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Spatial Analysis of Nitrate Contamination of Groundwater in Dodge County, Wisconsin

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SPATIAL ANALYSIS OF NITRATE CONTAMINATION OF GROUNDWATER IN DODGE COUNTY, WISCONSIN

by

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Department of Geography

Western Michigan University
Kalamazoo, Michigan
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DEDICATION

I would like to dedicate this thesis to all of my family and friends back in Lebanon, WI. I appreciate the support and love that you have given me. I would also like to dedicate this thesis to the people of Dodge County, Wisconsin. You are by far the hardest working and most caring people I have ever met. This especially holds true to the dairy farmers of Dodge County. You have done more for society than any other group in the history of mankind.

Jacob Andrew Maas

ACKNOWLEDGMENTS

SPATIAL ANALYSIS OF NITRATE CONTAMINATION OF GROUNDWATER
IN DODGE COUNTY, WISCONSIN

Jacob Andrew Maas, M.A.

Western Michigan University, 2006

The purpose of this research was to identify the primary variables that lead to high nitrate levels in Dodge County, Wisconsin. Trend surface analysis was used to identify which land use/land cover and aquifer characteristics are responsible for increased nitrate levels. A kriging model with residuals from the trend surface analysis, were then applied to estimate the spatial distribution of nitrate levels in the entire study area. Cross-validation was conducted to assess the uncertainty of the kriging model in the analysis.

The result from the trend surface analysis showed that, soil depth to bedrock, agriculture, urban, barren and shrub land, Y squared coordinate, depth of well, Y coordinate, and soil hydrologic group AD all had a significant relationship to nitrate levels. The kriging model showed that there are three areas of high nitrate levels in Dodge County, Wisconsin. The Pearson's correlation shows that the estimated and observed nitrate levels were highly correlated ($r = 0.932$). Areas of high, medium, and low risk for nitrate contamination were then identified in Dodge County. The results indicated that only the northern 16 percent of the county had nitrate levels in the medium and high risk categories. These areas should be targeted for water quality management.

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CHAPTER I

INTRODUCTION

Background

Nitrates are the most common groundwater contaminate in the United States

(Burkart and Stoner 2002). The Environmental Protection Agency's (EPA) maximum

contaminate level (MCL) of nitrates in drinking water allowed in the United States is 10

mg/L, with 3 mg/L being the background level for natural occurring nitrates in aquifers

(Spalding and Exner 1993). Studies throughout the United State have shown that

Midwest agricultural areas tend to lead high nitrate levels in groundwater in the nation

(Spalding and Exner 1993; Burkart and Stoner 2002; Nolan et al. 1997). Those areas

with high nitrate levels have several key characteristics: highly permeable soils, shallow

well depths, and intensive farming (Hamilton and Helsel 1995; Nolan et al. 1997).

Agriculture is the source of up to 90 percent of all nitrates found in Wisconsin's

groundwater (Chern *et al*. 1999). This may be due to over application of fertilizers and

manure. In the state of Wisconsin two out of three farmers buy more fertilizer than they

need (Shepard *et al*. 1997). Farmers on average, use an excess of 40 pounds of nitrogen

per acre than what is recommended by the University of Wisconsin-Cooperative

Extension Service. In addition to contributing to groundwater pollution, they are

spending an extra $9.20 per acre on nitrogen beyond recommendations, and the numbers

are rising (Chern *et al*. 1999).

The primary concern of high nitrate levels is human health problems caused by

ingestion (Chern *et al*. 1999). High levels of nitrates can cause a medical condition

called methemoglobanemia also known as blue-baby syndrome in infants under six

months of age. The nitrates in the water change the blood cells, causing red blood cells not to give enough oxygen to get to the body (Chern *et al.* 1999). High levels of nitrates have also been identified with cases on non-Hodgkin's lymphoma (Spaulding and Exner 1993).

Area of Study

Dodge County's surface area is 576,000 acres, of which nearly 2,200 farms make up a total of 428,000 acres (Figure 1) (Bethke 1999). Nearly 337,000 acres or 78 percent of the agricultural land is devoted to crop production. The remaining 22 percent of the land consist of wooded, developed, wetlands or lakes, or other recreation land (Bethke 1999). These factors make Dodge County one of the leading agricultural counties in Wisconsin.

Quaternary deposits overlie the majority of the bedrock throughout Dodge County (Devual *et al.* 1983). These deposits were formed when the Green Bay ice lobe moved through the county during the Pleistocene. Ground moraines are the dominant land features in the county. They are made up of unsorted glacial till. End moraines are located in the northern and southwestern part of the county. The moraine in the southeast was formed by the deposition between the margins of the Green Bay and Lake Michigan lobes, which is part of the Kettle Moraine (Devaul *et al.* 1983). Also located within the county is a 30,000 acre flat marsh called the Horicon Marsh. This marsh is a former glacial lake (Bethke 1999).

As glaciers moved through Dodge County during the Pleistocene it helped in creating the parent material for the soils. Most of the soils in Dodge County are silty and/or loamy types of soils. The major soil association in Dodge County is the St.

Charles-Miami-Elburn association with Theresa-Lamartine-Hochheim being the second major soil association (Bethke 1999).

The main aquifers that supply groundwater to Dodge County are the sand and gravel, the Silurian dolomite, the Galena-Platteville, and the sandstone (Devaul *et al*. 1983). The sand and gravel aquifer is present in over half, 54 percent, of Dodge County. In 95 percent of its range, the sand and gravel is less than 50 ft. deep (Devual *et al*. 1983). The Silurian dolomite aquifer occurs mostly in the Northeastern and Southeastern part of Dodge County. The Silurian dolomite aquifer is an important aquifer in areas where the sand and gravel aquifer do not occur. The Galena-Platteville aquifer makes up about one-half of the uppermost bedrock in the county, and underlies the eastern three-fourths of Dodge County. The Sandstone aquifer underlies the Galena-Platteville aquifer, and is the principal aquifer for municipalities and industry (Devual *et al*. 1983).

In Dodge County, the groundwater flows from recharge areas towards natural discharge areas, such as wetland, lakes, and streams (Devual *et al*. 1983). The only exception is in the Galena-Platteville and sandstone aquifers that underlie the Maquoketa Shale. In these areas the groundwater flows to the east into Washington County and north into Fond du Lac County, and are artesian in nature (Devual *et al*. 1983).

Problem Statement

A Wisconsin Department of Agricultural Trade and Consumer Protection (DATCP) study showed that in agricultural regions of Wisconsin, 17-26 percent of wells had nitrate levels exceeding the EPA's safe drinking water standards. In some of the agricultural areas, over 60 percent of the wells contained nitrates (Chern *et al*. 1999).

Dodge County, Wisconsin
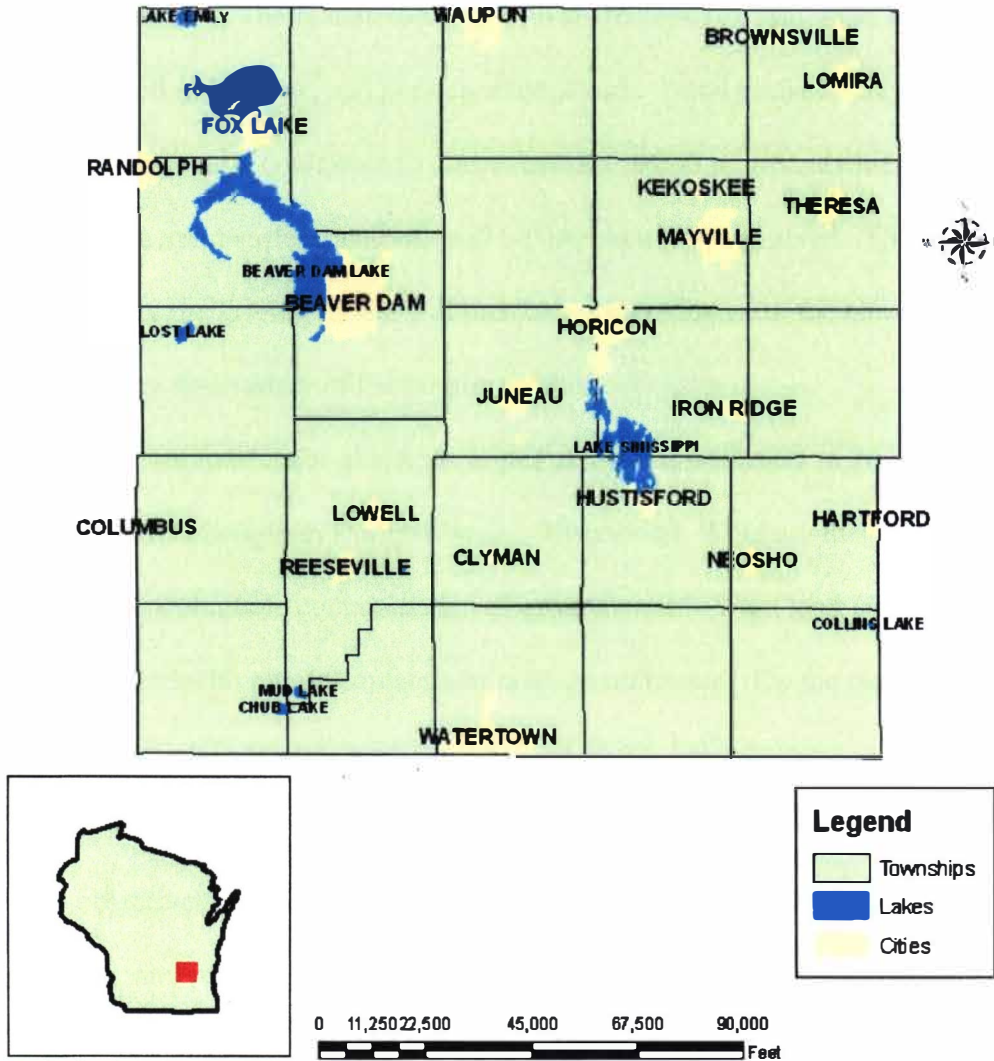
Figure 1. Study area

This research will use methods and techniques used in previous studies and apply them to Dodge County, Wisconsin for analysis of nitrate contamination. Though similar work has been done in other regions, Dodge County had never been specifically examined to see what factors are contributing to nitrate contamination and how nitrates are spatially distributed. The factors to be examined are depth of well, land use/land cover, depth of soil to bedrock, and permeability of soil. Trend surface analysis will be used to find which factors contribute to nitrate contamination of groundwater. The residuals from the trend surface analysis will be used in a kriging model. The estimated nitrate values from the kriging model will then be cross-validated to the observed nitrate levels to assess the uncertainty of the kriging model.

There are the four major questions in this study. How nitrates in groundwater are spatially distributed throughout Dodge County, Wisconsin? What are the primary factors that lead to high level nitrate contamination of groundwater? What land use/land cover types are associated with nitrate contamination of groundwater? Do the estimated values from the kriging model correlate with the observed nitrate levels?

Objectives

The objectives of the research are to analyze point well log data, to identify causes, sources, and related features that may explain high levels of nitrate contamination. The use of the kriging model will display the spatial pattern of nitrate levels over the entire area of Dodge County. The trend surface analysis model will be used to show the relationship between nitrates and the possible sources and causes of nitrate contamination of groundwater examined in this study. It is important to identify

areas within the county that have high nitrates levels. Once identified, proper

management techniques can be applied to stem further contamination of the groundwater.

CHAPTER II

LITERATURE REVIEW

Topics in nitrate contamination of groundwater have varied in their scope and methods. The major factor that has been extensively investigated by researchers is land cover, particularly agricultural lands. Depths of wells and aquifers along with soil permeability have been investigated in their contributions to nitrate contamination of groundwater. Statistics have been most commonly used to assess relationships between variables and nitrate contamination levels. Such studies have been conducted in the United States, New Zealand, Japan, Europe, and China. The size of the study areas ranged from single farms to nation wide surveys. The following sections will give a brief review of studies and literature on methodology, well and aquifer depth, soil permeability, and land cover in regards to their relationship to nitrate levels in groundwater.

Methods

Trend Surface Analysis

Trend surface analysis looks at the trend in point data that are distributed over an area (Agterberg 1984) Trend surface analysis uses least squares which is a used in multivariate regression to fit the trend of the surface to the data. Trend surface analysis is mostly universal its scope and only by adding higher order terms can some of the local detail be preserved (Bailey and Gattrell 1995). The observed residuals from the trend surface analysis are automatically correlated thus giving a bias to the estimates of any variogram (Bailey and Gattrell 1995).

