United States, comprising portions of Vermont, New Hampshire, Massachusetts, Connecticut, and Long Island, NY. Nitrate in groundwater samples from these areas increased significantly as population density increased (Figure 5).

Domestic sewage and residential fertilizer, two principal sources of nitrogen on Long Island (*30, 31*), might contribute to elevated nitrate levels in groundwater samples from the northeastern United States. Septic systems and cesspools in heavily populated areas of Long Island have been a major source of nitrate in groundwater for decades. Public supply wells in the upper glacial aquifer of Nassau County were abandoned in 1949 because of nitrate contamination (*31*). Additionally, turf grass associated with residential lawns, parks, highways, golf courses, playing fields, and commercial and industrial properties is the major crop in the county. Residential lawns form the largest acreage of turf grass in the county, with estimated annual application rates of nitrogen fertilizer ranging from 8.3 to 18.3 metric t/km^2.

Katz and others (*30*) estimated that 11.6 metric t of nitrogen/km^2 were contributed by cesspools and septic systems in Nassau County, Long Island, in 1975. Residential fertilizer contributed an estimated 22.9 metric t/km^2 to the study area, whereas contributions from animal wastes, sewer exfiltration, and rainfall were significantly less.

Eckhardt and Stackelberg (*32*) found that nitrate concentrations in groundwater samples from suburban and agricultural areas of Long Island were elevated as compared with samples from forested areas. Nitrate was detected in water

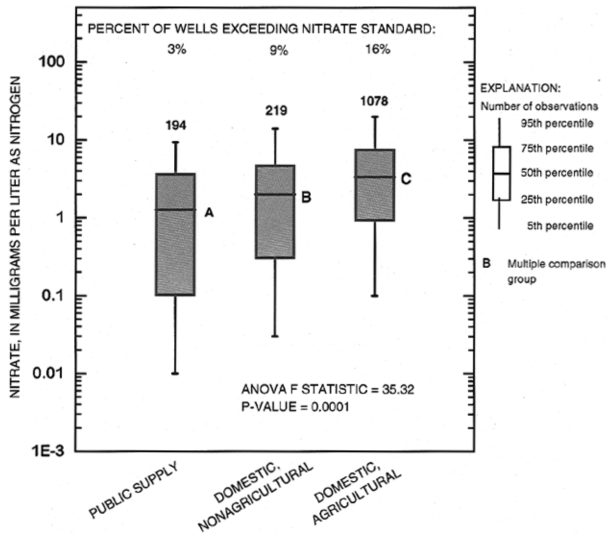

FIGURE 6. Relation of water source to nitrate concentration in groundwater for samples in the national retrospective data set corresponding to high-risk areas on the national map.

samples from 83 of 90 wells in the study area. Logistic regression equations were developed to predict the probability of exceeding 3 mg/L of nitrate in groundwater. Explanatory variables consisted of population density, percent medium-density residential land use, percent agricultural land use, and depth to the water table. The equations indicated that nitrate concentration generally increased as population density and percent residential and agricultural land use increased and as the depth to the water table decreased.

Some areas did not reflect very well the risk of groundwater contamination shown in Figure 2. For example, median nitrate concentration in groundwater samples from eastern North Dakota (shown in red on the map) was only 0.23 mg/L (David Lorenz, U.S. Geological Survey, written communication, 1996). Soils in this area are fine-textured, but are classified in STATSGO as well-drained because of the undulating, hilly landscape that causes hill soils to dry quickly. Water runs off the hills and collects in low points on the landscape, where denitrification can occur. Other factors not shown on the national map that can affect nitrate concentration in groundwater include local land use, aquifer type, rainfall and irrigation amounts, and the timing of rainfall in relation to fertilizer and manure applications.

Well Type Influences Groundwater Quality. People living in areas defined as high risk in Figure 2 are not necessarily exposed to elevated nitrate concentration in groundwater. People who get their water from domestic wells are more likely to drink water that contains high concentrations of nitrate than those who get their water from public-supply wells. In Figure 6, three types of wells are shown for high-risk areas. Samples from public-supply wells had a median nitrate concentration of 1.3 mg/L, with 3% of wells exceeding the MCL for nitrate. Public-supply wells typically are completed in deeper aquifers, where contamination is less likely to occur (*13*). Protection often is afforded by intervening, less permeable units. Low-oxygen conditions in deeper groundwater can promote natural remediation by denitrification. Finally, public-supply wells that become contaminated are abandoned. In contrast, domestic wells usually are shallower and located closer to potential sources of nitrate contamination. Compared with public-supply wells and domestic wells in nonagricultural areas, samples from domestic wells in agricultural areas had the highest median nitrate concentration (3.3 mg/L) and percent of wells (16%) from which water exceeded the MCL for nitrate. An ANOVA test on log-transformed nitrate data yielded an F statistic of 35.32 (p value = 0.0001), indicating that these differences were statistically significant at the 0.05 level. Tukey's multiple-comparison test indicated that median nitrate concentration in samples from each water source differed significantly from the others (Figure 6).

