Effects of Agriculture on Ground-Water Quality in Five Regions of the United States

by Pixie A. Hamilton[a] and Dennis R. Helsel[b]

Abstract

Water-quality conditions in surficial unconsolidated aquifers were assessed in five agricultural regions in the United States. The assessment covers the Delmarva Peninsula, and parts of Long Island, Connecticut, Kansas, and Nebraska, and is based on water-quality and ancillary data collected during the 1980s. Concentrations of nitrate in ground water in these areas have increased because of applications of commercial fertilizers and manure. Nitrate concentrations exceed the maximum contaminant level (MCL) for drinking water of 10 milligrams per liter as nitrogen established by the U.S. Environmental Protection Agency in 12 to 46 percent of the wells sampled in the agricultural regions. Concentrations of nitrate are elevated within the upper 100 to 200 feet of the surficial aquifers. Permeable and sandy deposits that generally underlie the agricultural areas provide favorable conditions for vertical leaching of nitrate to relatively deep parts of the aquifers. The persistence of nitrate at such depths is attributed to aerobic conditions along ground-water-flow paths. Concentrations of nitrate are greatest in areas that are heavily irrigated or areas that are underlain by well-drained sediments; more fertilizer is typically applied on land with well-drained sediments than on poorly drained sediments because well-drained sediments have a low organic-matter content and low moisture capacity. Concentrations of other inorganic constituents related to agriculture, such as potassium and chloride from potash fertilizers, and calcium and magnesium from liming, also are significantly elevated in ground water beneath the agricultural areas. These constituents together impart a distinctive agricultural-chemical trademark to the ground water, different from natural water.

Introduction

In 1986, the U.S. Geological Survey (USGS) began the National Water-Quality Assessment (NAWQA) Program to evaluate natural and human-induced factors that affect the quality of the Nation's surface- and ground-water resources (Leahy et al., 1990). One of the program's major objectives is to compile, integrate, and compare information from investigations across the Nation in order to provide regional and national assessment of water-quality conditions. This paper completes one of the initial regional analyses by the NAWQA program. Similarities and differences in water-quality conditions in surficial unconsolidated aquifers are assessed in five intense agricultural regions in the United States. Major factors that affect regional ground-water quality, such as land-use practices, hydrogeology, and composition of sediments, are investigated. The assessment includes the Delmarva Peninsula, and parts of Long Island, Connecticut, Kansas, and Nebraska (Figure 1). The Delmarva Peninsula of Delaware, Maryland, and Virginia was one of the first NAWQA study areas that began in 1986. The remaining four areas were studied in the mid- to late-1980s by the USGS through its Toxic Waste Ground-Water Contamination (TOXICS) program (Helsel and Ragone, 1984) (Figure 1). Each of the five investigations focuses on relatively shallow, unconfined, and unconsolidated aquifers underlying major agricultural areas of the Nation (Table 1). All studies are regional in scope with the primary objective of characterizing water-quality conditions within areas of tens to tens of thousands of square miles that might be typical of agricultural nonpoint-source contamination, rather than smaller areas less than one to a few square miles that might be typical of point-source contamination from a landfill or hazardous-waste disposal site.

Approach

Major findings developed in the five investigations are summarized, including definition of hydrogeologic systems, characterization of land use, and statistical comparisons of concentrations of water-quality constituents in agricultural areas (Chen and Druliner, 1987; Grady and Weaver, 1988; Druliner, 1989; Eckhardt et al., 1989a and 1989b; Grady, 1989; Helgesen and Rutledge, 1989; Helgesen et al., 1992). Additional analyses of the water-quality data were done to meet the objectives of this paper, including statistical relations between nitrate, depth of well, and depth to water;

[a]U.S. Geological Survey, 3600 W. Broad St., Room 606, Richmond, Virginia 23230.
[b]U.S. Geological Survey, National Center, MS 413, 12201 Sunrise Valley Dr., Reston, Virginia 22092.

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statistical relations between concentrations of nitrate and other inorganic constituents in ground water beneath agricultural areas; and general comparisons between ground-water quality and rates of fertilizer application and irrigation. Nonparametric statistical techniques were used in the analysis of data. Nonparametric statistics involve robust techniques that generally are not sensitive to outlying or inaccurate values or to assumptions of equal variance and normality. The Spearman correlation analysis, a nonparametric regression test, was used to examine significant increasing or decreasing trends in data. The alpha value used in this report is 0.05. The probability (or p-value) that represents the attained significance level is given; if the p-value is smaller than or equal to the alpha value, significant trends are assumed to exist between categories.

In general, the most recent analysis for each constituent at each well was used for statistical analysis in order to avoid bias toward wells for which many analyses were available. The number of wells at which inorganic constituents were sampled in each of the five study areas is given in Table 2. Most of the samples were analyzed for nitrite plus nitrate, hereafter referred to in this report as nitrate and reported as total nitrogen. General information on period of sampling and well characteristics also is given in Table 2.

Hydrogeologic Definition

All study areas are underlain by an unconfined aquifer that primarily is composed of unconsolidated or semiconsolidated sand, gravel, silt, or clay, and that primarily is recharged from the land surface. The aquifers generally contain water that has infiltrated from the land surface to the water table within the last 100 years (Cain et al., 1989; Hamilton et al., 1993a). General description of hydrogeologic settings are provided in Table 1; detailed descriptions are provided in references. The five study areas are diverse in aquifer composition and thickness, depositional environment, hydraulic conductivity, ground-water-flow rates, and annual precipitation.