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Semi-Variogram

A semi-variogram describes the expected difference for a value located between pairs of sample points (Clark 1979). Semi-variograms, as all geostatistics, are based on 3 assumptions; (1) the difference in values between samples are determined by relative spatial orientation, (2) mean and variance are the only interest and depend on relative orientation, (3) there is no trend in the variable, the interest rest mainly in the variance of the difference in value between the samples (Clark 1979).

Kriging

The purpose of kriging is to estimate the value of a variable over unsampled or unknown points (Webster and Oliver 2001). Kriging produces the best unbiased estimator (Clark 1979). Kriging was used by Ella *et al*. (2000) to analyze nitrate concentrations in glacial till. They found that kriging provided useful information on the spatial extent of nitrates in the glacial till. D'Agostino *et al*. (1998) used both ordinary kriging and cokriging techniques in there analysis of nitrate contamination of groundwater. They looked at temporal distribution and found that cokriging helped reduce the uncertainty in the estimation of nitrate values.

Cross-Validation

Cross-validation is used to validate kriging. Cross-validation may use a variety of methods to validated the kriging model, such as mean error, mean squared error, and mean squared deviation ratio (Webster and Oliver 2001). Ella *et al*. (2001) used cross-validation to validate their kriging model. The mean reduced error of the model was -0.01 to -0.074 and the model had a reduced variance of 0.6 to 2.18, which were satisfactory for their model (Ella *et al*. 2001).

Well and Aquifer Depth

Nolan (2001) used logistic regression to find which variables affect nitrate levels in the groundwater. The variables that Nolan found to affect nitrate levels are: (1) the amount of fertilizer being loaded; (2) the percentage of cropland-pasture; (3) the log of population density; (4) the percentage of well drained soils; (5) the depth to the seasonally high water table: and (6) absence or presence of a fracture zone within the aquifer. In the regression model all these variables were significant at the 0.05 level.

Tesoriero and Voss (1997) examined nitrate susceptibility in the Puget Sound Basin. They determined aquifer susceptibility by taking well depth and surficial geology to measure the likelihood that a well in this environment will have high levels of nitrates if nitrate sources were present. They found that wells that had shallow and course-grained glacial deposits were the most susceptible to nitrate contamination, while wells that were located in the alluvial and fine-grained glacial surficial deposits were the least susceptible to nitrate contamination. Hamilton and Helsel (1995) found nitrates levels in groundwater to be low at sites where depth to water was greater than 50 feet in the High Plains Aquifer of Nebraska.

Burkart and Koplin (1993) examined nitrate and herbicide levels in near surface aquifers throughout the Midwest. Nitrate contamination occurred mostly in unconsolidated aquifers as compared to bedrock aquifers. Excess nitrate was not significantly related to aquifer depth in the unconsolidated aquifer, but depth was significant in the bedrock aquifer. Burkart and Koplin believe this was due to the fact that the unconsolidated aquifer was receiving direct groundwater recharge. This constant recharge allowed for consistent contamination flow into the unconsolidated aquifer. The

Spearman's rank correlation test showed a weak but significant inverse relationship between well depth and nitrate concentrations. Nolan and Stoner's (2000) research found that the median nitrate concentrations to be highest in shallow wells beneath agricultural lands. In the Platte Valley of central Nebraska, groundwater had a median nitrate concentration of 5.8 mg/L, with 36 percent of the samples exceeding the MCL. They found that high nitrate values coincide with high nitrate loading values, which occurs most extensively in the Midwest.

Liu et al. (2005) looked at how regional differentiation of agricultural non-point source pollution of nitrate nitrogen in groundwater across Northern China. They used pairwised t-test to perform statistical analysis. They found that there was a significant correlation between nitrate concentration and sampling depths below 60 m. Chowdhury *et al.* (2003) used the AQUIPRO model, as apposed to standard statistical test, to show the relationship between nitrate contamination and groundwater pollution potential. The results showed that there was a positive correlation between decreasing AQUIPRO scores and increasing frequency of nitrate contamination levels. This showed that shallow outwash aquifer systems yielded very high relative vulnerability, while wells located on glacial moraines and till plain had lower venerability scores.

<center>Soil Permeability</center>

Nolan *et al.* (1997) incorporated nitrogen loading, population density, soil drainage characteristics, and woodland to cropland ratio into two groups: (1) nitrogen input and (2) aquifer vulnerability to assess risk groups. The soil survey hydrologic group data was used as the drainage characteristic, which is a measurement of permeability. Permeability is the rate at which a liquid can pass through a porous

<center>10</center>

medium (Fetter 2001). Areas in the study area that have well drained soils, high nitrogen input, and low woodland to cropland ratios had the highest levels of nitrates. The median concentration of nitrates was 0.2 mg/L in wells representing the low-risk group, and nitrate levels that exceeded the MCL occurred in 3 percent of the wells. The median concentration of nitrate was 4.8 mg/L in wells that represented the high-risk group, and nitrate levels that exceeded the MCL occurred in 25 percent of the wells.

Hamilton and Helsel (1995) while looking at the groundwater quality in five regions of the United States found that areas that have well drained soils and are irrigated have high levels of nitrates. This is due to the fact that more fertilizer is applied to land that is well drained than compared to poorly drained soils, and well drained soils have low organic matter content and have low moisture content. Nolan (2001) looked at percentage of soil hydrologic groups in his analysis of nitrogen sources in shallow ground waters of the United States. He found that the nitrate contamination increases with better drainage. Nolan and Stoner (2000) found that in areas that had 70 percent well-drained soil in the Central Columbia Plateau in Southeastern Washington State had a median nitrate concentration of 6.7mg/L.

<div align="center">Land Use/Land Cover</div>

Urban

Nolan and Stoner (2000) found that shallow groundwater beneath urban areas did not exceed the MCL as often as wells located in shallow groundwater beneath agricultural lands. Only 3.9 percent of the wells in the urban areas exceeded the MCL when compared to the 19 percent of wells that exceeded the MCL in agricultural areas. However, nitrate levels can get high in urban areas, a median of 8.9 mg/L in highly

populated areas of Long Island, New York, even though agricultural nitrates are not present (Nolan *et al.* 1997). Wakida and Lerner (2004) summarized that the major sources of nitrogen in urban aquifers throughout the world are mostly related to wastewater disposal and solid waste disposal.

Wetlands

Gallardo and Tase (2005) looked at the role of wetlands in removing nitrates from groundwater. Nitrate levels decreased as the groundwater approached the wetlands. The nitrates levels also decreased with depth in the wetlands. This was due to redoximorphic conditions in the wetlands, which led to denitrification. The process of denitrification needs nitrogen oxides as final electron acceptors, there must be a presence of bacteria possessing the metabolic capacity, suitable electron donors, and anaerobic conditions or restricted O_2 availability (Korom 1992).

Forest

Lowrance (1992) looked at how coastal riparian forests denitrify groundwater. He found that nitrate levels decrease by a factor of 7 to 9 in the first 10 meters. There was also a decrease from 1.80 to 1.81 mg/L of nitrates in the next 40 m of the forest. The rate of denitrification was higher, by two orders of magnitude, in the first 10 cm of the shallow soil when compared to first 10 cm in the shallow aquifer. The denitrification rate in the shallow soils may help in the removal of nitrates from the shallow aquifer. Koplin (1997) found a significant inverse relationship between forest and nitrate levels in groundwater. Nolan *et al.* (1997) found that high woodland to cropland ratios resulted in a lower risk of nitrate contamination of groundwater. Johnson (1992) argues that trees are the biggest competitors for nitrogen in the long term.

Agriculture

Nitrate contamination levels vary across the U.S. in relation to the type of agricultural system. Burkart and Stoner (2002) looked at 9 primary types of agriculture in the U.S.: corn, soybean, and hogs, dairy, poultry, beef cattle and grain, horticulture, small grains, livestock, tobacco, and cotton. The analysis showed that the sources, corn, soybean, and hogs averaged 59.7 kg/ha of nitrogen, cattle and grains averaged 24.41 kg/ha, and dairy averaged 19.5 kg/ha. Nearly 24 percent of wells located within the agricultural system of corn, soybean, and hogs had nitrogen levels exceeded the MCL of 10 mg/l. Multiple variable comparison test performed on the ranks of nitrate concentrations showed that groundwater nitrogen concentrations in corn, soybean, and hogs, cattle and grain, and small grain were significantly larger than all other systems at the .005 level.

In the U.S. Corn-Belt, alfalfa is a major contributor of nitrates to soils. Kavdir *et al.* (2005) looked at how decaying alfalfa roots affected nitrate leaching in Kalamazoo loam soils. In the Kalamazoo loam they found that alfalfa roots generated 36 kg ha^{-1} and alfalfa shoots generated 39 kg ha^{-1} which accumulated in the Ap horizons or plowed top soil layer (Kavdir *et al.* 2005). Decaying alfalfa roots in the Kalamazoo profile increased the saturated hydraulic conductivities by four times, which dramatically increased nitrate leaching following the eradication of alfalfa stands. The level that nitrates leached into deeper horizons approached 83 kg ha^{-1} with roots only and 144 kg ha^{-1} in root plus shoot fields during the period of April to December (Kavdir *et al.* 2005).

Böhlke and Denver (1995) found that nitrate levels in the Chesterville Branch and Morgan Creek watersheds near Locust Grove, Maryland have increased heavily in the

1970's. This increase related to the increase use of fertilizers in the watershed. Hamilton and Helsel (1995) looked at agricultural basins, the found a median nitrate level of 8.2 mg/L in the Delmarva Peninsula of Maryland and Delaware. The stratified-drift aquifers of Central and Western Connecticut had a median nitrate level of 2.9 mg/L. The upper glacial aquifer of Long Island, New York had a median nitrate level of 7.5 mg/L. In the high plains aquifer of Nebraska the median nitrate level of the aquifer was 9.2 mg/L., while the high plains aquifer of South-Central Kansas had a median nitrate level of 6.7 mg/L (Hamilton and Helsel 1995).

In the Midwest nitrates had a median concentration of 0.17 mg/L with 29 percent of the wells having nitrate levels above 3.0 mg/L (Burkart and Koplin, 1993). Burkart and Koplin also found that 31 percent of the wells had excess nitrates when there was more than 25 percent corn and soybeans within a 3.2 km radius. Koplin (1997) did a more in depth study of nitrate contamination and land use in the Midwest. Koplin found that wheat had a negative relationship with nitrate levels, which meant that as wheat acreage increased nitrates levels decreased. Oats had a positive relationship with nitrates, which meant that as oat acreage increased nitrates levels also increased.

Isotopic indicators are often used to determine sources of nitrate contamination. Lu *et al.* (2004) looked at what sources were causing nitrate contamination by using ^{1}H nuclear magnetic resonance (NMR) of dissolved organic matter. The study area is the Chino Basin in California, where dairy is the primary form of agriculture in the basin. Results showed that natural soil organic matter had a high relative resonance, while dairy waste had a characteristically low resonance. Using these signatures it was determined that dairy waste on croplands was the primary source on nitrate contamination of

groundwater. Panno *et al*. (2001) used isotopic indicators in karst hydrogeology to prove that nitrogen fertilizers were the main cause of nitrate contamination of groundwater. Using isotopic indicators Böhlke and Denver (1995) were able to distinguish which streams were oxic allowing for nitrates to pass through the groundwater system, and which streams were anoxic which caused denitrifying of the groundwater.

Tiling also has a major affect on nitrate levels in groundwater. In the Midwest where soils are poorly drained due to fine-grained glacial deposits, tiling of fields is common (Nolan *et al*. 1997). Bakhsh *et al*. (2005) looked at liquid swine manure on nitrate leaching losses to tile drainage. They found that flow weighted average of nitrate, which is the estimate of average annual load of nitrates and the average annual tile flow, concentrations in tile flow were affected significantly by nitrate application rates, growing season, and treatment effects. Nitrates from the swine manure were lost to groundwater from tile flows. Nolan and Stoner (2000) discuss that in areas of tiling nitrogen loading is most common in streams, because the water is diverted from the aquifer to the stream.

Irrigation has also been linked to nitrate contamination of groundwater. Koplin (1997) found that irrigation had a significant positive relationship to nitrate contamination. Irrigation can be a major contributor to nitrate contamination, and in counties where 50 percent or more of the crop land is irrigated the areas become concentrated and vulnerable to nitrates (Burkart and Stoner 2000). In the Willamette Basin, non-irrigated lands had a lower nitrate levels (0.05 mg/L) compared to the irrigated agricultural lands (2.80 mg/L) (Nolan and Stoner 2000). Burkart and Koplin (1993) found that wells that had irrigation occurring within a radius of 3.2 km of the well

had a 41 percent nitrate contamination rate. Wells that had no irrigation within a radius of 3.2 km had a nitrate contamination rate of 24 percent.

