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Steven Douglas Chidester

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A STUDY OF AQUIFER SENSITIVITY AND VULNERABILITY IN KALAMAZOO COUNTY, MICHIGAN BASED ON HYDROGEOLOGIC AND AGRICULTURAL FACTORS

by

Steven Douglas Chidester

A Thesis
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Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Department of Geology

Western Michigan University
Kalamazoo, Michigan
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Completion of this thesis heralds the begining of my new life and career. There are many people who have helped me make this dream possible. I thank my parents for their financial, emotional, and inspirational support. I thank my sisters for letting me survive my childhood. I thank my friends for believing in me and for providing humor during all those cloudy Michigan days. I thank Connie Cousins-Leatherman at the Kalamazoo County Human Services Department for all her efforts in developing a very impressive water-well and environmental database. I thank Julie Scott in Computing Services for all her assistance in running the never-ending statistics. I thank Dr. John Grace for inspiring me to join this program. I thank my thesis committee members Dr. Alan Kehew and Dr. Michael Stoline for their guidance and understanding. Finally, I thank my advisor and mentor Dr. Richard Passero for his generous devotion of time and knowledge which provided the major impetus for my research.

Steven Douglas Chidester

A STUDY OF AQUIFER SENSITIVITY AND VULNERABILITY IN KALAMAZOO COUNTY, MICHIGAN BASED ON HYDROGEOLOGIC AND AGRICULTURAL FACTORS

Steven Douglas Chidester, M.S.

Western Michigan University, 1993

Groundwater in Kalamazoo County, Michigan has been impacted by human activities. This study presents a statistical method for predicting aquifer sensitivity/vulnerability within a glacio-hydrogeologic system.

Computerized data including 3620 water well records with partial chemical analyses, soil surveys, land use maps, and hydrogeologic reports were used to quantify aquifer parameters, nitrate-N contaminant concentrations, soil factors, and agricultural practices. Statistical analyses included simple t-tests , correlation, ANOVA, and multiple regression analyses.

The results indicate that there are statistically significant relationships between nitrate-N concentrations and depth of well submergence, well depth, clay thickness, partial clay thickness, land use, and soil slope. Two multiple regression models are presented, a general aquifer sensitivity model which uses only the hydrogeologic parameters, and an agricultural ground-water vulnerability model which incorporates agricultural land use and soil slope. Less than 10 % of the total variance in nitrate-N concentration was accounted for by these models.

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CHAPTER I

INTRODUCTION

Purpose

Ground water from the glacial drift which is utilized by industry, agriculture, and municipalities, is the sole source of drinking water for the residents of Kalamazoo County, Michigan. Glacial drift aquifers are vulnerable to contamination from surface sources and activities. The principal objective of this study is to identify factors that influence and predict aquifer sensitivity/vulnerability. The results may be used to (a) provide a basis for the Environmental Protection Agency's (EPA) mandated state pesticide management program, (b) provide data for the application, storage, and discharge of agricultural chemicals, (c) provide guidance for the storage and release of hazardous industrial chemicals, and (d) provide information for wellhead protection programs.

Description of Study Area

Kalamazoo County is located in southwestern Michigan (Figure 1). The county is a 24 by 24 mile (576 m^2) area. Maps of landuse in 1978 show that approximately 86% of the county was "undeveloped," including 40.3% agriculture, 39.3% vacant and wooded lands, 6.5% in lakes, rivers, and streams (WMU

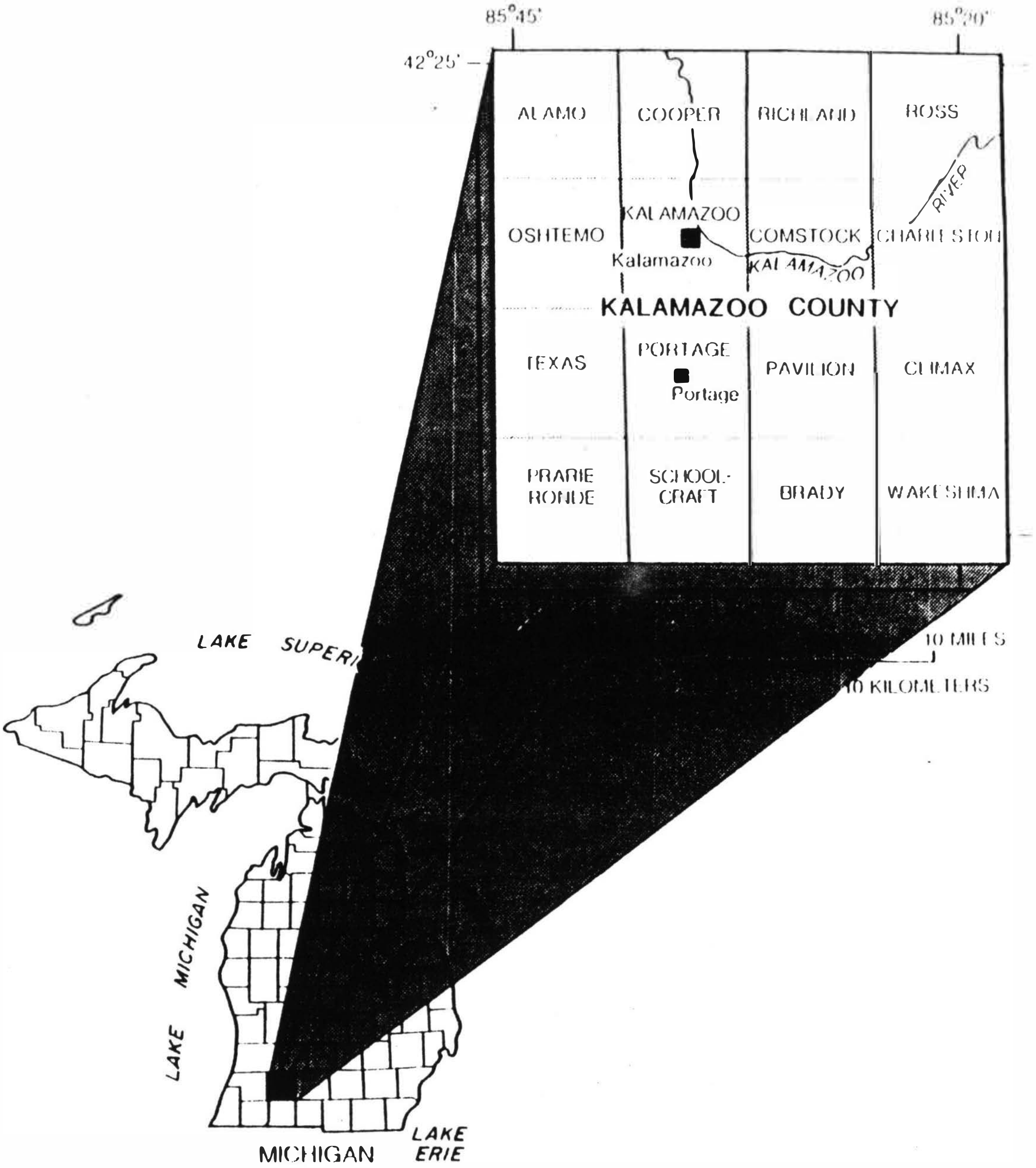


Figure 1. Map Showing Kalamazoo County Location.

Source: Rheaume, S. J., 1990, Geohydrology and water quality of Kalamazoo County, Michigan, 1986-88, U.S. Geological Survey Water-Resources Investigations Report 90-4028, p. 5.

Geography Department and Kalamazoo Co. Planning Commission, 1981). The remaining 14% of the county was composed of 6.6% residential, 3.4% roads, 2.0% industry, and 1.9% commercial and public service buildings and land.

The surface water of the county is included in three major drainage basins. The Kalamazoo River basin drains the northern two-thirds of the county, the southern portion is drained by the St Joseph River, and the westernmost part is drained by the Paw Paw River (Figure 2). All three basins drain to the west into Lake Michigan.

Hydrogeology

Kalamazoo County is characterized by thick glacial sediments which were deposited by two lobes of a late Wisconsian ice sheet. The Mississippian Coldwater Shale subcrops beneath these deposits in all but the northwestern corner of the county, where the Mississippian Marshall Sandstone subcrops beneath the drift (Figure 3). The glacial drift ranges in thickness from less than 50 feet in the northcentral portion of the county to approximately 600 feet in the northwestern part (Figure 4). The drift tends to be the thickest where moraines overlie bedrock valleys and thinnest where till plains overlie bedrock uplands. Eight distinct glacial landforms have been mapped in Kalamazoo county; the Alamo plain, Kalamazoo moraine, Tekonsha moraine, the fan complex between the Kalamazoo and Tekonsha moraines, the Climax-Scotts outwash plain, the Richland moraine, the Wakeshma till plain, and the Kalamazoo River Valley (Figure 5). The first four features were

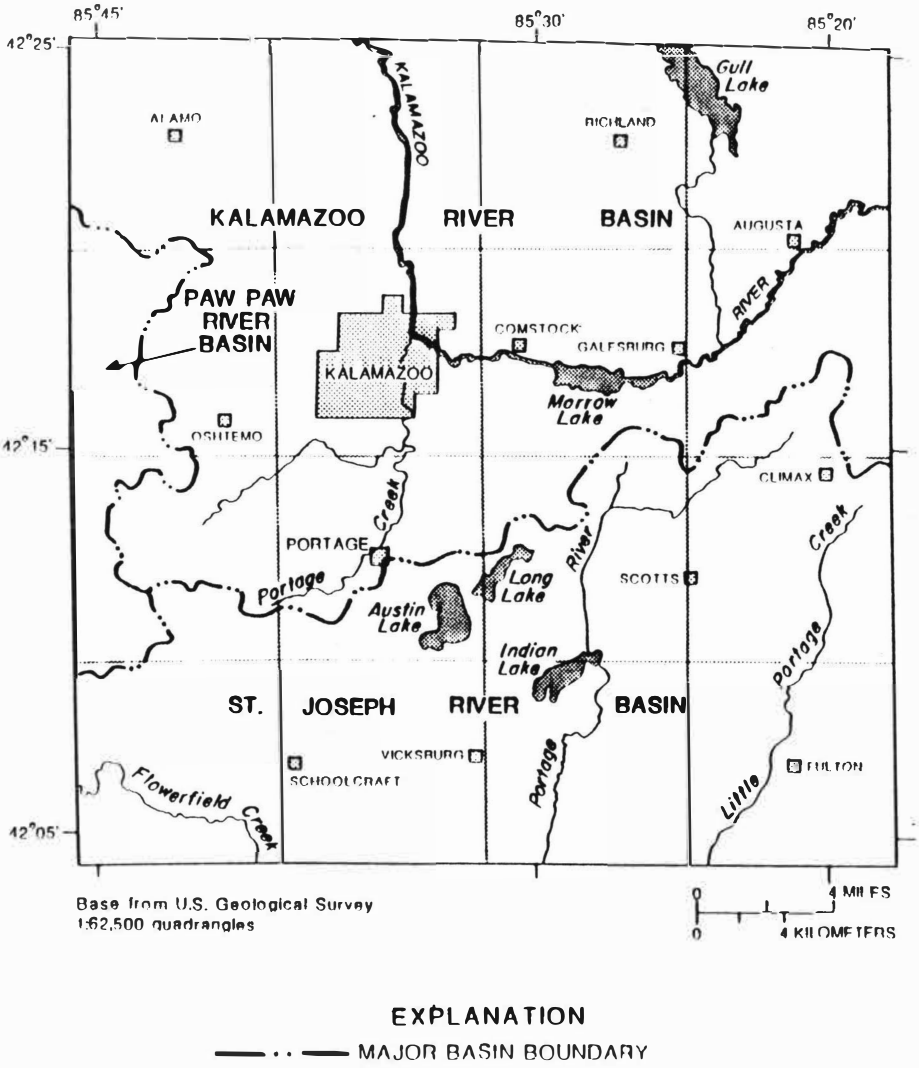


Figure 2. Major Surface-water Drainage Basins in Kalamazoo County.

Source: Rheaume, S. J., 1990, Geohydrology and water quality of Kalamazoo County, Michigan, 1986-88, U.S. Geological Survey Water-Resources Investigations Report 90-4028, p. 8.

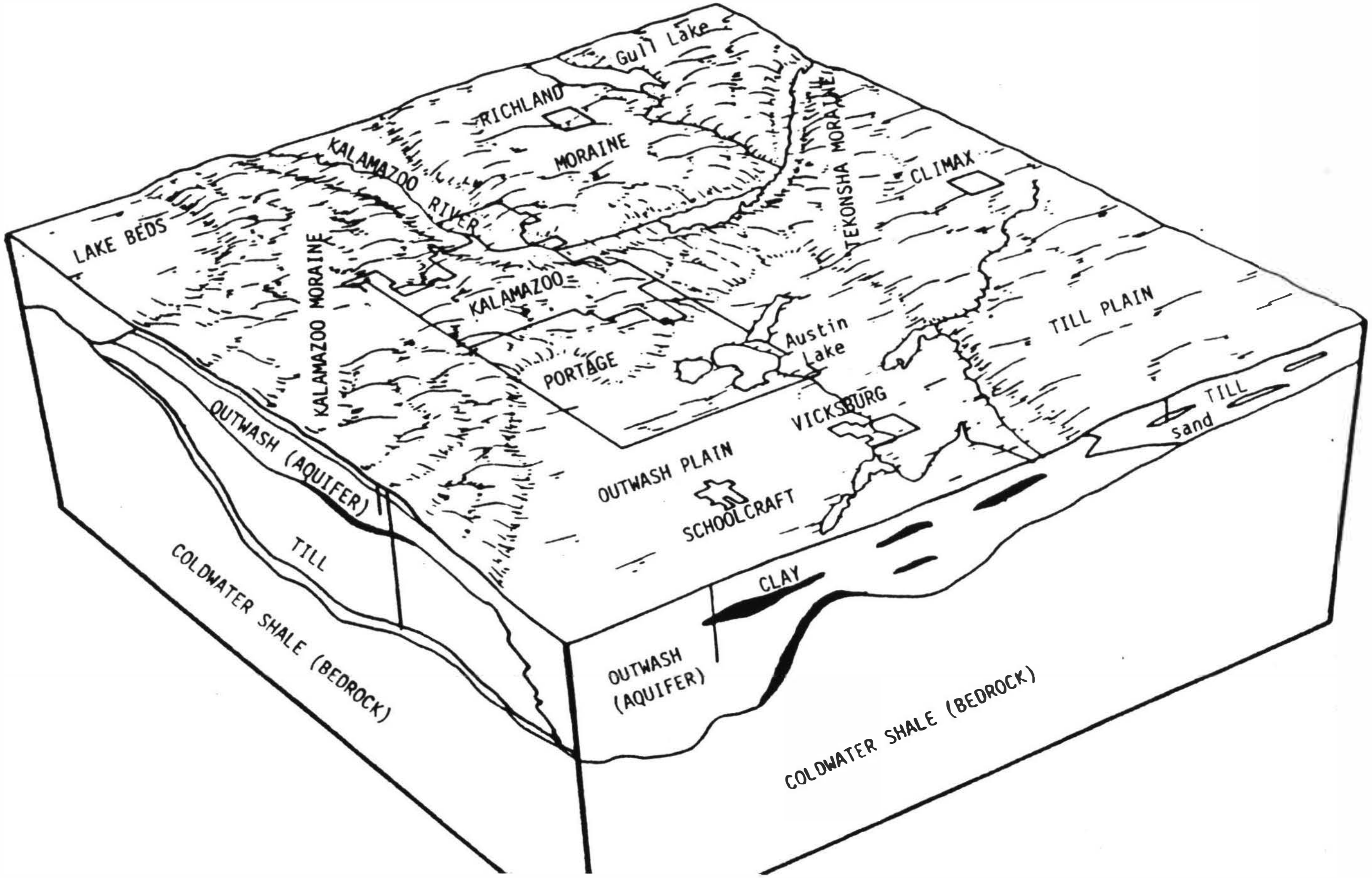


Figure 3. Map Showing the Landscape, Bedrock, and Major Aquifer Types in Kalamazoo County Viewed From the Southwest.

Source: Passero, 1989, Geology and Groundwater of Kalamazoo County, Michigan: Kalamazoo, MI, Western Michigan University Department of Geology, p. 16.

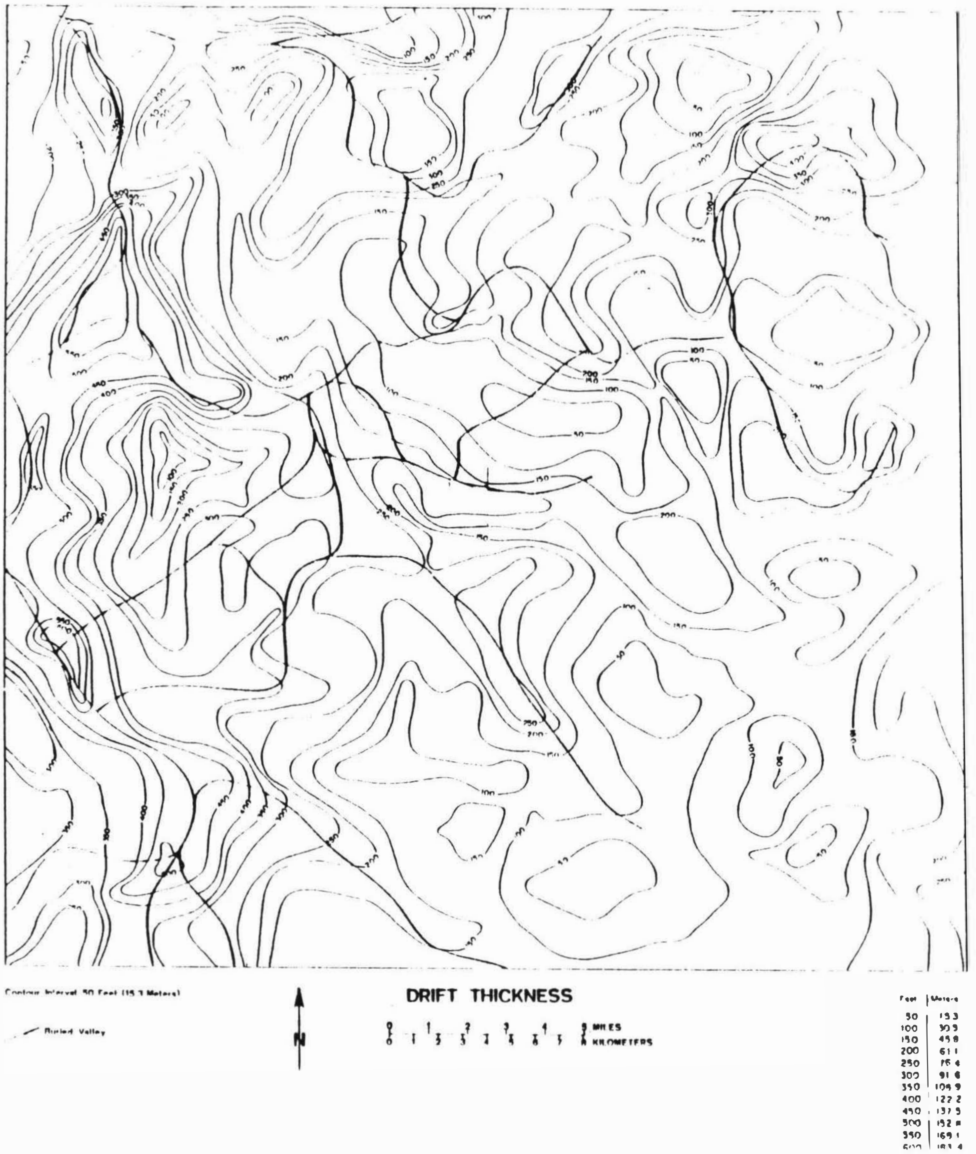
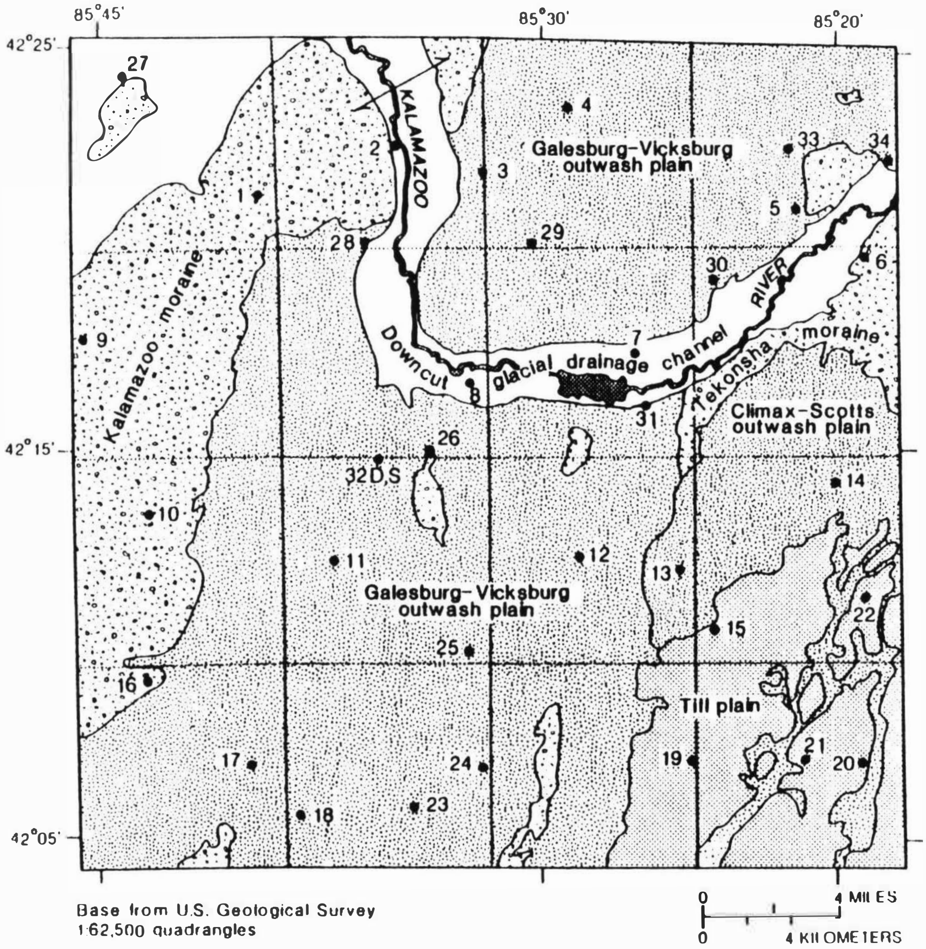


Figure 4. Map Showing the Glacial Drift Thickness in Kalamazoo County.

Source: Passero, R. N., (ed.), 1978, Kalamazoo County--Geology and the Environment: Kalamazoo, MI, Western Michigan University Department of Geology, p. 18.



Base from U.S. Geological Survey
1:62,500 quadrangles

Modified from G. Monaghan and G. Larson,
County Geologic Map Series -
Kalamazoo, 1983

Figure 5. Map Showing Kalamazoo County Glacial Landforms.

Source: Rheaume, S. J., 1990, Geohydrology and water quality of Kalamazoo County, Michigan, 1986-88, U.S. Geological Survey Water-Resources Investigations Report 90-4028, p. 15.

recently characterized in detail by Straw, Passero, and Kehew (1992) as a hydrogeologic glacial outwash fan facies.

The Alamo plain is a lowland feature underlain by lacustrine sediments deposited by glacial meltwater alternately flowing and ponded between the retreating Lake Michigan Lobe and the proximal margin of the Kalamazoo Moraine. This area is characterized by extensive muck, Holocene marl, and thin discontinuous silt and clay deposits.

The Kalamazoo Moraine was formed during a temporary halt in the retreat of the Lake Michigan Lobe. It is underlain generally by three sequences: an uppermost sequence of thin till layers interbedded with glaciofluvial deposits, a relatively thick till with a coarse upper facies and a fine-grained lower facies, and a thin layer of coarse outwash.

The Tekonsha Moraine represents the furthest eastward advance of the Lake Michigan Lobe. Most of the moraine is covered with outwash deposits from the ice that later stood at the Kalamazoo Moraine. The northernmost portion of the Tekonsha Moraine is present at the surface where the Lake Michigan lobe came to rest against a broad bedrock high. The moraine contains a thick (150') till core with up to 30 feet of overlying outwash sand.

The Climax-Scotts outwash plain lies to the south and east of the Tekonsha moraine. This unit is composed of medium to very coarse sand and gravel deposited by glacial meltwaters.

Three major glacial alluvial fans comprise a massive outwash deposit between the Kalamazoo and Tekonsha Moraines. These fans consist of sand and gravel deposits from streams flowing off the stagnant ice lobe that advanced from the west to the western and northern margins of the wasting Tekonsha ice mass. The Dry Prairie, Richland, and Prairie Ronde fans grade into each other in places but can be delineated on topographic maps.

The Richland Moraine is a complex unit formed from the combination of morainal material, outwash deposits, and alluvial fan deposits.

The Wakeshma Till Plain is located beyond the furthest advance of the Saginaw Lobe. This unit is comprised of primarily coarse sandy and cobbly till, with a surface marked by irregular drumlins.

The Kalamazoo River Valley is an erosional feature caused by the discharge of glacial meltwater from the east. The valley fill is composed of medium to very coarse sand and gravel with some isolated layers of clayey silt.

Depth to the water table has been considered an important parameter for the determination of aquifer vulnerability. Under contract by The Michigan Department of Agriculture, the WMU Institute for Water Sciences conducted a study of the reliability of using static water levels from well drillers' records to determine the depth to water table (Appendix A). The results showed that static water elevation maps generated from well drillers' records were very similar and consistent with the topography and drainage. A grid vs. data comparison was made between two groups of 882 randomly selected wells with ≤ 40 feet of submergence (the depth of the well screen below the water table) showed no more than 0.5 foot mean difference (standard deviation less than 14 feet). This small residual difference in means indicates that water well records are statistically reliable in producing potentiometric surface maps, and that the use of computerized water well records would rapidly provide a statistically reliable, first approximation of the regional water table.

The topographic and water table surfaces for Kalamazoo County are illustrated in Figure 6. Generally, groundwater flows from topographically high areas (the Kalamazoo, Richland, and Tekonsha Moraines) to low areas (the Alamo Plain, the Schoolcraft and Climax-Scotts outwash plains, the Wakeshma Till Plain, and the Kalamazoo River Valley). The depth-to-ground water contour map is shown in Figure 7. The greatest depths to water are generally found under the moraines and shallower depths to water are found under the outwash plains, the Kalamazoo River Valley, and the Wakeshma till plain. The greatest depth to water (230 feet) occurs beneath the Kalamazoo moraine, and the next greatest depth to water (125 feet) is found under the Richland moraine. In extreme cases up to 120 feet depth to water occurs under the Schoolcraft outwash plain and the Kalamazoo River Valley. The greatest depth to water under the Wakeshma till plain is approximately 55 feet.

Definition of Aquifer Sensitivity and Ground-Water Vulnerability

The U.S. Environmental Protection Agency is in the process of finalizing a

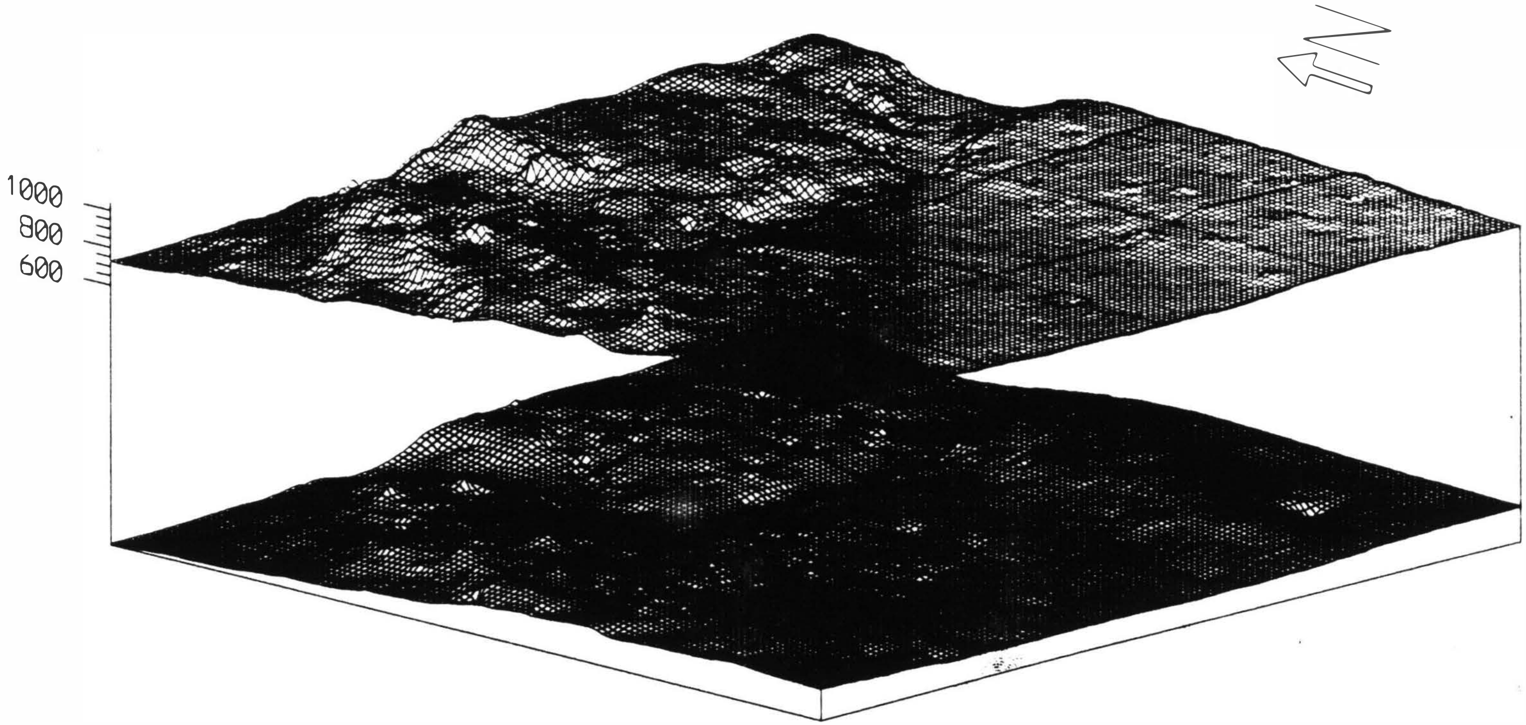
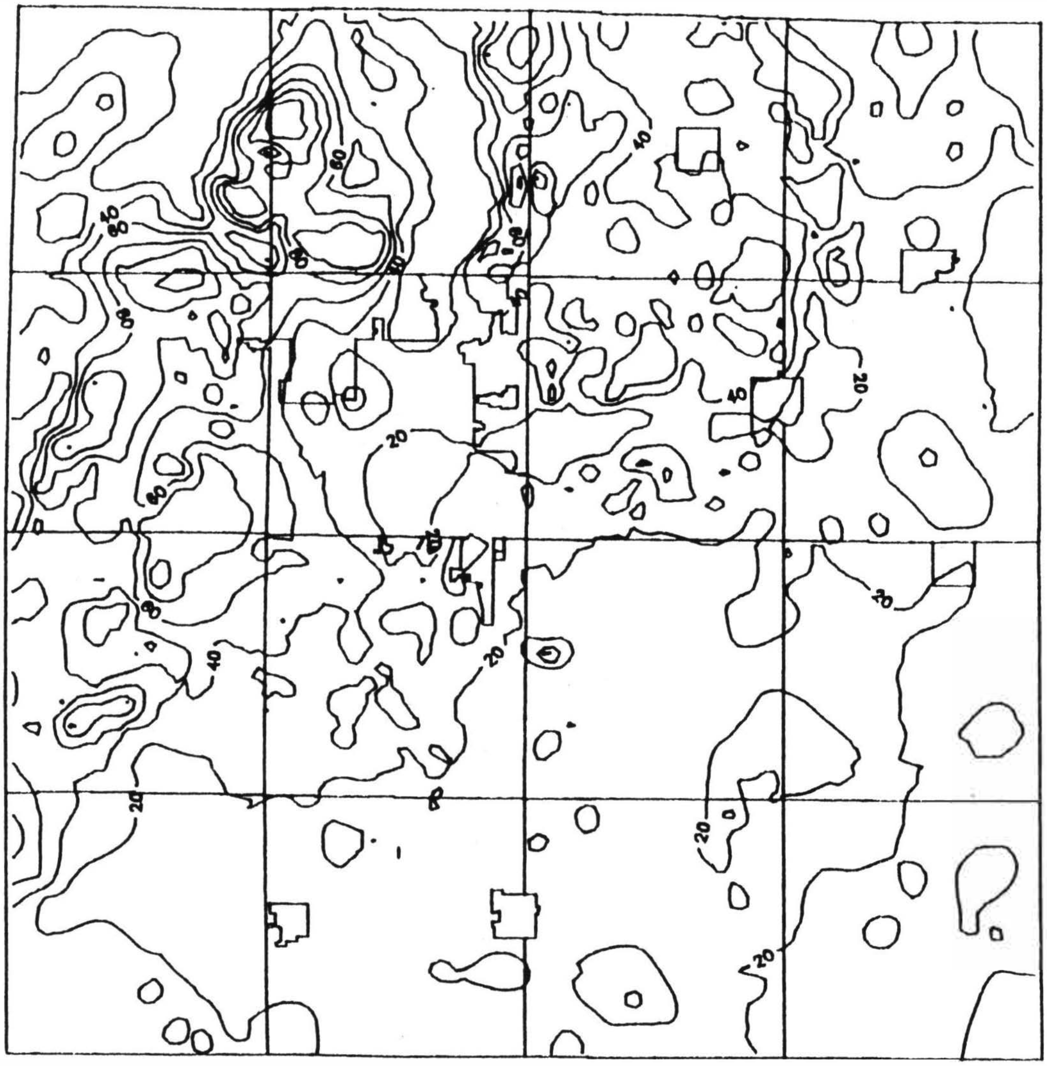


Figure 6. Map Showing the Topographic and Water Table Surface in Kalamazoo County Viewed From the Southwest.



C. I. = 20 feet

Figure 7. Map Showing Depth to Water Table in Kalamazoo County.

literature review of the assessment methods used to characterize aquifer sensitivity and ground-water vulnerability to pesticide contamination (USEPA, 1993). In general, the methods reviewed apply to any non-point source such as nitrate or chloride contamination. The EPA defines two broad categories of assessment methods, aquifer sensitivity and ground-water vulnerability. The EPA distinguishes between them by defining aquifer sensitivity as "the relative ease with which a contaminant applied on or near a land surface can migrate to the aquifer of interest." (USEPA, 1993, p.9) Aquifer sensitivity is a function of the intrinsic hydrogeologic characteristics of the soils and geologic materials which the contaminant passes through. Ground-water vulnerability is a measure of the aquifer sensitivity related to specific agronomic (or other) management practices and specific contaminant characteristics. Aquifer sensitivity assessment methods consider only hydrogeologic factors, and are classified as hydrogeologic setting classification methods or parameter weighting/scoring methods. The hydrogeologic setting classification method involves the identification, ranking, and subsequent mapping of the factors that control contaminant migration in a given area. The sensitivity within this area can then be read directly off the map. Parameter weighting/scoring methods involve the determination of an index or numerical score for a specific area which can then be compared with other areas.

Ground-water vulnerability assessment methods consider contaminant and management factors as well as hydrogeologic factors. These methods are classified as either contaminant loading methods (empirical models) or simulation models.

Empirical models include statistical models and leaching models. The statistical models may employ correlation analysis, regression analysis, or factor analysis to relate a dependant variable such as contaminant concentration to one or more independent variables. The leaching models relate the migration of contaminants to the physical and chemical properties of the soil or subsurface geology. In both cases, an empirical equation is derived which describes the movement of contaminants in a given physical setting. Simulation models are computer processed mathematical expressions which relate hydrogeologic processes to contaminant transport. The reliability of any method is highly dependant upon the selection of vulnerability factors, the choice of applicable weights or scores, and the user's interpretation of the results.

In this study, both a general and an agricultural model will be presented. Under the EPA definitions, the general model would be considered an aquifer sensitivity/scoring method, and the agricultural model would be a ground-water vulnerability/loading method. Statistical analyses including t-test comparisons, Pearson-r correlation coefficients, least squares analysis of variance, and stepwise multiple regression analyses will be used to develop both types of models.

CHAPTER II

LITERATURE REVIEW

Sources, Transport, and Attenuation of Nitrate-Nitrogen

The amount of nitrate-N found in the groundwater is determined by the source type and loading rate, nitrogen cycle transformations within the soil, transport through the zone of aeration, and transport through the zone of saturation (Figure 8). Agricultural research has largely focused on the soil zone. Much less research has been done on the fate of nitrate-N in the subsurface.

Nitrate-N in groundwater originates from both natural sources and human activities. Natural sources include precipitation carrying atmospheric nitrogen, dissolution of nitrate salts in geologic deposits, and the degradation of nitrogenous plant tissue (Bouchard, Williams, and Surampalli, 1992). Human activities such as septic waste disposal, industrial and food processing operations, and agricultural and livestock practices contribute significantly to the nitrate loading of ground water (Fedkiw, 1991; Lowrance, 1992; Tinker, 1991). It is often difficult to determine the specific source of nitrate contamination unless a point source can be identified. Studies have shown that nitrogen isotopes in ground water can be used to discriminate among nitrate-N sources (Heaton, 1985; Komor and Anderson, 1993; Spalding, Exner, Lindau, and Eaton, 1982).

A recent publication of the U.S. Geological Survey (Rheaume, 1990) identified four sources of nitrate-N in the groundwater of Kalamazoo County including: (1) precipitation 4.6 lb/acre/yr; (2) dry fall-out from the atmosphere 0.64

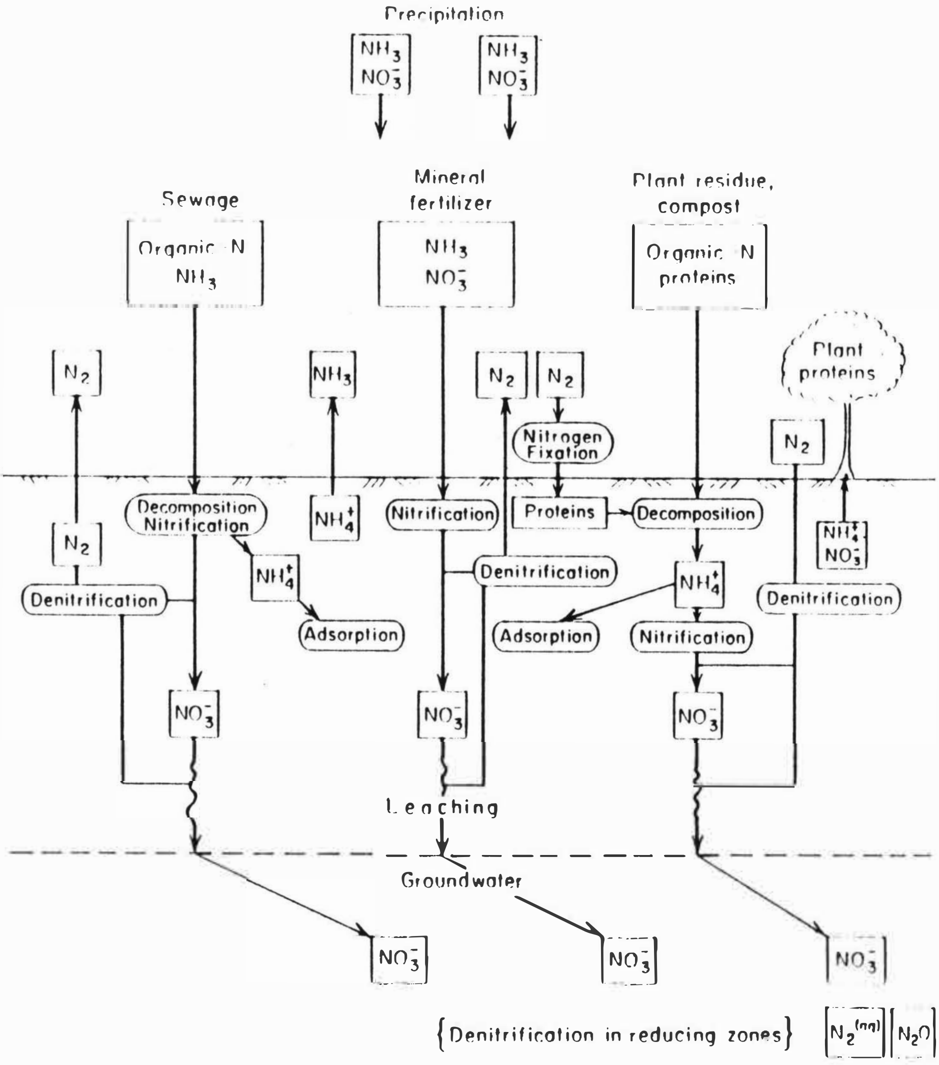


Figure 8. Sources and Pathways of Nitrogen in the Subsurface Environment.

Source: Freeze, R. A. and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, Inc. p. 414.

lb/acre/yr; (3) fertilizer application 389.7 lb/acre/yr; and (4) septic tanks 23.52 lb/acre/yr. In a publication by the Kalamazoo County Human Services Department (Leatherman, Foust, and West, 1993), human activities and landuse were found to significantly influence nitrate-N concentrations.

Pathways in the soil nitrogen cycle (N cycle) determine the amount of nitrate-N available for leaching below the root zone (Figure 8). The major processes involved are: (a) ammonification; (b) nitrification; (c) denitrification; and (d) plant uptake and recycling (Keeney, 1986). Ammonification is the conversion of organic N (nitrogen which is incorporated in organic matter) to the ammonium ion (NH_4^+). Nitrification is the microbial oxidation of NH_4^+ to nitrite (NO_2^-) and further into nitrate (NO_3^--N). Ammonification and nitrification generally occur above the water table in the soil zone under oxidizing conditions. Denitrification is the microbial reduction of NO_3^- to nitrous oxide (N_2O) or nitrogen gas (N_2). Given a sufficient source of organic matter and abundant NO_3^-, bacterial systems are capable of denitrifying large amounts of NO_3^- in the soil zone (Freeze and Cherry, 1979).

NO_3^--N tends to move through the zone of aeration at rates comparable to conservative tracers (Bobier, Frank, and Spalding, 1993). This is generally due to the high solubility of NO_3^- and its tendency to be repelled by negatively charged soil particles (Keeney, 1986).

