6-1999

A Comprehensive Approach for Evaluation of Groundwater Vulnerability to Contamination

Shafiul H. Chowdhury
Western Michigan University

A COMPREHENSIVE APPROACH FOR EVALUATION OF GROUNDWATER VULNERABILITY TO CONTAMINATION

by

Shafiul H. Chowdhury

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Geosciences

Western Michigan University
Kalamazoo, Michigan
June 1999

A COMPREHENSIVE APPROACH FOR EVALUATION OF GROUNDWATER VULNERABILITY TO CONTAMINATION

Shafiul H. Chowdhury, Ph.D.

Western Michigan University, 1999

Groundwater vulnerability to contamination from surface sources was evaluated for Nottawa Creek Watershed, Calhoun County Michigan using AQUIPRO and DRASTIC vulnerability methods. A geographic information system (GIS) was used to analyze and map the data. Forty groundwater samples were collected following a statistical sampling protocol from private wells. Samples were analyzed for nitrate-N and atrazine. Atrazine was not detected (detection limit 0.1 ppb) in any of the samples. Five samples contained detectable nitrate-N (detection limit 0.05 mg/L). Due to insufficient chemical data, the relative AQUIPRO and DRASTIC vulnerability scores could not be compared with the frequency of occurrences of groundwater contamination. The wells with detectable nitrate-N have indicated that the shallow glacial drift aquifers with low AQUIPRO scores and high DRASTIC scores are susceptible to contamination from surface sources.

In addition, AQUIPRO was used to evaluate groundwater vulnerability to contamination in Kalamazoo County, Michigan. Computerized water well records of 2,653 wells with partial chemistry data were utilized for this site. A previously prepared DRASTIC map of Kalamazoo County was utilized to obtain the DRASTIC

scores of the wells used in AQUIPRO. The relative AQUIPRO and DRASTIC vulnerability scores were compared with the frequency of occurrences of nitrate-N in groundwater wells. The average nitrate-N concentrations within each relative AQUIPRO and DRASTIC vulnerability category were also compared. The results indicated that the groundwater wells containing 5 mg/L or more nitrate-N showed a positive correlation between the frequency of occurrences of nitrate-N and relative increase of AQUIPRO ($r^2 = 0.98$) and DRASTIC ($r^2 = 0.46$) vulnerability. The results also showed that as the relative AQUIPRO ($r^2 = 0.99$) and DRASTIC ($r^2 = 0.33$) vulnerability increases the mean nitrate-N concentration also increases. Overall, the aquifer vulnerability prediction by AQUIPRO and DRASTIC methods were valid. However, the results also indicated that the vulnerability prediction by AQUIPRO proved superior to DRASTIC in this particular hydrogeologic setting.

UMI Number: 9935406

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

ACKNOWLEDGMENTS

I wish to express my sincere gratitude to Dr. Alan E. Kehew whose guidance and help made this work possible. I would like to thank Dr. Duane R. Hampton, Dr. R. V. Krishnamurthy and Dr. Michael R. Stoline for their critical readings and research consultations. I would also like to thank Mrs. Lauren Hughes of GEM Regional Center for her help and support. I am very grateful to Dr. Richard N. Passero for his help and advice. A special thanks goes to Mr. Greg Anderson of GIS Resource Center for providing me excellent technical support with GIS. I want to thank my fellow graduate students for sharing their knowledge and resources with me, especially Andrew Kozlowski and William Montgomery for their help. I would like to thank WMU Graduate College, Kalamazoo Foundation and Geological Society of America for funding the project. I am deeply indebted to Dr. Shirley C. Scott for preparing me to become a better educator. Finally I would like to thank my wife, Shuporna, for being encouraging, supportive and helpful during this study.

Shafiul H. Chowdhury

TABLE OF CONTENTS

CHAPTER

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER I

INTRODUCTION

The vulnerability of glacial drift and underlying bedrock aquifers to contamination is a major problem in Michigan and in other parts of the U.S. Groundwater from these aquifers is utilized not only by industry, agriculture, and municipalities but also provides the sole source of drinking water for the residents of southwest Michigan (Rheaume, 1990). Industrial and agricultural contaminants and the widespread use of septic tank systems have impacted groundwater quality in this region. Currently, the most commonly used method for determining aquifer vulnerability to contamination is the U.S. EPA's DRASTIC (Aller, Bennet, Lehr, Petty, & Hackett, 1987) model which has been shown to yield inaccurate results for glacial drift and underlying bed rock aquifers in Michigan (Garret, Willams, Rossol, & Tolman, 1987; Passero, 1992). This may be partly due to the fact that DRASTIC is unable to consider interfingering clay layers of glacial deposits. An alternative method, AQUIPRO (Passero, 1990), offers a computerized method based on data from water well logs. Both methods have been widely used to construct groundwater pollution potential maps, which offer some regional perspective as planning tools, even though neither of these methods has been validated in actual field situations.

Computerized water well records have become available for many midwestern states in recent years. Now it is essential to develop a better method for assessing

aquifer vulnerability by combining methods which consider both surface and subsurface factors and can be easily adapted for use by hydrogeologists and environmental scientists. This method must, however, be validated in order to give accurate results. Once fully developed and validated, this new hybridized method could be widely used in similar geological settings to prepare more reliable groundwater pollution potential maps that assist planners, managers, and administrators in evaluating the relative vulnerability of areas to groundwater contamination. These services would be of enormous value to private citizens, land-use planners, and local, state, and federal government agencies.

Objectives

The objectives of this study are to test the accuracy and validity of aquifer vulnerability scores by comparison to the measured distribution of contaminants within a test area (Nottawa Creek Watershed, Calhoun County, Michigan) and to propose a method of integrating both the computerized water well records used in AQUIPRO as well as the information that comprise DRASTIC. This new method, which will be applied to a larger area (Kalamazoo County, Michigan), will be very useful in delineating contaminant vulnerability in glacial drift and underlying bedrock aquifers and could be adopted widely in areas with computerized well log databases. This approach will open potential opportunities to combine surface and subsurface information for computer analysis using advanced geographic information system (GIS) technology.

Description of Study Area

Nottawa Creek Watershed

The Nottawa Creek Watershed covers 92.5 square miles (240 square kilometers) in south central lower Michigan. It is located in the townships of Athens, Burlington, Claredon, Eckford, Emmett, Fredonia, Newtown, and Teckonsha in Calhoun County (Figure 1). The main drainage is Nottawa Creek, which flows directly into the St. Joseph River, and ultimately to Lake Michigan. Nottawa Creek Watershed has a level to gently rolling topography. Nearly 68% of the land in the Nottawa Creek watershed is agricultural (Williams, 1998). Of this farmland, 50% is used for intensive row crops and livestock production. The remaining is in pasture, hay, and conservation reserve. Approximately 13% of the watershed is forested and 10% is wetlands, while 9% is urban and rural, non-farm (Williams, 1998). Soil types vary from well-drained sandy loams located predominantly along the outer ranges of the watershed boundary, with the medium textured poorly drained soils located primarily inland around lakes and streams (Tardy, 1997).

Geology

Glacial Geology. The surficial deposits of Calhoun County are the result of Pleistocene glaciation and post-glacial stream erosion and deposition. The surface topography was formed during the late Wisconsinan glaciation sometime between 20,000 and 14,000 years Before Present (B.P.). The surface topography of the

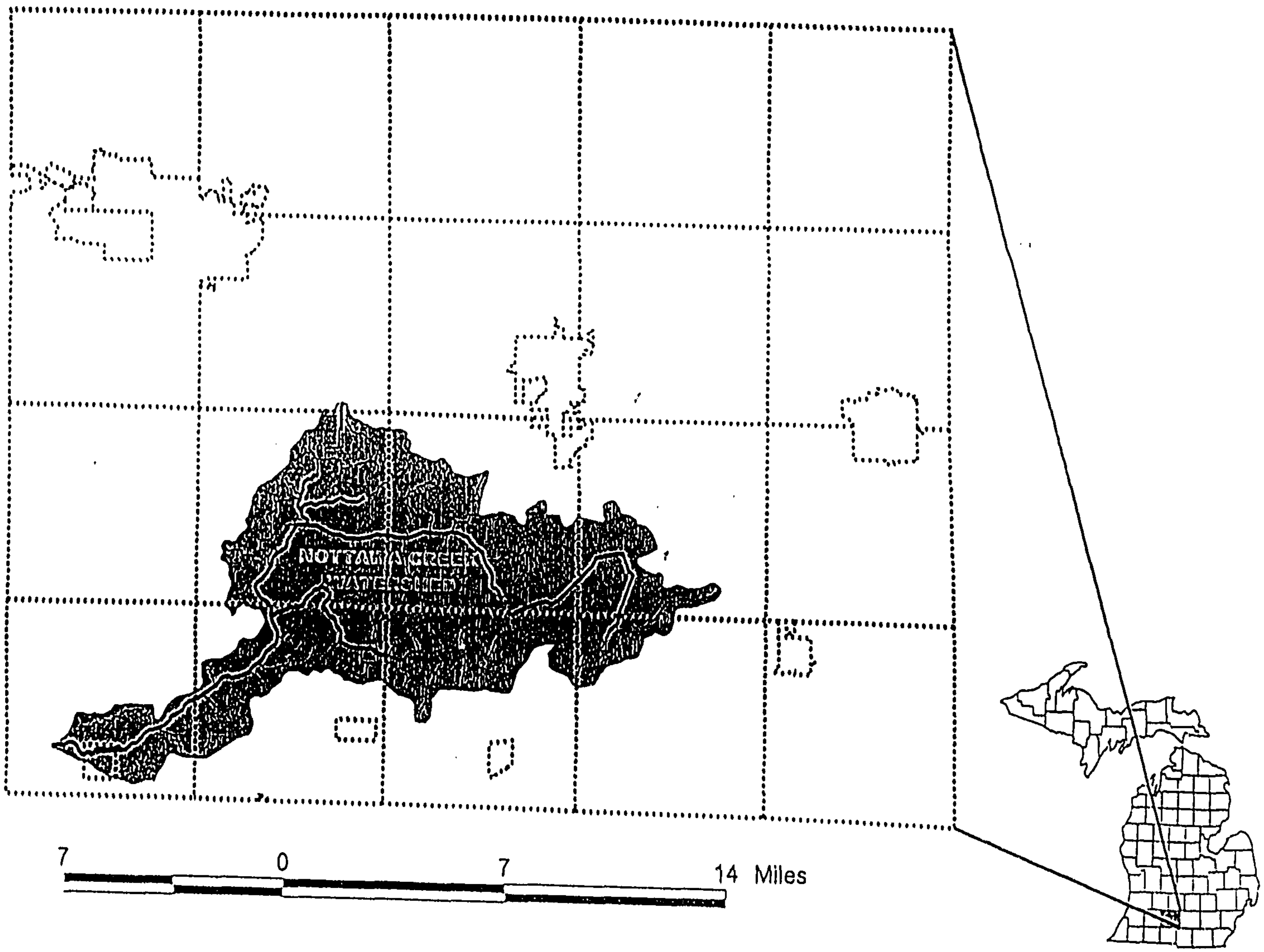


Figure 1. Location Map of Nottawa Creek Watershed, Calhoun County, Michigan.

watershed consists of rolling hills known as drumlins. Drumlins are subglacial landforms that trend southwest in the Nottawa Creek watershed (Kozlowski, 1999).

The Tekonsha moraine and its associated glacial deposits cover the Nottawa Creek Watershed (Kozlowski, 1999). The Tekonsha moraine is a recessional moraine that formed after 15,000 years B.P. and before 14,000 years B.P. (Kozlowski, 1999). Several bedrock valleys, which are interpreted as glacial tunnel valleys and glacially-modified stream valleys are present in the study area (Kozlowski, 1999). The moraine is composed of sandy till (Mickelson, Clayton, Fullerton and Borns, 1983) with lenses of sand or gravel and thin beds of clay, or a combination of these (Kozlowski, 1999). The outwash deposits that blanket much of the watershed are composed of stratified, sorted, medium-to-coarse grained sands and gravels. They were deposited as outwash plains or within buried valleys (Figure 2). Alluvial deposits, which consist mostly of Recent sand and gravel with some clay deposited in the valleys of present-day streams.

A widely distributed thick clay –rich diamicton was identified bneath the sand and gravel deposits in recent studies within the watershed and in neighboring areas (Flint, 1999; Gardner, 1997; Nicks, 1999). If present, his unit may serve as a confining unit. Beneath the clayey diamicton, a variety of materials may be present, including sand and gravel, clayey lacustrine sediment, and diamicton. A weathered soil zone (the Sangamon paleosol) has been encountered in the region. The presence of the Sangamon soil indicates a long hiatus in deposition between the glacial materials above and below. The Sangamon paleosol can be recognized by red, orange, or yellow colors in drill cuttings (Kehew, 1999). The thickness of the glacial deposits varies

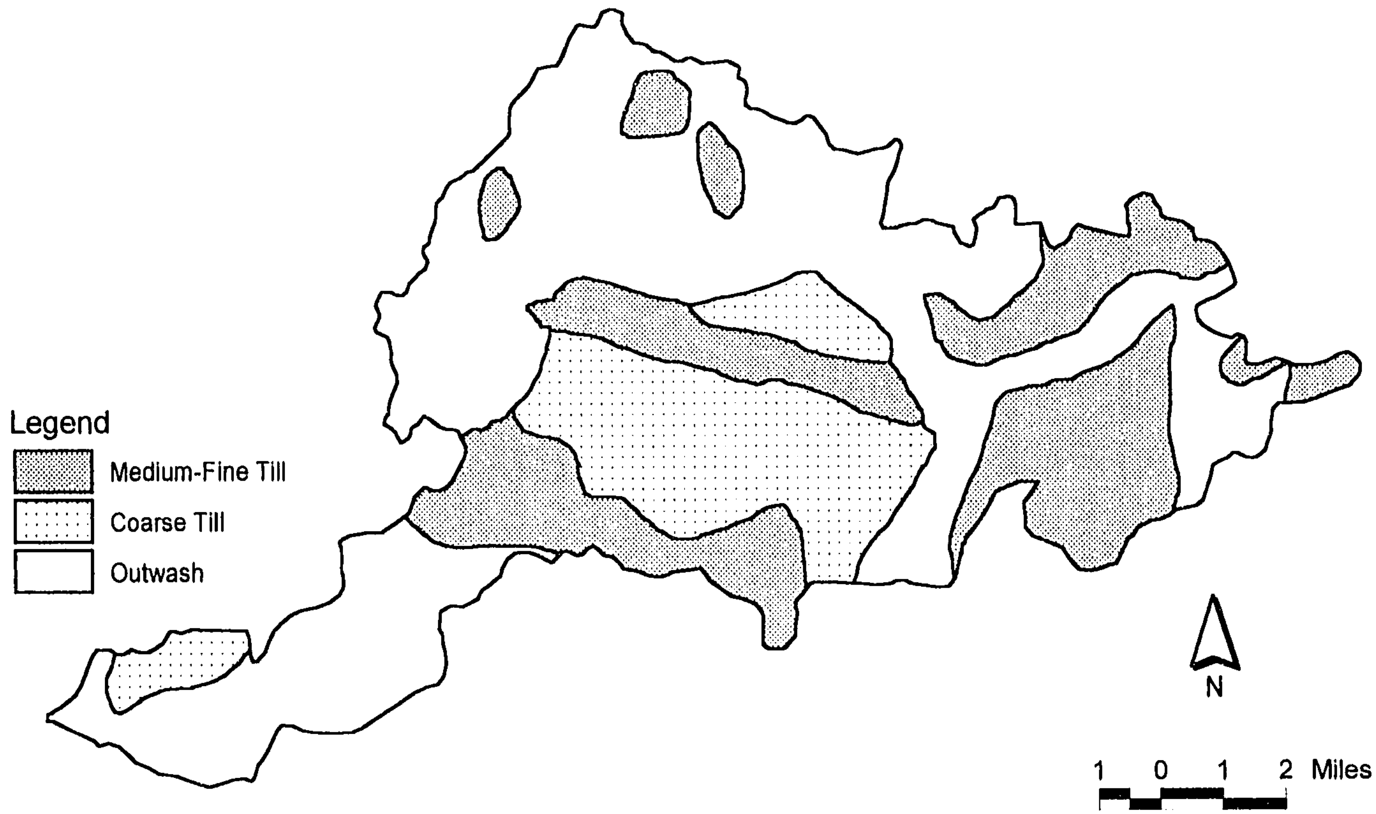


Figure 2. Glacial Map of Nottawa Creek Watershed.

from 10 to several hundred feet in buried bedrock valleys (Kozlowski, 1999).

Bedrock Geology. The bedrock formations, Coldwater Shale and Marshall Sandstone of Mississippian age, directly underlie the glacial deposits (Table 1). The Marshall Sandstone underlies the central and western part of the watershed, while Coldwater Shale underlies the lower western part and northeastern corner (Figure 3) (Moser & Passero, 1990). The Marshall is composed of siltstone and sandstone in a circular subcrop band in the Michigan Basin parallel to the Coldwater but narrower in width. Bedrock within the study area dip gently northeast into the Michigan Basin and trend northwest. The bedrock surface topography suggests that the land-scape has been modified by stream erosion and then later enhanced by glacial erosion (Rieck & Winters, 1979).

Hydrogeology. Both glacial drift and bedrock aquifers are present in the Nottawa Creek watershed. Glacial drift aquifers are common in the southern and eastern part of the watershed, whereas in the central and western parts, bedrock aquifers are dominant. In Nottawa Creek Watershed, domestic and industrial water is produced primarily from bedrock aquifers and, to a lesser degree, from glacial drift aquifers. Figure 4 shows the 350 water wells used in this study; 112 (32%) produce from glacial drift aquifers and 238 (68%) produce from bedrock aquifers. The depth to static water levels ranges from 0 to 58 ft (0 to 18 m). Assuming that groundwater flows from high water level to low water level, the static water level contour map indicates that groundwater flows towards the Nottawa Creek from the surrounding

Table 1

Geologic Column for Calhoun County Michigan

Era	Period	Epoch	Rock Formation	Formation Members	Aquifers
Cenozoic	Quaternary	Recent	Alluvium	-------	Yes
		Pliesto-cene	Glacial Drift	--------	Yes
Paleozoic	Pennsylvanian	Lower	Saginaw	Verne Limestone	Yes
				Parma Sandstone	Yes
	Mississippian	Upper	Bay Port	Limestone	Yes
			Michigan	--------	No
		Lower	Marshall	Napolean Sandstone	Yes
				Lower Marshall Sandstone	Yes
			Coldwater		Yes
	Devonian				No

Source: Moser & Passero, 1990.

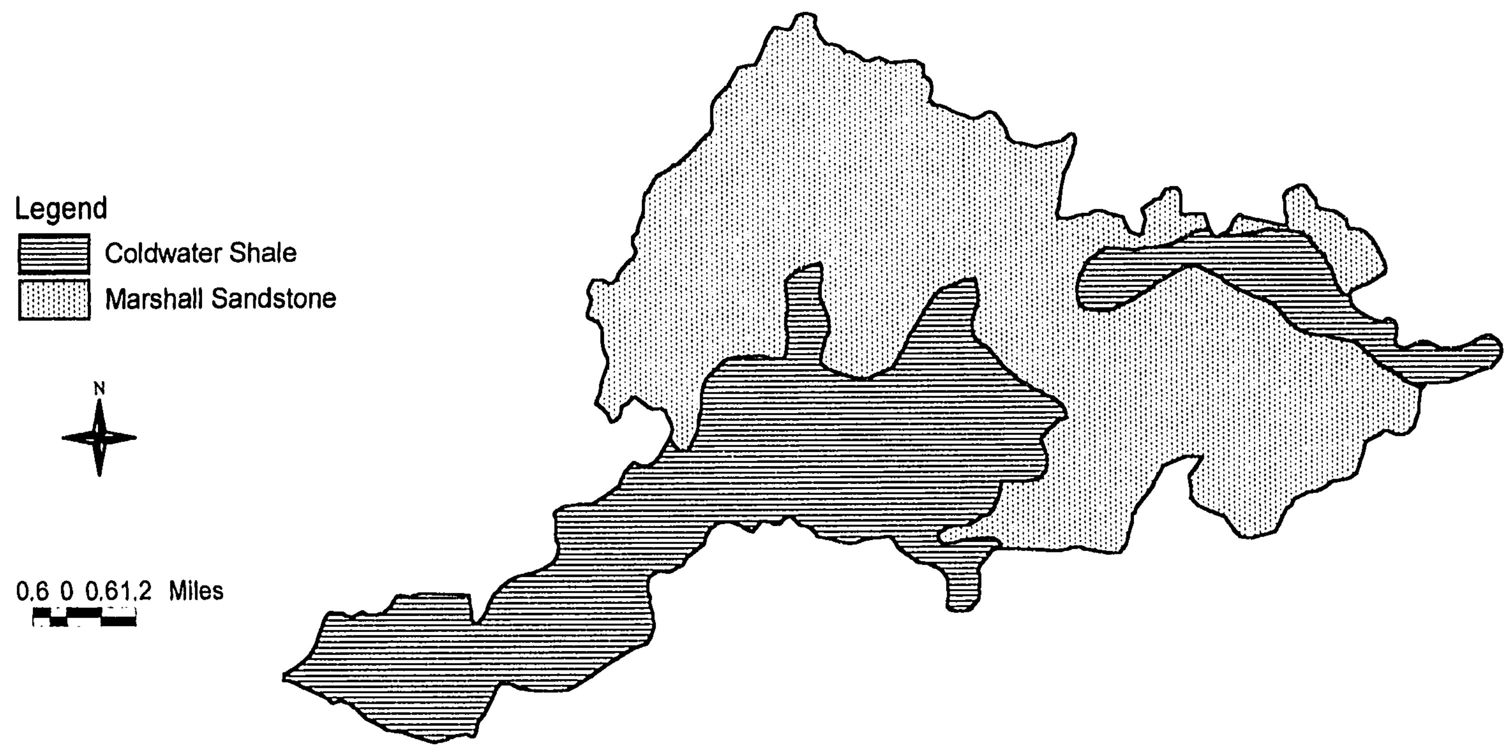


Figure 3. Bedrock Map of Nottawa Creek Watershed.

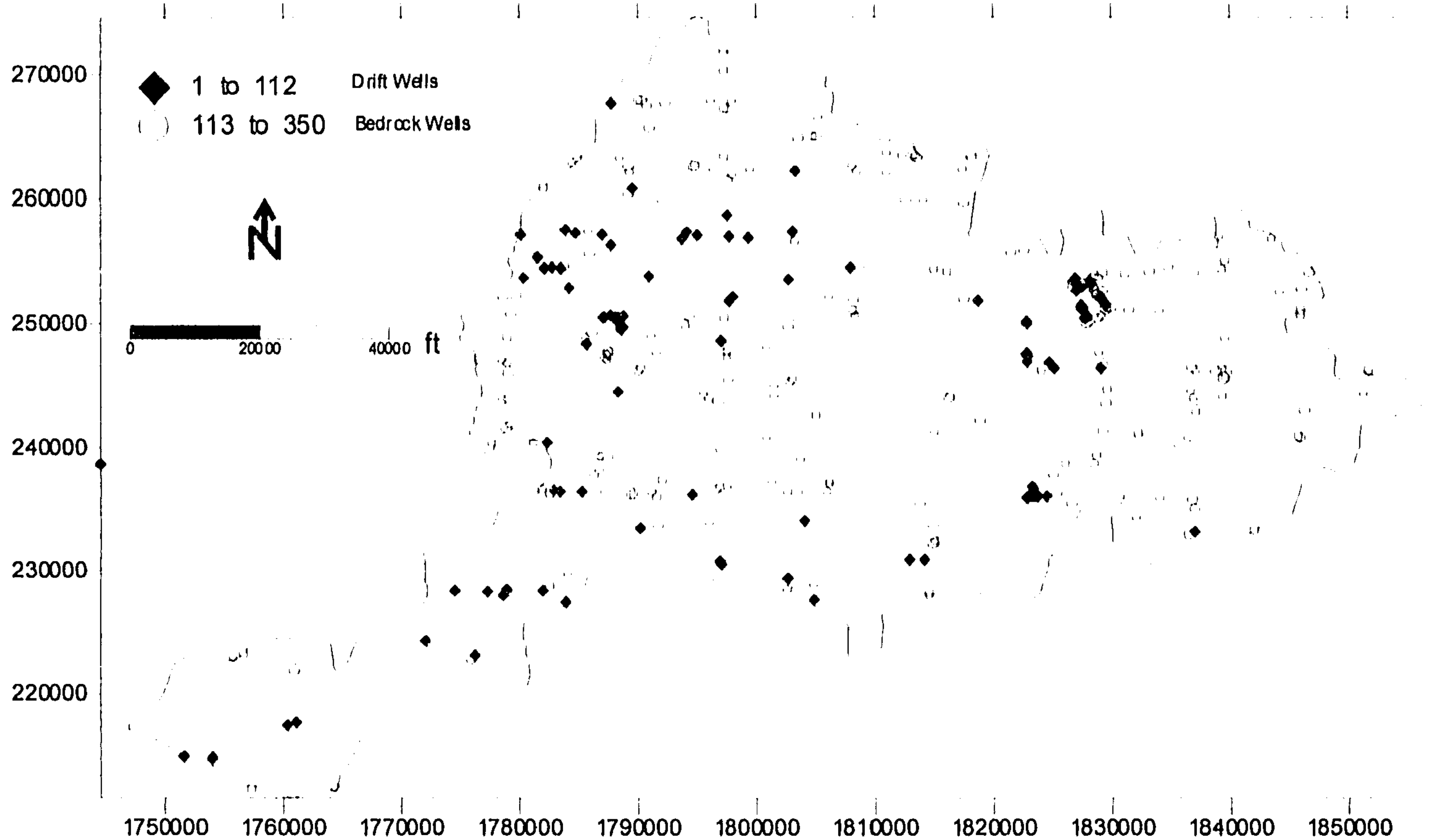


Figure 4. Map Showing Well Locations in Nottawa Creek Watershed.

areas (Figure 5).

Glacial drift aquifers of Nottawa Creek Watershed are composed of relatively clean, permeable sands or gravels, or a mixture of two. The potential yields from these aquifers are highly variable and range from 5 gallon per minute (gpm) (0.32 L/s) to 2,850 gpm (179.78 L/s) (Moser & Passero, 1990). Reduced yield may be attributed to zones of saturation, which are relatively thin and/or lower aquifer permeability related to increased concentrations of silt and clay within the aquifer. Most of the drift aquifers are unconfined to semiconfined in nature.

Water derived from bedrock aquifers in the watershed is produced primarily, though not exclusively, from the Marshall Sandstone. Although the Marshall Formation is utilized as the primary source for domestic and municipal water in the watershed, many wells in Athens and Burlington Townships are completed in the Coldwater Formation. The Michigan Groundwater Survey well database indicates that the Coldwater Shale, which has a thickness ranging from 565 to 1,080 ft (172 to 329 m), does supply water to many homes in southwestern Calhoun County, where this rock unit subcrops beneath thin till (Appendix A). These shales are probably highly fractured and highly weathered and capable of producing sufficient amounts of water. The Marshall Formation consists of a fine-to-coarse-grained sandstone that is interbedded with thin shales and siltstones. Its thickness, which ranges between 0 and 200 ft (0 and 61 m) (Grannemann & Twenter, 1985), is highly variable because of preglacial differential erosion and the irregular nature of the lower contact of the sandstone (Vanlier, 1966). Usually the bedrock aquifers are semiconfined to confined in nature.

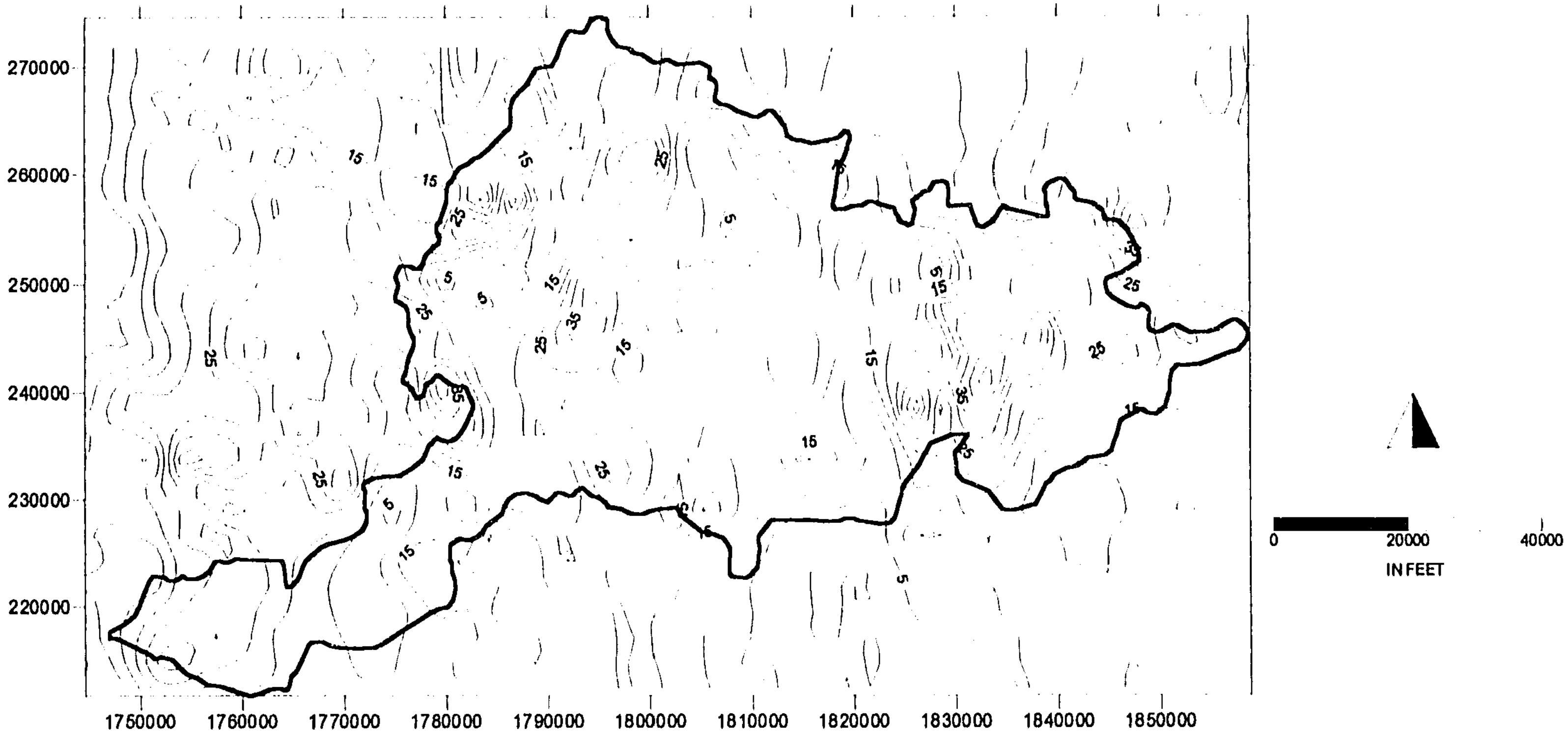


Figure 5. Depth to Static Water Level Contour Map of Nottawa Creek Watershed.

Kalamazoo County

Kalamazoo County is located in southwestern Michigan (Figure 6) and has an area of 576 square miles (1492 square kilometers). Agriculture is the largest land-use category, constituting approximately 40.3% of the county. About 18% of the county is considered "developed", 39.3% vacant and wooded lands and 6.5% in lakes rivers and streams (Chidester, 1993). The land surface is flat to rolling. The dominant soil type in the county is sandy loam (Austin, 1979).

Geology

Bedrock Geology. Kalamazoo County is underlain by unconsolidated deposits that consist of glacially derived deposits of Pleistocene age and alluvial deposits of Holocene age (Rheaume, 1990). These deposits range in thickness from 50 to 600 ft (15 to 183 m). Bedrock, which consists of Coldwater Shale and Marshall Formation of Mississippian age, underlies the glacial deposits and is nowhere exposed at land surface (Figure 7).

Glacial Geology. Kalamazoo County is characterized by thick glacial sediments, which were deposited by two lobes of the late Wisconsinan Laurentide Ice Sheet. The glacial drift ranges in thickness from less than 50 ft (15 m) in the north-central portion of the county to approximately 600 ft in the northwestern part (Figures 8 & 9). The drift tends to be thickest where moraines overlie bedrock valleys and thinnest where till plains overlie bedrock uplands. Eight areas with distinct glacial

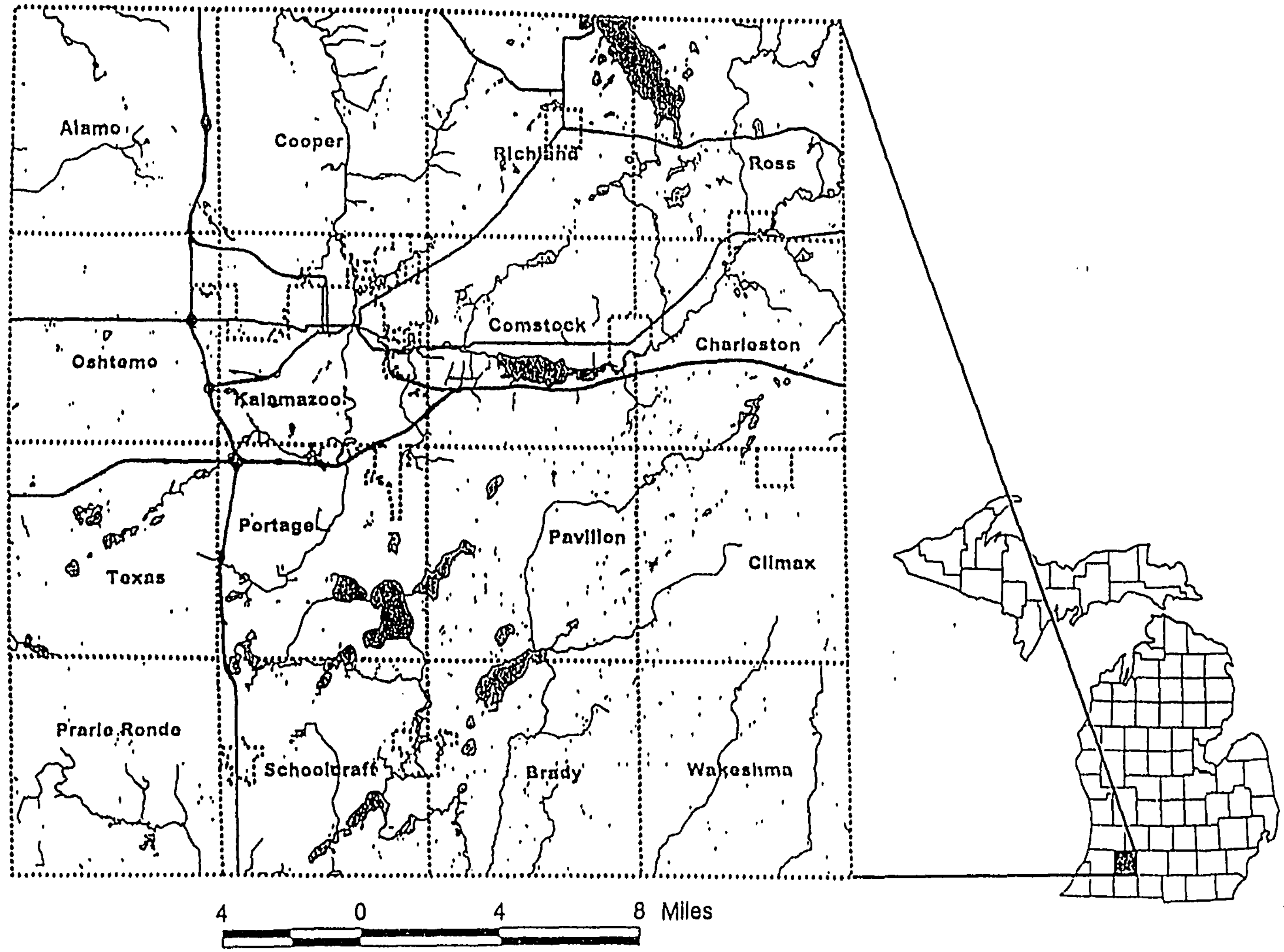


Figure 6. Map Showing the Location of Kalamazoo County, Michigan.