Fertilizer application rates and techniques can have an impact on nitrate loading in groundwater. Goderya *et al*. (1996) focused on the field level effects of spatial variability of initial soil nitrogen levels and crop yield. The first field scenario uses a uniform or traditional practice of fertilizer application over the field. Scenario two assumed same crop and uniform application, but the amount of nitrogen applied was modified based on one soil sample and yield information. The third scenario used variable application rates based on the spatial variation parameters. The area was divided into four sectors, and the application rate was based on the measurements of control location in each four sectors. The fourth and fifth scenarios were similar to the third, but were divided into 16 and 120 sectors. The results showed a 34 percent reduction in nitrates came when scenario two was used instead of scenario one. There was a 41 percent reduction in nitrate loading into groundwater when scenario three was used over scenario one. In scenario four and five there was a 9.6 percent to 13 percent reduction in nitrates respectively, when compared to scenario three.

The use of nutrient management practices can reduce the median nitrate concentration. Hall (1993) looked at how nutrient management affected nitrate levels of groundwater. This reduction was especially evident in areas where the pre-nutrient management concentrations were the highest. The nitrate levels decreased by 32 percent, 30 percent, 12 percent, and 8 percent in four of the five wells tested from the pre-nutrient management concentrations, with these decreases related to decreasing nitrogen applications in areas up gradient from these wells. The fifth well, which was the deepest

of the 5 wells, had an increase in nitrate levels by 8 percent. Nutrient management techniques reduced the amount nitrate application by 198 pounds per acre per year up to 378 pounds per acre per year.

Summary

Nitrates levels are influenced by many variables. Well and aquifer depths, soil permeability, and various land cover types all have been proven to affect nitrate levels. These variables have been examined exhaustively in other studies, but they have not been examined in Dodge County, Wisconsin. Spatial distribution of nitrates examined in other studies cannot explain the spatial distribution of nitrates in Dodge County. It is important to understand which variables are related to nitrate levels, and how nitrates are spatially distributed in Dodge County. From this research it is anticipated that the results can be used in nutrient management plans.

CHAPTER III

METHODOLOGY

This study aims to analyze the relationship between land cover/land use and

aquifer characteristics and nitrate levels in Dodge County, Wisconsin. This chapter

describes the methods used in this research to address the research questions. The first

part examines data collection and data processing techniques. The second part looks at

how trend surface analysis and kriging were used in the research.

Data Collection

Between 1990 and 2004, the University of Wisconsin-Cooperative Extension

Service at Dodge County performed a county-wide well sampling of wells. Voluntary

contributions from individual wells that were not part of the sampling project were also

included into the database. During this period of time, a total of 1,847 wells were

sampled. Each well was given coordinates so that it could be mapped out later for further

analysis. The wells were tested for nitrate levels along with other mineral and chemical

characteristics (Figure 2). The depths of the wells were recorded in some instances, but

not for every well. The Center for Watershed Science and Education at the University of

Wisconsin-Stevens Point, where the data was acquired from, maintains the data.

The soil database was obtained from the Dodge County Land Information

Department. This database is originally came the United States Department of

Agriculture-Natural Resources Conservation Service's Soil Survey Geographic

(SSURGO) database (Dodge County Land Information Department 2000). The

SSURGO database contains extensive variables on each soil type in Dodge County,

Wisconsin. Wisconsin Department of Natural Resources' (Wisconsin DNR)

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Groundwater Retrieval Network (GRN) database was acquired to incorporate well depth into the Center for Watershed Science and Education database (Wisconsin DNR 2004). This database contains well data for all private wells constructed between 1988 and present. The GRN database does not contain nitrate levels for those wells. Land cover data was acquired from the Wisconsin DNR's Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND) database (Wisconsin DNR 2005). The database came in raster format and was classified at the U.S. Geological Survey Land Use/Land Cover Classification System's (U.S.G.S Land Use/Land Cover Classification System) level III (Anderson *et al*. 1976).

Processing Data

Data Reduction

The first step in the data processing was to remove duplicate well logs and any wells sampled before 1990. This was done because when the well points were converted to raster there were complications. The major complication was that each raster cell could only contain data for one well, not several. All but one of the wells from the duplicate well logs was deleted. The well with the lowest ID number was kept because it had been the first well sampled at that coordinate. The duplication of wells most likely occurred from a high density of wells in a small geographic area; mostly attributed to dense housing and small lot size. This meant that they are individual wells, but the coordinates were not precise enough to create individual coordinates for each well. Wells tested before 1990 were removed because they pre-dated the period of this study. Only 4 wells were removed because they pre-dated 1990 and 827 wells were removed because of

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duplication. This left a total of 1,016 wells that that could be used in the analysis (Figure 3).

Well Depth

Not every well that came in the original data set from the Center for Watershed Science and Education had depth of the well data. In order to resolve this issue the Wisconsin DNR GRN database was used to get approximate well depth for each well. The purpose of using the GRN database was to get an estimate of well depths for wells that did not have well depths. Though these are not the exact well depths for each individual well, they do fill in data gaps with reliable data that can be used in the research. The average of the GRN well depths within an 805 meter radius or approximately .5 mile radius were used to fill in the missing depths. The 805 meter radius was used because it allows for variation at approximately the township section level. Each well in the sampled well database now had a reliable well depth that could be used in analysis (Figure 4).

Land Use/Land Cover

The land cover classification was aggregated from the U.S.G.S. Land Use/Land Cover Classification System's level III to level I to simplify the statistical analysis. The level I classification includes agriculture, urban, grassland, forest, wetland, water, and other land cover areas (Figure 5). Each individual land cover was then extrapolated separately for use in the statistical analysis. Once extrapolated, neighborhood statistics were applied to get ratios for land use/land cover within an 805 m radius. Ratios were calculated for each well that was sampled.

Well Nitrate Levels
Dodge County, Wisconsin
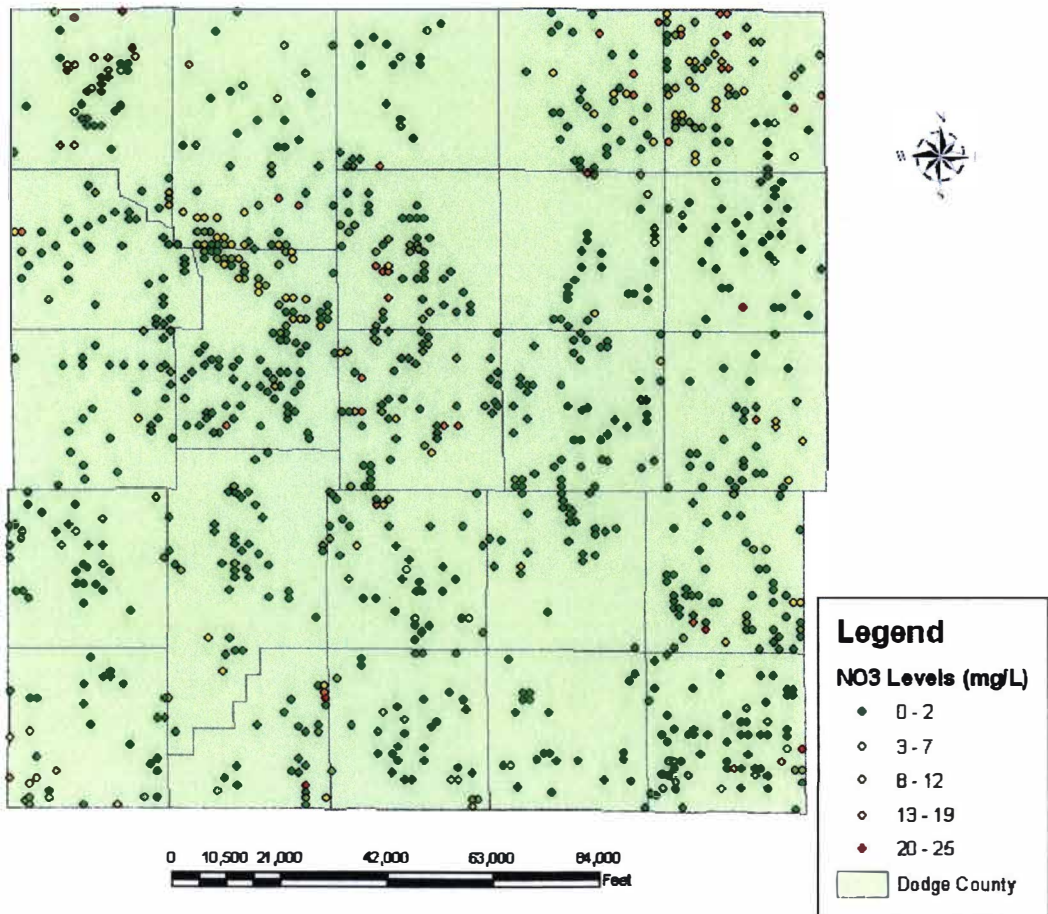
Figure 2. Level of nitrates of sampled wells in Dodge County, Wisconsin

Well Point Locations
Dodge County, Wisconsin
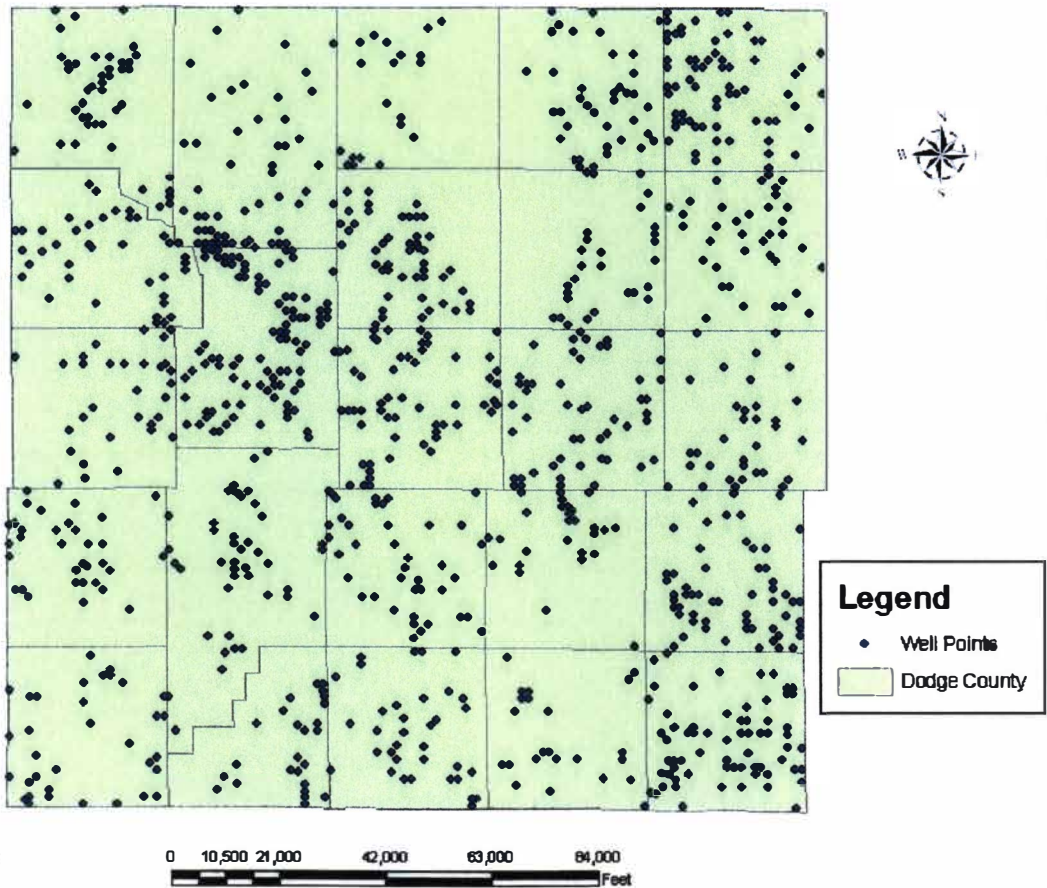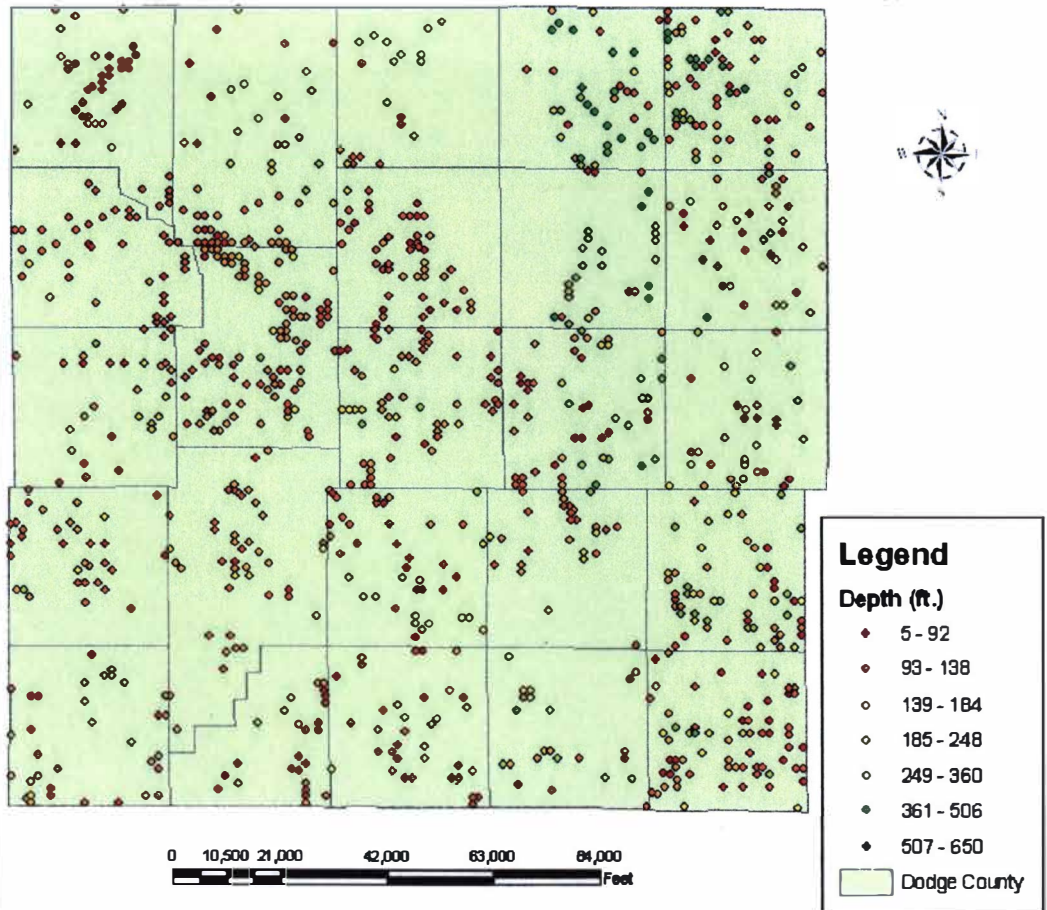
Jacob A. Maas, WMU Geography Dept., 2006