In the groundwater, dilution and denitrification are the major factors which control NO_3^- concentration. NO_3^- is highly mobile in groundwater under conditions of high dissolved O_2. Under reducing conditions (upper limit of 2.0 mg/l dissolved O_2), with a sufficient source of organic carbon, denitrification in the saturated zone can significantly reduce the NO_3^- concentration (Korom, 1993).

Approaches to the Study of Aquifer Sensitivity/Vulnerability

A thorough review of the approaches to the study of aquifer sensitivity/vulnerability is being finalized by the U.S. Environmental Protection Agency (EPA, 1993). This review presents the relevant scientific literature derived from databases including Water Resources Abstracts, Pollution Abstracts, CRIS-USDA, the Conference Paper Index, NTIS, and GEOREF. Together, these databases contain over 3.25 million papers, posters, and reports covering the last ten to twenty years.

Two of the most commonly used aquifer sensitivity parameter weighting/scoring methods are DRASTIC (Aller, Bennett, Lehr, and Petty, 1985) and SEEPPAGE (Moore, 1988). DRASTIC uses the following seven parameters to determine aquifer sensitivity: (1) depth to water; (2) net recharge; (3) aquifer media; (4) soil media; (5) topography; (6) impact of the vadose zone; and (7) hydraulic conductivity of the aquifer (Appendix B). SEEPPAGE uses: (a) the horizontal distance between a contamination source and the point of water use; (b) land slope; (c) depth to water table; (d) vadose zone material; (e) aquifer material; (f) soil depth; and (g) attenuation potential of the soil (Appendix C). These methods are empirically derived expressions which define aquifer sensitivity for a given set of conditions. A limitation of these methods is the general lack of sufficient information for some variables in specific geographic areas, although both methods have been widely applied, neither method has been statistically or otherwise validated.

AQUIPRO (Passero, 1990), a model similar to DRASTIC and SEEPAGE was developed at Western Michigan University for the Michigan Groundwater Survey (MGS). The MGS was established in 1983 in response to the need for improved local groundwater protection and management capabilities. AQUIPRO was designed to use parameters which are available in the MGS computerized well record database. It uses clay and partial clay layer thickness along with the well depth to calculate an aquifer sensitivity score (Appendix D). This model is also empirical in nature, and has not yet been statistically or otherwise validated.

Recently, a study was conducted in southwestern Michigan by Benton (1991) which analyzed the relationship between hydrogeologic factors and aquifer sensitivity primarily using Act 307 contamination sites. Statistical comparisons were also made between nitrate contamination concentrations and various hydrogeologic factors. The statistical techniques used were correlation analysis, factor analysis, and regression analysis. Using data from water wells in one rural subdivision, he found that three variables; clay thickness, well depth, and depth of well submergence, were correlated with nitrate concentration. The correlations ranged from -0.30 to -0.41 and were statistically significant at the 0.05 confidence level ($P \leq 0.05$).

Two important studies reviewed by the EPA (1993) have used statistical methods to assess the potential for ground-water contamination by nitrate (and pesticides). Chen and Druliner (1987) in a USGS study used simple correlation analyses, non-parametric statistics, and step-wise multiple regression to characterize the relationship between nitrate concentration and the following parameters: (a) hydraulic gradient, (b) aquifer hydraulic conductivity, (c) specific discharge, (d) depth to water, (e) well depth, (f) soil permeability, (g) annual precipitation, (h) irrigation-well density, and (i) nitrogen-fertilizer use. Steichen et al. (1988) used a number of statistical analyses including a multiple regression model to relate nitrate-N to age of the well, land use around the well, and distance from the well to the closest source of organic contamination.

The Chen and Druliner (1987) study included 82 wells in exclusively agricultural areas. Of the nine parameters initially tested, six showed a statistically significant correlation with nitrate-N concentration at the 95 % confidence level ($P \leq 0.05$). These six parameters with their correlation coefficients were: (1) hydraulic gradient [-0.25]; (2) aquifer hydraulic conductivity [0.45]; (3) specific discharge [0.22]; (4) depth to water [-0.33]; (5) well depth [-0.54]; and (6) irrigation-well density [0.51].

The hydraulic gradient, ranging from 0.0006 (3 ft/mile) to 0.0053 (26 ft/mile), was determined by measuring the distance between contours on potentiometric-surface maps constructed from water levels measured in observation wells.

Hydraulic conductivity ranged from 5 to 149 ft/day, but the method used for measurement of this parameter was unspecified. Specific discharge ranged from 0.0128 to 0.2998 ft/day and was determined by multiplying the hydraulic gradient by the hydraulic conductivity. The depth to water was calculated by subtracting the potentiometric-surface elevation from the ground-surface elevation and ranged from 3 to 239 feet. Well depth, measured from the ground surface to the bottom of the well, ranged from 40 to 550 feet, and averaged 199 feet. The irrigation-well density represented the number of active irrigation wells per square mile and ranged from 0 to 8 wells/mile^2.

Using stepwise multiple regression (Statistical Analysis System, SAS), Chen and Druliner (1987) found that 3 variables (well depth, irrigation-well density, and nitrogen-fertilizer use) combined to explain 51 % of the total variance in nitrate-N concentration. The remaining parameters each explained less than 1.5 % of the total variance. The multiple regression equation which describes the predicted nitrate-N concentration in mg/l is:

$$N = 41.97 - 7.85(\text{DEPTH}) + 0.006(\text{IRRIGATION}) + 0.036(\text{FERTILIZER USE})$$

where the nitrate concentration is inversely proportional to well depth and directly proportional to irrigation well density and nitrogen-fertilizer use. The choice of nitrogen-fertilizer use in the multiple regression model is somewhat confusing because it was not reported to have a statistically significant correlation with nitrate-N concentration when tested independently.

Steichen et al. (1988) used 103 farmstead wells in Kansas to build a multiple regression model to predict nitrate-N contamination concentration in ground water. They found that the parameters; age of the well, landuse around the well, and distance from the closest source of organic contamination, produced the best predictive model. These parameters combined to explain only 18 % of the total variance in nitrate-N concentration. The multiple regression equation which describes the predicted nitrate-N concentration in mg/l is:

$$N = 19.2 + 0.0941(\text{AGE}) - 0.509(\text{LANDUSE}) - 0.0108(\text{ORGANIC SOURCE})$$

where the nitrate concentration is directly proportional to the age of the well and inversely proportional to the landuse around the well, and distance from the closest source of organic contamination.

Other studies show that nitrate-N tends to decrease with depth (Geyer, Keller, Smith, and Johnstone, 1992; Murphy, 1992). Also, nitrate-N concentrations tend to be highest downgradient of agricultural type landuses (Murphy, 1992), and septic waste disposal systems (Murphy, 1992; Tinker, 1991).

These studies show that significant relationships exist between nitrate-N concentrations and hydrogeologic and landuse parameters. The landuse parameters appear to explain the majority of the variance in nitrate-N concentration in the ground water. Thus, even in very controlled situations very little of the total contaminant variance has been explained by the hydrogeologic parameters. Unfortunately, the landuse parameters are generally difficult to quantify.

CHAPTER III

METHODOLOGY

Database

The data used in this study was in part obtained from the Michigan Resource Information System (MIRIS) which is a program of the Land and Water Management Division of the Michigan Department of Natural Resources, to compile computerized natural resource geographic and hydrogeologic information. The goal of MIRIS is to facilitate storage, retrieval, and analyses of data pertinent to land utilization, management and resource protection. The information being compiled includes cultural features, land cover, soils, and surface-water and ground-water parameters (MDNR, 1992).

Geographic data in the form of digital base maps are now available for all counties in Michigan. Base map features were digitized from U.S. Geological Survey 7.5' topographic quadrangles. They include the locations of political boundaries, lakes, rivers, drains, roads, railroads, pipelines, airports, and the U.S. Public Land Survey section corners, lines, and numbers.

Computerized land-cover information is now available for roughly one-third of the counties in Michigan. For Kalamazoo County, the 1976-78 land use has been converted to both rastor (GRASS) and vector (C-MAP) digital format through the efforts of the Kalamazoo County Planning Department and the Department of Geography, Western Michigan University. Also, the USDA Soil Conservation Service and the Michigan Department of Natural Resources are in the process of converting the county soil survey maps to digital format.

The Michigan Groundwater Data Base is an on-going project to computerize information on municipal and private water wells. The verification and data entry is performed by county agencies, then sent to the MDNR. The Environmental Health Division of the Kalamazoo County Human Services Department is in the process of converting paper water well records to a computerized county-wide database. At present they have over 6000 water well locations field-verified and digitized with static water level and well depth. The records include approximately 5000 with well lithologies, and 4000 with partial chemical analyses matched to the well locations. A total of 3620 wells have complete database records including well record information and partial chemical analyses.

Hydrogeologic Parameters

The database used in this study consists of 3620 wells and focuses on the following 8 hydrogeologic parameters: (1) well depth, (2) depth to static water level, (3) depth of well submergence, (4) clay thickness, (5) thickness of clay units in the unsaturated zone, (6) partial clay thickness, (7) thickness of partial clay units in the unsaturated zone, and (8) the glacial stratigraphy for each well location. Each of these parameters were tested individually using the SAS unequal variance version of the t-test and Pearson-r correlation to determine if their relationship with nitrate-N concentration was statistically significant ($P \leq 0.05$). The variables that showed a statistically significant relationship with nitrate-N concentration were chosen to be included in an multiple regression aquifer sensitivity model. The well depth and depth to static water level are values contained in the county well record database. Values for the clay and partial clay thickness parameters were obtained by using the county well record database as input to the original AQUIPRO program (Appendix D). AQUIPRO calculates the clay and partial clay thicknesses for each well. It can be programmed to search for clay and partial clay within a specific depth interval or for layers located above the static water level. The glacial stratigraphy for each well was determined by using the OVERLAY routine in C-MAP (Enslin and Buckley, 1991). The water well locations were plotted over the digitized glacial unit polygons. The OVERLAY routine creates a glacial unit label field in the well record database then inputs the glacial unit labels corresponding to the location of each well.

Agricultural Parameters

Four agricultural parameters were considered: (1) agricultural land use, (2) recommended fertilizer loading, (3) soil attenuation potential, and (4) soil slope. Each of these parameters were tested individually using the SAS unequal variance version of the t-test and Pearson correlation coefficient to determine if their relationship with nitrate-N concentration was statistically significant ($P \leq 0.05$). The variables that showed a statistically significant relationship with nitrate-N concentration were combined with the statistically significant hydrogeologic parameters to formulate a multiple regression ground-water vulnerability model.

Agricultural landuse was determined by using the OVERLAY routine in C-MAP (Enslin and Buckley, 1991). The water well locations were plotted over the digitized 1978 landuse polygons (Dickason and Kalamazoo County Planning Commission, 1981). The 1978 landuse is shown in Figure 9. The OVERLAY routine creates a landuse label field in the well record database, then inputs the landuse labels corresponding to the location of each well. The landuse was then separated into two groups, agricultural and non-agricultural. Agricultural landuse included the MIRIS landuse codes corresponding to cropland, orchards, bush fruit, vineyards, ornamental horticulture, confined feeding, and permanent pasture. All other types of landuse were coded as non-agricultural.

The values for recommended fertilizer loading were obtained from a USGS study of Kalamazoo County (Rheaume, 1990). Estimates of the quantity of nitrogen deposited on land by agricultural fertilizers were based on a 1983 agricultural crop survey by the Kalamazoo County Planning Department and on fertilizer application rates for different crops provided by the Kalamazoo County Extension Office. The recommended fertilizer loading was estimated for each generalized ground-water drainage unit (Figure 10). These generalized ground-water drainage units are based on surface-water divides. The recommended fertilizer loading F in pounds per acre per year for each surface-water drainage unit was calculated by:

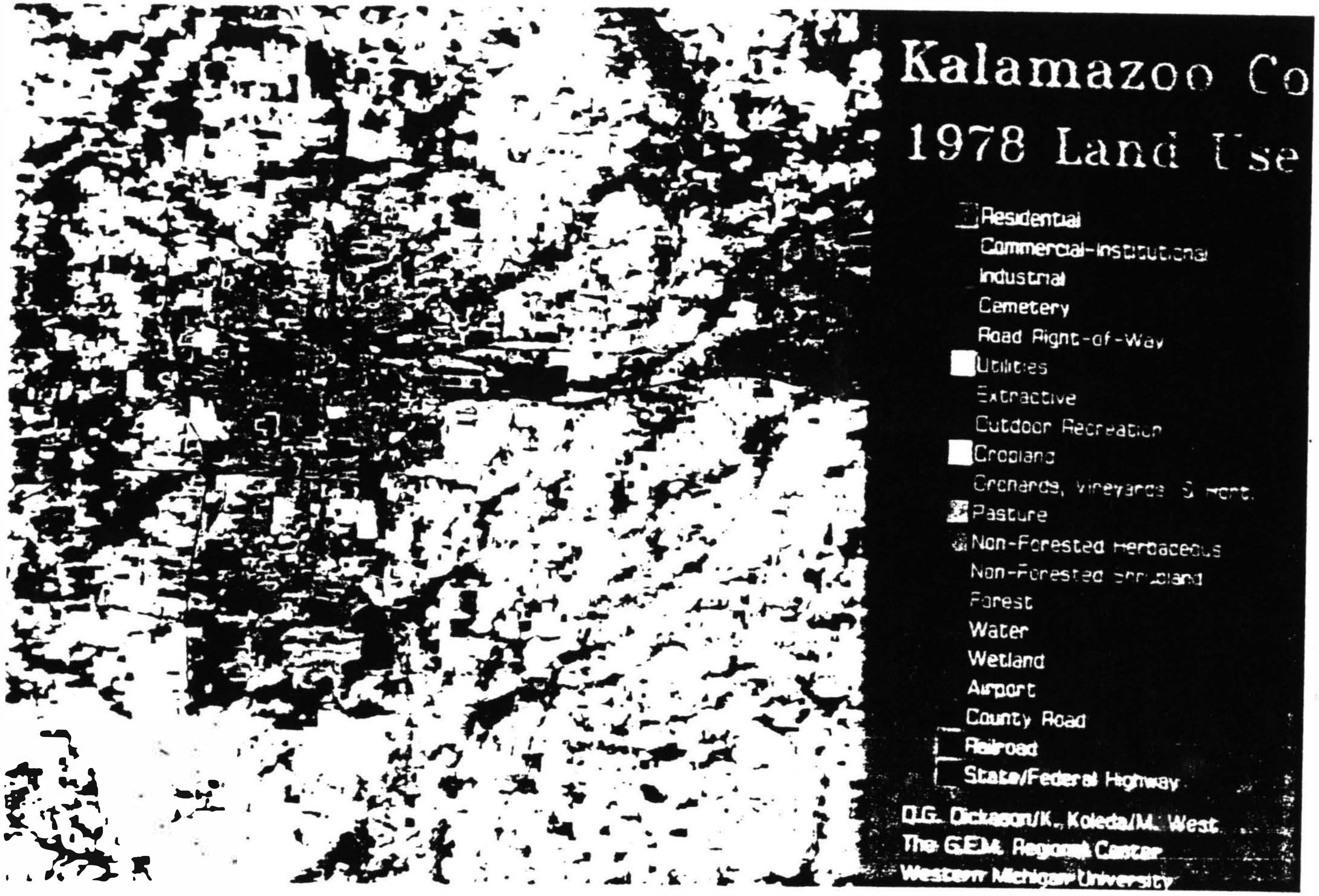


Figure 9. Map Showing 1978 Landuse in Kalamazoo County.

Source: Dickason, D. D. and Kalamazoo County Planning Commission, 1981, Digital Version of 1978 Landuse For Kalamazoo County: Kalamazoo, MI, Western Michigan University Department of Geography.

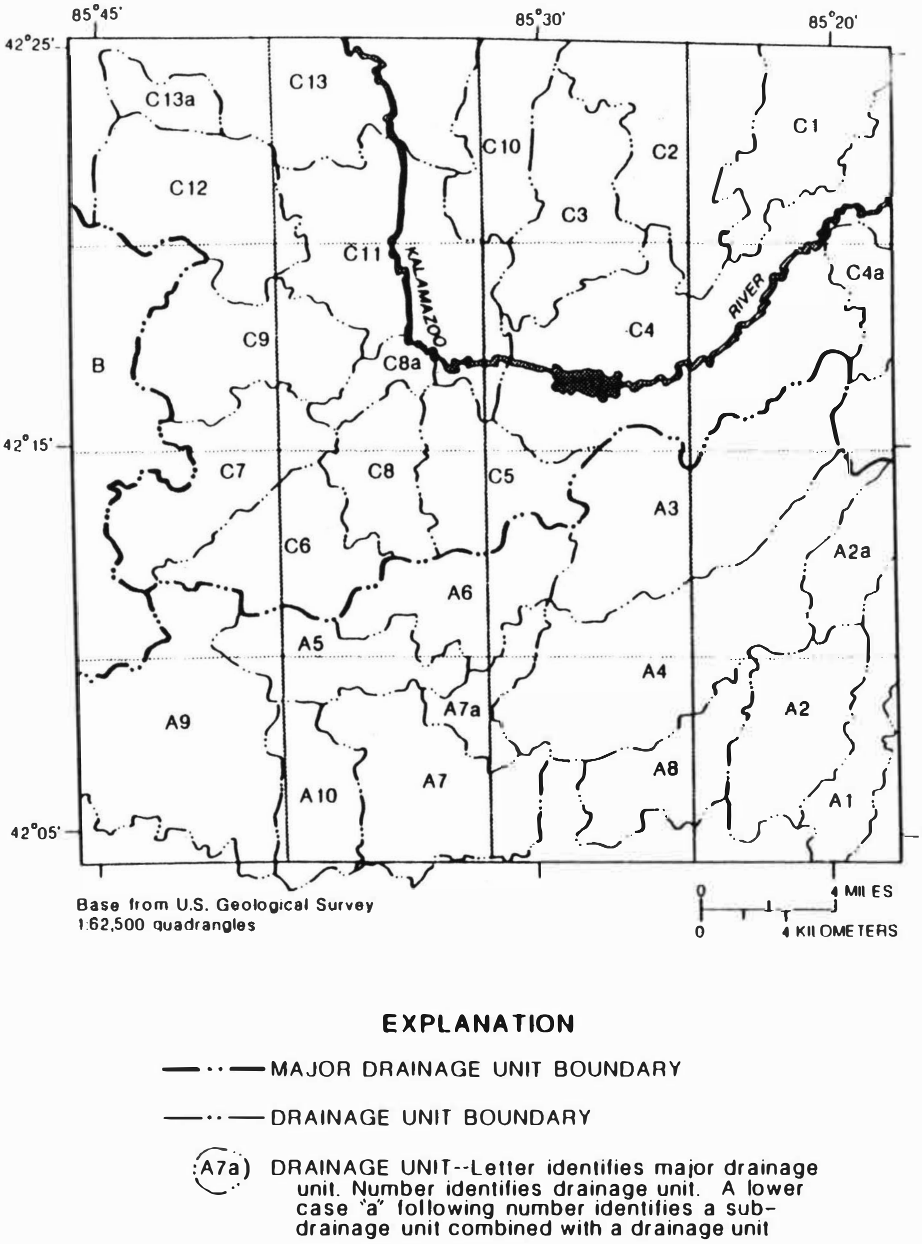


Figure 10. Map Showing Surface-water Drainage Units in Kalamazoo County.

Source: Rheaume, S. J., 1990, Geohydrology and water quality of Kalamazoo County, Michigan, 1986-88, U.S. Geological Survey Water-Resources Investigations Report 90-4028, p. 57.

F = total crop acreage x suggested fertilizer application rates

where the total crop acreage is the acreage of each crop type in each surface-water drainage unit. These surface-water drainage units were digitized into polygons, and OVERLAY was used to plot the wells over the drainage units. The OVERLAY routine created a drainage unit label field in the well record database, then input the drainage unit label corresponding to the location of each well. These drainage unit labels could then be converted to recommended fertilizer loadings at each well.

Soil attenuation potential is one of the seven SEEPPAGE factors (Moore, 1988). Attenuation potential is an estimate of the ability of a soil to prevent or slow the movement of pollutants, and is based on six physical/chemical characteristics: (1) texture of surface [A] soil horizon, (2) texture of subsoil [B or C] horizon, (3) pH of surface (A) soil horizon, (4) soil organic matter content, (5) permeability of least permeable subsoil [B or C] horizon, and (6) soil drainage class. The soil attenuation potential was determined for each well by using the OVERLAY routine to plot the well locations over a digitized version of the soil survey. The soil types were then converted to corresponding attenuation potentials for each well location (Appendix C).

Soil slope was determined using the percent slope values given for each soil type in the Kalamazoo County soil survey (Austin, 1979). The soil slope was determined for each well by using the OVERLAY routine to plot the well locations over a digitized version of the soil survey. The soil types were then converted to corresponding percent slope values for each well location.

Statistical Methods

Initially, the data were analyzed using a simple t-test with nitrate-N concentration as the independent variable (Appendices E and F). Wells with non-detect nitrate-N were eliminated from this part of the study because it could not be determined if non-detectable levels of nitrate-N were due to the hydrogeologic parameters or the absence of a source of nitrate-N. The database of wells was divided into two samples which were determined by nitrate-N concentration. The first sample consisted of all wells with a nitrate-N concentration of greater than non-detect to a value of 2.0 mg/l nitrate-N. The second sample contained all wells with greater than 2.0 mg/l nitrate-N. An average value was calculated for each aquifer parameter in each sample. A t-test was then used to compare the mean of a given aquifer parameter from the first sample with the mean of that parameter from the second sample.

A significance level of 95 % ($P \leq 0.05$) for the difference between the two means was used to determine if the means of the various parameters differed significantly between the two nitrate-N concentration ranges. This procedure was repeated for different ranges of nitrate-N concentration including non-detect to 3 vs. greater than 3 mg/l, non-detect to 4 vs. greater than 4 mg/l, and non-detect to 5 vs. greater than 5 mg/l. Several significant differences were found using this technique requiring the application of statistical methods which would offer additional information about the relationships between nitrate-N concentration and the various parameters.

The Statistical Analysis System (SAS) was used to produce the statistical output for the rest of the study. An unequal variances version of the t-test was chosen to determine which hydrogeologic parameters had a statistically significant relationship with the natural logarithm of the nitrate-N concentration. This test was considered to be the most statistically reliable for determining significant relationships (Stoline, 1993). There are three fundamental assumptions that apply to the use of these statistical tests. The first assumption, independence of sampling, is not a problem for our study because we are only using one nitrate-N sample for each well location. The second assumption, equality of variances, is the most important in our study due to the large differences found in the standard deviations of the two samples being compared. This assumption is best corrected using an unequal variances version of the t-test. For situations where the standard deviations were equal, the standard t-test was used. The third assumption, normality of distribution is the least important, and although a non-parametric statistical test would correct for this, a non-parametric test would not adequately correct for the unequal variances problem. The natural logarithm of nitrate-N concentration was used for these t-test comparisons and the remaining statistical analyses because of log-normal distribution of the nitrate-N concentration.

Pearson-r correlation was used to compare the hydrogeologic parameters and to compare the hydrogeologic parameters with the nitrate-N concentration and the natural logarithm of the nitrate-N concentration. The results were used to analyze the interrelationships among the individual hydrogeologic parameters.

A least-squares multiple regression was used to determine the amount of the total variance in nitrate-N concentration that was accounted for by the hydrogeologic parameters having statistically significant relationships with nitrate-N (Appendix E). The results of this multiple regression were used to modify the AQUIPRO equation and produce a general aquifer sensitivity model.

Aquifer sensitivity models often generalize the ratings applied to specific glacial geologic units. A least-squares analysis of variance was used to investigate the amount of change in each hydrogeologic parameter between different glacial geology units. Large differences in the parameters which control the variance in nitrate-N concentration would be expected to effect aquifer sensitivity.

The influence of agricultural parameters on nitrate-N concentration was investigated by using unequal variance t-test comparisons and Pearson-r correlation. The parameters that showed statistically significant relationships with the natural logarithm of nitrate-N concentration were used as input for a least-squares multiple regression. The results of this multiple regression was used to modify the AQUIPRO equation and produce an agricultural ground-water vulnerability model.

CHAPTER IV

ANALYSIS OF DATA

Case Studies: Cass County Monitoring Wells

The following case studies illustrate how contaminant concentrations vary with different hydrogeologic and landuse settings. This work is a portion of an on-going study of the Donnell Lake watershed being conducted by Western Michigan University and Michigan State University. A detailed description of the hydrogeology and ground-water chemistry for the Donnell Lake area can be found in the thesis study by Stuk (1992).

The initial monitoring well installations included twenty-three wells installed in eleven nests to provide an areal and vertical representation of ground-water flow systems and water chemistry within the drift aquifer system of the Donnell Lake area. A site map with the locations of three north-south cross sections using eight of the eleven monitoring well nests is shown in Figure 11.

The nitrate-N and chloride concentration for each of the three wells in well nest #1 is shown in Figure 12. This well nest is located downgradient from corn and soybean row crops in a strong ground-water recharge area. There is approximately 4 feet of head difference between the deepest well screened from 66 to 71 feet and the shallowest well screened from 8 to 13 feet (Table 1). Nitrate-N

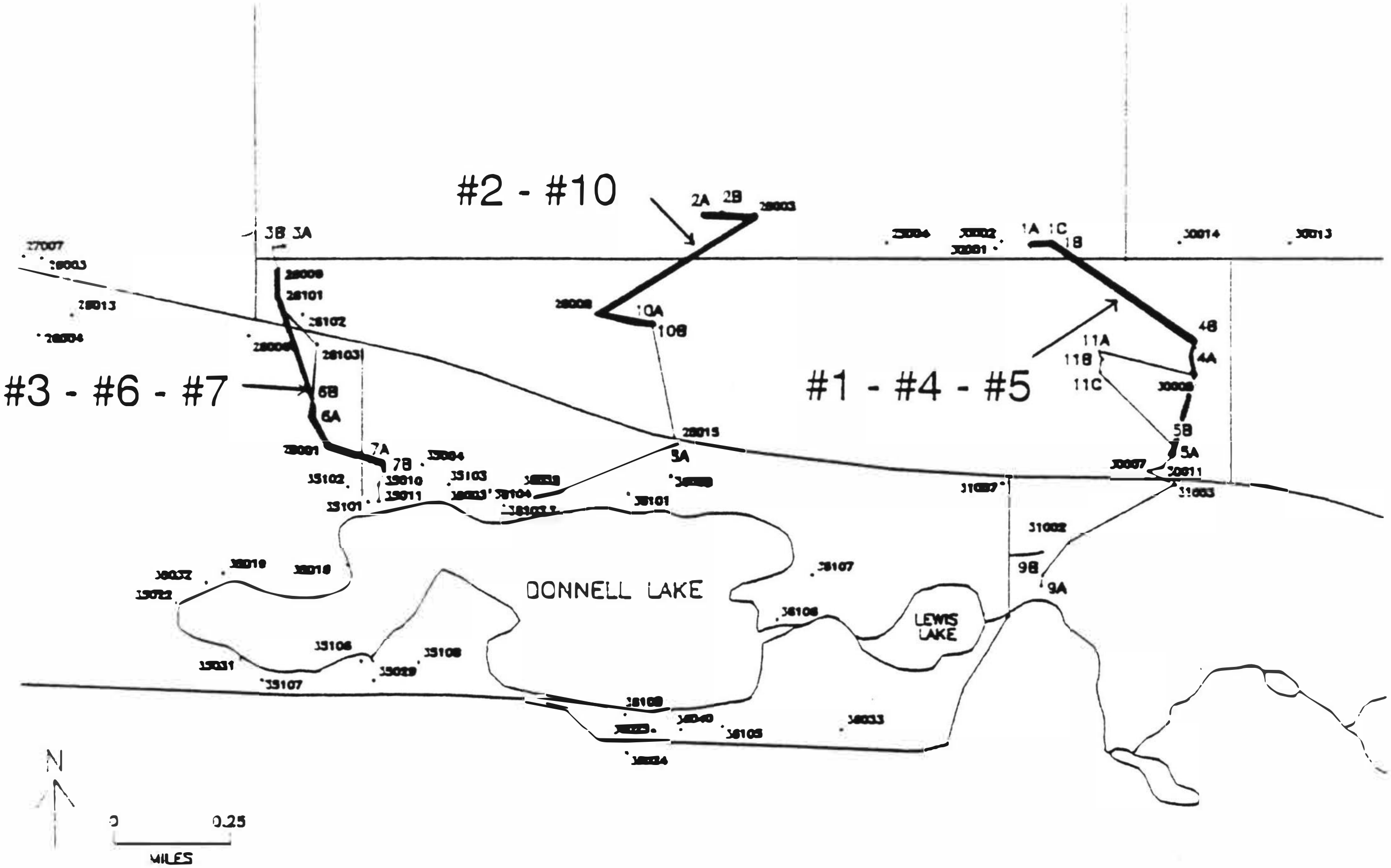


Figure 11. Map Showing North-South Hydrogeologic Cross Sections in the Donnell Lake Area, Cass County, Michigan.

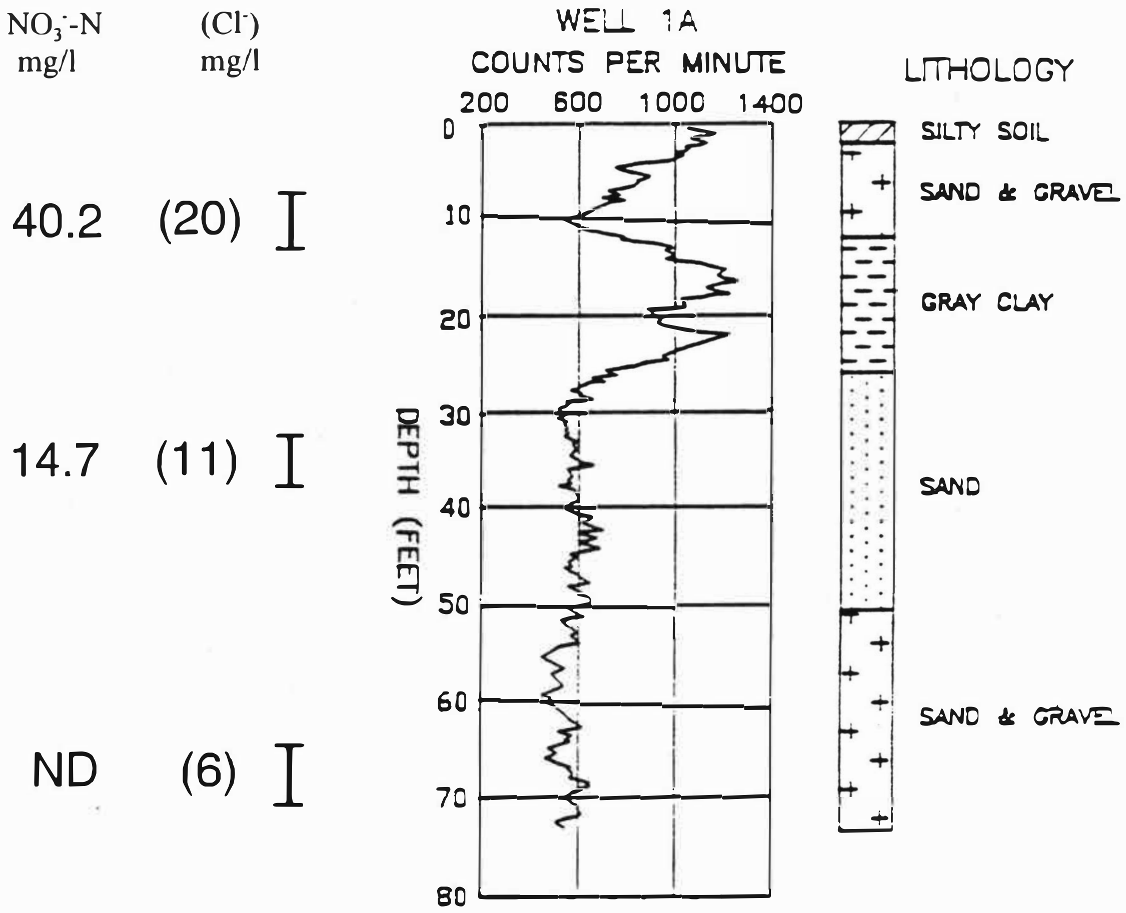


Figure 12. Well Nest #1 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Under Row Crops (Recharge Area) in the Donnell Lake Area, Cass County, Michigan.

Table 1

Cass County Monitoring Wells

Well Number	Well Depth feet	Screen Interval feet	Static Water Elevation feet
#1C	14	8 - 13	892.11
#1B	39	33 - 38	888.16
#1A	71	66 - 71	888.18
#2A	28	23 - 28	883.78
#2H	40	35 - 40	882.00
#2B	78	73 - 78	882.90
#3A	28	23 - 28	869.77
#3H	49	44 - 49	863.00
#3B	77	72 - 77	864.87
#4A	33	28 - 33	891.31
#4B	44	39 - 44	891.33
#4H	85	80 - 85	892.00
#10B	21	16 - 21	873.32
#10H	42	37 - 42	880.00
#10A	74	71 - 74	873.33
#5A	43	38 - 43	884.38
#5B	62	57.5 - 62.5	884.41
#5H	88	83 - 88	878.00
#6B	34	29 - 34	866.04
#6H	45	40 - 45	859.00
#6A	73	68 - 73	864.72
#7B	43	38 - 43	861.23
#7H	45	40 - 45	861.00
#7A	93	88 - 93	867.49

and chloride concentrations are highest in the shallow well. The nitrate-N concentration decreases from 40.2 to 14.7 mg/l across the clay confining layer but is still above the drinking water standard of 10 mg/l nitrate-N. The deepest well shows non-detectable (NO_3^--N $\leq$ 0.5 mg/l) nitrate-N at approximately 70 feet and the chloride concentration has diminished to 6 mg/l.

Well nest #2 (Figure 13) is downgradient from row crops and is in the ground-water recharge area with approximately one foot of vertical head between the shallow and deep well. The second lithologic record is from the house well located 40 feet east of the shallow and deep monitoring wells. The nitrate-N concentration is highest (11.1 mg/l) above the first confining layer. The concentration decreases to 7.6 mg/l across the confining layer and is non-detectable at 75 feet. The chloride concentration is low in all three wells (non-detect $Cl^- \leq 0.1$ mg/l).

Well nest #3 (Figure 14) is downgradient from row crops and a wetland in a strong ground-water recharge area with 5 feet of vertical head. The nitrate-N concentration is non-detectable in the intermediate and deep well, and 0.6 mg/l in the shallow well. These low nitrate-N concentrations are due to denitrification occurring in the wetland (Passero, Kehew, Sauck, Chidester, and Lovett, 1993). The chloride concentration decreases from 13 to 3 mg/l between the shallow and deep monitoring wells, but is non-detect in the intermediate residential well located across the street approximately 60 feet to the south.

Well nest #4 (Figure 15) is located 20 feet from a hog lot in a ground-water

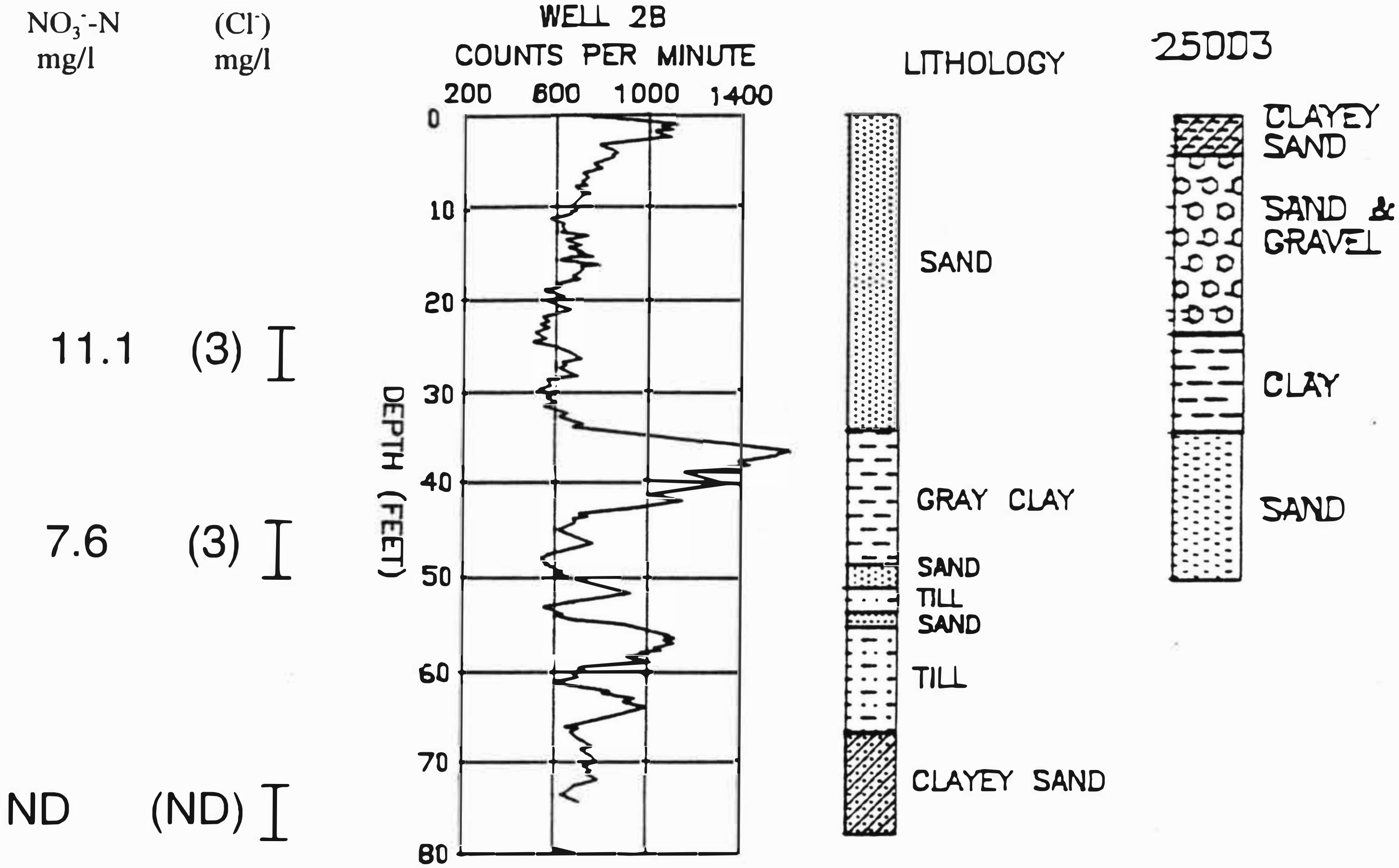


Figure 13. Well Nest #2 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Near Row Crops (Recharge Area) in the Donnell Lake Area, Cass County, Michigan.

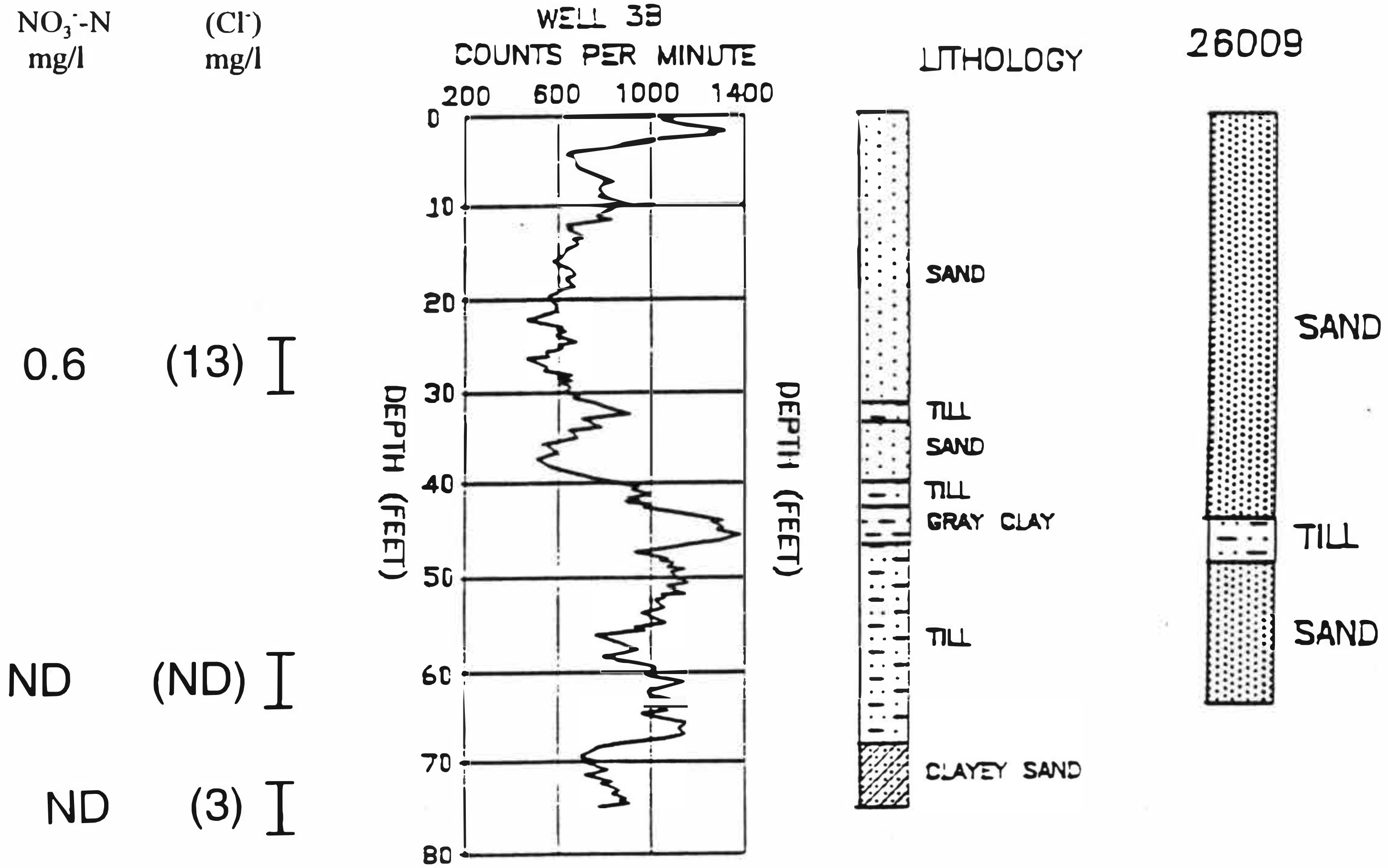


Figure 14. Well Nest #3 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Under Row Crops (Recharge Area) in the Donnell Lake Area, Cass County, Michigan.

