Utilizing GIS To Estimate The Quantity And Distribution Of Nitrate-Nitrogen And Chloride In Olmsted County Groundwater.

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Abstract

Data obtained from water samples collected from some 1,700 wells in Olmsted County were used to estimate the total mass of nitrate-nitrogen and chloride stored in the primary aquifer and to analyze the spatial distributions of these anions and their correlation with hydrogeologic factors and known land use classes. The study included separate analysis for each of the three water-bearing stratigraphic units making up the primary aquifer; these are the St. Peter sandstone (OSTP), the Prairie du Chien Group (OPDC), and the Jordan sandstone (CJDN). The hydrogeologic factors examined include aquifer position within the stratigraphic column, the presence or absence of Decorah-Platteville-Glenwood confining unit, the thickness of overlying surficial deposits, and the aquifer thickness. Cropland was the only land use examined on a subwatershed basis; cropland acreage is serving as a surrogate variable for nitrogen fertilizer use. All of these factors were analyzed using spatial and statistical methods.

The total nitrogen mass stored in the three units that compose the major source of drinking water in the county was estimated as approximately 17,500 tons, 3,000 of which is stored in the St. Peter, 12,000 in the Prairie du Chien, and 2,500 in the Jordan. The total chloride mass stored was estimated as approximately 86,000 tons 24,000 of which in the St. Peter, 43,000 in the Prairie du Chien and 19,000 in the Jordan. The yielded values for the total mass storage would account for two to three years of the estimated unaccounted for nitrogen and would account for approximately five years of the chloride inputs based on the County estimations.

Spatial analysis indicated a positive relationship between the density of croplands and nitrate-nitrogen levels in ground water. The denser the cropland within the subwatershed, the higher the concentration levels determined in the underlying aquifers. 65% of the total nitrogen mass stored in the aquifers is found within one half of the county area that is associated with higher cropland density. It was also found that concentrations of both nitrogen and chloride correlate with the vertical position of the aquifer within the strategraphic unit; concentration levels in aquifers decrease with the increase of the number of overlying bedrock units. The average concentrations of nitrate and chloride in aquifers, estimated by spatial analysis, are found to be much lower where the Decorah-Platteville-Glenwood confining unit is present; nitrogen and chloride are also found to decrease with increase in thickness of the overlying surficial deposits. Profiles extracted from a Triangular Irregular Network surface (TIN) interpolated from nitrate concentration values in Prairie du Chien showed a general decline in nitrate concentration with the increase in bedrock thickness.

Logarithmic values of elevated (more than .25 ppm) nitrogen and chloride concentrations are normally distributed (for nitrate nitrogen, the log variable was calculated as the natural log of 100 times the nitrate level). A linear regression analysis indicated significant correlation between the distribution of nitrate concentration and the examined variables, and the analysis of variable (ANOVA) of regression results indicated that among the examined variables cropland density within watersheds has the strongest relationship with nitrogen concentration in aquifers.

Introduction

Nitrates and chloride and nitrates are the most evident contaminants in groundwater in Olmsted County (Bruggeman 1988). In the early-1960s, Olmsted County abandoned many wells in the Upper Carbonate Aquifer as the aquifer does not meet the Minnesota Department of Health requirements for a potable water supply and today the lower St. Peter-Prairie du Chien-Jordan aquifer serves as the principal source of groundwater throughout most of the County (Olsen 1988b). In the last 15 years in Olmsted County, approximately 10,000 samples representing some 5,000 wells were analyzed. This study was able to link the location and geology information to about 1,700 of these wells. Since most of these wells have been tested for drinking water quality, very few shallow wells, whose records are found, are represented in this data set.

The study included separate analysis for distribution of nitrate-nitrogen and chloride anions in each of the three water-bearing stratigraphic units making up the primary aquifer; these are St. Peter sandstone (OSTP), Prairie du Chien Group (OPDC), and the Jordan sandstone (CJDN). Each unit is named and referred to in this study as a separate aquifer.

Land Use

It is hypothesized that the greater the percentage of agriculture row crops in the subwatershed, the higher the nitrogen concentrations in the underlying aquifers.

Concerns about nitrate contamination have prompted a number of studies dealing with the relationship between agriculture and nitrate contamination of groundwater due to excessive usage of nitrogen (N) at farms with and without livestock. A nutrient budget for agriculture in Olmsted County prepared in 1999, identified the largest nutrient inputs as agricultural fertilizer, livestock feed imports, legume-fixed N, and N in precipitation. The largest outputs identified were exports of crop and animal products and loss of nitrogen in form of ammonia volatilization, denitrification, surface water runoff, and ground water recharge. The same study suggested that about 60% of the county annual nitrogen inputs could not be accounted for in crop and animal product exports. This amounts to a loss of approximately 7,000 tons N/year. A portion of this missing N is likely accounted for in runoff and shallow aquifer recharge. Widespread agricultural nitrogen fertilizer applications largely began in the 1960s (Minnesota Pollution Control Agency 1991). Road salt, water softeners, and KCL fertilizer are the primary sources of chloride in county aquifers. This project does not examine chloride sources; chloride is examined as an independent predictor of aquifer susceptibility to nitrate pollution. The project focus is on fertilizer use as the major source of nitrate-nitrogen input into ground water. Percentage of cropland by subwatershed is the surrogate variable used for the nitrate loading; hence the project analyses are completed based on these percentages.

Aquifer Rank

"Aquifer rank" is a term used in this paper to refer to the vertical order of the aquifer position within the strategraphic column from the ground surface. The aquifer's rank indicates the number of overlying bedrock units. It is theorized that the greater the aquifers rank the lower the nitrate concentration in that aquifer will be.

The primary bedrock units that make up the strategraphic column in the Olmsted County area as shown in Olmsted County Geologic Atlas (Balban 1988) from top to bottom are:

Bedrock Name	**Code**
Maquoketa Formation	OMD
Stewartville Formation	OGS
Prosser Limestone	OGP
Cummingsville Formation	OGC
Decorah Shale, Platteville and Glenwood	ODCR
St. Peter Sandstone	OSTP
Prairie Du Chien Group	OPDC
Jordan Sandstone	CJDN
St. Lawrence and Franconia Formation	ESF

A scale of 1 to 9, from top to bottom, was used to vertically rank the position of each unit within this column. The typical ranks of St. Peter, Prarie du Chien and Jordan units are 6, 7, and 8 respectively (Figure 4), whereas the actual ranks vary from one place to another based on the number of the existing overlying bedrock units.