Figure 3. Location of sampled wells Dodge County Wisconsin

Figure 4. Depth of sampled wells in Dodge County, Wisconsin

Land Cover Classifications
Dodge County, Wisconsin
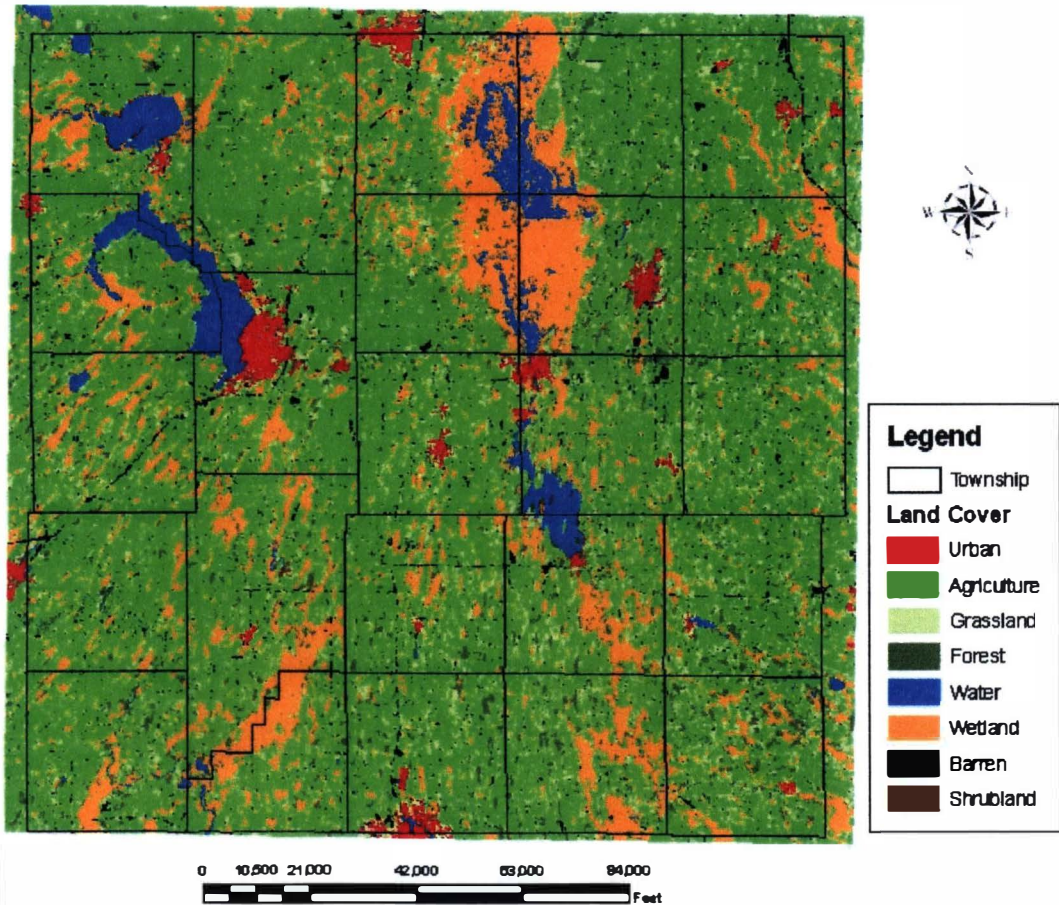
Legend

Township

Land Cover

Urban

Agriculture

Grassland

Forest

Water

Wetland

Barren

Shrubland

0   10,500 21,000   42,000   63,000   84,000
Feet

Source: Dodge County Land Information Dept., 2004

Jacob A. Maas, WMU Geography Dept., 2006

Figure 5. Land use/land cover types in Dodge County, Wisconsin

Soil Properties

The point variables', permeability and soil depth to bedrock were derived from the SSURGO soil database. To derive this data, the well points were intersected with the soil data. The combined database allowed for retrieval of the permeability rates of the soils at each well. The soil depths to bedrock were also retrieved and combined into the database (Figure 6 and 7). The soil depth to bedrock and permeability for each well point were then added to the sampled well database for statistical analysis.

The second part of the permeability variable was to look at how soil hydrologic groups, which relates to permeability, within an 805 meter radius or approximately half mile radius have an effect on each well (Figure 8). The soil hydrologic groups were turned into raster for easier ratio tabulation. This was done because it is easier to sum up the total number of raster cells than it is to calculate the actual area of each polygon in an 805 m radius for each hydrologic group. Once the sum of cells for each hydrologic group was calculated, the sum was then divided by the total sum of all the hydrologic groups. This created a ratio for each hydrologic group. The data table of the ratios was then added to the sampled well database for statistical analysis.

Analysis of Data

Multiple statistical methods were used in the analysis, including trend surface analysis, kriging, and cross-validation. In the analysis, NO3 (nitrate levels, mg/L) will be the dependent variable in the trend surface analysis. The independent variables will be:

- DepWELL (the depth in feet of each individual well)
- X (X coordinate of the well)
- Y (Y coordinate of the well)
- X^2 (Second order function of the X coordinate of the well)
- Y^2 (Second order function of the Y coordinate of the well)
- X*Y (X and Y coordinates multiplied by each other)

Shallow Soil Coverage
Dodge County, Wisconsin
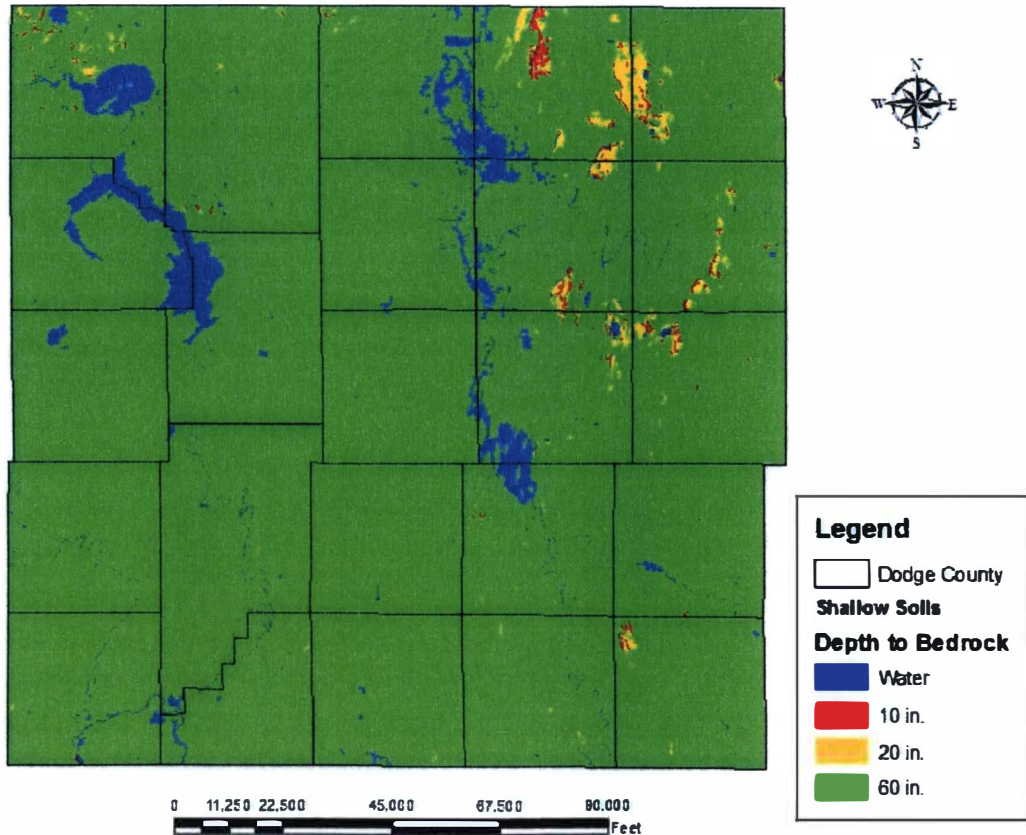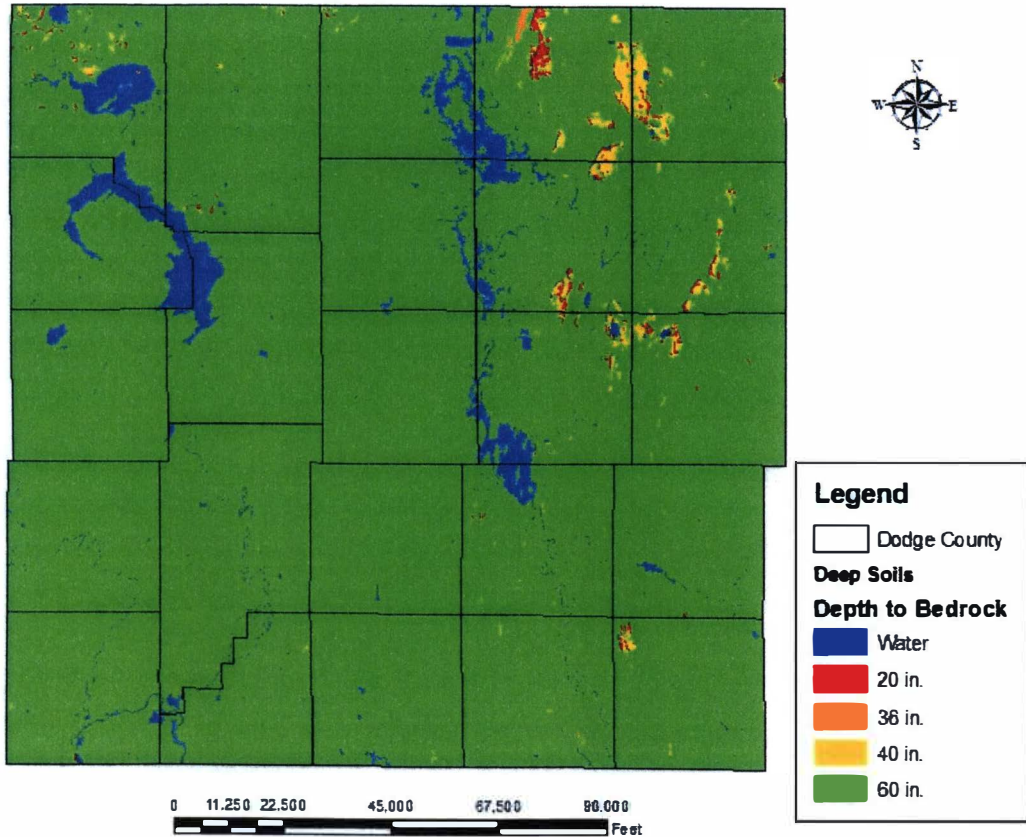
Legend

Dodge County
Shallow Soils
Depth to Bedrock
Water
10 in.
20 in.
60 in.