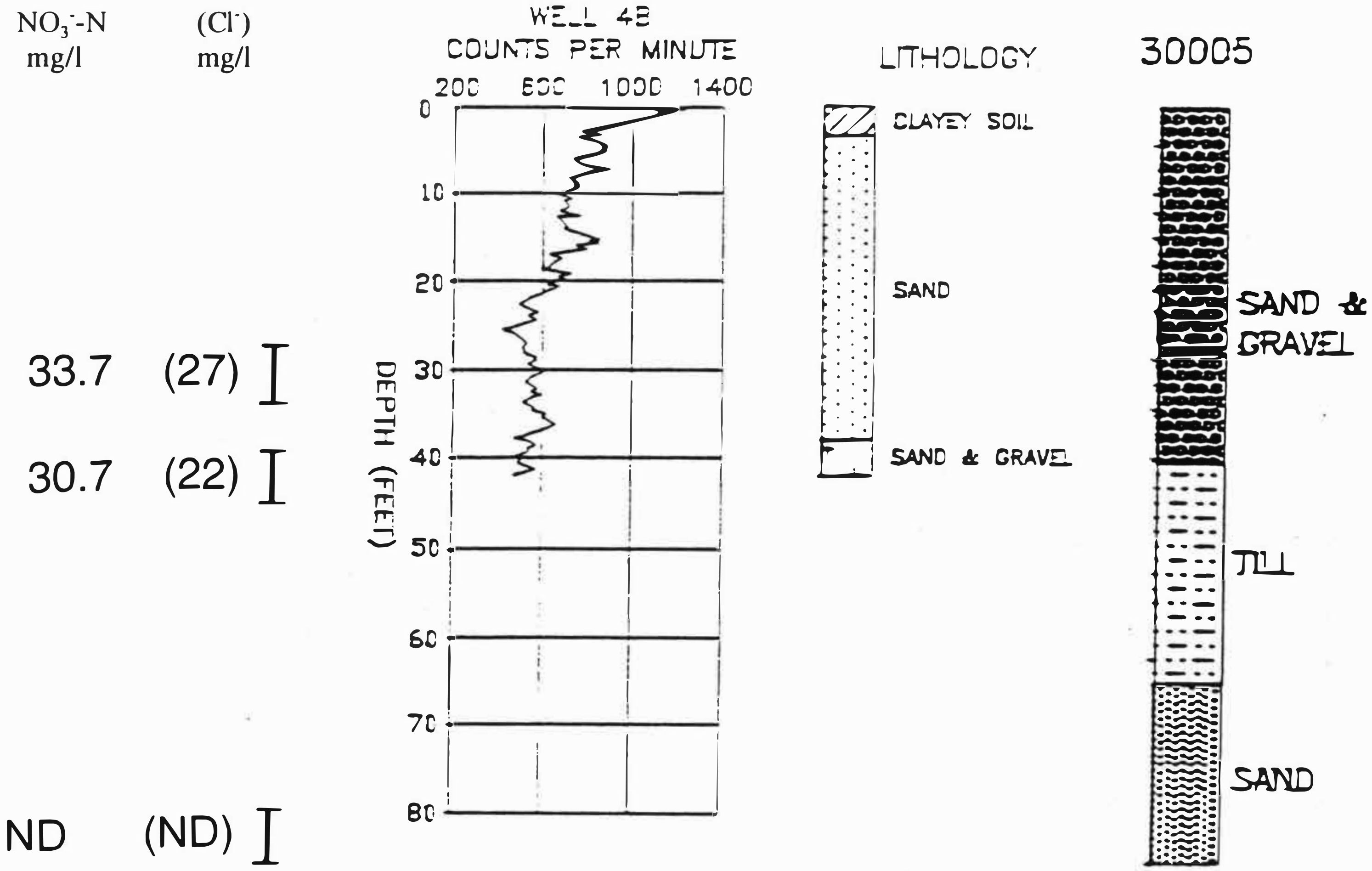


Figure 15. Well Nest #4 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Near Hog Lot (Transition Area) in the Donnell Lake Area, Cass County, Michigan.

transition zone. The nitrate and chloride concentrations are high in the two monitoring wells next to the hog lot. The deep residential well is located 100 feet south of the hog lot. The presence of a till confining layer and the depth and/or the distance from the hog lot may be responsible for the non-detect nitrate-N and chloride in the deep well.

Well nest #10 (Figure 16) is located in the center of a hog pasture in a ground-water transition zone. This shows a significant decrease in nitrate-N and chloride with depth across a confining layer of silt and fine sand. For this well nest the dominant ground-water flow is horizontal. The high nitrate-N and chloride concentrations are limited to the shallow flow system.

Well nest #5 (Figure 17) is located 15 feet north of M-60 in a ground-water transition zone. In this horizontal flow regime the nitrate-N and chloride decrease significantly over a short vertical distance without the presence of a confining layer. The closest residential well (Figure 11), has a nitrate-N concentration of 12.6 mg/l and a chloride concentration of non-detect at a depth of 88 feet.

Well nest #6 (Figure 18) is located in a row crop field in the ground-water transition area. The nitrate-N and chloride concentrations are low and decrease with depth in the shallow and deep monitoring wells. The intermediate residential well is located 200 feet to the south. The higher contaminant concentration in this well may be due to the proximity of the house septic system (elevated chloride due to presence of a water softener).

Well nest #7 (Figure 19) is located in a residential area 250 feet north of

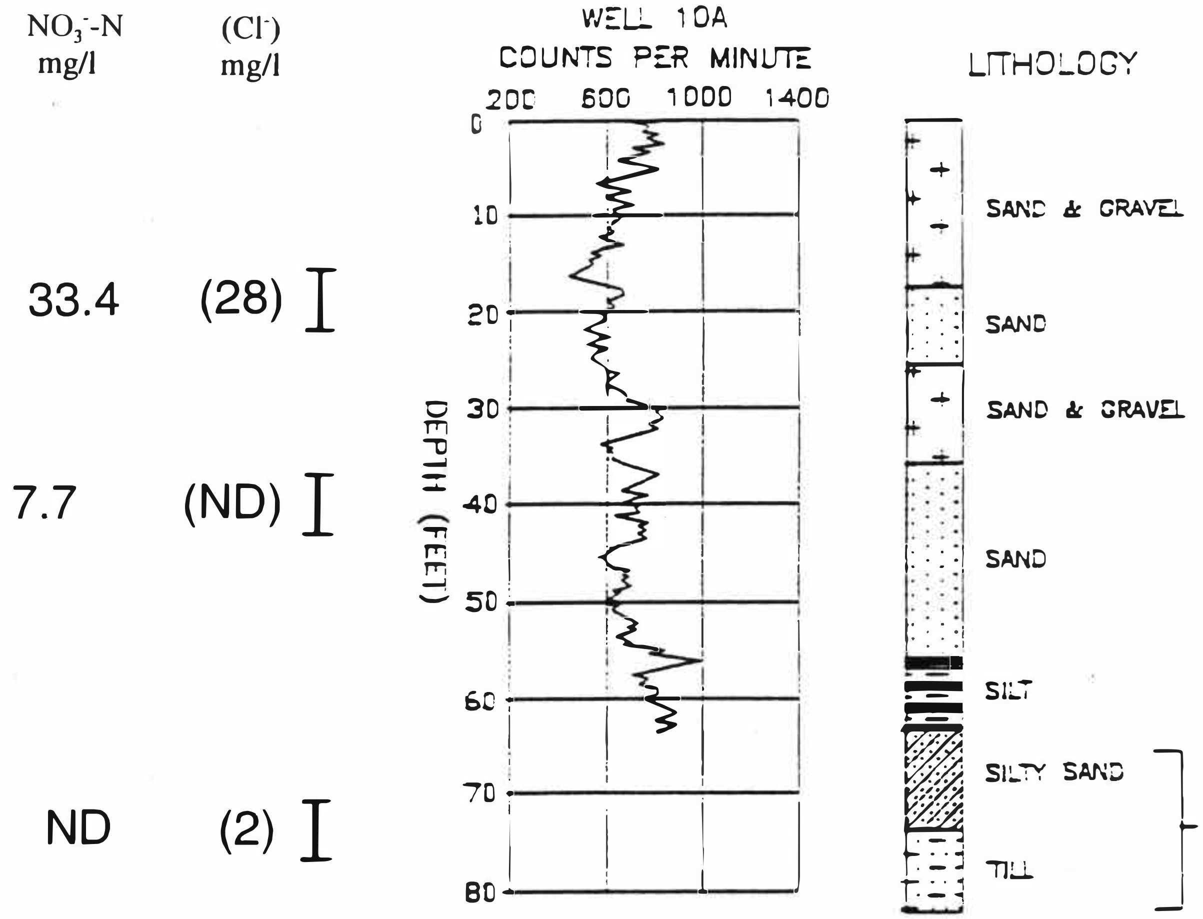


Figure 16. Well Nest #10 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Under Hog Pasture (Transition Area) in the Donnell Lake Area, Cass County, Michigan.

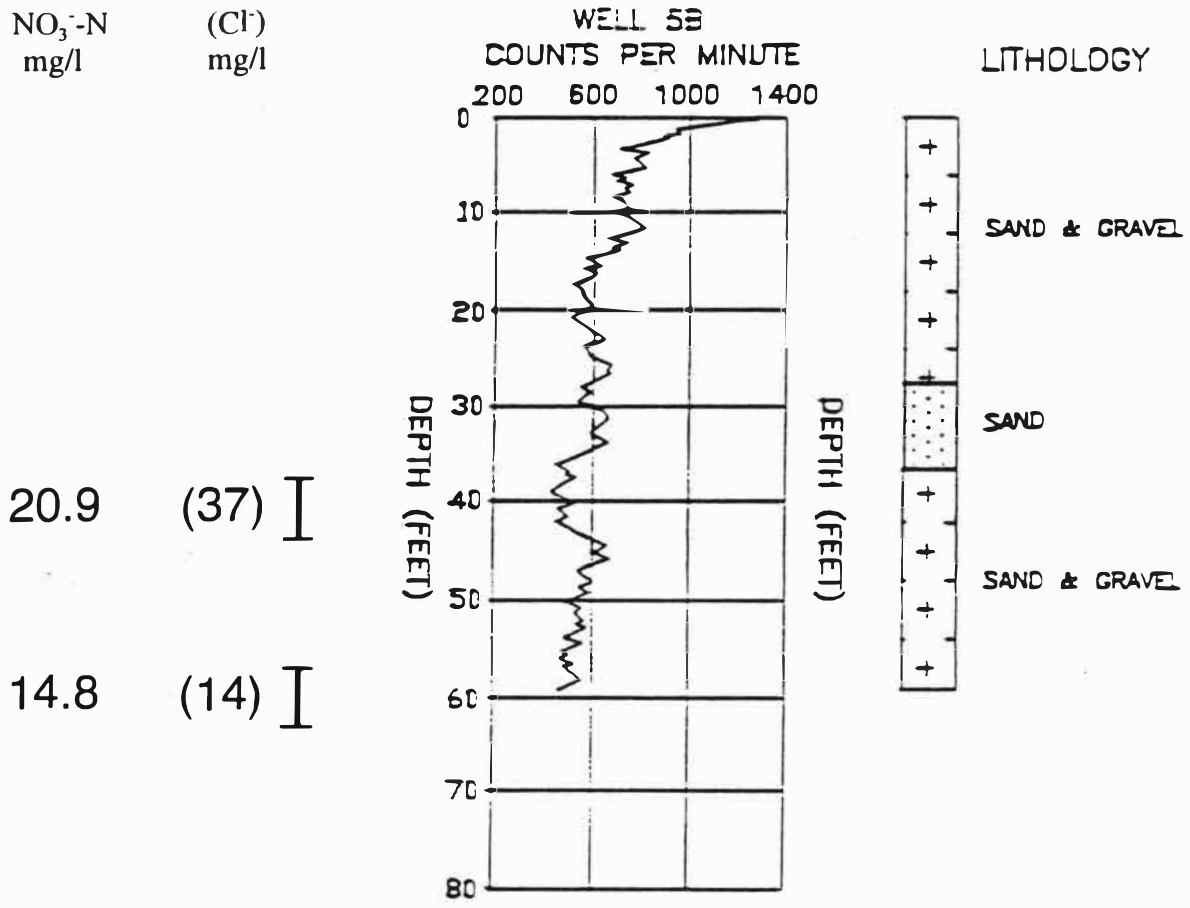


Figure 17. Well Nest #5 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Near Hog Pasture (Transition Area) in the Donnell Lake Area, Cass County, Michigan.

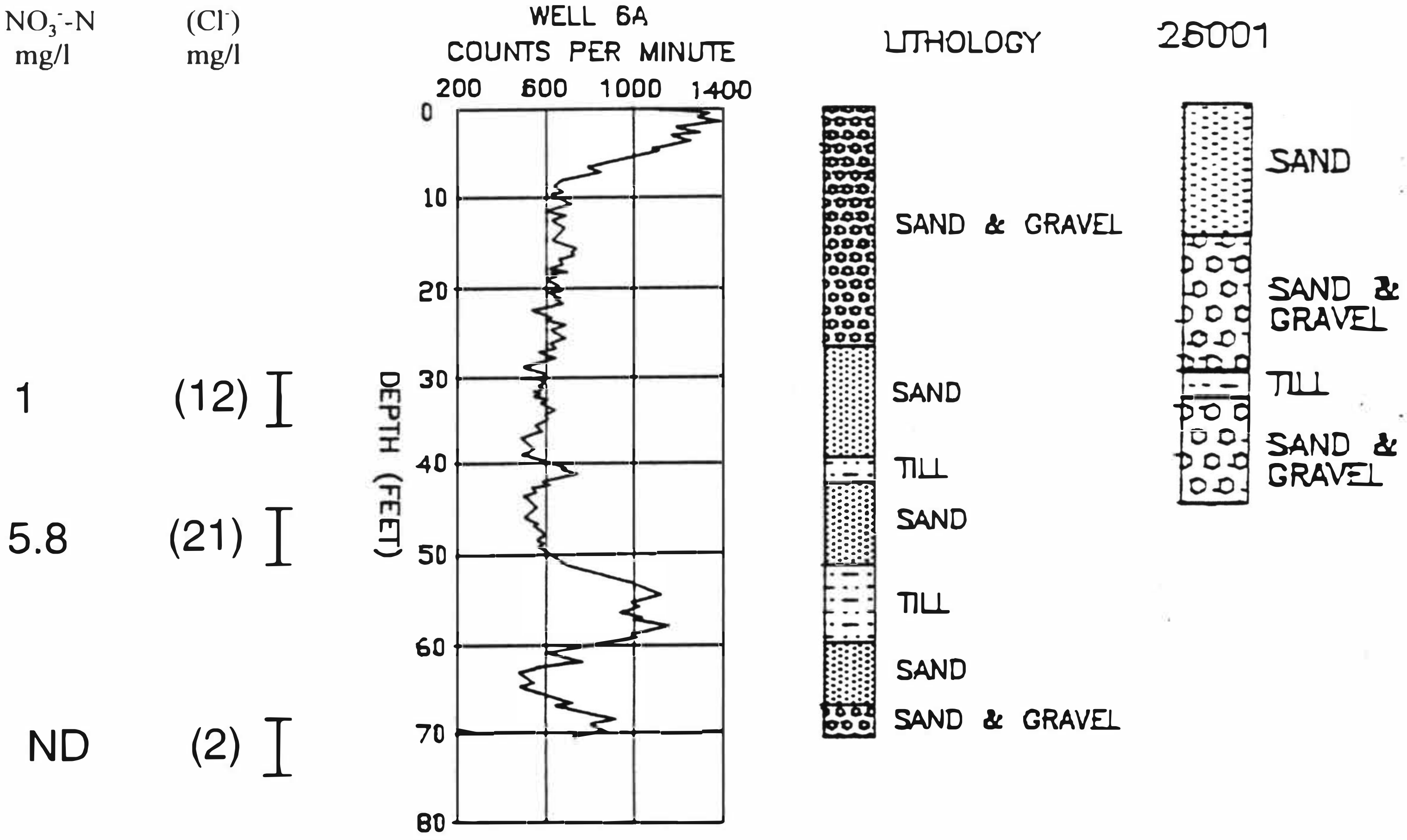


Figure 18. Well Nest #6 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations Under Row Crops (Transition Area) in the Donnell Lake Area, Cass County, Michigan.

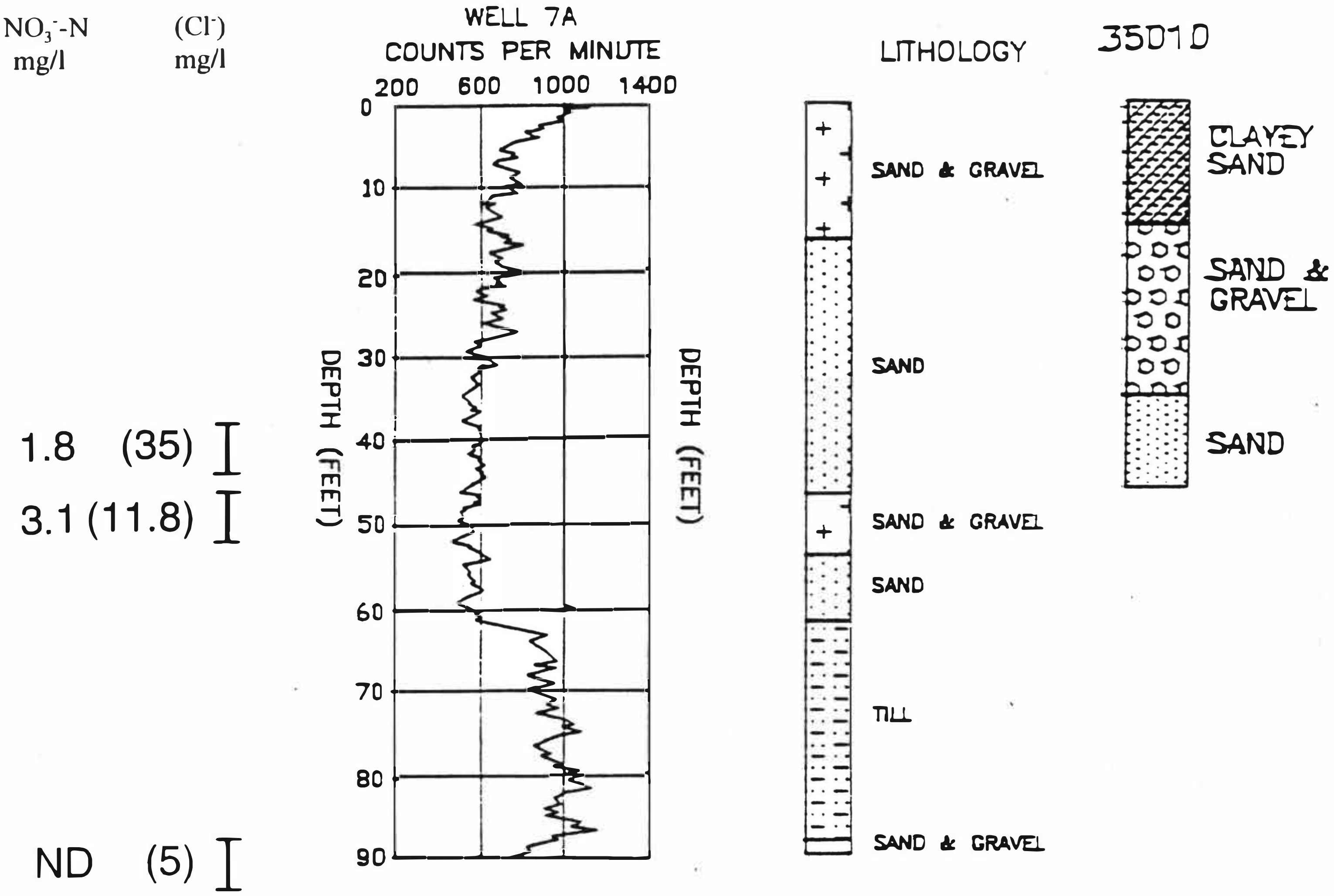


Figure 19. Well Nest #7 Gamma-ray and Lithologic Log With Nitrate-N and Chloride Concentrations in Residential Area (Discharge Area) in the Donnell Lake Area, Cass County, Michigan.

Donnell Lake in a strong ground-water discharge area. In the deep well the nitrate-N concentration is non-detect at 90 feet. Above the confining till layer the nitrate-N concentration is slightly higher and shows a decrease upward in the flow system. The chloride concentrations show the opposite relation with 35 mg/l chloride in the shallow monitoring well and 11.8 mg/l in the intermediate depth residential well. This discrepancy may be due to source differences for the nitrate-N and chloride.

These case studies show that in general, nitrate-N and chloride concentration decrease with depth. The ground-water flow appears to affect the change in contaminant concentration. The presence of clay and till layers does not necessarily prevent the migration of nitrate-N and chloride across these confining layers.

Overview of Nitrate-N Concentrations and Hydrogeologic Parameter Distribution in Kalamazoo County

A summary of the nitrate-N concentration and hydrogeologic parameter distribution is given in Table 2. The nitrate-N values range from non-detect (NO_3^--N ≤ 0.1) to 48.6 mg/l. A histogram showing the nitrate-N distribution (Figure 20) for the entire 3620 well database illustrates the log-normal distribution typical of contaminant concentrations. The nitrate-N distribution is highly skewed with nearly 50 % of the wells having non-detect nitrate-N.

A histogram of well depth (Figure 21) shows a left skewed distribution with approximately 95 % of the wells equal to or less than 150 feet in total depth. The well depth ranges from 20 to 410 feet with an average depth of 77 feet.

Table 2

Statistical Summary of Hydrogeologic Parameters for Kalamazoo County Wells

Parameters	Mean feet	Standard Deviation feet	Median feet	Minimum feet	Maximum feet
Nitrate	2.3	3.8	0.2	0	48.6
Well Depth	86	43	77	20	410
Depth to Static Water	41	32	32	0	230
Depth of Submergence	45	29	37	5	248
Clay Thickness	7.9	7.9	0	0	180
Clay Thickness Above SWL	2.1	7.3	0	0	119
Partial Clay Thickness	14.4	28.4	0	0	285
Partial Clay Above SWL	7.0	17.2	0	0	183

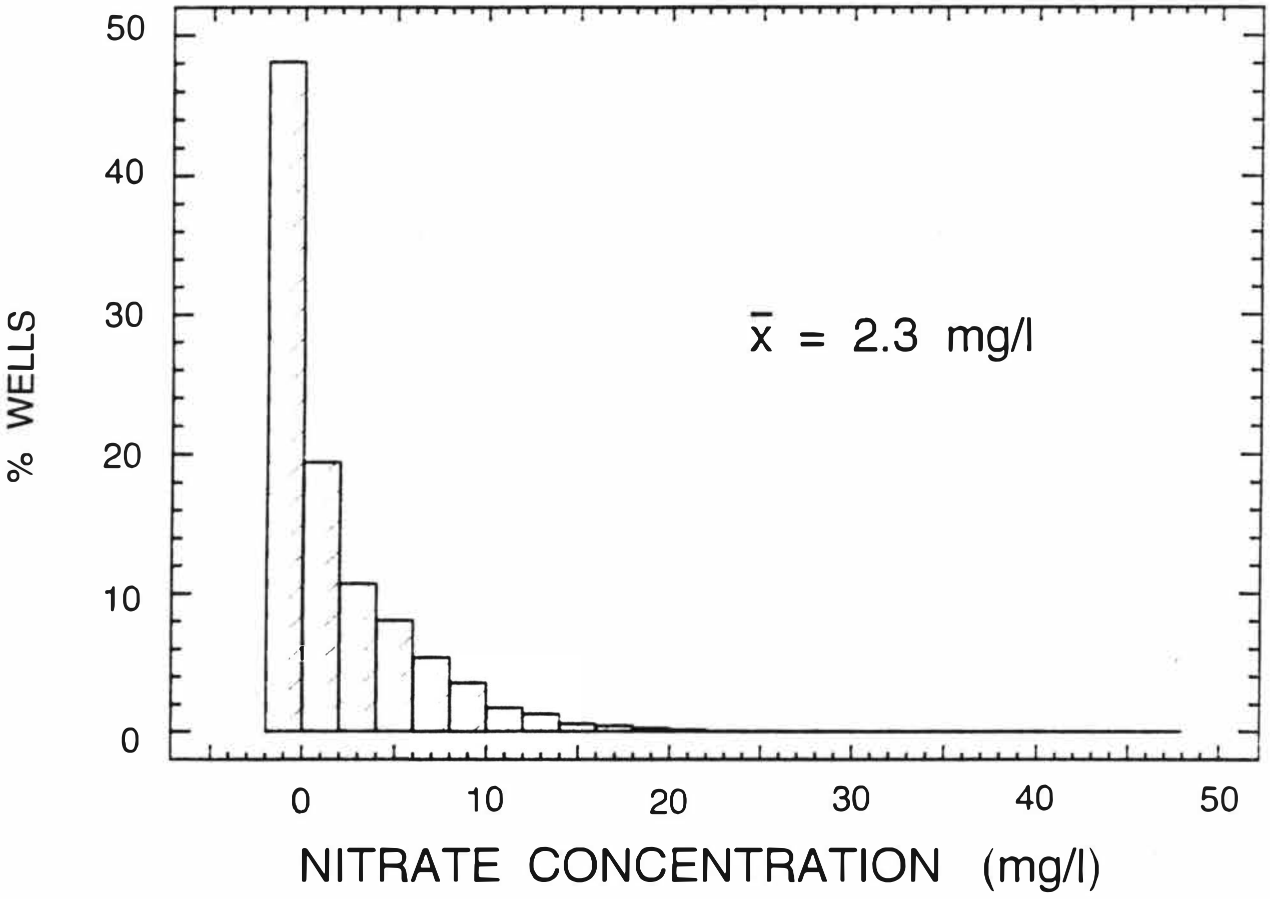


Figure 20. Histogram Showing Nitrate-N Distribution for All Study Wells (N = 3620).

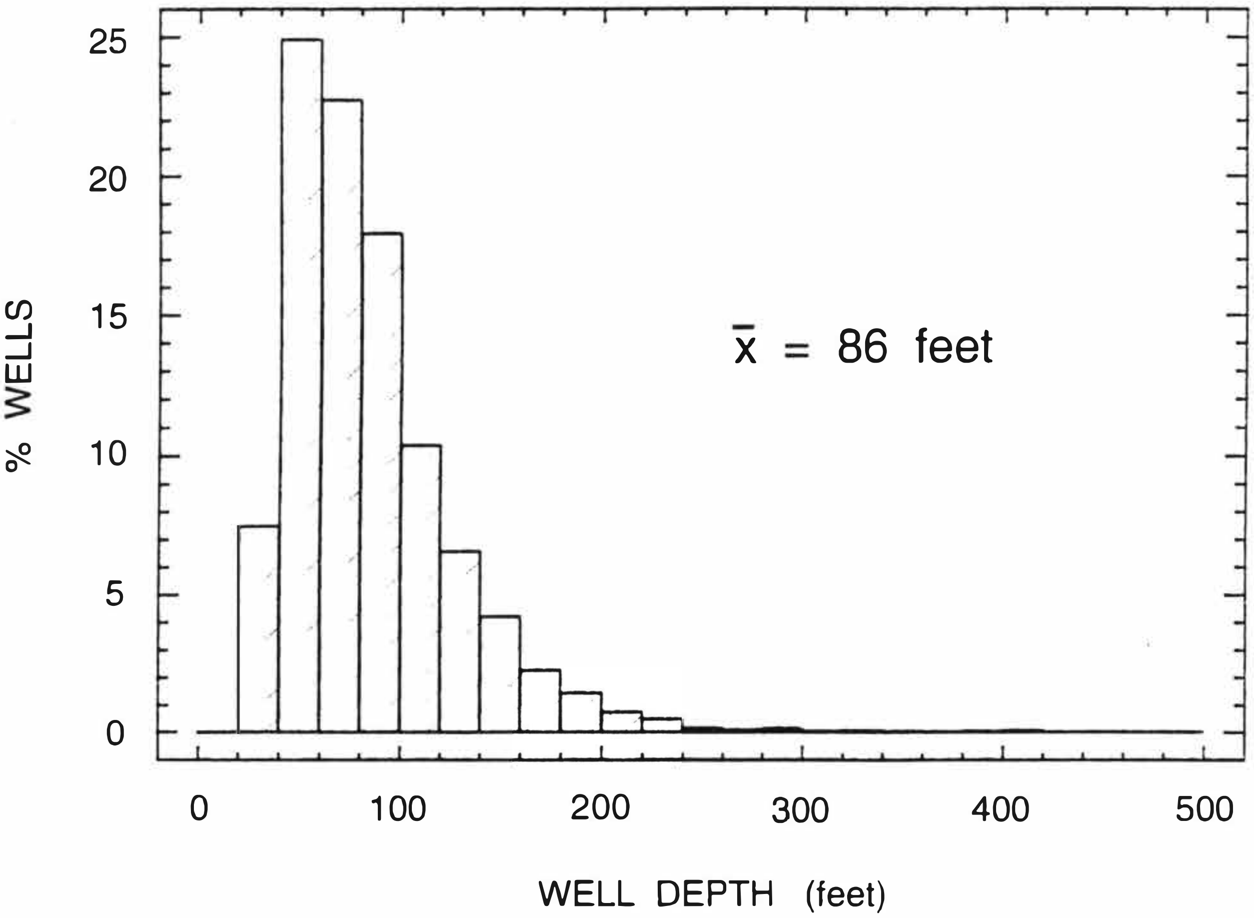


Figure 21. Histogram Showing Well Depth Distribution for All Study Wells (N = 3620).

A histogram of depth to static water (Figure 22) shows that in approximately 95 % of the wells depth to static water level is equal to or less than 100 feet. The depth to water ranges from 0 to 230 feet, with an average depth of 41 feet.

The distribution of depth of well submergence (Figure 23) shows that 95 % of the wells have depths of submergence equal to or less than 90 feet. Depths range from 5 to 248 feet with an average of 45 feet.

A histogram of clay thickness (Figure 24) shows the general lack of clay in Kalamazoo County. Sixty-five percent of the wells have no clay and average clay thickness is only 7.9 feet. Some wells, however, have as much as 180 feet of clay.

The partial clay mixtures of clay, sand, and gravel have a distribution similar to the clay distribution (Figure 25). Nearly 60 % of the wells have no partial clay and average 14.4 feet. The partial clay thickness ranges up to 285 feet in some wells.

These histograms illustrate that the hydrogeologic parameters are non-normally distributed. The statistical tests used to analyze these parameters were chosen to minimize the effect of non-normal distribution. A comparison of non-parametric and parametric statistical methods applied to the same data is shown in Appendix F.

Comparison of Nitrate-N Concentrations and Hydrogeologic Parameters by T-test and Correlation

Initially, the relationships between nitrate-N and the hydrogeologic parameters

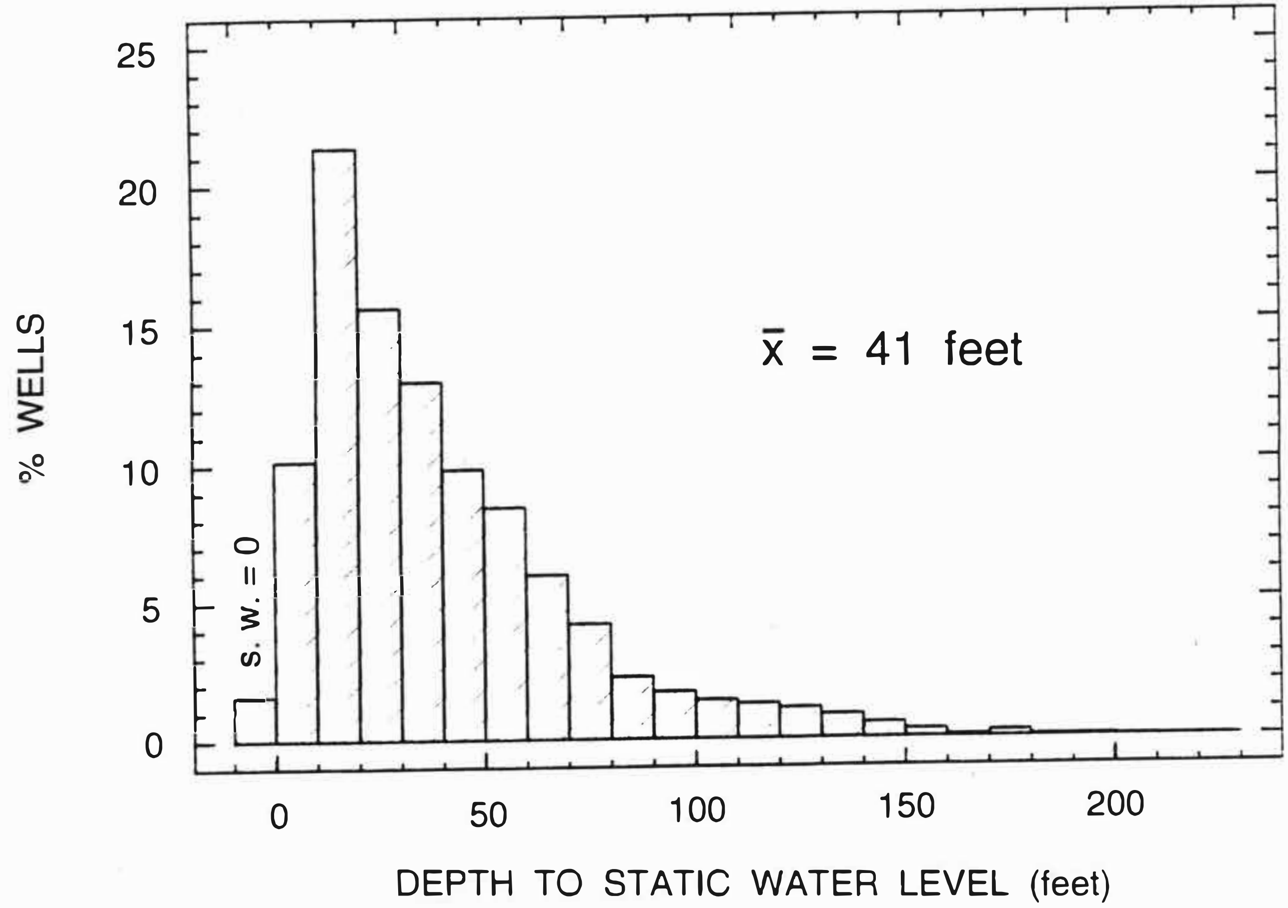


Figure 22. Histogram Showing Depth to Static Water Level Distribution for All Study Wells (N = 3620).

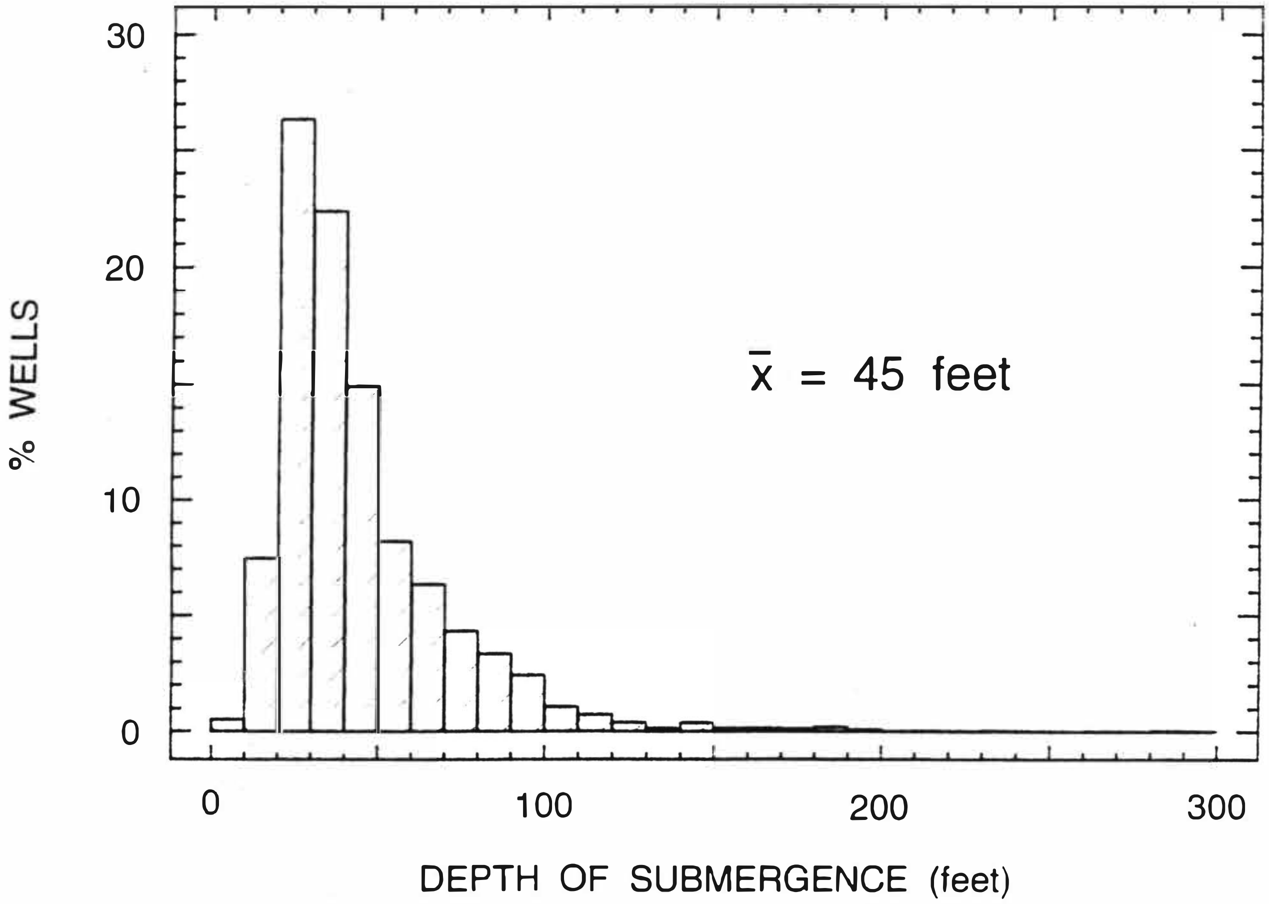


Figure 23. Histogram Showing Depth of Submergence Distribution for All Study Wells (N = 3620).

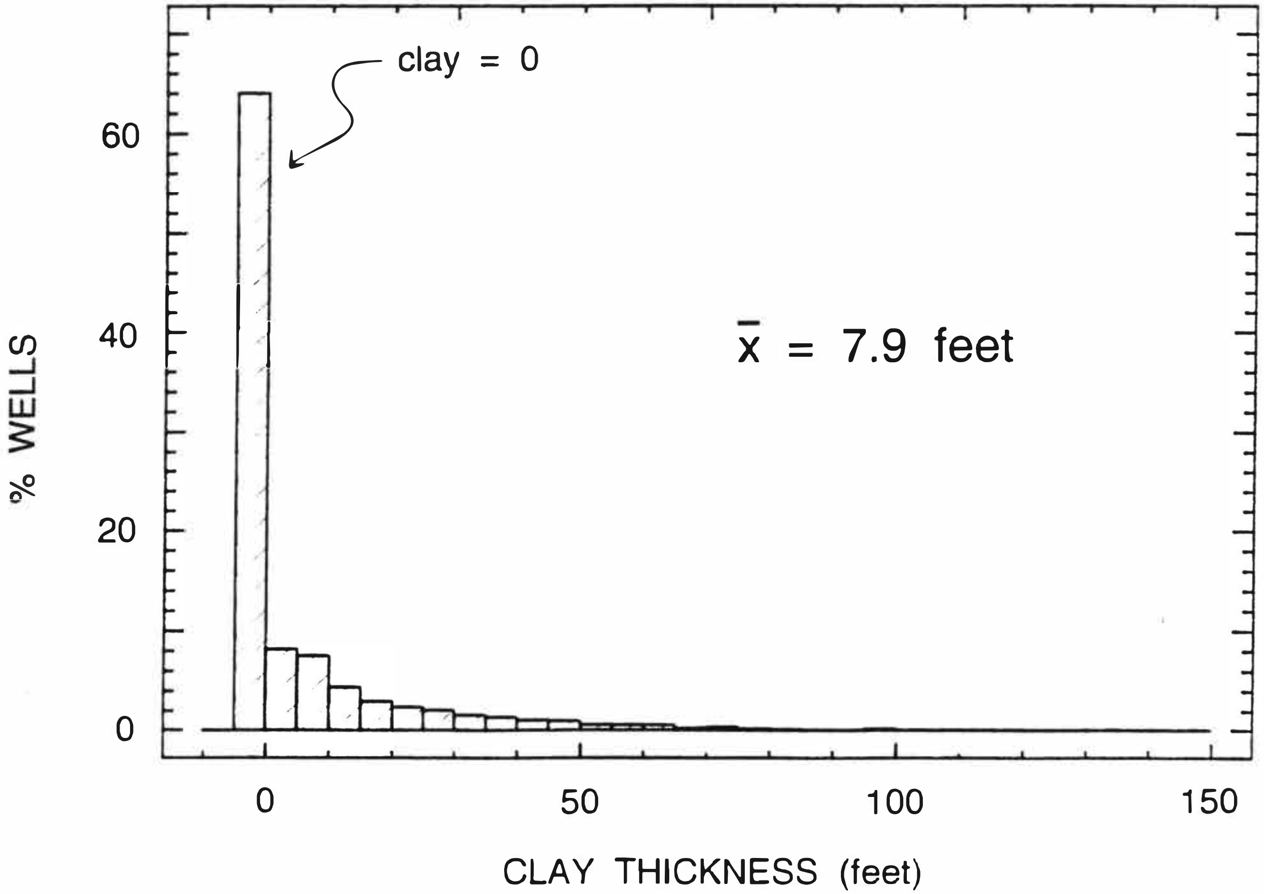


Figure 24. Histogram Showing Clay Thickness Distribution for All Study Wells (N = 3620).