Presence of a Confining Unit

The Decorah-Platteville-Glenwood formations represent a confining unit (hereafter referred to as "the confining unit") that hydrogeologically separates the upper carbonate aquifer from the underlying St. Peter-Prairie du Chien-Jordan aquifer (Kanivetsky 1988). The presence or absence of confining beds is one of the principal physical factors controlling water quality in Southeastern Minnesota (Tipping 1994). The assessed aquifers were assumed to be less susceptible to contamination where the overlying Decorah-Platteville-Glenwood confining unit is present.

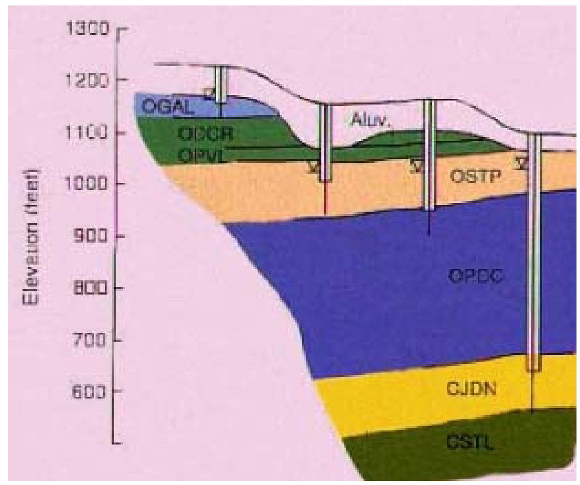


Figure 1. The setting of the three aquifers, Jordan sandstone (CJDN), Prairie du Chien formation (OPDC) and St. Peter sandstone (OSTP), and the Decorah-Platteville-Glenwood confining unit within the stratigraphic column (Figure source: Alexander, U of M, 1987).

Thickness of Overlying Surficial Deposits

The surficial deposits in Olmsted County have a high percentage of impermeable clay-rich materials. It is expected that the thicker the overlying surficial deposits the less vulnerable the aquifer is to nitrate and chloride contamination. Surficial deposits are glacial in origin and have largely been removed by erosive forces in most of the county. The thickest remaining surficial deposits overlying bedrock occur in the western parts of the county (Olsen 1988a).

Aquifer Volume

It is hypothesized that the thicker the aquifer the greater the dilution of nitrate concentrations in that aquifer. Volumes of bedrock forming the aquifers in Olmsted and surrounding counties are thickest in the southwest and taper to the northeast. Consequently, there is less water storage and dilution potential is assumed to be less in the northeastern-most area of each aquifer. That seems to be consistent with the elevated nitrate concentrations found in the northeastern area of Olmsted County and appears to be particularly true further east in Winona County. The Prairie du Chien and Jordan aquifers underlying the city of Lewiston have in the last decade reached levels that exceed the drinking water standard for nitrate. Aquifer test results from the Utica area suggest that they may soon be faced with the same situation as Lewiston.

Summary

The methodology for estimating the mass of nitrate-nitrogen and chloride stored in groundwater in Olmsted County was based on the results obtained from spatial and statistical analyses undertaken by this study. These analyses were aiming to examine the correlation between nitrogen and chloride concentrations and the variables discussed above.

Methods

Data Preparation

Data for this project were obtained from Olmsted County Planning Department, Minnesota Geological Survey and Olmsted County Public Health Department. The County land use coverage for the year 1992 and the subwatershed data were used to estimate different levels of nitrogen input. Water test results from the county Water Quality database were linked to the county wells information and to the parcel geocoding file from the same database. The anion concentrations for every tested well was estimated by directly averaging the water test results associated with that well. The geologic strata data from the County Well Index Database was then used to assign aquifers to the tested wells that could be linked to this data. Additional sources of data such as the County Geologic Atlas bedrock map and the well construction data from the County Well Index were used to assign aquifers for some more wells that could not be joined to the strata file (Figure 2). The integration of these different sources of information was resulted in about 1,700 wells with water quality data, well location and defined aquifer. Out of these wells, 669 wells are associated with Jordan, 726 with Prairie du Chein, and 238 with St. Peter aquifers. This data was used to create a point data files for each of the three aquifers. The distribution of point data (wells) within the County area can be seen in Figure 3.

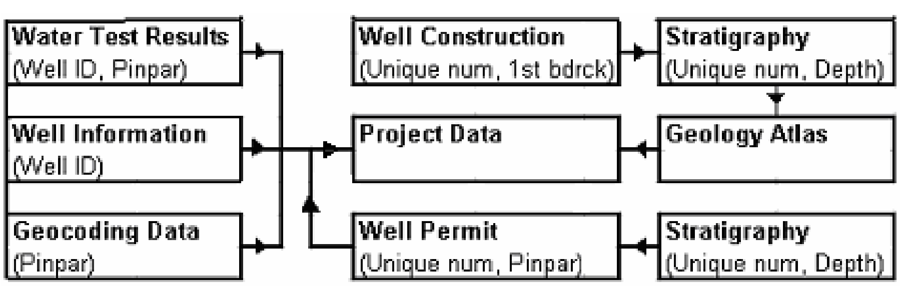


Figure 2. A Flowchart of The Project Data Preparation.

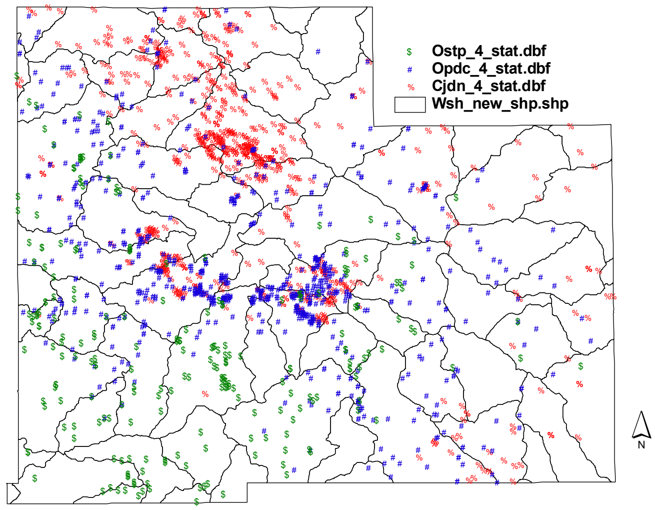


Figure 3. Locations of wells used in aquifer assessment overlain on subwatersheds.

Data Manipulation

GIS and Spatial Analysis completed involved creating TIN surfaces by interpolating the point data of nitrate and chloride concentration for each of the three aquifers, converting these surfaces to raster format layers (grids) and analyzing them based on the land use and hydrolgeologic variables of interest.

Zonal statistics were applied to calculate the average concentrations of nitrogen and chloride based on and grouped by several regions and zones of analysis designed using GIS to represent the examined landuse and hydrogeologic varables. These analysis zones were developed by transforming the spatial variations in cropland percentage, calculated by subwatersheds, aquifer rank, presence and absence of the overlying confining unit and thickness of the overlying surficial deposits, into raster format layers.