0   11,250 22,500   45,000   67,500   90,000
Feet

Source: Dodge County Land Information Dept., 2004   Jacob A. Maas, WMU Geography Dept., 2006

Figure 6. Shallowest soil depth to bedrock in Dodge County, Wisconsin

Figure 7. Deepest soil depth to bedrock in Dodge County, Wisconsin
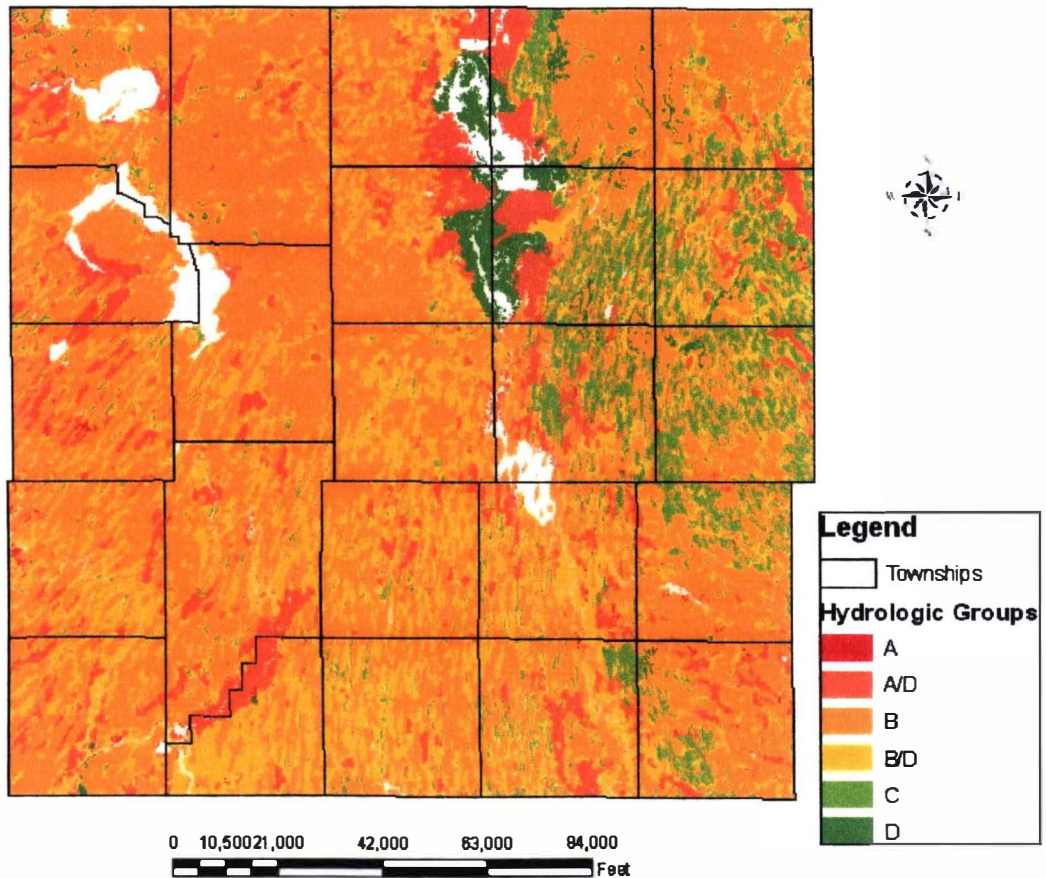
Figure 8. Soil hydrologic groups in Dodge County, Wisconsin

- Shallow (the lowest value for depth of soil to bedrock in inches)
- Deep (the highest value for depth of soil to bedrock in inches)
- PERML (the lowest value for the soils permeability rate in in./hour)
- PERMH (the highest value for the soils permeability rate in in./hour)
- Agri (ratio of agricultural land to total land cover)
- Other (ratio of barren and shrub land to total land cover)
- Forest (ratio of forest land to total land cover)
- ForttoAg (ratio of forest land to agricultural land)
- Grass (ratio of grassland to total land cover)
- Urban (ratio of urban land to total land cover)
- Wetland (ratio of wetland to total land cover)
- HydricA (ratio of soil hydrologic group A to total soil hydrologic groups)
- HydricAD (ratio of soil hydrologic group AD to total soil hydrologic groups)
- HydricB (ratio of soil hydrologic group B to total soil hydrologic groups)
- HydricBD (ratio of soil hydrologic group BD to total soil hydrologic groups)
- HydricC (ratio of soil hydrologic group C to total soil hydrologic groups)
- HydricD (ratio of soil hydrologic group D to total soil hydrologic groups)

The significance level that will be used is 0.05 and will be one-tailed.

Trend Surface Analysis

The independent variables and the dependent variables were first run through descriptive statistics to get a basic understanding of the variables (mean and standard deviation). Trend surface analysis was then applied:

$$Y(s) = x^T(s)\beta + \epsilon(s) \tag{1}$$

where $Y(s)$ is the random variable from the analysis at point s, $x^T(s)\beta$ (β is the coefficient) is the trend, and $\epsilon(s)$ which is the zero mean random variable that calculates for variance in the trend. The significance level from the output was then analyzed and any insignificant independent variable was excluded ($\alpha \geq 0.10$). After all the non significant variables were taken out, the trend surface analysis was run once more, this time saving the unstandardized residuals.

Kriging

The data from the trend suface analysis is first brought in, with the X and Y coordinates as the X and Y values and the unstandardized residuals being the Z values, and put into a semi-variogram. The semi-variogram used in the analysis was a spherical semi-variogram model. The spherical semi-variogram was used because it explains change in variation in an elliptical area the best (Webster and Oliver, 2001).

The semi-variogram then served as the basis for the kriging model. The kriging model:

$$\sum_{J=1}^{N} \lambda_i \, \gamma(X_i, X_j) + \Psi(X_0) = \gamma(X_j, X_o), \text{ for all } j$$

$$\sum \lambda_i = 1 \tag{3}$$

where $\gamma(X_i, X_j)$ is the semi-variance of Z between X_i and X_j, $\gamma(X_j, X_o)$ is the semi variance between X_j and X_o, $\Psi(X_0)$ is the Lagrange multiplier, and λ_i is the weights, was applied using all 1,016 well points. The results from the ordinary kriging model were then mapped out. The residuals from the trend surface analysis were also mapped out to show the spatial distribution of error in the kriging model. The purpose of this was to show which areas had overestimated, underestimated, or exactly predicted nitrate levels compared to the observed nitrate levels.

Cross-Validation

To check the fit of the ordinary kriging model, the technique of cross-validation was used. During the kriging process twenty percent of the wells were randomly chosen and used to validate the kriging model. The estimated nitrate levels derived from the

kriging were then run through Pearson's correlation with the observed nitrate values of the wells. The results were then used to validate the kriging model.

Hypothesis

One of the main purposes of this thesis is to find which independent variables explain nitrate levels across Dodge County, Wisconsin. The null hypothesis is that for each independent variable there is no relationship between it and the nitrate levels. The alternative hypothesis is that the land cover/land use and aquifer characteristics affect the nitrate levels of groundwater in Dodge County, Wisconsin. Each individual independent variable has its own hypothesis:

H_0: DepWELL=0 or H_a: there is a relationship between DepWell and NO3
H_0: Shallow=0 or H_a: there is a relationship between shallow and NO3
H_0: Deep=0 or H_a: there is a relationship between Deet and NO3
H_0: X=0 or H_a: there is a relationship between X and NO3
H_0: Y=0 or H_a: there is a relationship between Y and NO3
H_0: X^2=0 or H_a: there is a relationship between X^2 and NO3
H_0: Y^2=0 or H_a: there is a relationship between Y^2 and NO3
H_0: X*Y=0 or H_a: there is a relationship between X*Y and NO3
H_0: PERML=0 or H_a: there is a relationship between PERML and NO3
H_0: PERMH=0 or H_a: there is a relationship between PERMH and NO3
H_0: Agri=0 or H_a: there is a relationship between Agri and NO3
H_0: Other=0 or H_a: there is a relationship between Other and NO3
H_0: Forest=0 or H_a: there is a relationship between Forest and NO3
H_0: ForttoAg = 0 or H_a: there is a relationship between ForttoAg and NO3
H_0: Grass=0 or H_a: there is a relationship between Grass and NO3
H_0: Urban=0 or H_a: there is a relationship between Urban and NO3
H_0: Wetland=0 or H_a: there is a relationship between Wetland and NO3
H_0: Water=0 or H_a: there is a relationship between Water and NO3
H_0: HydricA=0 or H_a: there is a relationship between HydricA and NO3
H_0: HydricAD=0 or H_a: there is a relationship between HydricAD and NO3
H_0: HydricB=0 or H_a: there is a relationship between HydricB and NO3
H_0: HydricBD=0 or H_a: there is a relationship between HydricBD and NO3
H_0: HydricC=0 or H_a: there is a relationship between HydricC and NO3
H_0: HydricD=0 or H_a: there is a relationship between HydricD and NO3.

The null hypothesis for the kriging model is that the estimated spatial distribution of nitrate levels is not representing the observed nitrate levels in the study area. The

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alternative is that the estimated spatial distribution correlates to the observed nitrate levels in Dodge County, Wisconsin.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter discusses the results of the trend surface analysis and kriging models. The trend surface analysis will be examined first in groundwater nitrate levels. Relationships between the independent variables and nitrate concentrations along with the overall significance of the trend surface analysis will be examined and discussed. The kriging model will then be examined. The semi-variogram's and cross-validation's relationship to the kriging model will be analyzed subsequently.

Statistical Summaries

Trend Surface Analysis

The descriptive statistics of nitrate levels shows that the mean NO3 level is 2.7 mg/L at the county level, with a standard deviation of 4.5 mg/L (Table 1). While the mean nitrate level in the entire county is below the 3 mg/L threshold level (natural background level), a standard deviation of 4.5 mg/L suggests that in certain areas nitrates exceed 3 mg/L.

The preliminary trend surface analysis model had an adjusted R square of 0.136, indicating that 13.6 percent of the variation in NO3 can be explained by the independent variables (Table 2). The ANOVA test in the trend surface analysis indicates that the model is significant ($\alpha= 0.000$; F= 8.606) (Table 3). The variables, X, X*Y, PERML, PERMH, Forest, ForttoAg, Grass, Wetland, HydricA, HydricBD, HydricC, and HydricD are not significant at the 0.05 level (Table 4). The variables, shallow, deep, Urban, and HydricAD were not considered significant at the 0.05 level but were kept in for further analysis because their value was relatively close to the 0.05 significance level. The

variables X^2, Water, and HydricB were removed from the analysis because their

tolerance levels indicated that there was multicollinearity (Table 5).