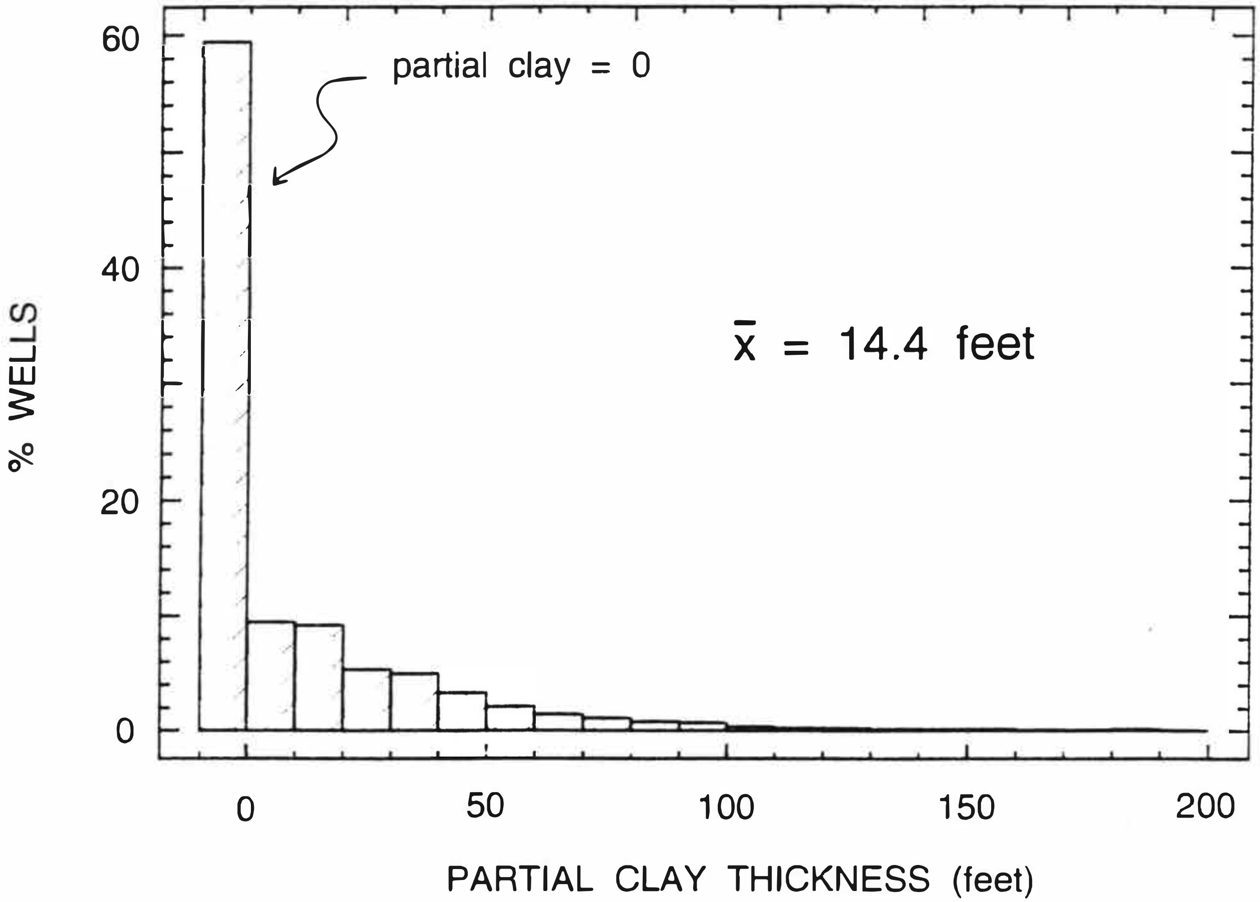


Figure 25. Histogram Showing Partial Clay Thickness Distribution for All Study Wells (N = 3620).

were analyzed using a simple t-test with nitrate-N as the independent variable (Table 3). The hydrogeologic parameters tested were: depth to static water level (SWL); well depth (WD); Depth of well submergence (DofS); clay thickness (CT); partial clay thickness (PT); clay thickness above the static water level (CTA); and partial clay thickness above the static water level (PTA). The nitrate-N intervals are given in the first column, followed by the mean nitrate-N value for that interval and the number of wells which have nitrate-N concentrations within that interval. The mean value for each hydrogeologic parameter within a nitrate-N interval is given, and the statistical significance of the comparison of the corresponding means is given under each set of means.

The parameters which show the greatest number of statistically significant differences are well depth, depth of submergence, clay thickness, partial clay thickness, and clay thickness above the static water level (Table 3). The set of nitrate-N intervals which show the greatest number of statistically significant differences are the greater than non-detect to 3 mg/l compared with the greater than 3 mg/l nitrate-N. This suggests that the background nitrate-N may be approximately 3 mg/l which is comparable to the value found by Leatherman, Foust, and West (1993). However, 50 % of the wells had non-detectable nitrate-N.

Unequal variance t-tests using the natural logarithm of the nitrate-N concentration as the dependant variable are given in Appendix F. Each hydrogeologic parameter, as the independent variable, was tested at numerous intervals to detect changes in the significance of the differences. The hydrogeologic

Table 3

T-test Results With Nitrate-N as Independant Variable for Kalamazoo County Wells

NO_3^--N mg/l	X mg/l	N	SWL feet	TD feet	DofS feet	CT feet	PT feet	CTA feet	PTA feet
> ND-2	0.87	704	46.4	86.9	40.5	7.4	13.2	2.4	7.7
> 2	6.48	1176	45.5	82.4	37.0	5.1	11.9	1.9	7.4
Significance			0.57	0.02	0.004	0.001	0.28	0.13	0.75
> ND-3	1.23	897	46.5	86.6	40.1	7.3	13.4	2.4	8.0
> 3	7.25	983	45.2	81.8	36.6	4.7	11.4	1.7	7.2
Significance			0.41	0.007	0.001	0.0001	0.07	0.04	0.36
> ND-4	1.64	1092	46.3	85.6	39.3	6.9	13.5	2.3	8.1
> 4	8.18	788	45.1	82	36.8	4.6	10.8	1.7	6.8
Significance			0.44	0.04	0.02	0.0003	0.02	0.06	0.13
> ND-5	2.02	1253	45.8	84.6	38.9	6.7	13.4	2.3	8.1
> 5	9.11	627	45.9	83.1	37.1	4.5	10.3	1.6	6.4
Significance			0.91	0.39	0.10	0.0008	0.007	0.04	0.04

parameter intervals are given first, followed by the number of wells within each interval and the mean nitrate-N value for each interval. The significance of the difference between the means in each set of intervals is given below the mean values. The parameters which show statistically significant differences are depth of well, depth of submergence, clay thickness, and partial clay thickness.

For shallow depths to static water level the relationship between nitrate-N and depth to water is the opposite of that which is expected (Appendix F). The average nitrate-N concentration for wells with equal to or less than 10 feet depth to water is 1.11 mg/l. This is lower than the mean nitrate-N value of 2.43 mg/l for the wells with depth to water greater than 10 feet. At a depth to water of 100 feet the relationship reverses and the deeper depths to water have the lower nitrate-N concentrations as predicted. These relationships suggest that the processes taking place in the vadose zone are not affecting the nitrate-N concentration as predicted except at deep depths to static water level.

For well depths equal to or less than 70 feet the relationship with nitrate-N concentration is similar to that found for depth to water (Appendix F). The deeper well depths have a higher mean nitrate-N concentration than the shallower wells, contrary to the expected results. Nitrate-N concentration should decrease with increasing depth (Chen and Druliner, 1987; Murphy, 1992). At well depth equal to 80 feet this relationship reverses to the expected results. For depth intervals greater than 80 feet the differences between the mean nitrate-N concentrations are significant. Murphy (1992), using a Mann-Whitney non-parametric test for wells in New Jersey, found that "well water deeper than 30 meters (98 feet) from the ground surface was found to contain significantly lower nitrate levels than water from wells less than 30 m deep" (Murphy, 1992, p.184).

The depth of submergence intervals show a statistically significant difference in mean nitrate-N for every interval except those equal to or less than 10 feet (Appendix F). Only 21 wells, however, have depths of submergence equal to or less than 10 feet. Wells with a greater depth of submergence have on average, a lower nitrate-N concentration.

Clay thickness shows statistically significant differences between the means for all the intervals compared (Appendix F). The greater the clay thickness, the lower the nitrate-N concentration as expected.

Partial clay thickness also shows statistically significant differences between the means for all the intervals compared (Appendix F). The greater the partial clay thickness, the lower the nitrate-N concentration as expected.

The clay thickness above the static water level shows statistically significant differences between the mean values only for wells in the first two intervals. For wells with thickness intervals greater than 5 feet, the difference between the mean nitrate-N concentrations is not significant. This can be attributed to the lack of clay above the static water level which is reflected in the well numbers in the higher clay thickness intervals. Only 50 wells have greater than 30 feet of clay above the static water level.

The partial clay thickness above the static water level shows no statistically significant differences between the mean values in nitrate-N. This is likely due to the lack of partial clay above the static water level. Of the 3620 wells, 112 have greater than 50 feet of partial clay above the static water level.

Pearson-r correlation coefficients were calculated for all combinations (pairs) of hydrogeologic parameters vs. the natural logarithm of nitrate-N concentration for all wells (Appendix F). The statistical significance of each correlation is given after the coefficient value.

Well depth shows a high positive correlation with depth to static water level (0.73), depth of submergence (0.66), clay thickness (0.41), and partial clay thickness (0.51). As well depth increases, the values of the depth to static water level, depth of submergence, clay thickness, and partial clay thickness also increase, as predicted. Well depth has a slight inverse correlation with the natural logarithm of nitrate-N concentration.

The depth to static water level shows positive correlation with clay and partial clay thickness. The depth to static water, however, shows no correlation with depth of submergence. This indicates that there is no significant relationship between the depth to water and the depth of submergence, i.e. the depth a well is drilled below the water table. Nor is there a correlation of the depth to static water level to the nitrate-N concentration, and this lack of relationship is statistically significant.

The depth of submergence shows positive correlation with clay and partial clay thickness as expected. Depth of submergence shows the highest correlation with nitrate-N concentration.

Clay and partial clay thickness are not correlated with each other. Clay and partial clay thickness show slight negative correlations with nitrate-N concentration.

Multiple Regression Model for Aquifer Sensitivity

Least-squares multiple regression was used to determine the amount of variance in the total nitrate-N concentration that is accounted for by the hydrogeologic parameters. The statistical model yielding the highest r^2 was obtained by using the hydrogeologic parameters which had statistically significant relationships with the natural logarithm of nitrate-N concentration from the t-test and correlation results. This model is represented by a multiple regression equation which explains 8.54 % of the total variance in nitrate-N concentration:

$$N = -0.451 - 0.021(DofS) + 0.011(WD) - 0.011(C) - 0.005(PT)$$

where DofS is the depth of submergence in feet, WD is well depth in feet, C is clay thickness in feet, and PT is partial clay thickness in feet. This equation describes a predicted natural logarithm of the nitrate-N concentration for specific values of each hydrogeologic parameter used. For example, if the values for well depth, clay thickness, and partial thickness were held constant, and the value for depth of submergence was allowed to vary, larger values of depth of submergence would yield lower predicted nitrate-N concentrations. This same procedure used for well depth (keeping the other parameters constant) implies that larger well depths produce higher predicted nitrate-N concentrations. This anomalous relationship is caused by two factors: (1) the amount of total variance explained (8.54 %) is not sufficient to produce a reliable predictive model, and (2) when a regression model uses more than one independent variable, the relationships between the independent and the dependent variables are influenced by the relationships between the independent variables themselves. To understand these relationships, the individual correlation coefficients must be examined. Well depth has a slight inverse correlation (-0.05) with the natural logarithm of nitrate-N concentration. This indicates that well depth has the expected relationship with nitrate-N when compared independently, but when influenced by the other hydrogeologic parameters, the weak inverse correlation changes to a direct correlation.

This multiple regression equation could be used to modify the existing AQUIPRO aquifer sensitivity model (Appendix D). The major change to AQUIPRO would be the addition of the depth of submergence parameter possibly in place of the well depth. To alter AQUIPRO it would first be necessary to test the predictive capabilities of the multiple regression equation. The equation could be modified to produce aquifer sensitivity scores similar to the AQUIPRO aquifer protection scores. Using a data set containing the hydrogeologic parameters and corresponding contaminant concentrations, scores could be produced by each method using the hydrogeologic data, and then statistically compared with contaminant concentrations. Modifications of the AQUIPRO model would be justified if the model obtained from the multiple regression yielded a higher statistical correlation with the contaminant concentration than the original

AQUIPRO model.

Comparison of Nitrate-N Concentrations and Hydrogeologic Parameters in Glacial Map Units by Analysis of Variance

An aquifer sensitivity model might be expected to yield different sensitivity values for different glacial map units. Figure 26 shows the digitized glacial map units for Kalamazoo County. The area within the dashed line is primarily urban and industrial supplied by municipal wells and therefore is not represented in the residential well database.

Figure 27 is a multiple box-and-whisker plot showing the surface elevation of wells for each of the glacial map units. The number of wells representing each unit is listed above the map unit abbreviation. The boxes represent the middle 50 % of the data, from the first quartile (lower horizontal line), to the third quartile (upper horizontal line). The horizontal line within the box represents the median value. The vertical lines projecting from the box (whiskers) represent data which have values up to 1.5 times the inter-quartile range. The square point symbols represent data values which fall between 1.5 and 3 times the inter-quartile range. The crosses represent extreme data with values greater than 3 times the inter-quartile range.

The highest well elevation (1050 feet) is on the Kalamazoo moraine as expected. The elevations for the Wakeshma till plain (850 to 990 feet) and the Climax-Scotts outwash plain (880 to 990 feet) are higher than might generally be

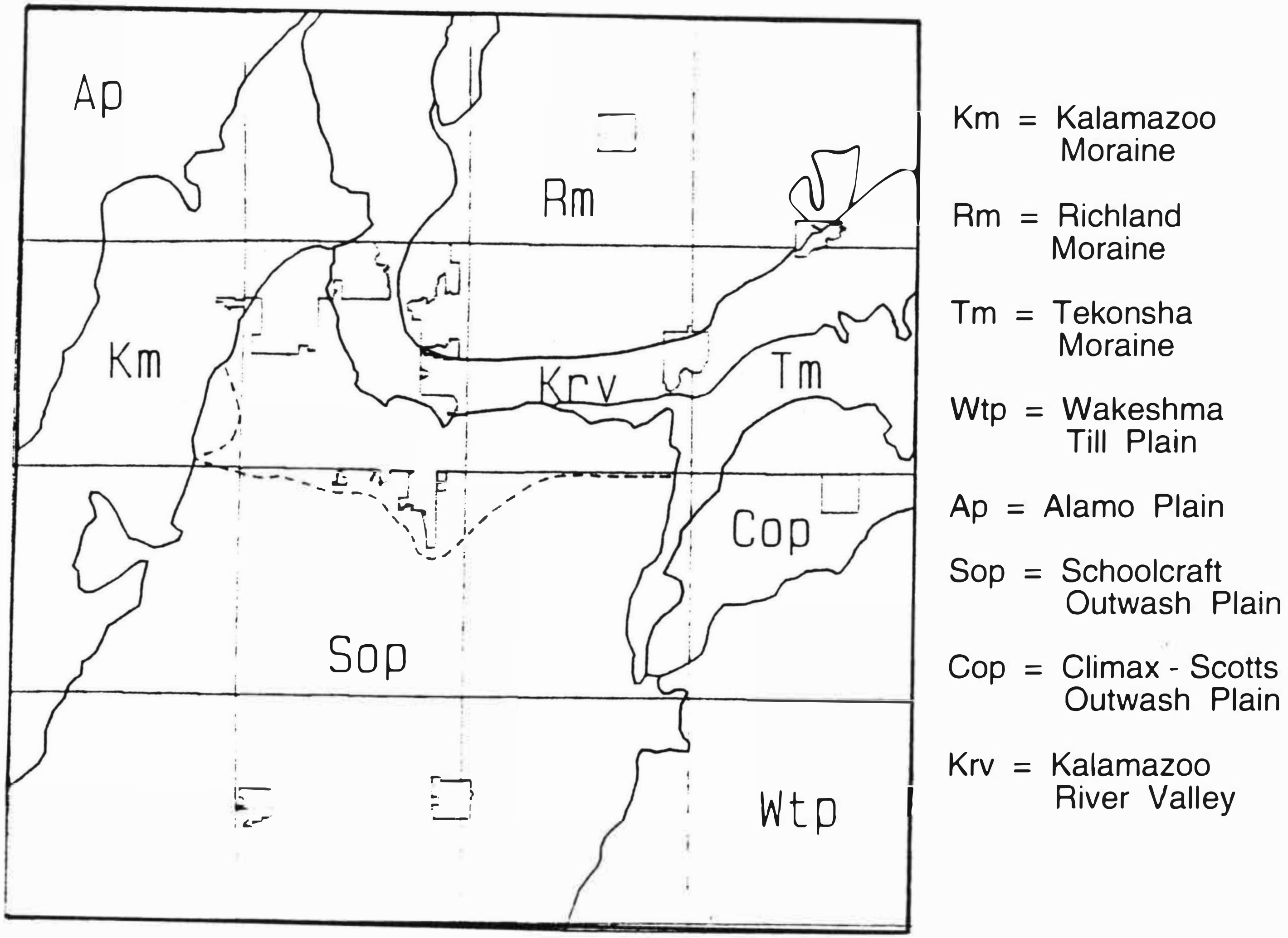


Figure 26. Map Showing Glacial Map Units in Kalamazoo County.

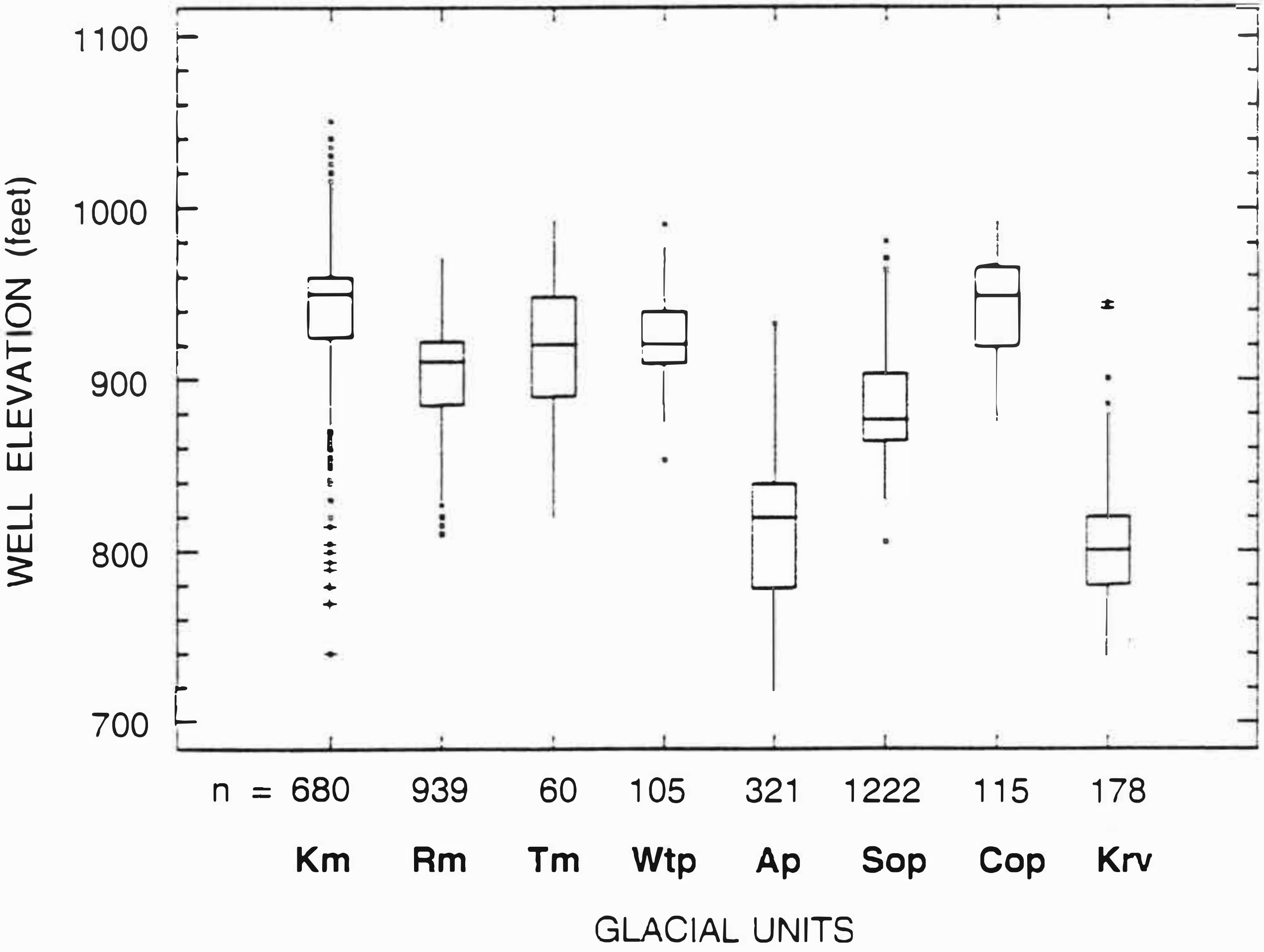


Figure 27. Multiple Box-and-Whisker Plot of Well Elevation by Glacial Map Units in Kalamazoo County.

predicted for till plains and outwash plains relative to moraines. The lowest well elevations are found in the Alamo plain (720 feet) and the Kalamazoo River Valley (740 feet).

A multiple box-and-whisker plot of well depth (Figure 28) shows that the median well depths are greatest under the moraines (90 to 128 feet), and shallowest under the outwash plains and the Kalamazoo River Valley (61 to 75 feet). An analysis of variance diagram (Figure 29) shows the ordering of the glacial map units by increasing mean values of the hydrogeologic parameters and nitrate-N. The bars (lines) below the mean values represent the values that are statistically from the same population. The individual bars under the moraines indicate that the three moraines are statistically different from the other glacial units. A significance level of 95 % ($P \leq 0.05$) was used to determine statistical significance.

A multiple box-and-whisker plot of depth to static water level (Figure 30) shows that the greatest depth to water (200 feet) is under the Kalamazoo moraine. The depths to water under the outwash plains and the river valley are shallower (up to 125 feet). The analysis of variance diagram (Figure 29) shows that the Wakeshma till Plain has the shallowest median depth to water (22 feet). The Wakeshma till plain, the Climax-Scotts outwash plain (26 feet), the Schoolcraft outwash plain (23 feet), and the Kalamazoo River Valley (25 feet) have statistically similar values.

A multiple box-and-whisker plot of depth of submergence (Figure 31) shows that in general, the variation in depth of submergence is small across the county.

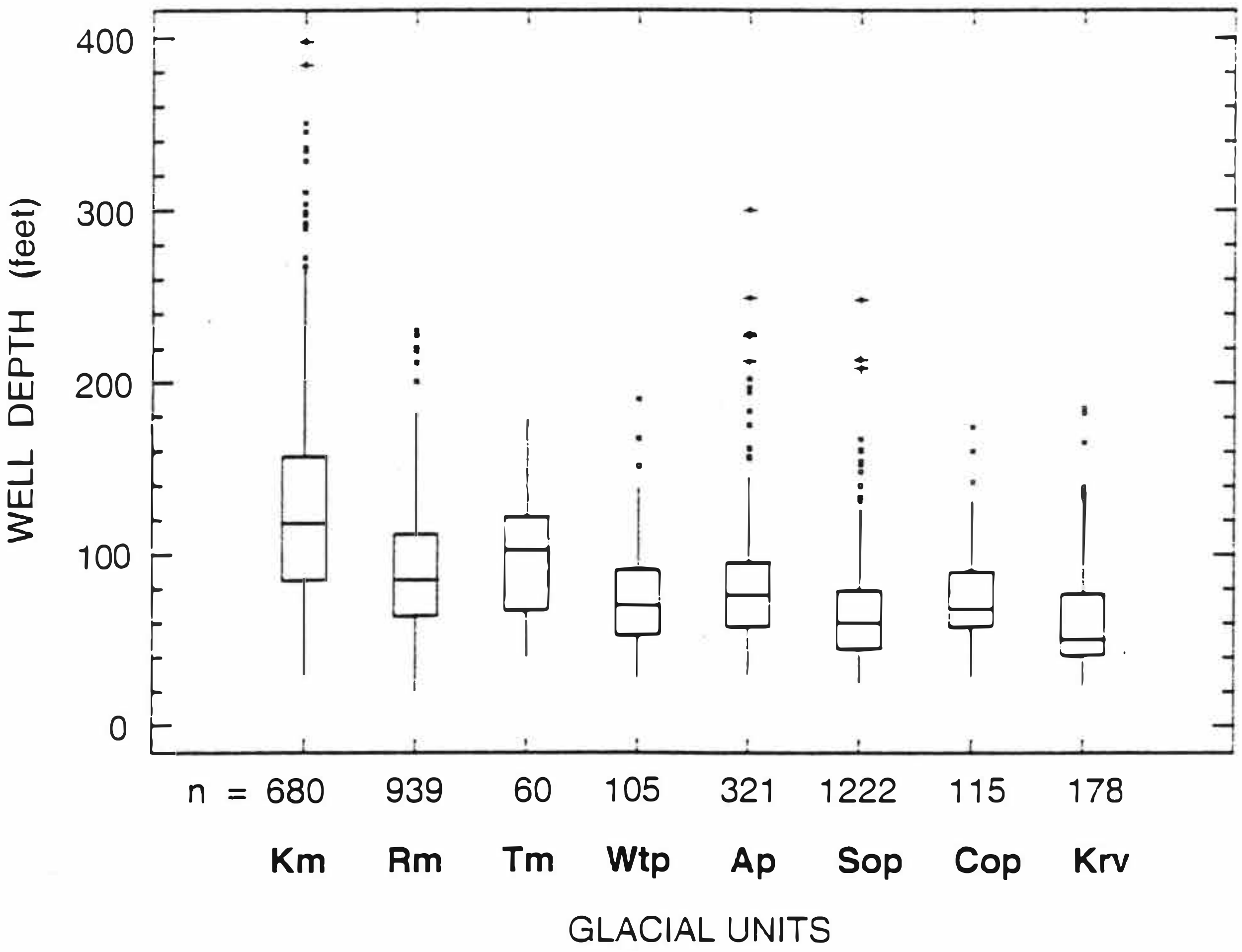


Figure 28. Multiple Box-and-Whisker Plot of Well Depth by Glacial Map Units in Kalamazoo County.

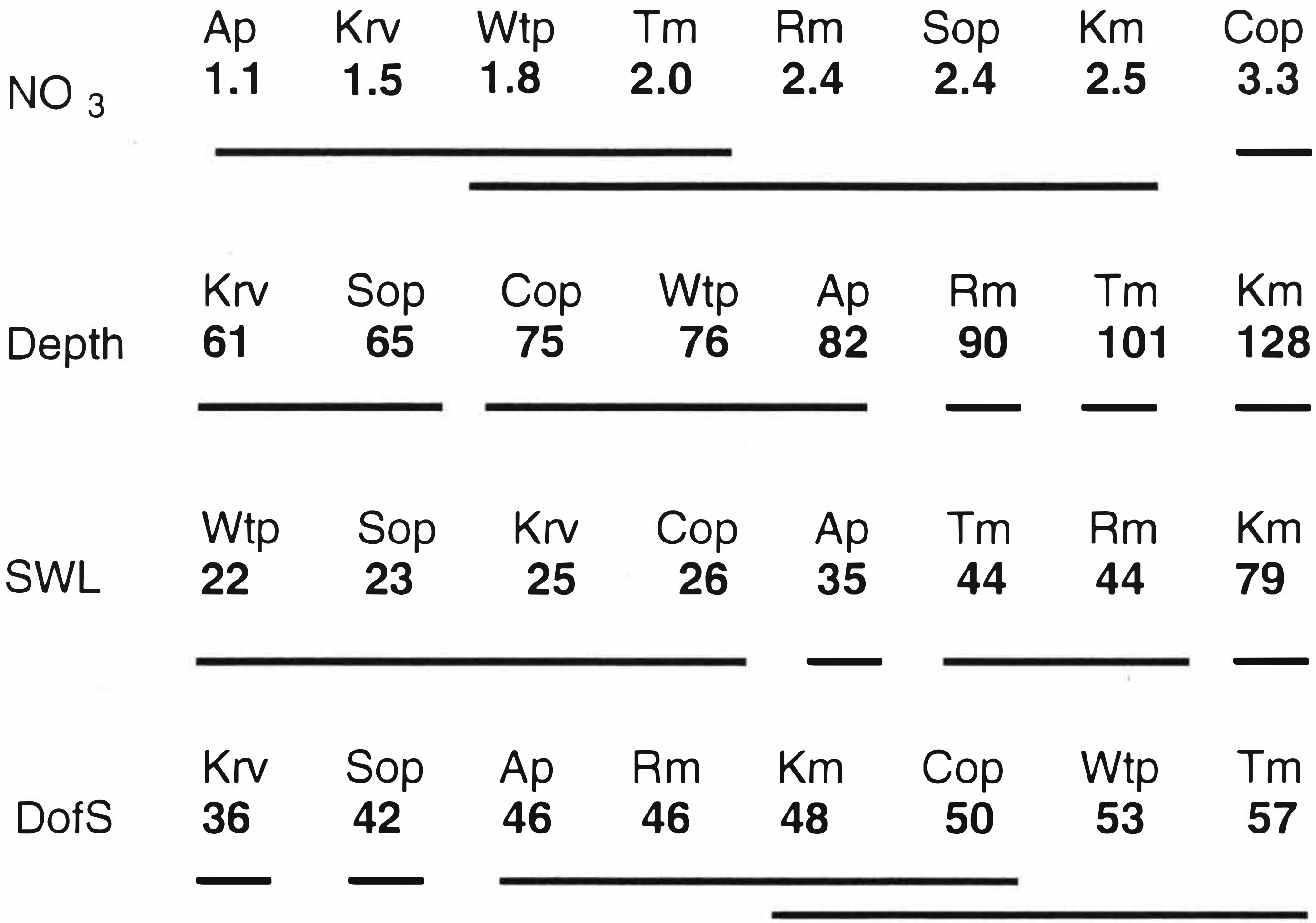


Figure 29. Analysis of Variance Summary for Well Depth, Depth to Static Water Level, and Depth of Submergence by Glacial Map Units in Kalamazoo County.

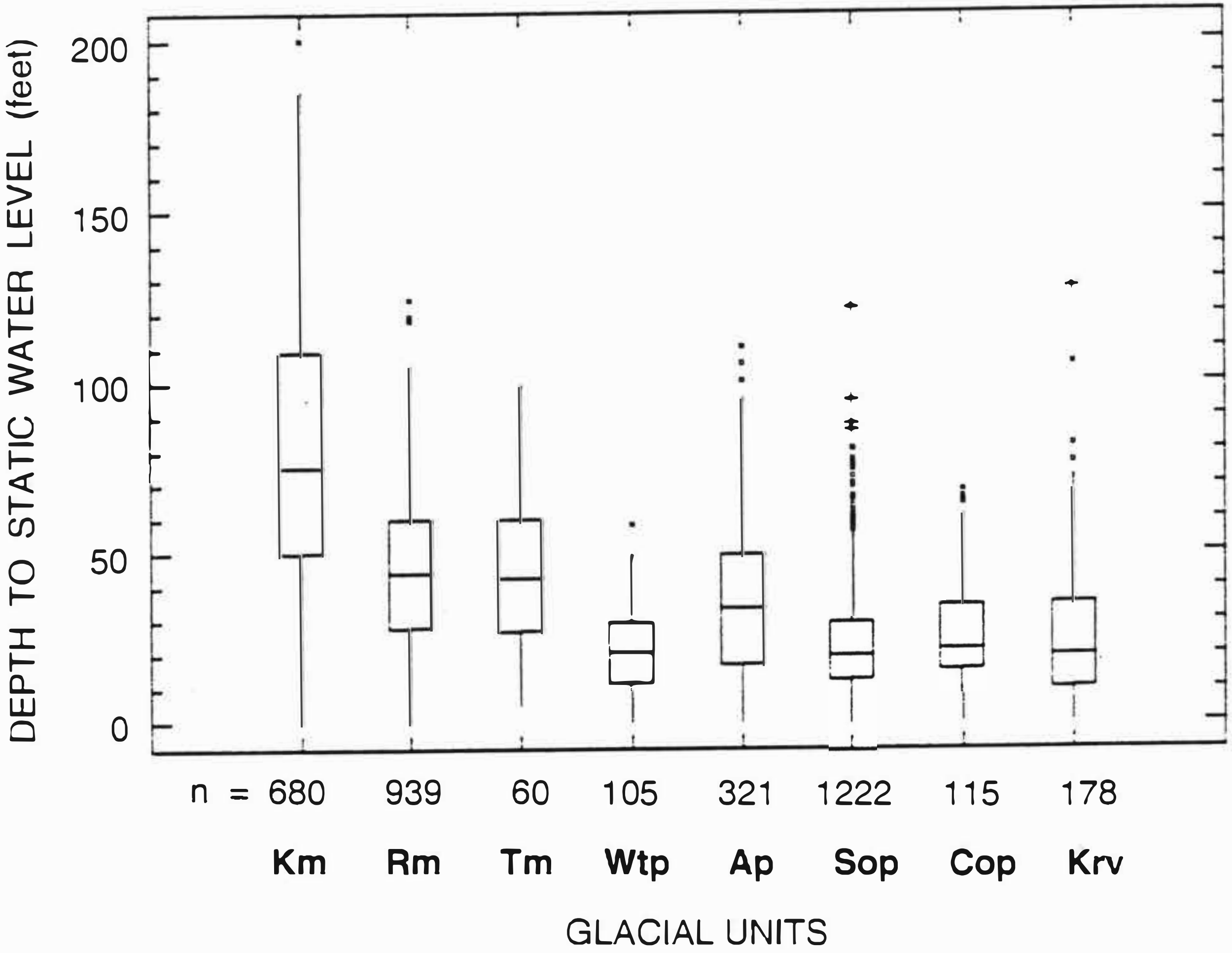


Figure 30. Multiple Box-and-Whisker Plot of Depth to Static Water Level by Glacial Map Units in Kalamazoo County.

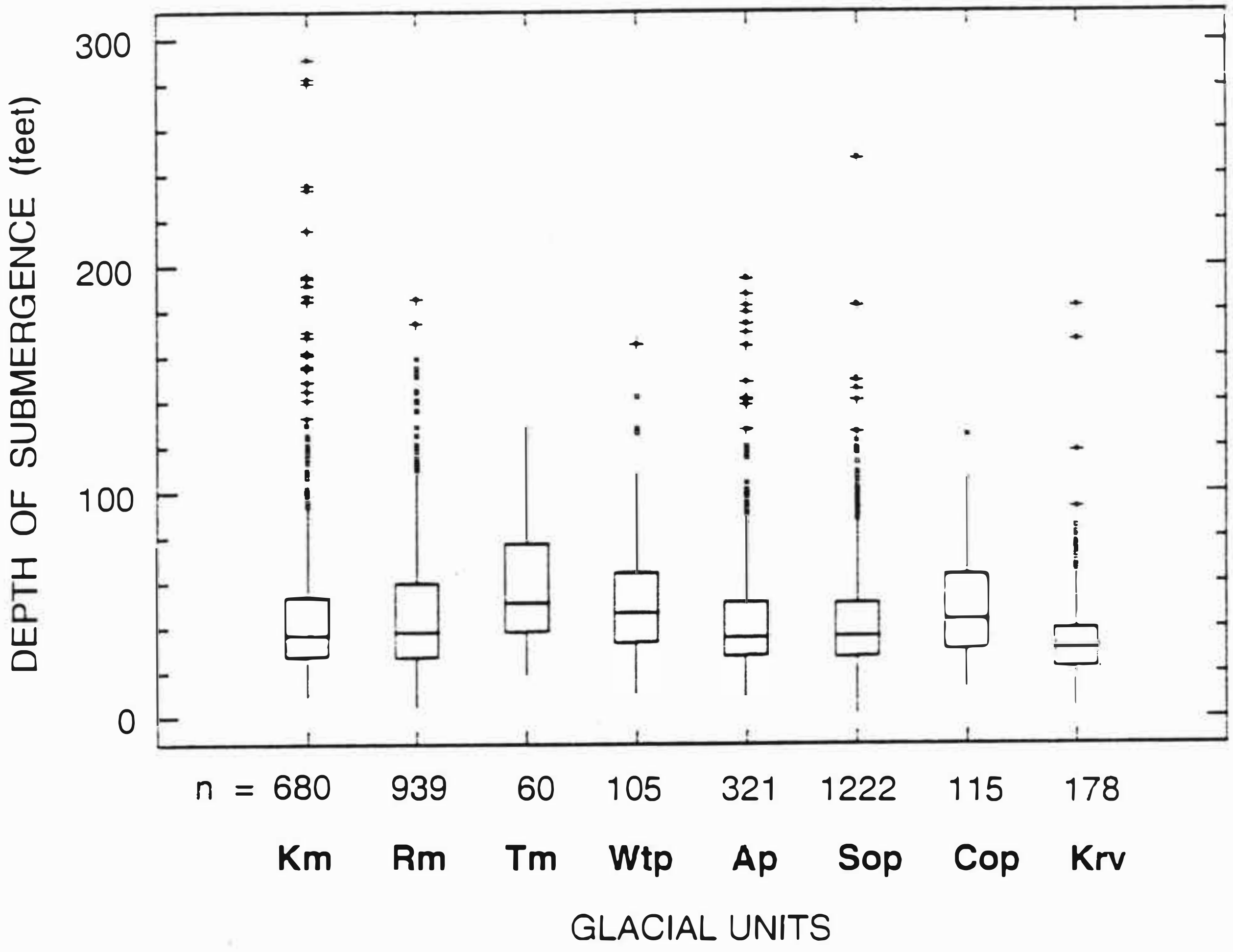


Figure 31. Multiple Box-and-Whisker Plot of Depth of Submergence by Glacial Map Units in Kalamazoo County.

This can be attributed to the economics of well drilling. Drilling deeper costs more; thus, wells are drilled to a minimum depth which will produce a safe and adequate supply. The analysis of variance shows that the greatest mean depths of submergence occur under Tekonsha moraine (57 feet) and the Wakeshma till plain (53 feet). The ordering of these glacial units from lowest to greatest suggests that the Wakeshma till plain and the Tekonsha moraine are different from the Richland moraine (46 feet) and the Alamo plain (46 feet) in terms of mean depths of submergence.

A multiple box-and-whisker plot of clay thickness (Figure 32) shows that there are a number of wells with large amounts of clay. The median values are all zero except for the median clay thickness for the Alamo plain which is approximately 4 feet. The analysis of variance (Figure 33) shows that the greatest mean clay thickness is under the Kalamazoo moraine (14 feet) and the Wakeshma till plain (16.3 feet). It is generally expected that the moraines will contain the thickest deposits of clay. The analysis of variance shows that the Richland moraine (mean clay thickness of 6.3 feet) and Tekonsha moraine (8.8 feet) are different from the Kalamazoo moraine, and similar in clay content to the Climax-Scotts outwash plain (3.9 feet), the Schoolcraft outwash plain (4.3 feet), and the Kalamazoo River Valley (7.5 feet). The outwash plains have the lowest average clay thickness as expected.

A multiple box-and-whisker plot of partial clay thickness (Figure 34) shows that the median partial clay thickness is zero for all the glacial units except the

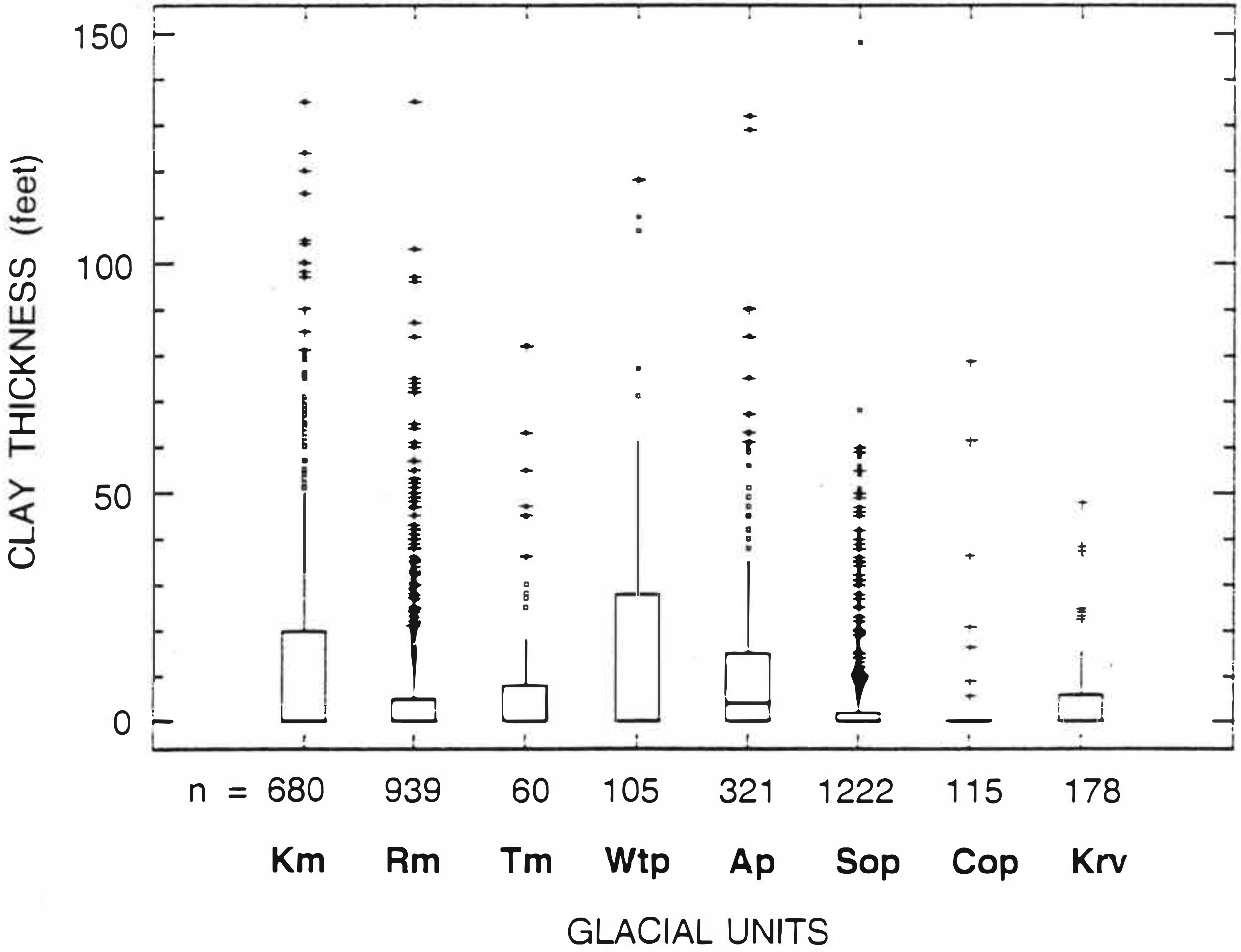


Figure 32. Multiple Box-and-Whisker Plot of Clay Thickness by Glacial Map Units in Kalamazoo County.