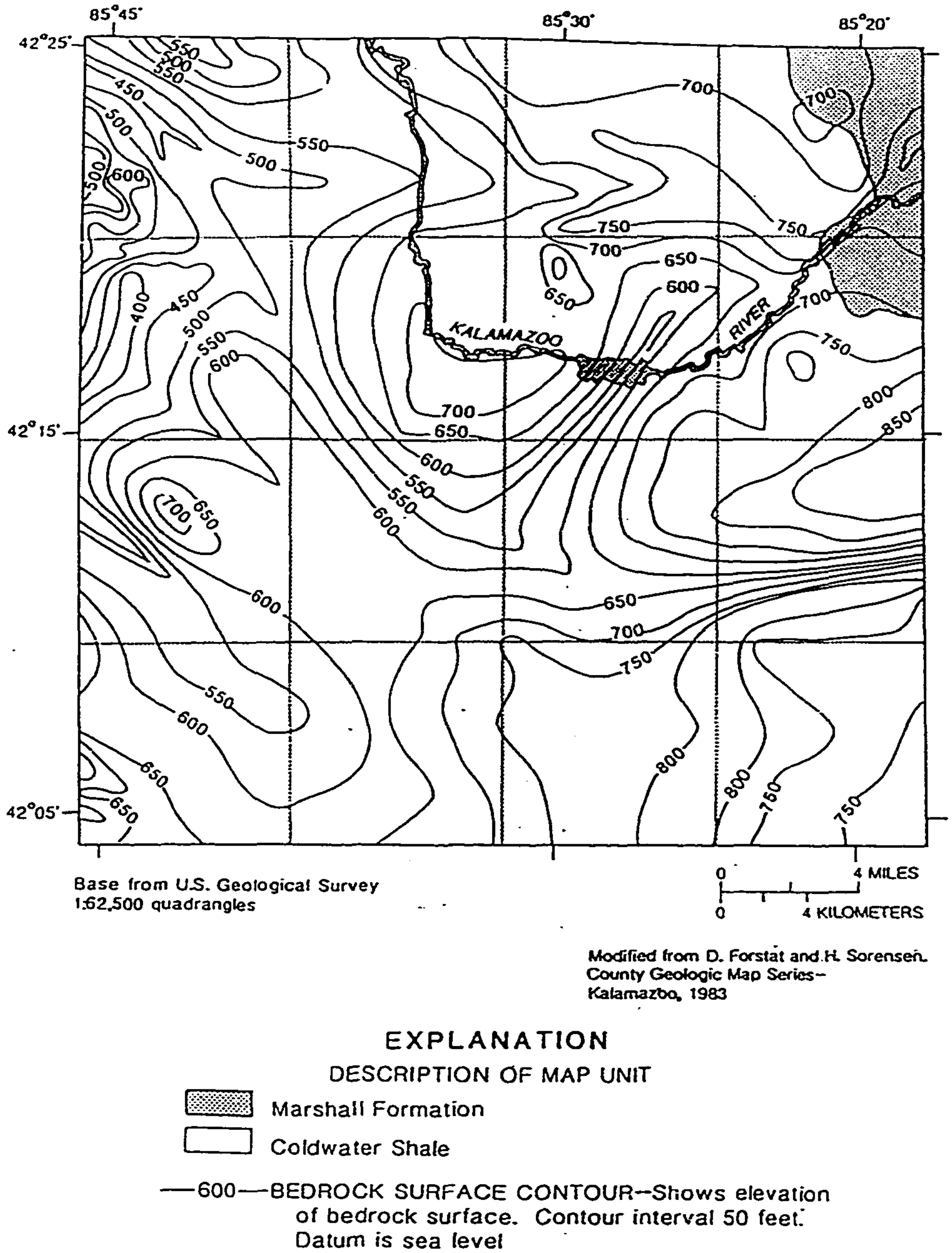


Figure 7. Elevation and Areal Extent of Bedrock Surfaces in Kalamazoo County (Source: Rheaume, 1990).

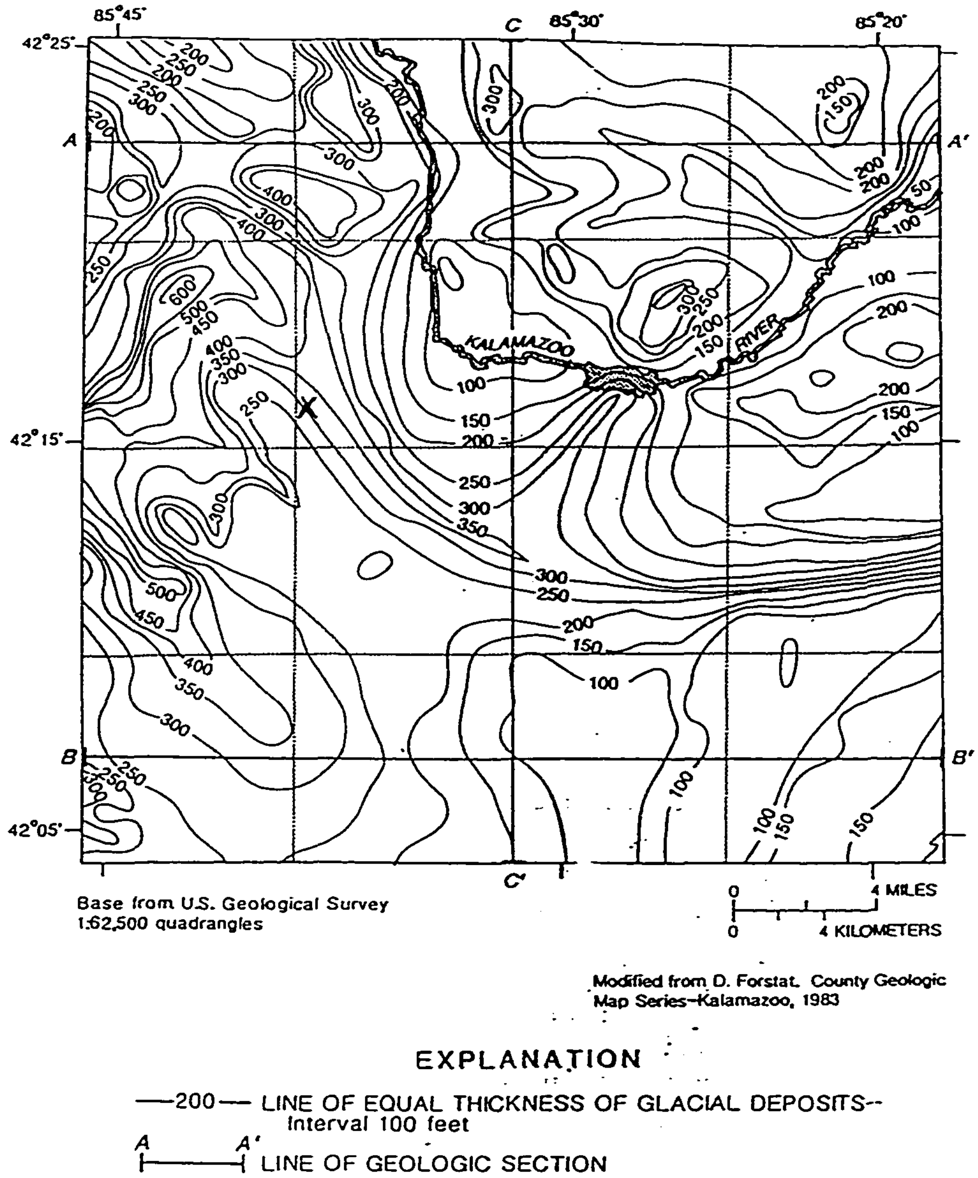


Figure 8. Location of Geologic Cross-Sections and Isopach Map of Glacial Deposits (Source: Rheaume, 1990).

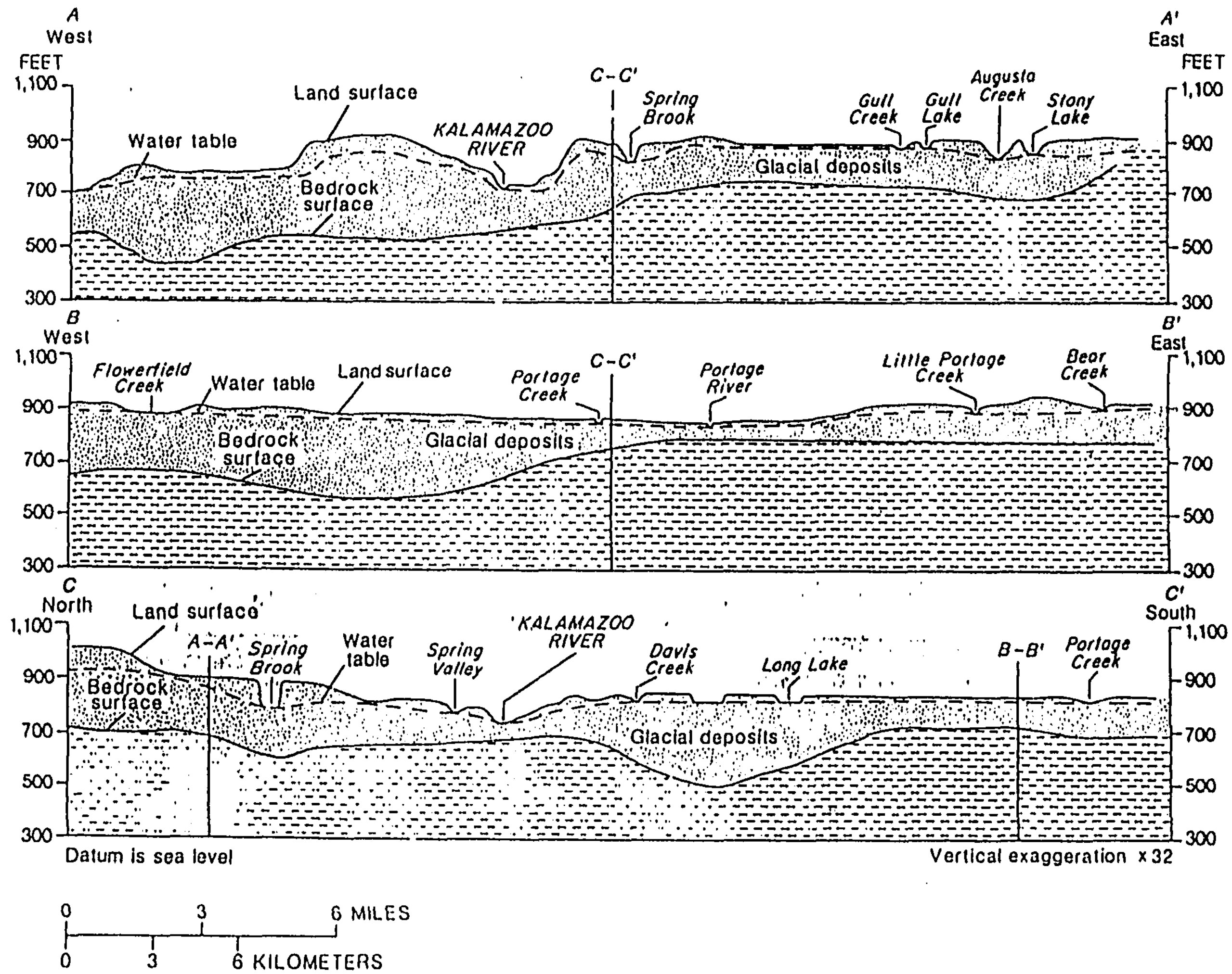


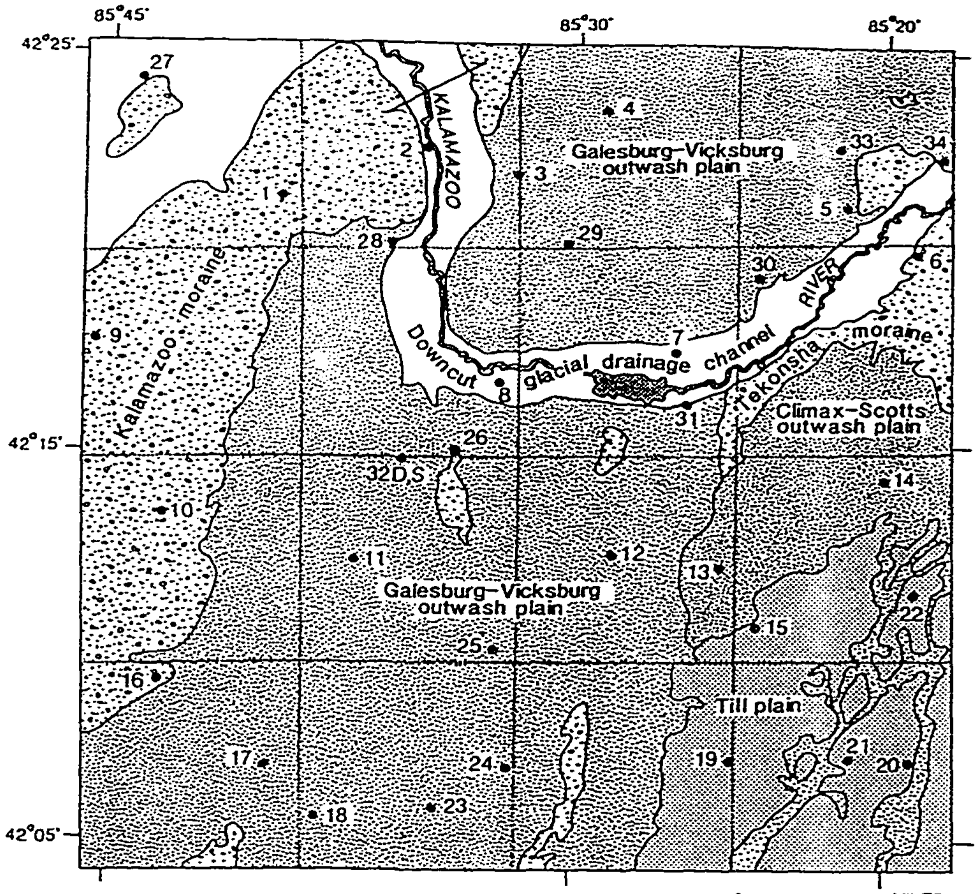
Figure 9. Geologic Cross-Sections Showing Thickness of Glacial Deposits (Source: Rheaume, 1990)

landforms have been mapped in Kalamazoo County: the Alamo plain, Kalamazoo moraine, Tekonsha moraine, the fan complex between Tekonsha and Kalamazoo moraines, the Climax-Scotts outwash plain, the Richland moraine, the Wakeshma till plain, and the Kalamazoo River Valley (Chidester, 1993) (Figure 10).

Straw, Passero and Kehew (1992) classified the glacial drift in Kalamazoo County into following four regional hydrogeologic facies: (1) till and lacustrine plains characterized by irregular and discontinuous aquifers embedded in till sheets and lacustrine sediements, (2) moraines composed of tills interbedded with glaciofluvial deposits, (3) outwash and fan complexes composed of medium to very coarse sand and gravel deposited by glacial meltwater, and (4) Kalamazoo River valley deposits composed of medium to coarse sand and gravel with some isolated layers of clayey silt.

Hydrogeology. The sources of most groundwater supplies in Kalamazoo County are glacial drift aquifers consisting largely of sand and gravel. The most productive aquifers underlie the outwash plains and the downcut glacial drainage channels, which together cover about two thirds of the county (Figure 10). Allen, Miller, and Wood (1972) identified an upper unconfined aquifer throughout almost the entire county and a lower semiconfined aquifer in about one-third of the county. These upper and lower aquifers are hydraulically connected.

The topographic and water level surfaces of Kalamazoo County indicate that groundwater flows from topographically high areas to low areas (Chidetser, 1994). Figure 11 shows the static water level surface contour map for Kalamazoo County.



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

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

EXPLANATION

DESCRIPTION OF MAP UNIT

Outwash plain--Mostly medium to very coarse sand and gravel. Pebble to cobble gravel common

Upland moraine, kame field, or highly collapsed outwash--Mostly sandy till. Boulders and cobbles common on the surface

Downcut glacial drainage channel--Mostly medium to very coarse sand and gravel. Deposits form a deeply incised valley train system

Till plain--Mostly coarse sandy and cobbly till. Clay-rich in areas. Boulders common on the surface

32D,S
● WELL--Location and number. Installed by U.S Geological Survey. (D-deep, S-shallow)

Figure 10. Glacial Map of Kalamazoo County (Source: Rheaume, 1990).

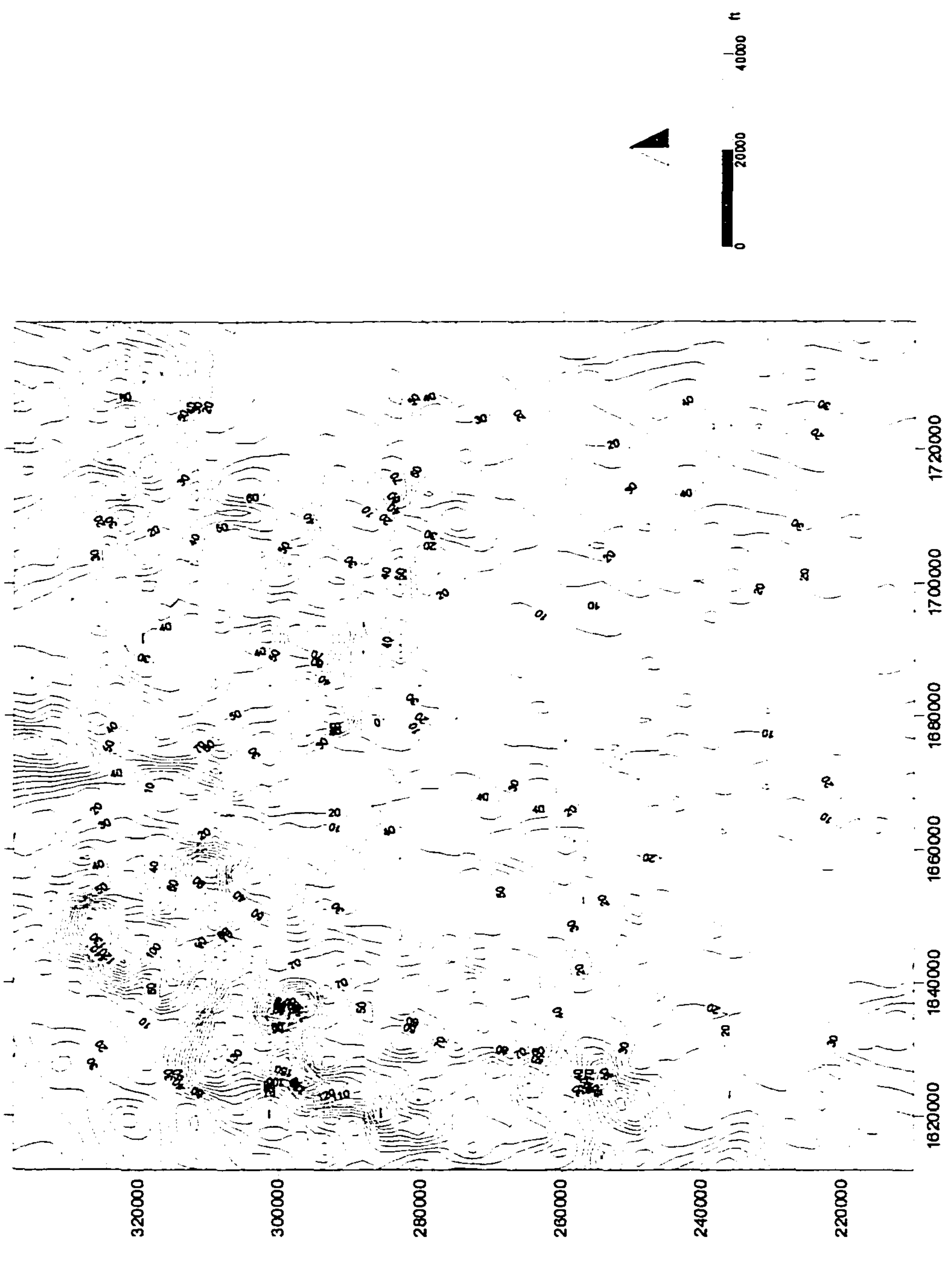


Figure 11. Depth to Static Water Level Contour Map of Kalamazoo County.

The static water level ranges between 0 to 230 ft (0 to 70 m). The greater depths to water are usually found in moraines and the shallower depths to water are found in outwash plains and river valleys. The average depth to water is 46 feet. The potential yield form these aquifers ranges from 100 to 4000 gpm (6 to 252 L/s) (Rheaume, 1990).

Aquifer Vulnerability/Sensitivity Methods

The US Environmental Protection Agency (EPA) defines two broad categories of assessment methods, aquifer sensitivity and groundwater vulnerability. The EPA defined 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). The groundwater vulnerability is defined as "the relative ease with which a contaminant (e.g., nitrate) applied on or near a land surface can migrate to the aquifer of interest under a given set of landuse practice, contaminant characteristics and aquifer sensitivity conditions". Aquifer vulnerability is a function of the intrinsic hydrogeologic characteristics of the soils, geologic materials, contaminant characteristics and landuse. In this study the term "aquifer vulnerability" is used to cover both aquifer sensitivity and groundwater vulnerability. The focus will be given only to hydrogeologic characteristics. There are many methods used to determine groundwater pollution potential. Usually these methods use parameter weighting and scoring devices. The reliability of any method is highly dependent upon using the statistically significant hydrogeologic and related factors, the applicable choice of rating and scoring, and the user's

interpretation of the results. Here, the most widely used USEPA's DRASTIC (Aller et al., 1987) method and AQUIPRO (Passero, 1990), a computerized method will be studied in detail.

In this study, AQUIPRO and DRASTIC methods will be used to test the accuracy and validity of aquifer vulnerability scores by comparing the measured distribution of contaminants within Nottawa Creek Watershed, Calhoun County, Michigan and in Kalamazoo County, Michigan. Statistically significant hydrogeologic factors will be identified which affect contaminant concentrations and distribution. A new aquifer vulnerability model will be proposed considering the statistically significant factors by combining DRASTIC and AQUIPRO.

AQUIPRO

The AQUIPRO model is a parameter/factor weighting system for rating the pollution potential of an aquifer. The factors used in this model are the clay and partial clay layer thickness and the well depth. Water well records, both driller's logs and wells logged by geotechnical experts, are the commonly available data source for the factors.

The pollution potential or aquifer vulnerability is calculated using the equation:

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

Where A is the AQUIPRO score, D is the well depth factor, C is the thickness of the clay layers above the aquifer, P is the thickness of partial clay layers above the

aquifer, and r (0, 2, 3, ... n) are the ranks of the clay and partial clay layers on a well record equaling the thickest layer (0), the second thickest (2), etc.

To calculate an AQUIPRO score, the number and thickness of the clay and partial clay layers are read from a well record. The thickest clay layer is assigned an r of zero. Thus, this layer is divided by one. This means that the entire thickness of the thickest clay layer is included and it has the highest weighting. The thinner layers are assigned higher values of r (2, 3, 4, ... etc.) and are divided by higher values (1.2, 1.3, 1.4, etc.) which progressively reduces their contribution to the resulting score. The results are summed and multiplied by three, which is the weighting assigned to clay.

The same procedure is followed for partial clay layers, which are mixtures of clay, silt, sand and gravel. The only exception is that the partial clay is assigned a weight of one indicating that the clay layers provide greater protection than partial clay layers. The assumption is that as the thickness of a clayey layer decreases it is less effective as a barrier to migrating contaminants and is probably less laterally extensive. The sums of the clay and partial clay layers are added and multiplied by the well depth factors (Table 2). The weight of depth-factor increases with depth.

The lowest possible AQUIPRO score is zero. This indicates that a well has no clay or partial clay layers. Ideally, as AQUIPRO scores increase aquifer protection increases and vulnerability decreases. Descriptive rankings can be assigned to ranges of AQUIPRO scores in order to indicate, in a relative manner, the vulnerability and/or protection of an aquifer (Table 3). The categories should be adjusted to the particular hydrogeology of an area.

Table 2

AQUIPRO Depth Ranges and Weights

Depth Ranges (ft)	Weights
< 5 to = 5	1.0
> 5 to < = 20	1.5
> 20 to < = 50	2.0
> 50 to < = 100	2.5
> 100 to < = 150	3.0
> 150 to < = 200	3.5
> 200 to < = 250	4.0
> 250 to < = 300	4.5
> 300 to < = 350	5.0
> 350 to < = 400	5.5
> 400 to < = 450	6.0
> 450 to < = 500	6.5
> 500 to < = 550	7.0
> 550 to < = 600	7.5
> 600	8.0

Table 3

AQUIPRO Vulnerability Ranges

Relative Vulnerability	AQUIPRO Score Ranges	Verbal Description
1	=>201	Low Vulnerability (High Protection)
2	101-200	Moderate Vulnerability (Moderate Protection)
3	1-100	High Vulnerability (Low Protection)
4	0	Very High Vulnerability (Very Low Protection)

DRASTIC

DRASTIC (Aller et al., 1987) is a standardized system for evaluating groundwater pollution potential using hydrogeologic settings. This system was designed for use by planners, managers, administrators and the general public to assist them in the task of evaluating the relative vulnerability of land areas to groundwater contamination. The DRASTIC system of mapping is divided into two basic tasks: define the area's hydrogeologic setting; and define the physical characteristics of those settings that may affect potential for groundwater pollution. The United States has been classified into 15 different and unique Groundwater Regions (Heath, 1984). Within each of those regions, numerous hydrogeologic settings can be identified and mapped. To define an area's hydrogeologic setting, all of the major geologic and hydrogeologic

factors that can control groundwater movement must be considered. Mappable areas with common hydrogeologic characteristics would also have common vulnerability to contamination.

The Nottawa Creek Watershed and Kalamazoo County study sites lie in region 7, the Glaciated Central Region. Hydrogeologic settings form the basis of the system and incorporate seven major hydrogeologic factors which affect and control groundwater movement: (1) D - Depth to Water, (2) R - (Net) Recharge, (3) A - Aquifer Media, (4) S - Soil Media, (5) T - Topography, (6) I - Impact of Vadose Zone Media, and (7) C - Conductivity (Hydraulic) of the Aquifer.

These factors, which form the acronym DRASTIC, are incorporated into a relative ranking scheme that uses a combination of weights and ratings to produce a numerical value called the DRASTIC index.

A specialized type of the DRASTIC mapping process, known as pesticide DRASTIC, has also been used to produce a pesticide DRASTIC map of the study area. Pesticide DRASTIC evaluates an area's relative vulnerability to contamination by pesticides through consideration of important processes that affect pesticide rate of transport.

Hydrogeologic Factors

Depth to water (D) is considered to be the depth from the ground surface to the water table in the unconfined aquifer conditions or the depth to the top of the aquifer under confined aquifer conditions. The depth to water determines the distance

a contaminant would have to travel before reaching the aquifer. The greater the distance the contaminant has to travel, the greater the opportunity for attenuation to occur or restriction of movement by relatively impermeable layers.

Net recharge (R) is the total amount of water reaching the land surface that infiltrates into the aquifer measured in inches per year. Recharge water is available to transport a contaminant from the surface into the aquifer and also affects the quantity of water available for dilution and dispersion of a contaminant. Factors included in the determination of net recharge were contribution due to infiltration of precipitation, infiltration from rivers, streams and lakes, irrigation and artificial recharge.

Aquifer media (A) represents consolidated or unconsolidated rock material capable of yielding sufficient quantities of water for use. Aquifer media accounts for the various physical characteristics of the rock that provide mechanisms of attenuation, retardation and flow pathways that affect a contaminant reaching and moving through an aquifer.

Soil media (S) refers to the upper six feet of the unsaturated zone that is characterized by significant biological activity. The type of soil media can influence the amount of recharge that can move through the soil column due to variations in soil permeability. Various soil types also have the ability to attenuate or retard a contaminant as it moves throughout the soil profile. Soil media is based on textural classifications of soils and considers relative thickness and attenuation characteristics of each profile within the soil.

Topography (T) refers to the slope of the land expressed as percent slope.

The amount of slope in an area affects the likelihood that a contaminant will run off from an area or be ponded and ultimately infiltrate into the subsurface. Topography also affects soil development and often can be used to help determine the direction and gradient of groundwater flow under water table conditions.

Impact of vadose zone media (I) refers to the attenuation and retardation processes that can occur as a contaminant moves through the unsaturated zone above the aquifer. The vadose zone represents that area below the soil horizon and above the aquifer that is unsaturated or discontinuously saturated. Various attenuation, travel time and distance mechanisms related to the types of geologic materials present can affect the movement of contaminants in the vadose zone. Where an aquifer is unconfined, the vadose zone media represents the materials below the soil horizon and above the water table. Under confined aquifer conditions, the vadose zone is referred to as a confining layer.

Hydraulic conductivity (C) of an aquifer is a measure of the ability of the aquifer to transmit water, and it is also related to groundwater velocity and gradient. Hydraulic conductivity is dependent upon the amount and interconnectivity of void spaces and fractures within a consolidated rock unit. Higher hydraulic conductivity typically corresponds to a higher vulnerability to contamination. Hydraulic conductivity considers the capability for a contaminant that reaches an aquifer to be transported throughout that aquifer over time.

Weighting and Rating System

DRASTIC uses numerical weighting and rating system that is combined with the DRASTIC factors to calculate a groundwater pollution potential index or relative measure of vulnerability to contamination. The DRASTIC factors are weighted from 1 to 5 according to their relative importance to each other with regard to contamination potential (Table 4). Each factor is then divided into ranges or media types and assigned a rating from 1 to 10 based on their significance to pollution potential (Table 4). The rating for each factor is selected based on available information and professional judgement. The selected rating for each factor is multiplied by the assigned weight for each factor. These numbers are summed to calculate the DRASTIC or pollution potential index. The equation for calculating a DRASTIC index is:

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

Where R = rating and W = weight.

Once a DRASTIC index has been calculated, it is possible to identify areas that are more likely to be susceptible to groundwater contamination relative to other areas. The higher the DRASTIC index, the greater the vulnerability to contamination. The index generated provides only a relative evaluation tool and is not designed to produce absolute answers or to represent units of vulnerability. Pollution potential indexes of various settings should be compared to each other only with consideration of the factors that were evaluated in determining the vulnerability of the area.

Table 4

Assigned Weights and Ratings for DRASTI

DRASTIC Features								
Depth to water (ft)		Recharge (inches/yr)		Aquifer Media		Soil Media		T (
Range	*Rating*	Range	*Rating*	Type	*Rating*	Type	*Rating*	Ra
0-5	*10*	0-2	*1*	massive shale	*2*	thin / absent	*10*	0
5-15	*9*	2-4	*3*	igneous/meta-morphic (IM)	*3*	gravel	*10*	2
15-30	*7*	4-7	*6*	weathered IM	*4*	sand	*9*	6-
30-50	*5*	7-10	*8*	glacial till	*5*	peat	*8*	12
50-75	*3*	10^+	*9*	bedded Sst, Lst, shale	*6*	aggregated clay	*7*	1
75-100	*2*	--	--	massive sandstone(Sst)	*6*	sandy loam	*6*	-
100^+	*1*	--	--	massive limestone(Lst)	*6*	silty loam	*5*	-
--	--	--	--	sand and gravel	*8*	clay loam	*4*	-
--	--	--	--	weathered basalt	*9*	muck	*2*	-
--	--	--	--	karst Lst	*10*	compact clay	*1*	-
Weight: 5 Pesticide Wt.: 5		Weight: 4 Pesticide Wt.: 4		Weight: 3 Pesticide Wt.: 3		Weight: 2 Pesticide Wt.: 5		Pe

Source: Aller, L., Bennet, T., Lehr, J. H., Petty, R. J. DRASTIC: A standardized system for evaluatin potential using hydrogeologic settings: National EPA –600/2-87-035.

Table 4

Assigned Weights and Ratings for DRASTIC Features

DRASTIC Features									
Media		Soil Media		Topography (% slope)		Vadose Zone		Conductivity (gpd/ft²)	
	Rating	Type	*Rating*	Range	*Rating*	Type	*Rating*	Range	*Rating*
:	*2*	thin / absent	*10*	0-2	*10*	confining layer	*1*	1-100	*1*
-)	*3*	gravel	*10*	2-6	*9*	silt / clay	*3*	100-300	*2*
[	*4*	sand	*9*	6-12	*5*	shale	*3*	300-700	*4*
	5	peat	*8*	12-18	*3*	limestone	*6*	700-1000	*6*
	6	aggregated clay	*7*	18^+	*1*	sandstone	*6*	1000-2000	*8*
)	*6*	sandy loam	*6*	--	--	bedded Lst, Sst, shale	*6*	2000^+	*10*
)	*6*	silty loam	*5*	--	--	sand/gravel with clay	*6*	--	--
	8	clay loam	*4*	--	--	IM	*4*	--	--
	9	muck	*2*	--	--	sand and gravel	*8*	--	--
	10	compact clay	*1*	--	--	karst Lst	*10*	--	--
t: 3 Wt.: 3		Weight: 2 Pesticide Wt.: 5		Weight: 1 Pesticide Wt.: 3		Weight: 5 Pesticide Wt.: 4		Weight: 3 Pesticide Wt.: 2	

L., Bennet, T., Lehr, J. H., Petty, R. J., and Hackett, G., 1987,
STIC: A standardized system for evaluating ground water pollution
ial using hydrogeologic settings: National Water Well Association,
-600/2-87-035.

Pesticide DRASTIC

A special version of DRASTIC was created because application of pesticides in the study area is a big concern and majority of the study area represents agricultural land. The weights assigned to the DRASTIC factors were changed to reflect the processes that affect pesticide movement into the subsurface with particular emphasis on soils (Table 4). In this study pesticide DRASTIC was used to evaluate ground-water vulnerability to agricultural chemicals. The process for calculating the pesticide DRASTIC index is identical to the process used for calculating the general DRASTIC index. Descriptive rankings were assigned to ranges of DRASTIC scores according to the guideline given in the DRASTIC manual (Table 5).

Table 5

DRASTIC Vulnerability Ranges

Relative Vulnerability	DRASTIC Score Ranges	Verbal Description
1	=<150	Low Vulnerability (High Protection)
2	151-175	Moderate Vulnerability (Moderate Protection)
3	176-200	High Vulnerability (Low Protection)
4	=> 201	Very High Vulnerability (Very Low Protection)

Limitations of DRASTIC and AQUIPRO

A significant body of literature reports that the commonly used aquifer vulnerability methods yield erroneous results for many hydrogeologic settings, especially for glacial drift aquifers because of their complex geology (Banton & Villeneuve, 1989; Benton, 1991; Chidester, 1993; Dutta, Das Gupta, & Ramnarong, 1998; Garret et al., 1987; Passero, 1990). Both of these methods assume that the contaminants have the mobility of water. An area of 100 acres (40.4 hectares) or larger is required to apply DRASTIC. In DRASTIC, although the factor I (Impact of Vadose Zone) should account for subsurface information above the water table, it is unable to account for interfingering clay layers in glacial deposits. It is also unable to account for interbedded low permeability rocks in sedimentary rocks of higher hydraulic conductivities.

On the other hand, AQUIPRO does not consider any surface or related hydrologic factors such as soil characteristics, slope and recharge. The criteria of land use, importance of the aquifer system and population density are ignored by both DRASTIC and AQUIPRO. Neither of these methods have been field validated. It is also unknown which of these hydrogeologic factors are statistically significant with respect to contaminant distribution and occurrences.

One study observed that DRASTIC gave a much higher vulnerability score to the sand and gravel aquifer setting than to the till over fractured bedrock aquifer setting (Garret et al., 1987). But the study also showed that the bedrock aquifer is more vulnerable to contamination than was scored by the DRASTIC method. In fractured

bedrock aquifers the groundwater velocity is much higher because of very small effective porosity; and in DRASTIC this cannot be considered. The quantitative weight functions in DRASTIC result in a simplistic index of unclear meaning that is less useful and less distinctive than desired (Rosen, 1994). The index is unclear because the system tends to overestimate the vulnerability of porous media aquifers compared to aquifers in fractured media. The rating tables need to be revised so that more weight could be given to specific surface and effective porosity, and less to hydraulic conductivity. The applicability of the results would be enhanced and the risk of misuse reduced if the results were more clearly directed toward scientifically defined factors, e.g. sorption, travel time and dilution.

The chemical characteristics of the potential contaminants, which are not considered in the DRASTIC and AQUIPRO models are important. One of the problems with comparing the DRASTIC and AQUIPRO vulnerability scores with water quality criteria is that these methods cannot quantify the pollution potential in terms of actual concentration. One study compared the DRASTIC vulnerability scores with a simulation model, PRZM (Carsel and et. al. 1984), and found no correlation between DRASTIC scores and PRZM leaching indexes (Banton and Villanuve, 1989). Theoretically, however, areas with high DRASTIC scores or low AQUIPRO scores should have more frequent occurrences of groundwater contamination events than areas with low DRASTIC and high AQUIPRO scores given similar land use, well construction, and well densities. The relationship between AQUIPRO and DRASTIC scores and levels of contamination, however, has not been well documented. This study focused

primarily on the field validation aspect of these methods and the relative comparison of DRASTIC and AQUIPRO with respect to the occurrences and distribution of nitrate in Kalamazoo County, Michigan.