Data from Iowa (*33*) demonstrate that people who drink groundwater from deep wells are less likely to ingest nitrate, even in areas with a high potential for groundwater contamination. Median well depth is 40 ft in western Iowa and 130−190 ft in eastern Iowa. Both areas are shown as high risk in Figure 2. Although median nitrate concentration in groundwater is 5.2 mg/L in western Iowa, confirming the national map in this area, groundwater in eastern Iowa has a median nitrate concentration of only <0.1−1.3 mg/L. Most wells in western Iowa are completed in shallow water table aquifers that are more likely to contain elevated nitrate. Regional bedrock aquifers in the area are deep and difficult to access because of high drilling cost. In contrast, bedrock aquifers in eastern Iowa occur at moderate depths and are more accessible. Nitrate contamination of deeper groundwater in bedrock aquifers is less likely to occur.

Acknowledgments

This study was conducted as part of the National Water Quality Assessment Program (NAWQA). We thank Daniel J. Hippe, Dana W. Kolpin, and Chester Zenone for providing helpful and timely reviews of the draft manuscript. We also thank those who provided constructive criticism on the accuracy of the national risk map in NAWQA study units: William J. Andrews, David W. Anning, Joseph M. Fenelon, Stephen J. Grady, Stephen J. Kalkhoff, Mark D. Kozar, Larry F. Land, Gary W. Levings, and David L. Lorenz. Most important, thanks to the many NAWQA personnel who organized and contributed data used in this investigation.

Literature Cited

(1) Solley, W. B.; Pierce, R. R.; Perlman, H. A. *Estimated Use of Water in the United States in 1990*; U.S. Geological Survey: Reston, VA, 1993; Circular 1081.

(2) Hamilton, P. A.; Shedlock, R. J. *Are Fertilizers and Pesticides in the Ground Water?*; U.S. Geological Survey: Reston, VA, 1992; Circular 1080.

(3) Puckett, L. J. *Nonpoint and Point Sources of Nitrogen in Major Watersheds of the United States*; U.S. Geological Survey: Reston, VA, 1994; Water Resources Investigations Report 94-4001.

(4) Puckett, L. J. *Environ. Sci. Technol.* **1995**, *29*, 408−414.

(5) Fan, A. M.; Steinberg, V. E. *Regul. Toxicol. Pharmacol.* **1996**, *23*, 35−43.

(6) U.S. Environmental Protection Agency. *Drinking Water Regulations and Health Advisories;* Office of Water: Washington, DC, 1995.

(7) Ward, M. H.; Mark, S. D.; Cantor, K. P.; Weisenburger, D. D.; Correa-Villaseñor, A.; Zahm, S. H. *Epidemiology* **1996**, *7*, 465−471.

(8) Mueller, D. K.; Helsel, D. R.; *Nutrients in the Nation's Waters—Too Much of a Good Thing?*; U.S. Geological Survey: Reston, VA, 1996; Circular 1136.

(9) National Research Council. *Ground Water Vulnerability Assessment—Contamination Potential under Conditions of Uncertainty*; National Academy Press: Washington, DC, 1993.

(10) Aller, L.; Bennett, T.; Lehr, J. H.; Petty, R. J.; Hackett, G. *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*; U.S. Environmental Protection Agency: Washington, DC, 1987; EPA/600/2-87/035.

(11) Richards, R. P.; Baker, D. B.; Creamer, N. L.; Kramer, J. W.; Ewing, D. E.; Merryfield, B. J.; Wallrabenstein, L. K. *J. Environ. Qual.* **1996**, *25*, 389−402.

(12) Kellogg, R. L.; Maizel, M. S.; Goss, D. W. *Agricultural Chemical Use and Ground Water Quality: Where are the Potential Problem Areas?*; U.S. Department of Agriculture: Washington, DC, 1992.