Table 1. Hydrogeologic Characteristics of the Surficial Aquifers Underlying the Five Study Areas[1]

	Study area				
Hydrogeologic characteristic	*Delmarva Peninsula*	*Central and Western Connecticut*	*Long Island, New York*	*Nebraska High Plains*	*South-Central Kansas High Plains*
Aquifer studied:	Surficial aquifer.	Stratified-drift aquifers in the Pootatuck, Pomperaug, Farmington, and Hockanum River valleys.	Upper glacial aquifer and parts of underlying Magothy aquifer.	High Plains aquifer.	High Plains aquifer.
Aquifer composition:	Unconsolidated sand, clay, silt, gravel, and some shells.	Unconsolidated sand and gravel with some silt and clay.	Unconsolidated gravel, sand, and silt, with some interbedded clay.	Semiconsolidated silt, sand, and sandstone, with locally coarse sand and gravel.	Unconsolidated clay, silt, sand, and gravel.
Aquifer thickness (feet):	40 to 100.	10 to 300.	0 to > 550.	100 to > 1,000.	0 to 200.
Depositional environment:	Fluvial, estuarine, marginal-marine.	Stratified-drift deposits.	Moraine/outwash glacial deposits.	Principally alluvial deposits.	Principally alluvial deposits.
Horizontal hydraulic conductivity (in feet per day):	Average of 90.	60 to 170.	130 to 270.	5 to > 700.	5 to 750.
Depth to water (feet):	0 to 50; median of 7.	2 to 45; median of 8.	About 10 to 185; median of 51.	0 to about 250; median of 44.	About 3 to 75; median of 26.
Primary source of recharge:	Precipitation (about 44 inches per year).	Precipitation (43 to 47 inches per year).	Precipitation (about 44 inches per year).	Precipitation (17 to 27 inches per year), irrigation-return flow, canal leakage, and stream recharge.	Precipitation (about 27 inches per year).
Typical rates of ground-water flow (feet per day):	1/4 to 2.	1 to 3.	1 to 2.	Average rate of natural flow is 0.4; however, flow affected by irrigation pumpage.	Not estimated.
Approximate residence time:	Decades; generally less.	Decades; generally less.	Decades; generally less.	Not estimated.	Not estimated.

[1]Detailed descriptions of hydrogeology for the Delmarva Peninsula are provided by Denver (1986) and Hamilton et al. (1993a); for the Connecticut study area by Grady and Weaver (1988) and Grady (1989); for the Long Island study area by Eckhardt et al. (1989a) and Soren and Stelz (1984); for the Nebraska study area by Chen and Druliner (1987) and Druliner (1989); and for the Kansas study area by Spinazola et al. (1985), Stullken et al. (1985), Hansen (1991), and Helgesen et al. (1992).

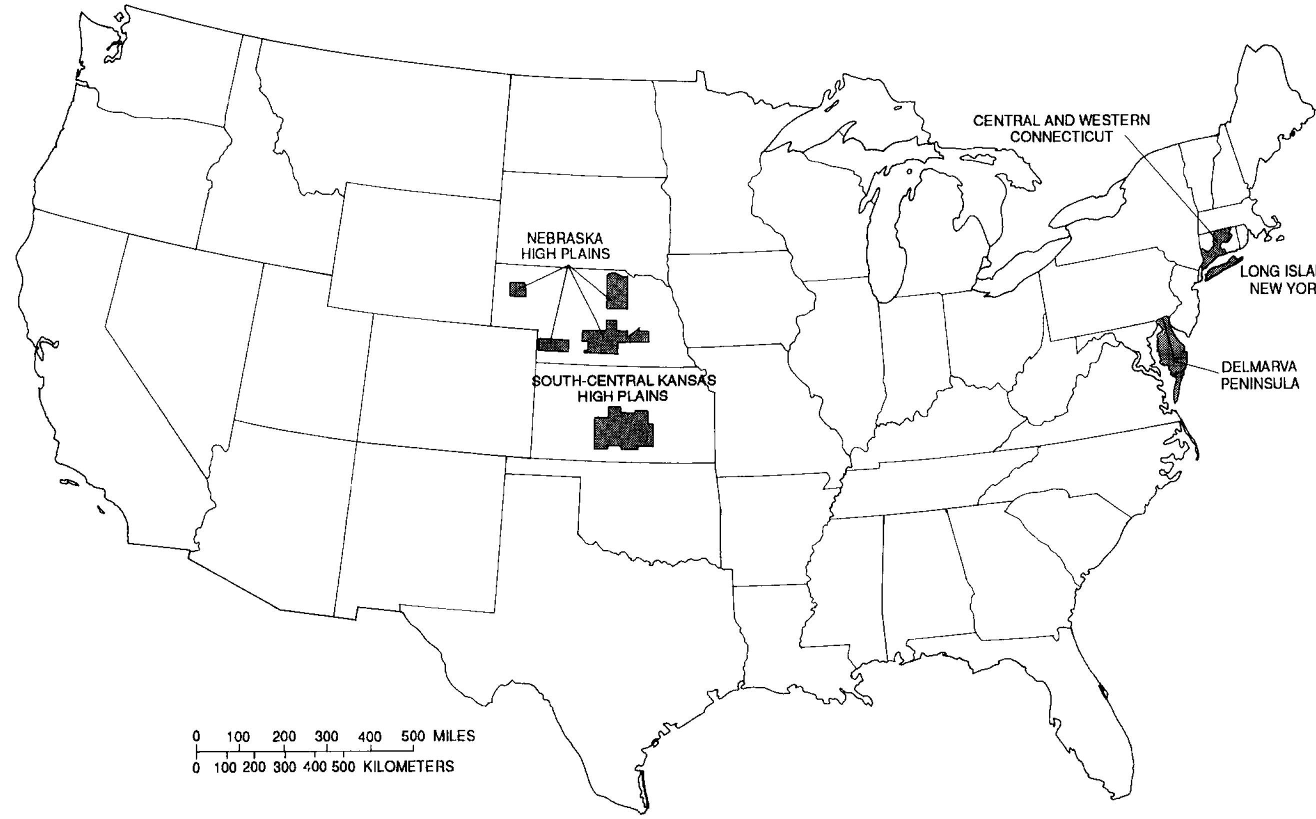


Fig. 1. Locations of study areas.