Previous Studies

Benton (1991) and Chidester (1993) studied the aquifer vulnerability of Kalamazoo County. Benton (1991) concluded that the AQUIPRO model could be used to determine the vulnerability of glacial drift aquifers in areas with one dominant source of contamination. His study indicated that the hydrogeologic factors that appear to affect nitrate concentration were clay thickness, total well depth, and well depth below static water level. The results of his study also showed that partial clay thicknesses of less than 50 feet did not affect nitrate concentration. He suggested that AQUIPRO model should be modified and another factor, well depth below static water level, should be included.

Chidester (1993) used T- tests, Pearson-r correlation, least-squares analysis of variance, and multiple regression to relate nitrate-N concentrations to hydrogeologic and agricultural parameters. He concluded that nitrate-N concentrations in Kalamazoo County have statistically significant relationships with depth of submergence, well depth, clay thickness, partial clay thickness, agricultural land use, and soil slope. He indicated that these six variables combine to explain approximately 9% of the total variance in the nitrate-N concentration. He also mentioned that 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 that study. Both Benton and Chidester treated AQUIPRO scores as quantitative (ratio) data. But in reality, AQUIPRO scores are qualitative (ordinal) in nature.

Hughes (1995) delineated areas of recharge-discharge potential utilizing computerized water well records of Kalamazoo County. The recharge-discharge methodology was based on the vertical head differences found between wells with shallow depth of submergence and those with deeper depth of submergence. She defined the depth of submergence as the difference between the static water level in a well and the total depth of the well or equal to the height of the water column in a well. In her study, the methodology was based on the premise that when a shallow depth of submergence well and a deeper depth of submergence well are located in close proximity in a recharge area of a water table aquifer, the shallow depth of submergence well would exhibit a higher static water elevation than would the deeper depth of submergence well. If these same wells were located in a groundwater discharge area the reverse would be true. She concluded that the use of computerized drillers' records for delineation of recharge-discharge potential was most effective over larger geographic regions underlain by homogeneous aquifers. She recommended that as the geographic area decreases and/or heterogeneity of the aquifer increases, there must be more careful selection of the data and the interpolation method be used in generating the gridded surfaces of the recharge-discharge potential map.

The glacial geology of southwest Michigan was studied by number of

investigators. Kozlowski (1999) did a very detailed glacial geological study in the eastern half of the Nottawa Creek Watershed. His study concluded that the landforms in the study area were created by the Saginaw lobe of the Laurentide Ice Sheet, which advanced southwesterly to its late glacial maximum about 21,000 years B.P. and retreated northeasterly. The Saginaw Lobe, during retreat periodically stabilized and formed a series of recessional moraines during intervals of positive mass balance. The Tekonsha Moraine most likely represents a recessional margin that formed after 15,000 years B.P. and before 14,000 years B.P.

Kozlowski (1999) recognized that the bedrock erosional surface coincided with drainage patterns in the study area. Several bedrock valleys paralleling the ice flow direction were present. These valleys were interpreted as tunnel valleys and modified stream valleys that formed by subglacial meltwater flow beneath the Saginaw Lobe or it's predecessors.

In Kozlowski's study area, the drift thickness ranges from 13 feet to nearly 200 feet. The thickest deposits contained the most productive aquifers and are located in the bedrock channels. The stratigraphy of the drift was also quite variable, consisting of alternating beds of glaciofluvial sediment and diamicton. He identified two different types of tills throughout the study area. The first occurs at the surface and is a sandy brown diamicton with variable boulder abundance. The second till is a thick, massive, gray clayey diamicton that occurs at depth. This till is a distinctive that has been used as a significant regional stratigraphic marker (Gardner, 1997; Flint, 1999; Nicks, 1999).

Kozlowski also proposed that the channels eroded by subglacial meltwater, tunnel valleys, were subsequently in-filled with sediment and stagnant ice, which later melted out. As the buried ice melted it created linear ice block depressions in which modern streams established their courses. He identified a strong correlation between surface water bodies and bedrock valleys in the study site. He pointed out that the Nottawa Creek and the St. Joseph River valleys were good examples of this relationship.

The glacial geology of the area between the Tekonsha and Kalamazoo moraines in Kalamazoo County were studied by Finkbeiner (1994). She concluded that the glacial sediments of her study area comprise a large outwash complex between two moraines. She also suggested that the Sturgis moraine in this area might actually be a push moraine resulting from the second advance of the Lake Michigan lobe. She mentioned that the north-south trending arm of the Tekonsha moraine is an end moraine delineating the farthest advance of the Lake Michigan Lobe, and that the interlobate boundary could be roughly depicted by the trace of the moraine throughout the study area.

Her study indicated that the surficial outwash complex at the surface of the study area was comprised of at least three glaciofluvial outwash fans. Two of these fans, located along the eastern margin of the Kalamazoo Moraine which trend, trend northwest-southeast, were deposited from meltwaters of the Lake Michigan Lobe as the ice stood at the Kalamazoo Moraine. The southernmost of these two fans was younger and might have resulted from a single breakthrough of meltwater.

CHAPTER II

DATA COLLECTION

Nottawa Creek Watershed Data

Three hundred and fifty computerized water well records from Nottawa Creek Watershed were obtained from the Ground Water Education in Michigan Center (GEM) of Western Michigan University. All of these wells were field verified and located using Global Positioning System (GPS) methods. These well records contain well locations as X and Y coordinates (State Plane Coordinates) names and addresses of well owners, pertaining geological, hydrogeological and well constructional information (Appendix B). Raw digitized soil survey data were collected from the Calhoun Conservation District, Michigan. Additionally, previous published literature was used to obtain geological, hydrological, and land use information.

Forty groundwater samples (Figure 12) were collected from private wells in Nottawa Creek Watershed for hydrogeochemical analyses. A water well sampling protocol was used for sample collections. The well selection process produced sampling sites that are geographically and hydrogeologically representative of near-surface aquifers. The groundwater sampling was done between June and August 1998. The sample-collection protocol ensured that the water collected was representative of the aquifer at that site.

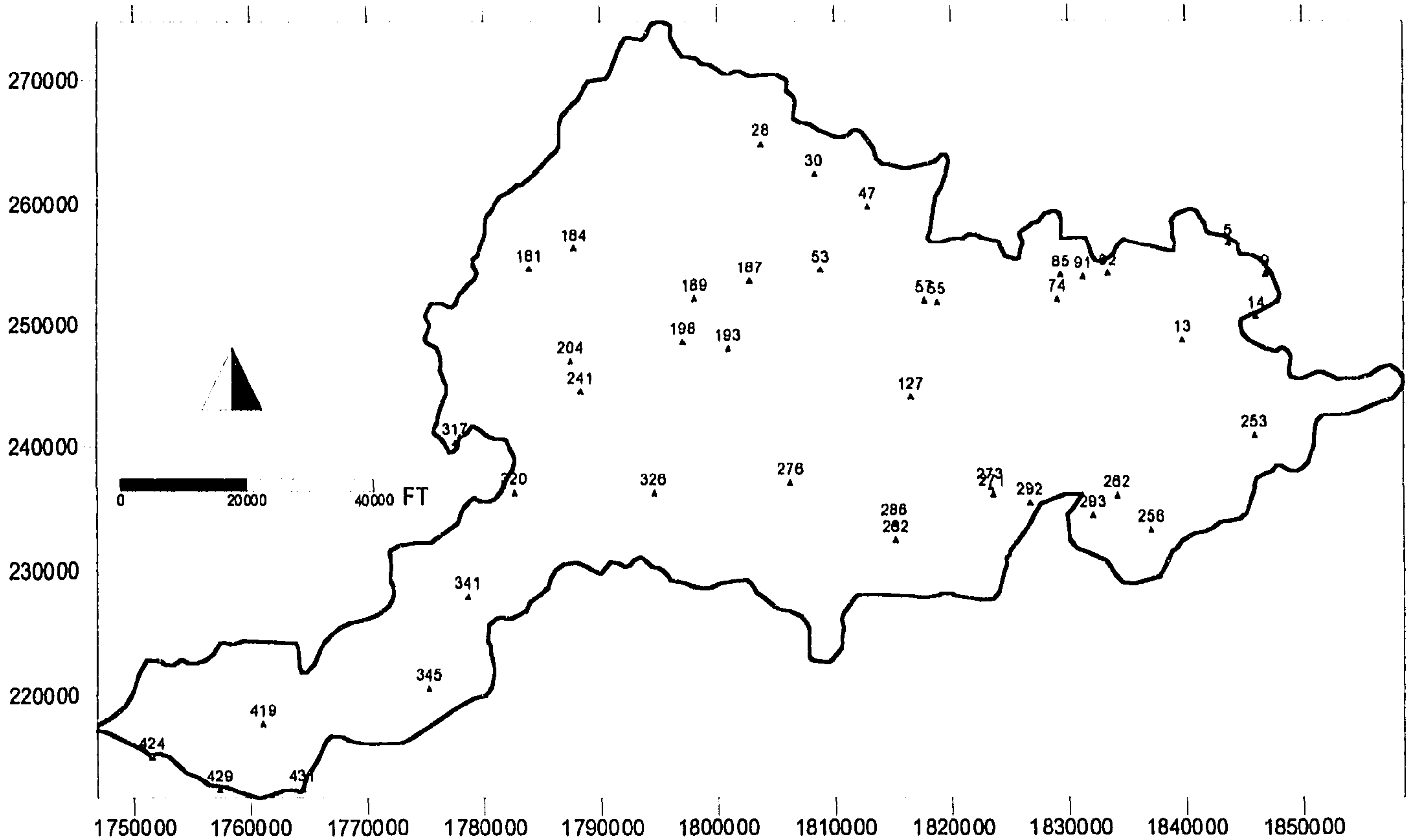


Figure 12. Location of Sampled Wells in Nottawa Creek Watershed.

Collected samples were sent to Department of Environmental Quality (DEQ) laboratory for chemical analysis. Some selected samples were sent to KAR Laboratories, Kalamazoo for atrazine analysis. Initial screening for atrazine was done using the IMMUNOASSAY (Suppleco, 1997) technique in the Water Quality Laboratory of the Institute of Water Sciences of Western Michigan University.

Sampling Design

Quantitative assessment of groundwater chemistry requires a highly organized data collection procedure. Available for the study were 350 drillers' well records from the Nottawa Creek watershed (Figure 4). The distribution of these wells was very inconsistent. There were clusters of wells located in different places of the watershed. In order to serve our study purpose we have used a three-step process for systematic sample selection was used.

Sample Grid Generation

First, a sampling grid was generated using SURFER (Golden Software, Inc., 1996) computer program. The grid consists of approximately 42 square cells. Each cell is comprised of 10^4 by 10^4 ft (3,048 m) on 10^8 square feet ($9x10^6$ m^2). Because the watershed boundary is irregularly shaped, each full grid and partial grid within the watershed boundary was assigned a weight depending on the percentage of area it contains. For example, a full square grid within the watershed boundary grid was assigned a weight of 4, whereas a grid containing 25% of the watershed area was

assigned a weight of 1. Then all the partial grids were combined with the adjacent full or partial grids. The plan was to collect a sample from a grid only when it had a weight of at least 4 so that the sampling was geographically uniformly distributed. After combining the partial grids the watershed contained 26 grids (Figure 13) with a weight of 4 or more. At least 2 wells were selected from a grid having a weight of 4. Table 6 shows the grid number, weight and number of wells selected from that grid.

Well Selection

From the grid, wells were selected based on several criteria. Selected wells were distributed geographically and hydrogeologically by grid, aquifer class, and relative depth within the aquifer (Koplin, Burkart, & Thurman, 1994). To be selected, a well has to be shallowest in the grid. Glacial drift wells were preferred over bedrock wells. If no drift wells were available, bedrock wells were selected. Figure 12 shows the selected drift and bedrock wells. Two batches of wells were progressively selected based on the above mentioned criteria. The first batch of wells identified that met the criteria for selection were designated as the primary wells; any additional wells that met the selection criteria were designated as alternate wells and included in second batch. Seventy-one wells were in the first batch and 61 were in the second batch. Altogether, 132 domestic wells were selected. Of these selected wells, 52 wells were completed in near-surface glacial drift aquifers and 80 were completed in bedrock aquifers.

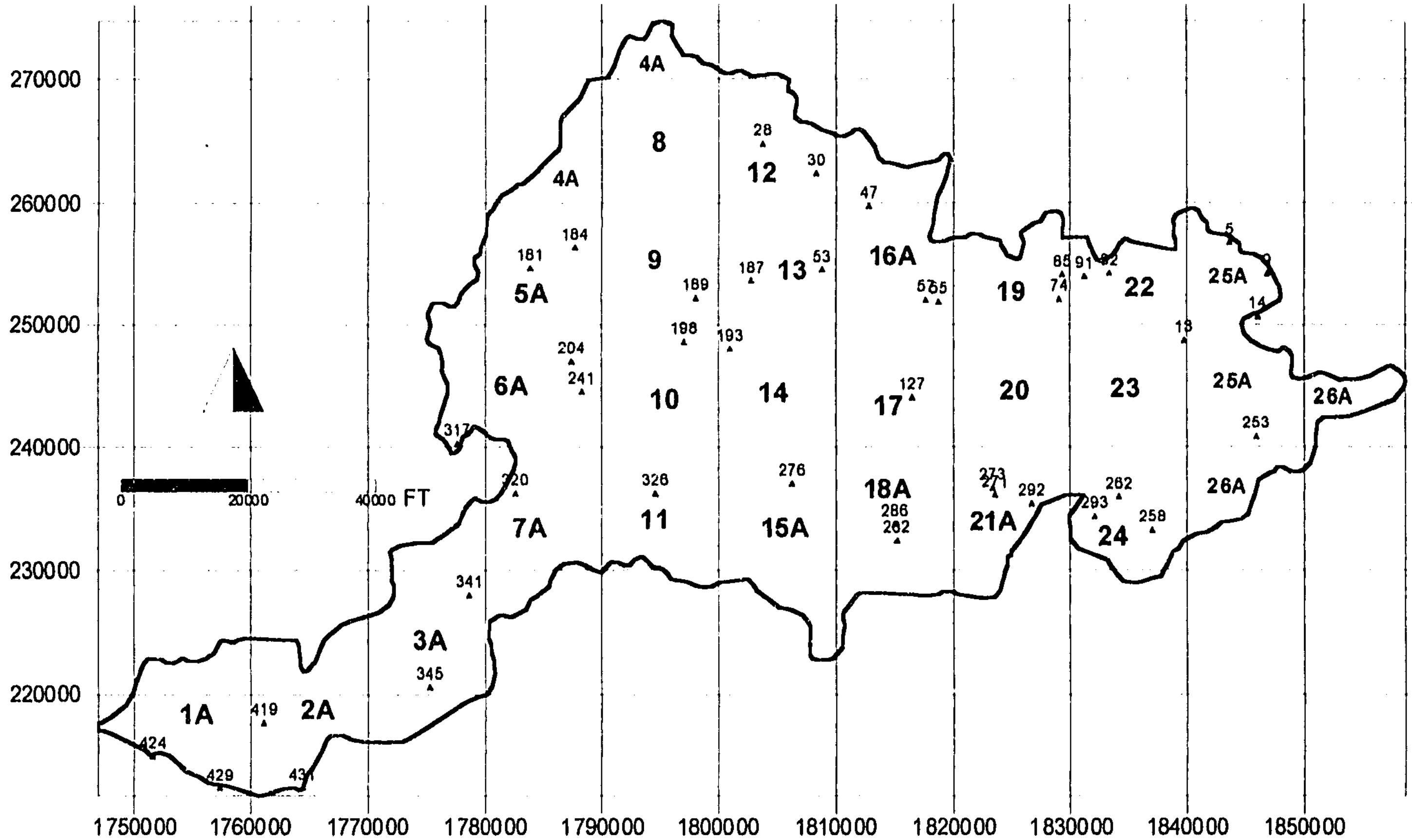


Figure 13. Map Showing the Grids Made for Sampling Well Selection.

Table 6

Sampling Design With Grid System in Nottawa Creek Watershed

Grid Number	Number of Pooled Grids	Code (total weight)	Number of Wells Selected
1A	3	6	4
2A	2	5	3
3A	3	7	5
4A	2	4	3
5A	2	5	3
6A	2	6	4
7A	2	6	4
8	1	4	2
9	1	4	2
10	1	4	2
11	1	4	2
12	1	4	2
13	1	4	2
14	1	4	2
15A	2	6	4
16A	2	6	4
17	1	4	2
18A	2	5	3
19	1	4	2
20	1	4	2
21A	2	4	2
22	1	4	2
23	1	4	2
24	1	4	2
25A	2	7	5
26A	2	4	2
*A indicates a grid which is combined with pooled partial grids			

Sample Collection Permission

The well owners of the first batch were notified by mail with self-addressed postcards to get their approval to get a sample from their wells. Twenty-one well owners were agreed to give samples. Then the well owners of the second batch were

notified, and nineteen well owners agreed. Many of the well owners asked to obtain copies of their sample analysis. Finally, 40 wells were selected for sample collection even though the initial plan was to get samples from 71 wells. Of these 40 wells, 15 were drift wells and 25 were bedrock wells.

Sample Collection and Analysis

All water samples were collected according to DEQ and EPA laboratory guidelines. Five 500-milliliter plastic sample bottles and a 1-liter amber glass bottle were used for partial chemical analysis per well. Samples were also collected for dissolved inorganic carbon (DIC) and isotope analysis. All wells were purged to chemical stability before water samples were collected to ensure a representative sample was obtained. Groundwater temperature, pH and conductivity were measured in the field for every sample (Table 7). Water samples for cation analysis were preserved with 5 ml of nitric acid (1:1 N), and water samples for nitrate and nitrite (nutrient) analysis were preserved with 5 drops of concentrated sulfuric acid. All collected samples were immediately chilled in a cooler with ice to 4° C.

Water samples were collected from 40 wells between June and August, which represented post-planting conditions. All of these samples were analyzed for calcium, iron, magnesium, potassium, sodium, ammonia, chloride, nitrate, nitrite, orthophosphate, sulfate, total dissolved solids and atrazine (Table 8). Twenty-five samples were also analyzed for carbon and oxygen isotopes. Ancillary data on land use, for example, "hog farm" or "close to a cemetery" were recorded by visual inspection. Local

Table 7

Temperature, pH and Conductivity of Groundwater in Nottawa Creek Watershed

WELL ID	PH	Temperature (°C)	Conductivity $\mu S/cm^2$	Comments
5	7.53	18	420	Cemetery
9	7.45	12.8	370	High ground
13A	7.52	15.2	360	
14	7.52	13.2	290	
28	7.52	14.4	360	
47	7.50	14.8	470	
53	7.39	14.9	450	
55	7.48	16.1	310	
57	7.60	14.5	320	
74	7.52	14	480	Soft water?
85	7.40	15.9	410	
91	7.44	14.1	350	
92	7.25	15.7	580	
127	7.84	16.4	390	
181	7.61	14	320	
184	7.42	15.1	450	
187	7.45	14.5	360	
189	7.61	14.	380	
193	7.50	15.7	650	Soft water?
198	7.45	13.2	490	
204	7.61	14.7	480	
241	7.45	15.6	420	
253	7.15	15.5	440	
258	7.78	17.7	570	
262	7.54	16.8	420	
271	7.73	16.5	470	
273	7.47	15	360	
282	7.53	15.2	380	
292	7.43	14.5	600	
293	7.25	12.5	480	
317	7.61	14.2	350	
320	7.80	16	420	
326	7.30	17.1	520	
341	7.79	16.1	400	Sulfur odor
345	7.60	15.8	600	Diary farm
419	7.50	11.9	420	
424	7.32	14.8	720	
429	7.78	13.4	320	
431	7.37	15	320	

Table 8

Summary of Partial Water Chemistry Data in Nottawa Creek Watershed

Chemical Name	Minimum Concen-tration	Maximum Concen-tration	Mean Concen-tration	Median Concen-tration	Std. Deviation
Nitrate	0.0	18.0	0.71	0.005	2.97
Chloride	2.0	116	7.46	12.0	28.57
Sodium	2.7	188	8.10	5.40	48.27
Iron	0.02	4.60	1.23	0.98	1.20
Atrazine	non-detect	non-detect	non-detect	non-detect	Non-detect
TDS	250.0	780	128.69	390.0	99.0

(all concentrations are given in mg/L; #39)

features, such as streams and lakes that could affect water quality also were noted at the time of sampling.

Laboratory Methods

Analyses for general water chemistry (cations, anions and TDS) were done in the DEQ Environmental Laboratory in Lansing, Michigan, using a colorimetric procedure automated with cadmium reduction (EPA, 1983; method-353.2). The laboratory reporting limit of those compounds were 0.05 mg/L. All of the constituents' concentrations were reported in mg/L (Table 8). The results of nitrite and nitrate were reported as nitrogen.

All samples were screened for atrazine using the Immunoassay method (Suppleco, 1997) in the water quality laboratory of Western Michigan University.

Although no atrazine was detected by immunoassay, 16 samples were sent to KAR Laboratory in Kalamazoo, Michigan for further analysis. At KAR lab, samples were analyzed by gas chromatography/mass spectrometry, using solid phase extraction techniques. The laboratory-reporting limit for atrazine was 0.1 μg/L.

Hydrogeochemistry

Water chemistry parameters examined for this study included field measurements of specific conductance, pH, water temperature, and laboratory analyses of some common anions, cations, and TDS and atrazine herbicide (Tables 7 & 8). The predominant ions present are calcium, sodium, iron, chloride, and sulfate. TDS concentrations range from 250 to 780 mg/L. The pH of groundwater ranged from 7.15 to 7.84 and temperatures ranged from 11.9 ^{0}C to 18 ^{0}C. The average nitrate concentration of water from 40 wells is 0.71 mg/L. A maximum concentration of 18 mg/L of nitrate was detected in water from well 419 in Athens Township. Nitrate would have been detected in more wells if shallow wells could have been sampled. Due to lack of cooperation from the well owners, some selected shallow wells could not be sampled. No atrazine was detected in any of the wells sampled in the watershed. Some higher sodium and chloride concentrations are probably due to road salt applied during winter and brine used to control dust during summer.

The statistical similarity of groundwater chemical parameters in the bedrock and drift aquifers suggests that the bedrock aquifer is recharged through the glacial drift (Tables 9 & 10) (Kehew, 1999). This means that contamination derived from the

Table 9

Summary Statistic for Bedrock Wells in Nottawa Creek Watershed

Item Name	Mean	Median	Mode	Std. Devia-tion	Kurtosis	Skew-ness	Range	C. L.
Depth (ft)	100.68	92	100	55.30	15.38	3.65	281	24.52
Score	344.45	196.5	191	447.32	12.99	3.29	2137	198.33
Drift Thickness (ft)	50.68	43.5	45	31.76	4.81	1.79	155	14.08
TDS	375.45	380	320	88.68	0.03	0.63	340	39.32
Calcium	70.70	72.15	N/A	18.05	-0.44	0.17	67.9	8
Chloride	20.55	11.5	2	25.82	7.18	2.57	109	11.45
Iron (μg/L)	1627	1235	2300	1264	0.01	0.82	4520	560.29
Potassium	1.37	0.94	0.7	1.03	4.62	2.18	3.98	0.46
Magne-sium	22.39	22	22	5.36	0.08	0.61	20.3	2.38
Sodium	16.19	4.5	3	32.6	13.35	3.54	147	14.45
Nitrate	0.08	0.01	0.01	0.33	21.89	4.67	1.55	0.15
Ammonia	0.09	0.06	0.24	0.09	-0.12	1.00	0.31	0.04
Phosphate	0.002	0.002	0.00 1	0.002	10.6	3.00	0.01	0.001
Sulfate	19.55	2.13	23	10	-0.41	-0.05	37	4.43

(all concentrations are given in mg/L; Total Well #22; Confidence Level (C.L.-95%)

surface could ultimately reach the bedrock aquifer. Some impacts of surface land use activities are suggested in the drift aquifer by higher means of several major ions. A large data set of wells would almost certainly include more wells with elevated nitrate.

The data also suggest, however, that the redox potential in the two aquifers is different. Groundwater in the bedrock aquifer is more reducing than water in the aquifer. This means that nitrate is unlikely to be present in high concentrations in the

Table 10

Summary Statistic for Drift Wells in Nottawa Creek Watershed

Item Name	Mean	Median	Mode	Std. Devia-tion	Kurtosis	Skew-ness	Range	C. L.
Depth (ft)	48.85	45	47	23.56	5.11	1.98	94	14.23
Score	92.69	81	90	83.24	1.48	1.39	271	50.3
TDS	410.77	390	390	121.34	8.25	2.55	520	73.32
Calcium	78.25	79.4	N/A	13.05	4.13	1.27	54.2	7.88
Chloride	28.15	15	15	36.2	2.98	2.01	114	21.87
Iron	881.08	770	N/A	1030	7.84	2.55	3980	622
Potassium	1.36	0.96	1.12	1.17	8.92	2.88	4.36	0.70
Magne-sium	22.52	22.8	N/A	4.47	-0.65	-0.15	14.3	2.70
Sodium	13.01	5.4	2.7	16.39	2.82	1.96	50.4	9.90
Nitrate	1.98	0.006	0.006	5.01	10.34	3.15	17.99	3.03
Ammonia	0.07	0.047	0.005	0.07	0.38	1.27	0.23	0.04
Phosphate	0.004	0.005	0.001	0.003	0.01	0.71	0.01	0.001
Sulfate	26.85	27	N/A	11.83	-0.76	0.21	38	7.15

(all concentrations are given in mg/L; Total Well #13; Confidence Level (C.L.-95%)

bedrock aquifer. It also means that iron concentrations in the bedrock aquifer are likely to be higher. This may be undesirable for domestic well owners due to the esthetical problems of iron-rich water, such as staining of plumbing fixtures and the occasional presence of iron bacteria. Where the glacial drift is very thin, bedrock wells should be recommended despite the potential for high iron because of the higher probability of nitrate contamination in shallow drift wells.

Both the oxygen and carbon isotope data suggest significant communication between bedrock and drift aquifers, especially the shallow ones (Krishnamurthy,

1999). In addition, the isotope data suggest that the shallow bedrock and drift aquifers are also in communication with surface waters. The carbon isotope data suggest that water from several wells (both drift and bedrock) is slowly evolving from open to a closed system. There are also samples (both drift and bedrock) that suggest fully evolved or "isotopically matured" water.

Kalamazoo County Data

The DRASTIC map of Kalamazoo County (Rheaume, 1990) was used in this study. Detailed computerized water well records of 8,733 wells, along with the partial chemistry results, were obtained from the Michigan Resource Information System (MIRIS). These wells are widely distributed throughout the county except in Kalamazoo Township, because the city water supply provides water for this area. MIRIS is a program of the Land and Water Management Division of the Michigan Department of Natural Resources that contains 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 Michigan groundwater database is an on-going project to computerize information on municipal and private wells. The verification of data entries is performed by county agencies, then sent to MDNR (Chidester, 1993). The Environmental Health Division of the Kalamazoo County Human Services Department has completed the process of converting paper well records to a computerized countywide database. The locations of these wells were field verified using Global Positioning System (GPS), and located

using State Plane Coordinate systems. These well records also contain names and addresses of well owners; geological, hydrogeological and well construction information. The County Health Department collected these groundwater samples to check the water chemistry as a regulatory measure. So there was no bias regarding sample selection with respect to groundwater vulnerability validation.

Partial chemical data included sodium, iron, chloride, fluoride, hardness, sulfate, nitrite and nitrate. All of these concentrations were given in mg/L (Table 11). The Department of Public Health Laboratory of Kalamazoo County analyzed the samples.

Water Chemistry

Groundwater in surficial aquifers is of calcium-bicarbonate type, although

Table 11

Summary of Partial Water Chemistry Data in Kalamazoo County

Chemical Name	Minimum Concentration	Maximum Concentration	Mean Concentration	Median Concentration	Std. Deviation
Nitrate	0.0	48.60	1.26	0.01	2.93
Chloride	0.0	550	7.46	0.0	27.53
Fluoride	0.0	1.80	0.03	0.0	0.08
Sodium	0.0	550	8.10	0.0	30.89
Iron	0.0	16.5	0.22	0.0	0.69
Sulfate	0.0	280	1.61	0.0	8.60
Hardness	0.0	651	128.69	0.0	142.16

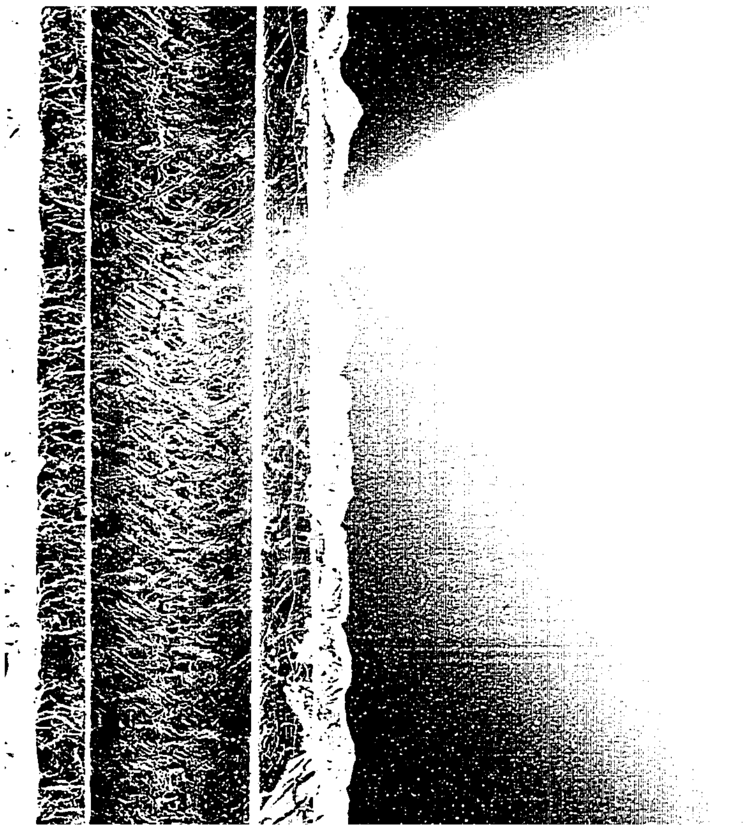
(all concentrations are given in mg/L; # 8733)

sodium, sulfate, and chloride are predominant ions at some locations. In general, groundwater quality of Kalamazoo County is good, and does not differ appreciably from statewide natural groundwater quality (Rheaume, 1990).

Specific conductance, hardness, and TDS concentrations are slightly higher than statewide averages (Rheaume, 1990). The pH of groundwater ranged from 6.6 to 8.24, with a mean of 7.3. Groundwater temperatures ranged from 9 ^{0}C to 14 ^{0}C; the mean was 11.0 ^{0}C.

The median concentration of nitrate (0.10 mg/L) in groundwater in Kalamazoo County is 0.01 mg/L which is equal to the statewide median of 0.01 mg/L. The highest concentration of nitrate (48.60 mg/L) was found in the water of well no. 39720928001 in Charleston Township. The mean concentration of nitrate in water from 8733 wells was 1.26 mg/L. Two hundred forty nine of the 8733 wells yielded water that had nitrate concentrations greater than the required maximum concentrations level (MCL) (EPA, 1993) of 10.0 mg/L. In this document all nitrate concentrations reported as Nitrate-N concentration. Pesticide (2, 4-D) was detected in water from one well in the city of Portage (Rheaume, 1990).

The sources of nitrate in groundwater in Kalamazoo from human activities are fertilizer application and septic tank effluent. Chemical fertilizer and manure are used in agricultural areas of the county. Fertilizer application accounts for 50.9% of the nitrogen and septic tanks account for 4.7% of the total nitrate load (Rheaume, 1990). The natural sources of nitrate are precipitation and dry fall-out from the atmosphere. These two natural sources of nitrate account for 43.3% of nitrogen deposited at the



surface every year (Rheaume, 1990). With the exception of nitrogen from septic tank system (4.7%) almost all the nitrates sources are at the surface.

The amount of nitrate available for leaching below the root zone is determined by the nitrogen cycle (Figure 14) (Freeze & Cherry, 1979). The major processes involved are: (a) ammonification, (b) nitrification, (c) denitrification, and (d) plant uptake and recycling (Keeney, 1986). Ammonification is the conservation of organic-nitrogen to the ammonium ion (NH_4^+). Nitrification is the microbial oxidation of NH_4^+ to nitrite (NO_2^-) and further into nitrate (NO_3^-). Nitrification and ammonification 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). If a sufficient source of organic matter and abundant NO_3^- are present, bacterial systems are capable of denitrifying large amounts of NO_3^- in the soil zone (Freeze & Cherry, 1979).

NO_3^- moves as a conservative tracer in the vadose zone (Bodier, Frank, & Spalding, 1993). This is generally due to the high solubility of NO_3^- and its tendency to be repelled by negatively charged soil particles (Keeny, 1986). Dilution and denti-trification are the major factors that control the concentrations of nitrate in subsurface water. NO_3^- is highly mobile in groundwater under conditions of high dissolved O_2. When dissolved O_2 is less than 2.0 mg/L with a significant source of organinc carbon, denitrification in the saturated zone can significantly reduce NO_3^- concentration (Korom, 1993).

The temporal variability in nitrate concentrations in groundwater can be

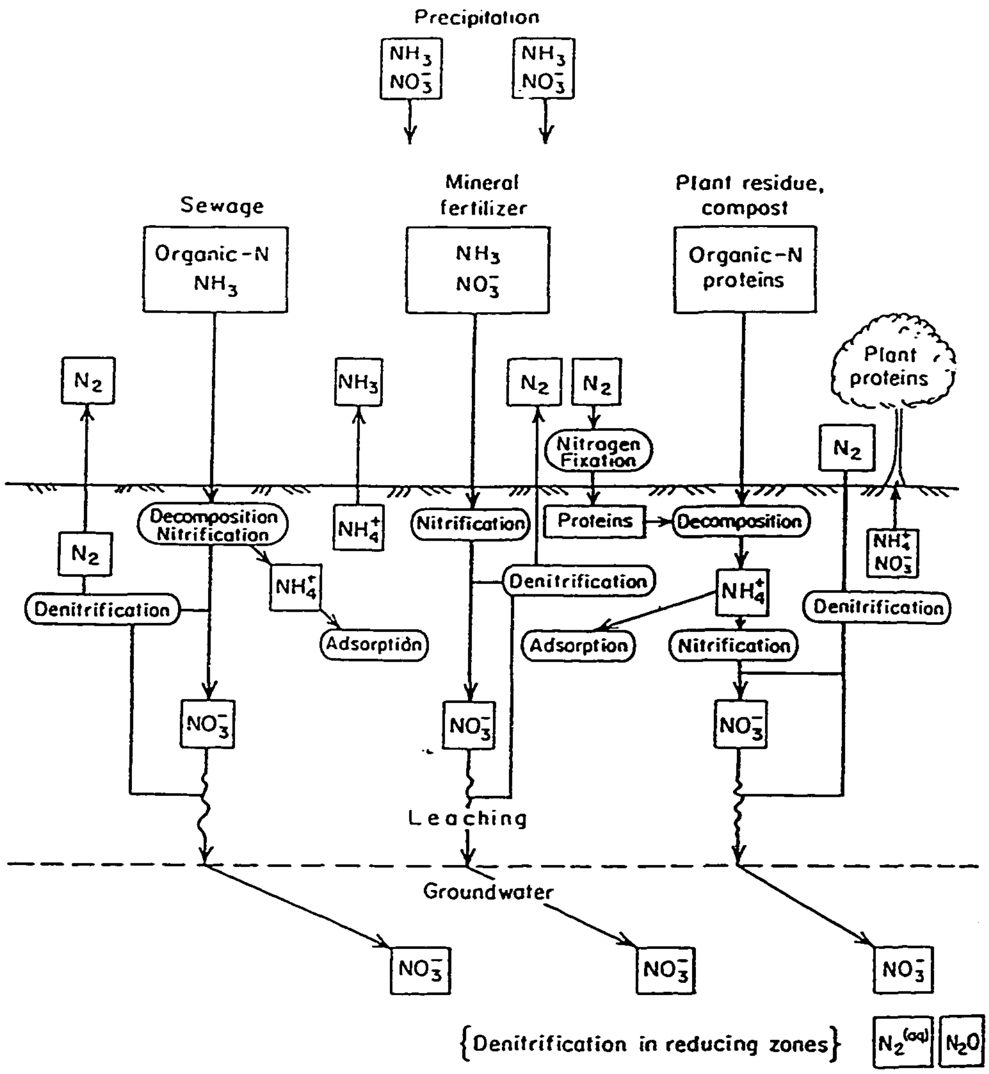


Figure 14. The Nitrate-N Cycle (Source: Freeze and Cherry, 1979).

attributed to the processes involved in the N-cycle as well as dilution. One study showed that the predominance of nitrate concentrations in shallow wells, coupled with large fluctuations of nitrate concentrations in such wells, suggest that nitrate concentrations may respond rather quickly to recharge events and dilution, depending upon the pathways of water movement and nitrate sources (Baker, 1990).