Table 1. Descriptive statistics of nitrate concentration and independent variables in Dodge County, Wisconsin

	Mean	Std. Deviation
NO3	2.713 mg/L	4.5109 mg/L
DepWELL	160.78 ft.	88.989 ft.
X	625698.972	14120.628
Y	327845.923	13528.449
X^2	391698399317.631	17666063759.976
Y^2	107665788434.630	8854274711.166
X*Y	205125368123.201	9508193035.416
shallow	58.99 in.	6.576 in.
deep	59.38 in.	4.302 in.
PERML	.96 in./hr	.230 in./hr
PERMH	2.21 in./hr	1.039 in./hr
Agri*	.66588	.167274
Other*	.02209	.022477
Forest*	.04485	.043201
ForttoAg**	.18746	2.096299
Grass*	.11147	.057976
Urban*	.02	.051
Wetland*	.1071	.10291
Water*	.03	.105
HydricA***	.00115	.005413
HydricAD***	.06	.083
HydricB***	.69449	.196723
HydricBD***	.16308	.127799
HydricC***	.08	.139
HydricD***	.01	.027

*= ratio of land use/land cover type to total land use/land cover in 805 m radius
**= ratio of forest to agricultural lands in 805 m radius
***=ratio of soil hydrologic group to total hydrologic groups in 805 m radius

Table 2. Summary of the trend surface analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.392(a)	.154	.136	4.1928

a Predictors: (Constant), HydricD, HydricA, Agri, X, HydricC, Other, HydricBD, shallow, PERML, ForttoAg, HydricAD, DepWELL, Y, Forest, Urban, PERMH, Grass, Wetland, deep, X*Y, Y^2

Table 3. ANOVA of the trend surface analysis

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3177.062	21	151.289	8.606	.000(a)
	Residual	17456.236	993	17.579		
	Total	20633.299	1014			

a Predictors: (Constant), HydricD, HydricA, Agri, X, HydricC, Other, HydricBD, shallow, PERML, ForttoAg, HydricAD, DepWELL, Y, Forest, Urban, PERMH, Grass, Wetland, deep, X*Y, Y^2

b Dependent Variable: NO3

Table 4. Coefficients of the trend surface analysis

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	563.457	163.368		3.449	.001		
	DepWELL	-.008	.002	-.158	-5.000	.000	.849	1.178
	X	.000	.000	.181	.254	.800	.002	597.686
	Y	-.004	.001	-10.917	-5.492	.000	.000	4638.026
	Y^2	.000	.000	11.411	7.377	.000	.000	2808.172
	X*Y	.000	.000	-.356	-.243	.808	.000	2531.893
	shallow	-.152	.081	-.221	-1.866	.062	.061	16.458
	deep	.211	.126	.201	1.668	.096	.059	17.013
	PERML	-.468	.707	-.024	-.662	.508	.656	1.523
	PERMH	-.144	.163	-.033	-.883	.377	.602	1.662
	Agri	5.072	1.528	.188	3.319	.001	.265	3.770
	Other	18.429	6.176	.092	2.984	.003	.900	1.111
	Forest	4.433	3.851	.042	1.151	.250	.626	1.596
	ForttoAg	.023	.070	.011	.326	.745	.813	1.230
	Grass	1.876	2.966	.024	.633	.527	.586	1.706
	Urban	5.805	3.421	.066	1.697	.090	.560	1.785
	Wetland	-1.109	2.026	-.025	-.547	.584	.399	2.508
	HydricA	-3.276	24.815	-.004	-.132	.895	.961	1.041
	HydricAD	-2.796	1.758	-.051	-1.591	.112	.814	1.229
	HydricBD	-1.488	1.087	-.042	-1.368	.172	.898	1.113
	HydricC	-.293	.968	-.009	-.303	.762	.954	1.048
	HydricD	3.974	5.272	.024	.754	.451	.868	1.152

a Dependent Variable: NO3

Table 5. Excluded variables of the trend surface analysis

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		Minimum Tolerance
						Tolerance	VIF	
1	X^2	6.706(a)	2.095	.036	.066	.000	12068.748	.000
	Water	8.877(a)	1.964	.050	.062	.000	24045.465	.000
	HydricB	-14.673(a)	-1.316	.188	-.042	.000	145915.470	.000

a Predictors in the Model: (Constant), HydricD, HydricA, Agri, X, HydricC, Other, HydricBD, shallow, PERML, ForttoAg, HydricAD, DepWELL, Y, Forest, Urban, PERMH, Grass, Wetland, deep, X*Y, Y^2
b Dependent Variable: NO3

The purpose of the preliminary trend surface analysis was to find which variables were significant. Variables that were not significant were removed in order to run a refined trend surface analysis. Variables were also removed from the model if they were not within the tolerance. The independent variables, DepWELL, Y, Y^2, shallow, deep, Agri, Other, Urban, and HydricAD were all kept for analysis in the refined trend surface analysis model because they were significant or borderline significant.

After analysis of the first trend surface model, a second or refined trend surface analysis model was run with only the significant variables. In the refined analysis, the adjusted R square of 0.140 translates to 14.0 percent of the variation in NO3 (Table 6). The reduction in adjusted R square from the preliminary trend surface analysis can be associated with the removal of the insignificant variables (Table 7). In the refined model, the variables, shallow, deep, Urban, and HydricAD stay within the range of significance (Table 8).

Table 6. Summary of the refined trend surface analysis model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.385(a)	.148	.140	4.1822

a Predictors: (Constant), HydricAD, Urban, deep, Other, DepWELL, Y, Agri, shallow, Y^2
b Dependent Variable: NO3

Table 7. ANOVA of the refined trend surface analysis

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3055.361	9	339.485	19.410	.000(a)
	Residual	17577.938	1005	17.490		
	Total	20633.299	1014			

a Predictors: (Constant), HydricAD, Urban, deep, Other, DepWELL, Y, Agri, shallow, Y^2
b Dependent Variable: NO3

Table 8. Coefficients of the refined trend surface analysis

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	606.025	82.001		7.390	.000		
	DepWELL	-.008	.002	-.151	-5.003	.000	.929	1.077
	Y	-.004	.001	-11.364	-7.530	.000	.000	2686.583
	Y^2	.000	.000	11.536	7.641	.000	.000	2689.344
	shallow	-.169	.077	-.247	-2.208	.027	.068	14.725
	deep	.233	.117	.222	1.992	.047	.068	14.702
	Agri	4.803	.925	.178	5.192	.000	.720	1.388
	Other	17.513	5.964	.087	2.937	.003	.960	1.042
	Urban	5.933	2.922	.068	2.030	.043	.764	1.309
	HydricAD	-.001	.001	-.062	-2.025	.043	.904	1.106

a Dependent Variable: NO3

The results from the refined trend surface analysis showed that the independent variables, DepWELL, Y, shallow, and Hydric AD all have a negative relationship with NO3. This means that with the increasing well depth, Y coordinate, depth of shallow soils (soils that lay directly on outcropped bedrock), and soil hydrologic group AD, the nitrate level decreased. There was a positive relationship with nitrates and the independent variables, deep, Y^2, Agri, Other, and Urban. That is nitrate levels increased with the increasing depth of deep soils (soils that lay over glacial till), Y squared coordinate, ratio of agricultural land, ratio of barren and shrub land, and ratio of urban land. The variables Y^2 and Y, with t-test values of 7.641 and -7.530 respectively,

were the most significant variables in influencing nitrate levels. HydricAD is the least significant variable to influence nitrates with a t-test value of -2.025.

Kriging Analysis

The residuals from the trend surface analysis were then used to fit the sill, nugget, and range of the semi-variogram. Using the spherical semi-variogram a sill of 8.5, a nugget of 7, and a range of 1,500 m were determined through analysis of the semi-variogram (Figure 9). The range of the semi-variogram shows that nitrate levels are spatially correlated (spatially related) within 1,500 meters or almost 1 mile (Figure 9). The anisotropy angle was 0 and the anisotropy ratio was 1 for the spherical semi-variogram model. The newly determined sill, nugget, and range values were used to setup the semi-variogram model that was used by the kriging analysis. The spatial distributions of estimated nitrate values, coming from the kriging model, were shown in Figure 10.

The results from the kriging model show that there are high nitrate levels in the northern part of Dodge County, Wisconsin. In the northern part of the county the northwest and northeast corners have the highest nitrate levels. The region northeast of Beaver Dam Lake is also an area of concern for nitrate contamination because of the high nitrate levels there. Across the county as a whole the range of estimated nitrate levels range from 0 mg/L in the rock river valley south of Lake Sinissippi to 8 mg/L in the northwest corner of the county. There is some minor edge effect occurring in the kriging model

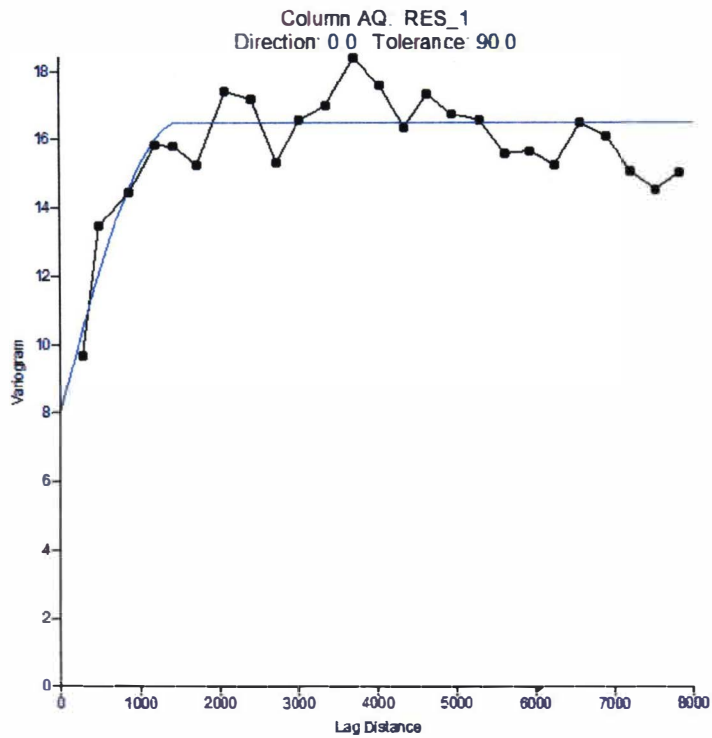Figure 11 shows the spatial error occurring in the kriging model.

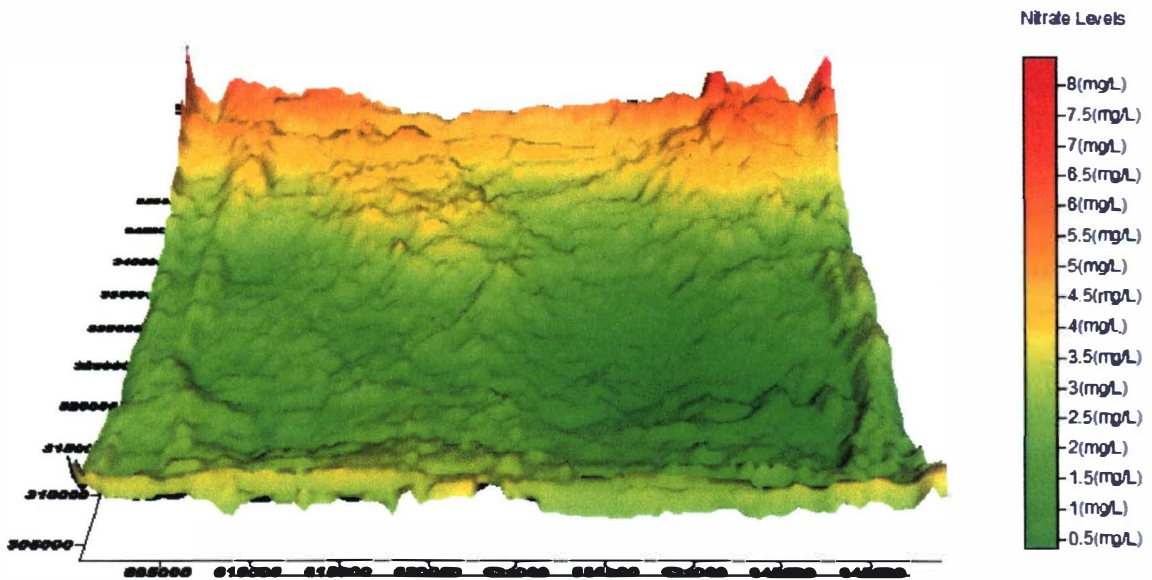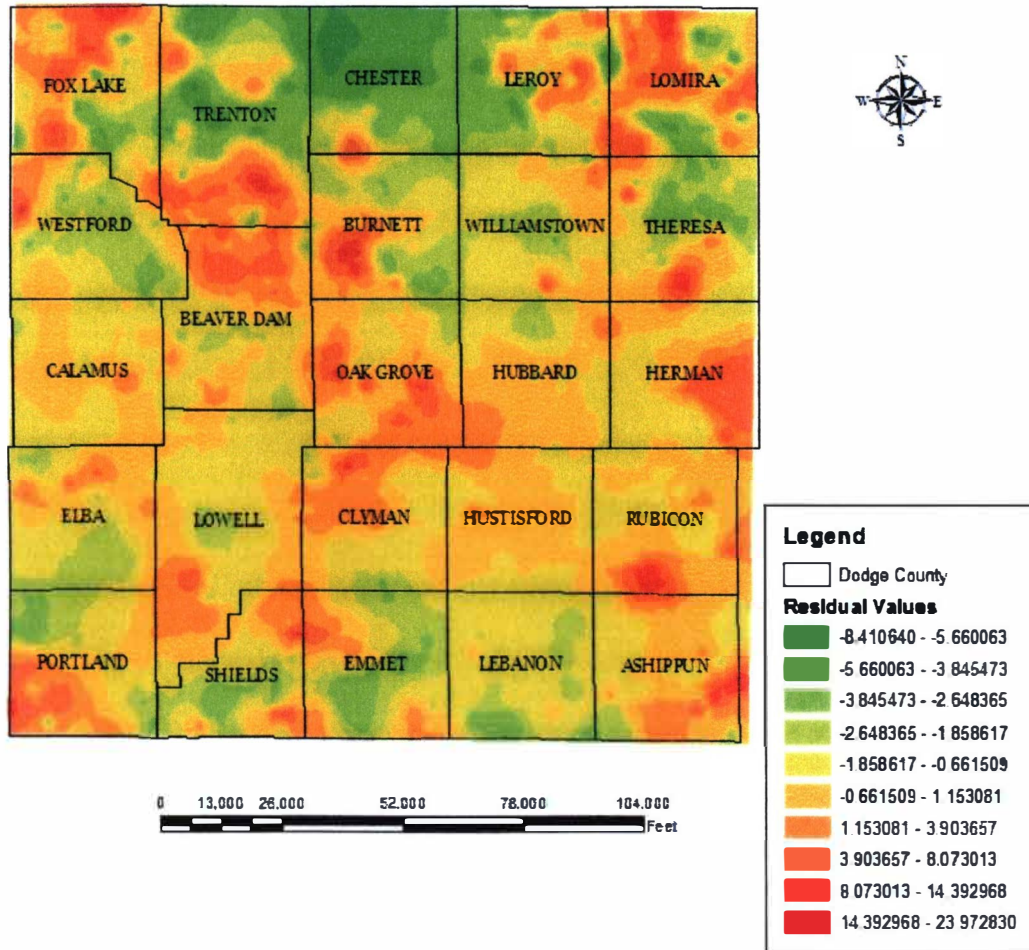Figure 9. Semi-variogram of the trend surface analysis residuals