Table 2. Sampling Characteristics Among Five Study Areas

Sampling characteristics	*Study area*: *Delmarva Peninsula*	*Central and Western Connecticut*	*Long Island, New York*	*Nebraska High Plains*	*South-Central Kansas High Plains*
Total number of wells sampled:	296	116	153	268	104
Number of agricultural wells sampled:	185	26	22	268	60
Type of well sampled:	70% observation; 8% agriculture or stock; 22% other.	100% observation.	97% observation; 3% irrigation.	91% irrigation or stock; 9% other.	53% irrigation or stock; 43% domestic; 4% other.
Depth of all sampled wells (in feet):	Median: 43.0 Maximum: 140	Median: 19.5 Maximum: 55.6	Median: 108 Maximum: 560	Median: 182 Maximum: 550	Median: 74.0 Maximum: 223
Depth of sampled wells in agricultural areas (in feet):	Median: 42.5 Maximum: 140	Median: 16.2 Maximum: 24.5	Median: 93.5 Maximum: 200	Median: 182 Maximum: 550	Median: 90.0 Maximum: 223
Sampling period:	1981-90	1985-88	1987-88	1984-87	1987
Number of wells at which inorganic constituents were sampled:					
Properties					
Alkalinity as $CaCO_3$[1]	296	0	153	0	104
Dissolved oxygen	177	28	148	11	0
pH	296	116	153	268	104
Specific conductance	296	116	148	268	104
Major inorganic constituents (dissolved)					
Calcium	296	112	153	0	104
Magnesium	296	112	153	0	104
Potassium	296	0	153	0	104
Sodium	296	111	153	0	104
Chloride	296	116	153	0	104
Sulfate	296	115	153	0	104
Nutrients (dissolved)[2]					
Ammonium	272	114	153	0	0
Nitrite plus nitrate	296	116	153	268	104
Phosphorus, orthophosphate	107	115	152	0	104

[1] Bicarbonate is represented in this paper by alkalinity because bicarbonate is the dominant carbonate species in most of the ground water in the study.
[2] Nutrient data for Long Island represent ammonia plus ammonium, total nitrate, and total phosphorus.

Table 3. Agricultural Land-Use Classification and Practice in the Five Study Areas

	Study area				
	Delmarva Peninsula	*Central and Western Connecticut*	*Long Island, New York*	*Nebraska High Plains*	*South-Central Kansas High Plains*
Source of land-use data:	U.S. Geological Survey (1979a, 1979b, 1979c, 1980a, 1980b, 1980c) and onsite mapping.	Connecticut Office of Policy and Management (1970) and onsite mapping.	Long Island Regional Planning Board (1982).	Nebraska Department of Water Resources, unpublished data.	U.S. Geological Survey (1979d, 1979e, 1979f, 1979g) and Landsat-satellite imagery for July and August 1984.
Method of designating agricultural land-use category[1]:	Wells located in or immediately downgradient from agricultural land use.	Wells located in or immediately downgradient from agri- from agricultural	Predominant land use within 0.5 mile radius of well.	Intensively irrigated if 2 or more irrigation wells within 1 square mile; otherwise, less intensively irrigated.	Predominant land use within 3 to 10 square miles.
Principal crops:	Soybeans and corn; poultry.	Corn, hay, and berries.	Potatoes, cabbage, broccoli, and grapes.	Corn and wheat.	Wheat, grain sorghum, and corn.
Total nitrogen fertilizer (pounds) per acre of fertilized cropland (weighted mean)[2]:	93	173	268[3]	158[4]	85
Number of counties for which data were available/total number of counties:	12/14	5/5	1/1	10/12	10/12
Percentage of irrigated harvested cropland per acre of harvested cropland (weighted mean)[5]:	15	2	59	63	26
Number of counties for which data were available/total number of counties:	5/14	1/5	1/1	12/12	11/12

[1] Modified from Cain et al. (1989).
[2] Assessed by county on the basis of fertilizer sales data, U.S. Environmental Protection Agency, 1990a; application rates can differ locally.
[3] Local rates in the North Fork agricultural region of Long Island generally range from 100 to 225 pounds per acre (Sieczka, Joseph, Cornell University Coop Extension, written commun., 1993).
[4] Most interviewed farmers in 1984-1985 applied about 200 pounds of total nitrogen per acre of corn per year (Druliner, 1989).
[5] Assessed by county on the basis of Agriculture Census data, U.S. Bureau of the Census, 1989; application rates can differ locally and can differ seasonally depending on precipitation.

Definition of Agricultural Land Use

The five study areas include productive and intensively cropped land, primarily used to grow corn, grain, soybeans, and vegetables (Table 3). Rates of nitrogen fertilization differ among the study areas, ranging from about 85 pounds of total nitrogen per acre in the Kansas study area to more than 200 pounds in the Long Island study area (Table 3). (Rates of fertilization and irrigation are assessed by county on the basis of Agriculture Census data, U.S. Bureau of the Census, 1989 and fertilizer sales data, U.S. Environmental Protection Agency, 1990a; application rates can differ locally.) Rates of irrigation also differ among the study areas; percentage of harvested cropland that is irrigated ranges from about 2 percent in the Connecticut study area to 63 percent in the Nebraska study area. Heavy irrigation is typical of agricultural land throughout the State of Nebraska; Nebraska has the second largest amount of irrigated land in the Nation, second to the State of California (Power and Schepers, 1989).