Initially, the following raster format layers (grids) were created:

1. Geology: created based on the County 100,000-scale geology map, it indicates the spatial variation in the first encountered bedrock on the county area. Grid value varies from 1 to 9 representing the nine bedrock units of the strategraphic column from top to bottom respectively (Figure 4).
2. N and Cl concentrations: interpolations from the anion concentration point data for the three aquifers converted into grids.
3. Cropland: created based on a selection of the cultivated land class from the 1992 county land use coverage. Grid value indicates the presence or absence of crop lands.
4. Subwatershed grid: An integer grid converted from the county subwatershed coverage.

By overlaying the cropland grid on the subwatershed grid the total row crop area within each subwatershed was calculated using the grid *Zonalsum* function. The percentages of cropland by subwatersheds were then calculated in a look up table and joined to the subwatershed value attribute table (VAT). Aquifer rank grids were calculated based on the typical order of the aquifer in the strategraphic column (Figure 4) and the order of the first encountered bed rock (which equals the geology grid value).

Aquifer rank grid = (the typical aquifer rank + 1) – (geology grid)

Aquifer rank for OSTP ranges from 1 to 6, for OPDC from 1 to 7, and for CJDN from 1 to 8.

The typical rank of the confining unit in the stratigraphic column is five (Figure 4). The aquifer rank grid was consequently used to determine the presence and absence of the overlying confining unit. The confining unit is present if the aquifer rank is greater than the difference between the aquifer typical rank and the confining unit typical rank. Each of the three aquifer rank grids were accordingly reclassified into two grids based on presence and absence of the confining unit and by applying the relationship:

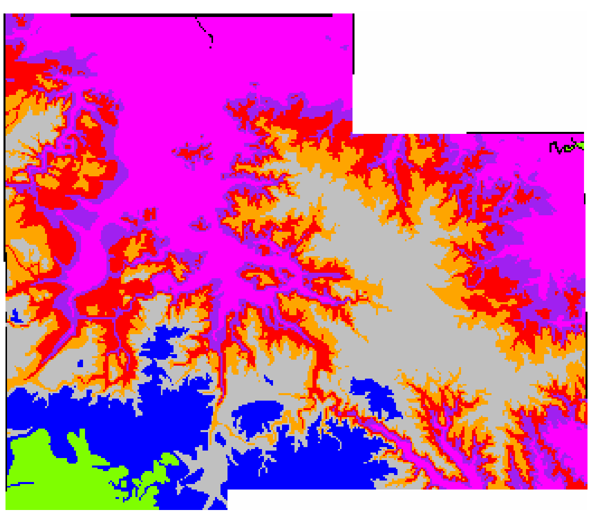
If aquifer rank grid > (Aquifer typical rank – 4) then the confining unit is present.

A grid that indicates the thickness of the surficial deposits was created based on the Depth to Bedrock map of the County Geologic Atlas. Grid value ranges from 1 to 5 indicating the following ranges of thicknesses in feet: 0 to 50, 51 to 100, 101 to 150, 151 – 200, >200. The available information from the well construction data was insufficient to estimate the spatial variation of the thicknesses of the aquifers within the county area; hence no GIS layer was created to stand for the aquifer volume variable.

Manipulation processes explained above were completed using the Environmental Systems Research Institute, Inc. (ESRI) software. The various manipulation tools of ArcInfo, ArcGIS and ArcView3.3 and their components and extensions were utilized to convert the land use and hydrogeologic variables of interest into raster format layers and numeric values required for the spatial and statistical analyses undertaken by this study.

Spatial Analysis

The distributions of nitrogen and chloride concentrations were analyzed for correlation with the aforementioned variables. The spatial analyses were completed using zonal statistics, average concentrations of nitrogen and chloride were calculated from the anion concentration grids based on the variable grids.



Aquifer Typical Rank
within the strata column

	OSTP	OPDC	CJDN
OMD	6	7	8
OGS	5	6	7
OGP	4	5	6
OGC	3	4	5
ODCR	2	3	4
OSTP	1	2	3
OPDC		1	2
CJDN			1

Figure 4. The geology grid is developed based on the county (1: 100,000) scaled geologic map. Aquifer rank grids were calculated from the geology grid value and the aquifers typical ranks as shown above

Analyses of nitrate and chloride were completed based on the subwatershed grid, the aquifer rank grids, the reclassified aquifer rank grids based on the presence and absence of the confining unit, and the surficial deposits thickness grid reclassified.aquifer rank grids based on the presence and absence of the confining unit, and the surficial deposits thickness grid. Spatial analysis of anion concentrations by the surficial deposits thickness were done apart from the influence of the confining unit, a mask was set to limit the zonal analysis to areas where the confining unit is not present. Analysis for correlation between nitrogen concentrations and aquifer volume was done for the Prairie du Chien aquifer only. The geology map was overlaid on the grid developed from the nitrogen concentration values in the aquifer and four profiles were extracting from the nitrate grid following the typical gradient of the aquifer thickness in the geology grid.

Statistical Analysis

Functionalities of Microsoft Access, Microsoft Excel and SPSS applications were utilized to statistically analyze nitrogen and chloride concentrations in the three aquifers based on the variables of interest. The raster layers created by GIS to stand for these variables were utilized to join all the wells, by location, to these variables. Water chemistry data were first added as point events to ArcMap, and each point was then linked by location to the required information from the subwatershed, aquifer rank, and surficial deposit GIS layers. Accordingly, "subwatershed," "Percentage of cropland by subwatershed," "aquifer rank," "Estimated depth to aquifer," "depth of surficial deposits," and "presence of confining unit" items were joined in a numeric format to the attribute of the water chemistry points. Depth to aquifer is estimated using the average aquifer thicknesses from the strategraphic column as in the County Geologic Atlas (Balban 1988). Data was then exported to database files for statistical analysis. Mean concentrations of nitrogen and chloride grouped by the examined variables in Microsoft Access were exported to SPSS to run the statistical analysis. Data were analyzed for correlations between the distribution of nitrate and chloride concentrations in aquifers (as dependant variables) and each of percentage of cropland in subwatershed, aquifer rank, estimated depth to aquifer, depth of surficial deposits, and the data point X, and Y coordinates (as independent predictors). The high significance of the correlation between the cropland percentage in the subwatershed as well as the aquifer rank and the distribution of anion concentration is the justification behind using the two variables in estimating the nitrogen and chloride mass storage in the aquifers.