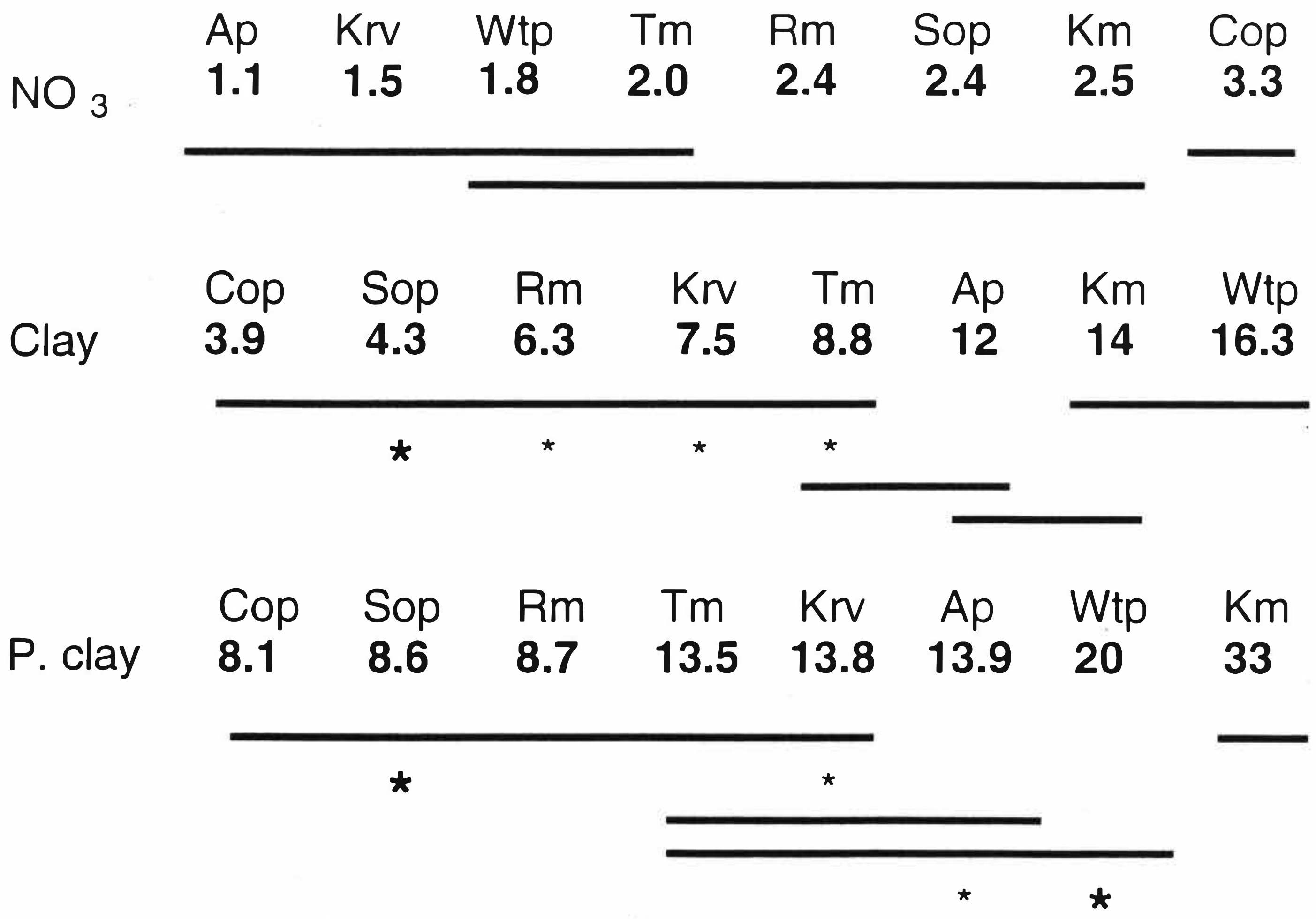


Figure 33. Analysis of Variance Summary for Clay and Partial Clay Thickness by Glacial Map Units in Kalamazoo County.

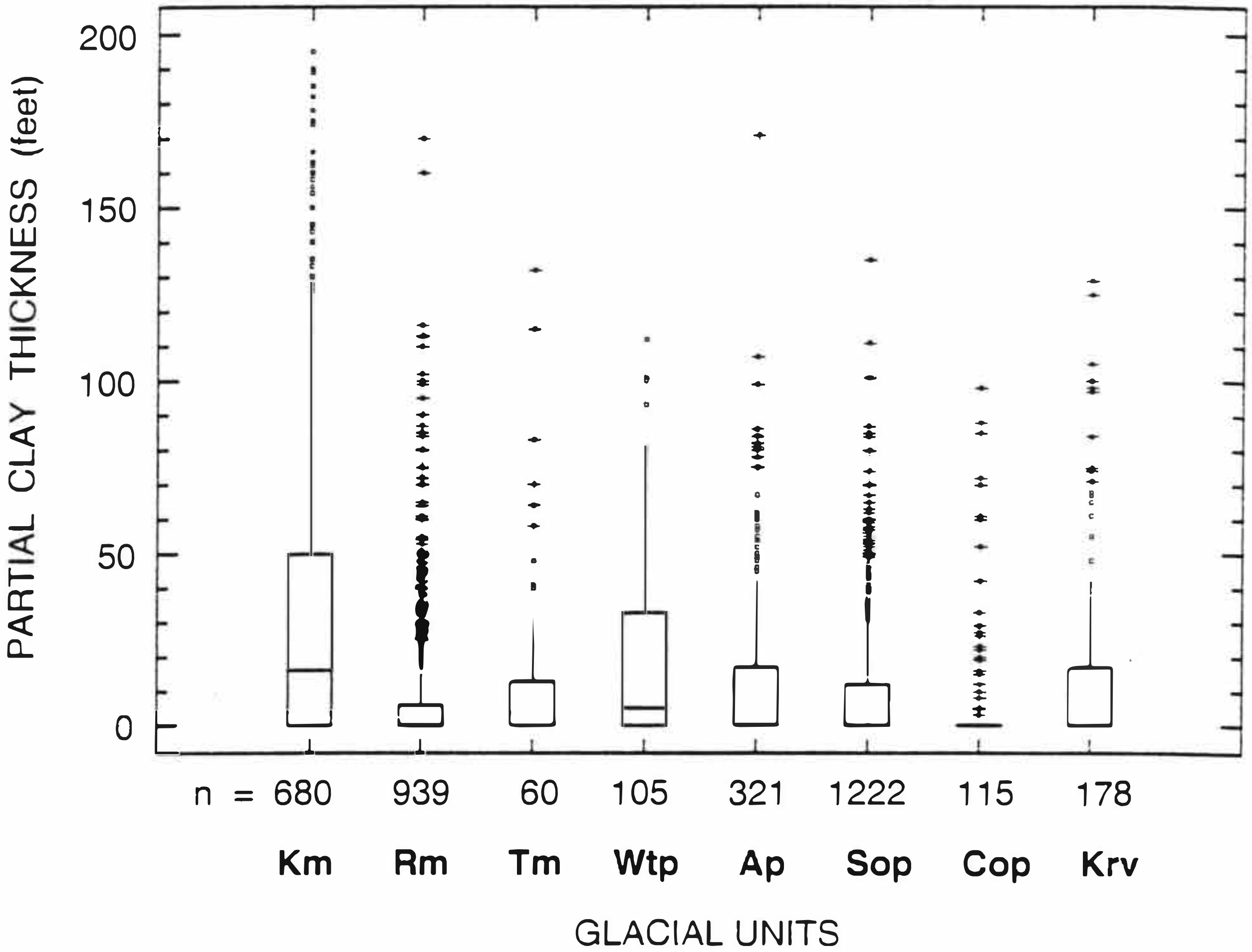


Figure 34. Multiple Box-and-Whisker Plot of Partial Clay Thickness by Glacial Map Units in Kalamazoo County.

Kalamazoo moraine (15 feet) and the Wakeshma till plain (5 feet). This corresponds to the analysis of variance with the greatest mean partial clay located under the Kalamazoo moraine (33 feet) followed by the Wakeshma till plain (20 feet). The outwash plains have the least partial clay (approximately 8 feet) and are similar to the Richland moraine (8.7 feet), the Tekonsha moraine (13.5 feet), and the Kalamazoo River Valley (13.8 feet).

A multiple box-and-whisker plot of greater than non-detect nitrate-N (Figure 35) shows that the highest median values of nitrate-N are in the Climax-Scotts outwash plain (7 mg/l), the Wakeshma till plain (4 mg/l), the Richland moraine (3.8 mg/l), and the Schoolcraft outwash plain (3.7 mg/l). These four glacial map units are the most cultivated areas in the county (Dickason and Kalamazoo County Planning Commission, 1981).

The Wakeshma till plain has the lowest mean depth to static water level (22 feet) and the second greatest mean depth of submergence (53 feet). This is explained by the large amount of clay (mean of 16.3 feet) and partial clay (mean of 20 feet) encountered under the Wakeshma till plain. Thick clay and partial clay layers near the surface will generally raise the water table. Encountering these layers below the water table will force the driller to go deeper to obtain a sufficient water supply.

The distributions of the hydrogeologic variables across the glacial map units are somewhat different from what was expected. Well depth is the only parameter which yielded the expected results with the moraines having the deepest wells, and

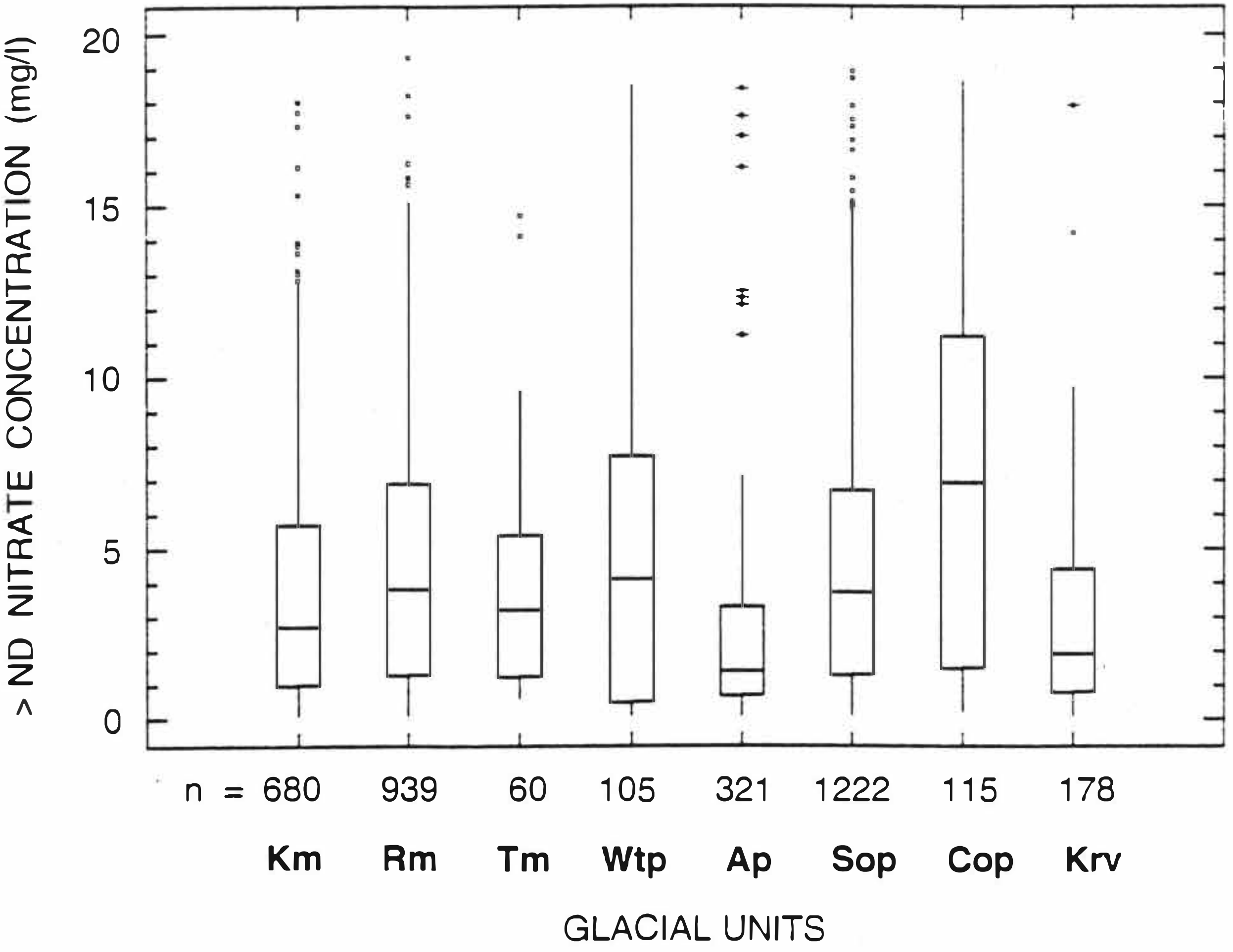


Figure 35. Multiple Box-and-Whisker Plot of Greater Than Non-Detect Nitrate-N Concentration by Glacial Map Units in Kalamazoo County.

the outwash plains and the Kalamazoo River Valley having the shallowest wells. The depth to static water level and depth of submergence do not appear to be directly correlated with each other. Clay and partial clay thicknesses indicate that in general the moraines are not similar and do not necessarily have the thickest clay and partial clay. In terms of an aquifer sensitivity model, the composition of the individual units must be understood to truly understand the vulnerability. Aquifer sensitivity cannot be based on generalizations for glacial map units.

Comparison of Nitrate-N Concentrations and Agricultural Parameters by T-test and Correlation

In an effort to explain a larger percentage of the total variance in nitrate-N concentrations, t-tests and Pearson-r correlation statistics were used to investigate the relationships between agricultural parameters and the natural logarithm of nitrate-N concentration. The results of previous studies show that different agricultural landuse parameters such as fertilizer loading, irrigation, and livestock management account for a significant amount of the total variance in the nitrate-N concentrations found in groundwater (Chen and Druliner, 1987; Steichen et al., 1988). Information on these parameters is difficult to obtain for a large number of well sites in an area such as Kalamazoo County. The agricultural parameters which were quantified included: (a) agricultural landuse, (b) recommended fertilizer loading, (c) soil attenuation potential, and (d) soil slope.

The 1978 landuse for Kalamazoo County (Figure 9) shows that approximately

40 % of the county is in agriculture (WMU Geography Department and Kalamazoo Co. Planning Commission, 1981). Twenty-five percent of the wells in the county database fall in the agricultural landuse areas. The discrepancy between these numbers can be attributed to wells being located on rural residential plots (e.g. farmsteads and rural subdivisions). These wells coded as non-agricultural may be completely surrounded by agricultural land.

An unequal variance t-test applied to agricultural landuse vs. non-agricultural landuse found that the mean nitrate-N concentration for agricultural landuse (2.7 mg/l) was higher than the mean nitrate-N (2.1 mg/l) for non-agricultural landuse (Table 4). This difference was statistically significant at the 95 % confidence level ($P \leq 0.05$). Using only wells having greater than non-detect nitrate-N, the mean nitrate-N concentration is 5.2 mg/l for the wells in agricultural landuse areas and 4.1 mg/l for wells in non-agricultural landuse areas. This difference was also statistically

Table 4

T-test Results for Agricultural Landuse vs. Non-agricultural Landuse in Kalamazoo County

Landuse	% of Total Area	Nitrate-N mg/l	Nitrate-N > 0 mg/l
Agricultural	25	2.68	5.15
Non-agricultural	75	2.14	4.13

significant at the 95 % confidence level ($P \leq 0.05$).

Recommended fertilizer loading (obtained using suggested fertilizer application rates) did not show a statistically significant relationship with nitrate-N concentration. An unequal variance t-test with nitrate-N concentration as the dependant variable shows that in general, the smaller loading rates had higher average nitrate-N concentrations (Table 5). This suggests that the actual fertilizer loading rates may be quite different from the recommended fertilizer loading.

Table 5

T-test Results for Low Fertilizer Loading Rates vs. High Fertilizer Loading Rates for Kalamazoo County

Fertilizer Loading lb/acre/yr	Nitrate-N mg/l	Nitrate-N > 0 mg/l
≤ 8	2.48	4.24
> 16	2.11	5.34

Soil SEEPPAGE attenuation potential (Appendix C), did not yield a statistically significant relationship with nitrate-N concentration (dependant variable). An unequal variance t-test found that the higher the soil attenuation potential, the higher the nitrate-N concentration. It is expected that higher attenuation potential soils should yield lower nitrate-N concentrations. A possible explanation for this anomalous result is that the soils which have the highest attenuation potentials are those soils which are the best for crop cultivation. Fertilizer loading on cultivated soils would increase the nitrate-N concentrations under the high attenuation soil types. Table 6 lists the Kalamazoo County soils with their attenuation potentials and the average nitrate-N concentration found in the wells within each soil type. For Kalamazoo County, the two highest attenuation potential soils are the Kalamazoo and the Schoolcraft series. These are also the soils most cultivated in Kalamazoo County (Heffner, 1993).

An unequal variance t-test was used to test for a statistically significant relationship between nitrate-N (dependant variable) and soil slope value (Table 7). The soils with 0 to 6 % slope (A and B slopes) had a mean nitrate-N concentration of 2.5 mg/l. The soils with greater than 6 % to 26.5 % slopes (C and D slopes) had a lower mean concentration of 1.8 mg/l nitrate-N. This difference was statistically significant at the 95 % confidence level ($P \leq 0.05$).

Thus the only agricultural parameters which showed statistically significant relationships with nitrate-N concentration are agricultural landuse and soil slope. Agricultural parameters such as irrigation and fertilizer loading were not successfully quantified in this study but should be addressed in future studies.

Multiple Regression Model for Ground Water Vulnerability

The agricultural landuse and soil slope were combined with the hydrogeologic parameters from the aquifer sensitivity model to develop a ground-water

Table 6

Nitrate-N Concentrations and Attenuation Potentials for Kalamazoo County Soils

Soil	N	NO3	TexA	TexB	pH	Organ	Perm	Drain	Aten
Ad	5	1.66	7	1	4	9	2	1	24
BdA	2	2.45	1	1	1	5.5	3	1	12.5
BrA	2	0.7	1	1	6	5	4	4	21
CoB	95	2.4	1	1	4	1	2	7	16
CoC	79	2.36	1	1	4	1	2	7	16
CoD	55	2.99	1	1	4	1	2	7	16
DoA	14	6.04	9	7	4	5	4	10	39
Gd	4	1.03	1	1	6	6	4	1	19
Gy	1	0.2	1	1	4	8	2	1	17
Hn	3	5.8	7	7	6	9	6	1	36
Hs	5	1.94	7	7	6	1	6	1	28
KaA	74	6.02	9	7	6	5	6	10	43
KaB	398	4.83	9	7	6	5	6	10	43
KaC	120	4.49	9	7	6	5	6	10	43
OsB	316	4.13	1	1	6	4	4	10	26
OsC	145	3.76	1	1	6	4	4	10	26
OsD	67	4.11	1	1	6	4	4	10	26
OsE	87	3.66	1	1	6	4	4	10	26
PfB	2	2.45	1	1	1	1	2	1	7
RdB	36	5.89	9	7	6	1	6	10	39
RdC	5	5.56	1	7	6	1	6	10	39
SaA	46	8.75	9	7	6	5	6	10	43
SaB	37	7.94	9	7	6	5	6	10	43
Sb	3	3.4	9	7	6	5.5	6	1	34.5
SeA	12	4.46	9	7	6	1	6	1	30
SpB	224	4.67	1	1	4	6	2	10	24
SpC	105	3.82	1	1	4	6	2	10	24
SpD	21	4.9	1	1	4	6	2	10	24
StE	5	2.18	1	1	4	6	3	10	25
ThA	2	1.2	1	1	1	5.5	4	1	13.5

Table 7

T-test Results for Low Percent Slope vs. High Percent Slope Soil Units in Kalamazoo County

Slope %	Nitrate-N mg/l
0 - 6 (A & B Soils)	4.24
> 6 - 26.5 (C & D Soils)	5.34

vulnerability model. A least-squares multiple regression was used to determine the amount of variance in the total nitrate-N concentration that is accounted for by the addition of the agricultural parameters to the model. This model is represented by a multiple regression equation which explains 9.3 % of the total variance in nitrate-N concentration:

$$N = -0.442 - 0.022(DofS) + 0.012(WD) - 0.011(C) - 0.279(S) - 0.005(PT) + 0.172(A)$$

where DofS is the depth of submergence in feet, WD is well depth in feet, C is clay thickness in feet, S is the soil slope, PT is partial clay thickness in feet, and A is agricultural landuse. This equation describes a predicted natural logarithm of the nitrate-N concentration for specific values of each hydrogeologic and agricultural parameter used. In this multiple regression, nitrate-N concentration is inversely proportional to depth of submergence, clay thickness, soil slope, and partial clay thickness. Nitrate-N is directly proportional to well depth and agricultural landuse. These relationships are consistent with theory with the exception of the well depth relationship. As in the previous multiple regression aquifer sensitivity equation, this relationship is explained by the low r^2 and the interrelationships between each parameter.

The multiple regression equation could also be used to modify AQUIPRO (Appendix D) resulting in a agricultural ground-water vulnerability model. Modifications of the AQUIPRO model would be justified if the modified model when compared with the original AQUIPRO model yielded a higher statistical correlation with the contaminant concentrations found in agricultural areas.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Two methods were used to describe how contaminants applied at the ground surface can affect the quality of groundwater. Aquifer sensitivity methods consider only the effects of the hydrogeologic parameters on contaminant concentrations. Ground-water vulnerability methods consider the contaminant source parameters as well as the hydrogeologic parameters. T-tests, Pearson-r correlation, least-squares analysis of variance, and multiple regression were used to relate nitrate-N concentrations to hydrogeologic and agricultural parameters. An aquifer sensitivity model and a ground-water vulnerability model were developed.

Nitrate-N concentrations in Kalamazoo County have statistically significant relationships with depth of submergence, well depth, clay thickness, partial clay thickness, agricultural landuse, and soil slope. These six variables combine to explain approximately 9 % of the total variance in the nitrate-N concentration. Factors from previous studies that were found to be significantly related to nitrate-N concentration such as nitrate-N loading rates, irrigation, precipitation, and distance from source were not quantified in this study.

Kalamazoo County is characterized by course-textured glacial drift.

Compared with some areas of Michigan and other glaciated areas, clay and partial clay is less abundant within the county.

Conclusions

This study supports the findings of previous studies which show that hydrogeologic parameters account for only a small percentage of the total contaminant variance. Although other factors such as agricultural management practices may explain most of the total contaminant variance, once the contaminant reaches the subsurface, virtually all of the contaminant variance is controlled by the hydrogeologic and hydrochemical parameters.

The limitations which exist for building an aquifer sensitivity or vulnerability model using the Kalamazoo County well database include: 1) the availability of information relevant to aquifer sensitivity or vulnerability, 2) the lack of abundant clay and partial clay in Kalamazoo County, and 3) the variability found in the database including wells sampled at different times and lithologic descriptions subject to the interpretations of different well drillers.

Future research should focus on characterizing the parameters which have been found to explain a higher percentage of the total variance in contaminant concentrations. Two studies are in progress in southwestern Michigan which are attempting to analyze aquifer sensitivity and vulnerability in better defined test sites. The Donnell Lake area in Cass county is being studied in detail by faculty and students at Western Michigan University and Michigan State University. Also, a four township area in Van Buren County is the focus of a Michigan Department of Agriculture/Western Michigan University study to characterize aquifer sensitivity and vulnerability to nitrate and pesticide contamination.

Appendix A

Van Buren County Study: Static Water Level Mapping

DRAFT

Feasibility of Using The Computerized Water Well Records for Mapping the Water Table and Delineating Ground-water Recharge-Discharge Potential Areas in Van Buren County, Michigan

Richard N. Passero, Steven D. Chidester
Lauren D. Hughes and David D. Dickason

Institute for Water Sciences
Western Michigan University
Kalamazoo, Michigan

September 28, 1992

INTRODUCTION

The Institute for Water Sciences at Western Michigan University, under contract from the Michigan Department of Natural Resources and the Michigan Department of Agriculture, conducted the hydrogeologic portion of an aquifer vulnerability pilot study for Van Buren County, Michigan (Passero, August, 1992). The objective of the study was to provide hydrogeologic information necessary for establishing guidelines for the state pesticide management program. A detailed analysis (master's thesis) of the relationship between land use, hydrogeology and water quality in Hartford, Lawrence, Keeler, and Hamilton townships directed by WMU in cooperation with the Michigan Department of Agriculture is also being conducted. Statistical analysis of nitrate concentrations in groundwater relative to land-use and hydrogeologic factors for this area has recently been completed (Stoline and Smith, September, 1992).

The current project is to examine (1) the use of shallow static water levels as an indicator of the water table and (2) the feasibility for using well depth of submergence (screen depth below static water level) for determining vertical hydraulic pressure gradients (heads) in relation to aquifer sensitivity. Western Michigan University maintains a computerized database of approximately 3,240 water well drillers' records for wells located in Van Buren County. Data from these records can be used to map static water levels and vertical head distributions. Specifically, the three objectives of this project are:

Objective 1. To compare various contouring methods used to map point static water level information between data points with regard to their relative effect on computer-generated potentiometric surfaces.

Objective 2. To Determine the reliability and validity of static water level elevation maps derived from well drillers' records in conjunction with surface water elevations for mapping the water table.

Objective 3. To determine the potential for using differences (residuals) among groups of wells screened at different depths below the static water level for delineating areas of groundwater recharge, discharge, and transition and evaluating their respective influence on aquifer sensitivity.

METHODOLOGY

All potentiometric surface and residual maps were produced with Surfer (version 4, Golden Software, Inc.). Surfer is a computer software package that uses randomly distributed data to produce contour maps. The GRID, TOPO, and UTIL subroutines of Surfer were used to grid Van Buren County water well and surface water data, generate contour maps for the water table (potentiometric surface), and evaluate the reliability of using well records to map the water table. GRID uses distributed X and Y coordinates to produce regularly spaced data. The program creates a grid over the randomly spaced data and interpolates new values from this data for each node in the grid. GRID provides three options for interpolating the data, Inverse Distance, Kriging, and Minimum Curvature. (See Surfer manual for a more detailed explanation of GRID.)

In order to evaluate how well the GRID subroutine approximates another data set, it is necessary to be able to compare the interpolated values of the grid to the second data set. The RESIDUAL option in Utility permits a data file to be compared to a grid file. This option subtracts the Z value at that same X,Y location on the gridded surface. RESIDUAL also determines the mean and the standard deviation for the surface - data fit.

The Van Buren County well data base was used to create several different data files. The Data Base containes 3240 well entries with X, Y state plane coordinates, well elevation, static water level and well depth. Lotus was used to calculate the depth of submergence and static water level elevation for each well. The depth of submergence is equal to the depth of the well screen below the static water level. It was decided on the basis of well depths that wells with a depth of submergence of equal to or less than 40 feet (N=1764) were sufficient to contour the water table surface. The shallow well files (SET A and SET B) were created by sorting the combined shallow well data on WELLID and assigning every other well to SET B. This yields two data sets of equal number that are spatially similar. Surface water data was obtained by digitizing surface elevations from perennial rivers and streams with C-MAP using 7.5 minute USGS Quadrangle maps (1981). A summary of the files created are as follows:

1) Two well files, data SET A (Group A) and data SET B (Group B) representing two halves of the total data set of wells having a depth of submergence equal to or less than 40 feet (N=882 for each).

2) Surface water elevations only (N=283).

3) SET A with 283 surface water elevations added (N = 1165).

4) SET A and SET B combined without surface water elevations (N = 1764).

5) SET A and SET B combined with surface water elevations (N = 2047).

6) All wells without surface water elevations (N = 3242).

7) All wells with a depth of submergence $\geq$ 65 feet and $\leq$ 100 feet for comparison with 5 above and use in interpreting recharge/discharge relationships (N = 441).

GRID allows the user to choose from several options in creating the grid file. The first option is grid size. The user can choose how many grid lines to use in the X direction and how many to use in the Y direction. The intersections of the grid lines define the grid nodes. Increasing the number of grid nodes can increase the "accuracy" of the resulting grid. However, the higher the number of grid nodes, the longer it will take the computer to create the grid.

The number of X and Y lines combined with the grid limits, determines the size of each grid cell and vice versa. For this project it was decided to use a cell size of 1000 feet by 1000 feet. This produces a sufficient density of interpolated nodes for Van Buren County. To obtain this cell size, X and Y minimum and maximum values were found for Van Buren County. The grid limits are X minimum 1449800, X maximum 1613800; Y minimum 209902, Y maximum 341902. This yields 165 lines in the X direction and 133 lines in the Y direction, approximately 18,500 nodes for Van Buren County due to its' irregular shape (see Surfer manual for details).

GRID provides the user with three options for generating the grid. These are Inverse Distance, Kriging and Minimum Curvature. Inverse Distance uses an exponential weighting power such that the influence of a data point decreases exponentially with increased distance from the node point being determined. Kriging uses the regional variable theory technique. Minimum Curvature involves the setting of a maximum absolute error and a maximum number of iterations. Once the initial value is established for the grid element this method applies an equation repeatedly to the surface. The equation attempts to smooth the gridded surface.

When using the Inverse Distance method or the Kriging method, the user can specify search constraints. The constraints consist of the search method, the search radius and the number of nearest data points. Minimum

Curvature does not use the search constraints as this method uses all points.

The Normal method of search uses the "nearest neighbor search" determined by the number of nearest data points selected by the user. Quadrant divides the entire search radius into quadrants searching for the number of nearest data points within each quadrant. Octant uses the same approach only with eight sectors. If the user chooses All, no search is activated and all points are used. Establishing a search radius limits the number of nearest points to within the search radius.

All search constraints were used in conjunction with all search methods where applicable. Radii of 1000 ft., 8000 ft., 10,000 ft. ,20,000 ft., and 50,000 ft. were used. The number of search points consisted of 24 data points and 48 data points or nearest number divisible by 4 and 8 (quadrant and octant search constraints). When a search radius of less than 10,000 ft. was used the resulting contour lines were segmented.

With the Kriging method, the All option for number of data points will not operate with files as large as those used in this study. The GRID program limits the number of search points to 127 with Kriging.

Minimum Curvature would not run with a grid cell size as small as 1000 ft. x 1000 ft. (165 x 133 grid lines, 21,945 nodes) because the output exceeds the limit of 16383 nodes. In order to test the Minimum Curvature method, therefore, a cell size of 2000 ft. x 2000 ft. was used, reducing the number of grid nodes to within the program limits.

Once the limitations for method and search constraints for large data files are understood, the successful options can be run on all data files. The resulting grid files can then be evaluated through TOPO, UTILITY/Residual and the GRID/Math/Modify options.

Computer run times are also a factor. Inverse Distance is generally the fastest method, however, how the search constraints are configured can greatly increase or decrease the time needed to complete the gridding process. In addition, the inverse distance method took over 4 hours to complete one file on a 386 computer with 25 MHZ. The same file took only 92 seconds on a 486 computer with 33 MHZ. All other methods took longer. With a 486, the longest run was about 20 minutes.

To calculate residuals, the Modify/Math function was used. This option permits subtracting one grid file from another grid file which produces a residuals grid file. It is important to use grid files produced with the same limits in order to have confidence in the resulting residual grid file.

RESULTS

1. Potentiometric Surface Maps: A Comparison of Contouring Methods.

Digital records of water wells (1764 records) screened in the glacial drift aquifer at depths $\leq$ 40 feet below the static water level were divided into Groups A and B. Group A was used to map a reference potentiometric surface (water table) using three contouring methods (Kriging, Inverse Distance and Minimum Curvature using Surfer (Figures 1, 2 and 3). All three methods are reasonably consistent with the topography and surface drainage and are therefore considered acceptable generalizations of the potentiometric surface. The Inverse Distance method yields the most detailed interpretation and the Minimum Curvature method yields the most generalized interpretation.

To establish the reliability of using water well records for mapping potentiometric surfaces, Group B was used to generate a potentiometric surface map for comparison with the reference surface generated with Group A data. Only the Inverse Distance and Minimum Curvature maps are included in this report as they are considered representative of the range of detail obtained by the three methods (Figure 4 and 5). Group B potentiometric surface maps are also consistent with the topography and surface drainage.

2. Potentiometric Surface Maps: A Comparison of Wells Sorted by Depth of Submergence.

Wells were divided into three groups based on depth of submergence ($\leq$ 40 feet; $\geq$ 65 to $\leq$ 100 feet; and all wells). Because no significant differences were found among the potentiometric surfaces generated by the three contouring methods, only potentiometric surface maps for $\leq$ 40 feet and all wells using the most rapid contouring method (Minimum Curvature, Figures 6 and 7) are included. These maps are very similar to each other, and to those shown in Figures 1 through 5.

3. A Comparison of Potentiometric Surfaces

Calculation of residuals were made to determine the differences between Group A and Group B by subtracting the data for Group A from the potentiometric surface grid from Group B and Group B from Group A for the three contouring methods (Table 1).

In all comparisons where surface water data was included, the maximum mean difference (residual) is 0.5 foot and the maximum standard deviation is 13.8 feet. With the exception of the mean for Group B-Group A (Inverse Distance) all values are very similar. In all comparisons where surface water data points were not included, the maximum mean difference (residual) is 0.65 and the maximum standard is 16.2 feet.

A maximum mean residual of 0.5 foot is extremely small particularly considering that the data represent over 20 years during which time the water table fluctuated at least 6 feet. The standard deviation reflects the fact that at least 95% of the residual values were within ± 30 feet.

Maps of residual values are included for only the Inverse Distance and Minimum Curvature methods (Figures 8 and 9). The maps illustrate the generally small residual values, but also show that the residual values are related to topography. Residual values are least, almost negligible, beneath the relatively flat topography (low relief) intramorainal outwash plain and greatest beneath the highest topographic areas with maximum relief, the northeast-trending Kalamazoo and Valparaiso Moraines. This is due to the fact that the water table and well depths beneath the moraines are more variable than beneath the low relief outwash plain.

The Inverse Distance map shows greater contrast in positive and negative residuals than the Minimum Curvature map, but the mean residual is lower. The Minimum Curvature map shows a larger area of less than 10 feet residual value.

4. Use of Supplementary Surface Water Data

To produce a more representative reference water table map, 283 surface water elevation points were digitized, mapped using the more rapid Minimum Curvature method (Figure 10), and incorporated into the data sets for Group A and Group B (Figures 11 and 12). Comparisons were made between:

A. Group B (without the surface water data) and Group AW (Group A with the surface water data);
B. Groups BW and AW (both with surface water data); and
C. Group B without surface water data and the Surface Water Data.

The map of 283 surface water points is similar to, but more general than, the previous potentiometric surface maps based on a greater number of water well data points.

The Minimum Curvature mean residual value for Group B vs. Group AW is 0.52 feet and the standard deviation is 13.8 feet. These values are very similar to those obtained by comparing Groups A and B. The mean residual value for Group BW vs. Group AW is 0.52 feet and the standard deviation is 13.1 feet (Figure 13). The map shows a larger area of less than 10 feet of residual values, however, adding surface water data did not decrease the residuals significantly. Group B was also compared with the Surface Water Data surface map (Figure 14). The mean residual value is 10.98 feet and the standard deviation is 34.2 feet. These residual maps also reflect the topography (glacial geology) and the greater residual values of Group B vs. Group AW suggests that the potentiometric surface map generated from only 283 surface water points has too few data points. Nevertheless, the possibility of generating a water table map based on more surface water data points should be considered.

5. Shallow vs. Total Well Data Sets

A comparison of the potentiometric surface for wells with $\leq$ 40 feet of submergence (Group A and Group B) and the potentiometric surface for All Wells of all depths (Figure 15) shows little difference in the two surfaces (minimal residuals). The mean residual value is 0.85 feet and the standard deviation is 14.6. Maximum values here also are beneath the Kalamazoo and Valparaiso Moraines. The high values in Covert Township to the west are due to the paucity of well records in this township. The low residual values result from the fact that the glacial drift is a generally single hydraulically interconnected aquifer system.

6. Comparison of Vertical Pressure Differentials (Heads) for Mapping Recharge, Transition and Dicharge Areas.

Wells were sorted by depth of submergence into several groups. Only the residual map derived by comparing the wells with $\leq$ 40 feet of submergence and the wells with $\geq$ 65 to $\leq$ 100 feet of submergence mapped using Minimum Curvature is included in this report (Figure 16) because it provided more than 2000 wells total and could be compared with other maps produced for the study.

The map generally indicates ground-water recharge in the topographically high areas (the Kalamazoo, Valparaiso and Lake Border Moraines); discharge along the major rivers (the Paw Paw and the Black Rivers); and transition elsewhere, noteably in the low relief, intramorainal area between the Valparaiso and Kalamazoo Moraines. The locally high values reflect extremes in the data which could be eliminated by disregarding the upper and lower percentiles. The method could not be related to nitrate data in this study because this data has not yet been computerized in Van Buren County.

CONCLUSIONS

1. Maps of static water levels in wells (potentiometric surface maps) for Van Buren County generated by Inverse Distance, Kriging and Minimum Curvature contouring methods using Surfer are very similar and consistent with the topography and drainage. There appears to be no graphic advantage to using any one method; however, the Minimum Curvature method is approximately twice as fast as the others.
2. A map-grid comparison of two groups of 882 randomly selected wells with ≤ 40 feet of submergence showed no more than 0.5 foot mean difference (standard deviation less that 14 feet). The small difference in means indicates that water well records are statistically reliable in producing potentiometric surface maps.
3. The differences in the means and standard deviations for the three contouring methods are minimal and do not favor the use of any one method; however, the map residuals produced using the Minimum Curvature method produces the largest minimal residual area.
4. The residuals in these comparisons are greater for the morainal (topographically high) areas where the well depths and static water levels are more variable.
5. Water table maps can be generated using digitized surface water data if sufficient time is available. In this study, 283 surface water points were used for Van Buren County. The resultant surface was generally consistent with the topography and drainage, but a greater number of widely spaced data points would be necessary to create an accurate water table map. Surface water data, however, can be used effectively to increase the shallow well data base for creating a more truly representative water table map.
6. Comparing maps of shallow well static water levels with those generated using all wells showed much less difference than expected and suggests that the commonly used technique of mapping all static water levels for all wells may be as effective as mapping wells pre-selected by depth.
7. A residual map produced by subtracting grids of wells sorted by depth produced a vertical ground-water pressure (head) map for Van Buren County that is consistent with the topography and generally shows ground-water recharge in the topographically high areas, dicharge in the topographically low areas along the major drainage ways, and transition flow elsewhere. The technique appears to have

promise and should be used in smaller areas of contrasting geology and in a county for which the water quality data has been computerized. This was not available for Van Buren County and time did not permit work in another county.

8. Of 3240 well records, only four had to be discarded. There were numerous duplicate WELLID's; however, GRID can be programmed to ignore duplicate points. Also, because Minimum Curvature uses a larger cell size than that selected for the project, contours may not extend completely to the county borders.
9. Use of computerized water well records provides a statistically reliable, rapid, first approximation of the regional water table. The relationship could be improved by deleting the upper and lower 5% of the range of residual values without significantly affecting the size of the data set. The validity of the method could be further evaluated by comparing static water levels in wells with a very detailed map of surface water elevation points as a reference map of the water table.

Table 1. Residuals for Group A and Group B With and Without Surface Water Data Included.

	Inverse Distance		Kriging		Minimum Curvature	
	A-B	B-A	A-B	B-A	A-B	B-A
<u>A/B With Surface Water</u>						
MEAN	+0.54	-0.06	+0.46	-0.33	+0.52	-0.42
STANDARD DEVIATION	13.1	13.8	12.6	13.0	13.1	13.3
<u>A/B Without Surface Water</u>						
MEAN	+0.39	-0.37	+0.39	-0.43	+0.65	-0.50
STANDARD DEVIATION	15.5	16.2	14.8	15.4	15.3	15.6

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY

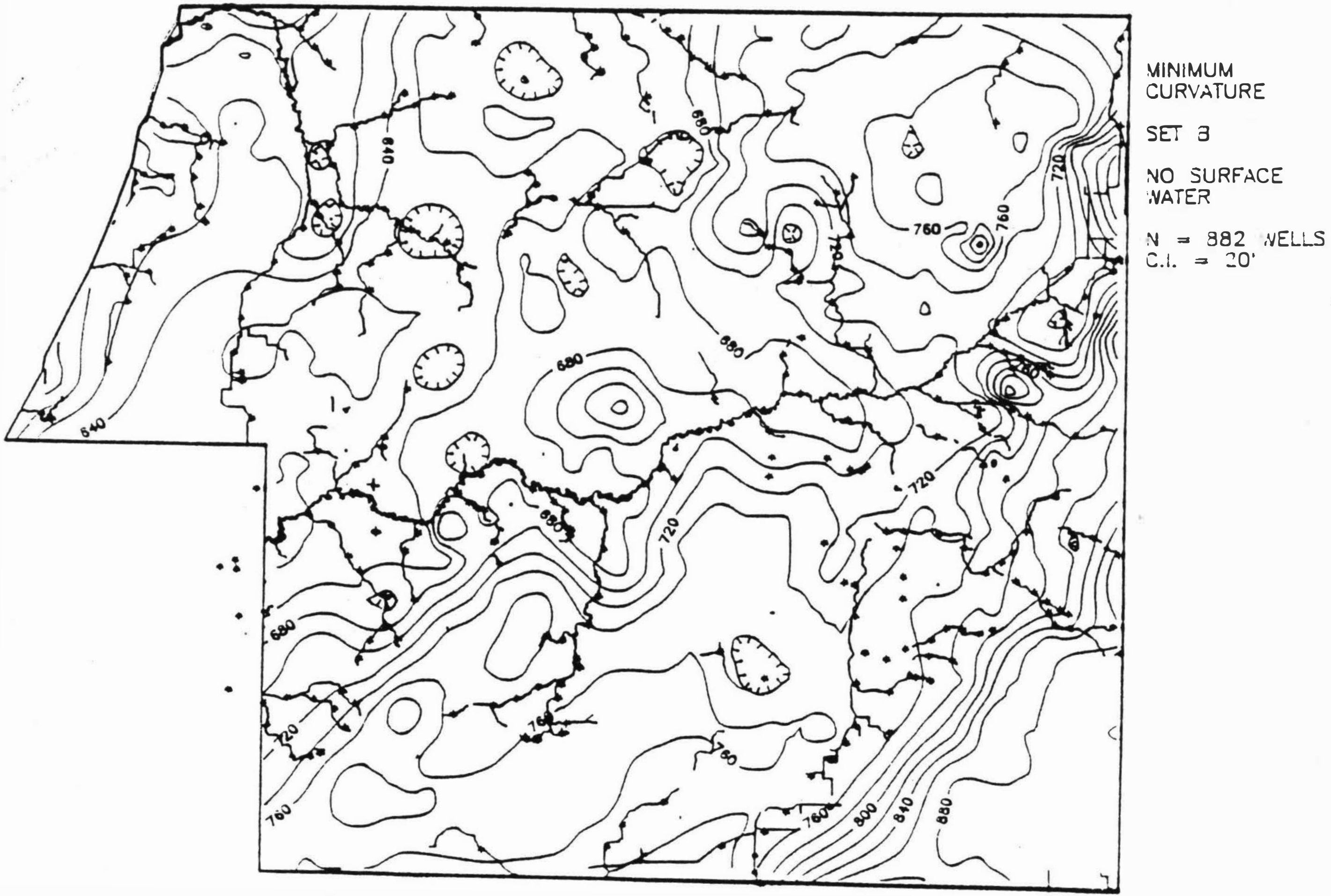


Figure 5. Minimum curvature map of Group B static water levels (882 wells with ≤ 40 feet of submergence).