The scale at which agricultural land use was categorized was based on the availability of existing land-use information. The categorization generally is based on a designated amount of percentage of agricultural land upgradient to or within a given radius of a well or based on a numerical measure of intensity, such as number of irrigation wells within a given radius (Table 3). Detailed descriptions of land-use classification are provided in the references.

Limitations of Water-Quality and Ancillary Data for Regional Water-Quality Assessment

Data collected in independent studies generally are limited for national assessment of the Nation's water resources because of different characteristics of the water samples and data, including sampling procedures and laboratory analytical methods, spatial coverage of the sampled sites, water-quality constituent coverage, and availability of ancillary site information (Hamilton et al., 1993b). Limitations of the existing data described in this paper refer only to the use of the data for regional and national water-quality comparisons; data from the individual studies fully meet the specific objectives for which they were collected, yet possibly are limited for water-quality comparisons of national scope. Specific data-limitation considerations include:

1. Field and laboratory procedures are not uniform among studies.

2. Spatial distribution of sampling sites, both areally and with depth, differ among the studies (Table 2). Differences in the distribution could possibly cause difficulties with comparison of results from different programs. For example, comparison of data bases from two different regions might indicate that nitrate concentrations in one region are higher than those in another simply because the bulk of the data are from shallow wells in one area and from deep wells in the other.

3. Types of wells used in the analyses differ among programs, including observation and monitoring, irrigation, stock, domestic, and public-supply wells (Table 2). Differences in casing material, frequency of pumping, and circulation through holding tanks can affect water-quality results.

4. Chemical analyses include a limited set of field-determined physical properties and constituents and different analytical detection limits in some programs.

5. Information on site and ancillary characteristics, including soils, crop types, and rates of fertilizer application and irrigation, is limited and inconsistent. Methods used to define agricultural land use are different among study areas (Table 3).

Results—Effects of Agricultural Activities on Nitrate and Other Inorganic Constituents in the Surficial Aquifers

Chemical Signatures

Delmarva Peninsula. Nitrate is generally the dominant anion in ground water beneath agricultural areas in the Delmarva Peninsula. Concentrations of nitrate in ground-water samples collected in agricultural areas are as much as 48 milligrams per liter as nitrogen (mg/l as N), with a median of 8.2 mg/l as N. About 33 percent of the samples exceed the U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) for drinking water of 10 mg/l as N (U.S. Environmental Protection Agency, 1990b) (Figure 2). Concentrations of nitrate in ground water underlying undeveloped areas in the Delmarva Peninsula are generally less than 0.5 mg/l as N.

Agricultural applications of inorganic fertilizers, manure, and lime have changed the natural quality of water