Extended Analysis

Extended spatial analysis was done to examine the influence of aquifer rank on the distribution of the nitrogen concentrations separated from the influence caused by cropland intensity. This analysis was also required for obtaining the averages of nitrogen concentrations used in calculating the nitrogen mass storage

The percentage of cropland by subwatershed as calculated by this study is ranging from 8% to 96%; this wide range of variation must have a great control on the distribution of nitrate concentrations in aquifers, therefore influence of other variables would hardly be differentiated. Consequently, aquifer rank could not be examined based on subwatersheds because of their small areas that may not allow for existence of spatial variation in aquifer rank adequate for analysis. Moreover, a large number of the subwatersheds are not associated with wells from at least one of the three studied aquifers.

As a result, more sizeable zones to include considerable number of wells from each assessed aquifer were developed by aggregating subwatersheds based on the percentage of cropland. The average range of crop percentage in these zones is 10%. The average nitrate concentrations calculated from these zones will be more relevant as they contain actual values from wells of each aquifers. Their sizable areas will also involve spatial variation allowing for examining the aquifer rank variable within only 10% ranges of cropland intensity.

Six zones were developed by aggregating (classifying) subwatersheds based on the percentage of cropland. These zones, hereafter referred to as "cropland zones," are shown in Figure 5. Nitrogen concentration grids were clipped onto cropland zones to create six new sub-layers of nitrogen concentration in each aquifer. Each sub-layer (representing the distribution of nitrogen concentration in a certain cropland zone) is re-analyzed based on aquifer rank and presence of a confining unit and thickness of surficial deposits.

3-D model for anion concentration and mass storage in aquifers:

Furthermore, the cropland zones and the aquifer ranks, as manipulated by GIS, were used in estimating the nitrogen mass storage. For each of the three aquifers of interest, the mean nitrogen concentrations were grouped horizontally by the cropland percentage in subwatershed (using cropland zones) and vertically by number of overlying bedrock units (using aquifer rank) were illustrated in a three dimensional model. Each cell in the model represents a certain component (part) of the aquifer defined by the number of overlying bedrock units and the cropland zone associated with it. The average concentration of nitrogen in each cell was then used to calculate the nitrogen mass storage to that cell.

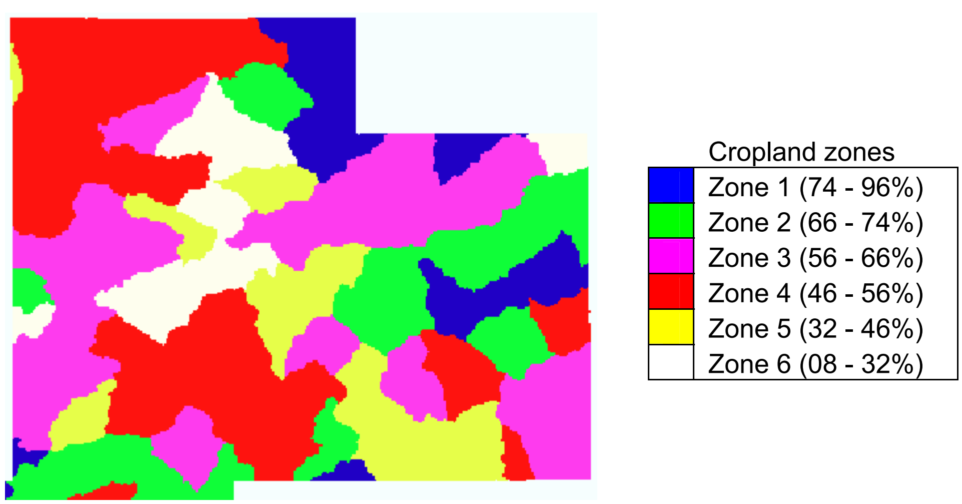


Figure 5. Subwatersheds were aggregated (classified) based on percentage of row crops into six cropland zones.

The chloride mass storage was calculated on aquifer rank basis. The average concentrations of chloride estimated by GIS based on aquifer rank were used to estimate the mass of chloride stored in each aquifer.

Volume of groundwater stored in each part was calculated based on the rock volume and the published porosity values (Lindgren 2000). Porosity values used are 0.23 for the St. Peter Sandstone, 0.09 for the Prarie du Chien fornmation, and 0.10 for the Jordan Sandstone. Rock volumes were calculated based on the typical thickness of the bedrock (Balaban 1988) and the aerial extent of that part as resulted from spatial analysis. A certain value was assigned for the remaining rock of each aquifer when it is the first encountered bedrock (aquifer rank = 1).

Results and Discussions

Spatial Analysis

Cropland

Based on the 1992 county landuse cover, the cultivated land is estimated as 56% of the county area. Out of 1631 wells included in this study, 22 have nitrogen concentrations higher than the EPA federal standard for drinking water (10 mg/L). 18 of these wells are associated with subwatersheds having more than 50 percent of row crop land. Test results from 417 wells indicated an elevated nitrogen concentration higher than 0.25 mg/L.

As it was hypothesized, results of the completed spatial and statistical analysis indicated a linear relationship between the distribution of nitrogen concentrations in aquifers and the intensity of cropland within subwatershed area. This finding is consistent with the nitrogen budget for Olmsted County which shows large annual nitrogen inputs in agricultural areas. Regression analysis completed for subwatershed that have more than 30% of their area associated with cropland indicated a positive correlation between the percentages of cropland and the distribution of nitrogen concentration in these subwatersheds ($r^2 = 0.178$, $p < 0.00088$). The positive correlation for the three aquifers is graphically represented in Figure 6.

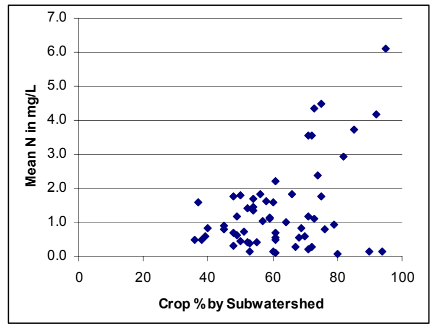


Figure 6. A graphical representation for the correlation between percentages of cropland and the mean nitrogen-nitrate concentrations by subwatershed in the three aquifers. Percentage of cropland and mean nitrogen concentrations were calculated using GIS.

The average concentrations of nitrogen in Prairie du Chien and Jordon aquifers were estimated by spatial analysis for the six areas developed by aggregating the subwatersheds based on the percentage of cropland and referred to as cropland zones. The estimated average concentration of nitrogen increases with the increase of cropland percentage (Figure 7 and Table 1).