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY

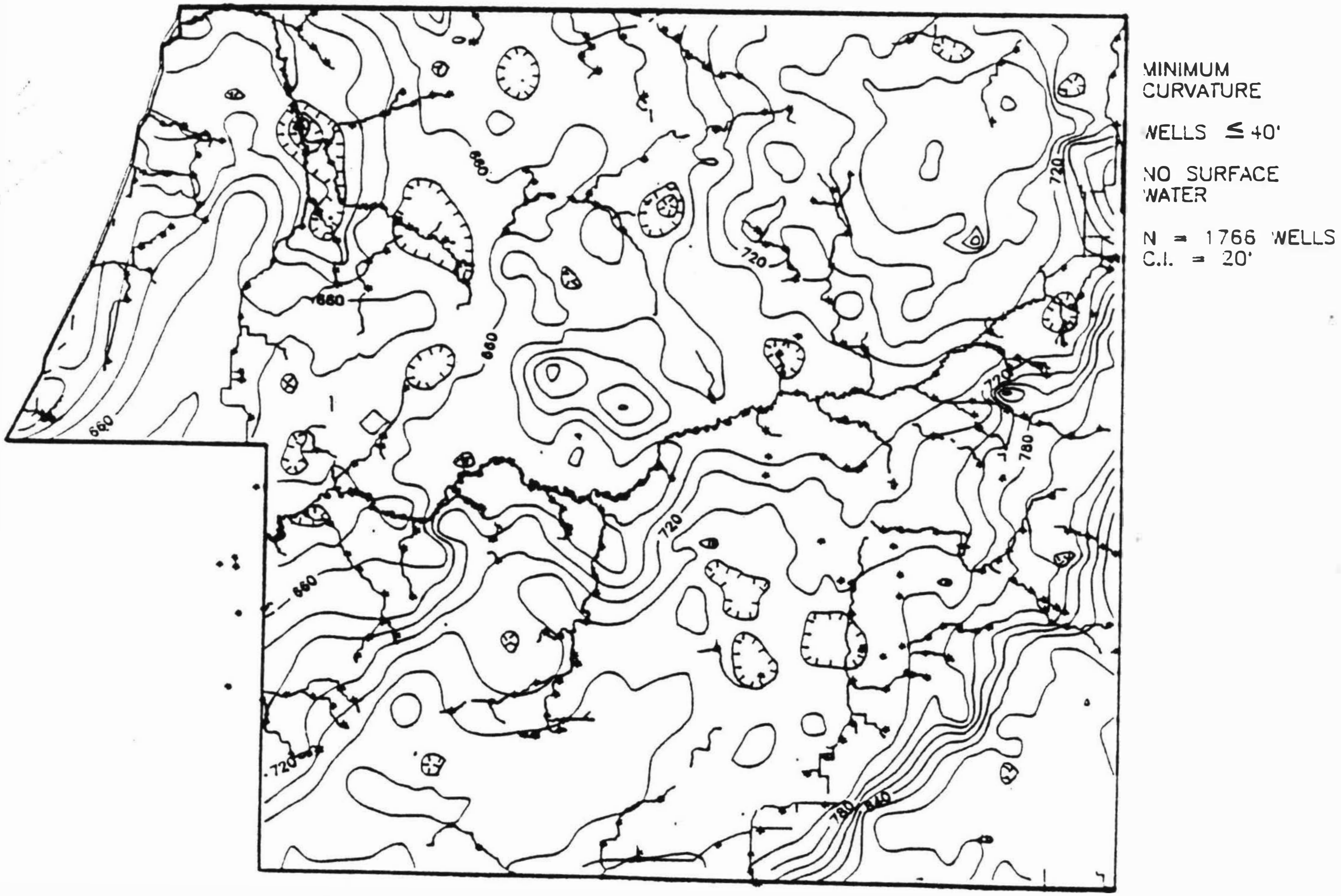
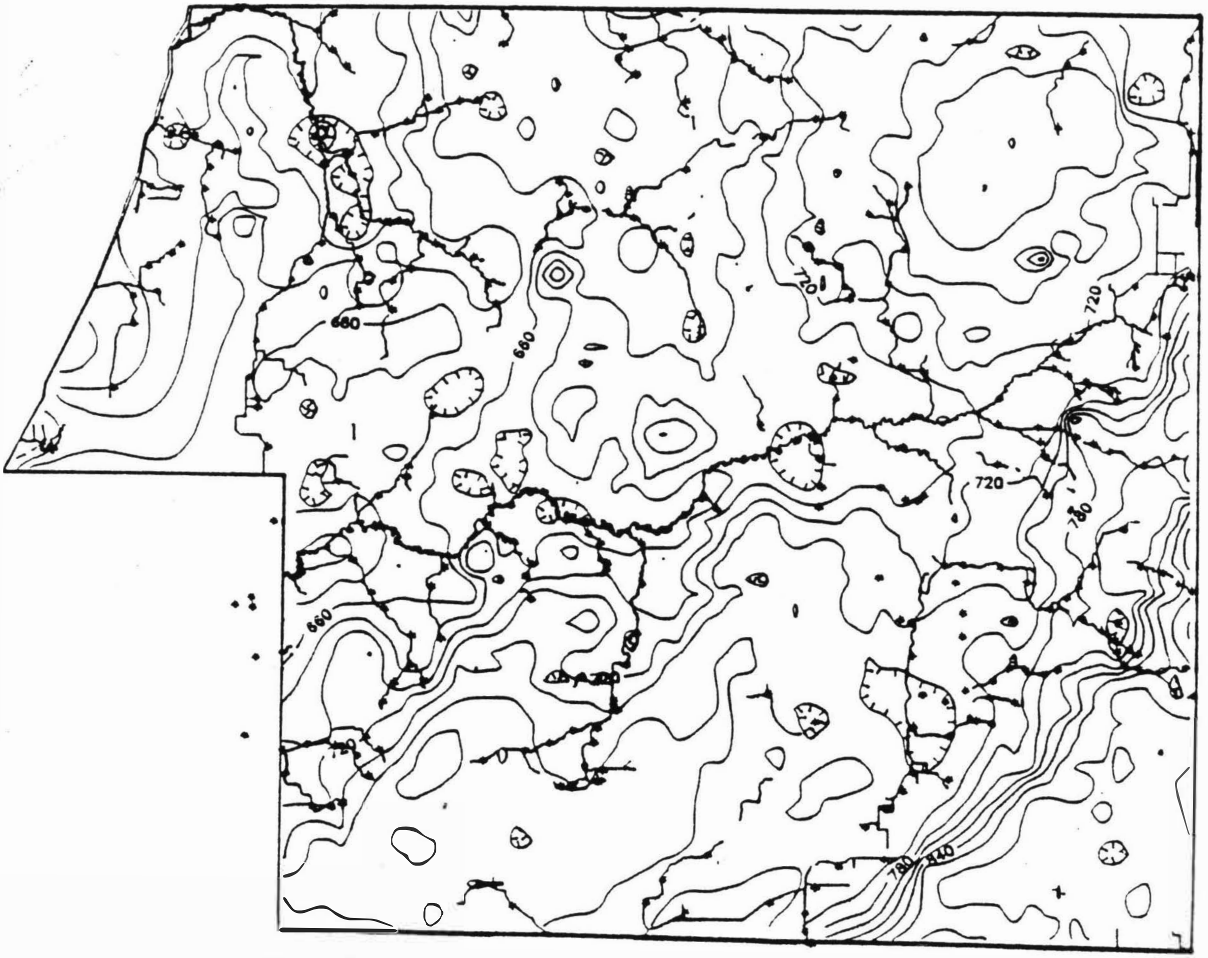


Figure 6. Minimum curvature map of static water levels for All Wells with ≤ 40 feet submergence (1766 wells).

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY



MINIMUM
CURVATURE

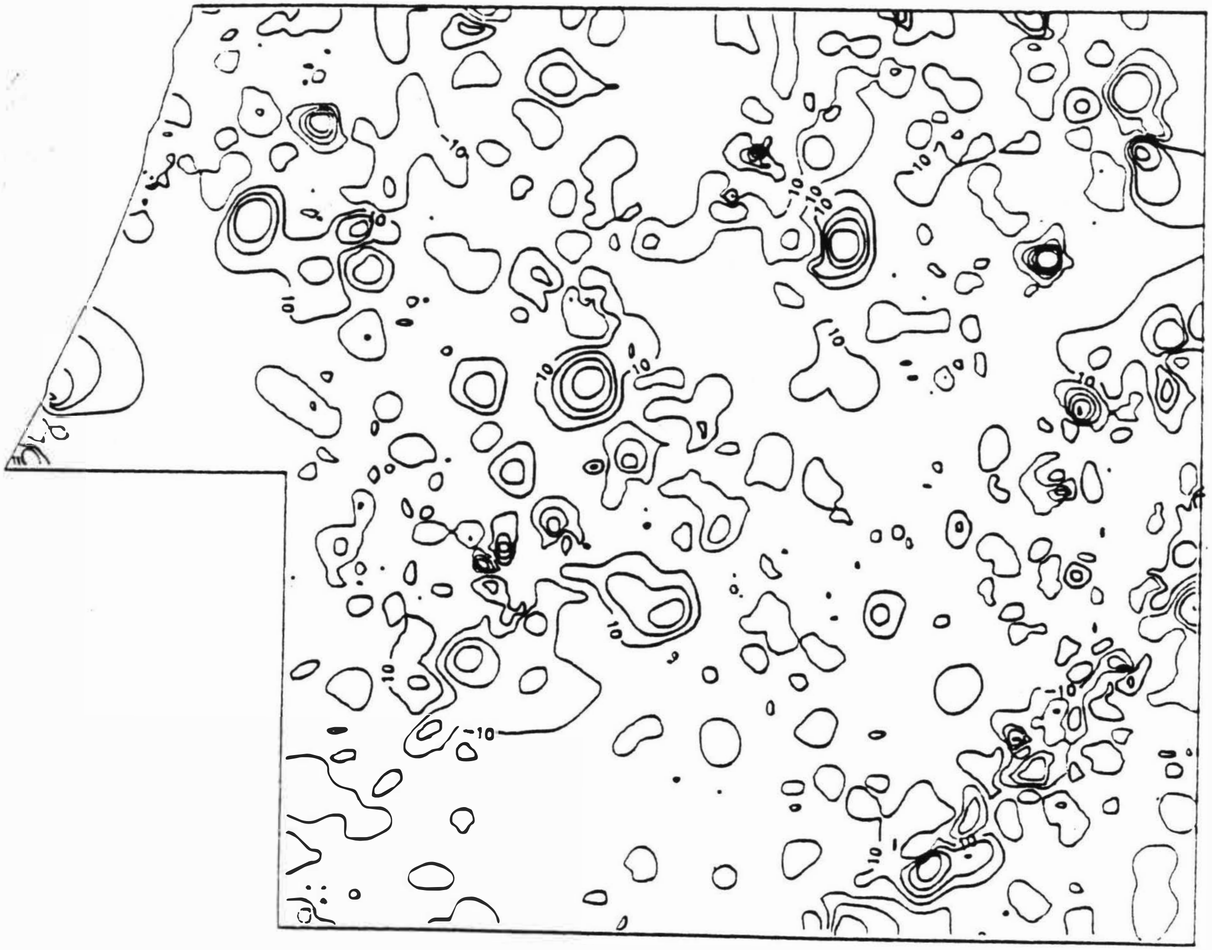
ALL WELLS

NO SURFACE
WATER

N = 3241 WELLS
C.I. = 20'

Figure 7. Minimum curvature map of static water levels for All Wells in data base (3241 wells).

MAP SHOWING RESIDUAL SURFACE: VAN BUREN COUNTY



INVERSE
DISTANCE

SET A – SET B

NO SURFACE
WATER

C.I. = 20'

Figure 8. Inverse distance map of residuals Group A vs. Group B.

MAP SHOWING RESIDUAL SURFACE: VAN BUREN COUNTY

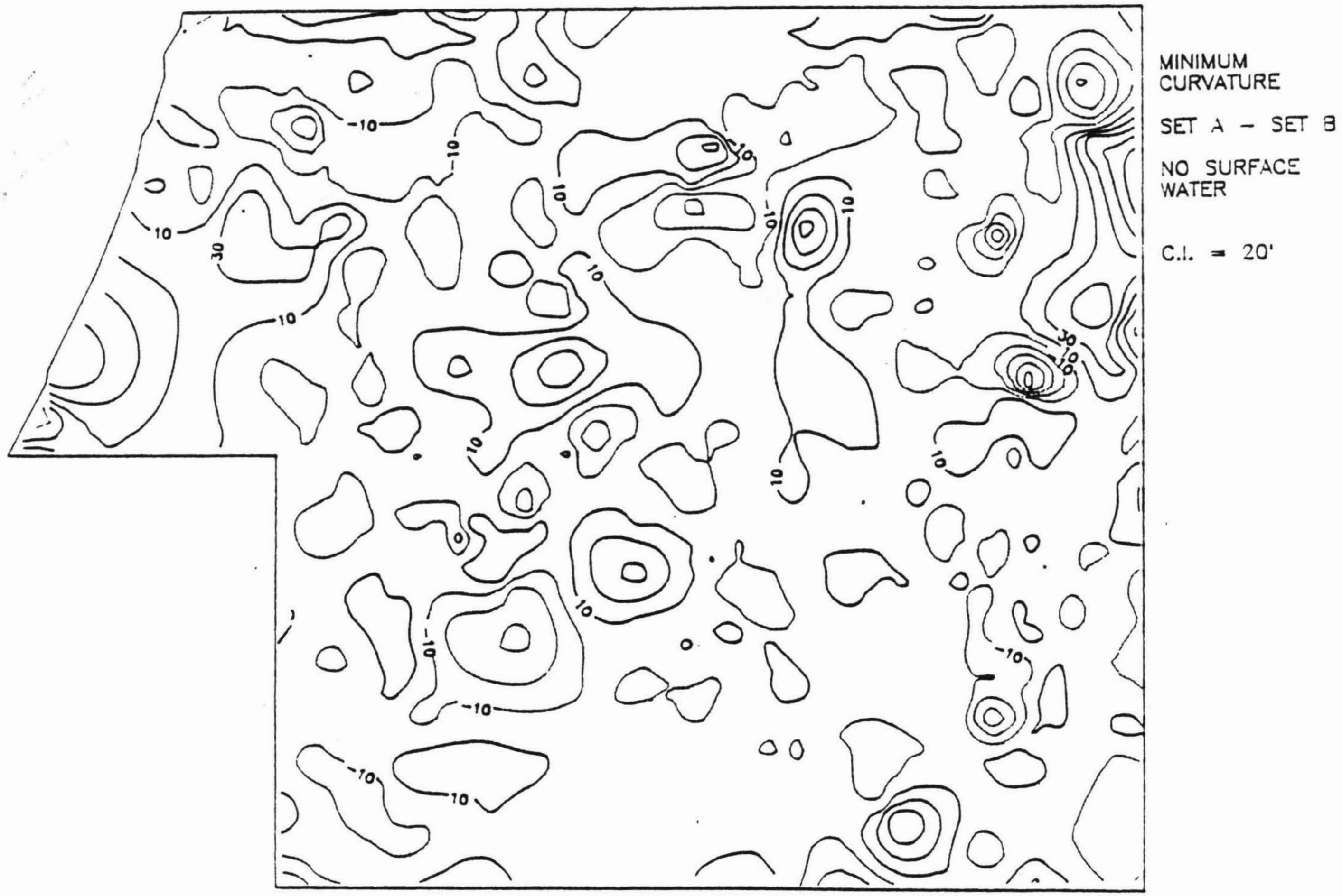


Figure 9. Minimum curvature map of residuals Group A vs. Group B.

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY

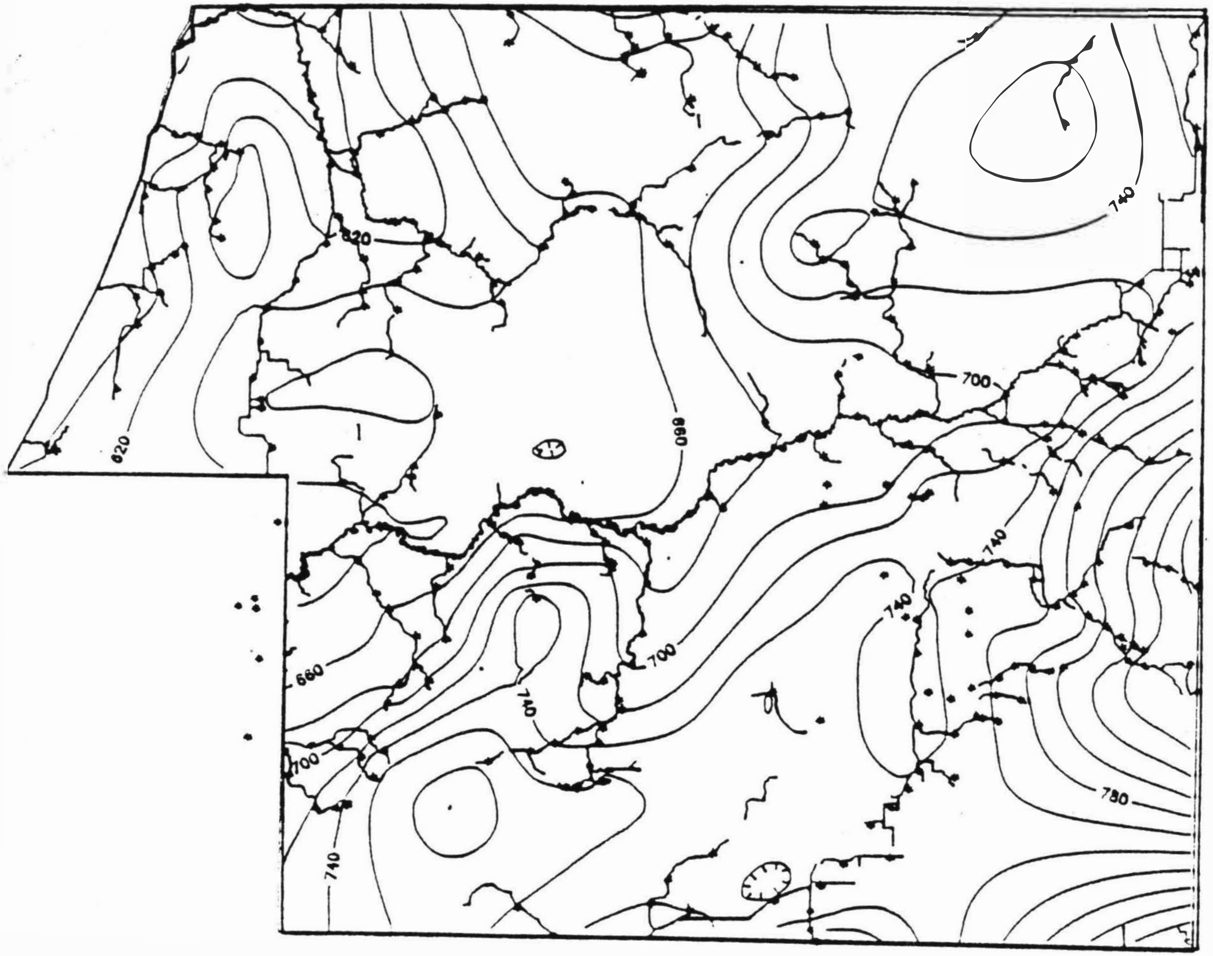


Figure 10. Minimum curvature map of 283 surface water elevation points.

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY

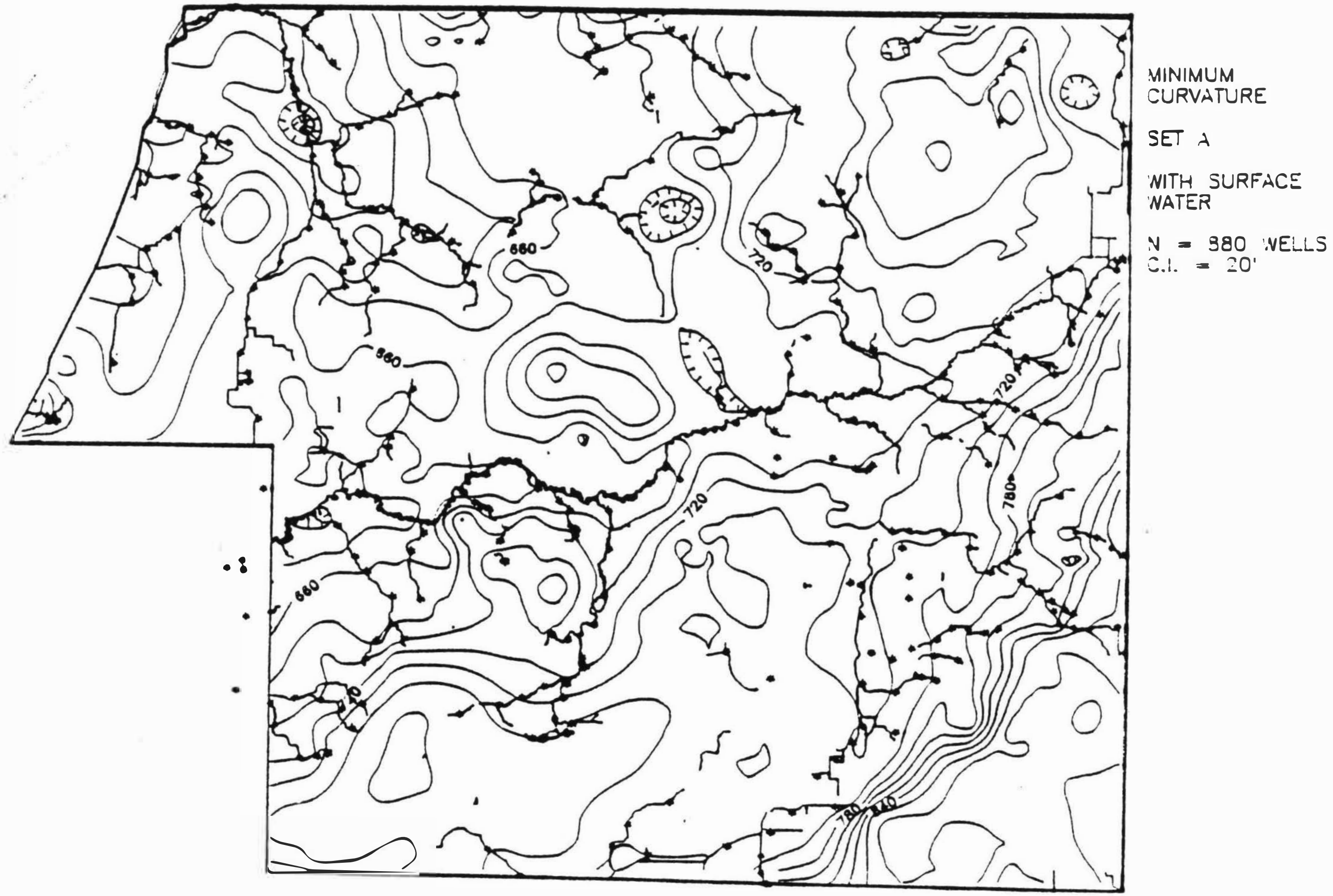
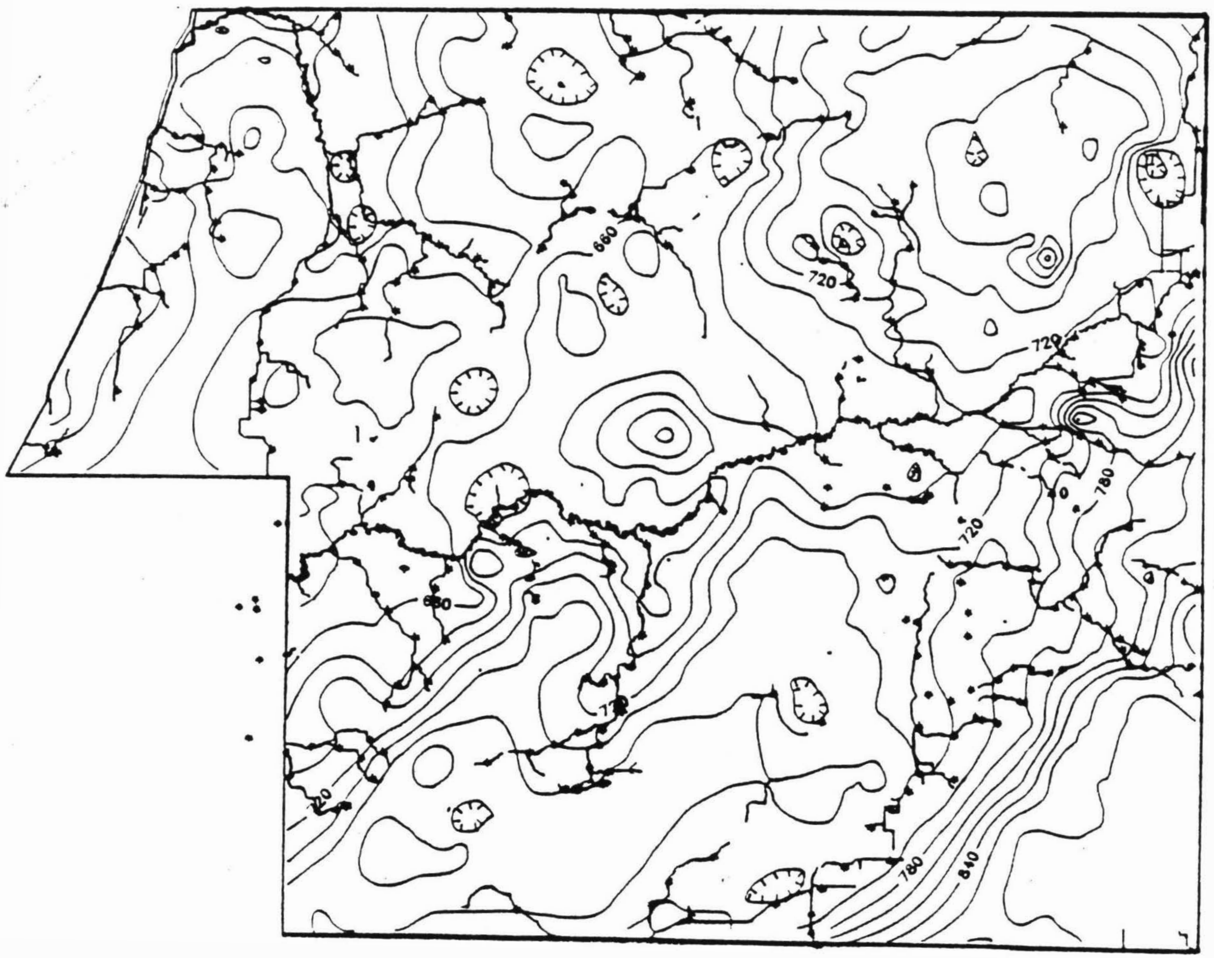


Figure 11. Minimum curvature map of Group A static water levels and 283 surface water points.

MAP SHOWING STATIC WATER ELEVATION: VAN BUREN COUNTY



MINIMUM CURVATURE

SET B

WITH SURFACE WATER

N = 880 WELLS
C.I. = 20'

Figure 12. Minimum curvature map of Group B static water levels and 283 surface water points.

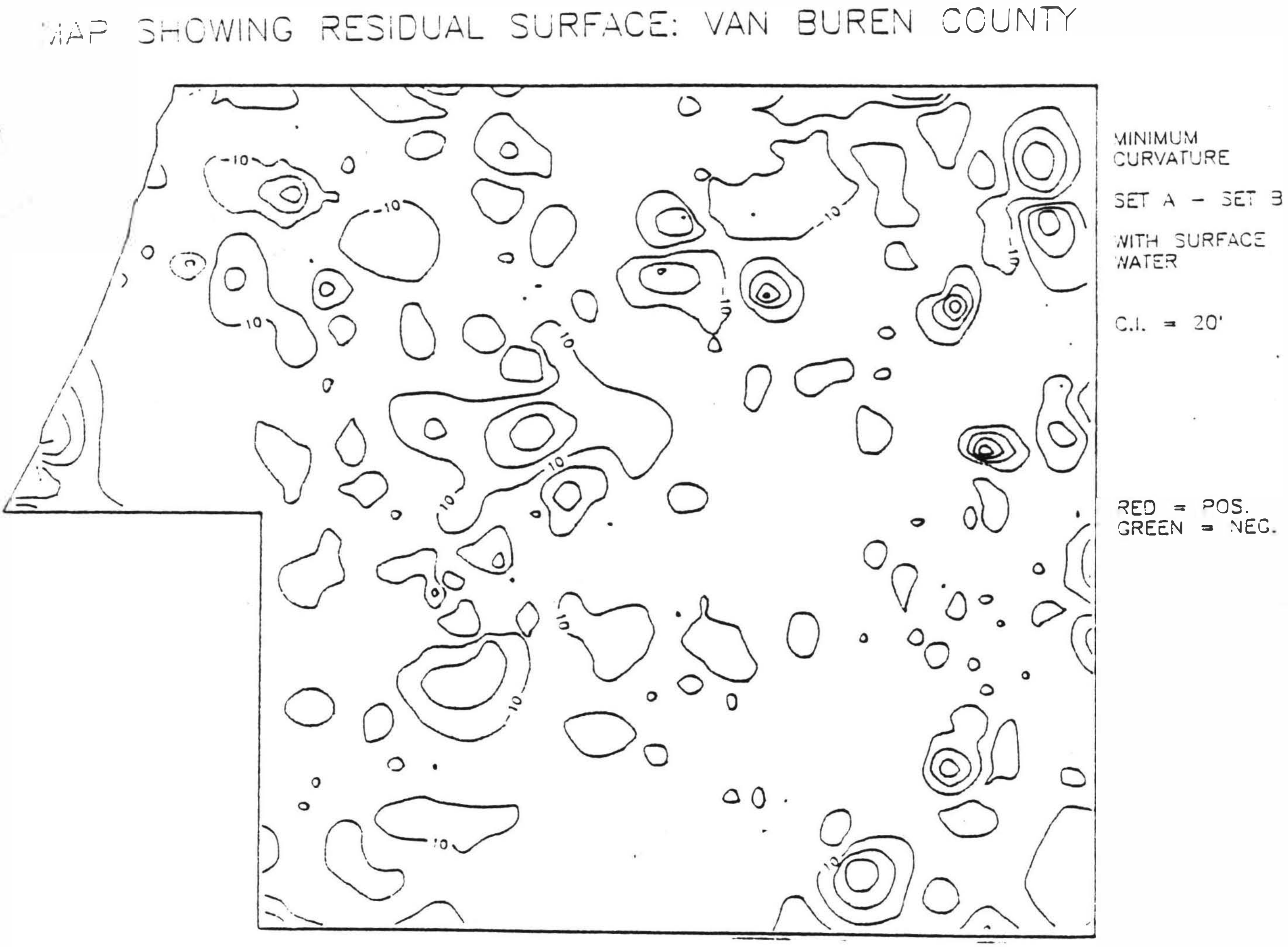


Figure 13. Minimum curvature map of Group A vs. Group B. (Both groups supplemented with 282 surface water points.)

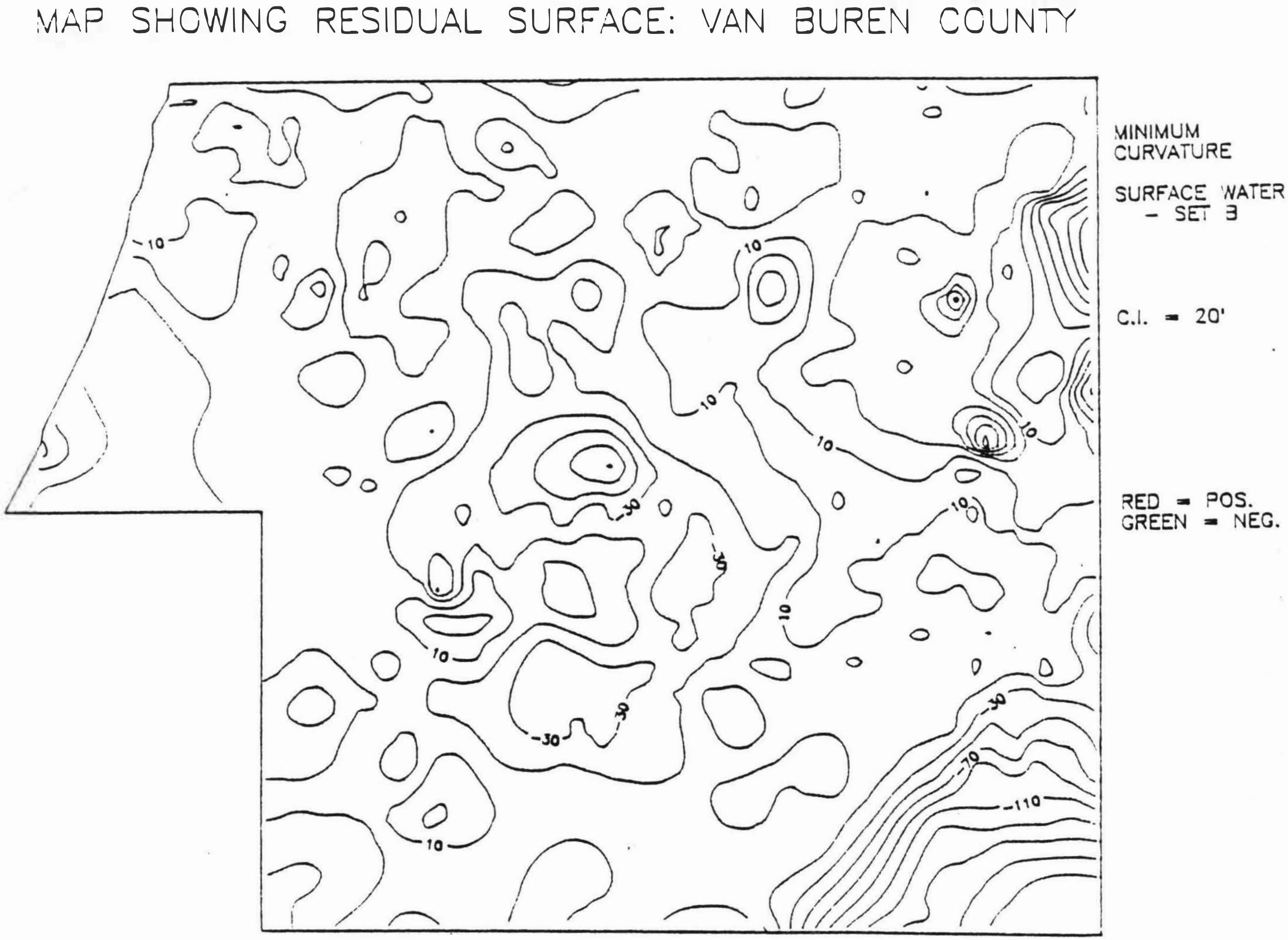


Figure 14. Minimum curvature map of residuals for Group B vs. 283 surface water points.

MAP SHOWING RESIDUAL SURFACE: VAN BUREN COUNTY

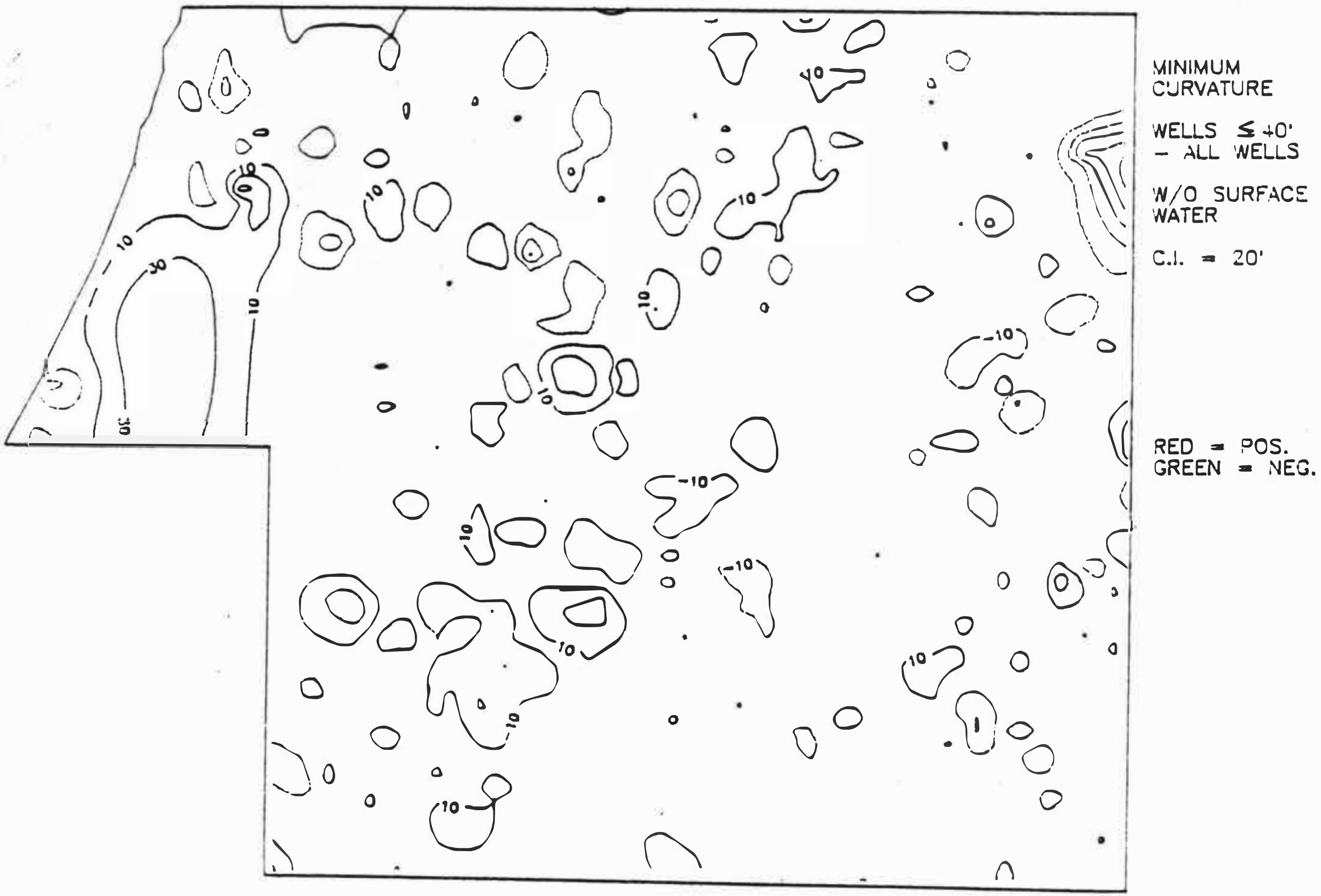


Figure 15. Minimum curvature map of residuals for All Wells with ≤ 40 feet of submergence (1766 wells) vs. All Wells in data base (3241 wells)

MAP SHOWING RECHARGE, TRANSITION, AND DISCHARGE:

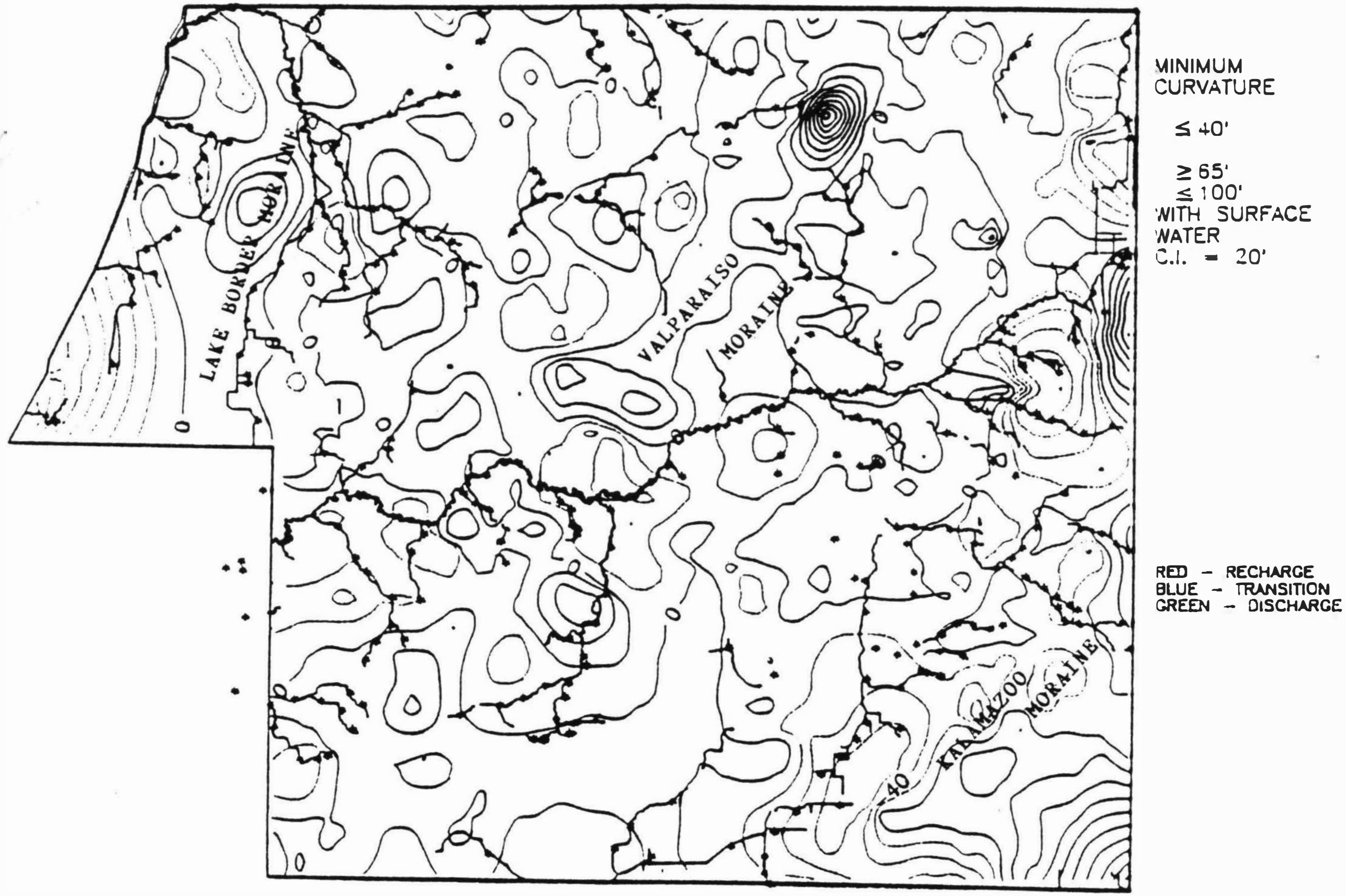


Figure 16. Minimum curvature map of residuals for wells ≤ 40 feet of submergences vs. wells ≥ 65 - ≤ 100 feet of submergence showing ground-water recharge, transition and discharge areas. Contours are vertical pressure (head) differences.