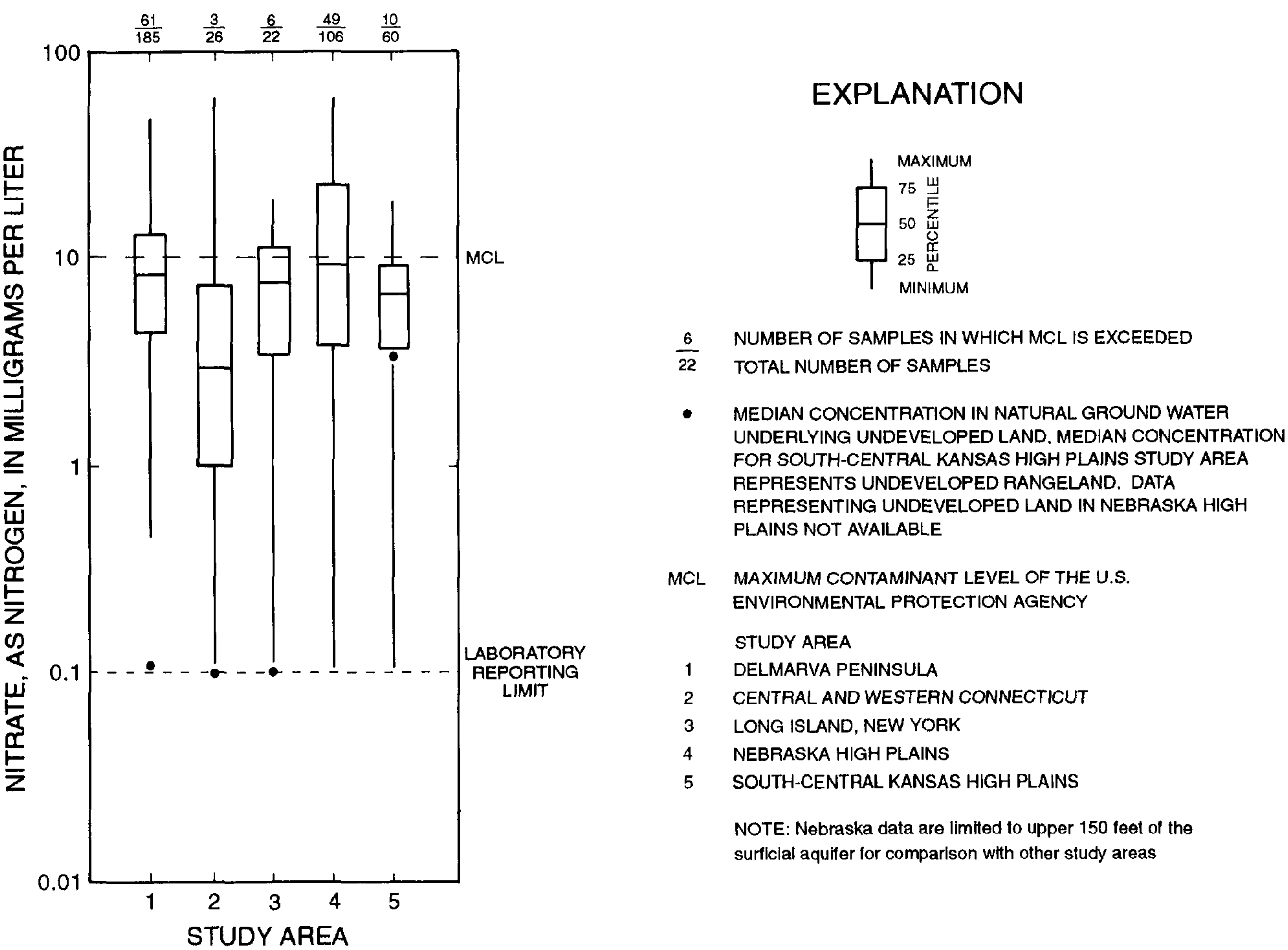


Fig. 2. Box plots showing nitrate concentrations in water in surficial aquifers underlying agricultural land in the five study areas.

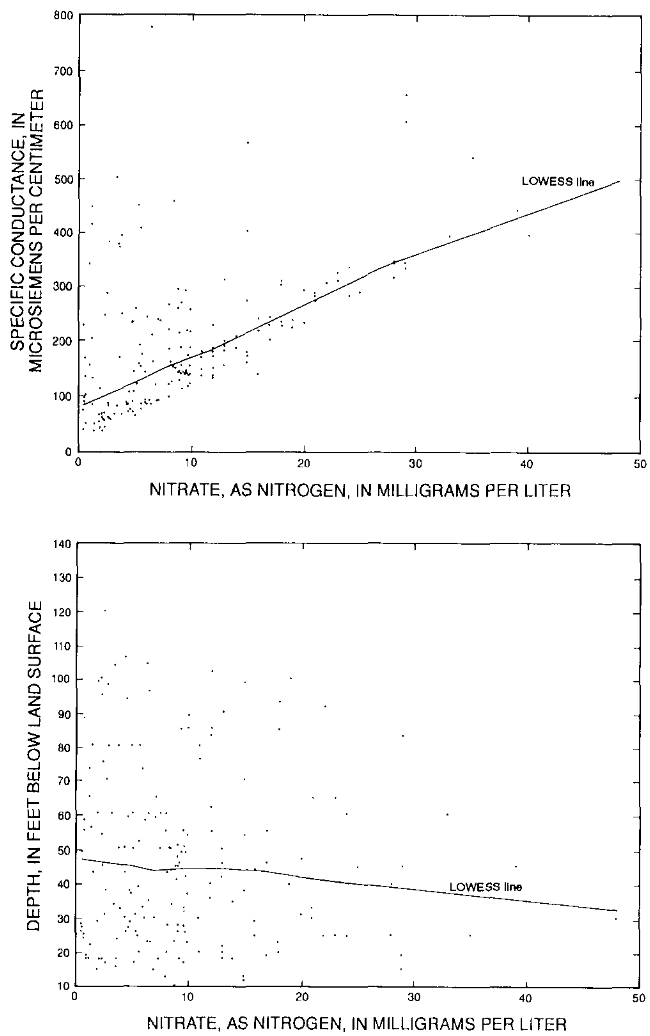
in the surficial aquifer in a large part of the Delmarva Peninsula (Hamilton et al., 1993a). Ground water affected by agricultural activities in the peninsula contains significantly higher concentrations of dissolved constituents [indicated by a median specific conductance value of 170 microsiemens per centimeter (μS/cm)] than does natural ground water (indicated by a median specific conductance value of 115 μS/cm). Concentrations of calcium and magnesium are significantly higher because of liming of soils, and concentrations of potassium and chloride are significantly higher because of applications of potash, a supplement to the nitrogen-based fertilizers. The overall chemistry of ground water underlying agricultural areas, primarily a calcium magnesium nitrate-type, differs significantly from natural ground-water chemistry, primarily a calcium or sodium bicarbonate-type (Hamilton et al., 1993a). Nitrate concentration increases significantly (Spearman p-value < 0.001) with increasing specific conductance (Table 4) in ground water beneath agricultural land; therefore, specific conductance is a general indicator of nitrate concentration superimposed on naturally occurring concentrations of dissolved solids (Figure 3a). Nitrate concentration also increases significantly (Spearman p-values < 0.001) with increasing concentrations of other major ions associated with fertilizer applications, including calcium, magnesium, barium, strontium, potassium, and chloride.

Stratified-drift aquifers, Central and Western Connecticut. Nitrate concentrations for 26 ground-water samples collected from wells in agricultural areas in the Connecticut study area are as much as 60 mg/l as N, with a median of 2.9 mg/l as N. About 12 percent of the water samples exceed the USEPA MCL for drinking water (Figure 2). The median nitrate concentration in ground water underlying undeveloped land is about 0.1 mg/l as N.

Concentrations of dissolved constituents are significantly higher in agricultural areas (as indicated by a median specific conductance value of 170 μS/cm) than in undeveloped areas (as indicated by a median specific conductance value of 99 μS/cm) because of the application of inorganic chemicals to the land (Grady, 1989). Ground water in agricultural areas contains significantly higher concentrations of calcium, magnesium, sulfate, and nitrate than ground water in undeveloped areas. Use of inorganic fertilizers and soil treatments also has resulted in a significant increase in the frequency of detections of ammonium, strontium, and boron in ground water beneath agricultural land compared to undeveloped areas (Grady, 1989). [Analysis of water types in undeveloped and agricultural areas was not done because data are lacking (Table 2)]. Nitrate concentration increases significantly (Spearman p-value < 0.001) with increasing specific conductance in ground water beneath agricultural land (Table 4). Nitrate concentration also increases significantly (Spearman p-values < 0.050) with increasing concentrations of other major ions associated with fertilizer applications, including calcium, magnesium, sulfate, and strontium.