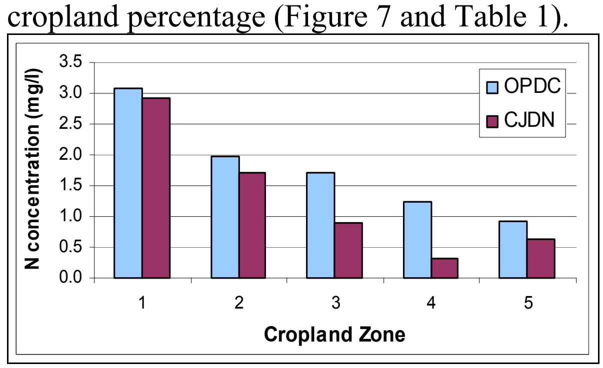


Figure 7. Average of N Concentration in mg/L by cropland zone.

Table 1. Average of N concentrations in Prairie du Chien and Jordan aquifers are much higher in the zones associated with denser cropland.

Aquifer	56% - 96% Crop land	8% - 56% Crop land
OPDC	2.25 mg/L	1.27 mg/L
CJDN	1.80 mg/L	0.59 mg/L

Aquifer Rank

Spatial analysis completed has also supported the hypothesis that the level of anion concentrations in an aquifer is influenced by the number of overlying bedrock units. Spatial analysis for correlation between distribution of nitrogen and chloride concentrations and aquifer rank within the stratigraphic column revealed that both the nitrogen and chloride levels in any of the three aquifers decrease with the increase of the aquifer rank (Figure 8). This conclusion is consistent with longer time of travel associated with groundwater flow from the land surface to the deeper aquifers.

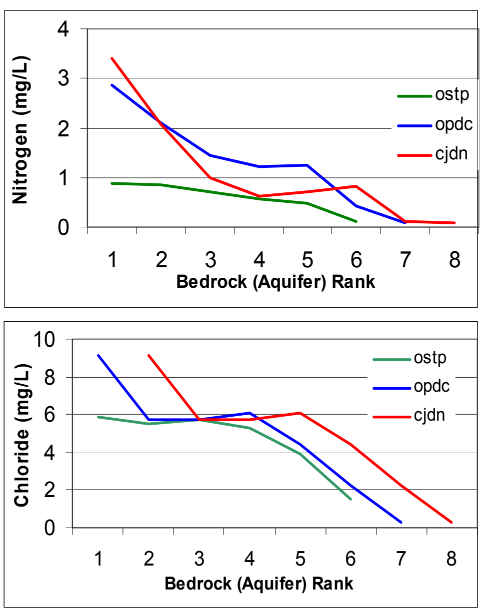


Figure 8. The average of nitrate and chloride concentrations in the three aquifers decreases with the increase of aquifer rank (increase in # of overlying bedrock layers).

Overlying Material

The presence of the confining unit and the thick surficial deposits overlying aquifers as indicated by analysis reduces the levels of nitrogen concentrations as was assumed. Zonal statistics showed lower nitrogen levels in the presence of the Decorah/Plateville/Glenwood unit (Figure 9), and also indicated a decrease in the nitrogen levels with the increase of the thickness of overlying surficial deposits (Figure 10). This finding could be explained by the geologic nature of these materials which are associated with low permeability. Both permeability and thickness affect the time of travel of the contaminant (Minnesota Department of Natural Resources 1991).

The drop in chloride levels as a result of the presence of the confining unit is not as much as in nitrogen levels. From the results of the spatial analysis of nitrogen and chloride levels based on aquifer rank as shown by Figure 8, the nitrogen levels gently decline below the confining unit whereas chloride levels decline abruptly. This might indicate that the decline in chloride levels below the confining unit is influenced by the aquifer rank (number of overlying units) more than by the presence of the confining unit.

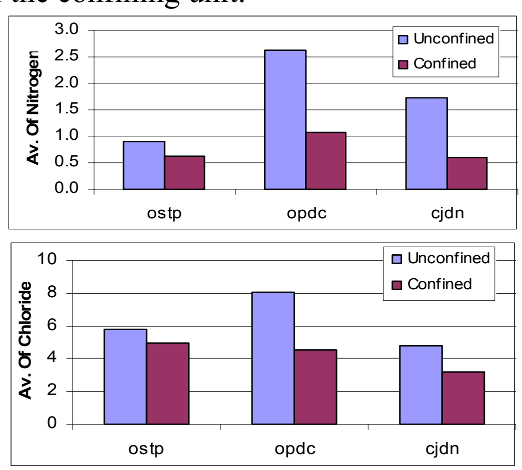


Figure 9. Lower averages of nitrogen and chloride concentrations are calculated in the presence of the confining unit.

In order to examine the effect of the presence of the overlying surficial deposits apart from the other overlying confining units, analyses were limited to the western parts of the county where the thickest remaining surficial deposits occur, and where no confining unit exists. Since the portion of the St. Peter aquifer that is directly overlaid by these surficial deposits is relatively small, the analysis was limited to the Prairie du Chien and the Jordan aquifers. The averages nitrate in the Prairie du Chien and the Jordan aquifers calculated based on the thickness of the overlying surficial deposits are generally decreasing with the increase of the thickness of the overlying surficial deposits (Figure 10).

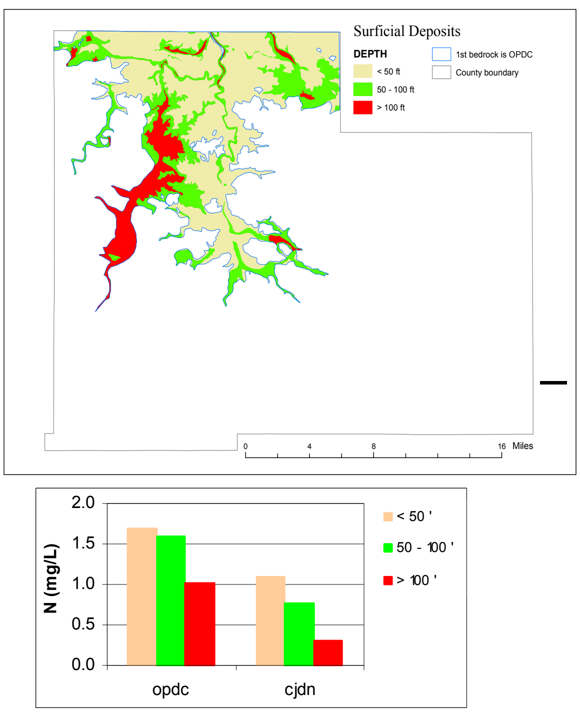
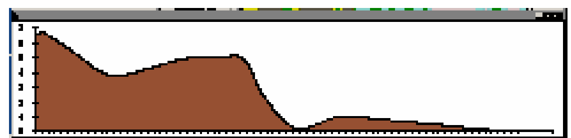


Figure 10. Average nitrogen levels estimated with spatial analysis indicates a negative linear correlation with the thickness of the overlying surficial deposits. Analysis is limited to the area shown in the map.