Appendix B

DRASTIC

DRASTIC

Inherent in each hydrogeologic setting are the physical characteristics which affect the ground-water pollution potential. A wide range of technical positions was considered regarding the relative importance of the many physical characteristics that affect pollution potential. Factors including aquifer chemistry, temperature, transmissivity, tortuosity, gaseous phase transport, and others were evaluated. The availability of mappable data has also been considered. As a result of this evaluation, the most important mappable factors that control the ground-water pollution potential were determined to be:

D—Depth to water
R—(Net) Recharge
A—Aquifer Media
S—Soil Media
T—Topography (Slope)
I—Impact of the Vadose Zone
C—Conductivity (Hydraulic) of the Aquifer

These factors have been arranged to form the acronym, DRASTIC, for ease of reference. A complete description of the important mechanisms considered within each factor and a description of the significance of the factor are included in Section 3, DRASTIC: A Description of the Factors. While this list is not all inclusive, these factors, in combination, were determined to include the basic requirements needed to assess the general pollution potential of each hydrogeologic setting. The DRASTIC factors represent measurable parameters for which data are generally available from a variety of sources without detailed reconnaissance. Sources of this information are listed in Table 1.

A numerical ranking system to assess ground water pollution potential in hydrogeologic settings has been devised using the DRASTIC factors. The system contains three significant parts: weights, ranges, and ratings. A description of the technique used for weights and ratings can be found in Dee et al., (1973).

Table 1. **Sources of Hydrogeologic Information**

Source	Depth to Water Table	Net Recharge	Aquifer Media	Soil Media	Topography	Impact of the Vadose Zone	Hydraulic Conductivity of the Aquifer
U.S. Geological Survey	X	X	X		X	X	X
State Geological Surveys	X	X	X			X	X
State Department of Natural/Water Resources	X	X	X			X	X
U.S. Department of Agriculture-Soil Conservation Service		X		X	X		
State Department of Environmental Protection	X	X	X			X	X
Clean Water Act "208" and other Regional Planning Authorities	X	X	X			X	X
County and Regional Water Supply Agencies and Companies (private water suppliers)	X		X			X	X
Private Consulting Firms (hydrogeologic, engineering)	X		X			X	X
Related Industry Studies (mining, well drilling, quarrying, etc.)	X		X			X	
Professional Associations (Geological Society of America, National Water Well Association, American Geophysical Union)	X	X	X			X	X
Local Colleges and Universities (Departments of Geology, Earth Sciences, Civil Engineering)	X	X	X			X	X
Other Federal/State Agencies (Army Corps of Engineers, National Oceanic and Atmospheric Administration)	X	X	X			X	

(1) Weights—Each DRASTIC factor has been evaluated with respect to the other to determine the relative importance of each factor. Each DRASTIC factor has been assigned a relative weight ranging from 1 to 5 (Table 2). The most significant factors have weights of 5; the least significant, a weight of 1. This exercise was accomplished by the committee using a Delphi (consensus) approach. These weights are a constant and may not be changed. A second weight has been assigned to reflect the agricultural usage of herbicides and pesticides (Table 3). These weights are also constants and cannot be changed. A description of the usage of this second system can be found in Section 2 under the heading, "Agricultural DRASTIC."

Table 2. Assigned Weights for DRASTIC Features

Feature	Weight
Depth to Water Table	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of the Vadose Zone	5
Hydraulic Conductivity of the Aquifer	3

Table 3. Assigned Weights for Agricultural DRASTIC Features

Feature	Agricultural Weight
Depth to Water Table	5
Net Recharge	4
Aquifer Media	3
Soil Media	5
Topography	3
Impact of the Vadose Zone	4
Hydraulic Conductivity of the Aquifer	2

(2) Ranges—Each DRASTIC factor has been divided into either ranges or significant media types which have an impact on pollution potential (Tables 4-10). A discussion of the media types is included in Section 3, Aquifer Media, Soil Media, and Impact of the Vadose Zone. The ranges and media types are graphed to show the linearity and non-linearity of the factor (Figures 3-9).

(3) Ratings—Each range for each DRASTIC factor has been evaluated with respect to the others to determine the relative significance of each range with respect to pollution potential. Based on the graphs, the range for each DRASTIC factor has been assigned a rating which varies between 1 and 10 (Tables 4-10). The factors of D, R, S, T, and C have been assigned one value per range. A and I have been assigned a "typical" rating and a variable rating. The variable rating allows the user to choose either a typical value or to adjust the value based on more specific knowledge. The ratings are the same for both the DRASTIC Index and the modified Agricultural DRASTIC Index.

This system allows the user to determine a numerical value for any hydrogeologic setting by using an additive model. The equation for determining the DRASTIC Index is:

$$D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W = \text{Pollution Potential}$$

where:

R = rating
W = weight

Table 4. Ranges and Ratings for Depth to Water

Depth to Water (feet)	
Range	Rating
0-5	10
5-10	9
15-30	7
30-50	5
50-75	3
75-100	2
100 +	1
Weight: 5	Agricultural Weight: 5

Table 5. Ranges and Ratings for Net Recharge

Net Recharge (Inches)	
Range	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10 +	9
Weight: 4	Agricultural Weight: 4

Table 6. Ranges and Ratings for Aquifer Media

Aquifer Media		
Range	Rating	Typical Rating
Massive Shale	1-3	2
Metamorphic/Igneous	2-5	3
Weathered Metamorphic/Igneous	3-5	4
Thin Bedded Sandstone, Limestone, Shale Sequences	5-9	6
Massive Sandstone	4-9	6
Massive Limestone	4-9	6
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	9-10	10
Weight: 3	Agricultural Weight: 3	

Table 7. Ranges and Ratings for Soil Media

Soil Media	
Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Nonshrinking and Nonaggregated Clay	1
Weight: 2	Agricultural Weight: 5

Table 8. Ranges and Ratings for Topography

Topography (percent slope)	
Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18 +	1
Weight: 1	Agricultural Weight: 3

Table 9. Ranges and Ratings for Impact of Vadose Zone Media

Impact of Vadose Zone Media		
Range	Rating	Typical Rating
Silt/Clay	1-2	1
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded Limestone, Sandstone, Shale	4-8	6
Sand and Gravel with significant Silt and Clay	4-8	6
Metamorphic/Igneous	2-8	4
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	8-10	10
Weight: 5	Agricultural Weight: 4	

Table 10. Ranges and Ratings for Hydraulic Conductivity

Hydraulic Conductivity (GPD/FT²)	
Range	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000 +	10
Weight: 3	Agricultural Weight: 2

Once a DRASTIC Index has been computed, it is possible to identify areas which are more likely to be susceptible to ground-water contamination relative to one another. The higher the DRASTIC Index, the greater the ground-water pollution potential. The DRASTIC Index provides only a relative evaluation tool and is not designed to provide absolute answers. Therefore, the numbers generated in the DRASTIC Index and in the agricultural DRASTIC Index cannot be equated.

Figure 3 Graph of ranges and ratings for depth to water

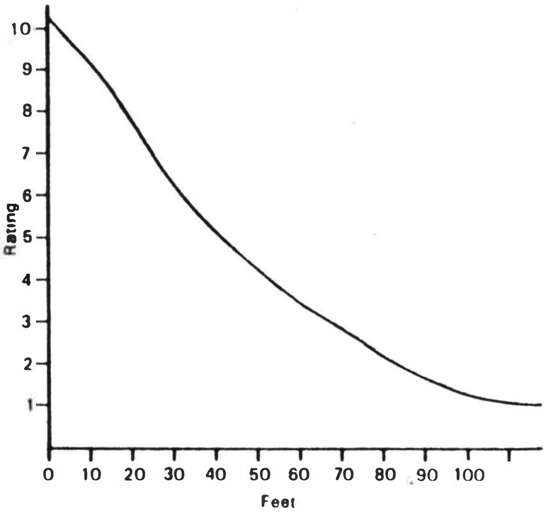
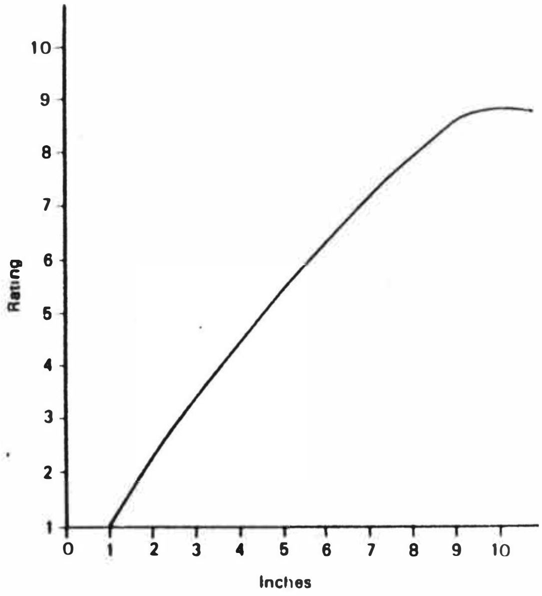


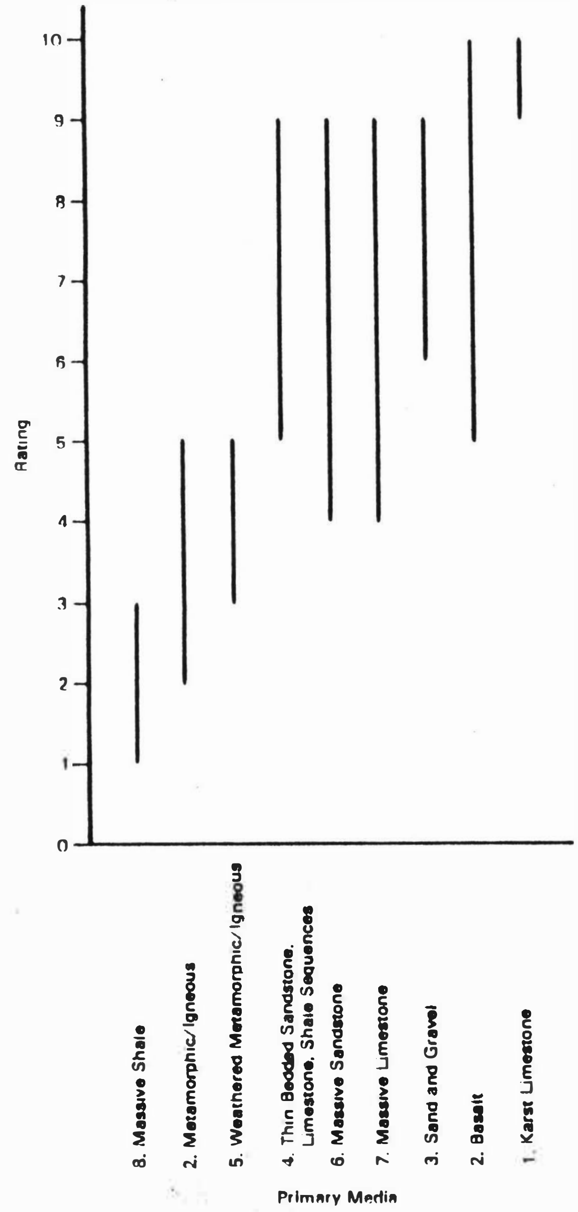
Figure 4. Graph of ranges and ratings for net recharge.



Agricultural DRASTIC

Agricultural DRASTIC is designed to be used where the activity of concern is the application of herbicides and pesticides to an area. It represents a special case of the DRASTIC Index. The only way in which Agricultural DRASTIC differs from DRASTIC is in the assignment of relative weights for the seven DRASTIC

Figure 5. Graph of ranges and ratings for aquifer media.



Relative ranges of ease of pollution for the principal aquifer types.

Ranges are based upon consideration of:
- a) route length and tortuosity
- b) potential for consumptive sorption
- c) dispersion
- d) reactivity and
- e) degree of fracturing

Primary factors affecting rating:

1. Reactivity (solubility and fracturing)
2. Fracturing
3. Route length and tortuosity, sorption, dispersion. All essentially determined by grain size, sorting, and packing
4. Route length and tortuosity as determined by bedding and fracturing
5. Sorption and dispersion
6. Fracturing, route length and tortuosity, influenced by intergranular relationships
7. Reactivity (solubility) and fracturing
8. Fracturing and sorption

factors. All other parts of the two indexes are identical; the ranges, ratings, and instructions for use are the same. If the user is concerned with the ground-water pollution potential of an area by herbicides and pesticides, then the weights for Agricultural DRASTIC should be used.

Agricultural DRASTIC was created to address the important processes which specifically offset the fate and transport of herbicides and pesticides in the soil. These processes, however, may not be as significant when assigning weights to the other DRASTIC factors for non-agricultural activities. Thus, by comparing Tables 2 and 3, it can be seen that for non-agricultural activities, Soil Media is assigned a weight of 2, while for the modified Agricultural DRASTIC, the Soil Media is assigned a weight of 5. Topography, Impact of the Vadose Zone, and Hydraulic Conductivity of the Aquifer are also slightly different. By making these adjustments, the committee addressed the special conditions which influence the potential for ground-water contamination by pesticides and herbicides. It is important to note that the relative relationship between the DRASTIC factors was not deemed significantly different enough to warrant the development of any other modified DRASTIC indexes. The user should be reminded that weights may not be changed for any of the DRASTIC factors. These relative weights form the basis for the system and any changes will make the system invalid.

Figure 6. Graph of ranges and ratings for soil media.

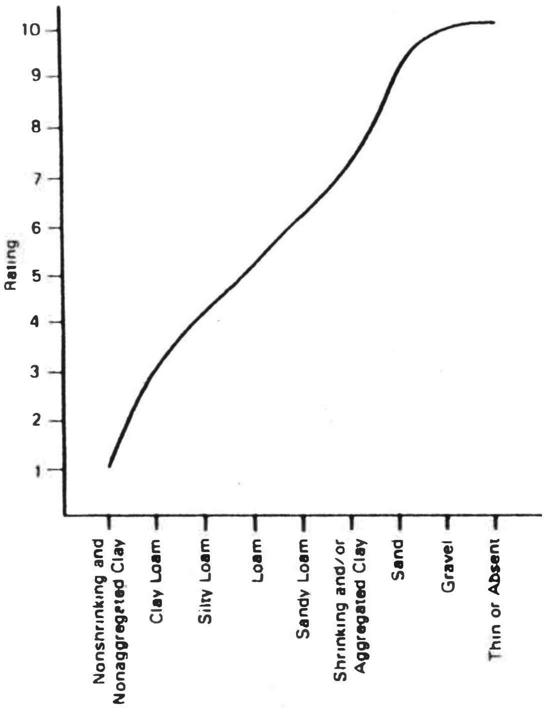
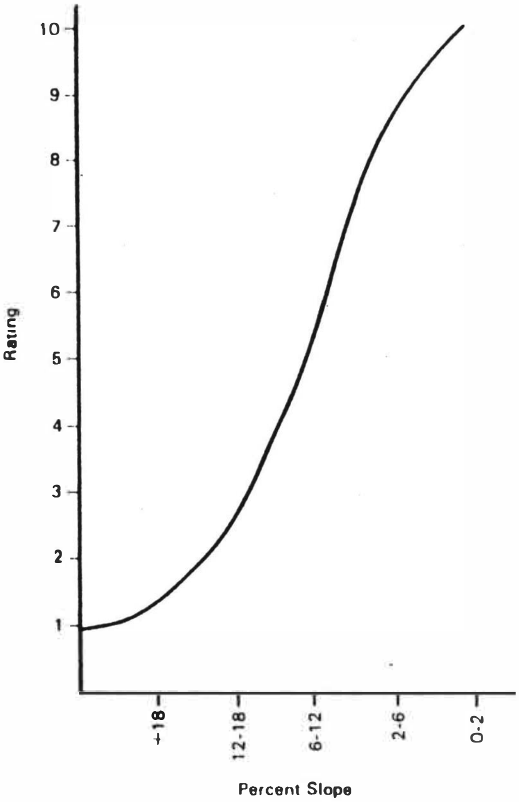


Figure 7. Graph of ranges and ratings for topography.



Appendix C

SEEPPAGE

SEEPPAGE: A SYSTEM FOR EARLY EVALUATION OF THE POLLUTION POTENTIAL OF AGRICULTURAL GROUNDWATER ENVIRONMENTS

Background

The importance of our nation's ground water resource cannot be overstated. Over 50 percent of the U.S. population (1980 Census) is served by ground water; 97 percent of the rural population depends upon it for domestic supplies (U.S. Geological Survey, 1985). Our reliance upon the ground water resource has been steadily growing. Ground water withdrawals have increased 159 percent between 1950 and 1980 while surface water withdrawals have risen only 107 percent (Solley, et. al., 1983).

Currently, less than one percent of the resource is estimated to be polluted (Lehr, 1982). The most frequently cited sources of contamination of ground water are deficient septic systems, leaking underground storage tanks, and agricultural activities, such as fertilizer and pesticide applications. The most common contaminants affecting the nation's ground water are sewage, nitrates (such as fertilizers), and synthetic organic chemicals, such as those used in the manufacture of pesticides, as well as petroleum hydrocarbons used in gasoline (US EPA, 1987). More than 99 percent of all contamination problems are in the shallow aquifers (LeGrand, 1983).

The problems of air and surface water pollution are being worked on through the legislative process to restrict or discontinue the release of contaminants. However, the problem of ground water degradation is far more difficult to overcome. Ground water contamination is hard to detect because it is hidden from view; it is almost always discovered by detection in someone's well. Moreover, it typically takes a long time for ground water pollution to show itself, and it takes a very long time for an aquifer to flush itself of the pollutant. Since flushing periods are typically in the range of tens, hundreds, or even thousands of years, the result is often a permanently damaged aquifer (Freeze and Cherry, 1979). Defining the extent of aquifer contamination is extremely costly and technically challenging. Restoring polluted ground water to its original quality is nearly impossible.

Scope

The protection of ground water quality is probably best accomplished by prevention of contamination. The U.S. Department of Agriculture (1987) encourages private landowners to use agricultural practices that prevent, minimize, or avoid harmful levels of contamination in ground water. Although the Soil Conservation Service provides technical assistance on many types of activities that may affect ground water, there is little guidance provided in SCS technical references concerning ground water quality.

Technical Note 5 has been developed to provide guidance on the evaluation of hydrogeologic conditions at proposed sites for such elements of resource management systems that could have the potential to adversely influence ground water quality.

The procedure is based on three recently developed systems (Aller, 1987; LeGrand, 1983; and Wisconsin Geological and Natural History Survey, 1985) and uses quantitative ranking of some of the most important factors affecting a site's susceptibility to ground water contamination. The method makes a systematic evaluation of proposed conservation practice sites. Information used is generally available in field offices: Soil Survey Reports, topographic maps, State and US Geological Survey reports, and simple, on-site observations. The system can be used by those with diverse backgrounds and a basic understanding of ground-water hydrology.

Purposes

* The system serves as a screening tool early in the conservation planning process when sites for practices are being selected. Potential problems that previously may have gone unrecognized are identified early in planning. Sites that have very high pollution potential can be avoided or afforded appropriate defensive design measures.

* The system allows the user to compare the relative risks of ground water contamination among various sites and to select the most favorable site.

* The system identifies when a specialist is needed, or when a more detailed, site-specific evaluation is necessary.

* The system provides insight on how either the site or the practice may need to be modified to provide for protection of ground water.

Discussion of Methodology

The system focuses on two main subsurface zones: the vadose zone where water and leachable contaminants move vertically downward, and the uppermost saturated zone where ground water moves essentially laterally. The system is best suited for situations where the contaminant is assumed to be introduced at the ground surface, dissolved in water, and has the mobility of water. The system is designed to apply only to the uppermost ground water system (the water table aquifer), and not to deeper, confined aquifers.

There are many hydrogeologic factors which influence the behavior and movement of contaminants in the ground. This system addresses seven of the most important ones that can be evaluated with readily available information. The seven factors include:

1. Horizontal distance between site and point of water use
2. Land slope
3. Depth to water table
4. Vadose zone material
5. Aquifer material
6. Soil depth
7. Attenuation potential of soil

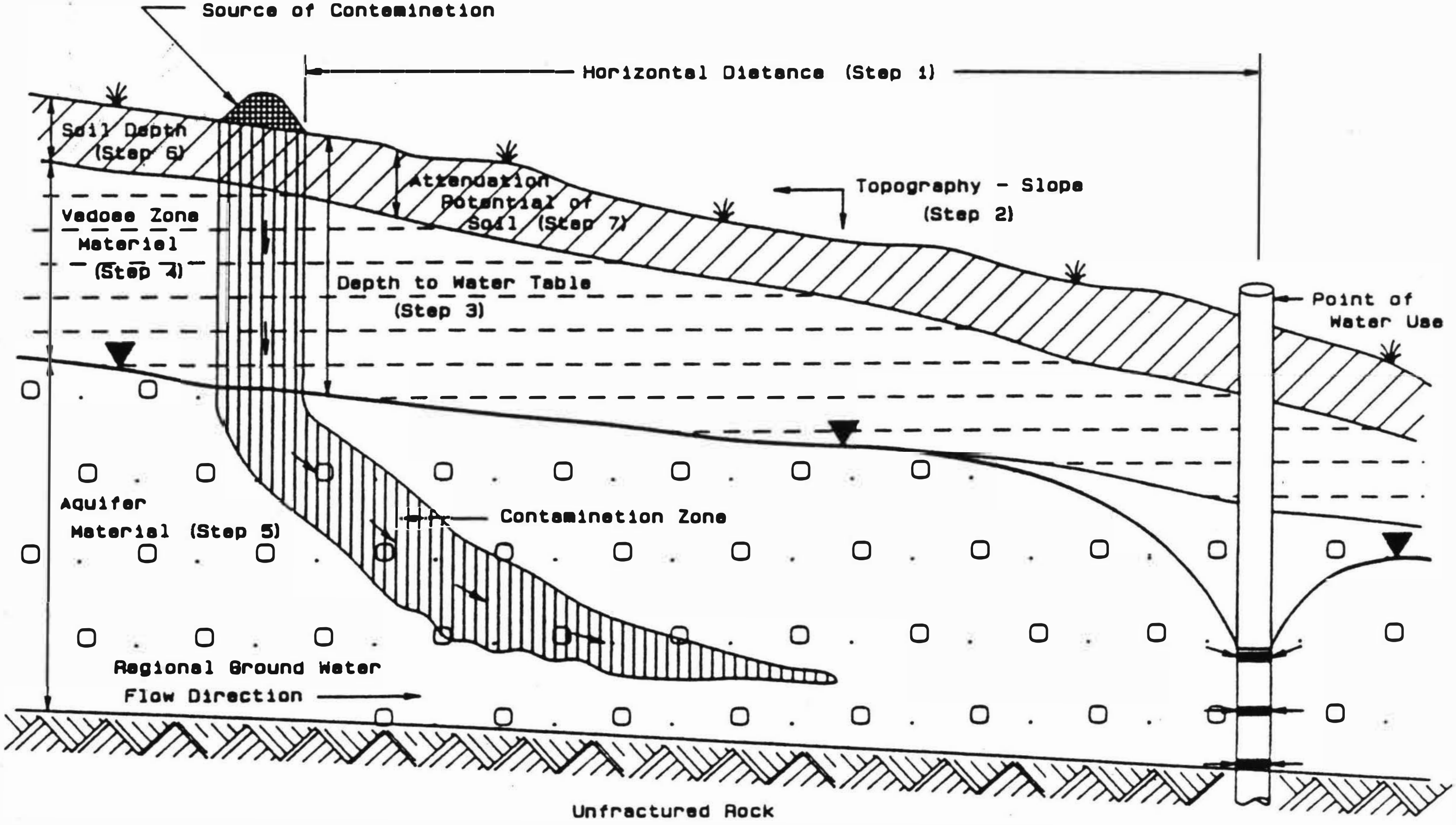
See Figure 1 for a typical setting of the seven steps viewed in cross-section.

Each factor has been assigned a numerical weight ranging from one to five, with the most significant having a weight of five and the least significant a weight of one. The weight is a function of the relative contribution of the factor and whether the contamination is from a concentrated or dispersed source. The weights for each factor are constants; they were determined by a panel of experts for the Aller (1987) system and must not be changed. Dispersed sources of contamination are from nonspecific, diffuse origins; concentrated sources are derived from site-specific, readily observable origins. For example, if the site covers a relatively broad area, such as in the case of application of pesticides on a field, then "dispersed source" weights are used in the analysis. If the site would tend to concentrate pollutants in a relatively small, confined area, such as an animal waste storage pond, then "concentrated source" weights are selected.

Each factor is divided into numerical ranges with values which vary between one and ten. The ratings for aquifer and vadose zone materials may vary; a rating value can be interpolated and selected according to specific available information, or in the absence thereof, the typical rating can be selected. Scores for each factor are obtained by multiplying the weight by the rating.

Once the scores for the seven factors have been determined, they are summed. The sum of the scores is the Site Index Number (SIN). Site Index Numbers can be used to compare various sites for a proposed conservation practice. The site with the lowest SIN is the least sensitive to ground water contamination. The Site Index Numbers are ranked into Pollution Potential Catego-

Figure 1: Typical setting for seven steps in SEEPPAGE method, as shown in cross-section.



NOT TO SCALE

Key to Symbols

▨	Surface Soil (As mapped by U.S.D.A.)
▤	Vadose Zone Material (Unsaturated zone above aquifer and below surface soils; may be soil or rock materials.)
0 . 0 . 0 . 0 . 0 .	Aquifer Material (Saturated zone capable of yielding useful supplies of water; may be soil or rock materials.)
▩	Unfractured Rock (Non-waterbearing; defines lower limit of aquifer in this case.)
▥	Contaminant Plume (Assumes contaminant has same density and solubility as water, and is dissolved in water.) Arrows denote direction of flow of plume.

ies of LOW, MODERATE, HIGH, and VERY HIGH for both concentrated and dispersed sources of contamination (Table 8). A HIGH or VERY HIGH Pollution Potential Category is a good indication that the site has significant constraints and should be reviewed by a qualified specialist. A ranking of LOW is not necessarily a guarantee that the site will be trouble-free since the procedure addresses only some of the factors that influence ground water contamination. Generally speaking, a site with a ranking of LOW or MODERATE will be superior to one of HIGH or VERY HIGH and is, consequently, more preferable.

An assessment of the scores of the individual factors can provide insight on how the site or the practice may need to be modified to provide for the protection of the ground water. A summary of the score ranges for the seven parameters is given in Table 9. For example, in the case of an animal waste storage pond, high scores in Soil Depth and Aquifer Material (such as thin soil over karst limestone) are indications that the site will need defensive design measures to protect against ground water contamination. Measures may include the use of some type of liner (such as compacted clay, concrete, or plastic) or abandonment of the site for a more favorable location. If all factors are low except Horizontal Distance, then relocating the site further from the water supply well (or point of concern) would be advisable, in addition to lining.

LIMITATIONS OF THE SYSTEM

The ground water pollution potential of a site is a function of many interrelated hydrogeologic, environmental, and cultural factors, and contaminant characteristics. Only a few important hydrogeologic factors are considered in this system. The overriding concern in the development of this system is ease of use. Some information is not readily available or easily developed so such information was excluded. Although the system is simple in concept, it is logical and systematic in its approach, and will achieve the intended purposes.

While recharge is an important climate-related factor, it is not addressed by this system. Recharge is water derived mainly from precipitation or irrigation. It percolates from the ground surface through the soil and vadose zones to an aquifer. Recharge water that originates directly above a source of contamination is responsible for the leaching and movement of pollutants. Generally speaking, the potential for pollution at a site with increases with increasing recharge. Recharge outside the boundaries of a contamination source is generally considered beneficial to the aquifer. The general lack of readily available data and the complexities in its evaluation preclude considering it in this system.

It is important to know whether a contaminant is moving toward or away from a water supply. In humid areas, the frequency of precipitation is usually sufficient to provide recharge to maintain a permanent water table that generally reflects surface topography. Land slope can often be used to ascertain the direction of flow. Unfortunately, radial flow paths, unusual geology, and peculiar contaminant characteristics can too often invalidate this assumption. Hence, the system does not address direction of flow.

The system does not take into account the size and proximity of the population at risk, nor the importance of the aquifer itself to that population.

The system is not designed to apply to specific types of contamination; it does not address contaminant severity (which includes contaminant toxicity, volume, mobility, and persistence), contaminant magnitude (which includes concentration of contaminant, number of contaminants, and plume size), or how the contaminant is released into the environment (as a slug, intermittently, or continuously).

Another point to remember is that some conditions that may be beneficial for ground water protection can be harmful to surface water quality. Consider for example, a large field on steep slopes with freshly applied chemicals. If a heavy rain occurs, the steep slopes promote high erosion rates and rapid runoff of contaminated surface water. Steep slopes are rated favorably in Table 2 (Land Slope) for ground water protection, but of course, they are detrimental to erosion rates and surface water quality. Conversely, the installation of terraces on the slopes would reduce soil erosion and runoff while causing greater infiltration of chemical-laden water into the ground. Conservationists must carefully consider these potentially conflicting effects.

The Pollution Potential Category does not reflect the site's suitability for a particular conservation practice. The suitability of a site depends upon many criteria, including hydrogeologic, environmental, engineering, economic, political, and regulatory. The Category is an indication of the ground-water pollution potential of an area.

This system is intended to be used as a screening tool in the conservation planning process. It **must not** be utilized as a substitute for a professionally conducted, detailed investigation for design purposes.

Instructions

Use the Worksheets in the back of this Technical Note (pp. 21 and 22) for recording data and calculating the Site Index Number (SIN) and the Pollution Potential Category for each site under consideration. Follow the instructions for each step carefully.

STEP 1. DISTANCE BETWEEN SITE AND POINT OF WATER USE

A. Determine whether the potential source of pollution at the site classifies as Concentrated or Dispersed, then select the appropriate weight given at the bottom of Table 1.
B. Measure the horizontal distance between the site and the point of water use (such as a well) or some designated point of concern (such as a property line).
C. Determine rating for distance using Table 1.
D. Multiply rating times weight to obtain score for Step 1.
E. Record the weight, rating, and score for Step 1 on the Worksheet for Site Index Number, p. 21.

Table 1: Ratings for Distance Between Site and Point of Water Use

Distance (Feet)	Rating
0 - 30	10
30 - 60	9
60 - 100	8
100 - 160	7
160 - 250	6
250 - 500	5
500 - 1000	4
1000 - 3200	3
3200 - 6400	2
> 6400	1
Concentrated Source, Weight: 5	Dispersed Source Weight: 2

Significance of Factor: Distance directly affects the amount of time available for attenuation processes to work. The greater the distance, the greater the time of travel for the pollutant. The longer the pollutant is in contact with the material through which it passes, the greater will be the opportunity for decay, degradation, dilution, and sorption of the pollutant.

STEP 2. LAND SLOPE

A. Measure the slope of the land surface at the site.
B. Determine rating value for slope using Table 2.
C. Select weight for appropriate source given at bottom of Table 2.
D. Multiply rating times weight to obtain score for Step 2.
E. Record the weight, rating, and score for Step 2 on the Worksheet for Site Index Number, p. 21.

Table 2: **Ratings for Land Slope**

Percent Slope	Rating
0 - 2	10
2 - 6	9
6 - 12	5
12 - 18	3
> 18	1
Concentrated Source, Weight: 1	Dispersed Source, Weight: 3

Significance of Factor: The slope of the land surface at the site influences runoff/infiltration relationships. The flatter the slope, the greater will be infiltration of water (and any dissolved pollutants) into the soil, and therefore, the greater will be the ground-water pollution potential. Steeper slopes tend to induce greater surface water runoff, a condition which can be detrimental from the standpoint of erosion and surface water quality.

Steeper slopes can often indicate higher ground water velocities.

Summary: The flatter the slope of the land surface, the greater the ground-water pollution potential. The steeper the slope, the greater the potential for erosion and surface water pollution.

STEP 3. DEPTH TO WATER TABLE

A. Estimate the shallowest depth to the water table that is below the elevation of the base (or proposed base) of the site more than 5 percent of the year. Use Soil Survey Reports, well logs, or hand auger observations for shallow depths.
B. Determine rating value for depth using Table 3.
C. Select weight for appropriate source given at bottom of Table 3.
D. Multiply rating times weight to obtain score for Step 3.
E. Record the weight, rating, and score for Step 3 on the Worksheet for Site Index Number, p. 21.

Table 3: Ratings for Depth to Water Table

Depth to Water (Feet)	Rating
0	10
0 - 2	9
2 - 5	8
5 - 15	7
15 - 25	6
25 - 35	5
35 - 60	4
60 - 90	3
90 - 200	2
> 200	1
Concentrated Source, Weight: 5	Dispersed Source, Weight: 5

Significance of Factor: The water table can be defined as the boundary between the unsaturated zone and underlying zone of saturation. The depth to the water table determines the vertical distance through which a pollutant must move to reach the top of an aquifer. The greater the depth, the greater the time of travel. The greater the time that the pollutant is in contact with the surrounding material, the greater will be the opportunity for attenuation of the pollutant by processes such as oxidation, decay, and sorption.

Summary: The shallower the water table, the greater the groundwater pollution potential.

STEP 4. VADOSE ZONE MATERIAL

A. Determine type of material in vadose zone (between surface soils and aquifer).
B. Select rating for type of materials in the vadose zone using Table 4.
C. Select weight for appropriate source given at the bottom of Table 4.
D. Multiply the rating times weight to obtain score for Step 4.
E. Record the weight, rating, and score for Step 4 on the Worksheet for Site Index Number, p. 21.

Table 4: **Ratings for Type of Material in Vadose Zone**

Vadose Zone Material	Rating*	Typical Rating
Silt or Clay	1 - 2	1
Shale, Claystone	2 - 5	3
Limestone	2 - 7	6
Sandstone	4 - 8	6
Limestone, Sandstone, and Shale Sequences	4 - 8	6
"Dirty" Sand and Gravel (having > 12% silt and clay)	4 - 8	6
Metamorphic/Igneous Rocks	2 - 8	4
"Clean" Sand and Gravel (having < 12% silt and clay)	6 - 9	8
Basalt	2 - 10	9
Karst Limestone	8 - 10	10

* Note: Use higher ratings if there are open joints, fractures, or other macro-pores in any of these deposits. Base adjustment on spacing and size of openings.

Concentrated Source, Weight: 5	Dispersed Source, Weight 4

Significance of Factor: The vadose zone can be defined as the unsaturated (or discontinuously unsaturated) material that is above the water table and below the surface soil. The type of material in the vadose zone determines the flow path and rate of flow of the water (and pollutants) percolating downward through it. The rate of flow is a function of the permeability of the vadose zone material; permeability rates are greatly increased by the presence of fractures in the material. Thus the time available for attenuation processes (such as sorption, oxidation, dispersion, mechanical filtration, etc.) to take place is inversely related to permeability. Permeability rates can be inferred from the type of materials.

Summary: The greater the permeability of a material, the lower will be its attenuation capacity, and therefore the higher will be the ground-water pollution potential.

STEP 5. AQUIFER MATERIAL

A. Determine aquifer material using geologic maps of area and on-site inspection.
B. Select the rating for aquifer material from Table 5; use the typical rating unless more specific knowledge justifies modifying it within the given ranges.
C. Select the weight for appropriate source given at the bottom of Table 5.
D. Multiply the rating times the weight to obtain score for Step 5.
E. Record the weight, rating, and score for Step 4 on the Worksheet for Site Index Number, p. 21.

Table 5. **Ratings for Aquifer Material**

Aquifer Material	Rating*	Typical Rating
Shale, Claystone	1 - 3	2
Unweathered Metamorphic/Igneous Rock	2 - 5	3
Weathered/Fractured Metamorphic/Igneous Rock	3 - 5	4
Glacial Till	3 - 5	4
Sandstone, Limestone, and Shale Sequences (rate higher if fractured)	5 - 9	6
Massive Sandstone	4 - 9	6
Massive Limestone/Dolomite	4 - 9	6
Sand and Gravel	6 - 9	8
Basalt (rate higher if fractured/vesicular)	2 - 10	9
Karst Limestone (highly fractured/cavernous)	9 - 10	10

* **Note:** Use higher ratings if there are any open joints, fractures, or other macro-pores in any of these materials. Base adjustment on the spacing and size of the openings.

Concentrated Source, Weight: 3	Dispersed Source, Weight: 3

Significance of Factor: An aquifer can be defined as a saturated geologic material which will yield useable quantities of water. Ground water can be transmitted through an aquifer two ways: (1) through the pore spaces between the particles that make up the material (called primary porosity) and, (2) through the fractures and cavities that developed after the material was formed (called secondary porosity). The type of aquifer material controls the flow path and path length which a pollutant must follow; it also influences its permeability, the aquifer's ability to transmit water. Generally speaking, permeability is lower in fine-grained materials (such as clays or shales) and in materials lacking interconnecting fractures (such as unweathered rocks); permeability tends to be higher in coarse-grained materials, such as clean sands and gravels. The occurrence of secondary fractures in a geologic material greatly increases the paths available for ground water flow and, hence, greatly increases the permeability. Permeability can be inferred from the type of aquifer material. The aquifer materials listed in Table 5 are arranged by increasing permeabilities.

Summary: The greater the permeability of aquifer material, the greater the rate at which a pollutant can spread through the aquifer. The greater the permeability, the less time for attenuation processes to occur. Thus, aquifers comprised of materials with high permeabilities will have high ground-water pollution potential.

STEP 6. SOIL DEPTH

A. Determine depth of soil using information from the local Soil Survey Report or by on-site inspection.
B. Select rating for soil depth using Table 6.
C. Select weight for appropriate source given at bottom of Table 6.
D. Multiply the rating times the weight to obtain score for Step 6.
E. Record the weight, rating, and score for Step 6 on the Worksheet for Site Index Number, p. 21.

Table 6: **Ratings for Soil Depth**

Soil Depth (inches)	Rating
> 60 (very deep)	1
40 - 60 (deep)	2
20 - 40 (mod. deep)	6
10 - 20 (shallow)	9
< 10 (very shallow)	10
Concentrated Source, Weight: 2	Dispersed Source, Weight: 5

Significance of Factor: Soil depth classes are defined to depths up to 60 inches. These depth classes are based upon depth to restricting or contrasting layers (or bedrock) which influence the downward movement of water and root-penetration. Many important processes attenuate pollutants in the soil zone (see Step 7 for more discussion on significance of attenuation potential of soil). Deeper soils affect the contact time that a pollutant will have with the mineral matter and organic matter of the soil. Very shallow soils (thin to absent) provide little to no protection against ground-water pollution.

STEP 7. ATTENUATION POTENTIAL OF SOIL

Note:
This step is somewhat different from the previous six steps in that two tables must be used to arrive at the attenuation potential of soil. Table 7 is modified from the work of the Wisconsin Geological Survey (1985, p. 35) which assigned factor levels for various physical/chemical soil characteristics that were directly proportional to their attenuation potential. The purpose of Table 7a is to provide a single value for these various characteristics that is inversely proportional to attenuation potential, that is, the higher the numeric rating, the lower the attenuation potential of the soil. Carefully follow the instructions below and use the worksheet (p. 22) to obtain a value for Step 7.

A. Select a factor level for each of the six physical/chemical soil characteristics given in Table 7 using information from the local Soil Survey Report. Use the Step 7 Worksheet (p. 22) to record the selected values.
B. Sum values of the six factor levels.
C. Use this sum to determine the rating for the attenuation potential of the soil from Table 7a.
D. Select the weight for the appropriate source given at the bottom of Table 7a.
E. Multiply the rating for attenuation potential of the soil times the weight to obtain score for Step 7.
F. Record the weight, rating, and score for Step 7 on the worksheet for Site Index Number, p. 21.

Significance of Factor: In the surface soil zone, a great variety of biological, physical, and chemical processes act on a pollutant and tend to lessen its potency or reduce its volume. These processes, collectively referred to as attenuation, prevent or retard the movement of pollutants into deeper subsurface zones. The degree of attenuation depends on the time a pollutant is in contact with the material through which it passes, and the amount of surface area of the particles making up the material. Both the time and the surface area are functions of the grain size of the material and the distance through which the pollutant must pass. Thus, the finer the grain size of the material and the thicker the deposit, the greater will be the attenuation of the pollutant. The eventual fate of most pollutants and the resulting quality of ground water will thus depend on the degree of attenuation that takes place.

The attenuation potential of a soil can be estimated from six physical/chemical characteristics listed in Soil Survey Reports:

(1) Texture of Surface (A) Horizon: The USDA Soil Classification System is used to define soil textures. Medium-textured, well-aerated soils provide optimum conditions for contaminated water to move through the horizon with maximum contact with the

organic and mineral constituents of the soil. Coarse-textured soils and those with large wood fragments tend to be least desirable.

(2) Texture of Subsoil (B) Horizon: Fine-textured soils are desirable in the subsoil horizon to retard the movement of contaminated soil water and allow time for the attenuation processes to work. Shrinking or aggregated types that tend to form macro-pores (fractures in the soil mass itself) are less desirable because such features increase the permeability. Again, coarse-textured soils are the least desirable.

(3) pH of the Surface (A) Horizon: Many attenuation processes in the soil zone function best when the pH of the soil (the degree of acidity or alkalinity) is neutral.