Upper Glacial aquifer, Long Island, New York. Nitrate is generally the dominant anion in ground water beneath agricultural areas in the Long Island study area. Nitrate concentrations for 22 ground-water samples collected from wells in agricultural areas are as much as 18 mg/l as N, with a median of 7.5 mg/l as N. About 27 percent of the water samples exceed the USEPA MCL for drinking water (Figure 2). Median nitrate concentration in ground water underlying undeveloped land is about 0.1 mg/l as N.

Concentrations of dissolved constituents are significantly higher (as indicated by a median value of about 350 μS/cm) in the agricultural area than in the undeveloped area (as indicated by a median value of about 100 μS/cm). Concentrations of nitrate, calcium, magnesium, potassium, sulfate, and boron are significantly higher in samples collected from the agricultural area than in samples collected from the undeveloped area (Eckhardt et al., 1989b; LeaMond et al., 1992) Water-type analyses indicate that ground water underlying agricultural land, primarily a calcium magnesium sulfate nitrate-type, differs from natural ground-water chemistry, primarily a calcium chloride- or calcium bicarbonate-type. Nitrate concentration increases significantly (Spearman p-value < 0.001) with increasing specific conductance (Table 4). The strong statistical correlation (Table 4) indi-



EXPLANATION

LOWESS line--LOcally WEighted Scatterplot Smoothing (Helsel and Hirsch, 1992)

Fig. 3. Relations between nitrate concentrations in water collected from wells completed in the surficial aquifer underlying agricultural land in the Delmarva Peninsula and (a) specific conductance and (b) depth of well.

cates that specific conductance is a useful predictor of nitrate contamination in the upper glacial aquifer underlying agricultural land in the Long Island study area. Nitrate concentration also increases significantly (Spearman p-values < 0.050) with increasing concentrations of other major ions associated with fertilizer applications, including calcium, magnesium, potassium, chloride, sodium, sulfate, and boron.

High Plains Aquifer, Nebraska. Nitrate concentrations for 106 ground-water samples collected from wells (less than 150 ft BLS) in agricultural land in the Nebraska study area are as much as 57 mg/l as N, with a median of 9.2 mg/l as N. (Analysis is limited to upper 150 ft of the surficial aquifer for comparison with other investigations.) About 46 percent of the water samples exceed the USEPA MCL for drinking water (Figure 2). [Data for major cations and anions are not available to test statistical relations with nitrate concentration or to assess ground-water types in agricultural areas (Table 2).] Nitrate concentration increases significantly (Spearman p-value < 0.001) with increasing specific conductance (Table 4), despite a relatively high ionic strength of ground water in Nebraska compared to the eastern study areas (as indicated by a median specific conductance value of 560 μS/cm versus values of 170 μS/cm in the Delmarva Peninsula and Connecticut study area and 350 μS/cm in the Long Island study area).

High Plains Aquifer, South-Central Kansas. Nitrate concentrations for 60 ground-water samples collected from wells in agricultural areas in the Kansas study area are as much as 18 mg/l as N, with a median of 6.7 mg/l as N. About 17 percent of the water samples exceed the USEPA MCL for drinking water (Figure 2). Median nitrate concentration in undeveloped rangeland is about 3.4 mg/l as N.

Ground water beneath irrigated cropland is characterized by significantly higher concentrations of hardness, alkalinity, calcium, magnesium, potassium, fluoride, and nitrate than in water beneath undeveloped rangeland (Helgesen and Rutledge, 1989; Helgesen et al., 1992). Ground-water type is similar in both agricultural land and rangeland and is primarily a calcium bicarbonate-type. Nitrate concentration does not correlate significantly (Spearman p-value = 0.774) with increasing specific conductance (Table 4). Lack of correlation is most likely due to the relatively high ionic strength of ground water (as indicated by a median specific conductance value of 456 μS/cm) and relatively low rates of fertilization (about 85 pounds of nitrogen per acre of cropland) and irrigation (about 26 percent of harvested cropland is irrigated). Nitrate concentration does not correlate significantly with increasing concentrations of agricultural-related inorganic constituents, such as calcium, magnesium, or potassium.

Variation of Nitrate with Depth

Delmarva Peninsula. Effects of agricultural activities on ground-water quality are not limited to the near-surface parts of the surficial aquifer in the Delmarva Peninsula but also are common at or near the base of the aquifer, generally 80 to 100 feet (ft) below land surface (BLS) (Figure 3b). The median concentration of nitrate in agricultural areas in water collected from 24 wells deeper than 80 ft BLS is 8.5 mg/l as N, and concentrations in nine of these samples exceed the MCL (Hamilton et al., 1993a). Nitrate concentration does not correlate significantly (Spearman p-value =

Table 4. Statistical Relations Between Concentrations of Nitrate, Specific Conductance, Well Depths, and Depth to Water in the Surficial Aquifer Underlying Agricultural Land in the Five Study Areas[1]

	Study area				
	Delmarva Peninsula	*Central and Western Connecticut*	*Long Island, New York*	*Nebraska High Plains*	*South-Central Kansas High Plains*
Relation between nitrate concentration and specific conductance:	$p < 0.001$ $R^2 = 56\%$	$p < 0.001$ $R^2 = 64\%$	$p < 0.001$ $R^2 = 90\%$	$p < 0.001$ $R^2 = 30\%$	$p = 0.774$ $R^2 = 3.8\%$
Relation between nitrate concentration and well depth:	$p = 0.480$ $R^2 = -5.2\%$ (includes well depths to 140 feet below land surface).	—[2]	$p = 0.115$ $R^2 = -34\%$ (includes well depths to 200 feet below land surface).	$p = 0.346$ $R^2 = -12\%$ (includes well depths to 100 feet below land surface). $p < 0.001$ $R^2 = -42\%$ (includes well depths to 550 feet below land surface).	$p = 0.190$ $R^2 = -18\%$ (includes well depths to 200 feet below land surface).
Relation between nitrate concentration and depth to water:	$p = 0.410$ $R^2 = 7.9\%$	$p = 0.039$ $R^2 = 41\%$	$p = 0.084$ $R^2 = 52\%$	$p < 0.001$ $R^2 = -33\%$	$p = 0.142$ $R^2 = -22\%$