CHAPTER III

METHODOLOGY

Evaluation of Groundwater Pollution Potential

Nottawa Creek Watershed

AQUIPRO and DRASTIC methods were used to evaluate the groundwater pollution potential of Nottawa Creek Watershed. Three hundred and fifty computerized water well records were used for the AQUIPRO method. AQUIPRO produced a GIS compatible file, which was used to create an AQUIPRO vulnerability map using PC ARCINFO (ESRI, 1996) and ARCVIEW (ESRI, 1997) software. AQUIPRO creates vulnerability scores as point locations. These AQUIPRO scores were compared with DRASTIC indexes by overlaying the AQUIPRO map (points) with DRASTIC map (polygons).

For the DRASTIC method, seven different maps (Appendix C) were created, one for each factor as an individual layer using ARCINFO and ARCVIEW. DRASTIC ratings were assigned for the individual layers as polygon attributes. Because the DRASTIC rating system uses U.S. units, SI equivalents are not given.

Water levels do not vary greatly in the study area for both consolidated and unconsolidated aquifers (Appendix C). Depths of 5 to 15 ft were typical of areas near floodplains and within groundwater discharge areas near the streams. A small area in

Newton Township has a very shallow (0 to 5) ft depth to water. The ratings for the rest of Nottawa Creek Watershed are between 15 to 30 ft. These areas include the higher features such as moraines. The recharge factor was evaluated using many criteria including depth to water, topography, soil type, surface drainage, and annual precipitation. Values of 7 to 10 in/yr and more than 10 in/yr were assigned to the majority of the basin (Appendix C). The higher recharge values were used in areas of highly permeable soils overlying outwash and buried valley deposits. Values of 4 to 7 in/yr (3) and 2 to 4 in/yr were primarily used for high, steep ridges and muck deposits.

Information on aquifer media was primarily derived from water-well logs and report on the aquifers of Calhoun County (Moser & Passero, 1990). Bedrock was chosen as the aquifer for the majority of the study area except for the eastern and lower central part of the watershed. Glacial sand and gravel aquifers were delineated in the rest of the watershed (Appendix C). Aquifer ratings varied with the nature of the sand and gravel, including sorting, grain size, and sorting.

The soil media factor was primarily evaluated by using the Soil Survey of Calhoun County (Tardy et al., 1997). Information on all soil types was evaluated and the appropriate ratings were selected (Appendix C). Sandy loam and loam are the main types of soil in the study area.

Percent slope was estimated by using surface elevation contour map by using the AQUIPRO output file. SURFER (Golden Software, 1996) was used to create this contour map. Most slopes average 6 to 12% in the study area. Areas occupying stream valleys have 0 to 2% slopes. Slopes of 2 to 6% are also common.

The vadose zone factor was primarily determined using the water-well logs and glacial map of Calhoun County (Moser & Passero, 1997). The Soil Survey of Calhoun County (Tardy et al., 1997) was also utilized to differentiate till units. Till is the most common vadose zone media for the majority of the study area. The tills in Nottawa Creek Watershed are primarily composed of sand (66% or above), silt and clay (less than 20%) (Kozlowski, 1999). The rating was assigned (Appendix C) depending on the type of glacial deposits with a higher rating reflecting a coarser till texture. The thickness and nature of unconsolidated deposits varied considerably within the study area.

Hydraulic conductivity data were utilized from the DRASTIC manual. The typical ratings of sandstone aquifers and sand and gravel aquifers were used for bed-rock and drift aquifers respectively (Appendix C). Textbook tables (Freeze & Cherry, 1979) were useful in obtaining estimated values for a variety of sediments. For sand-stone aquifers, hydraulic conductivity values range from 300 to 700 gpd/ft2. Conduc-tivity values range from 1000 to 2000 gpd/ft2, were assigned for coarse-grained, well-sorted (clean) sand and gravel deposits associated with outwash and buried valley deposits.

A GIS was used to create the final DRASTIC and Pesticide DRASTIC pollu-tion potential maps (Plate I and II). The maps of the seven DRASTIC factors were overlaid to get the final map. The DRASTIC index (scores) for the individual poly-gons were calculated by using the data analysis capability of PC ARCINFO and the attributes were given as polygon attributes.

Kalamazoo County

The pesticide DRASTIC map of Kalamazoo County (Rheaume, 1990), MI was used in this study (Plate I). This map was digitized and polygon attributes were added using ARCVIEW and ARCINFO. A general DRASTIC map was also prepared by changing the necessary attributes of the pesticide DRASTIC map (Plate II). This approach was taken for computer analysis using GIS. Figure 15 showed the 2,653 computerized water well records utilized for Kalamazoo County. An AQUIPRO pollution potential map was also created to compare DRASTIC and AQUIPRO scores. The same data analyses approach was taken as was the techniques used to analyze Nottawa Creek Watershed data.

Statistical Analysis

Three statistical techniques were used to analyze the relationships between chloride, sodium and nitrate (chemical data) and various hydrogeologic factors. The computer program, MINITAB (Minitab, Inc., 1998) was used to do the calculations. Techniques used include correlation analysis, frequency distribution, data classification and linear regression analysis. Correlation analysis was also used to determine the relationship between DRASTIC and AQUIPRO scores.

Atrazine and nitrate data were not used to analyze the Nottawa Creek Watershed data because no atrazine was detected, and nitrate was detected in only five wells. In Kalamazoo County only nitrate data were used. In this statistical analysis the dependent variables were the individual chemical data and the independent

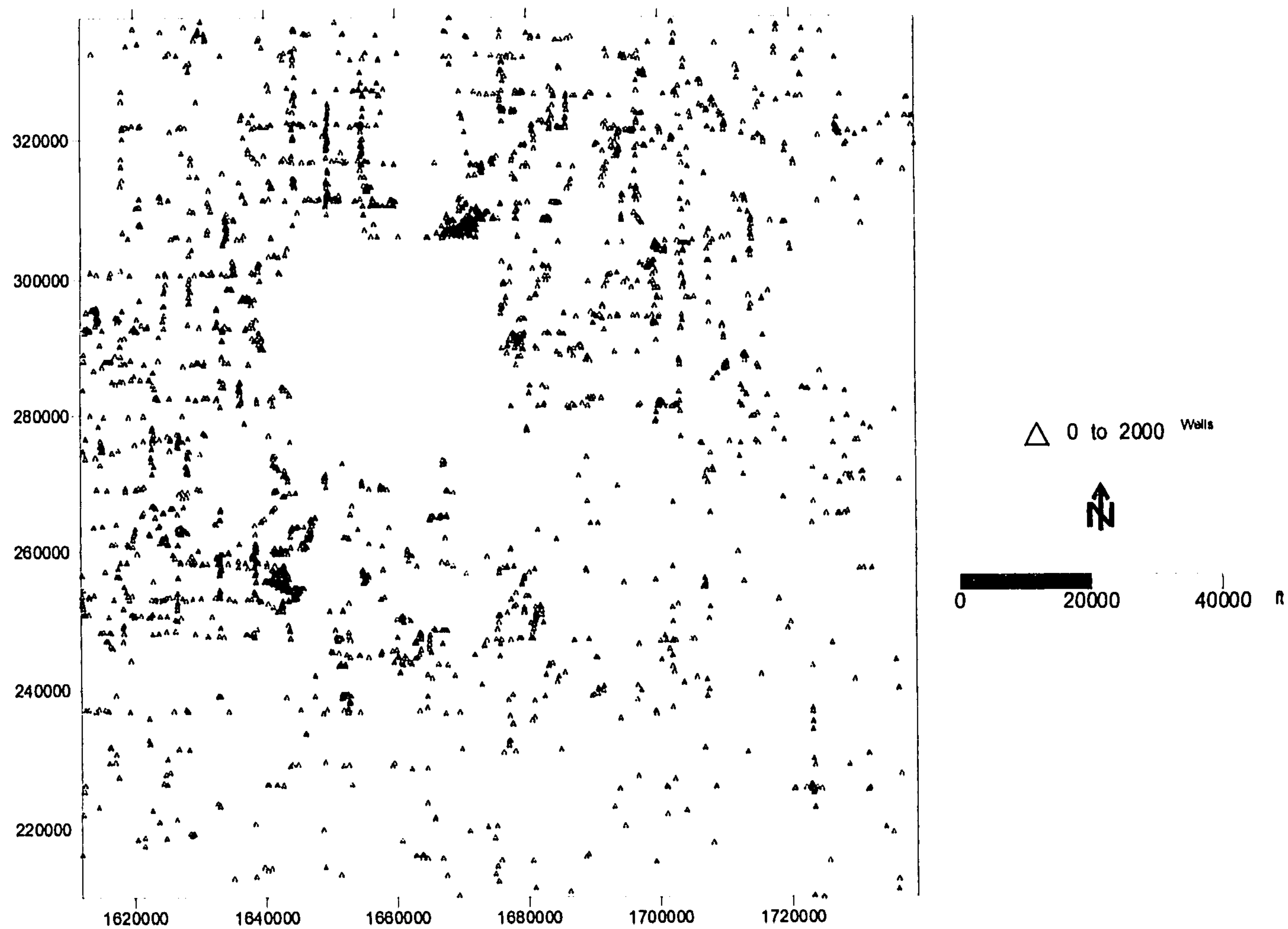


Figure 15. Map Showing Well Locations in Kalamazoo County.

variables are the DRASTIC and AQUIPRO factors.

Correlation coefficients were first used to determine any statistically significant relationship between the DRASTIC and AQUIPRO scores and the hydrogeologic factors and the concentrations of sodium and chloride. If a significant relationship between factors and concentration were found, statistically significant factors were identified by factor analysis.

The frequency distribution (Minitab Tables-Tally command) was used to determine the counts, percent frequency and cumulative percent frequency for ordinal data. Histograms were used to display some of these results.

A linear regression model ($Y = a + bX$), which gives the slope and intercepts was used in this study. A negative slope indicates an inverse relationship between the variables. A positive slope indicates a direct relationship. A significance level of $\alpha = 0.05$ was used throughout to establish statistical significance, which was the default value of the software used.

Data Transformation

The AQUIPRO and DRASTIC scores are numbers but these scores represent relative value. In other words these are ordinal data. For example, a 200 AQUIPRO or DRASTIC score may not indicate double the vulnerability or protection of a sore of 100. The arithmetic operations of addition, subtraction, multiplication, and division are not meaningful for ordinal data. In this study, the AQUIPRO and DRASTIC scores are categorized into four different groups (Table 12). The classifications are

Table 12

AQUIPRO and DRASTIC Vulnerability Category

Relative Vulnerability	AQUIPRO Score Ranges	DRASTIC Score Ranges	Verbal Description
1	=>201	=< 150	Low Vulnerability (High Protection)
2	101-200	151-175	Moderate Vulnerability (Moderate Protection)
3	1-100	176-200	High Vulnerability (Low Protection)
4	0	=> 201	Very High Vulnerability (Very Low Protection)

made considering the number and distribution of score ranges within each category. These four groups of score ranges yield four different types of aquifer protection (Table 12).

The laboratory detection limits of chloride, sodium and nitrate were 0.1 mg/L. Chemical concentrations of 0.1 mg/L and higher were used in the analysis. Wells with non-detect nitrate were not considered in this study because it could not be determined if non-detectable levels of nitrate were due to hydrogeologic factors or the absence of a source of nitrate. The minimum, maximum, mean, median, true mean and standard deviations of nitrate, sodium and chloride concentrations were determined for both Nottawa Creek Watershed and Kalamazoo County.

Nitrate with 0.1 mg/L or more were detected in 2,653 wells in Kalamazoo County. Nitrate concentrations were treated as ordinal data for certain types of

analyses, and were classified into six categories (Figure 16). The well database was also divided into four groups on the basis of nitrate concentration range. These sample groups consisted of wells with nitrate concentrations of 0.1 mg/L - 3.99 mg/L; 3.99 – 4.99 mg/L, 4.99-5.99 mg/L and greater than 5.99 mg/L. These four samples were used for comparison with the distributions and occurrences of nitrate and four different types AQUIPRO and DRASTIC score categories.

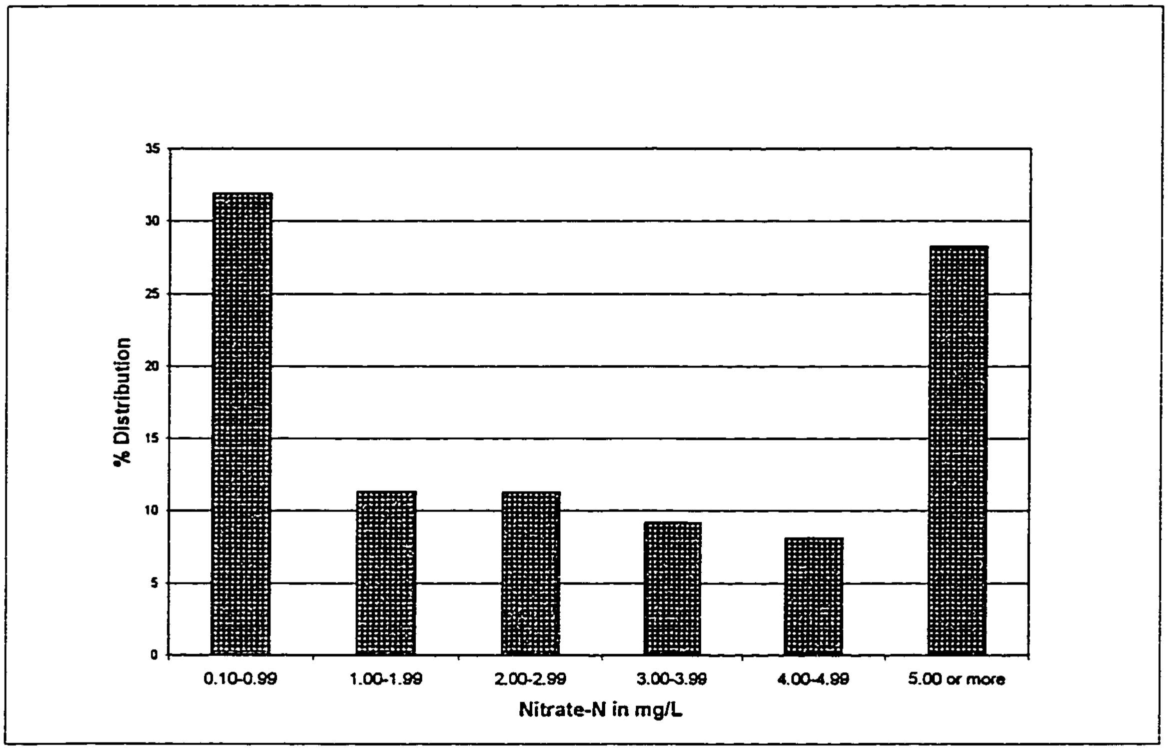


Figure 16. Histogram Showing the Distributions of Nitrate in Different Concentration Ranges in Kalamazoo County.

CHAPTER IV

ANALYSIS OF DATA

Nottawa Creek Watershed

Aquifer Vulnerability

Computerized data of 350 water well records were used to assess aquifer vulnerability using AQUIPRO. The vulnerability scores of the study area indicate that the aquifers in the Nottawa Creek watershed have low to moderate vulnerability. (Figure 17). The shallow wells in the glacial drift yielded low AQUIPRO scores. The aquifers in and around Athens Township are highly susceptible to contamination.

Both general and pesticide DRASTIC maps were prepared for Nottawa Creek Watershed (Plate I and II). The watershed lies within the glaciated central hydro-geologic region. The entire study area is covered by variable thicknesses of glacial till and outwash sands and gravels that have a moderate to high pollution potential index. A buried valley underlies Nottawa Creek in the southeastern part of the watershed (Kozlowski, 1999), which exhibits a moderate to high vulnerability to contamination. In the central and eastern part of the study area the glacial deposits are underlain by sandstone of the Marshall Formation and show relatively low to moderate pollution potential. The shale of the Coldwater Formation underlying the till in the eastern part also shows moderate to low pollution potential. Areas containing recent alluvium in

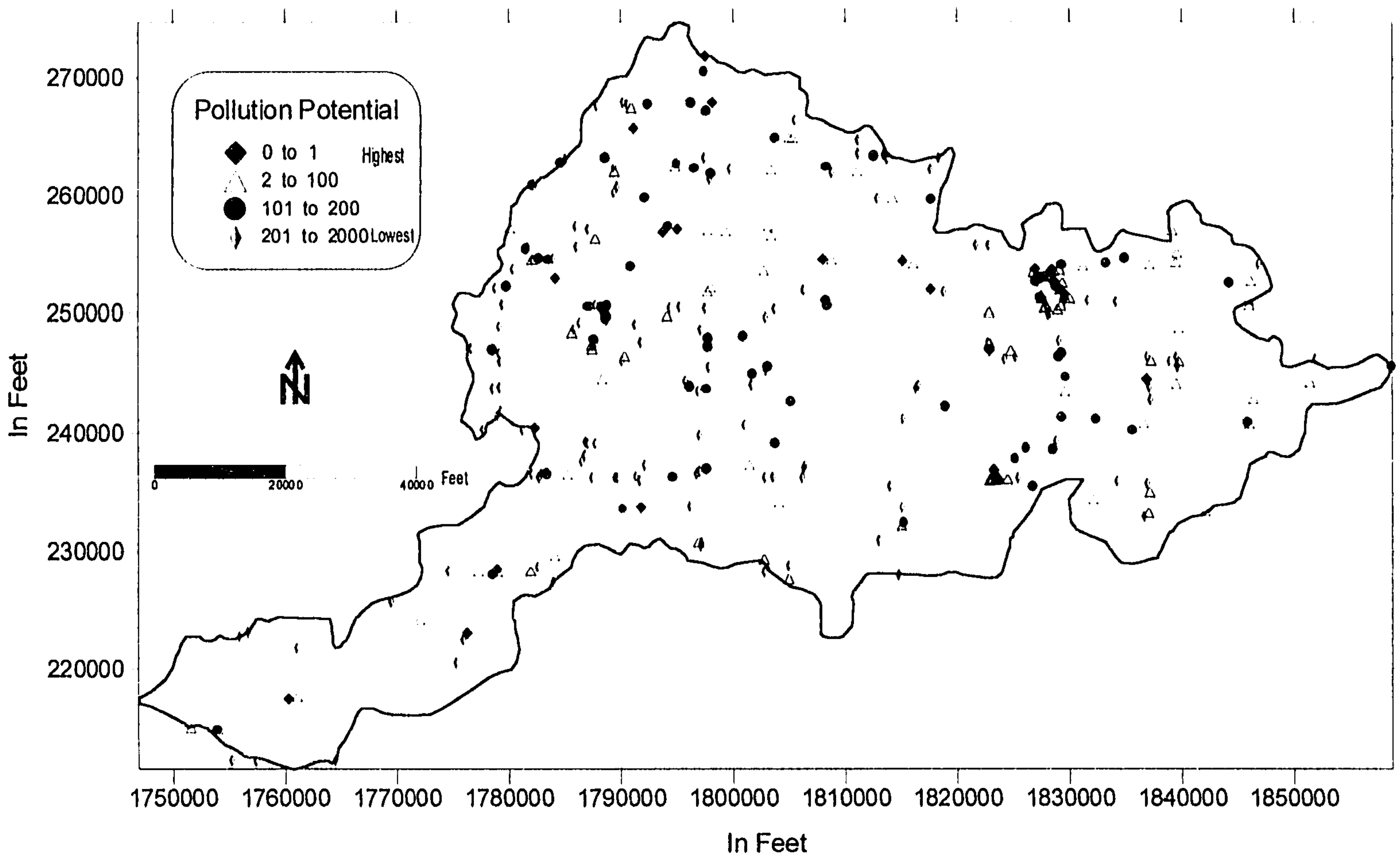


Figure 17. Groundwater Pollution Potential Map of Nottawa Creek Watershed (AQUIPRO).

valleys exhibit moderately high susceptibility to contamination. Pollution potential indexes for these areas range from very high to high.

Groundwater pollution potential maps of Nottawa Creek watershed have been prepared to assist planners, managers, and administrators in the task of evaluating the relative vulnerability of areas to groundwater contamination from various surface sources.

Comparison Between DRASTIC and AQUIPRO Scores

The individual DRASTIC scores of the wells were obtained using GIS. As expected, the DRASTIC and AQUIPRO scores showed a poor negative correlation with a Pearson's correlation coefficient of 0.25. Forty-three percent of the wells showed low AQUIPRO vulnerability and only 1% of the wells showed low DRASTIC vulnerability (Figure 18). Figures 19 and 20 also show the frequency and distribution of AQUIPRO and DRASTIC scores within each category. The DRASTIC and AQUIPRO scores within each vulnerability category are randomly distributed. One of the reasons for this could be the presence of two types of aquifer systems in the watershed. The AQUIPRO vulnerability scores indicated that a highly vulnerable well could be very close to a very highly protected well. The major advantage of the AQUIPRO method over DRASTIC is its ability to assess the subtle spatial variations in vulnerability of glacial and underlying bedrock aquifer systems.

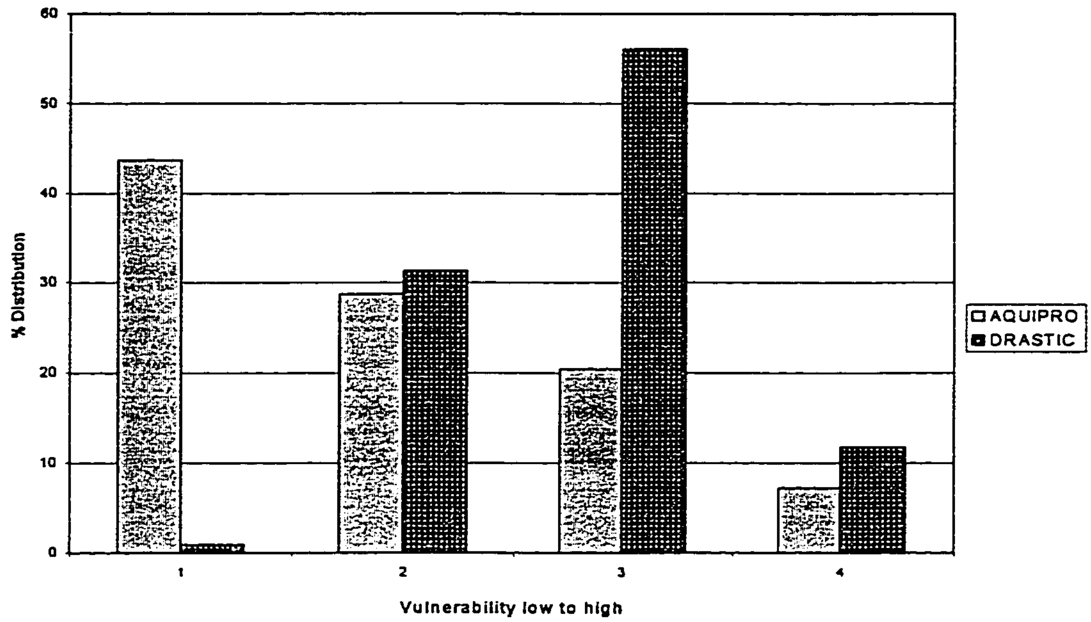


Figure 18. Distribution of DRASTIC and AQUIPRO Relative Vulnerability Scores in Nottawa Creek Watershed.

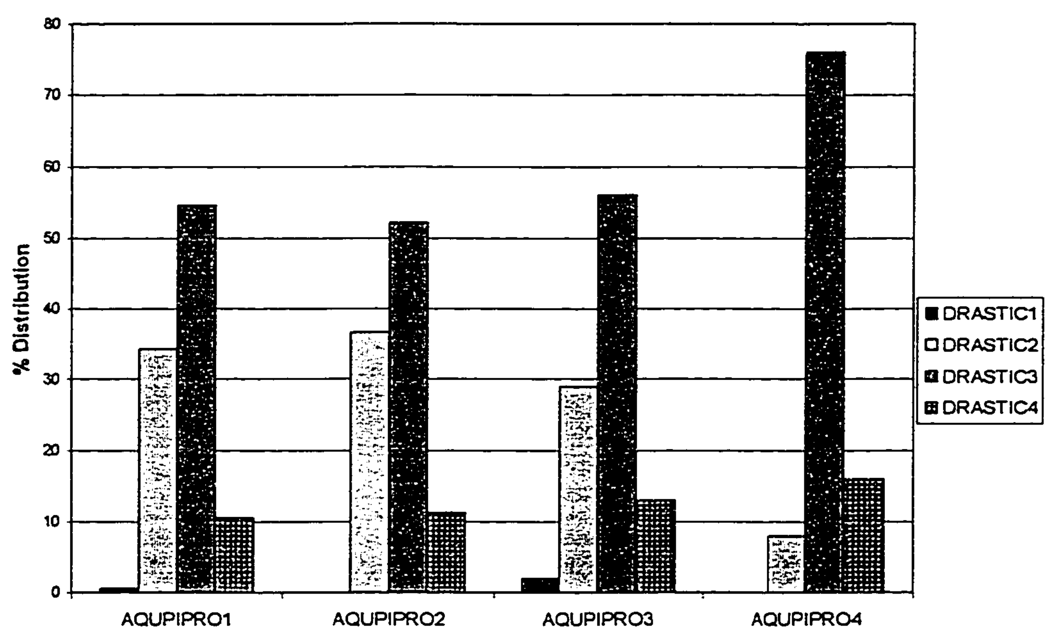


Figure 19. Distribution of DRASTIC Scores in Each Vulnerability Category of AQUIPRO Scores in Nottawa Creek Watershed.

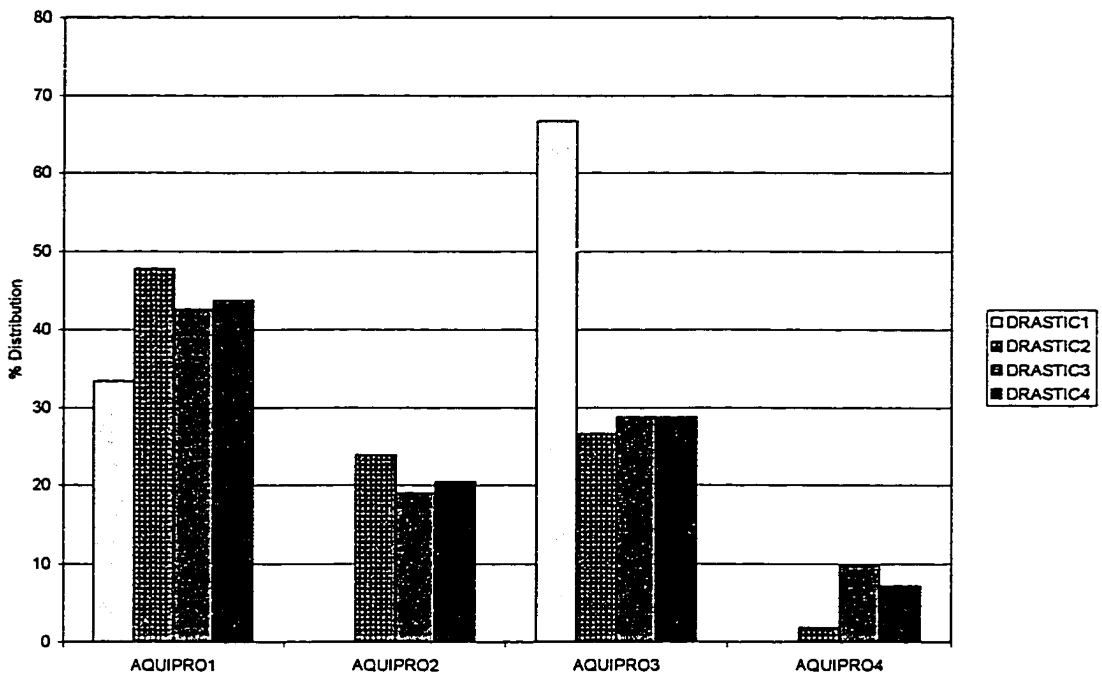


Figure 20. Distribution of AQUIPRO Scores in Each Vulnerability Category of DRASTIC Scores in Nottawa Creek Watershed.

<u>Validation of AQUIPRO and DRASTIC</u>

Nitrates were detected in only 5 groundwater samples collected out of 39. Due to lack of cooperation from the private well owners the potential groundwater samples which might contain nitrate could not be collected. Due to the uncertainty of sources of chloride, sodium and total dissolved solid detected in groundwater samples, those were not used for comparison with the AQUIPRO and DRASTIC scores. The five wells with detected nitrate fell in the high vulnerable category with respect to AQUIPRO and DRASTIC (Table 13). Among these five wells, four are located in glacial drift and one well is in bedrock. The highest level of nitrate (18 mg/L) was

Table 13

Nitrate Containing Wells in Nottawa Creek Watershed

Nitrate-N mg/L	Depth	Aquifer Type	AQUIPRO Score	DRASTIC Score	Well ID
18.0	21	Drift	90	191	419
4.2	43	Drift	112	176	326
3.4	30	Drift	35	147	258
1.55	80	Bedrock	97	143	293
0.10	54	Drift	17	185	424

detected in well 419, which is the shallowest drift well sampled in the whole watershed (Table 13).

Kalamazoo County

Aquifer Vulnerability

The vulnerability scores of the study area indicate that most aquifers in Kalamazoo County are poorly protected (Figure 21). A data set of 2,653 water well records was used to assess aquifer vulnerability using AQUIPRO. Low AQUIPRO scores are concentrated in areas with shallow glacial outwash aquifer systems (Figures 11 & 21). On the other hand, wells in aquifers in glacial moraines and till plains generated high AQUIPRO scores (Figures 11 & 21). Wells located in Texas and Portage Townships are highly susceptible to contamination. In Comstock, Richland

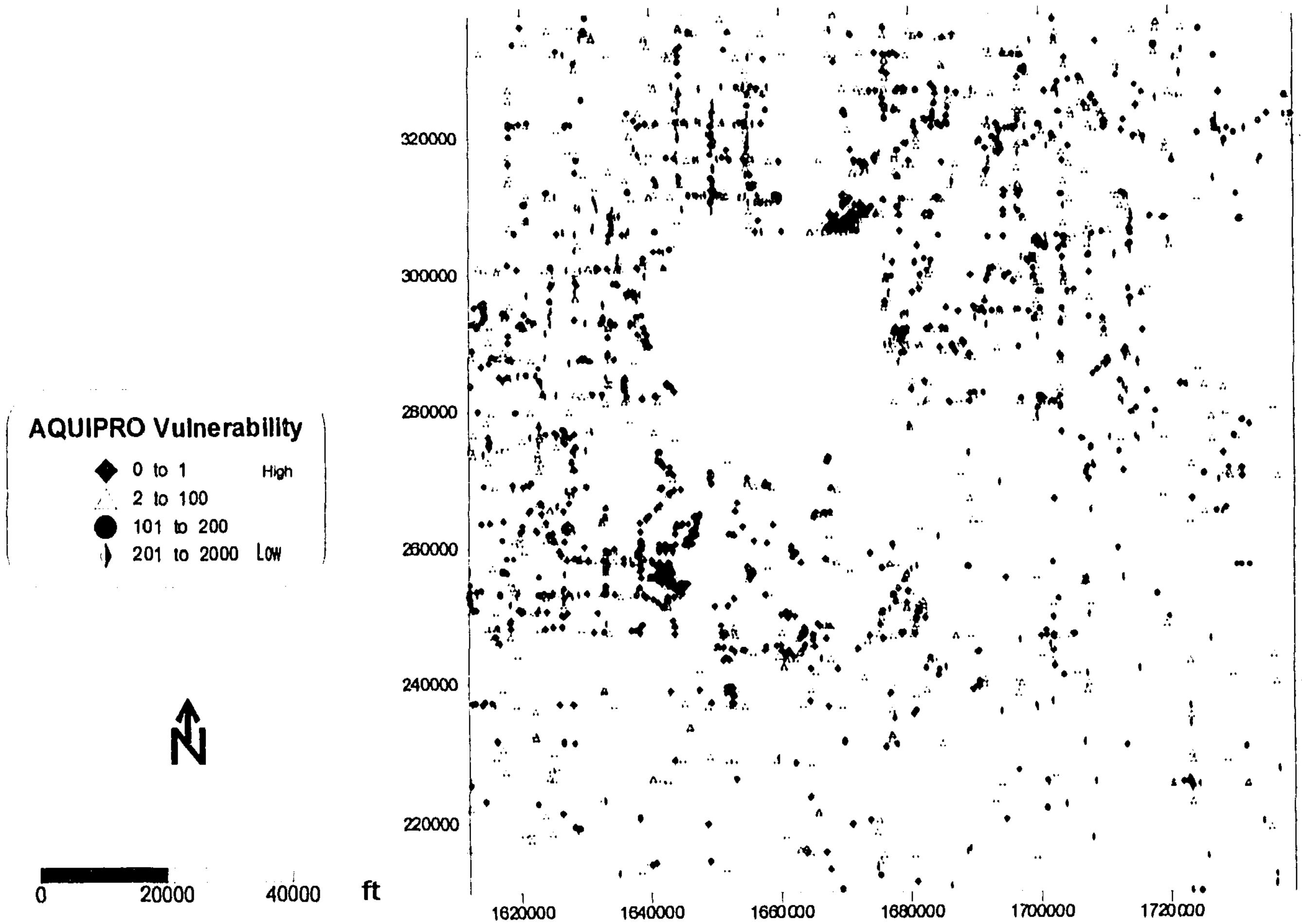


Figure 21. Groundwater Pollution Potential Map of Kalamazoo County (AQUIPRO).

and Cooper Townships, aquifer vulnerability ranges from moderate to high. The rest of the areas in Kalamazoo County show low to moderate AQUIPRO vulnerability.

A Pesticide DRASTIC map was prepared for Kalamazoo County by digitizing the map made by Rheaume (1990) (Plate III). A general DRASTIC map was also prepared by modifying the rating systems using GIS (Plate IV). Like Nottawa Creek Watershed, Kalamazoo County also lies within the glaciated central hydrogeologic region. The entire study area is covered by very thick glacial drift sediments that have a moderate to high pollution potential index. The highly vulnerable areas are located in and around river/stream valleys. The spatial distributions of DRASTIC vulnerability ranges are similar to AQUIPRO.

Comparison Between DRASTIC and AQUIPRO Scores

DRASTIC scores for the wells were obtained following the same procedure used in Nottawa Creek Watershed. In Kalamazoo County the DRASTIC and AQUIPRO scores showed a relatively better negative correlation than that of the Nottawa Creek Watershed. The Pearson's correlation coefficient was 0.32. Here the distribution of the wells in each category is somewhat uniform except in the high vulnerable category (Figure 22). In DRASTIC 10% wells fell into this category whereas in AQUIPRO 30% wells fell into this category (Figure 22). Figures 23 and 24 show the frequency and distribution of AQUIPRO and DRASTIC scores within each category. The DRASTIC and AQUIPRO scores within each vulnerability category are relatively less randomly distributed than Nottawa Creek Watershed. In this

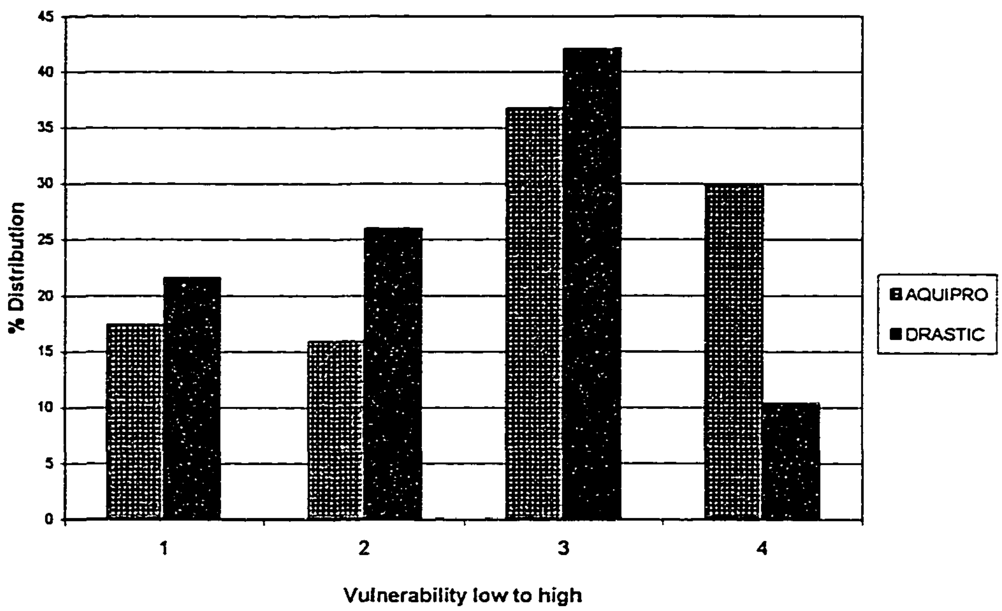


Figure 22. Distribution of DRASTIC and AQUIPRO Relative Vulnerability Scores in Kalamazoo County.