Figure 10. 3-Dimensional map of estimated nitrate levels

Figure 11. Over and under estimation of nitrate values in Dodge County, Wisconsin

This map is derived from the residuals (observed minus estimated values) of the trend surface analysis. Residuals with a negative value are overestimated while the residuals with a positive value are underestimated. Figure 11 shows that the majority of the residuals fall in the -3 to 3 mg/L range. This means that the estimated values are not that far off the observed values. However, there are regions on the map where nitrate levels are underestimated by as much as 24 mg/L. In the northern zone of high nitrates in Dodge County the Horicon Marsh Area is highly overestimated. This could come from the lack of well samples in Horicon Marsh. In the three regions of highest nitrate values located in the northern zone there is a gross underestimation of the nitrate values. This means that actual nitrate levels are higher than what is estimated.

Cross-Validation Analysis

In order to cross-validate the results, 203 wells were randomly chosen from the 1,016 wells. The cross-validation results show that there is a significant correlation between the estimated nitrate values and the observed nitrate values. The Pearson's correlation shows that the two variables are highly correlated with values of 0.932 (Table 9). This strong correlation between the estimated nitrate values and observed nitrate values validates the kriging model.

Table 9. Correlation of estimated nitrate values and observed nitrate levels

		Predicted	Observed NO3
Estimated	Pearson Correlation	1	.932(**)
	Sig. (2-tailed)	.	.000
	N	203	203
Observed NO3	Pearson Correlation	.932(**)	1
	Sig. (2-tailed)	.000	.
	N	203	203

** Correlation is significant at the 0.01 level (2-tailed).

The scatterplot (Figure 12) shows that the estimated nitrate values and observed nitrate values are mostly linear and directly related. In the cross-validation scatterplot it is noticeable that there are a large number of wells with nitrate levels at or near 0 mg/L.
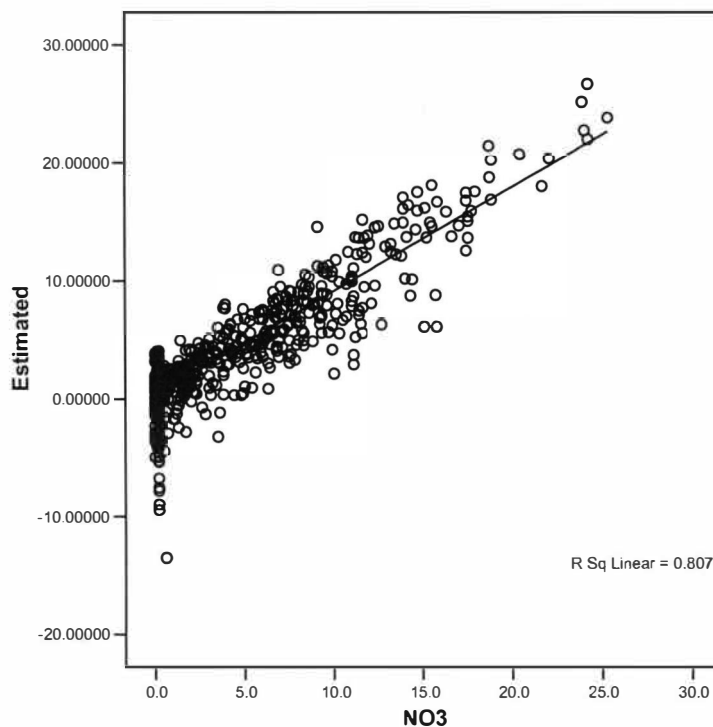
Figure 12. Scatterplot of estimated nitrate values and observed nitrate values

The cross-validation results show that the kriging model is an excellent method for estimating spatial distribution of nitrates in Dodge County, Wisconsin.

Interpretation

Trend Surface Analysis

The trend surface analysis indicated that the variable, depth of well had a negative relationship with nitrate levels. This is very understandable because nitrates close to the surface have just entered the soil and have not had a chance to be diluted. As nitrates percolate downward, deeper into the aquifer, they become diluted. This diluting of

nitrates is what gives deeper wells lower values, while the undiluted near surface nitrates give the shallow wells higher nitrate values.

Shallow soils have a negative relationship with nitrate levels. The majority of the shallow soils are located in the northwest and northeast corner of the county. There is a total of 9,114 acres of shallow soils covering 1.5 percent of the county. Most shallow soils are around 20 in. thick, and underlined by outcropped bedrock. In Dodge County most shallow soils are located on or near the Niagara Escarpment that runs through the eastern part of the county, with the Silurian Dolomite actually exposed in Northeastern Dodge County. The Silurian Dolomite associated with shallow soil, especially the physically and chemically weathered and exposed dolomite, allows for easy percolation of contaminated water into the shallow aquifer. This "super highway" allows for nitrates to enter the shallow aquifer and raise nitrate levels more readily. As the dolomite bedrock gets deeper under the soil the "super highway" gets cutoff, which makes nitrate percolation downward more arduous.

Deep soils have a positive relationship with nitrates levels. Deep soils are 60+ in. thick and are related to glacial till. Deep soils make up 98.5 percent of the county. The glacial till is loosely sorted and composed of sand, gravel, and cobbles. Glacial till is highly permeable, which means that nitrates have an easy flow path downward. In some areas the A and B horizons may only be a foot thick, but the C horizon (weathered parent material) can go down for some distance, especially on the ground moraines. High nitrate levels in association with deep soils most likely occur in agricultural areas where top soil has been extensively eroded away from traditional agricultural practices (moldboard plowing). The lack of topsoil allows for easy nitrate access into the C

horizon. This especially holds true when these methods are applied to highly erodible steep sloped ground moraines.

The ratio of agricultural land has a positive relationship to nitrate levels. Agriculture is the third most significant variable overall and is the most significant of the land use/land cover types. Agricultural land is the major land use/land cover in Dodge County. It spreads out relatively even throughout the county. Manure and fertilizers are used in agricultural areas to increase crop productivity. Farmers often over fertilize their crops, this excess either runs off into streams or percolates downward unutilized by the crops they were meant for. This over saturation of manure and fertilizer creates heavy nitrate loads in the area of application. The unutilized nitrates coming from manure and/or fertilizer then contaminate the aquifer.

The variable, other, is the ratio of barren and shrub land that has a positive relationship with nitrates. Other makes up 1 percent of the total land area in Dodge County. Barren land makes up 5862 acres while shrub land only makes up 134 acres. Certain areas of barren land are related to shallow soils of the county. The barren land in these areas may be bare rock outcroppings of the Silurian Dolomite. Highways and roads also make up part of the barren land use/land cover. Shrub lands are associated with all types of land use/land cover. Shrub land is for the most part spread out throughout the county.

Urban land has a positive relationship with nitrate levels. Most nitrate contamination of groundwater in the urban areas is related to the over use of fertilizers by private landowners. Urban land area makes up only 3.5 percent of the total land area in Dodge County. Beaver Dam is the largest city in Dodge County. Only 1/3 of the City of

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Watertown and 1/2 of the City of Waupun are located in Dodge County. There are several small villages in Dodge County. The villages of Fox Lake, Kekoskee, Mayville, Brownsville, Lomira, Theresa, and the City of Waupun are located within the regions of high nitrate levels. Just like farmers, the residential landowner often over fertilizes their land. Fertilizer is often applied to lawns before growth of grass even begins. Instead of fertilizing the plants these nitrates are either washed down storm sewers or percolate down through the soil into the groundwater.

The soil hydrologic group AD has a negative relationship with nitrates. The major area of this soil group is in the Horicon Marsh area, and is associated with wetlands throughout the county. Soil hydrologic group AD consist of muck type soils. The negative relationship comes from the fact that its low permeability sequesters the nitrates in the soil. These soils have a high water table, which causes hydric conditions to occur in the soil. The hydric nature of this soil allows for denitrification of the soil to occur. This denitrification of the groundwater sharply reduces the level of nitrates.

Y coordinates are negatively related to nitrate levels while the Y squared coordinates are positively related to nitrate levels. However, Y coordinates and Y squared coordinates should be examined together. Y coordinate and Y squared coordinate are used to look at the quadratic relationship and bring out the curve-linear nature of the model. The Y coordinate represent lower value (southern) coordinates in Dodge County. The lower latitudes are associated with low nitrate levels in the southern part of the county. The southern part of the county is dominated by agricultural land use/land cover, but lacks shallow soils. The Y squared coordinate represents the higher latitude values in Dodge County. The Y squared coordinates are a second order function

of the Y latitudes used to show relation in the higher latitudes. The higher latitudes in Dodge County have high nitrate values associated with them. The high latitude areas of Dodge County contain the majority of the shallow soils.

Kriging Model and Cross-Validation

From the kriging map it is easily noticeable that nitrates levels are elevated in three regions (Figure 10). These regions are in the northwest corner, northeast corner, and northeast Beaver Dam Lake area in Dodge County. These three regions are located in the northern 1/3 of the county. The distribution shows that there is a north (high nitrate levels) to south (low nitrate levels) variation in the data, which explains why the Y coordinates and Y squared coordinates are the most significant variables in the trend surface analysis. These areas have shallow soils underlined with outcropped bedrock. The shallow soils act as "super highways" allowing for nitrate to easily percolate into the shallow aquifer. Agriculture is just as intensive in these areas as elsewhere in the county, but it is the shallow soils that amplify agricultural affects. A majority of the barren land areas are located in the northeast area and can be associated with bedrock outcroppings. These outcroppings also act as conduits for nitrate to easily percolate down into the shallow aquifer.

The city of Beaver Dam is located to the south of the northeast Beaver Dam Lake (Figure 1). This city does not affect the northeast Beaver Dam Lake region because groundwater flow moves southward towards the Beaver Dam River (Devaul *et al*. 1983). The villages of Lomira, Theresa, Mayville, Kesoskee, and Fox Lake are located in the center of these northeast and northwest contamination regions. There is a possibility that these villages and city could be contributing to the nitrate contamination through over use

of fertilizer by private landowners. The City of Waupun, which is situated near the Horicon Marsh, is also in an area of high nitrate levels. However, this part of the region has overestimated levels of nitrates and needs to be examined more precisely.