[1]The Spearman correlation analysis, a nonparametric regression test, is used to examine increasing or decreasing trends in data. The alpha value used in this report is 0.05. The probability (or p-value) that represents the attained significance level is given; if the p-value is smaller than or equal to the alpha value, significant trends are assumed to exist between categories. The coefficient of determination (R^2) indicates the percentage of variability in nitrate concentration that can be accounted for by specific conductance, well depth, and depth to water. A negative number indicates an inverse relation between categories; a positive number indicates a direct relation between categories.

[2]Statistical correlations between nitrate concentrations and well depths were not done because wells are limited to depths less than 25 feet below land surface.

0.480) with increasing well depth (maximum of 140 ft BLS) in the surficial aquifer (Table 4). Nitrate remains relatively stable along ground-water-flow paths because aerobic conditions are found even in the deepest parts of the surficial aquifer; the median concentration for dissolved oxygen in 24 wells deeper than 80 ft BLS is 7.7 mg/l.

Depth to water in 112 sampled wells in agricultural areas ranges from about 0 to 28 ft BLS, with a median of about 7.7 ft BLS. According to Hamilton et al. (1993a), nitrate concentrations are significantly lower in the poorly drained region of the peninsula underlain by a high water table (less than or equal to 5 ft BLS) and anaerobic aquifer conditions than in the well-drained region of the peninsula underlain by a deeper water table and aerobic aquifer conditions. A nonparametric regression test (Spearman) of data collected at 112 sites distributed throughout the peninsula indicates that nitrate concentration does not correlate significantly (Spearman p-value = 0.410) with increasing depth to the water table (Table 4). The lack of a significant relation in the broader data set covering the entire peninsula probably reflects increased variability due to other factors, such as hydrogeology.

Stratified-drift aquifers, Central and Western Connecticut. Wells located in agricultural areas in the Connecticut study area are limited to depths less than 25 ft BLS and, therefore, statistical correlations between nitrate concentrations and well depth were not done. Nitrate concentration increases significantly (Spearman p-value = 0.039) with increasing depth to the water table (Table 4). Depth to water in 26 sampled wells in agricultural areas is relatively shallow, ranging from about 2.7 to 10.5 ft BLS, with a median of about 6.7 ft BLS. Low nitrate concentrations are in poorly drained areas underlain by a high water table (less than 5 ft BLS) and anaerobic aquifer conditions.

Upper Glacial aquifer, Long Island, New York. Effects of agricultural activities on ground-water chemistry extend deep into the surficial aquifer in the Long Island study area. The median concentration of nitrate in agricultural areas in water collected from 15 wells deeper than 80 ft BLS is 7.8 mg/l as N, and concentrations in four of these samples exceed the MCL. Nitrate concentration does not correlate significantly (Spearman p-value = 0.115) with increasing well depth to 200 ft BLS (Table 4). Aerobic conditions persist deep in the aquifer; the median concentration for dissolved oxygen in 13 wells deeper than 80 ft BLS is 9.8 mg/l.

Nitrate concentration does not correlate significantly (Spearman p-value = 0.084) with increasing depth to the water table (Table 4). Depth to water in 12 wells in the agricultural area ranges from about 16 to 64 ft BLS, with a median of about 42 ft. These findings indicate that sampling sites in the agricultural area primarily represent well-drained areas underlain by aerobic aquifer conditions.

High Plains Aquifer, Nebraska. Well depths are relatively large in the Nebraska study area compared to other study areas, with a maximum of 550 ft BLS. Nitrate concentration decreases significantly (Spearman p-value < 0.001) with increasing well depth to 550 ft BLS (Table 4). Highest concentrations (maximum of 57 mg/l as N) are found in the upper 100 ft of the surficial aquifer; statistical analysis of 66 water samples confirmed that nitrate concentration does not decrease significantly (Spearman p-value = 0.346) with well depth to 100 ft BLS (Table 4). Elevated concentrations are not limited to the upper 100 ft of the surficial aquifer, however; nitrate concentrations in water collected from 33 wells greater than 100 ft BLS (about 16 percent) exceed the MCL. Data for dissolved oxygen are lacking and, therefore, the depth to which aerobic aquifer conditions extend was not assessed (Table 2).

Nitrate concentration decreases significantly (Spearman p-value < 0.001) with increasing depth to the water table (Table 4). Depth to water is relatively large compared to other study areas, ranging from about 0 to 240 ft BLS, with a median of about 44 ft BLS for 268 sampled wells. Highest concentrations of nitrate are found at sites where depth to water is less than 50 ft BLS and sediments are permeable. Lower nitrate concentations are primarily in upland areas with less permeable sediments and depths to water greater than 50 ft BLS (Druliner, A. D., U.S. Geological Survey, written commun., 1993).

High Plains Aquifer, South-Central Kansas. Nitrate concentration does not correlate significantly (Spearman p-value = 0.190) with increasing well depth to 200 ft BLS in the surficial aquifer underlying agricultural areas in the Kansas study area (Table 4). Highest concentrations (maximum of 18 mg/l as N) are found in the upper 100 ft of the surficial aquifer. Data for dissolved oxygen are lacking and, therefore, the depth to which aerobic aquifer conditions extend was not assessed (Table 2).