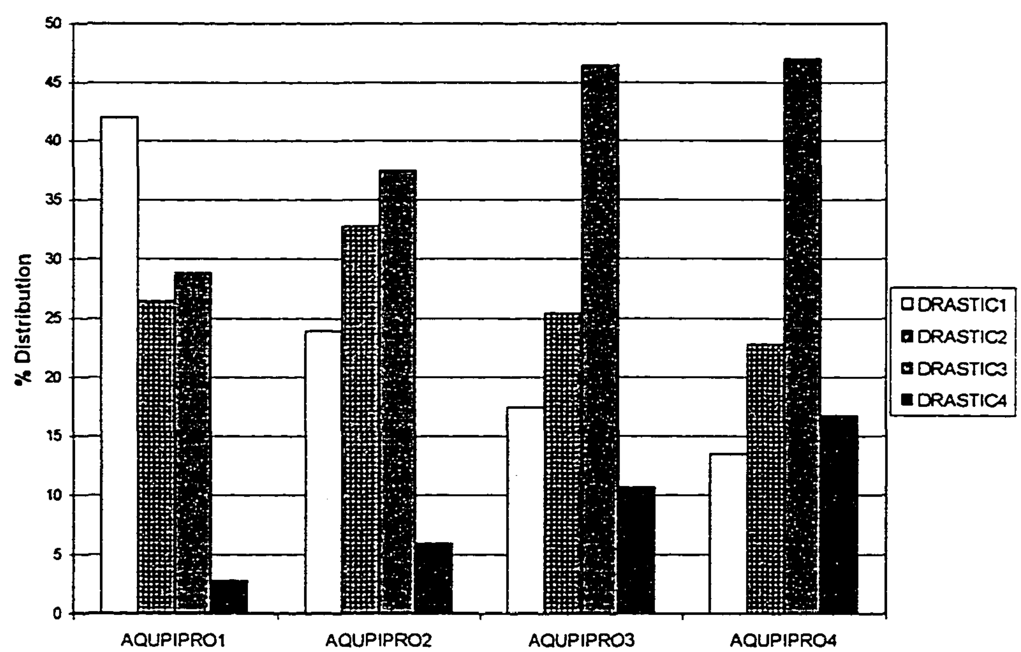


Figure 23. Distribution of DRASTIC Scores in Each Vulnerability Category of AQUIPRO Scores in Kalamazoo County.

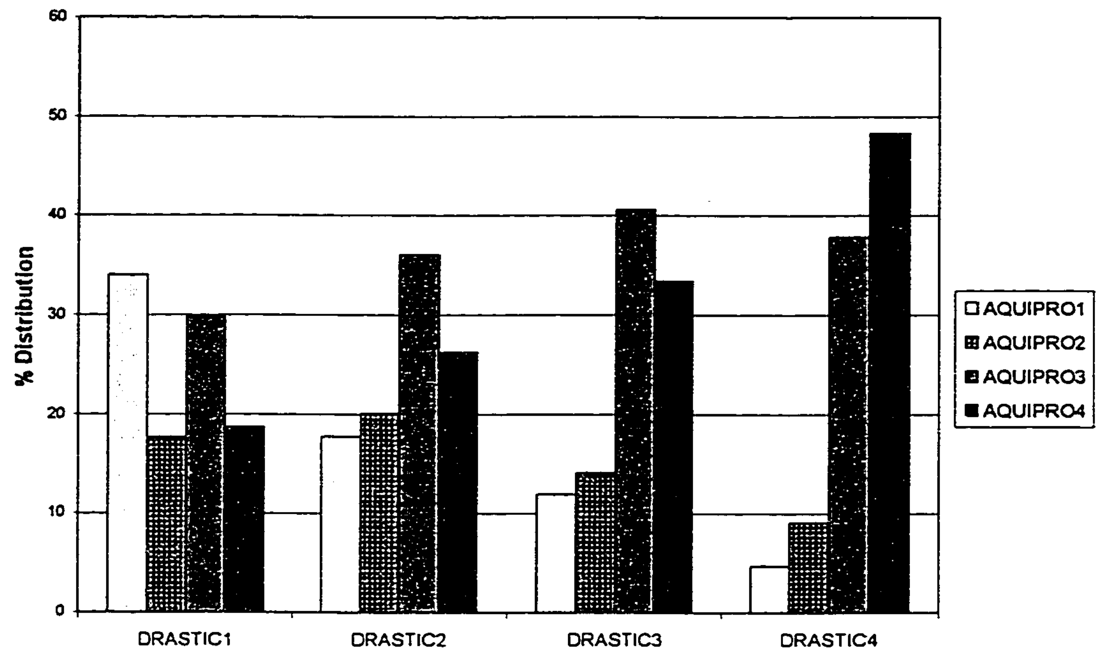


Figure 24. Distribution of AQUIPRO Scores in Each Vulnerability Category of DRASTIC Scores in Kalamazoo County.

case the reason could be the similar types of aquifer systems throughout the county.

Validation of AQUIPRO and DRASTIC

Two approaches were used to validate DRASTIC and AQUIPRO. The first approach was to determine the relationship between AQUIPRO and DRASTIC scores and the incidents of nitrate contamination. The second approach used was to compare the average nitrate concentration within each relative category of AQUIPRO and DRASTIC vulnerability. It may be mentioned here, that neither of these methods was designed to predict the concentration of contaminants in groundwater. But the hypothesis here is that in highly vulnerable areas higher concentration levels of

contaminants should occur given the same land use condition.

Correlation of Nitrate Impacted Wells and AQUIPRO and DRASTIC Scores

To determine if there is a correlation between numbers of nitrate impacted groundwater wells and the AQUIPRO and DRASTIC scores, the relative DRASTIC and AQUIPRO scores for impacted wells were determined from the DRASTIC and AQUIPRO maps of Kalamazoo County. A GIS was used to extract the scores from those maps for each well location. The assigned relative risk numbers for those scores range from 1 to 4, with 4 being the highest vulnerability to groundwater contamination. A well with a particular relative AQUIPRO and DRASTIC rating is represented by Vi where the subscript "i" represents a relative AQUIPRO and DRASTIC ratings (i = 1, 2, 3, 4).

The frequency of occurrences of impacted wells in a particular relative AQUIPRO and DRASTIC rating category Fi, is described by

$$F_i = \frac{(\text{Number of Impacted Wells})_i}{(\text{Number of Wells})_i}$$

In addition to hydrogeologic factors, the frequency of occurrences of groundwater contamination from nitrate is dependent upon land use and well construction. In this procedure, land use and well construction practices that could result in nitrate contamination are assumed to be similar throughout the study area. It is also assumed that the wells are screened in the glacial drift aquifers for which the relative AQUIPRO and DRASTIC ratings were evaluated. In Kalamazoo County, the

relatively shallow glacial drift deposits serve as the primary aquifers (Rheaume, 1990). The assumptions for the correlation analysis that the groundwater wells are uniformly screened in the glacial drift aquifers is valid throughout the county.

In an attempt to make sure that nitrates that were detected in groundwater wells are from surface sources, two different nitrate threshold concentrations were used. The concentration ranges of nitrate used here are wells with nitrate: (a) 0.1 – 3.99 mg/L and (b) greater than or equal to 5 mg/L.

Results of the Analysis. The frequency of occurrences of nitrate within each relative AQUIPRO and DRASTIC vulnerability category are summarized in Tables 14 through 17 for the two different types of nitrate concentration ranges. Figures 25 through 28 are the regression plot of frequency of occurrences of nitrate and relative vulnerability of AQUIPRO and DRASTIC for two different nitrate concentration thresholds.

The plots for 0.1-3.99 mg/L nitrate range indicate a negative correlation

Table 14

Frequencies of Nitrate (0.1 – 3.99 mg/L) Impacted Wells and the Relative AQUIPRO Vulnerability

V_i	Number of Impacted Wells	Total Number of Wells	F_I
1	293	462	0.63
2	252	422	0.60
3	577	975	0.59
4	439	794	0.55

Table 15

Frequencies of Nitrate (=> 5.0 mg/L) Impacted Wells
and the Relative AQUIPRO Vulnerability

V_i	Number of Impacted Wells	Total Number of Wells	F_I
1	140	462	0.30
2	132	422	0.31
3	324	975	0.33
4	278	794	0.35

Table 16

Frequencies of Nitrate (0.1 – 3.99 mg/L) Impacted Wells
and the Relative DRASTIC Vulnerability

V_i	Number of Impacted Wells	Total Number of Wells	F_I
1	387	572	0.68
2	445	689	0.65
3	570	1117	0.51
4	159	275	0.58

Table 17

Frequencies of Nitrate (=> 5.0 mg/L) Impacted Wells
and the Relative DRASTIC Vulnerability

V_i	Number of Impacted Wells	Total Number of Wells	F_I
1	147	572	0.26
2	183	689	0.27
3	453	1117	0.41
4	91	275	0.33

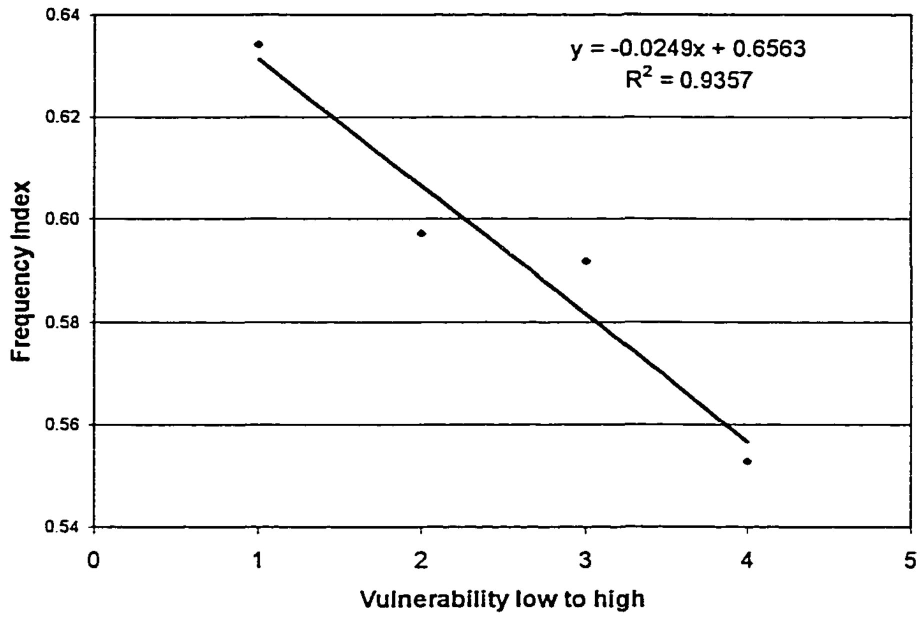


Figure 25. Correlation Between AQUIPRO Vulnerability and Frequency of Occurrences of Nitrate (0.1 – 3.99 mg/L) in Kalamazoo County.

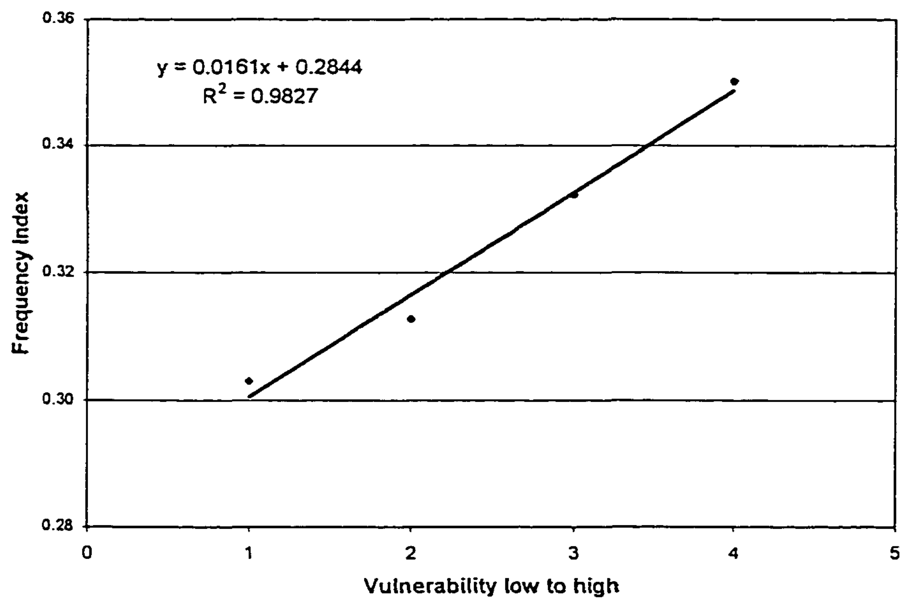


Figure 26. Correlation Between AQUIPRO Vulnerability and Frequency of Occurrences of Nitrate (=> 5.0 mg/L) in Kalamazoo County.

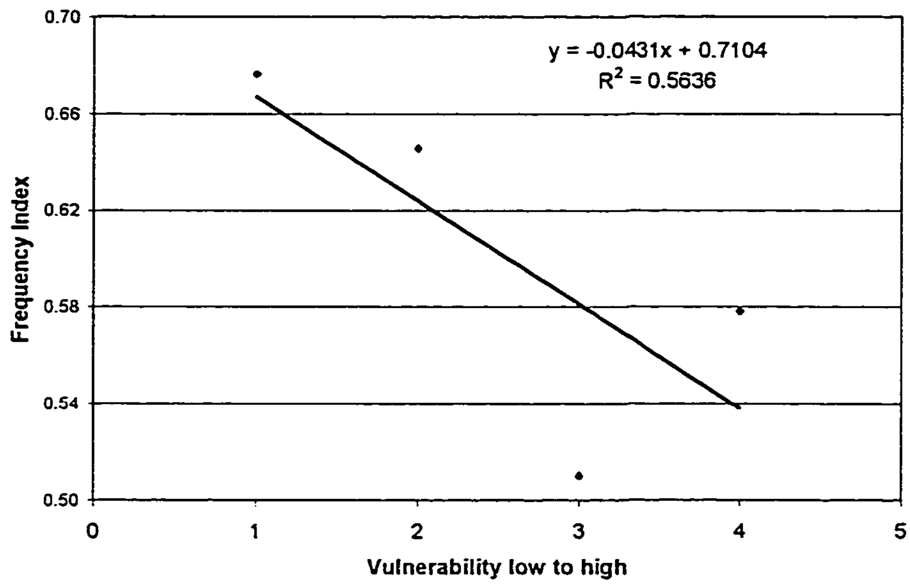


Figure 27. Correlation Between DRASTIC Vulnerability and Frequency of Occurrences of Nitrate (0.1 – 3.99 mg/L) in Kalamazoo County.

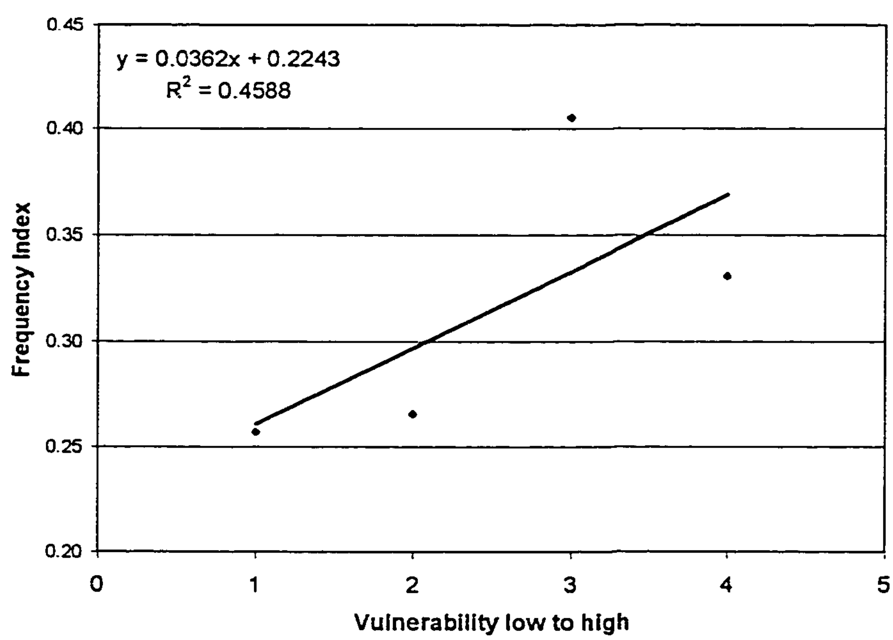


Figure 28. Correlation Between DRASTIC Vulnerability and Frequency of Occurrences of Nitrate (=> 5.0 mg/L) in Kalamazoo County.

between both AQUIPRO and DRASTIC vulnerability (Figures 25 & 27). This relationship indicates that the lower the vulnerability the higher the frequency of occurrences of nitrate in this concentration range. In other words, by these vulnerability methods, the occurrences of nitrate in groundwater could not be explained. This could be attributed to number of reasons such as sampling or analytical error, non-surface nitrate source or lateral migration of nitrate with the aquifer or geochemical environment not conducive to nitrate stability. A positive linear relationship was observed in nitrate concentration greater than or equal to 5 mg/L (Figure 26). In this case the obtained linear relationship between relative AQUIPRO vulnerability and frequency of the occurrences of nitrate is $V_i = 0.0161F_i + 0.2844$ with an $R^2 = 0.99$. Statistical hypothesis testing yields over a 95% confidence level for positive correlation between relative AQUIPRO vulnerability and the occurrences of nitrates in wells that contain more 5 mg/L nitrate. The y intercept of the regression relationship shown by Figure 26 is approximately 0.29 frequency of the occurrences of nitrate. This may represent the probability of contamination that is independent of the factors considered in AQUIPRO. From this observation it can be concluded that the vulnerability prediction by AQUIPRO is valid.

On the other hand the regression plot and the Pearson's correlation coefficient indicated a poor relationship between relative DRASIC vulnerability and the occurrences of nitrates. With a nitrate threshold of 5 mg/l, this relationship shows a positive correlation with an $R^2 = 0.46$ (Figure 28). The reason for this poor relationship is because in the very high DRASTIC vulnerability category the occurrences frequency

much less than in the high vulnerability category. This can be attributed to the fact that the very high DRASTIC vulnerability areas lie near streams and in flood plains. Wells in these areas contain less nitrate than they should because groundwater in these areas may interact with the stream water, which causes dilution. A high quantity of organic carbon commonly occurs in the unsaturated zone near stream valleys, which causes denitrification of nitrate moving downward from the unsaturated zone. For nitrate concentrations greater than or equal to 5 mg/L, the obtained linear relationship between relative DRASTIC vulnerability and occurrence frequency of nitrate is $V_i = 0.0431F_i + 0.2243$ with an $R^2 = 0.46$ (Figure 28). The y intercept of the regression relationship shown by Figure 28 has a value of approximately 0.22. This may represent the probability of contamination that is independent of the factors considered in DRASTIC. The above observation indicates that the vulnerability prediction by DRASTIC is also valid. Overall, AQUIPRO gives much better prediction than that of DRASTIC in this particular hydrogeologic setting (Figures 29 & 30).

Comparison Between Average Nitrate Concentrations and Relative AQUIPRO and DRASTIC Vulnerability

The average nitrate concentrations of groundwater wells within each relative vulnerability category of AQUIRO and DRASTIC were determined (Tables 18 & 19). A relationship between average nitrate concentrations and the relative DRASTIC and AQUIPRO vulnerability were established.

Results of the Analysis. Pearson's correlation coefficients between AQUIPRO

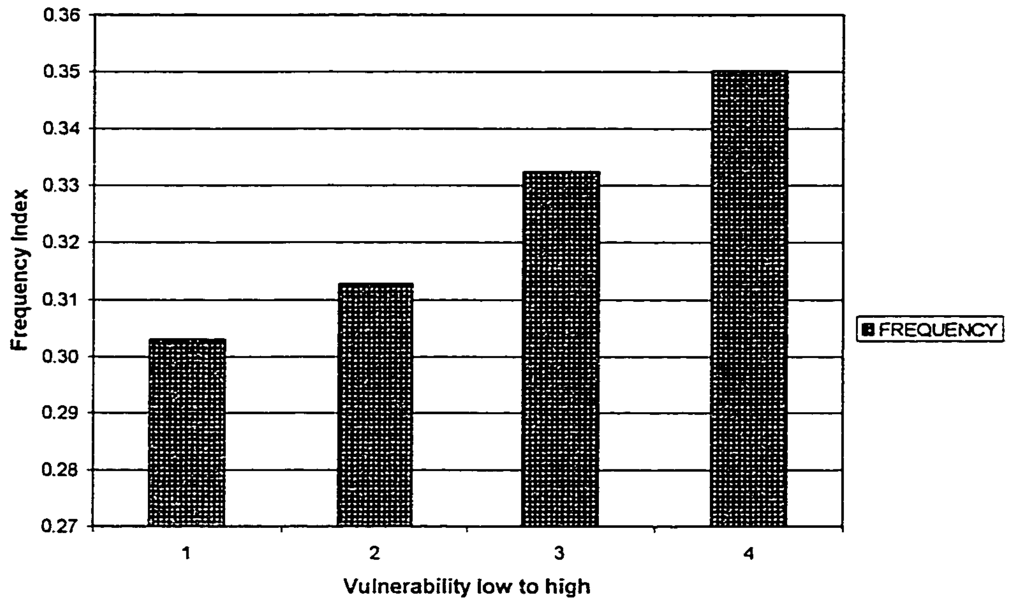


Figure 29. Histogram Showing AQUIPRO Vulnerability and Frequency of Occurrences of Nitrate (=> 5.0 mg/L) in Kalamazoo County.

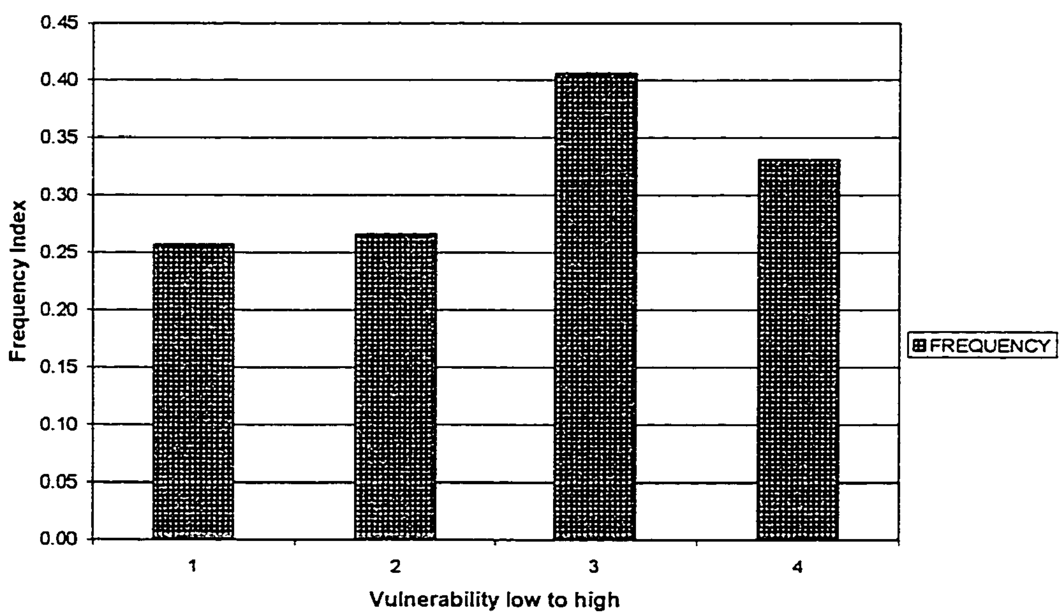


Figure 30. Histogram Showing DRASTIC Vulnerability and Frequency of Occurrences of Nitrate (=> 5.0 mg/L) in Kalamazoo County.

Table 18

AQUIPRO Vulnerability and Mean Nitrate Concentrations in Kalamazoo County

Vulnerability	Mean Nitrate Concentration (mg/L)	Total Number of Wells
1	3.91	462
2	4.09	422
3	4.22	975
4	4.34	794

Table 19

DRASTIC Vulnerability and Mean Nitrate Concentrations in Kalamazoo County

Vulnerability	Mean Nitrate Concentration (mg/L)	Total Number of Wells
1	3.60	572
2	3.77	689
3	4.79	1117
4	4.04	275

and mean nitrate concentration indicate a positive correlation (0.99, P-value = 0.0004). The distribution of mean nitrate and AQUIPRO relative vulnerability is illustrated in Figure 31. The regression plot of relative AQUIPRO vulnerability and the mean nitrate concentrations (Figure 32) shows a very strong positive linear relationship (R^2 = 0.99). The y intercept of the regression relationship shown by Figure 32 is approximately 3.8 mg/L mean concentration of nitrate. This may represent that the average nitrate concentration equal or less than 3.8 mg/L could not be interpreted by this vulnerability method.

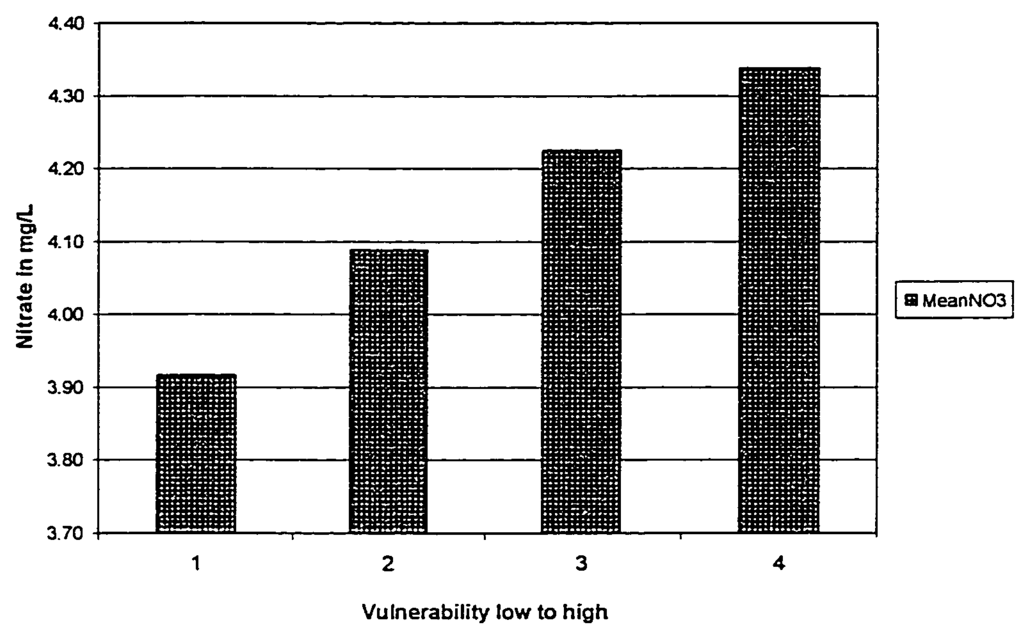


Figure 31. Histogram Showing AQUIPRO Vulnerability and Mean Nitrate Concentrations in Kalamazoo County.

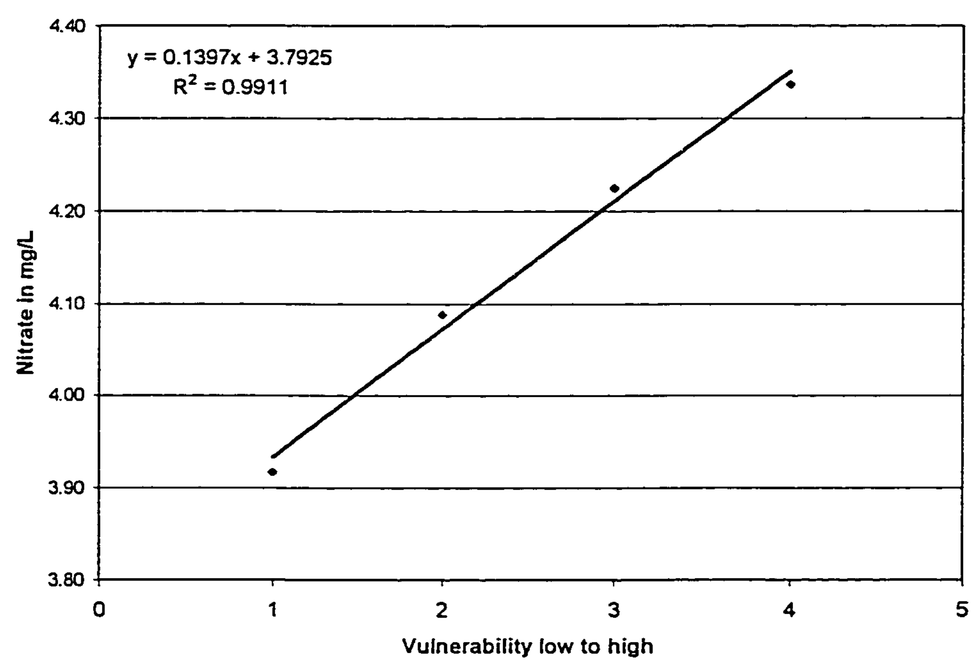


Figure 32. Correlation Between AQUIPRO Vulnerability and Mean Nitrate Concentrations in Kalamazoo County.

Unlike AQUIPRO, DRASTIC shows a poor correlation between relative DRASTIC vulnerability and mean nitrate concentration with a Pearson's correlation coefficient of 0.58 and P-value = 0.425. Figure 33 illustrates the distribution of mean nitrate and DRASTIC relative vulnerability. The regression plot of relative DRASTIC vulnerability and the mean nitrate concentrations (Figure 34) shows a weak positive linear relationship ($R^2 = 0.33$). The y intercept of the regression relationship shown by Figure 34 is approximately 3.5 mg/L mean concentration of nitrate. This may indicate that the average nitrate concentration equal or less than 3.5 mg/L could not be interpreted by this vulnerability method. It could be suggested from this study that a nitrate-N concentration of 5 mg/L or more in groundwater is indicative of contamination from surface sources. Once again, it is found to be true that the AQUIPRO vulnerability prediction is much better than that of DRASTIC in these particular hydrogeologic settings.

Significant Factors Identification

The seven hydrogeologic factors considered in AQUIPRO and DRASTIC showed no correlation with the nitrate concentration. However, previous studies indicated that the well depth and clay thickness factor had a negative linear relationship with nitrate concentration in some localized areas in Kalamazoo County (Benton, 1990). In the present study, the relationship between the frequency of occurrences of nitrate in groundwater wells and the relative vulnerability of AQUIPRO and DRASTIC clearly indicate that the unsaturated zone (clay thickness) and the depth to

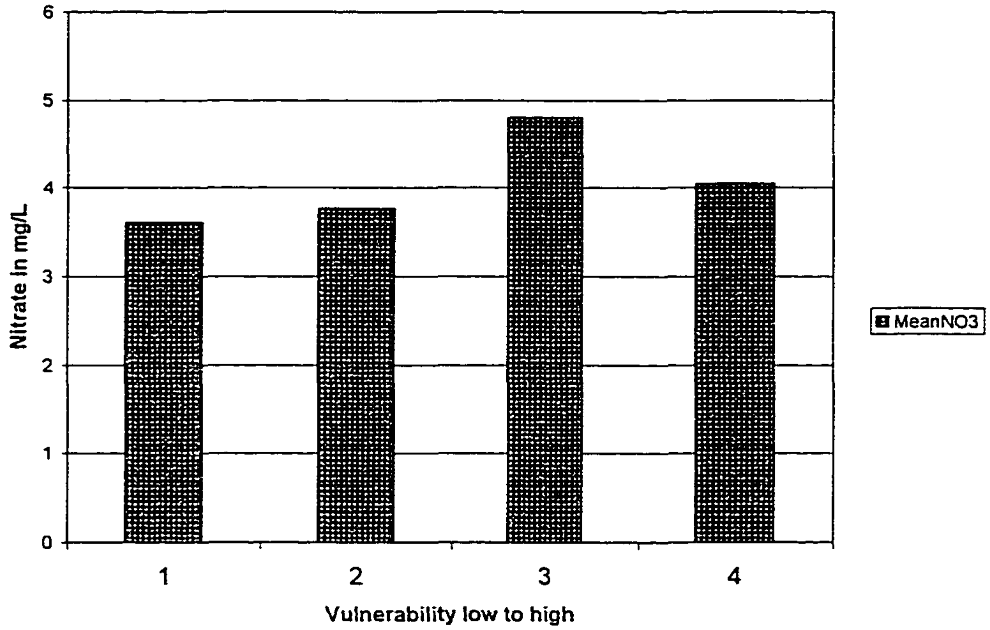


Figure 33. Histogram Showing DRASTIC Vulnerability and Mean Nitrate Concentrations in Kalamazoo County.

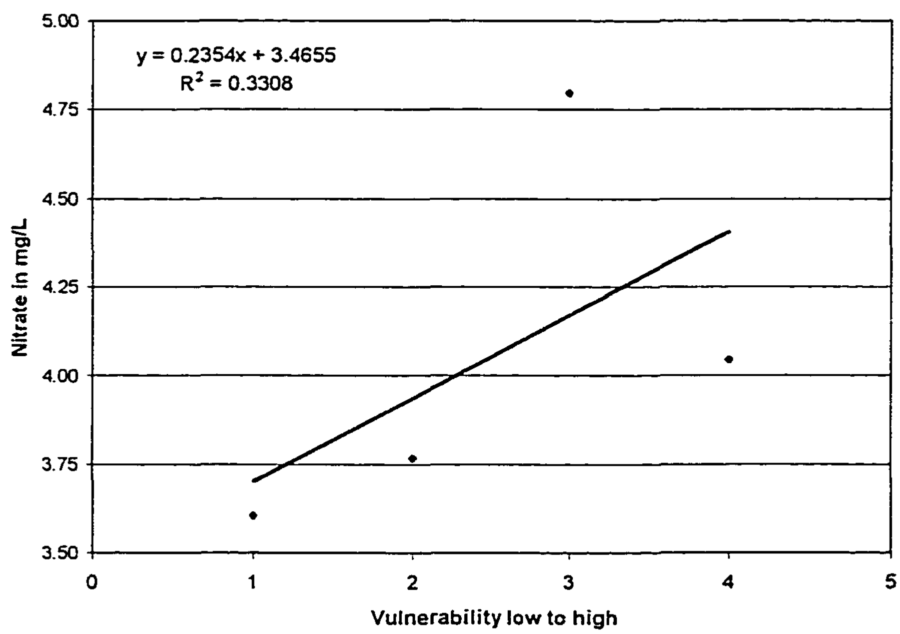


Figure 34. Correlation Between DRASTIC Vulnerability and Mean Nitrate Concentrations in Kalamazoo County.

water had a greater control over nitrate contamination in groundwater in Kalamazoo County. The reason only these two factors were evaluated was that AQUIPRO showed better results than DRASTIC and these two hydrogeologic factors are common in these two methods.

Discussions of AQUIPRO and DRASTIC

The initial objective of this study was to propose a new method utilizing the statistically significant hydrogeologic factors included in AQUIPRO and DRASTIC. The individual significant factors could not be identified statistically because correlation between nitrate concentration and the hydrogeologic factors could not be established. However, this study proved that the aquifer vulnerability prediction by AQUIPRO is much more valid than that of DRASTIC.

In AQUIPRO two of the seven DRASTIC factors are considered to evaluate aquifer vulnerability. They are depth to water (depth of well) and impact of the vadose zone. But the AQUIPRO model produces better result than DRASTIC model. The travel-time of an advective, nonreactive solute through a relatively thick vadose zone released at the ground surface can be approximated by

$$t_v = \frac{1}{q}\sum_{i=1}^{n} h_i \theta_i$$

Where q is the groundwater recharge rate, and h_i and θ_i are thicknesses and volumetric water contents, respectively, of the vadose zone layers (Haith & Laden, 1989; Wosten, Bannik, DeGruijter, & Bouma, 1986). Recharge rate and depth to water

table are factors considered in DRASTIC method that are included in the above equation. In AQUIPRO the vadose zone factor is considered in more detail than DRASTIC and produces better results even without considering the recharge rate. The results of this study suggest that the seven factors considered in DRASTIC are not necessary. More careful consideration of the vadose zone in a meaningful way including depth to the water table and recharge should produce better results. It is likely that vadose zone travel-time is one of the most important factors assessing vulnerability to groundwater contamination. As a result, AQUIPRO scores are proven to be an effective predictor of the occurrences of nitrate contamination.