Examination of the spatial error in the kriging model garnered interesting results. In the three regions of high nitrate levels there is an underestimation by the kriging model of nitrate levels. This underestimation only emphasizes the need for conservation practices in these three regions. This underestimation is occurring because the model can not estimate the outlier nature of these three regions. There also is an extreme underestimation occurring in areas that were estimated to have relatively low levels of nitrates, especially in the southeastern part of Dodge County. This could be due to the fact that there are small outcropping of Silurian Dolomite in this region. The Horicon Marsh area is overestimated because of the lack of sample wells and denitrification occurring in the marsh itself. Most of the estimated nitrate values in Dodge County are within a -3 to 3 mg/L range of the observed. This supports the fact that the kriging model is a good model overall to predict nitrate levels.

The trend surface analysis, while only explaining 14 percent of the variation of nitrates, was able to identify key variables that affect how nitrates are distributed in Dodge County. The relationship these variables had with nitrates was visually displayed in the kriging map. Shallow soils appear to magnify the affect of the other variables. The kriging model was able to show three specific regions of nitrate concern in Northern Dodge County. In these three regions the model is underestimating nitrate levels. Overall it is the northern 1/3 of Dodge County that has the highest levels of nitrates. Through

cross-validation the kriging model was able to show that estimated values from the model correlated to the observed nitrate levels.

CHAPTER V

CONCLUSIONS

This study analyzed the impacts of land use/land cover and aquifer characteristics on nitrate contamination in Dodge County, Wisconsin. A total of 1,016 well logs, collected between 1990 and 2004, were used in the statistical analyses. Of the 1,016 wells, 9.65 percent of the wells sampled had nitrate levels at or above the MCL of 10 mg/L and 27.17 percent of the wells sampled had ≥ 3 mg/L of nitrate.

Trend surface analysis was used to analyze the relationship between land use/land cover, aquifer characteristics and nitrate levels in the groundwater. The trend surface analysis model only explained 14% of the variance in nitrate levels. This can be explained by the fact that trend surface analysis does not account for local variation. Instead it focuses on the universal variation in the entire study area. The 15 year time period that this research covers can also help in explaining the low percentage of variance. The difficulty lies in the fact that it is hard to represent change in land use/land cover and aquifer characteristics over the length of the study. The land use/land cover data came from a 1992 satellite image, while the well samples where collected at different periods with variations in sampling procedures (Wisconsin DNR 2006). The variables, depth of well, Y coordinate, shallow soils, and soil hydrologic group AD had a negative relationship with nitrate levels. Thus, as these variables increase, the nitrate levels decrease. While the variables, Y squared coordinate, urban, deep soils, agriculture, and barren and shrub land had a positive relationship with nitrate levels. This means as these variables increase, the nitrate levels also increase.

Application of the semi-variogram in the kriging model found that nitrate levels are spatially correlated over a range of 1,500 m. The 1,500 m radius came from the fact that the estimated nitrate levels have the strongest relationship to the observed nitrate levels within this range of 1,500 m. The level of correlation between the estimated nitrate levels and observed nitrate levels were 0.932. Outside of the 1,500 m radius there is no spatial correlation among observed and estimated nitrate levels. Land use/land cover and aquifer characteristics within the 1,500 m radius are mostly likely to affect nitrate levels in that well. The errors of the estimated nitrate values by the kriging model were in a range of -3 to 3 mg/L off the observed nitrate values.

The majority of high nitrate levels are located in the North, with Beaver Dam Lake area, Northwest, and Northeast corners. However, there was an underestimation of nitrate values by the kriging model in these three regions (Figure 11). The high nitrate levels are associated with shallow soils which have shallow depths to bedrock. These shallow soils cover 2.5 percent of the county and occur in these three regions. The land use/land cover class, other (1 percent of total land cover/land use) covers portions of these outcroppings.

The land use and land cover of these regions is mostly agriculture, which occurs in 74 percent of the county. Agriculture land use is occurring in areas of shallow bedrock, this may help in explaining why high nitrate levels are all located in these three regions. Urban areas make up 3.5 percent of the county. The villages of Fox Lake, Kekoskee, Mayville, Brownsville, Lomira, Theresa, and the City of Waupun are all located in the three high nitrate regions. Over use of fertilizers in the agricultural and urban areas may explain these high nitrate levels.

The Horicon marsh and other wetland regions in Dodge County are associated with soil hydrologic group AD. The marshes may act as a buffer to nitrate contamination because of the natural denitrification. Denitrification along with a lack of well samples taken attributes to the fact that wetland areas, especially the Horicon Marsh area, have nitrate levels that are overestimated by the kriging model (Figure 11). This means that the estimated values in the Horicon Marsh area are higher than what is actually observed.

Areas located in the middle part of the county southward are least affected by high nitrate levels. The middle part of the county had some of the smallest errors occurring in the kriging model. The middle and southern part of the county is also dominated by agricultural land. However, other land use/land covers spread out through most of this region. This region has thick layers (60+ in.) of glacial till. Deep soil, which make up 98.5 percent of the county, are the true dominate soil type in this region.

Areas of concern for nitrate contamination in Dodge County, Wisconsin are identified in Figure 13. It should be noted that the kriging model did not predict areas with nitrate levels at or above the EPA's 10 mg/L MCL. This is because of the fact that the three areas that had the highest nitrate levels have extreme values that are considered outliers compared to the rest of the well logs. That means that the values are so high that an appropriate estimate value can not be achieved through ordinary kriging methods. Areas of high risk are identified by nitrate levels in the 6-8 mg/L range. These areas were deemed high risk because that the levels are relatively close to the EPA's 10 mg/L MCL. The medium risk areas have nitrate levels in the 4-5 mg/L range. The medium risk was assigned to these levels because of the fact that there are anthropogenic factors causing

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the raised levels of nitrate. The low risk areas have nitrate levels in the 0-3 mg/L range and are well with in naturally occurring nitrate background level.

The townships of Fox Lake, Trenton, Chester, Leroy, and Lomira are most susceptible to nitrate contamination. Figure 13 shows that these townships have nitrate levels in the medium and high risk categories. The townships of Lomira and Fox Lake have the highest land area in the high risk category. Figure 13 shows a south to north trend as indicated by the variables Y coordinate and Y squared coordinate. It should be remembered that these variables should be looked at as a pair, because of their curve-linear relationship with nitrate levels. The Y squared coordinates explained the high nitrate levels in the north, while the Y coordinates indicate lower levels in the south. Table 10 shows that 15.71 percent or 90,454.81 acres are in areas of high risk or medium risk of nitrate contamination. The low risk area makes up 84.29 percent of the county, with 14.29 percent of the county made up of medium risk nitrate levels. Only 1 percent of the county contains nitrate levels in the high risk category.

The spatial patterns in Figure 13 can be used in administrating nutrient management plans and wellhead protection programs. Local and federal government official can use the map as a base for program implementation. They can focus first on areas that have the highest risk for nitrate contamination.
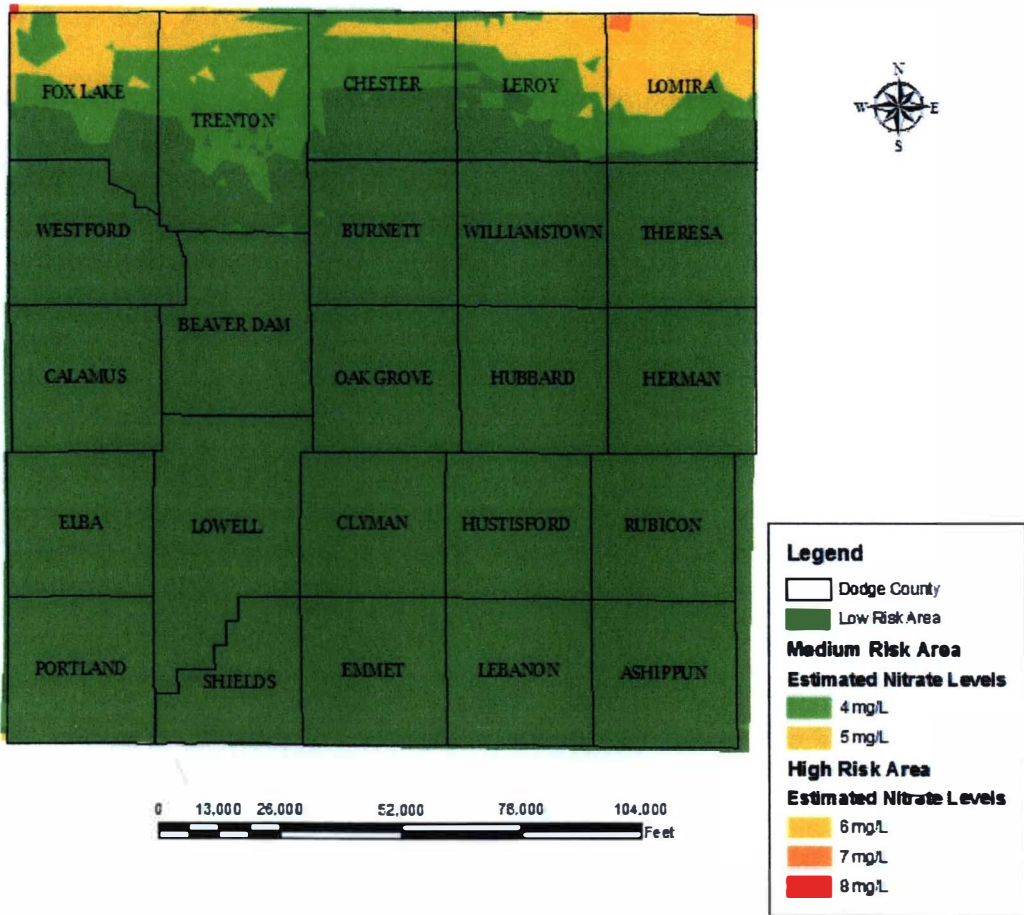
Figure 13. Areas of concern in Dodge County, Wisconsin

Table 10. Acreage and percentage of Dodge County acres in areas of concern

	High Risk Areas			Medium Risk Areas		
	8 mg/L	7 mg/L	6 mg/L	5 mg/L	4mg/L	Total
% of Total Acres	.01	0.13	1.28	5.04	9.25	15.71
Acres	59.78	739.22	7,364.76	29,023.39	53,267.66	90,454.81

Projects in areas of medium risk can be prioritized over low risk areas. At the township level individual landowner in areas of concern can be identified. Groundwater education programs can be focused towards the landowners so that they become aware of the dangers of nitrate contamination and conservation methods can be used to reduce nitrate contamination of the groundwater.

Limitation of Study

There are several limitations to the study that must be noted. The first limitation is that there were only 1,016 useable well logs available in this study. That is the equivalent of 1 well for every 567 acres or nearly 1 well for every square mile. Each of the 1,016 wells were only sampled once over the 15 year time period of this study. Lack of temporal sampling and variation in the sampling procedure made the trend analysis difficult.

Another limitation that occurred in the study was the constraint that certain data had. Changes in variables, especially the land use/land cover data, can not be taken into account over the 15 year period of this study. This is because the land use/land cover data is from 1992. Any association of land use/land cover types before or after 1992 is a generalization because it does not account for change for that specific year. The permeability rates came from the soil that the well was dug in. Permeability rates were not looked at spatially across the 805 m radius like land cover and soil hydrologic groups. This is because it was thought that soil hydrologic groups would give a better explanation

across the range of the 805 m radius. A better understanding of permeability rates across the region for each well would have helped in determining the significance of permeability. The buffer size used in data analysis was predetermined to be 805 m in radius or 1,610 m in diameter to analyze township level influence on the variables. The use of larger or smaller buffers may have different influences on the relation of some variables with nitrate levels.

Management Suggestions

Nutrient management plan establishment is a major task in Wisconsin. Farmers in Wisconsin are mandated to have nutrient management plans for their farms by 2005 for high priority watershed and 2008 for all other areas (Wisconsin DNR 2004). The map of nitrate distribution produced in this study can be utilized by Dodge County in prioritizing implantation of management programs. In Dodge County this would be the northern 16 percent of the county. In other regions of the U.S. this method could also be used to illustrate areas of concern. Different variables may be needed based on data availability. The results from the model could be used in wellhead protection and best management practices techniques.

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