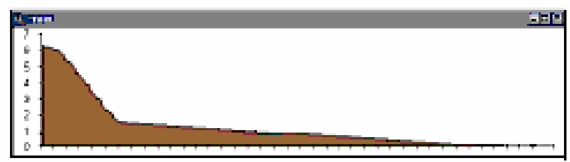
Aquifer Volume

Available data on aquifer thickness was insufficient to be analyzed for correlation between aquifer volume and distribution of anion concentration. A comparison of nitrate concentration versus aquifer volume was completed for Prairie du Chien by extracting four transects in the northern part of Olmsted County where the Prairie du Chien is the first encountered bedrock. Transects shown in Figure 11 were extracted in Arcview 3.3 by applying "Profile Extractor" extension on the interpolated surfaces of N concentrations following the typical slope in aquifer thickness based on the county geologic map. A map of the transect locations can be seen in Figure 12.

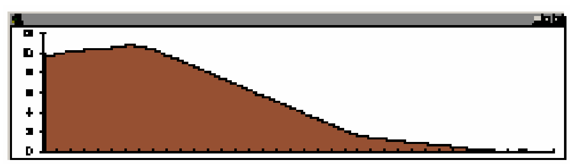
Transect 1



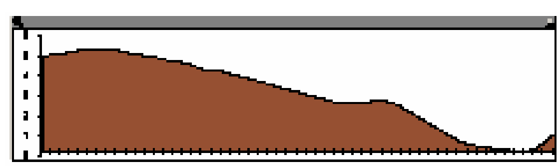
Transect 2



Transect 3



Transect 4



Thickness of Prarie du Chien formation typically increases in this direction →

Figure 11. Four transects illustrating nitrate concentrations in the Prairie du Chien. Mean nitrate concentrations in mg/L are on the Y-axis. Transect are plotted on the X-axis starting from the thinnest area of the aquifer on the left and the thickest area to the right.

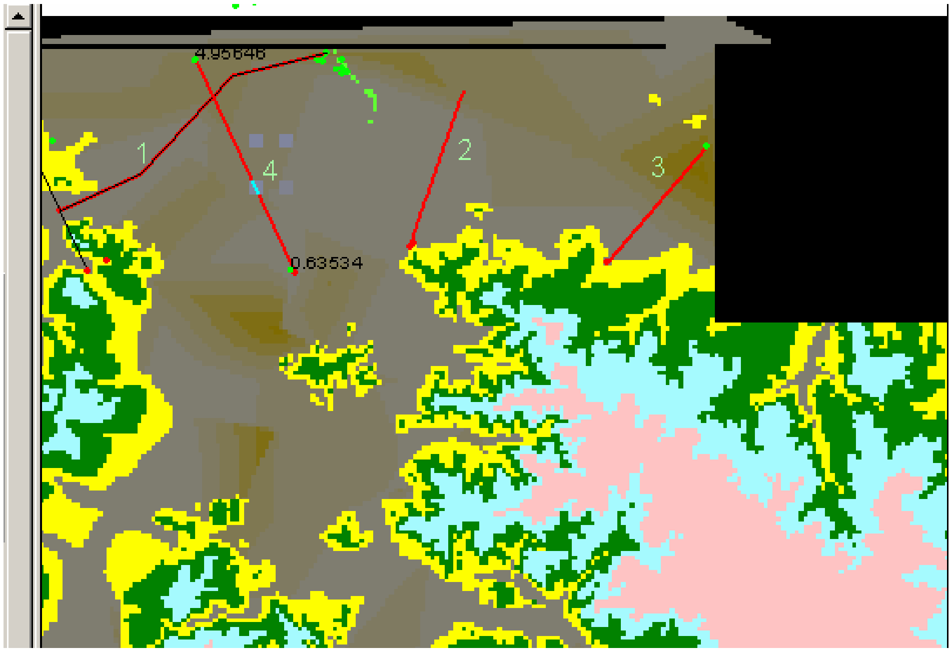


Figure 12. Locations of four transects extracted from Prairie du Chien nitrogen raster format layer displayed with the county geologic map. Transects followed an up-gradient of the aquifer thickness.

Statistical Analysis

The water chemistry data for the wells is used to directly average nitrogen and chloride concentrations in aquifers grouped by the same variables used in spatial analysis. The raster layers created by GIS were used to join these variables by location, and to link them as numeric values to the nitrogen and chloride point data.

Regression analysis and analysis of variance (ANOVA) of regression were completed in the Statistical Package SPSS version 11, using the natural log of 100 times the N value the natural log of chloride as dependent variables and the land use and geology variables and log of chloride as predictors. Nitrogen and chloride were analyzed for correlation with these variables: crop percentage, aquifer rank, estimated depth to aquifer, thickness of surficial deposits, northing(y) and easting(x) coordinates, and the distance from the southwest corner of the County, calculated from the northing and easting. Analysis was limited to wells with elevated nitrate values (>= 0.25 mg/L). As shown by SPSS histograms, the logarithmic values of nitrogen and chloride are normally distributed for such wells and the values of cropland percentage by subwatersheds calculated in ArcMap are normally distributed too.

Regression analysis of variables indicated a number of predictive relationships. Nitrogen values significantly correlated with the intensity of row cropland within subwatershed, followed by the thickness of surficial deposits, followed by the number of overlying bedrock units (Table 2). The higher the percentage of cropland the higher the nitrogen value, and the higher the thickness of surficial deposits or the aquifer rank the lower the nitrogen value. Regression equations also indicated that the x and y coordinate points are statistically relevant independent variables, nitrogen values increase towards the north east direction. This finding may be related to the decrease in the number of overlying bedrock units including protective layers in that direction, which correlates as shown by spatial analysis with increase in nitrate concentration levels (figure 8). It might also indicate either a larger scale groundwater movement phenomenon and/or the cumulative influence of nitrates in up-gradient watersheds. No dependent relationship between chloride concentrations and cropland was indicated by regression analysis of variable. The correlation shown in the analysis results is between chloride levels and the depth of overlying surficial deposits and the hypotenuse x and y coordinates (Table 3).