The quality of these methods could be improved by integrating the critical factors considered in DRASTIC and AQUIPRO so that the evaluated groundwater pollution potential, qualitative or quantitative, with respect to specific factors of importance could be used. Sometimes, classification of DRASTIC or AQUIPRO scores in a meaningful way could be very difficult. By adding parameters in the AQUIPRO equation which could account for recharge rate, contaminant characteristics and land use a better method could be developed that would be more directly oriented toward the consequences of polluting activities. In this way this method would decrease the risk for misuse and enhance the applicability of the results.

CHAPTER V

CONCLUSIONS

The benefits of groundwater pollution potential methods to control and prevent groundwater contamination from non-point sources are becoming more apparent. One of the most commonly used methods for determining aquifer vulnerability to contamination is the U.S. EPA's DRASTIC. In glacial and underlying bedrock aquifer systems the applicability of DRASTIC is questionable because this method is unable to consider interfingering clay layers of glacial deposits. On the other hand, the AQUIPRO model offers a computerized method based on data from water well logs. Although these methods are widely applied, their efficiency and effectiveness of using these methods are not yet fully known. Very little attempt has been made to correlate the relative vulnerability scores with the occurrences of contaminants in actual field situations. The main objective of this study was to test the accuracy and validity of AQUIPRO and DRASTIC relative vulnerability scores by comparison to the measured distribution of contaminants within a test area.

Both AQUIPRO and DRASTIC methods were used to evaluate groundwater vulnerability to contamination from surface sources for Nottawa Creek Watershed, Calhoun County, Michigan and Kalamazoo County, Michigan. The relative AQUIPRO and DRASTIC vulnerability were compared with the occurrences and distribution of contaminants. A geographic information system (GIS) was used to

analyze and map the data. The distribution of AQUIPRO and DRASTIC scores were also compared for these two study areas.

Due to insufficient chemical data, the relative AQUIPRO and DRASTIC vulnerability scores could not be compared with the frequency of occurrences of groundwater contamination in Nottawa Creek Watershed. But the wells with detectable nitrate-N have indicated that the shallow glacial drift aquifers with low AQUIPRO scores and high DRASTIC scores are vulnerable to contamination from surface sources.

In Kalamazoo County, relative AQUIPRO and DRASTIC vulnerability scores were compared with the measured distribution of contaminants by using two different approaches. First, the occurrence frequency of nitrate-N in wells was compared with the relative AQUIPRO and DRASTIC vulnerability. Second, the average nitrate-N concentrations within each relative AQUIPRO and DRASTIC vulnerability category were also compared.

The distribution of AQUIPRO and DRASTIC scores are different in different hydrogeologic settings. The DRASTIC and AQUIPRO scores within each vulnerability category are relatively less randomly distributed in Kalamazoo County than in Nottawa Creek Watershed. This is due to the differing aquifer systems in each study area. The Nottawa Creek Watershed contains two systems (glacial drift and bedrock), whereas, Kalamazoo County is characterized by one aquifer system (glacial drift).

The AQUIPRO vulnerability scores of the Nottawa Creek Watershed indicate that the aquifers in the watershed have low to moderate vulnerability. The DRASTIC

maps of Nottawa Creek Watershed indicate a moderate to high pollution potential for this area. The shallow glacial drift aquifers are highly susceptible to surface contamination. The aquifers in and around Athens Township are highly susceptible to contamination. The bedrock aquifers are moderately to highly protected from surface contamination.

The AQUIPRO and DRASTIC vulnerability scores of Kalamazoo County indicate that the aquifers in the country are highly to very highly vulnerable. The shallow glacial outwash aquifer systems yielded very high relative vulnerability. On the other hand, wells in aquifers in glacial moraines and till plains yielded low relative vulnerability. Wells located in Texas and Portage Townships are highly susceptible to contamination. The DRASTIC map of Kalamazoo County indicated that the very highly vulnerable areas are located in and around river/stream valleys.

The occurrence frequency of nitrate within each relative AQUIPRO and DRASTIC vulnerability category for the 0.1-3.99 mg/L nitrate range could not be explained primarily because of the uncertainty of the sources of nitrate. But in the wells containing 5 mg/L or more nitrate-N, there is a positive correlation between the occurrence frequency of nitrate-N and relative increase of AQUIPRO ($r^2 = 0.98$) and DRASTIC ($r^2 = 0.46$) vulnerability. A very strong positive correlation ($r^2 = 0.99$) between the relative AQUIPRO vulnerability and mean nitrate concentration was observed. The correlation ($r^2 = 0.33$) between relative DRASTIC vulnerability and the mean nitrate-N concentration is weakly positive. This weak relationship can be attributed to the fact that the very high DRASTIC vulnerability areas lie within the

stream valley areas, which are also groundwater discharge areas. Relatively higher denitrification potential in stream valley areas causes the nitrate to occur in a lesser concentration. It can also be concluded from this study that a nitrate-N concentration of 5 mg/L or more in groundwater is indicative of surface source contamination. Both AQUIPRO and DRASTIC proved to be a valid method for this hydrogeologic setting. The vulnerability prediction by AQUIPRO was superior to DRASTIC.

The comparison between the relative vulnerability with the occurrence frequency of nitrate and mean nitrate concentrations in groundwater clearly indicated that the unsaturated zone and the depth to water had a greater control over nitrate contamination in groundwater from surface sources, because these two factors were common in both AQUIPRO and DRASTIC. AQUIPRO showed better results than DRASTIC in this analysis.

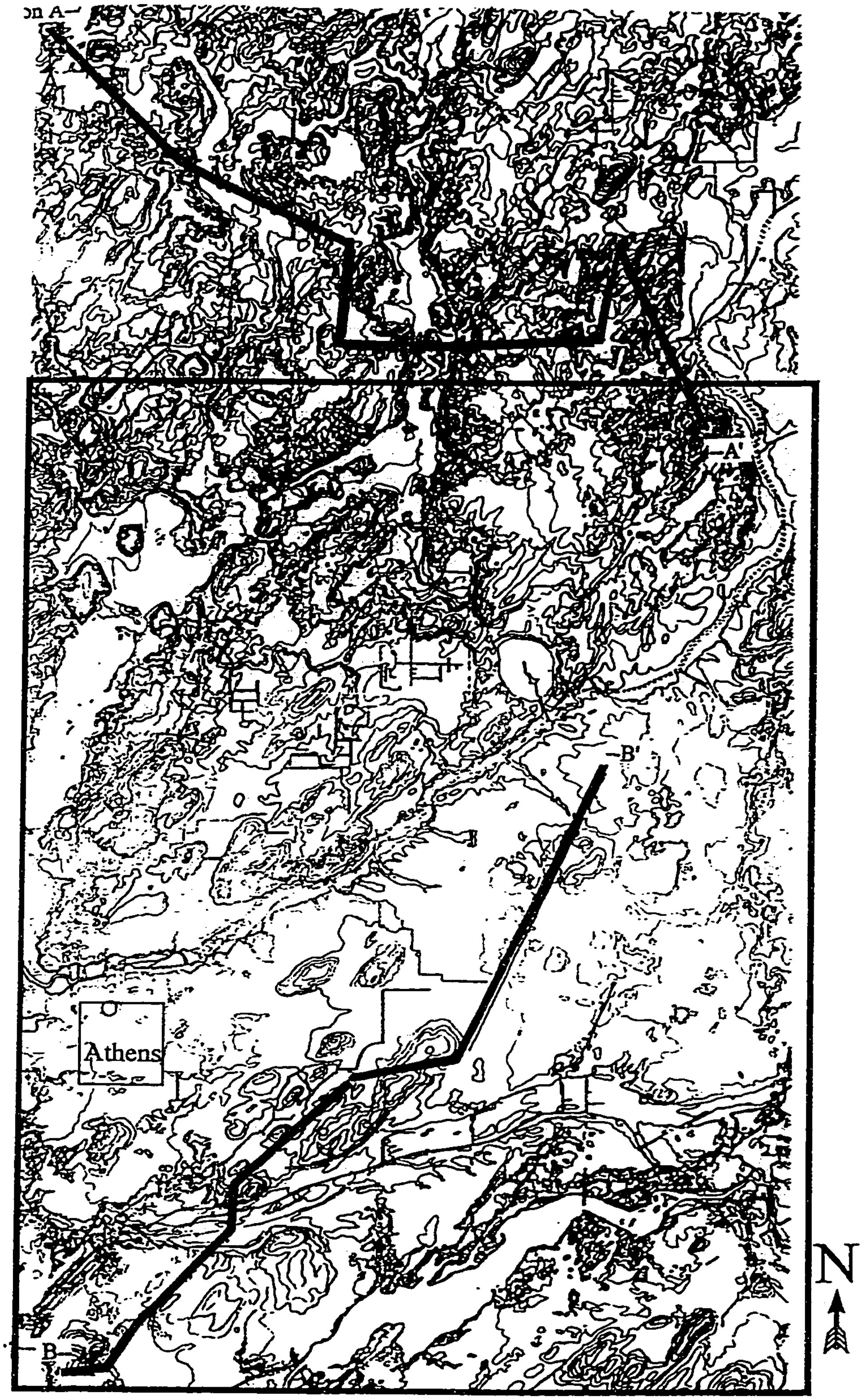
One of the objectives of this study was to propose a method combining the statistically significant hydrogeologic factors included in both AQUIPRO and DRASTIC. Although the individual significant factors could not be identified statistically because of lack of correlation between nitrate concentration and the hydrogeologic factors, the significant factors identified from this study are depth to water and the lithology of the unsaturated zone.

In AQUIPRO the vadose zone factor is considered in more detail than DRASTIC and produces better results even without considering the five other DRASTIC factors. According to this study it seems that the seven factors considered in DRASTIC are not necessary. It is likely that vadose zone travel-time is one of the

most important factors assessing vulnerability to groundwater contamination. As a result, AQUIPRO scores are proven to be an effective predictor of the occurrences of nitrate contamination. But the quality of these methods could be improved by developing relative vulnerability classification systems for different hydrogeologic settings. The AQUIPRO equation should be revised by adding parameters in the AQUIPRO equation which could account for recharge rate, contaminant characteristics (e.g. sorption, dilution etc.) and by doing so, a better method could be developed that would be more directly oriented toward the consequences of polluting activities. This method would decrease the risk of misuse and enhance the applicability to more site-specific conditions.

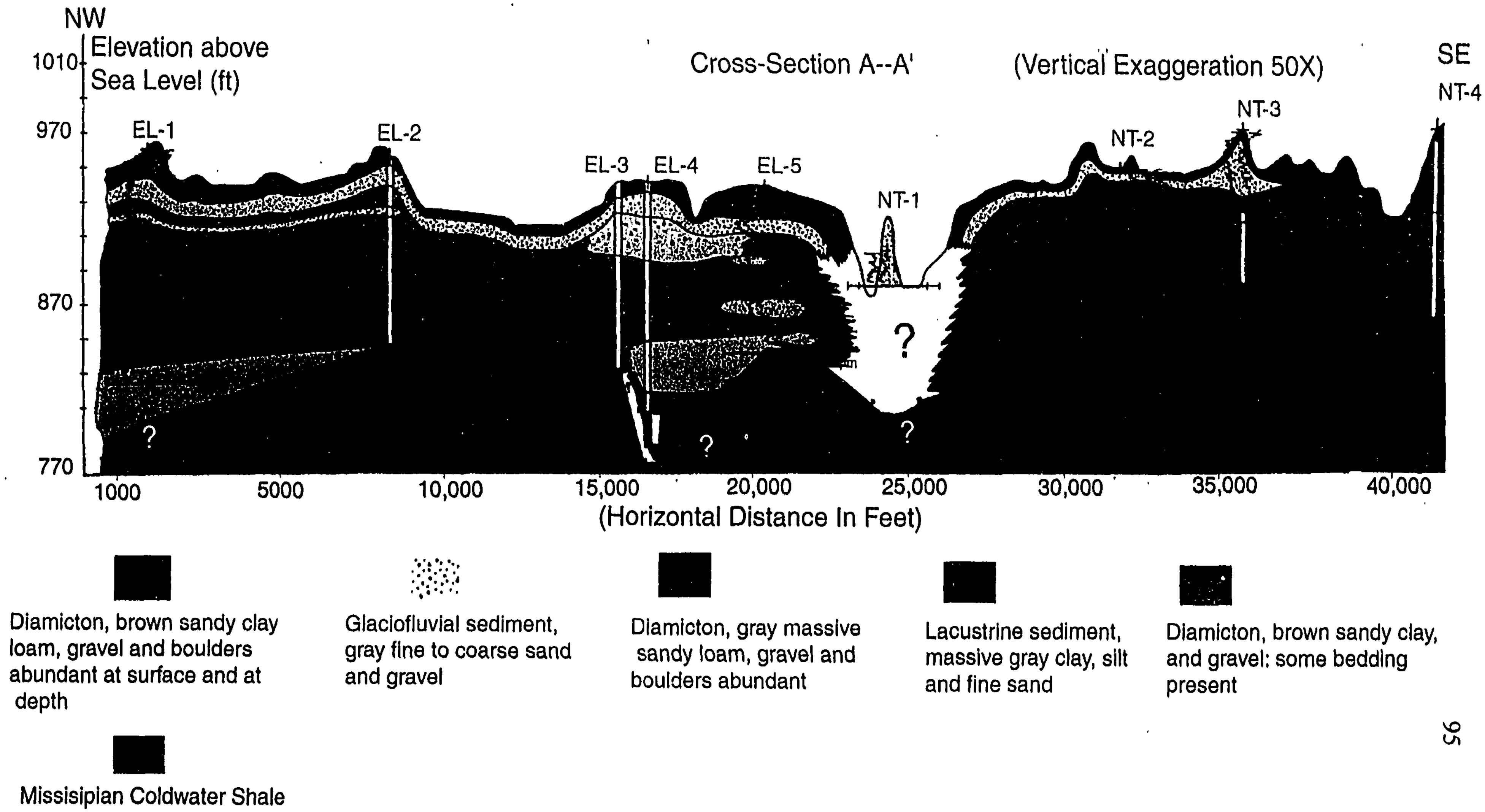
Appendix A

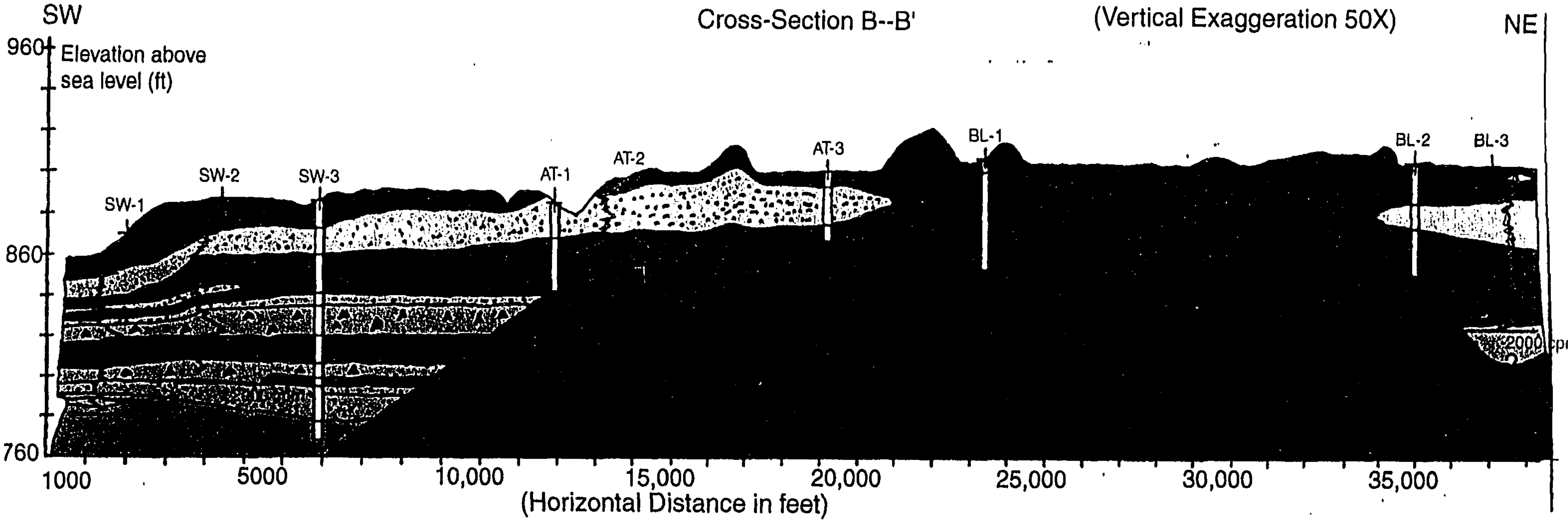
Generalized Glacial Stratigraphy of Nottawa Creek
Watershed (Source: Kozlowski, 1999)



Scale 1:92160

Topography of Study Area and Location of Cross Section Lines A--A' and B--B'. Note contour Interval 5 Feet.


NW
Elevation above Sea Level (ft)
Cross-Section A--A'
(Vertical Exaggeration 50X)
SE
1010
970
870
770
EL-1
EL-2
EL-3
EL-4
EL-5
NT-1
NT-2
NT-3
NT-4
?
1000
5000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
(Horizontal Distance In Feet)
Diamicton, brown sandy clay loam, gravel and boulders abundant at surface and at depth
Glaciofluvial sediment, gray fine to coarse sand and gravel
Diamicton, gray massive sandy loam, gravel and boulders abundant
Lacustrine sediment, massive gray clay, silt and fine sand
Diamicton, brown sandy clay, and gravel: some bedding present
Missisipian Coldwater Shale



Diamicton,brown sandy clay loam, gravel and boulders abundant at surface and at depth

Glaciofluvial sediment, gray fine to coarse sand and gravel, bedding present

Diamicton, gray massive sandy loam, gravel and boulders abundant

Diamicton,brown sandy clay, with gravel: some bedding present

Glaciofluvial sediment, red fine to coarse sand and gravel; oxidized and bedded

Lacustrine sediment, gray clay,silt

Glaciofluvial sediment,dark gray indurated, fine sand and gravel

Mississipian Coldwater Shale

Appendix B

Sample of Well Records Used in This Study

WELLID	CNTY	TWP	QQQS	QQS	QS	SEC	TIER	N_S	RANGE	E_W
13740701001	13	1305	SE	SE	SE	1	04	S	07	W
13740701002	13	1305	NW	NW	SW	1	04	S	07	W
13740701003	13	1305	NW	SE	SE	1	04	S	07	W
13740701004	13	1305				1	04	S	07	W
13740702001	13	1305	SW	SE	SE	2	04	S	07	W
13740702002	13	1305	SE	SE	NE	2	04	S	07	W
13740702003	13	1305	SW	SE	SE	2	04	S	07	W
13740703001	13	1305	SW	SW	NW	3	04	S	07	W
13740703002	13	1305	SE	SE	SE	3	04	S	07	W
13740703003	13	1305				3	04	S	07	W
13740703004	13	1305	SW	SW	NE	3	04	S	07	W
13740704001	13	1305	NW	NE	NW	4	04	S	07	W
13740704002	13	1305	SE	SE	SE	4	04	S	07	W
13740704003	13	1305	NE	NE	SE	4	04	S	07	W
13740704004	13	1305	SE	SE	SW	4	04	S	07	W
13740704005	13	1305				4	04	S	07	W
13740704006	13	1305	SE	SE	SW	4	04	S	07	W
13740704007	13	1305	SW	SE	SW	4	04	S	07	W
13740704008	13	1305	SW	SW	SW	4	04	S	07	W
13740704009	13	1305	SE	NE	SE	4	04	S	07	W
13740705001	13	1305	NW	SE	NW	5	04	S	07	W
13740705002	13	1305	NE	SE	NE	5	04	S	07	W
13740707002	13	1305	SE	SE	NE	7	04	S	07	W
13740709001	13	1305	NE	NE	NW	9	4	S	07	W
13740710001	13	1305	NW	NE	NW	10	04	S	07	W
13740710002	13	1305	NW	NW	NW	10	04	S	07	W
13740710003	13	1305	NW	NW	SE	10	04	S	07	W
13740710004	13	1305	NE	NE	NW	10	04	S	07	W
13740710005	13	1305	NW	NW	NE	10	04	S	07	W
13740711001	13	1305	NE	NE	NW	11	04	S	07	W
13740711002	13	1305	SE	SW	NE	11	04	S	07	W
13740711003	13	1305	NW	NE	NW	11	04	S	07	W
13740713001	13	1305	NE	NE	SE	13	04	S	07	W
13740713002	13	1305	NE	NE	NE	13	04	S	07	W
13740714001	13	1305				14	04	S	07	W
13740714002	13	1305	NE	NE	NE	14	04	S	07	W
13740714003	13	1305	NE	NE	NE	14	04	S	07	W
13740716001	13	1305	SE	NE	SW	16	04	S	07	W

X_COORD	Y_COORD	COORD_S	COORD_M	VERIFIED	DATA_SO	ELEV
1802773	236270	S	G	F	U	950.89
1797630	236934.8	S	G	F	U	957.41
1801451	237277.9	S	G	F	U	947.47
1800934	240738.8	S	G	F	U	955.77
1796921	236767.3	S	G	F	U	950
1796914	239860.5	S	G	F	U	940.19
1796659	236553.8	S	G	F	U	948.13
1787676	239165.2	S	G	F	U	960.14
1791269	236386.8	S	G	F	U	955.15
1792065	237318.3	S	G	F	U	961.94
1787000	239176	S	G	F	U	932.02
1782295	240468.5	S	G	F	U	924.9
1786801	239279.9	S	G	F	U	934.65
1786730	238145.3	S	G	F	U	943.31
1785236	236501.8	S	G	F	U	904.27
1783917	236423.7	S	G	F	U	1039.11
1783355	236504.6	S	G	F	U	922.83
1782862	236571.8	S	G	F	U	946.13
1781986	236578.8	S	G	F	U	938.94
1786428	237612.7	S	G	F	U	942.06
1777640	240308.6	S	G	F	U	939.57
1781191	240284.2	S	G	F	U	963.78
1776021	233794.2	S	G	F	U	928.08
1782640	236261.5	S	G	F	U	942.62
1787368	236267.8	S	G	F	U	940.62
1791776	233711.2	S	G	F	U	962.47
1790162	233550.1	S	G	F	U	947.83
1789439	236254.5	S	G	F	U	974.9
1789608	236255.4	S	G	F	U	971.82
1794580	236234.4	S	G	F	U	955.18
1796068	233859.3	S	G	F	U	962.5
1791630	236012.9	S	G	F	U	957.71
1802705	228330.8	S	G	F	U	974.18
1802709	229357.3	S	G	F	U	961.58
1797121	230728.7	S	G	F	U	970.7
1797053	230520.4	S	G	F	U	965.06
1796895	230776.9	S	G	F	U	965.42
1783913	227443.2	S	G	F	U	924.11

ELEV_MTD	WELL_ADD	WELL_CITY	OWNER_NAME
G	11995 N DRIVE SOUTH		RUSS JOHNSON
G	5140 11 MILE ROAD		MARTIN MARKO
G	11777 N DRIVE SOUTH		DPU;E CP,BS
G	6000 11 1/2 MILE RD		RONALD BENOIT
G	5121 11 MILE RD		GEORGE ABBOTT
G	5701 11 MILE RD		DON LUTES
G	10855 N DRIVE S.		RICHARD ADAMS
G	9103 M DRIVE SOUTH		KEVIN MORRIS
G	9899 N DRIVE SOUTH	BURLINGTON	CHARLES SALYER
G	10135 N DRIVE SOUTH	BURLINGTON	BARRY L. GOODWIN
G	9001 M DRIVE SOUTH		JAMES WOGOMON
G	8149 M DRIVE SOUTH	BURLINGTON	
G	8977 M DRIVE SOUTH		ART BLACK
G	5401 9 MILE ROAD		RANDY MYERS
G	8783 N DR. SOUTH	BURLINGTON	FRED BARRIOS
G	8435 N DRIVE SOUTH	BURLINGTON	MARY CHAFFEE
G	8373 N DR. SO.		STEVE ROCHO ?
G	8251 N DR. SO.	BURLINGTON	(CAN'T READ)
G	8105 N DRIVE SO.		CHARLES CRANE (?)
G	5243 9 MILE RD		ALVIN SMITH
G	7300 M DRIVE SOUTH		STEVE HU??
G	7980 M DRIVE SOUTH	BURLINGTON	ADAMS
G	4501 7 MILE RD	UNION CITY	JOHN CONVERSE
G	RD. 8240 N DR. SO.	BURLINGTON	KEN EYRE
G	9250 N DR. SOUTH		RICK CAMERON
G	9977 O DRIVE S.	BURLINGTON	ROSS BRANDT
G	9698 0 DRIVE SOUTH	BURLINGTON	LYNN CLARK
G	4987 9 1/2 MILE ROAD		ALAN FRYE
G	4990 9 1/2 MILE RD		WILMA BRANDT
G	10450 N DR. S.	BURLINGTON	NORMAN EYRE
G	4561 11 MILE RD	BURLINGTON	IRVING CRAW
G	10751 N DRIVE S.		JAN CRONKHITE
G	3511 12 MILE RD	BURLINGTON	LLOYD COATS
G	3725 12 MILE ROAD		VERN PRAY
G	3970 11 MILE RD		ROBERT HILL
G	3962 11 MILE RD	BURLINGTON	MIKE LAMPKE
G	3954 11 MILE RD		OLIN RODENBAUGH
G	3311 8 1/2 MILE RD		REX KREIG

OWNER_ADD1	OWNER_CITY	OWNER_STAT	DEPTH
11995 N DRIVE SOUTH			100
5140 11 MILE ROAD			57
11777 N DRIVE SOUTH			98
6166 S 44TH STREET	CLIMAX	MI	120
1145 HARMON(?) LOT 8	BATTLE CREEK	MI	90
817 KIRBY RD	BATTLE CREEK	MI	100
10855 N DRIVE S.			80
9103 M DRIVE SOUTH			147
9899 N DRIVE SOUTH	BURLINGTON		60
10135 N DRIVE SOUTH	BURLINGTON	MI	70
9001 M DRIVE SOUTH			79
8149 M DRIVE SOUTH	BURLINGTON		28
8977 M DRIVE SOUTH			122
100 ILLINOIS	BATTLE CREKK	MI	119
8783 N DR. SOUTH	BURLINGTON	MI	32
8435 N DRIVE SOUTH	BURLINGTON	MI	35
8373 N DR. SO.			71
BOX 113 - ROUTE 1	BURLINGTON	MI	71
8105 N DRIVE SO.			160
401 DIVISION	UNION CITY	MI	125
7300 M DRIVE SOUTH			90
7980 M DRIVE SOUTH	BURLINGTON		148
4501 7 MILE RD	UNION CITY	MI	43
RD. 8240 N DR. SO.	BURLINGTON	MI	140
9250 N DR. SOUTH		MI	121
9977 O DRIVE S.	BURLINGTON	MI	43
9698 0 DRIVE SOUTH	BURLINGTON	MI	90
4987 9 1/2 MILE ROAD			93
9977 O DR. SOUTH	BURLINGTON	MI	118
10450 N DR. S.	BURLINGTON	MI	44
4561 11 MILE RD	BURLINGTON	MI	102
10751 N DRIVE S.			130
3511 12 MILE RD	BURLINGTON	MI	115
3725 12 MILE ROAD			40
3970 11 MILE RD			142
3962 11 MILE RD	BURLINGTON	MI	62
3954 11 MILE RD			65
3311 8 1/2 MILE RD			59

MONTH	DAY	YEAR	NEW_WEI	RIG	USE	DRY_HOL	C_TYPE
11	03	72	U	C	DOM	N	U
10	16	87	R	C	DOM	N	S
09	28	84	U	R	DOM	N	P
10	24	89	N	R	DOM	N	P
08	28	90	N	R	DOM	N	P
05	30	95	N	R	DOM	N	P
06	16	76	U	C	DOM	N	U
05	31	85	U	R	DOM	U	P
09	20	91	N	R	DOM	N	P
09	04	94	N	C	DOM	N	S
08	30	85	U	C	DOM	N	S
03	17	70	U	D	DOM	U	U
11	14	80	U	R	DOM	U	P
12	21	90	N	U	DOM	N	P
11	17	83	U	C	DOM	N	U
07	27	94	R	R	DOM	N	P
11	10	95	R	R	DOM	N	P
04	21	77	U	C	U	N	U
10	02	96	R	R	DOM	N	P
12	23	93	N	R	DOM	N	P
01	28	95	R	R	DOM	U	P
12	02	94	R	R	DOM	N	P
08	28	80	U	R	DOM	N	P
03	26	76	U	C	DOM	N	U
09	13	77	U	C	DOM	N	U
05	21	79	U	R	DOM	N	U
07	16	78	U	H	DOM	N	U
01	18	86	U	C	DOM	N	S
10	17	89	N	R	DOM	N	P
11	09	95	R	C	DOM	N	S
09	16	93	R	R	DOM	N	P
10	16	90	N	R	DOM	N	P
06	27	90	U	R	DOM	N	P
10	23	91	R	R	DOM	N	P
12	12	95	N	C	DOM	N	S
09	14	78	U	R	DOM	N	U
01	14	88	N	C	DOM	N	S
08	13	81	U	R	DOM	N	P

C_JOIN	C_DIAM1	C_DEPTH1	C_DIAM2	C_DEPTH2	H_DIAM1	H_DEPTH
T	4	72	0	0	0	0
U	4	51	0	0	0	0
U	5	98	0	0	8	98
U	5	91	0	0	8	91
U	5	58	0	0	8	58
U	5	47	0	0	0	0
T	4	54	0	0	0	0
U	5	85	0	0	0	0
U	5	50	0	0	8	50
T	4	56	0	0	0	0
T	4	62	0	0	0	0
T	1.25	28	0	0	0	0
T	5	50	0	0	0	0
U	5	60	0	0	8	60
U	4	27	0	0	0	0
U	5	20	0	0	8	30
W	5	55	0	0	8	55
W	4	65	0	0	0	0
W	5	58	0	0	8	58
U	5	57	0	0	8	57
U	5	45	0	0	0	45
U	5	122	0	0	8	122
U	5	38	0	0	0	0
T	4	70	0	0	0	0
T	4	48	0	0	0	0
T	4	38	0	0	0	0
T	2	90	0	0	0	0
U	4	80	0	0	0	0
U	5	87	0	0	8	87
T	4	38	0	0	0	0
W	5	69	0	0	8	69
U	5	70	0	0	8	70
W	5	70	0	0	8	70
W	5	36	0	0	8	36
T	4	111	0	0	0	0
T	4	57	0	0	0	0
T	4	60	0	0	0	0
U	5	54	0	0	5	54

H_DIAM2	H_DEPTH:	C_HGTH	D_SHOE	S_TYPE	S_DIAM	SLOT_GA	S_OPENIN
0	0	0	Y	N	0		0
0	0	1	Y	N	0		0
0	0	1	Y	N	0		0
0	0	1	N	N	0		0
0	0	1	Y	N	0		0
0	0	0	U	N	0		0
0	0	1	Y	N	0		0
0	0	0	N	N	0		0
0	0	1	N	N	0		0
0	0	1	Y	N	0		0
0	0	1	Y	N	0		0
0	0	0	U	O	1.25		0
0	0	1	Y	N	0		0
0	0	0	Y	N	0		0
0	0	1	Y	S	4	S	0.012
0	0	1	N	S	4		15
0	0	1	N	S	4	S	0.015
0	0	1	Y	S	3		25
0	0	1	U	N	0		0
0	0	0	U	N	0		0
0	0	1	N	N	0		0
5	148	0	N	N	0		0
0	0	0	N	S	4	S	0.015
0	0	1	Y	N	0		0
0	0	1	Y	R	0		0
0	0	1	N	S	4	S	0.015
0	0	0	Y	N	0		0
0	0	1	Y	N	0		0
0	0	1	Y	N	0		0
0	0	1	Y	S	4		18
0	0	1	Y	N	0		0
0	0	1	Y	N	0		0
0	0	1	N	N	0		0
0	0	1	N	S	4	S	0.015
0	0	2	Y	N	0		0
0	0	1	N	S	4	S	0.01
0	0	1	Y	S	4	S	0.03
0	0	1	N	S	4	S	0.012

S_LENGTI	S_DEPTH	S_DEPTH	FITTINGS	S_ABOVE	SWL	FLOW
0	0	0		0	20	N
0	0	0		0	21	N
0	0	0		0	17	N
0	0	0		0	20	N
0	0	0		0	22	N
0	0	0		0	16	N
0	0	0		0	11	N
0	0	0		0	23	N
0	0	0		0	15	N
0	0	0		0	16	N
0	0	0		0	9	N
3	0	0		0	16	U
0	0	0		0	20	U
0	0	0		0	18	N
5	27	32	P	0	14	N
5	30	35	P	0	16	N
10	61	71	P	0	29	N
6	65	71	P	0	40	N
0	0	0		0	34	N
0	0	0		0	17	N
0	0	0		0	25	N
0	0	0		0	48	N
4	38	43	U	0	9	N
0	0	0		0	37	N
0	0	0		0	18	N
4	38	43	O	0	10	N
0	0	0		0	10	N
0	0	0		0	29	N
0	0	0		0	46	N
5	38	43	P	1.5	22	N
0	0	0		0	28	N
0	0	0		0	42	N
0	0	0		0	18	N
4	36	40	O	0	9	N
0	0	0		0	28	N
4	57	62	O	0	20	N
5	60	65	P	1	25	N
4	54	59	P	0	27	N

PUMP_LEV1	PUMP_HR	PUMP_RA	PUMP_LE'	PUMP_HR	PUMP_RA	WELL_HE
0	0	0	0	0	0	U
25	2	15	0	0	0	A
20	1	30	0	0	0	G
40	1	30	0	0	0	G
30	1	25	0	0	0	G
0	0	0	0	0	0	A
11	1	25	0	0	0	A
0	0	0	0	0	0	A
15	1	40	0	0	0	A
28	1	20	0	0	0	A
42	1	12	0	0	0	A
0	0	0	0	0	0	U
60	1	4	0	0	0	G
0	0	0	0	0	0	A
0	0	0	0	0	0	A
0	0	0	0	0	0	A
50	1	25	0	0	0	A
40	0	0	0	0	0	A
160	1	5	0	0	0	A
0	0	0	0	0	0	A
45	1	6	0	0	0	G
0	0	0	0	0	0	A
0	0	0	0	0	0	G
80	8	10	0	0	0	A
15	1	10	0	0	0	A
10	1	30	0	0	0	G
0	0	0	0	0	0	A
31	2	10	0	0	0	A
80	1	20	0	0	0	G
0	1.5	15	0	0	0	A
42	0	30	0	0	0	A
50	1	10	0	0	0	G
0	0	0	0	0	0	A
0	0	0	0	0	0	A
28	1	4	0	0	0	A
20	1	25	0	0	0	G
25	1	35	0	0	0	A
27	1	20	0	0	0	G

GROUT_T	G_DEPTH	G_DEPTH	CNTM_TY	CNTM_DIS	CNTM_DIF	DISINFEC	PLUGGED
N	0	0	U	0		Y	U
B	0	0	SP	50	NE	Y	Y
B	0	98	SP	100	S	Y	U
B	0	91	SP	50	E	Y	U
B	0	58	SP	55	NE	Y	U
B	0	0	SP	50	N	U	U
N	0	0	SP	60	W	Y	U
B	0	84	U	0		Y	U
B	0	50	SP	160	E	Y	Y
U	0	54	SP	100	N	U	U
B	0	62	SP	100	SE	Y	U
U	0	0	OT	100	N	Y	U
B	0	50	SP	60	S	Y	U
B	5	60	U	0		Y	U
U	0	0	SP	75	W	Y	U
B	4	30	SP	50	ENE	U	Y
B	0	55	SP	50	NE	U	Y
N	0	0	SP	100	S	Y	U
B	0	58	SP	50	W	U	Y
B	5	57	U	0		Y	U
B	0	45	SP	50	S	U	U
B	5	122	U	0		U	U
B	0	38	SP	70	W	Y	U
U	0	0	SP	80	E	Y	U
U	0	0	SP	60	S	Y	U
B	0	38	U	0		Y	U
N	0	0	SP	65	E	Y	U
N	0	0	SP	75	W	Y	Y
B	0	87	SP	50	S	Y	U
B	0	38	SP	60	SE	U	N
B	0	69	SP	50	SW	Y	Y
Y	0	70	SP	50	SW	Y	U
B	0	88	SP	50	SW	Y	U
B	0	38	OT	70	W	Y	Y
B	0	111	SP	50	E	U	U
B	0	57	SP	75	N	Y	U
B	0	60	SP	50	E	Y	U
B	0	54	U	0		Y	U