Nitrate concentration does not correlate significantly (Spearman p-value = 0.142) with increasing depth to the water table in agricultural areas (Table 4). Depth to water in 46 sampled wells ranges from about 11 to 75 ft BLS, with a median of about 30 ft BLS.

Discussion

Concentrations of nitrate are elevated in ground water underlying the five agricultural regions because of irrigation and applications of inorganic fertilizers and manure. Nitrate concentrations exceed the MCL for drinking water in 12 to 46 percent of the sampled wells in agricultural land (Figure 2). Concentrations of other inorganic constituents related to agriculture, such as potassium and chloride from potash fertilizers, and calcium and magnesium from liming, also are significantly elevated in ground water beneath agricultural areas. These constituents together impart a distinctive agricultural-chemical trademark to the ground water, different from natural water. Except for nitrate, these inorganic constituents do not pose a health risk; however, their presence does provide an efficient means for distinguishing ground water affected by agricultural practices and can be used to identify areas that might be vulnerable to contamination from other agricultural chemicals, such as pesticides. Nitrate concentration increases significantly with increasing specific conductance in ground water underlying agricultural land in four of the five study areas, indicating that specific conductance is a general indicator of nitrate concentration superimposed on naturally occurring concentrations of dissolved solids.

Nitrate extends to relatively deep parts of the aquifers underlying agricultural areas in the five study areas. Correlations between nitrate and well depth were insignificant except in the Nebraska study area, which included deeper well depths (maximum of 550 ft BLS) than in the other study areas. Well-drained and permeable deposits that generally underlie agricultural areas in the five study areas provide favorable conditions for vertical leaching of nitrate to relatively deep parts of the aquifers; nitrate concentrations do not decrease significantly with well depths to 100 ft BLS in the Nebraska study area, to about 150 ft BLS in the Delmarva Peninsula, and to 200 ft BLS in the Long Island and Kansas study areas. In addition, nitrate is not chemically reduced along many of the ground-water-flow paths because aerobic conditions commonly are found even in the deep parts of the surficial aquifers. The full impact of vertical penetration of nitrate will not be noted for decades because water moves relatively slowly through aquifers (Hallberg, 1989). Slow rate of vertical ground-water movement, however, is not the only factor controlling nitrate concentration with depth; denitrification can also account for nitrate loss in some deep ground water (Spalding and Exner, 1993).

Relations between depth and nitrate concentration also are affected by depth to the water table (Hallberg, 1989). As indicated in parts of the Delmarva Peninsula and central and western Connecticut, nitrate concentrations are low in poorly drained areas underlain by a high water table (generally less than 5 ft BLS) and anaerobic aquifer conditions. These conditions can inhibit nitrification of ammonia and promote denitrification of nitrate (Hamilton et al., 1993a). Nitrate concentrations are high in well-drained areas of the study areas that are underlain by a relatively deep water table and aerobic aquifer conditions. However, nitrate concentrations are low at sites where depth to water is greater than 50 ft BLS, as indicated in parts of the Nebraska study area, because of the increased potential for denitrification in areas underlain by large amounts of unsaturated sediments.

Other factors that affect nitrate concentration include composition of sediments and rates of irrigation and fertilizer application. Nitrate concentrations are greatest in areas that are heavily irrigated or in areas that have well-drained sediments; more fertilizer is typically applied on irrigated land than on nonirrigated land, and more fertilizer is typically applied on land with well-drained sediments than on poorly drained sediments because well-drained sediments have a low orgranic-matter content and low moisture capacity (Spalding and Exner, 1993). These factors may explain, in part, differences in nitrate concentrations in the Nebraska and Kansas study areas. For example, nitrate concentrations are relatively high (as indicated by a median concentration of 9.2 mg/l as N and a large percentage (about 46 percent) of sampled wells that exceed the MCL) in the surficial aquifer beneath agricultural land in the Nebraska study area. The sandy and permeable sediments are fertilized at a high rate (about 158 pounds of nitrogen per acre) and are heavily irrigated (about 63 percent of the harvested cropland is irrigated, the highest rate found in any study area). In contrast, nitrate concentrations are lower (as indicated by a median of 6.7 mg/l as N and a lower percentage (about 17 percent) of sampled wells that exceed the MCL) in the High Plains aquifer in the Kansas study area. The Kansas study area contains a significantly higher percentage of clay in the unsaturated zone (60 percent of the sampled wells in the Kansas study area are located in areas with more than 25 percent clay in the unsaturated zone versus 40 percent in the Nebraska study area). The abundant fine-textured materials and clay deposits in the unsaturated zone (Helgesen and Rutledge, 1989) have a higher organic-matter content and moisture holding capacity than sandy deposits underlying the Nebraska study area, and applications of nitrogen fertilizers (about 85 pounds per acre of cropland) and irrigation (only 26 percent of harvested cropland is irrigated) are lower. Differences in sampling times, precipitation, crop type, and sources of lithologic data also may affect the comparison between the two studies. Similar relations between nitrate concentration, sediment composition, and rates of fertilization and irrigation are shown in other agricultural regions of the Nation by Spalding and Exner (1993).

The assessment presented in this paper is based on water-quality and ancillary data collected from five independent investigations with varying objectives. Limitations associated with the aggregation of such data for regional and national comparisons include inconsistent analytical techniques, incomplete suites of constituents, and limited ancillary information for soils and land-use practices. Despite these limitations, the data proved useful for identifying similarities in ground-water quality among agricultural regions in different geographic settings of the Nation, and in developing hypotheses about major factors that affect regional ground-water quality in these areas. An understanding of these factors and data needs is critical to those individuals who make water-resources decisions in agencies at the Federal, State, and local levels.

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