Table 2. ANOVA And Model Summary Of Regression Analysis For Log Nitrogen Concentration (Dependent Variable) And The Significant Examined Variables (Predictors)

Model		df	F	R^2
1 Distance from southwest corner of the county	Regression Residual Total	1 415 416	10.093	.024
2 + Crop percentage by subwatershed	Regression Residual Total	2 414 416	7.955	.037
3 + Thickness of surficial deposits	Regression Residual Total	3 413 416	6.599	.046
4 + Aquifer rank	Regression Residual Total	4 412 416	6.210	.057

Table 3. ANOVA And Model Summary Of Regression Analysis For Log Chloride Concentration (Dependent Variable) And The Significant Examined Variables (Predictors)

Model		df	F	R^2
1 Distance from southwest corner of Olmsted County	Regression Residual Total	1 393 394	6.886	.017
2 + Thickness of Surficial Deposits	Regression Residual Total	2 392 394	5.464	.027

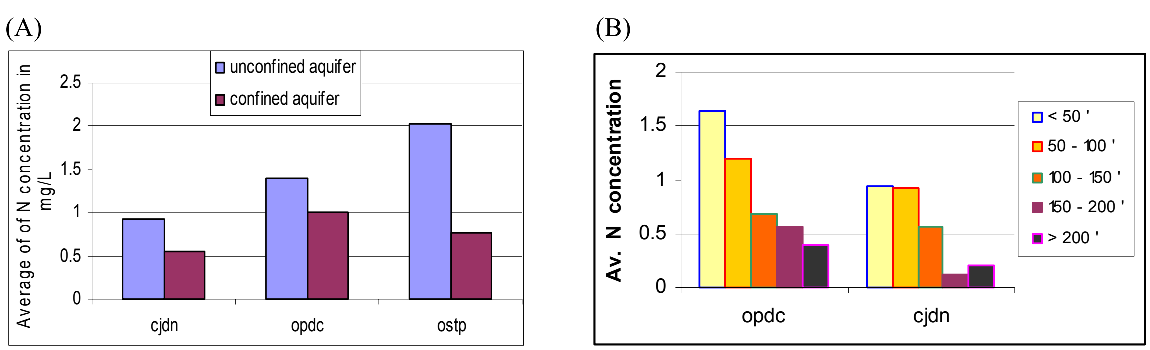


Figure 14. Averaging the nitrogen concentrations based on (A) Presence of the Decorah confining unit (B) Thickness of overlying surficial deposits ended with as similar indication as obtained by spatial analysis.

The calculated averages of nitrogen concentrations in the aquifers in Microsoft Access and Microsoft Excel (Figure 14) appeared to be fairly comparable to the zonal analysis (spatial analysis) results.

Extended Analysis: Aquifer Rank Vs. Cropland Zone And Nitrogen Vs. Chloride

The nitrogen mass storage in aquifers is calculated based on the average levels of concentration, and water volume. As the completed spatial and statistical analysis indicated, significant correlation existed between the nitrate-nitrogen levels in aquifers and the variables examined in this study. Therefore, it is concluded that a reliable calculation of the nitrogen mass storage should be based on the mean nitrogen concentrations estimated by cropland intensity and aquifer rank. The effect of the presence and absence of the confining unit and the overlying surficial deposits were excluded, the first is indirectly implicit in the aquifer rank variable and the second have a limited extent (Figure 10).

The estimated cropland intensity is signified by subwatersheds. But as it was discussed earlier, there are a large number of the subwatersheds that are not associated with wells from one or more of the three studied aquifers, and also no considerable spatial representation of variations in aquifer rank within the relatively small areas engaged by these subwatersheds. Therefore, the cropland zones were used as surrogate for subwatersheds as a base for analyzing nitrate levels and aquifer rank variable.

Nitrogen concentration grids clipped on cropland zones were spatially analyzed by aquifer rank to estimate the mean nitrogen levels by cropland zone and by aquifer rank in the same time. These mean values were used in estimating the nitrogen mass storage in aquifers (Figure 15).

Statistical analysis was extended to assess the correlation between the distribution of nitrogen concentrations and the chloride concentrations in aquifers. Regression analysis was repeated after adding the natural log chloride as an independent variable. In the resulting multiple regression equation (applied to individual wells with elevated nitrate levels), the log of chloride is the most significant independent variable. This indicates the strong relationship between the distribution of nitrate and chloride in the aquifers. Since chlorides are not well predicted by the independent variables that predict nitrates, the result indicates that the level of chlorides provides an indicator of susceptibility to pollution, and does not show similarity of land use. By adding chloride to the analysis the aquifer rank factor is excluded from the list of the significant predictors, instead the estimated depth to aquifer entered and the thickness of the surficial deposits was pushed one rank down in the list. Change in regression analysis results as resulted from including chloride in the analysis is shown in Table 4.

Table 4. ANOVA And Model Summary Of Regression Analysis For Log Nitrogen Concentration (Dependent Variable) And The Significant Examined Variables (Predictors) Including Chloride Concentration.

Model		df	F	R^2
1 Log of Chloride concentration	Regression Residual Total	1 393 394	165.	0.296
2 + Distance from SW corner	Regression Residual Total	2 392 394	100.	0.339
3 + Estimated depth to aquifer	Regression Residual Total	3 391 394	69.8	0.349
4 + Crop percentage by subwatershed	Regression Residual Total	4 390 394	53.6	0.355
5 + Thickness of surficial deposits	Regression Residual Total	5 389 394	44.1	0.362

Calculation of Nitrate-nitrogen and Chloride Stored in Aquifers

The total mass of nitrate-nitrogen stored in OSTP, OPDC, and CJDN aquifers is estimated as about 17,500 (Table 5). More than two thirds of this mass is stored in the Prairie du Chien aquifer; almost 43% of the nitrogen mass is calculated from the first and the second ranks of aquifers, while the total mass of chloride is estimated as 86,000 tons (Table 6). The yielded value of total nitrogen and chloride mass storage would account from about three years of the estimated unaccounted for nitrogen based on the County nitrogen budget, and for about five years of chloride input based on the annual chloride inputs estimated by the county staff (Terry Lee, Olmsted County, personal communication, 2003).

Table 5. Total Nitrate-Nitrogen Storage In Tons Estimated By (A) Cropland Zones (B) Aquifer Rank

(A)

CROP_Z	OSTP	OPDC	CJDN	TOTAL
1	68	1,942	489	2,699
2	810	2,316	587	3,713
3	524	3,738	664	4,926
4	842	2,203	281	3,326
5	398	863	196	1,458
6	165	825	229	1,219
Total	**3,007**	**11,888**	**2,446**	**17,341**

(B)

ORDER	OSTP	OPDC	CJDN	TOTAL
1	194	3,547	4	3,745
2	762	2,174	827	3,763
3	749	2,046	370	3,165
4	874	1,500	330	2,703
5	396	2,206	320	2,922
6	32	389	544	965
7		25	43	68
8			9.2	9.2
Total	**3,007**	**11,888**	**2,446**	**17,341**

Table 6 Total Chloride Storage In Tons Estimated By Aquifer Rank.