PUMP_IN	PUMP_TY	PUMP_MAKER	PUMP_HP	PUMP_PIF	PUMP_GF	DRILLER_
N				0	0	0386
D	S	GRUND FOS	.5	40	10	1039
D	S	MCDONALD	.5	40	12	0393
D	S	FLINT & WALLING	.5	40	10	0393
D	S	MCDONALD	.5	40	10	0393
D	S	GENERAL 2000	.5	46	16	1972
D	S	MCDONALD	.5	30	12	0393
D	S	STANDARD PUMP (	.5	76	9	0386
D	S	GOULDE	.5	40	10	0285
D	S	RED JACKET	.5	45	10	0285
D	S	GRUNDFOS	.5	62	15	0769
O	O	DEMMING	0.33	23	0	
N				0	0	0393
D	S	FLINT & WALLING	.5	50	10	0386
D	S	GRUNDFOS	.5	23	1	0769
D	S	MYERS RUETTER	.5	22	12	0386
D	S	MCDONALD	.5	40	10	1593
D	S	F&W	.5	63	12	0393
D	S	MCDONALD	.5	48	10	1593
D	S	FLINT & WALLING	.5	50	10	0386
D	S	GGRUNDFOS	.5	40	10	1593
D	S	MEYERS RUSTTER	.5	110	12	0386
D	S	MCDONALD	.5	28	12	0393
D	S	FLINT & WALLING	.5	2	10	0393
D	S	REDA (?)	.5	115	9	0769
D	S	MCDONALD	.5	31	12	0393
U				21	0	1099
D	S	GRUNDEFOS	.75	78	10	1039
D	S	FLINT & WALLING	.5	70	10	0393
D	S	RED JACKET	.5	32	10	0769
D	S	MCDONALD	.5	40	10	1593
D	S	MCDONALD	.5	50	10	1593
O	S	GRUNDFOS	113	65	5	0107
O	S	GRUNDFOS	113	30	10	0107
D	S	RED JACKET	.5	131	10	0769
D	S	MCDONALD	.5	42	12	0393
D	S	GRUNDFOS	0.33	50	7	0769
D	S	MCDONALD	.5	40	12	0393

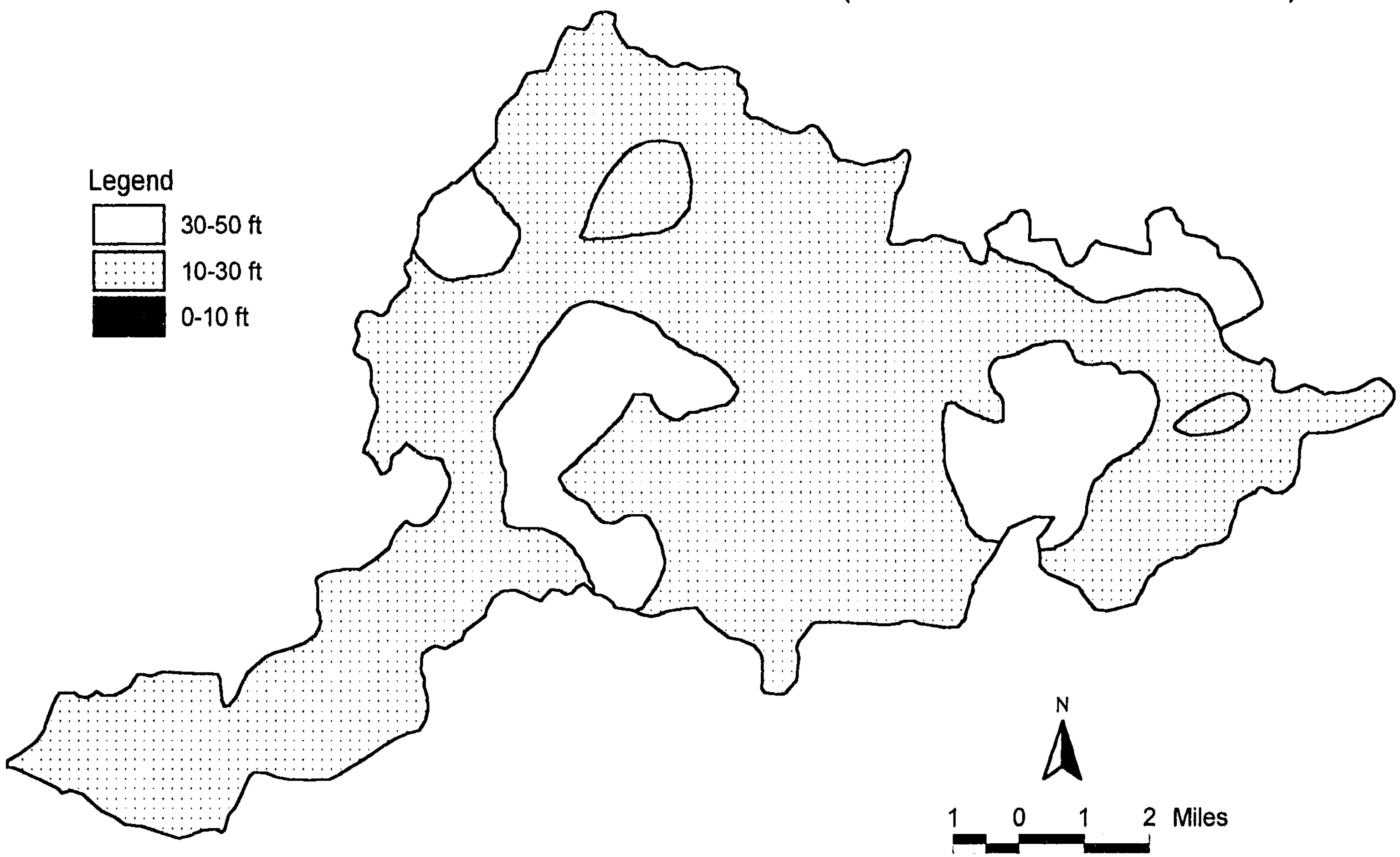
OPERATOR	ENTRY_M	ENTRY_YI	CHARHEIGHT
ED WOOD	06	97	0
CLIFF GRIFFIN	06	97	0
RICK FREY	06	97	0
RICK FREY	06	97	0
RICK FREY	06	97	0
LYN BRACEY	06	97	0
	06	97	0
	06	97	0
WALTER DRAI	06	97	0
WALTER DRAI	06	97	0
	06	97	0
	06	97	0
RICK FREY	06	97	0
RICK GWILT &	06	97	0
	06	97	0
RICK GWILT	06	97	0
MARC MCKEA(	06	97	0
	06	97	0
MARC MCKEA(	06	97	0
RICK GWILT &	06	97	0
RICH FREY	06	97	0
RICK GWILT	06	97	0
	06	97	0
	06	97	0
	06	97	0
	06	97	0
	06	97	0
	06	97	0
	06	97	0
RAY LEONARD	06	97	0
MARC MCKEA(	06	97	0
RICK FREY	06	97	0
	06	97	0
	06	97	0
RAY LEONARD	06	97	0
	06	97	0
	06	97	0
	06	97	0

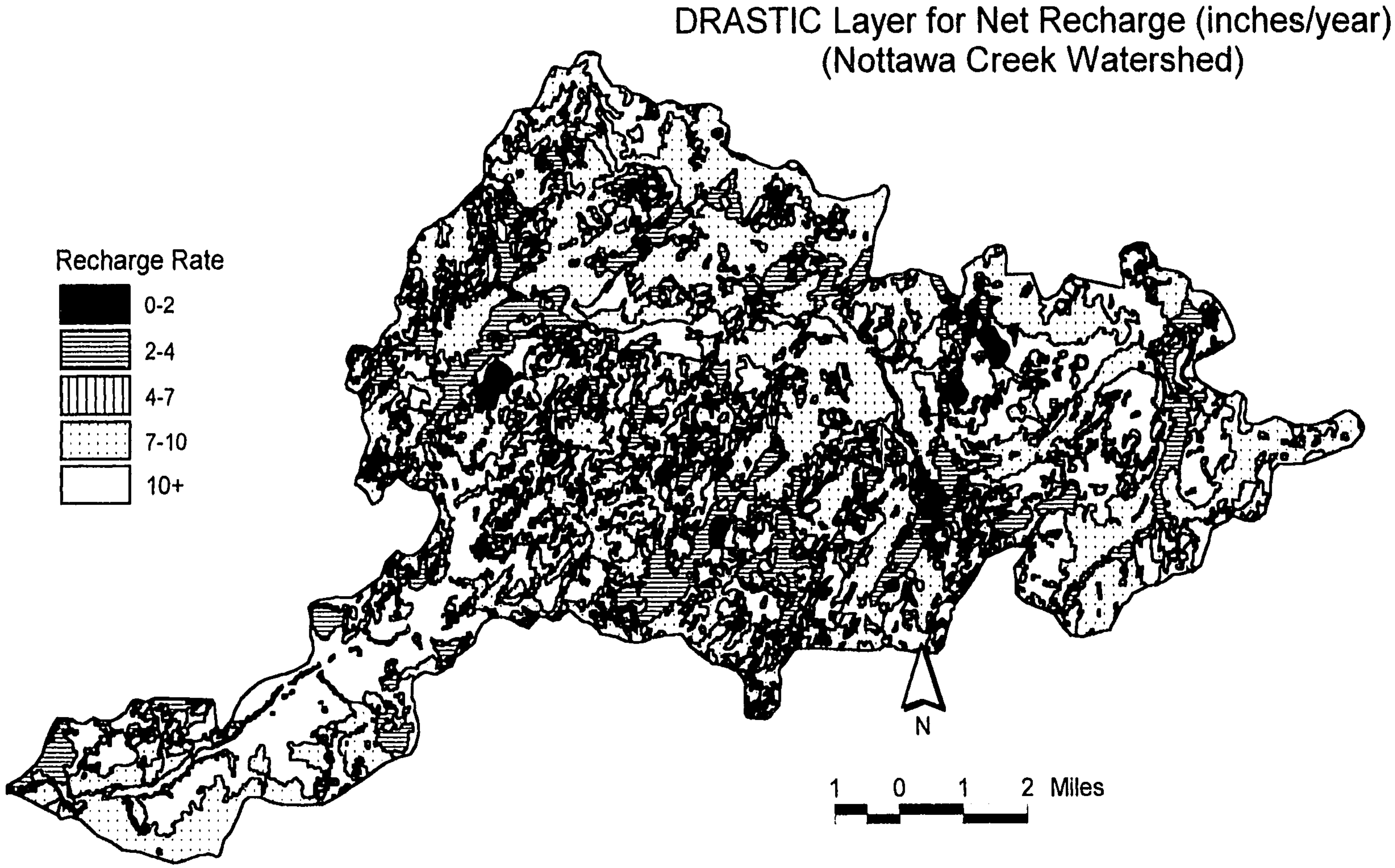
WELLID	FORM	THK	BOT	SC
13740701001	SAND - GRAVEL	25.0	25.0	25
13740701001	CLAY - GRAVEL	25.0	50.0	17
13740701001	BLUE SHALE	50.0	100.0	55
13740701002	TOP SOIL	1.0	1.0	40
13740701002	BROWN SAND	3.0	4.0	22
13740701002	BROWN SAND-CLAYEY	5.0	9.0	27
13740701002	SAND-SOME GRAVEL MUDDY & CLAYEY	12.0	21.0	19
13740701002	SANDY GREY CLAY	9.0	30.0	13
13740701002	GREY CLAY SOME GRAVEL	18.0	48.0	17
13740701002	SHALE (FIRM)	9.0	57.0	55
13740701003	GRAVEL & SAND	76.0	76.0	32
13740701003	CLAY	6.0	82.0	10
13740701003	BR. ROCK & GRAVEL STREAKS	16.0	98.0	59
13740701004	GRAVEL & SAND	30.0	30.0	32
13740701004	SOFT GREY CLAY & SAND	7.0	37.0	16
13740701004	GRAVEL & SAND	8.0	45.0	32
13740701004	SOFT GREY CLAY & GRAVEL & SAND	25.0	70.0	19
13740701004	BROKEN ROCK & STONES & GRAVEL	21.0	91.0	59
13740701004	WATER BEARING SHALE	29.0	120.0	55
13740702001	GRAVEL & SAND	27.0	27.0	32
13740702001	GREY CLAY & SAND	4.0	31.0	16
13740702001	GRAVEL & SAND	9.0	40.0	32
13740702001	BROKEN ROCK & SHALE	18.0	58.0	59
13740702001	WATER BEARING SHALE	32.0	90.0	55
13740702002	SANDY CLAY	7.0	7.0	13
13740702002	SAND	17.0	24.0	20
13740702002	GREY CLAY	14.0	38.0	10
13740702002	SHALE	7.0	45.0	55
13740702002	SANDROCK & SHALE	8.0	53.0	54
13740702002	SANDROCK	7.0	60.0	54
13740702002	SHALE & SANDROCK LAYERS	40.0	100.0	55
13740702003	SAND, CLAY	34.0	34.0	27
13740702003	BROKEN ROCK AND GRAVEL	19.0	53.0	30
13740702003	WATER BEARING BLUE ROCK AND SHALE	27.0	80.0	55
13740703001	SANDY CLAY	15.0	15.0	14
13740703001	CLAY AND SAND	25.0	40.0	16
13740703001	BLUE AND GRAVEL	30.0	70.0	30
13740703001	BROKEN ROCK AND CLAY	14.0	84.0	31
13740703001	SHALE WITH SMALL STREAKS OF MARSHA	63.0	147.0	56
13740703002	TOP SOIL	1.0	1.0	40
13740703002	CLAY	11.0	12.0	10
13740703002	GRAVEL	5.0	17.0	30
13740703002	CLAY	23.0	40.0	10
13740703002	SAND	4.0	44.0	20
13740703002	CLAY	5.0	49.0	10
13740703002	SANDSTONE(GREY)	11.0	60.0	50

Appendix C

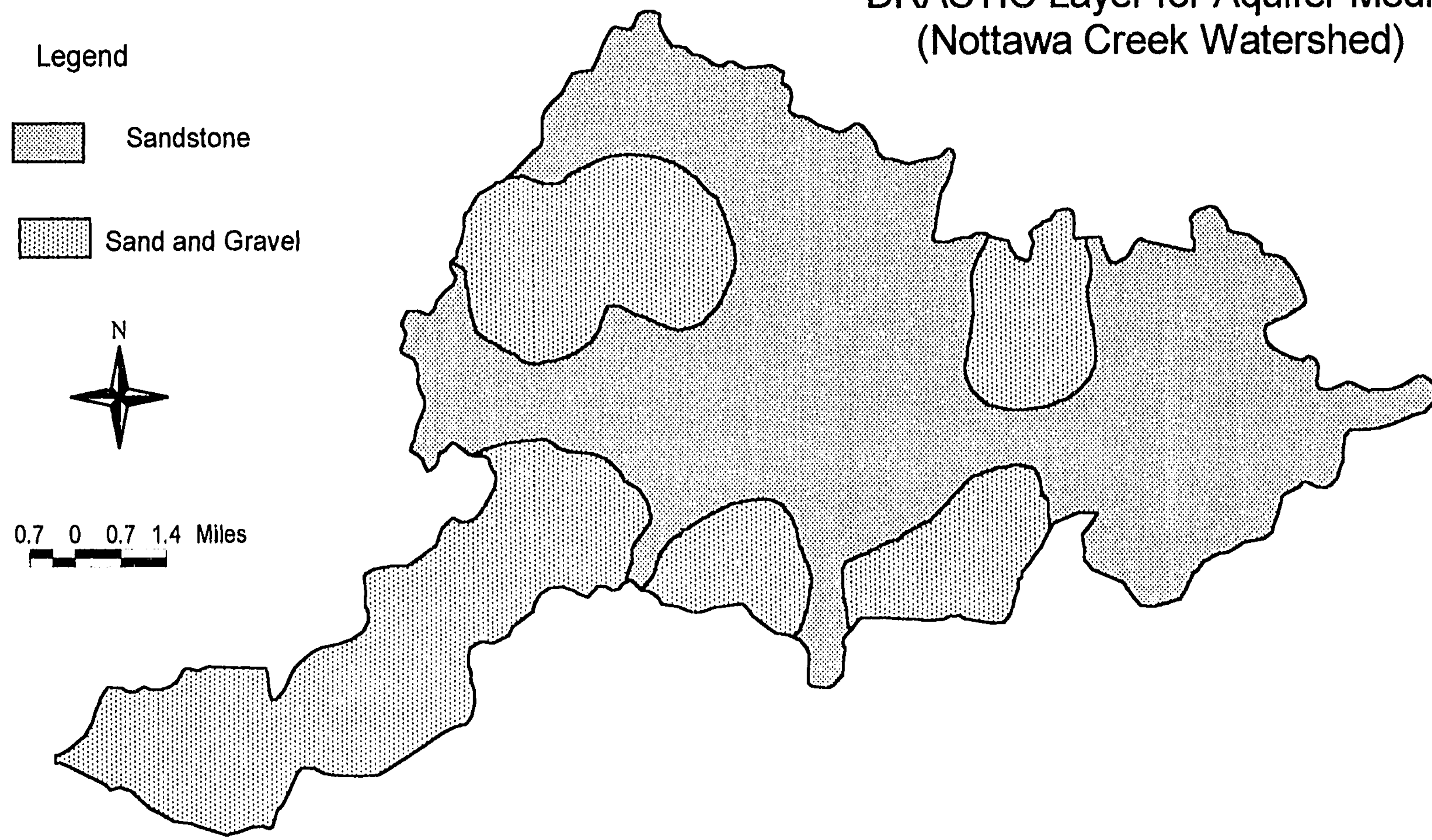
DRASTIC Map Layers of Nottawa Creek Watershed

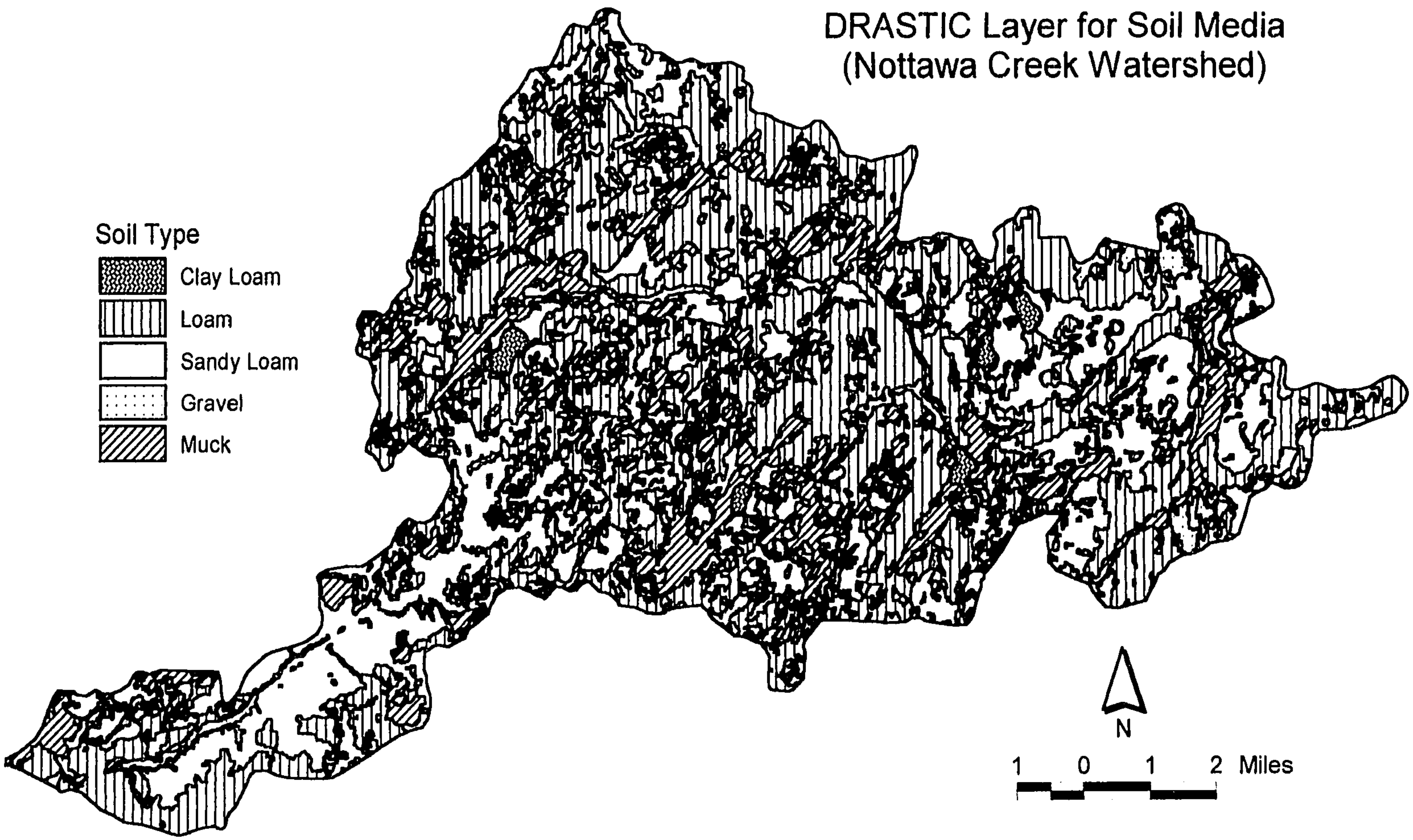
DRASTIC Layer for Depth to Water
(Nottawa Creek Watershed)

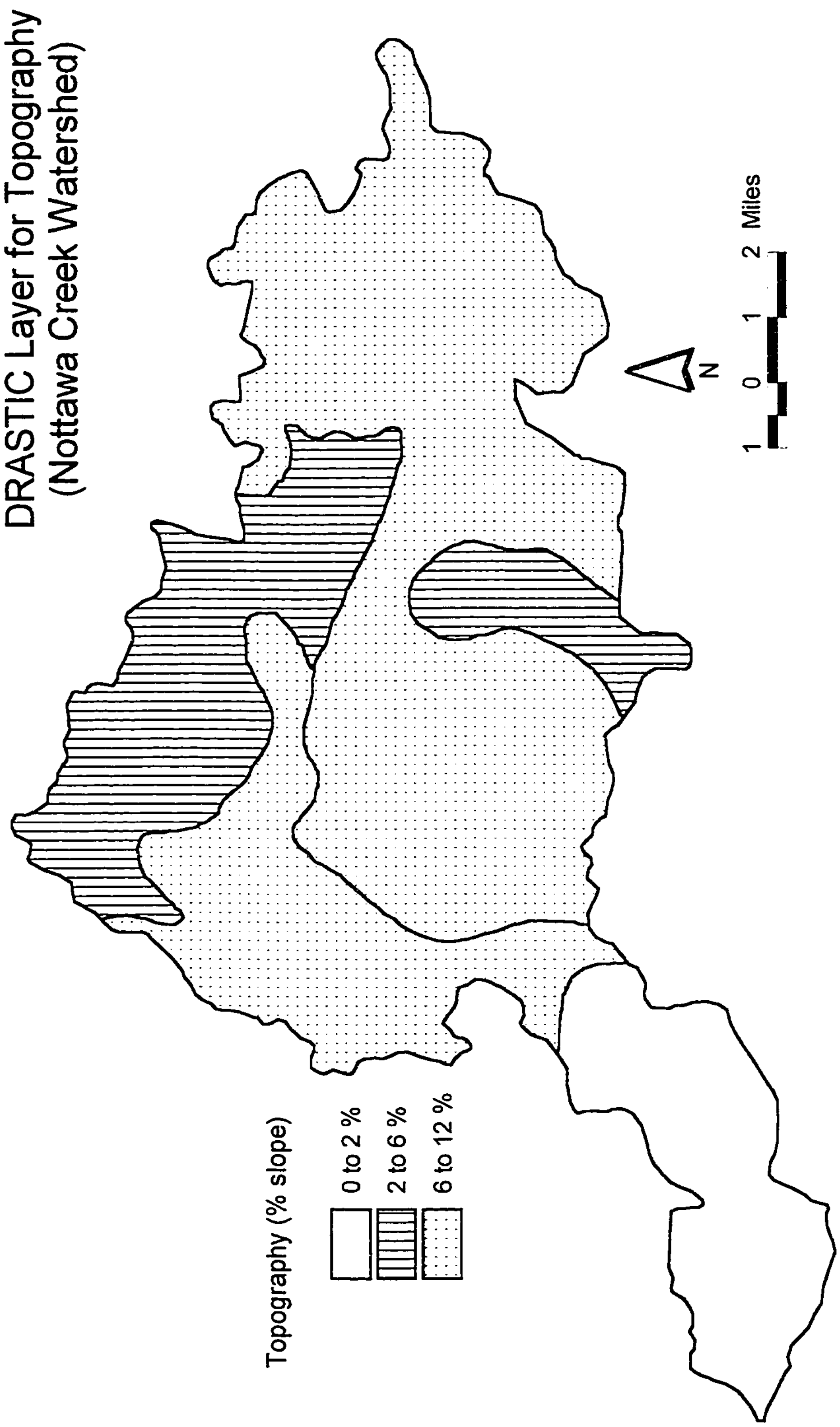



DRASTIC Layer for Net Recharge (inches/year)
(Nottawa Creek Watershed)
Recharge Rate
0-2
2-4
4-7
7-10
10+
N
1 0 1 2 Miles

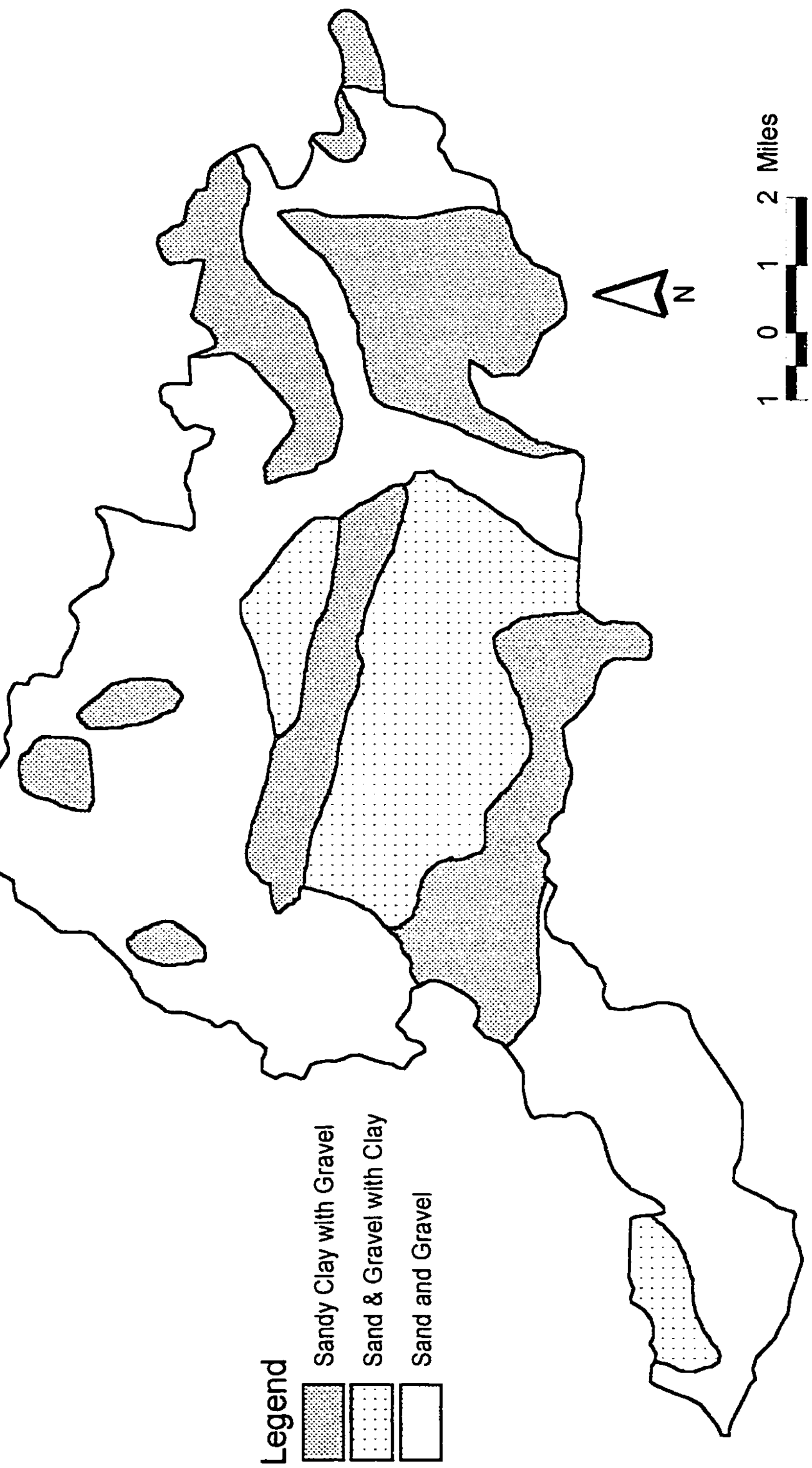
DRASTIC Layer for Aquifer Media
(Nottawa Creek Watershed)

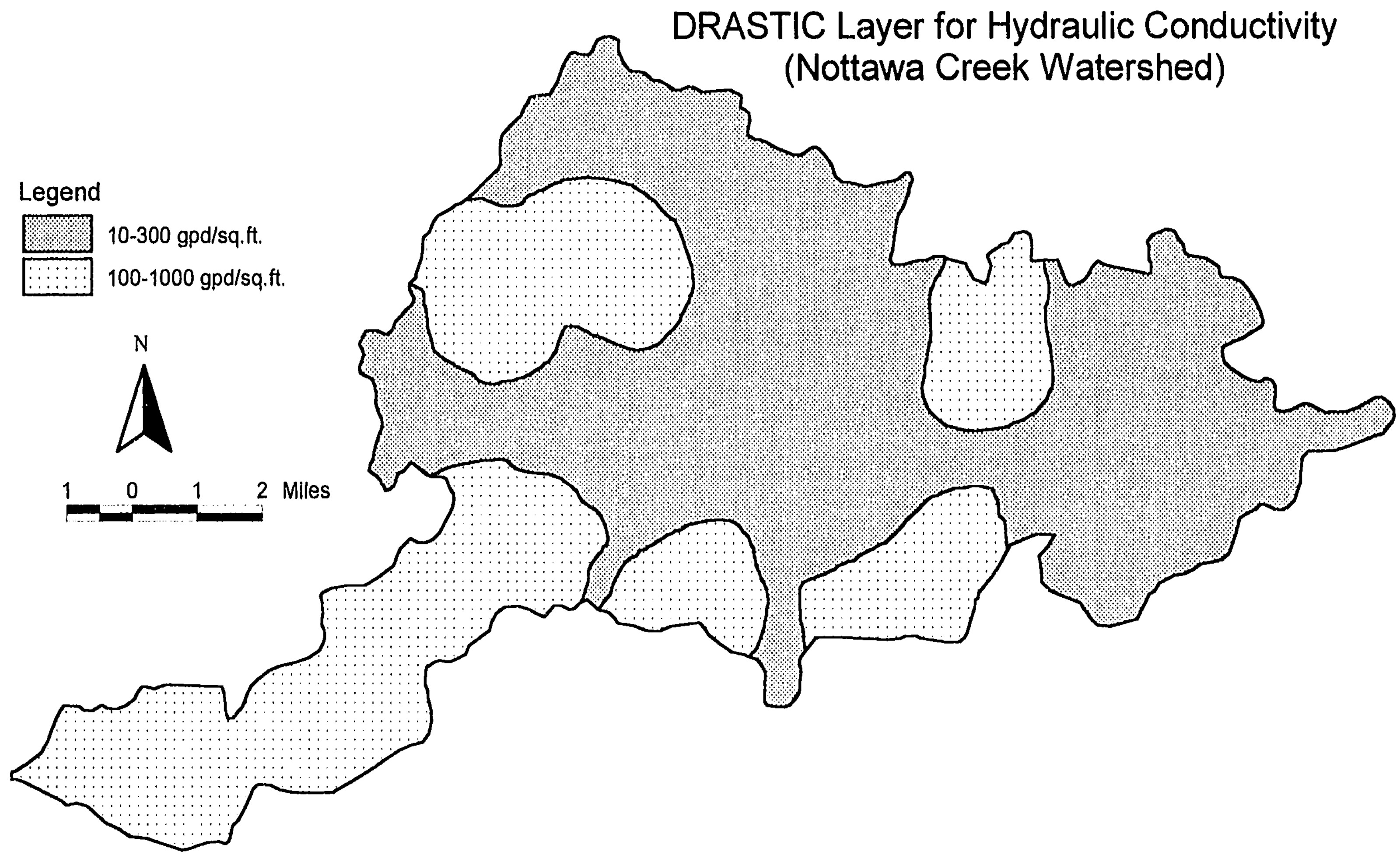



DRASTIC Layer for Soil Media
(Nottawa Creek Watershed)
Soil Type
Clay Loam
Loam
Sandy Loam
Gravel
Muck
N
1 0 1 2 Miles


DRASTIC Layer for Topography
(Nottawa Creek Watershed)
Topography (% slope)
0 to 2 %
2 to 6 %
6 to 12 %
N
1 0 1 2 Miles

DRASTIC Layer for Impact of the Vadose Zone
(Nottawa Creek Watershed)




DRASTIC Layer for Hydraulic Conductivity
(Nottawa Creek Watershed)
Legend
10-300 gpd/sq.ft.
100-1000 gpd/sq.ft.
N
1 0 1 2 Miles

BIBLIOGRAPHY

Allen, W. B., Miller, J. B., Wood, W. W. (1972). Availability of water in Kalamazoo County, Michigan. U. S. Geological Survey (USGS) Water-Supply Paper, 1973.

Aller, L., Bennet, T., Lehr, J. H., Petty, R. J., and Hackett, G. (1987). DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. National Water Well Association, EPA –600/2-87-035.

Austin, G. R. (1979). Soil Survey of Kalamazoo County, Michigan. U.S. Department of Agriculture, Soil Conservation Service.

Baker, D. B. (1990). Groundwater quality assessment through cooperative private well testing: An Ohio example. Journal of Soil and Water Conservation.

Banton, O. & Villeneuve, J. (1989). Evaluation of groundwater vulnerability to pesticides: A comparison between the pesticide DRASTIC index and the PRZM leaching quantities. Journal of Contaminant Hydrology, 4, 296.

Barringer, T., Dunn, D., Battaglin, W., and Vowinkel, E. (1990). Problems and methods involved in relating land use to ground-water quality. Water Resources Bulletin, 26(1).

Basin. Wayne County, Ohio. Master's Thesis, The University of Akron, Ohio.

Benton, S. E. (1991). An analysis of hydrogeologic factors affecting aquifer vulnerability in southwest Michigan. Master's Thesis. Western Michigan University, Kalamazoo, MI.

Bodier, M. W., Frank, K. D., & Spalding, R. F. (1993). Nitrate-N movement in a fine textured vadose zone. Journal of Soil and Water Conservation, 48(4), 350-354.

Carsel, R. F., Jones, R. L., Hansen, J. L., Lamb, R. L., and Anderson, M. P. (1988). A simulation procedure for ground water quality assessment of pesticides. Journal of Contaminant Hydrology, 2, 125-138.

Carsel, R. F., Smith, C. N., Mulkey, L. A., Dean, J. D. and Jowise, P. (1984). User manual for the Pesticide Root Zone Model (PRZM). Release 1. U. S. EPA,

Athens, GA, EPA/600/13-84/109.

Chidester, D. S. (1993). A study of aquifer sensitivity and vulnerability in Kalamazoo County, Michigan based on hydrogeologic and agricultural factors. Master's Thesis, Western Michigan University, Kalamazoo, MI.

Cummings, T. R. (1989). Natural ground waters in Michigan: 1974-1987. U. S. Geological Survey Open-File Report 89-259.

Dorr, J. A. & Eschman, D. F. (1970). Geology of Michigan. Ann Arbor, MI: University of Michigan Press.

Dutta, D., Das Gupta, A., & Ramnarong, V. (Winter, 1998). Design and optimization of a ground water monitoring system using GIS and multicriteria decision analysis. Ground Water Monitoring Review, 139-147.

Ehteshami, M., Peralta, R. C., Eisele, H, Deer, H, and Trindall, T. (1991). Assessing pesticide contamination to ground water : A rapid approach. Ground Water, 29(6), 162.