(4) Organic Matter Content: Organic matter is an important constituent in soil because it holds nutrients, water, and heavy metals; and absorbs many types of organic pesticides. It serves as an energy source to microörganisms that break down many types of organic pesticides. Generally speaking, the higher the organic matter content of the soil, the greater will be its attenuation potential.

(5) Permeability of Least Permeable Horizon (below the A): The slower the permeability of the soil, the greater will be the time available for attenuation processes to work in the lower horizons.

(6) Soil Drainage Class: Soil drainage class is an indication of the frequency and duration of periods when the soil is free of saturation or wetness. A well-drained soil is most desirable because the water from all rains can be distributed within the profile and move out by evapotranspiration without disturbing the aeration of the soil. Somewhat poorly to very poorly drained, and excessively drained soils are least desirable. Attenuation potential is lower for the more poorly drained soils which tend to be wet much of the year; it is also lower for excessively drained soils because the movement of the contaminated water is too rapid for the processes to take effect.

In Table 7 below, the following abbreviations are used for Soil Texture Classes (USDA Classification): l = loam, sil = silt loam, scl = sandy clay loam, si = silt, c = clay, sic = silty clay, cl = clay loam, sicl = silty clay loam, sc = sandy clay, lvfs = loamy very fine sand, vfsl = very fine sandy loam, lfs = loamy fine sand, fsl = fine sandy loam, s = sand, ls = loamy sand, sl = sandy loam.

Table 7: Factor Levels for Characteristics Affecting Attenuation Potential of Soil

Physical/Chemical Characteristics	Classes	Factor Level
Texture of Surface (A) Horizon (if A is absent, Factor Level equals 0)	l, sil, scl, si	9
	c, sic, cl, sicl, sc	8
	lvfs, vfsl, lfs, fsl	4
	s, ls, sl, > 15 % wood fragments > 3/4 in. across, and all textural classes with coarse fragment class modifiers	1
Texture of Subsoil (B, or if absent, C horizon)	c, sic, sc, si (if clay fraction is a shrinking or aggregated type, subtract 3 points)	10
	scl, l, sil, cl, sicl (if clay fraction is a shrinking or or aggregated type, subtract 3 points)	7
	lvfs, vfsl, lfs, fsl	4
	s, ls, sl, > 15 % wood fragments > 3/4 in. across, and all textural classes with coarse fragment class modifiers	1
pH - Surface (A) Horizon (if absent, use uppermost soil horizon)	6.6 - 7.3 (neutral)	6
	6.1 - 6.5 (slightly acid)	4
	> 7.3 or < 6.1	1
Organic Matter Content (Percent) of Surface Layer of Mineral Soils	4.0 - 10.0 (high)	8
	2.0 - 4.0 (medium)	6
	1.0 - 2.0 (moderately low)	5
	0.5 - 1.0 (low)	3
	< 0.5 (very low)	1
Permeability (in./hr.) of Least Permeable Horizon in Profile (below the A)	< 0.06 (very slow)	10
	0.06 - 0.2 (slow)	8
	0.2 - 0.6 (moderately slow)	7
	0.6 - 2.0 (moderate)	6
	2.0 - 6.0 (moderately rapid)	4
	6.0 - 20.0 (rapid)	2
	> 20.0 (very rapid)	1
Soil Drainage Class	well drained	10
	somewhat excessively drained	7
	moderately well drained	4
	somewhat poorly, poorly, and very poorly drained; and excessively drained	1

Table 7a: **Ratings for Attenuation Potential of Soils**

Range of the Sum of 6 Factor Ratings for Characteristics in Table 8a.	Rating for Attenuation Potential	Verbal Rating
5 - 10	10	Least Potential
11 - 15	9	Least Potential
16 - 20	8	Least Potential
21 - 25	7	Marginal
26 - 30	6	Marginal
31 - 34	5	Good
35 - 40	4	Good
41 - 44	3	Best
45 - 48	2	Best
49 - 53	1	Best
Concentrated Source Weight: 2	Dispersed Source, Weight: 5	

STEP 8. DETERMINATION OF SITE INDEX NUMBER AND POLLUTION POTENTIAL CATEGORY

A. After determining the 7 scores in Steps 1 through 7 above, add them up. The sum is the Site Index Number (SIN). The SIN can vary between 23 and 230 for Concentrated Sources, and between 27 and 270 for Dispersed Sources.

B. Use Table 8 to determine the Pollution Potential Category of the SIN.

Table 8: **Pollution Potential Categories of Site Index Numbers**

Source of Pollution	Pollution Potential Category of Site Index Numbers			
	LOW	MODERATE	HIGH	VERY HIGH
Concentrated	23 - 63	64 - 136	137 - 188	189 - 230
Dispersed	27 - 65	66 - 158	159 - 228	229 - 270

Significance of Site Index Number (SIN): The larger the SIN, the greater the pollution potential of the ground water at the site. The number itself has no intrinsic value. Concentrated Source SINs can only be compared to other Concentrated Source SINs (and Dispersed Source SINs only with Dispersed Source SINs); Concentrated Source SINs cannot be compared to Dispersed Source SINs.

Significance of Pollution Potential Category: The Pollution Potential Category provides a basis for ranking the relative magnitude of the SIN. It also provides a rationale for requesting a specialist if the site is not rejected. If the category is HIGH or VERY HIGH, or if the investigator is not confident in some of the values selected in the analysis, a specialist should be requested to provide detailed technical assistance. See "Discussion of Methodology" (p. 3), and "Limitations of System" (p. 7), for additional information.

Table 9: Summary of Score Ranges for Each Step

	CONC. WEIGHT	DISP. WEIGHT	SUMMARY OF SCORE RANGES FOR EACH PARAMETER			
			LOW	MODERATE	HIGH	V. HIGH
STEP 1: DISTANCE	5	5	1 - 3	4 - 5	6 - 7	8 - 10
STEP 2: LAND SLOPE	1	3	1	3	5	9 - 10
STEP 3: WATER DEPTH	5	5	1 - 3	4 - 5	6 - 7	8 - 10
STEP 4: VADOSE ZONE	5	4	1 - 3	4 - 5	6 - 7	8 - 10
STEP 5: AQUIFER	3	3	1 - 3	4 - 5	6 - 7	8 - 10
STEP 6: SOIL DEPTH	2	5	1	2	6 - 9	10
STEP 7: ATTENUATION	2	5	1 - 3	4 - 5	6 - 7	8 - 10

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Appendix D

AQUIPRO

AQUIPRO: A Computerized Method for Determining Aquifer Vulnerability

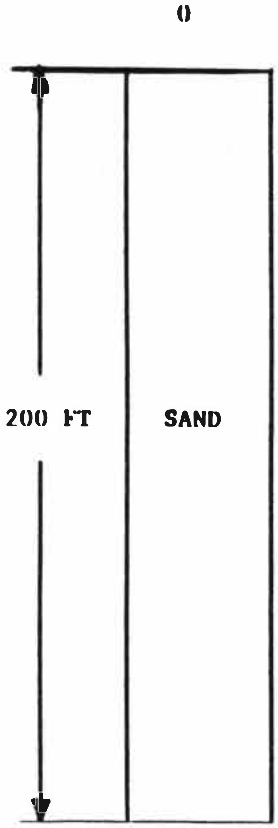
Richard N. Passero
Institute for Water Sciences
Western Michigan University
Kalamazoo, Michigan

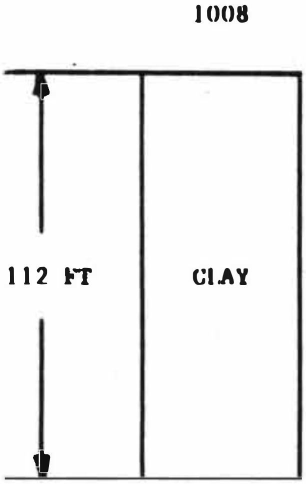
Several approaches have been developed to determine the vulnerability of aquifers to contaminants discharged onto the land surface or at shallow depths. Assessing the vulnerability or pollution potential of aquifers is currently underway at many state geological and environmental agencies in the country. The systems being used range from the National Water Well Association's DRASTIC program to approaches created by individual state agencies. As part of the Southwest Michigan Groundwater Survey and Monitoring Program, the Institute for Water Research at Western Michigan University has carefully examined DRASTIC as to its applicability in Michigan. DRASTIC presents certain limitations for an area such as southern Michigan where glacial drift aquifers are most commonly used and there are only a limited number of bedrock aquifers.

Because of these perceived limitations and in an attempt to develop an approach which would utilize the current computerized groundwater data base of the Michigan Groundwater Survey and the variety of data bases available through the Michigan Resource Inventory System (MIRIS), an alternative aquifer vulnerability assessment system is being developed. The emphasis is on applicability to Michigan, availability of data, and ease of presentation with current computer software and expertise. The system is based on the assumption that clays and clayey glacial sediments and certain low permeability rocks such as shale, provide natural protection for glacial and bedrock aquifers. Aquifer vulnerability is determined easily on the microcomputer from well record files, using a program (AQUIPRO) that multiplies the weighted depth of the well times the weighted thickness of the protective clay, clayey glacial sediments and confining and semi-confining bedrock types (Table 1). An aquifer vulnerability score is determined for each water well location from the water well record for that well (Figure 1.). Wells can be sorted for aquifers of any depth range.

Table 1. AQUIPRO Clay Equivalents

AQUIPRO RANGE	REQUIRED WELL DEPTH AND CLAY THICKNESS
(0-100)	(MAX 50 FT WELL, 17 FT CLAY UNIT)
(101-200)	(50 FT WELL, 18-33 FT CLAY UNIT)
(201-400)	(100 FT WELL, 27-53 FT CLAY UNIT)
(401-1000)	(100 FT WELL, 54-100 FT CLAY UNIT)
(1000+)	(>100 FT WELL, >100 FT CLAY UNIT)





696

(5)	SANDY CLAY	25 FT
(1)	CLAY	25 FT
	SANDY GRAVEL	50 FT
	SAND	20 FT
(4)	CLAYEY SAND	30 FT
(3)	CLAY	10 FT
	SAND	20 FT
(2)	CLAY	20 FT

$$A = D[3 \sum_{0,1}^{n} Cr/(1 + r/10) + 1 \sum_{0,1}^{n} Pr/(1+r/10)]$$

$$A = 3.5[0 \times 150/(1 + 0/10)] = 0$$

$$A = 3[3 \times 112/(1 + 0/10)] = 1008$$

$$A = 3.5[\underbrace{3(25/1(1+0/10))+3(20/(1+2/10))+3(10/(1+3/10))}_{\text{CLAY UNITS}}+\underbrace{1(30/(1+0/10))+1(25/(1+2/10))}_{\text{CLAYEY UNITS}}]$$

(0-100)	(101-200)	(201-400)	(401-1000)	(1000+)
★	▲	◆	●	■

WEIGHTED DEPTH OF WELL SCREEN

DEPTH (FT)	WEIGHT
0-5	1
6-20	1.5
21-50	2
51-100	2.5
101-150	3
151-200	3.5
201-250	4
251-300	4.5
301-350	5
351-400	5.5
401-450	6
451-500	6.5
ETC.	ETC.

WEIGHTED TYPES OF PROTECTIVE UNITS
(See Table 13 - for equivalent bedrock types)

PROTECTIVE UNIT	WEIGHT
CLAY	3
SAND/GRAVEL/CLAY MIXTURES	1
SAND/CLAY MIXTURES	
GRAVEL/CLAY MIXTURES	
MISCELLANEOUS CLAYEY UNITS	
OTHERS	0

$$A = D[3 \sum_{0,1}^{n} Cr/(1 + r/10) + 1 \sum_{0,1}^{n} Pr/(1+r/10)]$$

D = Depth of well (aquifer)

C = Total thickness of clay

P = Total thickness of partial clay

r = Rank of each clay or partial clay

AQUIPRO Version 2.52, (c) Western Michigan University, 1989

Welcome to AQUIPRO. This program produces a C-Map compatible well-analysis file from your WELLKEY files. It will work with WELLKEY v1 (LAB and LTH files), and with WELLKEY v2 (PNT and LTH files). The file created will allow you to map and display:

> Aquipro Scores and analysis can be calculated from the land surface down to several depths: All well, drift only, drift & shale atop bedrock, static water level, any fixed value.
>
> Elevations for land, static water level and bedrock are caculated so they can be contoured. Drift thickness is calculated for bedrock wells. Total thickness of clay, part-clay and no-clay layers, the number of layers of each type, and the thickest layer in each type can be calculated to several depths (see above). Total clay and total part clay any range of the well can be calculated.
>
> The options you select are included in the Aquipro file, and can be used for further calculations or queries.

AQUIPRO RELEASE NOTES: Version 2.51, November 25, 1991

This is a revised version of Aquipro. The basic Aquipro formula is the same, and the program itself is still slow, but several features have been added. Here is a short list of new features:

- You can calculate Aquipro scores from the land surface down to several different spots. (All well, drift only, drift & shale atop bedrock, static water level, any fixed value).
- You can set all the options at the front of the program and let it run uninterrupted.
- You can search for partial clay as well as clay.
- You can keep track of which options and ranges you specified in your final records, and use queries to display them.

Estimate 1-4 seconds per record. Use of a RAM disk will greatly increase the speed.

If you notice anything unusual, please do call (phone numbers are at the end of this). This is the first release of these changes, and we would like to know if anyone discovers odd circumstances.

AQUIPRO SUMMARY:

Aquipro analyzes and reports well depth and lithology details, applies a formula, and produces a well analysis file of information pertinent to aquifer protection/vulnerability. The higher the Aquipro score, the more protected the well. Here are three example wells with varying lithologies taken from the well construction database:

	WELL #1	WELL #2	WELL #3
Wellid	080110101	080110102	080010103
Depth	100	100	112
Screen Placement			95-100
Lithology	20 Sand	100 Clay	30 Sand
	35 Clay		60 Sand/gravel
	50 Sand/clay		100 Gravel
	55 Sand		112 Clay
	60 Gravel/clay		
	70 Clay		
	100 Sandstone		

The first well (080110101) is a mixed lithology, the second (080110102) is a theoretical well representing an extreme in clay-layer protection, the third (080010103) represents an extreme in unprotected lithology.

The Aquipro program reads the well construction database and prepares a companion database which contains an analysis of each well's lithology, and assigns an Aquipro score.

	WELL #1	WELL #2	WELL #3
Wellid	080110101	080110102	080010103
Depth	100	100	100
Clay Layer Count	2	1	0
Clay Total Thickness	25	100	0
Clay Thickest Layer	15	100	0

Part-clay Layer Count	2	0	0
Part-clay Total Thickness	20	0	0
Part-clay Thickest Layer	15	0	0
Non-clay Layer Count	3	0	3
Non-clay Total Thickness	55	0	100
Non-clay Thickest Layer	30	0	40
Aquipro Score	222	750	0
Clay in first 50 ft.	15	50	0
Bedrock Elevation	880	0	0
Drift Thickness	70	0	0

The model can take into account specific circumstances. For example, some bedrock units may or may not be aquifers. If a well produces water from a low-permeability bedrock type, it is treated as it is treated as partial-clay on the assumption that it is permeable enough to serve as a source of groundwater. And for example, if a screen is placed at some point above the well's depth, then the bottom of the screen is used as well depth, as can be seen in the third well, on the assumption that the well's vulnerability depends on the layer water comes from more than how deep the driller bored the hole. In the case of the third well, the last layer (clay) is not included in the calculations.

The complete file created by Aquipro is shown below:

Structure for database: C:\WLG2WKY\AQUIPRO\AQUIPRO.PNT

Field	Field Name	Type	
1	WELLID	Character	Wellid -make sure no dupes.
2	X_COORD	Numeric	in PNT, Loc_e in LAB
3	Y_COORD	Numeric	in PNT, Loc_n in LAB
4	ELEV	Numeric	Elevation
5	LOG_DEPTH	Numeric	Actual depth on well log
6	DEPTH	Numeric	Depth as set by Aquipro
7	V_DEPTH	Numeric	Weighting for depth
8	SWL	Numeric	Static Water Level
9	C_COUNT	Numeric	Total clay layers
10	C_THICK	Numeric	Total clay thickness
11	C_MAX	Numeric	Thickest clay layer
12	P_COUNT	Numeric	Total part-clay layers
13	P_THICK	Numeric	Total part-clay thickness
14	P_MAX	Numeric	Thickest part-clay layer

15	N_COUNT	Numeric	Total non-clay layers
16	N_THICK	Numeric	Total non-clay thickness
17	N_MAX	Numeric	Thickest non-clay layer
18	SCORE	Numeric	Aquipro Score
19	V_SCORE	Numeric	Score Grouping - option set
20	BED_TOP	Numeric	Bedrock surface elevation
21	DRIFT_THK	Numeric	Drift thickness
22	CLAY_HUNT	Numeric	Clay found in hunt range
23	PCLAY_HUNT	Numeric	Part-clay found in hunt range
24	LOCAL_C	Character	Well summary:
25	LOCAL_N	Numeric	Used as Group Symbol in Surfer
26	MODE	Character	Option chosen by operator
27	F_FT	Numeric	Fixed feet if "F" option used
28	HUNT_START	Numeric	Hunt range for clay and part-clay
29	HUNT_STOP	Numeric	Hunt range finish
30	RANGE1	Numeric	Options set for Grouping
31	RANGE2	Numeric	and symbol for Surfer
32	RANGE3	Numeric	
33	RANGE4	Numeric	
34	CHARHEIGHT	Numeric	CMap fields for display
35	CHARWIDTH	Numeric	CMap fields for display
36	CHARANGLE	Numeric	CMap fields for display

The actual Aquipro formula takes these variables into account: well depth, amount of clay, and part-clay material found in the lithology, and thickness of the individual clay and part-clay layers encountered (eg, one clay layer 20 feet thick provides more protection than 20 clay layers 1 foot thick).

The program produces other useful information from the well data, including drift thickness, amount of clay in a search range you choose, and the bedrock elevation. Aquipro's analysis can be useful to decide which wells to sample for a chemistry database. For example, you could group wells as bedrock or non-bedrock (drift) based on values in the bedrock elevation field (Bed_top).

TO RUN AQUIPRO

To run from DOS, copy your wellkey PNT (LAB) and LTH files to the Aquipro directory. Type FOXPRUN WKY2AQP (which stands for wellkey to Aquipro). As the program runs, it creates a file called VALUE.ASC, an ascii file that AQUIPRO.EXE chews on to produce AQUIPRO.ASC, which is then stuffed into a filename you specify.

You will see these prompts:

```
Are the location fields LOC_E & LOC_N or X_COORD & Y_COORD? (E/X)

Enter the .LAB file name, with extension (ex. HOPE.LAB)
Enter the .LTH file name, with extension (ex. HOPE.LTH)
Enter new output file name (dBase format - ex. QHOPE.LAB)

Please choose which Aquipro option you wish to use.  This option
determines how far down into the well the Aquipro analysis goes:

A = All layers to well depth
D = Drift layers only
    Drift & 1st bedrock layer when S=shale, O=shale/coal
    L=limestone,C=coal,B=black  shale,I=fire shale, N=any of these
W = Water table (SWL field)
F = Fixed number of feet
                    Your choice (A/D/S/O/L/C/B/I/N/W/F):
```

This option sets the depth the Aquipro score is calculated to. In fact, all the information pertains to this depth used.

You can compare the difference between the LOG_DEPTH (what appeared on the original well log) and the DEPTH used to calculate layers, thicknesses and Aquipro scores. Remember that option "W" uses the Static Water Level value, and confined aquifers often push the SWL higher than the water table. If you choose "F" you will be asked to state the fixed distance to use. The default is 50.

Several advanced options are shown. S,O,L,C,B,I, and N all pertain to the first type of bedrock material encountered. These options allow inclusion of protective bedrock types over aquifers in Aquipro and other calculations. The geology of your area will determine which option is best applied. For example, if shale sits atop bedrock in part of your county, run this option to include that layer in calculations of Aquipro scores for the bedrock aquifer. You could run the program once on D) drift alone, then on S) Shale atop bedrock and drift and use these results to contour the thickness of shale atop bedrock aquifers.

```
Enter search range for clay types - Top:    0   Bottom:   50
```

This option calculates clay and part-clay found in a range you select. Remember that this hunt range will not extend beyond the Aquipro calculations range. For example, if you use Fixed calculation to 50 feet, you cannot hunt for clay and part-clay between 50-100.

0 - 100 - 200 - 400 - 1000 +

Do you wish to change the VSCORE group ranges? (Y/N)

If you choose Y, you can set the range for grouping Aquipro scores. This also groups the symbols that are used in Local_N for surfer maps. The default numbers are applicable to drift wells. Bedrock wells might have Aquipro scores up to 15000, so the groupings could be changed to:

0 - 1000 - 2000 - 3000 - 4000+

Do you wish to change any entries? (Y/N)

****

Aquipro Formula Technical Information:

Here are the values used to weight well depths. Well depth comes from the well depth value unless the record shows the screen to be set above the well depth. For example, if the record shows W.DPTH to be 120 ft., and the Screen to be set from 100-110 ft., then AQUIPRO considers the well depth to be 110.

Depth	Depth Value
<= 5	1
> 5 and <= 20	1.5
> 20 and <= 50	2
> 50 and <= 100	2.5
> 100 and <= 150	3
> 150 and <= 200	3.5
> 200 and <= 250	4
> 250 and <= 300	4.5
> 300 and <= 350	5
> 350 and <= 400	5.5
> 400 and <= 450	6
> 450 and <= 500	6.5
> 500 and <= 550	7

> 550 and <= 600	7.5
> 600 and	8

The following page shows how the layers are grouped, based on their wellkey SC field values:

FORMATION DESCRIPTIONS, STRATA CODES, AQUIPRO GROUP

CLAY-TYPE MATERIALS

CLAY	10	C
CLAY FILL	10	C
HARD CLAY	11	C
SOFT CLAY	12	P
SANDY CLAY	13	P
SANDY SILTY CLAY	13	P
FINE SANDY CLAY	14	P
SILT	15	P
SANDY SILT	15	P
CLAY & SAND	16	P
SILTY CLAY	16	P
CLAY & GRAVEL	17	P
HARDPAN	18	P
TILL (ANY COMBINATION OF CLAY, SAND, GRAVEL)	19	P

SAND-TYPE MATERIALS

SAND	20	N
SANDY FILL	20	N
FINE SAND	21	N
SILTY SAND	21	N
MEDIUM SAND	22	N
COARSE SAND	23	N
SAND & GRAVEL	25	N
SAND W/GRAVEL	26	N
SAND & CLAY	27	P
SAND W/CLAY	28	P
WATER SAND	29	N

GRAVEL-TYPE MATERIALS

GRAVEL	30	N
GRAVEL & CLAY	31	P
GRAVEL & SAND	32	N
FINE GRAVEL	33	N

SANDSTONES/SHALES

SANDSTONE	50	N
SANDSTONE W/LIME	51	P
SANDSTONE W/SHALE	52	P
SANDSTONE W/COAL	53	P
SANDROCK	54	N
SHALE	55	C
SHALE W/SANDSTONE	56	C/P
SHALE W/LIMESTONE	57	C/P
SHALE W/COAL	58	C
ROCK	59	N

EVAPORITES

EVAPORITES	60	C
LIMESTONE	61	C/P
GYPSUM	62	C
LIME	63	C/P
LIMESTONE/COAL	64	C/P
GYPSUM/COAL	65	C/P
COAL	66	C/P
BLACK 'SOFT' SHALE	67	C
FIRE CLAY	68	C
BONE COAL	69	C/P

METAMORPHIC/IGNEOUS

METAMORPHIC	70	C/P
IGNEOUS	75	C/P

DRIFT/UNKNOWN

DRIFT	80	N
UNKNOWN	99	N

MEDIUM GRAVEL	34	N
COARSE GRAVEL	35	N
WATER GRAVEL	36	N
GRAVEL & COBBLES	37	N
GRAVEL & BOULDERS	38	N
BOULDERS	39	N

ORGANICS/FILLS		
TOP SOIL	40	N
ORGANIC SOIL	41	N
BLACK DIRT	42	N
MUCK	44	N
CLAY MARL	45	P
PEAT	46	N
FILL	49	N

********************** AQUIPRO GROUPS: ************************
C=CLAY P=PARTIAL CLAY N=NON C/P=CLAY unless poducing aquifer, then PARTIAL CLAY.

Information on the Aquipro formula itself, geological applications in Michigan, research results and findings can be obtained from Dr. Richard Passero, at the addresses below:

Dr. Richard Passero
Western Michigan University
Institite for Water Sciences
Kalamazoo, MI 49008.
phone: 616-387-5505
Gemnet ID: dpassero

Sylvia Dulaney
Pass.word, Inc.
11400 Bacon Rd.
Plainwell, MI 49080
616-664-5282
Gemnet ID: dulaney

Appendix E

Statistical Tests (Equations)

Statistical Methods (Equations)

Simple t-test for equal variance (Statgraphics, 1991):

t-test:

$$t = \frac{\bar{x}_1 - \bar{x}_2 - \Delta}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where

$\bar{x}_1$ = mean of sample 1

$\bar{x}_2$ = mean of sample 2

Δ = hypothesized difference between the means

Simple t-test for unequal variance (SAS, 1982):

The Approximate *t* Statistic

Under the assumption of unequal variances, the approximate *t* statistic is computed as

$$t' = (\bar{x}_1 - \bar{x}_2) / \sqrt{w_1 + w_2}$$

where

$$w_1 = s_1^2/n_1, \qquad w_2 = s_2^2/n_2 \quad .$$

Least-squares means analysis of variance (Statgraphics, 1991):

Treatment Mean:

$$\bar{x}_t = \frac{\sum_{i=1}^{n_t} x_{it}}{n_t}$$

Df = degrees of freedom for the error term:

$$n - k$$

Least-squares means analysis of variance--continued (Statgraphics, 1991):

MSE = Mean Square Error:

$$\frac{\sum_{t=1}^{k} (n_t - 1)\, s_t^2}{\left(\sum_{t=1}^{k} n_t\right) - k}$$

where

$$s_t^2 = \sum_{i=1}^{n_t} \frac{(x_{it} - \bar{x}_t)^2}{n_t - 1}$$

Standard error (internal):

$$\sqrt{\frac{s_t^2}{n_t}}$$

Standard error (pooled):

$$\sqrt{\frac{MSE}{n_t}}$$

where

k = number of treatments

n = number of observations

n_t = number of observations for treatment t

x_{it} = ith observation for treatment t

Least-squares multiple regression (Statgraphics, 1991):

Gram-Schmidt decomposition (with tolerance = 1.0E – 08) is used to estimate the coefficients.

Notation:

$\underset{\sim}{Y}$ = vector of n observations for the dependent variable

$\underset{\sim}{X}$ = n-by-p matrix of observations for p independent variables, including constant term, if any

~ indicates that a variable is a vector or matrix

Mean:

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}$$

where n is the number of observations.

Least-squares multiple regression--continued (Statgraphics, 1991):

Estimated Coefficients:

$$\underset{\sim}{b} = (\underset{\sim}{X}'\underset{\sim}{X})^{-1}\underset{\sim}{X}'\underset{\sim}{Y}$$

where X' is the transpose of $\underset{\sim}{X}$.

Standard Errors:

$$S(\underset{\sim}{b}) = \sqrt{\text{diagonal elements of }(\underset{\sim}{X}'\underset{\sim}{X})^{-1}\ \text{MSE}}$$

where

$$\text{SSE} = \underset{\sim}{Y}'\underset{\sim}{Y} - \underset{\sim}{b}'\underset{\sim}{X}'\underset{\sim}{Y}$$

$$\text{MSE} = \frac{\text{SSE}}{n-p}$$

and where p is the number of coefficients estimated.

t-Values:

$$\underset{\sim}{t} = \frac{\underset{\sim}{b}}{S(\underset{\sim}{b})}$$

Significance Level:

t-values follow the Student's t distribution with $n - p$ degrees of freedom.

Predictions:

$\underset{\sim}{X}_h$ = m-by-p matrix of independent variables for m predictions

Standard Error of Estimate:

$$\text{SE} = \sqrt{\text{MSE}}$$

Predicted Values:

$$\hat{\underset{\sim}{Y}} = \underset{\sim}{X}\underset{\sim}{b}$$

Residuals:

$$\underset{\sim}{e} = \underset{\sim}{Y} - \hat{\underset{\sim}{Y}}$$

Durbin-Watson Statistic:

$$D = \frac{\sum_{i=1}^{n-1}\left(e_{i+1} - e_i\right)^2}{\sum_{i=1}^{n} e_i^2}$$

Mean Absolute Error:

$$\frac{\left(\sum_{i=1}^{n} | e_i |\right)}{n}$$

Least-squares multiple regression--continued (Statgraphics, 1991):

Predicted Value:

$$\hat{\underset{\sim}{Y}}_h = \underset{\sim}{X}_h \underset{\sim}{b}$$

Standard Error of Prediction:

$$S\left(\hat{\underset{\sim}{Y}}_{h(new)}\right) = \sqrt{\text{diagonal elements of MSE } (1 + \underset{\sim}{X}_h (\underset{\sim}{X}'\underset{\sim}{X})^{-1} \underset{\sim}{X}'_h)}$$

R-Squared:

$$R^2 = \frac{SSTO - SSE}{SSTO}$$

where

$$SSTO = \begin{cases} \underset{\sim}{Y}' \, \underset{\sim}{Y} - n\,\overline{Y}^2 & \text{if constant in model} \\ \underset{\sim}{Y}' \, \underset{\sim}{Y} & \text{if no constant} \end{cases}$$

Adjusted R-Squared:

$$1 - \left(\frac{n-1}{n-p}\right)\left(1 - R^2\right)$$

Standard Error of Mean Response:

$$S\left(\hat{\underset{\sim}{Y}}_h\right) = \sqrt{\text{diagonal elements of MSE } (\underset{\sim}{X}_h (\underset{\sim}{X}'\underset{\sim}{X})^{-1} \underset{\sim}{X}'_h)}$$

Normal Probability Plot:

The system sorts the input data from smallest to largest to compute order statistics. The system then generates a scatterplot where:

$$\text{horizontal position} = \chi_{(i)}$$

$$\text{vertical position} = \Phi\left(\frac{i - \frac{3}{8}}{n + \frac{1}{4}}\right)$$

Appendix F

Statistical Tables

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDANT VARIABLE

DEPTH	N	NO3	DEPTH	N	NO3	DEPTH	N	NO3
<=20	2	4.65	<=90	2332	2.37	<=150	3357	2.34
>20	3618	2.27	>90	1288	2.1	>150	263	1.4
SIG		0.7	SIG		0.04	SIG		0.0001
<=30	50	1.85	<=100	2647	2.36	<=160	3413	2.33
>30	3570	2.28	>100	973	2.05	>160	207	1.38
SIG		0.27	SIG		0.04	SIG		0.0001
<=40	273	1.66	<=110	2830	2.35	<=170	3458	2.32
>40	3347	2.33	>110	790	1.99	>170	162	1.32
SIG		0.0001	SIG		0.02	SIG		0.0001
<=50	689	2	<=120	3022	2.33	<=180	3495	2.31
>50	2931	2.34	>120	598	2	>180	125	1.22
SIG		0.02	SIG		0.05	SIG		0.0001
<=60	1174	2.14	<=130	3153	2.34	<=190	3523	2.31
>60	2446	2.34	>130	467	1.83	>190	97	1.03
SIG		0.14	SIG		0.002	SIG		0.0001
<=70	1537	2.28	<=140	3260	2.34	<=200	3547	2.31
>70	2083	2.27	>140	360	1.7	>200	73	0.76
SIG		0.95	SIG		0.0002	SIG		0.0001
<=80	1997	2.36						
>80	1623	2.17						
SIG		0.13						

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDENT VARIABLE

SWL	N	NO3	SWL	N	NO3	SWL	N	NO3
<=0	59	2.29	<=60	2893	2.18	<=110	3456	2.29
>0	3561	2.28	>60	727	2.65	>110	164	1.9
SIG		0.98	SIG		0.003	SIG		0.07
<=10	426	1.11	<=70	3109	2.24	<=120	3502	2.29
>10	3194	2.43	>70	511	2.51	>120	118	1.87
SIG		0.0001	SIG		0.11	SIG		0.1
<=20	1198	1.48	<=80	3261	2.26	<=130	3542	2.28
>20	2422	2.67	>80	359	2.46	>130	78	1.99
SIG		0.0001	SIG		0.3	SIG		0.38
<=30	1763	1.82	<=90	3343	2.27	<=140	3573	2.29
>30	1857	2.71	>90	277	2.29	>140	47	1.52
SIG		0.0001	SIG		0.96	SIG		0.04
<=40	2232	2.07	<=100	3405	2.29	<=150	3593	2.28
>40	1388	2.61	>100	215	2.06	>150	27	1.06
SIG		0.0001	SIG		0.25	SIG		0.002
<=50	2588	2.09						
>50	1032	2.73						
SIG		0.0001						

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDENT VARIABLE

DofS	N	NO3	DofS	N	NO3	DofS	N	NO3
<=0	2	5.65	<=60	2887	2.54	<=110	3520	2.31
>0	3618	2.27	>60	733	1.23	>110	100	1.12
SIG		0.52	SIG		0.0001	SIG		0.003
<=10	21	2.59	<=70	3116	2.45	<=120	3547	2.3
>10	3599	2.37	>70	504	1.22	>120	73	0.97
SIG		0.62	SIG		0.0001	SIG		0.002
<=20	291	3.48	<=80	3272	2.38	<=130	3562	2.3
>20	3329	2.17	>80	348	1.25	>130	58	0.96
SIG		0.0001	SIG		0.0001	SIG		0.005
<=30	1243	3	<=90	3393	2.37	<=140	3568	2.29
>30	2377	1.9	>90	227	0.86	>140	52	0.95
SIG		0.0001	SIG		0.0001	SIG		0.02
<=40	2052	2.75	<=100	3481	2.33	<=150	3582	2.29
>40	1568	1.66	>100	139	0.82	>150	38	0.81
SIG		0.0001	SIG		0.0001	SIG		0.03
<=50	2591	2.59						
>50	1029	1.48						
SIG		0.0001						

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDENT VARIABLE

CTT	N	NO3	CTT	N	NO3	CTT	N	NO3
<=0	2317	2.55	<=35	3368	2.34	<=70	3566	2.3
>0	1303	1.78	>35	252	1.37	>70	54	0.62
SIG		0.0001	SIG		0.0002	SIG		0.0001
<=5	2612	2.53	<=40	3418	2.34	<=75	3580	2.3
>5	1008	1.62	>40	202	1.22	>75	40	0.52
SIG		0.0001	SIG		0.0002	SIG		0.0001
<=10	2884	2.44	<=45	3457	2.33	<=80	3587	2.29
>10	736	1.62	>45	163	1.16	>80	33	0.43
SIG		0.0001	SIG		0.0007	SIG		0.0001
<=15	3042	2.41	<=50	3493	2.31	<=85	3592	2.29
>15	578	1.57	>50	127	1.19	>85	28	0.5
SIG		0.0001	SIG		0.008	SIG		0.0001
<=20	3149	2.39	<=55	3515	2.31	<=90	3595	2.29
>20	471	1.49	>55	105	1.25	>90	25	0.56
SIG		0.0001	SIG		0.04	SIG		0.0001
<=25	3235	2.37	<=60	3536	2.31	<=95	3595	2.29
>25	385	1.47	>60	84	0.71	>95	25	0.56
SIG		0.0001	SIG		0.0001	SIG		0.0001
<=30	3310	2.35	<=65	3557	2.3	<=100	3602	2.28
>30	310	1.52	>65	63	0.76	>100	18	0.59
SIG		0.0005	SIG		0.0001	SIG		0.001

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDENT VARIABLE

PTT	N	NO3	PTT	N	NO3	PTT	N	NO3
<=0	2147	2.47	<=35	3101	2.36	<=70	3445	2.31
>0	1473	1.99	>35	519	1.77	>70	175	1.52
SIG		0.0001	SIG		0.0004	SIG		0.0006
<=5	2290	2.47	<=40	3195	2.37	<=75	3466	2.31
>5	1330	1.94	>40	425	1.58	>75	154	1.4
SIG		0.0001	SIG		0.0001	SIG		0.0001
<=10	2489	2.45	<=45	3250	2.35	<=80	3487	2.31
>10	1131	1.89	>45	370	1.63	>80	133	1.42
SIG		0.0001	SIG		0.0001	SIG		0.0007
<=15	2656	2.4	<=50	3315	2.33	<=85	3507	2.3
>15	964	1.93	>50	305	1.72	>85	113	1.51
SIG		0.0005	SIG		0.004	SIG		0.008
<=20	2821	2.41	<=55	3350	2.32	<=90	3517	2.29
>20	799	1.79	>55	270	1.72	>90	103	1.64
SIG		0.0001	SIG		0.006	SIG		0.04
<=25	2911	2.4	<=60	3392	2.32	<=95	3524	2.3
>25	709	1.76	>60	228	1.62	>95	96	1.53
SIG		0.0001	SIG		0.002	SIG		0.009
<=30	3014	2.38	<=65	3420	2.32	<=100	3544	2.29
>30	606	1.75	>65	200	1.56	>100	76	1.51
SIG		0.0001	SIG		0.0007	SIG		0.02

KALAMAZOO CO. t-TESTS: ALL WELLS, NITRATE-N = DEPENDENT VARIABLE

CTA	N	NO3	CTA	N	NO3	CTA	N	NO3
<=0	2985	2.33	<=20	3510	2.29	<=40	3593	2.28
>0	635	2	>20	110	1.88	>40	27	1.59
SIG		0.02	SIG		0.21	SIG		0.2
<=5	3234	2.34	<=25	3544	2.28	<=45	3599	2.28
>5	386	1.75	>25	76	1.99	>45	21	1.76
SIG		0.0004	SIG		0.49	SIG		0.43
<=10	3397	2.3	<=30	3570	2.28	<=50	3608	2.27
>10	223	1.92	>30	50	2	>50	12	2.57
SIG		0.1	SIG		0.59	SIG		0.78
<=15	3467	2.29	<=35	3583	2.28	<=55	3611	2.27
>15	153	1.86	>35	37	1.55	>55	9	2.68
SIG		0.12	SIG		0.11	SIG		0.77

NO3	K	N	SWL	TD	DofS	C	PC	C+PC	C	PC	C+PC	AS
						TOTAL			ABOVE SWL			
>ND-2	0.92	444	49.5	89	39.5	9	14.1	23.1	2.9	8.1	11	119
>2	6.22	771	49	36	36.7	6.2	15.1	21.3	2.2	9.5	11.3	95
SIG	0		0.31	0.16	0.04	0.002	0.54	0.33	0.16	0.22	0.55	0.02
>ND-3	1.3	585	49.3	39.1	39.3	8.8	15.5	24.3	2.9	9	11.9	122
>3	7	630	48.7	85	36.2	5.7	14.1	19.8	2.1	9	11.1	87
SIG	0		0.59	0.07	0.02	0.0003	0.35	0.01	0.07	0.97	0.47	0.0005
>ND-4	1.7	709	49.4	80	38.5	8.2	15.9	24.1	2.3	9.5	12.2	117
>4	7.9	506	49	35	36.5	5.8	13.2	18.9	2.1	8.4	10.4	86
SIG	0		0.79	0.24	0.11	0.005	0.08	0.005	0.13	0.33	0.14	0.002
>ND-5	2.1	820	49	87	38.3	8	15.3	23.8	2.8	9.6	12.3	114
>5	8.8	395	50.3	87	36.6	5.6	12.6	18.1	1.9	7.9	9.8	82
SIG	0		0.47	0.96	0.22	0.009	0.05	0.003	0.08	0.16	0.05	0.003
>ND-3	1.3	585	50	89	39.3	3.3	15.5	24.3	2.9	9	11.9	122
>9.99	14.3	94	42	42	39.3	6.4	13.3	19.7	2.6	6.5	9.2	37
SIG	0		0.08	0.13	0.36	0.2	0.46	0.2	0.78	0.23	0.23	0.11

KALAMAZOO COUNTY NITRATE CONCENTRATIONS VS AQUIFER PARAMETERS
ALL WELLS > ND (N=~~1520~~); PARAMETRIC t-TEST
2 FEB., 1993

NO3	X	N	SWL	TD	DofS	C	PC	C+PC	C	PC	C+PC	AS
						TOTAL			ABOVE SWL			
>ND-2	223	444	594	620	654	644	610	633	612	603	610	640
>2	830	771	616	601	582	587	607	594	605	611	607	590
SIG	0		0.28	0.37	.0006	0.002	0.87	0.05	0.63	0.69	0.87	0.01
>ND-3	293	585	602	620	639	639	618	637	614	612	617	640
>3	901	630	613	597	579	579	598	581	603	604	600	578
SIG	0		0.59	0.25	0.003	0.0005	0.27	0.005	0.43	0.66	0.35	0.001
>ND-4	355	709	606	615	629	627	618	631	610	614	617	633
>4	963	506	611	598	578	581	593	575	605	599	595	573
SIG	0		0.79	0.38	0.01	0.008	0.18	0.005	0.68	0.4	0.23	0.003
>ND-5	411	820	596	603	622	626	614	624	613	614	616	626
>5	1018	395	633	619	580	571	595	574	598	596	591	570
SIG	0		0.08	0.46	0.05	0.003	0.32	0.02	0.35	0.34	0.21	0.007
>ND-3	293	585	343	342	340	345	341	343	343	341	342	343
>9.99	633	94	323	327	338	312	335	323	319	334	330	320
SIG	0		0.37	0.48	0.90	0.09	0.75	0.35	0.1	0.73	0.57	0.28

KALAMAZOO CO. NITRATE CONCENTRATIONS VS AQUIFER PARAMETERS
ALL WELLS > ND (n = 1520); NON-PARAMETRIC U-TEST
2 FEB., 1993

	DEPTH	SWL	DofS	CT	PT	ln NO3
DEPTH	1	0.73	0.66	0.41	0.51	-0.05
	0	0.0001	0.0001	0.0001	0.0001	0.0031
SWL	0.73	1	-0.03	0.23	0.35	0.15
	0.0001	0	0.05	0.0001	0.0001	0.0001
DofS	0.66	-0.03	1	0.35	0.36	-0.23
	0.0001	0.05	0	0.0001	0.0001	0.0001
CT	0.41	0.23	0.35	1	0.1	-0.12
	0.0001	0.0001	0.0001	0	0.0001	0.0001
PT	0.51	0.35	0.36	0.1	1	-0.08
	0.0001	0.0001	0.0001	0.0001	0	0.0001
ln NO3	-0.05	0.15	-0.23	-0.12	-0.08	1
	0.0031	0.0001	0.0001	0.0001	0.0001	0

Pearson-r Correlation Coefficients and Significance Levels

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