RANK	OSTP	OPDC	CJDN	Total
1	1,268	11,368	4	12,640
2	5,035	5,849	7,485	18,369
3	5,993	8,123	2,166	16,282
4	8,006	7,547	3,009	18,562
5	3,175	7,941	2,795	13,912
6	400	2,157	2,941	5,498
7		92	799	891
8			34	34
Total	**23,877**	**43,078**	**19,233**	**86,188**

The total mass of nitrate-nitrogen and chloride in aquifers was calculated based on the water volume and the average anion concentrations estimated by the spatial analysis based on aquifer rank and cropland zones. The mass of the chloride storage in aquifers was calculated based on the water volume and anion concentration estimated by aquifer rank (Figure 16). And the mass of nitrate-nitrogen storage was calculated based on the water volume and the average anion concentrations of small units of each aquifer, these units were determined by the aquifer rank and the area of the cropland zone associated with it (Figure 15). An error of (+/- 10) and (+/- 15) were estimated for the calculated total mass of nitrogen and chloride respectively. These errors were approximated from the calculated standard errors of averaging nitrogen concentrations by aquifer rank and cropland zone, and chloride concentrations by aquifer rank. These errors do not account for the porosity values and the saturated thicknesses used in calculations.

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			0.67 / 16.5	0.84 / 78.8	0.95 / 79	1.25 / 90.9	0.05 / 1.3	0.11 / 1.9
OPDC		4.15 / 728	2.77 / 323	2.19 / 328	2.7 / 259	3.29 / 290	0.37 / 13	0.06 / 1
CJDN		5.68 / 246	2.15 / 92.0	0.93 / 50.5	1.35 / 48.4	1.6 / 50.6	0.05 / 0.6	0.06 / 0.5

Cropland Zone 1
Very high crop percentage (74% - 96%)

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			1.35 / 33.97	2.16 / 174.2	1.9 / 229.3	0.98 / 309.6	0.28 / 48.5	0.08 / 14.24
OPDC		4.28 / 577	5.9 / 721	2.79 / 347	1.69 / 245	1 / 369	0.23 / 46.9	0.05 / 10.1
CJDN		5.31 / 180	1.76 / 76.7	1.21 / 56.8	1.18 / 62.2	1.45 / 200	0.08 / 5.8	0.08 / 6.1

Cropland Zone 2
High crop percentage (66% - 74%)

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			0.74 / 48.9	0.6 / 178	0.42 / 151	0.27 / 125	0.12 / 17.5	0.09 / 3.3
OPDC		1.96 / 452	1.9 / 601	1.82 / 834	1.52 / 641	2.03 / 1121	0.44 / 77.8	0.28 / 11.5
CJDN		1.14 / 64.8	1.16 / 134	0.83 / 142	0.83 / 128	0.91 / 184	0.16 / 10.2	0.08 / 1.3

Cropland Zone 4
High-moderate crop percentage (56% - 66%)

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			0.76 / 40.87	0.57 / 133.6	0.47 / 129.6	0.63 / 250.2	0.97 / 285	0.11 / 2.78
OPDC		2.85 / 1,137	1.13 / 280.7	0.68 / 252.1	0.52 / 168.6	0.31 / 148	0.62 / 215.7	0.05 / 1.47
CJDN	0.2 / 0.05	0.53 / 138.2	0.25 / 23.6	0.22 / 29.92	0.24 / 29.36	0.25 / 43.25	0.12 / 15.8	0.06 / 0.68

Cropland Zone 4
Moderate crop percentage (46% - 56%)

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			1.19 / 32.96	1.04 / 119.4	0.85 / 127	0.35 / 69.2	0.3 / 40.13	0.67 / 9.83
OPDC		1.5 / 138.6	1.02 / 135.1	0.95 / 167.1	0.79 / 141.6	1.09 / 248.5	0.2 / 31.56	0.05 / 0.97
CJDN		1.37 / 31.5	0.58 / 28.11	0.49 / 32.31	0.56 / 36.55	0.66 / 56.61	0.17 / 10.14	0.1 / 0.65

Cropland Zone 5
Low-moderate crop percentage (32% - 46%)

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			1.12 / 21.08	0.95 / 78.19	0.6 / 33.01	0.49 / 28.88	0.29 / 3.56	
OPDC		2.49 / 515.8	1.23 / 113.6	0.93 / 118	0.67 / 44.66	0.42 / 29.66	0.24 / 3.8	
CJDN	4.73 / 3.64	1.2 / 165.6	0.48 / 15.8	0.37 / 17.51	0.65 / 15.58	0.39 / 10.14	0.11 / 0.6	

Cropland Zone 6
Low crop percentage (32% - 46%)

Figure 15. Summary Of Estimated N Mass Storage And Average Concentration* By Cropland Zone And Aquifer Rank.

* Explanation: *2.15* Mean concentration in mg/l 91.98 Amount of N stored in tons

OMD								
OGS								
OGP								
OGC								
ODCR								
OSTP			5.84 1268	5.53 5035	5.7 5993	5.27 8006	3.93 3175	1.5 400
OPDC		9.13 11368	5.73 5849	5.7 8123	6.11 7547	4.45 7941	2.28 2157	0.29 92
CJDN	3.27 4	9.13 7485	5.73 2166	5.7 3009	6.11 2795	4.45 2941	2.28 799	0.29 34

Figure 16. Summary Of Calculated Chloride Mass Storage And Average Concentration* by Aquifer Rank.

* Explanation: *5.85* Mean concentration in mg/l
1268 Amount of N stored in tons

Recommendations for Further Research

Further studies can offer a greater focus on the bedrock stratigraphy and take into account confining units not considered in this study. For example the Shakopee and Oneota members of the Prairie du Chien aquifer should be considered separately. Similar distinctions could be made for other bedrock confining units as identified by Runkel (2003).

In this paper, the only land use considered was agriculture as it has been identified as the primary nitrogen source in county aquifers. A more refined assessment of agricultural loadings could be made using newly available cropping data from the U.S. Natural Resources Conservation Service. That data will be available by field and by crop year. Also, Olmsted County Extension Service is completing an inventory of animal feedlots. That inventory will provide the information necessary to more accurately spatially distribute nitrogen inputs associated with manure losses. A similar inventory of septic systems is available from Olmsted County Environmental Services. While the relative contribution of nitrogen from septic systems to groundwater is small, there may be localized impacts.

A study of the distribution of chloride in aquifers might provide a better understanding of the impacts of urban and suburban land use. It might also be useful in understanding changes in nitrate/chloride ratios that may be attributed to biogeochemical removal of nitrate. Road salt, water softeners, and KCl fertilizer are the primary sources of chloride in county aquifers.

A better estimate of groundwater volumes could be made using GIS. The volume of water contained in the bedrock units could be better estimated using static water level information from well logs contained in the County Well Index and more specific porosities for smaller hydrogeologic units as presented by Lindgren (2000).

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