(13) Mueller, D. K.; Hamilton, P. A.; Helsel, D. R.; Hitt, K. J.; Ruddy, B. C. *Nutrients in Ground Water and Surface Water of the United States—An Analysis of Data through 1992*; U.S. Geological Survey: Reston, VA, 1995; Water Resources Investigations Report 95-4031.

(14) U.S. Soil Conservation Service. *State Soil Geographic (STATSGO) Database—Data Use Information*; U.S. Government Printing

Office: Washington, DC, 1993; Miscellaneous Publication No. 1492.
(15) Nolan, B. T.; Ruddy, B. C. *Nitrate in Ground Waters of the United States—Assessing the Risk*; U.S. Geological Survey: Reston, VA, 1996; Fact Sheet FS-092-96.
(16) Helsel, D. R.; Hirsch, R. M. *Statistical Methods in Water Resources*; Elsevier: New York, 1992.
(17) Battaglin, W. A.; Goolsby, D. A. *Spatial Data in Geographic Information System Format on Agricultural Chemical Use, Land Use, and Cropping Practices in the United States*; U.S. Geological Survey: Reston, VA, 1995; Water Resources Investigations Report 94-4176.
(18) U.S. Environmental Protection Agency. *County-Level Fertilizer Sales Data*; Office of Policy, Planning, and Evaluation: Washington, DC, 1990; PM-221.
(19) Smith, R. A.; Schwartz, G. E.; Alexander, R. B. Regional Interpretation of Water-Quality Monitoring Data. In preparation.
(20) U.S. Bureau of the Census. *1987 Census of Agriculture—Final County File*; Data Users Services Division: Washington, DC, 1989.
(21) U.S. Soil Conservation Service. *Agricultural Waste Management Field Handbook*; U.S. Government Printing Office: Washington, DC, 1992; National Engineering Handbook.
(22) *National Atmospheric Deposition Program (NRSP-3)/National Trends Network*; NADP/NTN Coordination Office: Ft. Collins, CO, 1992.
(23) U.S. Bureau of the Census. *1992 Census of Agriculture*; The Bureau: Washington, DC, 1995 (machine-readable data files).
(24) U.S. Bureau of the Census. *1990 Census of Population and Housing, Public Law 94-171 Data (United States)*; The Bureau: Washington, DC, 1991 (machine-readable data files).
(25) U.S. Department of Agriculture. *Agricultural Chartbook*; U.S. Government Printing Office: Washington, DC, 1988; Agriculture Handbook 673.
(26) Spalding, R. F.; Exner, M. E. *J. Environ. Qual.* **1993**, *22*, 392−402.
(27) Hubbard, R. K.; Sheridan, J. M. *J. Soil Water Cons.* **1989**, *44*, 20−27.
(28) Hamilton, P. A.; Denver, J. M.; Phillips, P. J.; Shedlock, R. J. *Water-Quality Assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia—Effects of Agricultural Activities on, and the Distribution of, Nitrate and other Inorganic Constituents in the Surficial Aquifer*; U.S. Geological Survey: Reston, VA, 1993; Open-File Report 93-40.
(29) Lowrance, R. *J. Environ. Qual.* **1992**, *21*, 401−405.
(30) Katz, B. G.; Lindner, J. B.; Ragone, S. E. *Ground Water* **1980**, *18*, 607−616.
(31) Porter, K. S. *Ground Water* **1980**, *18*, 617−625.
(32) Eckhardt, D. A.; Stackelberg, P. E. *Ground Water* **1995**, *33*, 1019−1033.
(33) Kross, B. C.; Hallberg, G. R.; Bruner, D. R.; Libra, R. D.; Rex, K. D.; Weih, L. M. B.; Vermace, M. E.; Burmeister, L. F.; Hall, N. H.; Cherryholmes, K. L.; Johnson, J. K.; Selim, M. I.; Nations, B. K.; Seigley, L. S.; Quade, D. J.; Dudler, A. G.; Sesker, K. D.; Culp, M. A.; Lynch, C. F.; Nicholson, H. F.; Hughes, J. P. *The Iowa State-Wide Rural Well-Water Survey—Water-Quality Data: Initial Analysis*; Iowa Department of Natural Resources: Ames, IA, 1990; Technical Information Series 19.

Received for review September 23, 1996. Revised manuscript received February 6, 1997. Accepted March 25, 1997.[⊗]

ES960818D

[⊗] Abstract published in *Advance ACS Abstracts,* June 1, 1997.