EPA. (1983). Methods for chemical analyses of water and waste.

Farrand, W. R. & Eschman, D. F. (1974). Glaciation of the southern peninsula of Michigan. Published map (1:500,000). Ann Arbor, MI: University of Michigan, Department of Geological Sciences.

Finkbeiner, K. (1994). Subsurface glacial geology of the area between the Tekonsha and Kalamazoo moraines, Kalamazoo, Michigan. Masters Thesis. Western Michigan University, Kalamazoo, MI.

Flint, A. C., Brown, A. C., Gardner, R. C., Kehew, A. E., Kendzierski, S. J., Kozlowski, A. P., Lee, J. N., & Nicks, L. P. (1999). Characterization and correlation of a widely distributed subsurface diamicton in Southwest Michigan. GSA Abstracts with Programs, 31(5).

Freeze, R. A. & Cherry, J. A. (1979). Groundwater. Englwood Cliffs, NJ: Prentice-Hall.

Gardner, C. R. (1997). Lithologic and stratigraphic analysis of glacial diamictons, Sturgis, Michigan. Masters Thesis. Western Michigan University, Kalamazoo, MI.

Garret, P., Willams, J. S., Rossol, C. F., and Tolman, A. L. (1987). Are ground water vulnerability classification systems workable? In Proceedings of the FOCUS Conference on Eastern Regional Ground-Water Issues (pp. 329-343). Kitchener, Ontario, Canada. National Ground Water Association, Columbus, OH..

Gerhart, J. M. (1986). Ground-water recharge and its effects on nitrate concentration beneath a manured field site in Pennsylvania. Ground Water, 24(4).

Granneman, H. G. & Twenter, F. R. (1985). Geohydrology and groundwater flow at Verona Well Field, Battle Creek, Michigan. USGS Water Resources Investigation Report 85-4056.

Haith, D. A., & Laden, E. M. (1989). Screening of groundwater contaminants by travel-time distributions. Journal of Environmental Engineering, ASCE, 24(2), 231-233.

Hsiu-Hsiung, C., & Druliner, A. D. (1987). Nonpoint-source agricul'ural chemicals in ground water in Nebraska--preliminary results for six areas of the High Plain Aquifers. U. S. G. S. Water-Resources Investigation Report 86-4338.

Hughes, L. D. (1995). A feasibility study for using computerized water well records to delineate areas of recharge-discharge potential. Masters Thesis. Western Michigan University, Kalamazoo, MI.

Jury, W. A., Focht, D. D., & Farmer, W. J. (1987). Evaluation of pesticide groundwater pollution potential from standard indices of soil-chemical adsorption and biodegradation. Journal of Environmental Quality, 16(4).

Kalinski, R. J., Kelly, W. E., Bogardi, I., Ehrman, R. l. & Yamamoto, P. D. (1994). Correlation between DRASTIC vulnerabilities and incidents of VOC contamination of municipal wells in Nebraska. Ground Water, 32(1), 31-34.

Keeny, D. R. (1986). Nitrate in ground water – agricultural contribution and control. Proceedings of the Agricultural Impacts on Ground Water Conference, Aug., 1986.

Kehew, A. E. (1999). Ground water quality of Nottawa Creek Watershed. Unpublished Report. Groundwater Eduaction in Michigan (GEM) Regional Center, Western Michigan University, Kalamazoo, MI.

Komor, S. C., & Anderson, H. W. Jr. (1993). Nitrogen isotopes as indicators of nitrate sources in Minnesota sand-plain aquifers. Ground Water, 31(2), 260-270.

Koplin, D. W., Durkart, M. R., & Thurman, E. M. (1994). Herbicides and nitrate in near-surface aquifers in the midcontinental United States, 1991. U.S. Geological Survey Water-Supply Paper 2413.

Kozlowski, A. L. (1999). Three dimensional mapping of the east Leroy and Union City 7.5 minute quadrangles in southwest Michigan. Masters Thesis. Western Michigan University, Kalamazoo, MI.

Krishnamurthy, R. V. (1999). Summary of stable isotope investigations of Nottawa Creek Watershed. Unpublished Report. Groundwater Eduaction in Michigan (GEM) Regional Center, Western Michigan University, Kalamazoo, MI.

Kruger, E. L., & Coats, J. R. (1996). Fate of atrazine and atrazine degradates in soils of Iowa. Herbicide Metabolites in Surface and Groundwater. American Chemical Society.

Meyer, M. T., Thurman, E. M., & Goolsby, D. A. (1996). Cyanazine, atrazine, and their metabolites as geochemical indicators of contaminant transport in the Mississippi River. Herbicide Metabolites in Surface and Groundwater. American Chemical Society.

Mickelson, D. M., Clayton, L., Fullerton, D. S., & Borns, H. W. (1983). The late Wisconsin glacial record of the Laurentide ice sheet in the United States. In S. C. Porter (Ed.), Late quaternary environments of the United States, Vol. I. The Pleistocene. Minneapolis: University of Minnesota Press.

Morre, J. S. (1988). Geology technical note no. 5: A system for early evaluation of the pollution potential of agricultural groundwater environments: Chester, PA. U. S. Department of Agriculture, Soil Conservation Service, Northeast National Technical Center.

Moser, J.E. & Passero, R. N. (1990). Geology and aquifers in Calhoun County, Michigan. Kalamazoo, MI: Western Michigan University.

Nicks, L. P., Kehew, A. E., & Sauck, W. (1998). Three dimensional mapping using geophysics and conventional techniques has shown a correlation between tunnel valleys and buried bedrock surface [abs.]. Geological Society of America, Annual Meeting Toronto, 30(7), 137.

Passero, R. N. (1978). Kalamazoo County--geology and the environment. Kalamazoo, MI: Western Michigan University.

Passero, R. N. (1989). Geology and groundwater of Kalamazoo County, Michigan. Kalamazoo, MI: Western Michigan University.

Passero, R. N. (1990). AQUIPRO. Kalamazoo, MI: Western Michigan University.

Passero, R. N. (1992). Report on the hydrogeology of Van Buren County for the Michigan Pesticide Aquifer Sensitivity Project. Institute for Water Sciences, Western Michigan University, Kalamazoo, MI.

Passero, R. N., Chidester, S. D., Hughes, L.D. & Dickason, D.D. (1992). Feasibility of using computerized water well recorrds for mapping the water table and delineating ground-water recharge-discharge potential areas in Van Buren County, MI. Kalamazoo, MI: Western Michigan University Institute for Water Sciences.

Passero, R. N., Kehew, A.E., Sauck, W.A., Chidester, S.D., & Lovett, C. (1992). Determinants of ground-water quality in a multi-layer glacial drift aquifer system: Implications for wellhead protection of small community water supply systems in agricultural areas. Kalamazoo, MI: Western Michigan University Institute for Water Sciences.

Pionke, H. B., Glotfelty, D. E., Lucas A. D., & Urban, J. B. (1988). Pesticide contamination of groundwaters in the Mahantango Creek Watershed. Journal of Environmental Quality, 17(1).

Reick, R. L. & Winters, H. A. (1979). Lake, stream, and bedrock in south-central Michigan. Annals of the Association of American Geographers, 69(2), 276 –288.

Rheaume, S. J. (1990). Geohydrology and water quality of Kalamazoo County, Michigan, 1986-1988. U.S. Geological Survey Water-Resources Investigations Report 90-4028.

Rosen, L. (1994). A study of the DRASTIC methodology with emphasis on Swedish conditions. Ground Water, 32(2), 279-285.

Spalding, R. F., Exner, M. E., Lindau, C. W. & Eaton, D. W. (1982). Investigation of sources of groundwater nitrate contamination in the Burbank-Wallula area of Washington, U. S. A. Journal of Hydrology, 58, 307-324.

Squillace P. J., & Thurman E. M. (1992). Herbicide transport in rivers: Importance of hydrology and geochemistry in nonpoint-source contamination. Environmental Science Technology, 26(3).

Straw, T. W., Passero, R. N. & Kehew, A. E. (1992). Conceptual hydrogeologic glacial facies model: Implications for aquifers and agrichemicals in southwest Michigan. In Y. Eckstein & A. Zaporozec (Eds.), Hydrogeologic investigation, evaluation, and ground water modeling (pp. 35-68), Proceedings of the Second USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology. Alexandria, VA: Water Environment Federation.

Suppleco, Inc. (1997). Supleco Park, Bellefonte, PA 16823-0048

Tardy, W. (1997). Soil survey of Calhoun County, Michigan. U.S. Department of Agriculture, Natural Resources Conservation Service.

Twenter, F. R. (1966a). General availability and quality of groundwater in the bedrock deposits in Michigan. State Resources Planning Division, Michigan Department of Commerce and Michigan Water Resources Commission, map (color).

Twenter, F. R. (1966b). General availability and quality of groundwater in the glacial deposits in Michigan. State Resources Planning Division, Michigan Department of Commerce and Michigan Water Resources Commision, map (color).

Vanlier, K. E. (1966). Ground-water resources of the Battle Creek area, Michigan. USGS Water Investigation, 4.

Widmer, S. K., & Spalding, R. F. (1996). Assessment of herbicide transport and persistence in groundwater: A review. Herbicide Metabolites in Surface and Groundwater. American Chemical Society.

Williams, S. (1998). Nottawa Creek Watershed water quality planning project (Watershed Plan). Cahoun Conservation District, Marshall, MI.

Wosten, J. H., Bannik, J. J., DeGruijter, J. J., and Bouma, J. (1986). A procedure to identify different groups of hydraulic conductivity and moisture retention curves for soil horizons. Journal of Hydrology, 86, 133-145.

Yuan-Ming, H., Myers, G., Clark, T., Jakes, D., & Schlotthauer, J. (1993). Integrating GIS/GPS into Minnesota's Statewide Ground Water Monitoring and Assessment Program. GIS/LIS Proceedings (pp. 323-330). Minneapolis Convention Center, Minneapolis, Minnesota.

PLEASE NOTE:

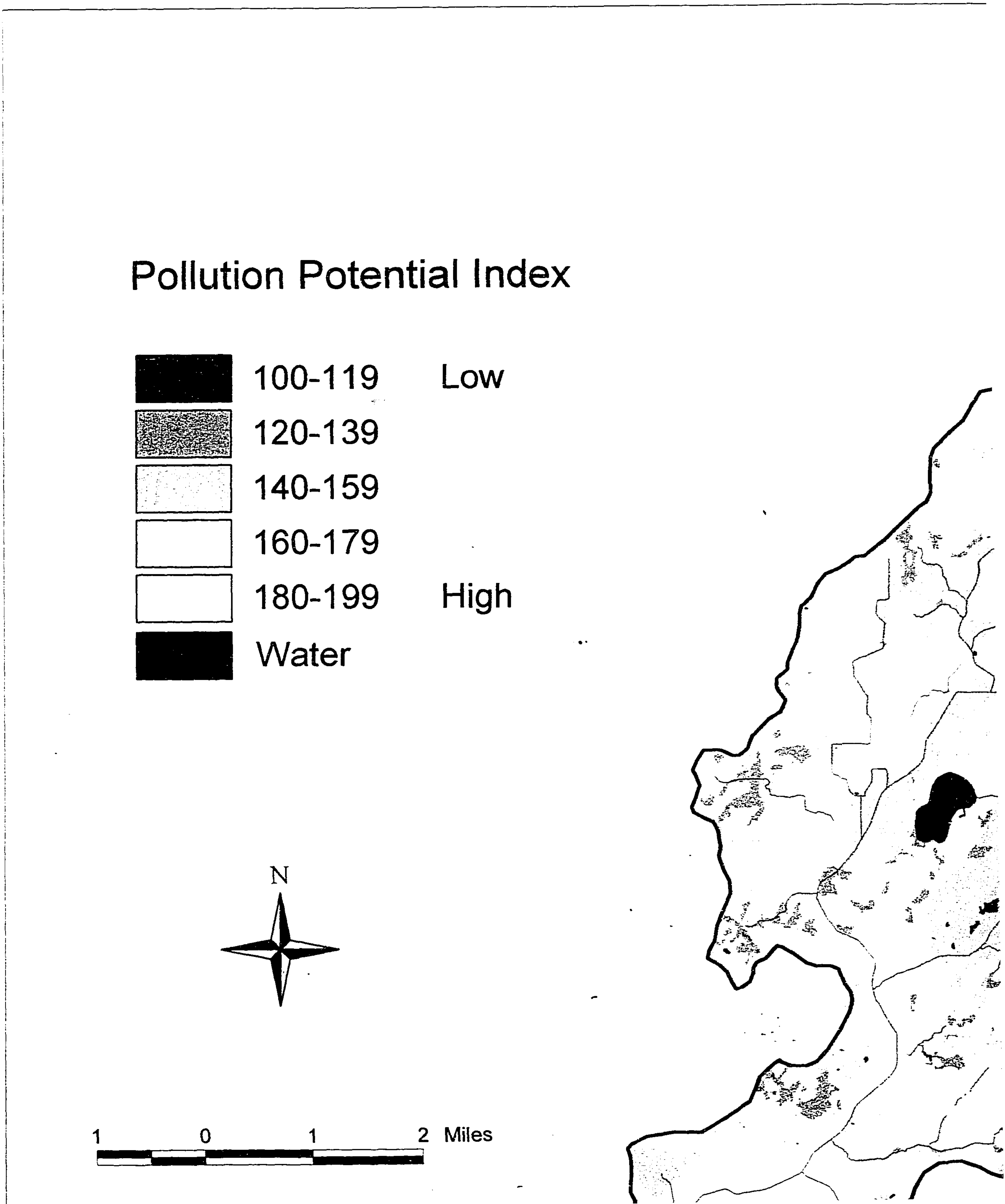
Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

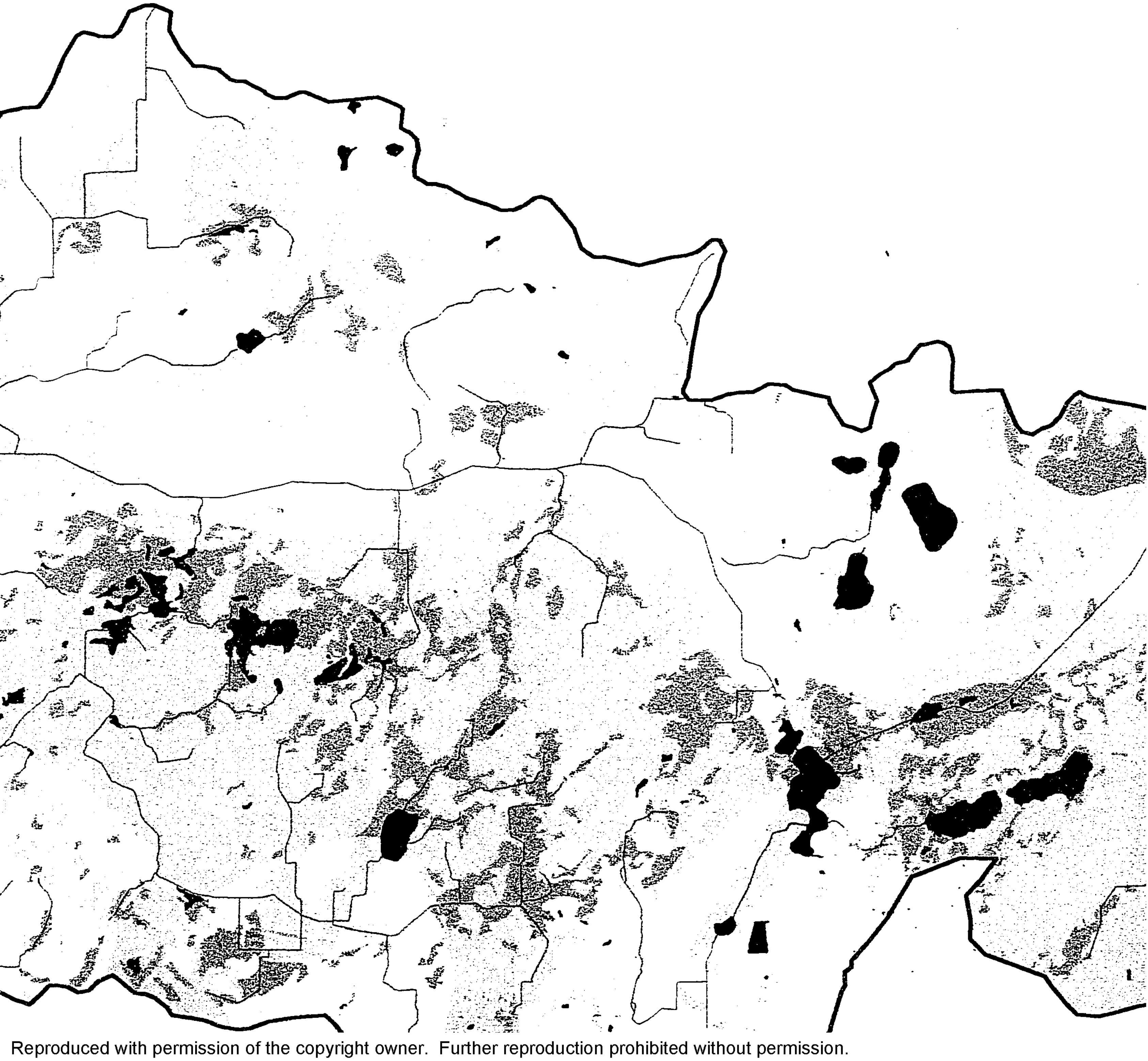
Black and white photographic prints (17" x 23") are available for an additional charge.

UMI

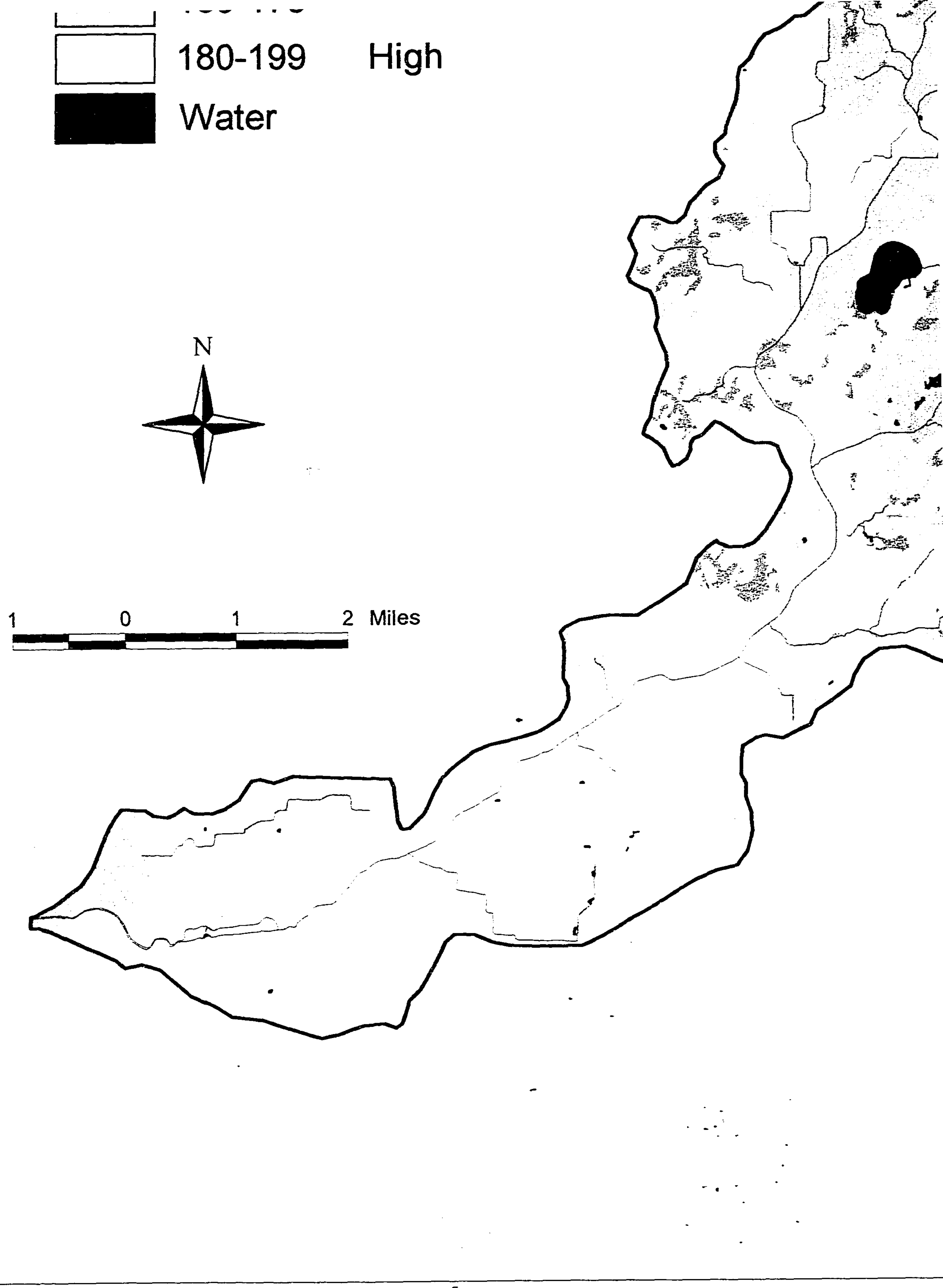

Pollution Potential Index
100-119 Low
120-139
140-159
160-179
180-199 High
Water
N
1 0 1 2 Miles

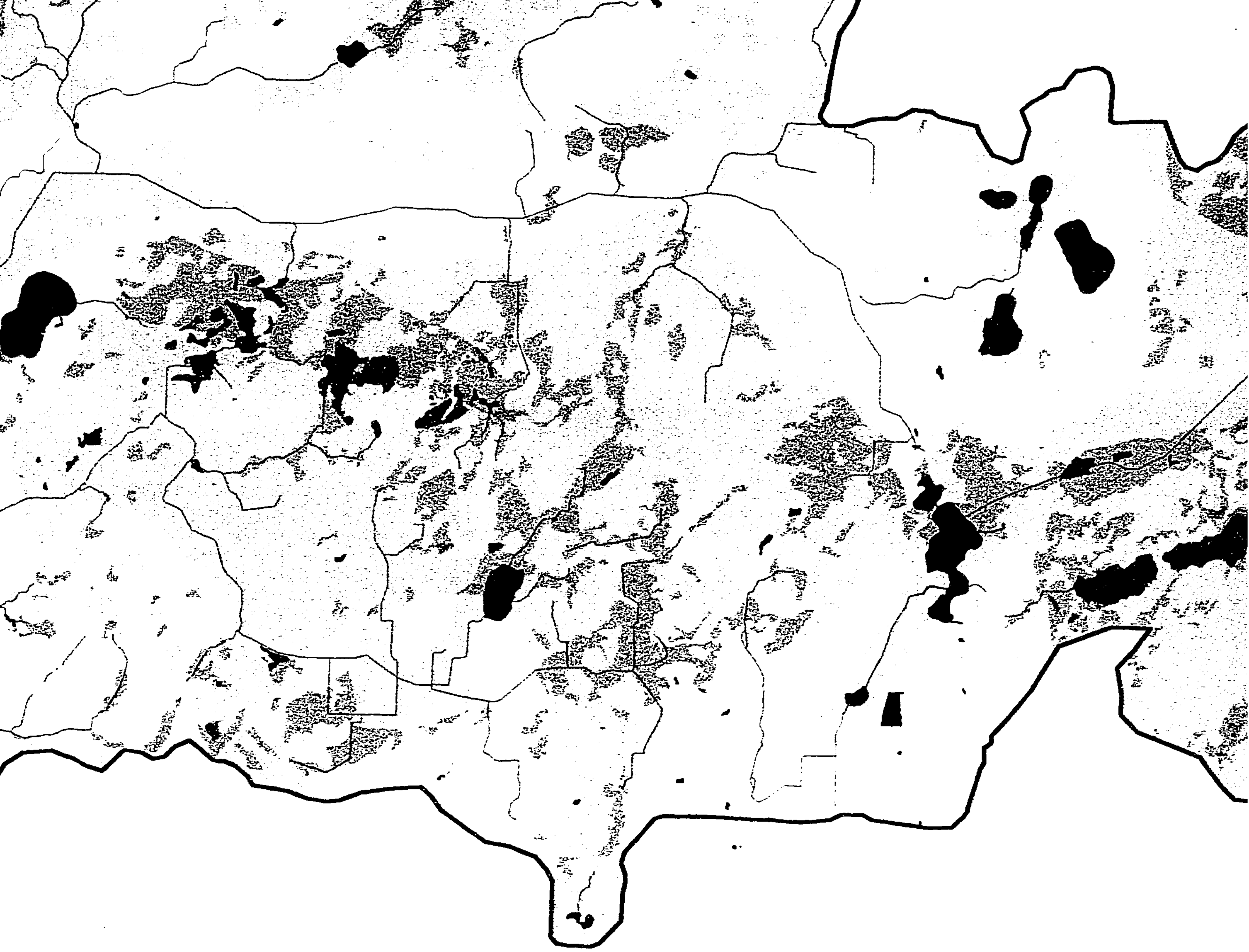
(PLATE I)

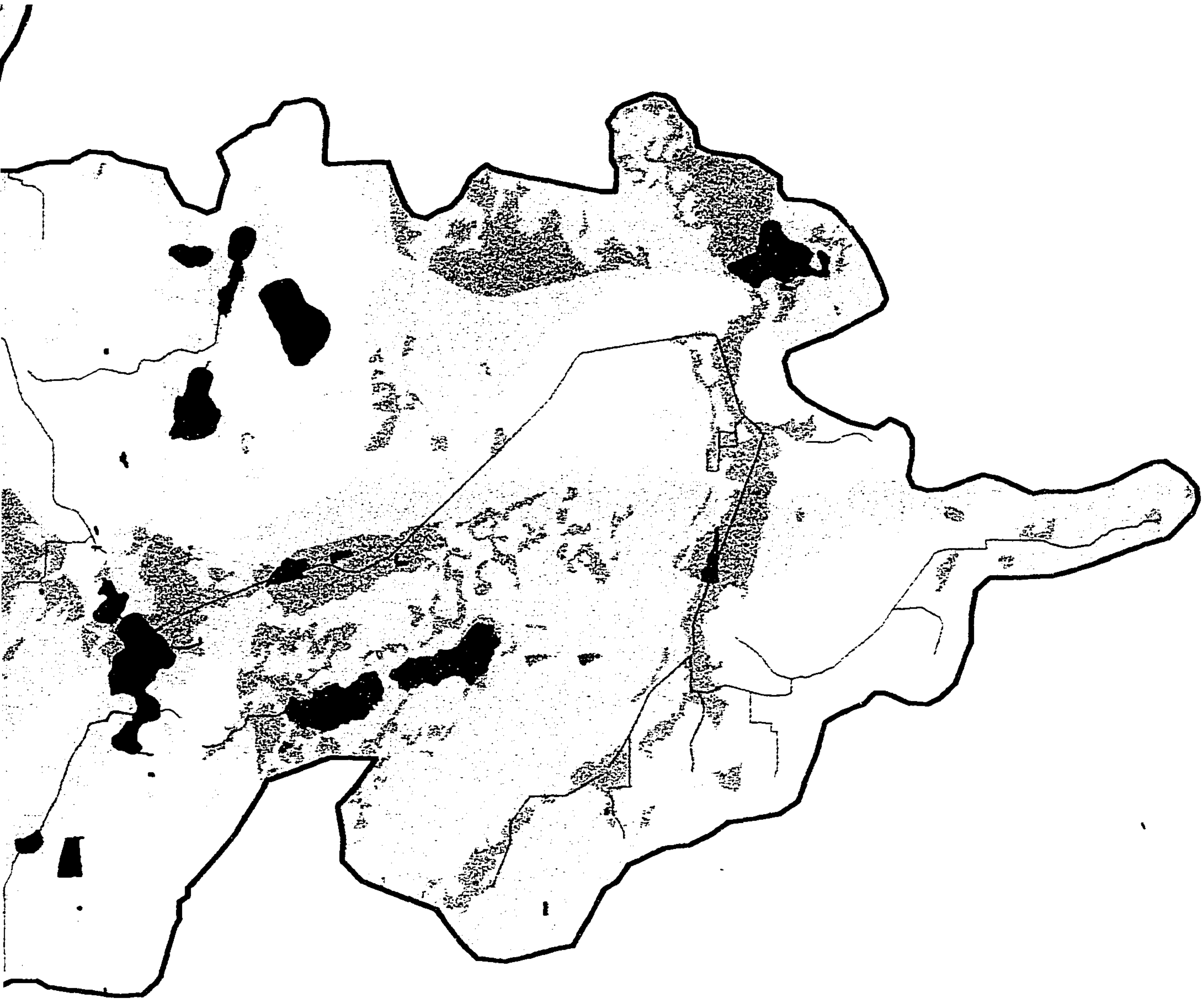
Groundwater Pollution Potential M
of Nottawa Creek Watershed, Calhou



(PLATE I)
llution Potential Map (DRASTIC)
atershed, Calhoun County, Michigan


180-199
High
Water
N
1
0
1
2
Miles





PLEASE NOTE:

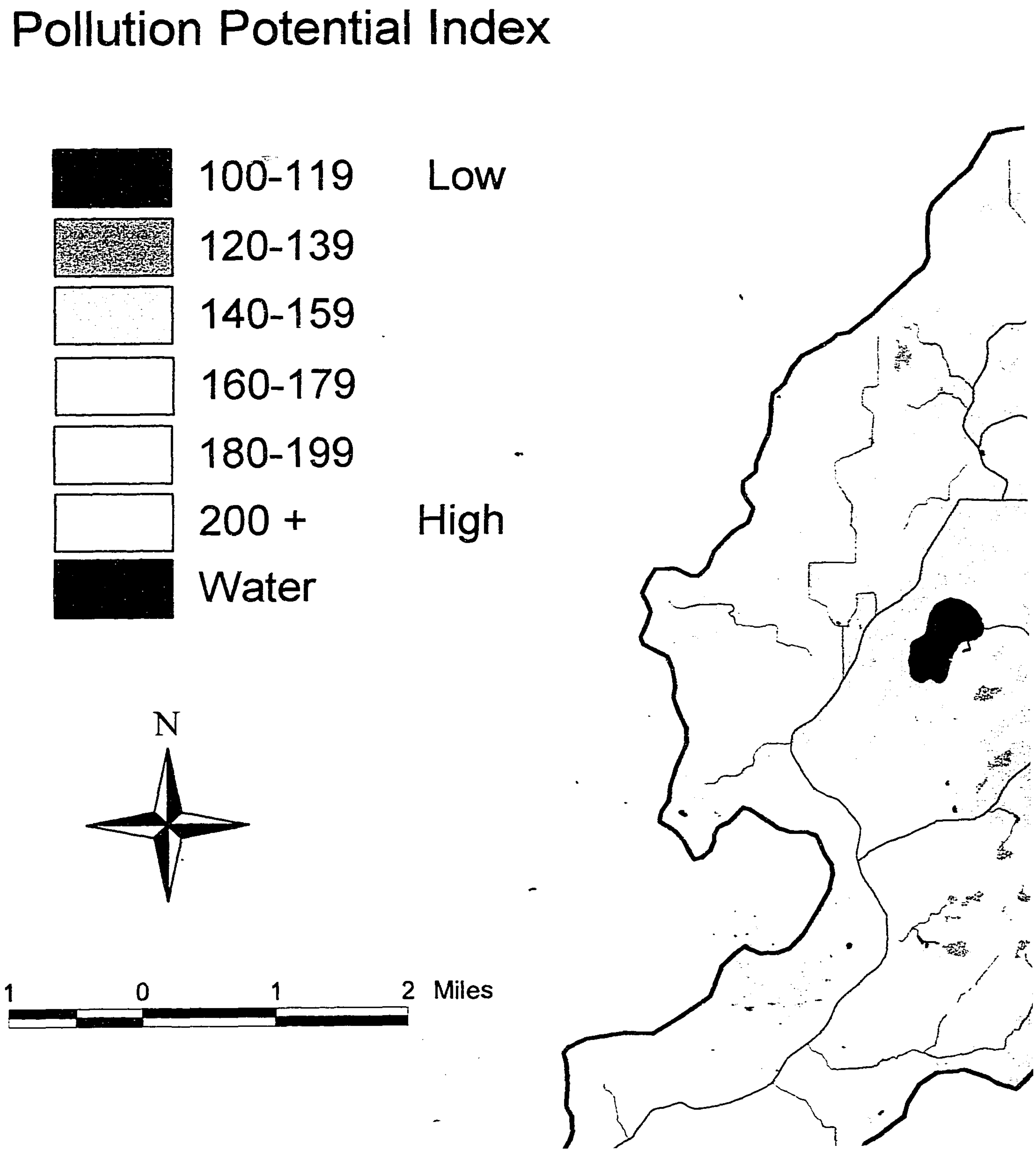
Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

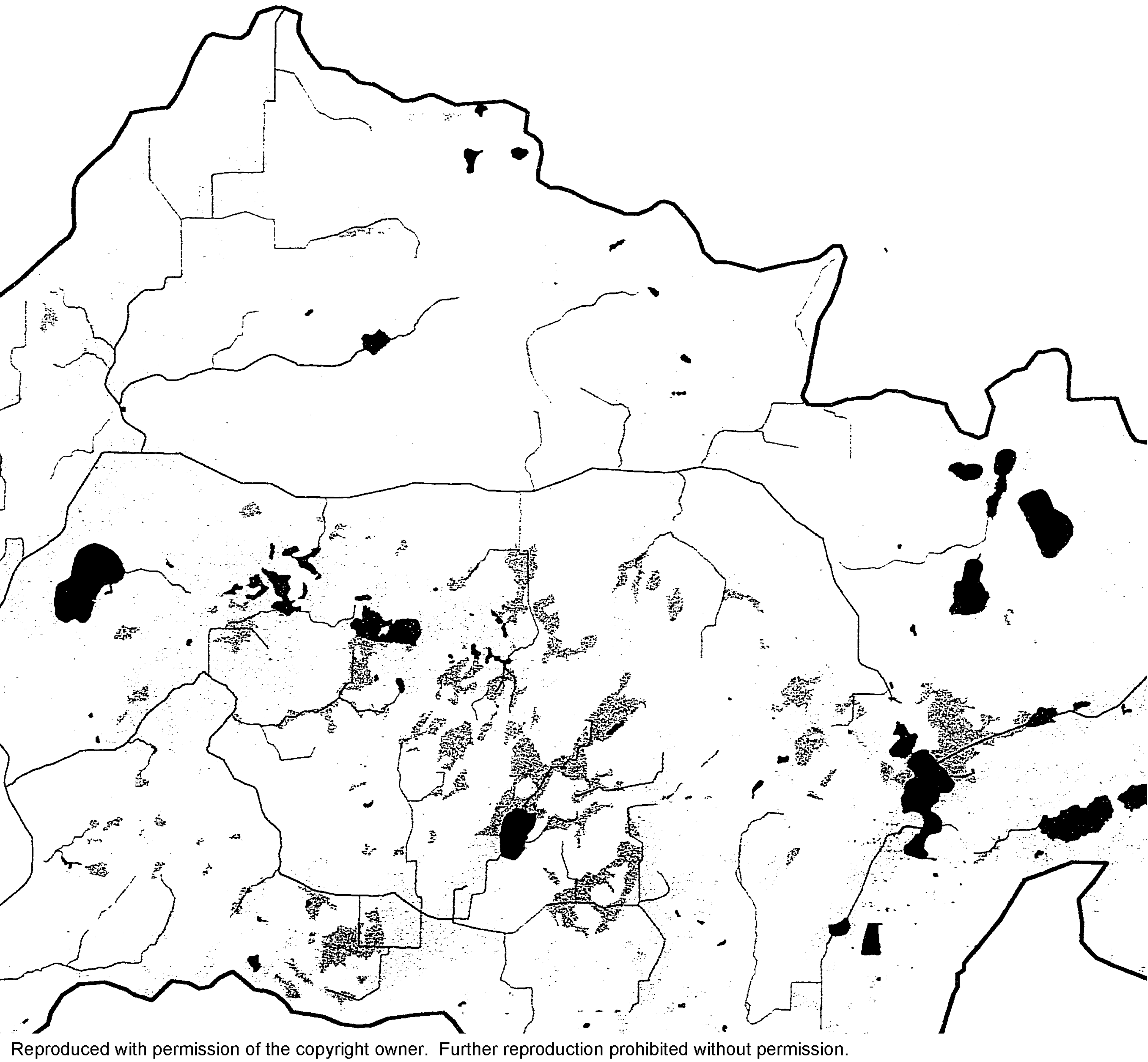
Black and white photographic prints (17" x 23") are available for an additional charge.

UMI

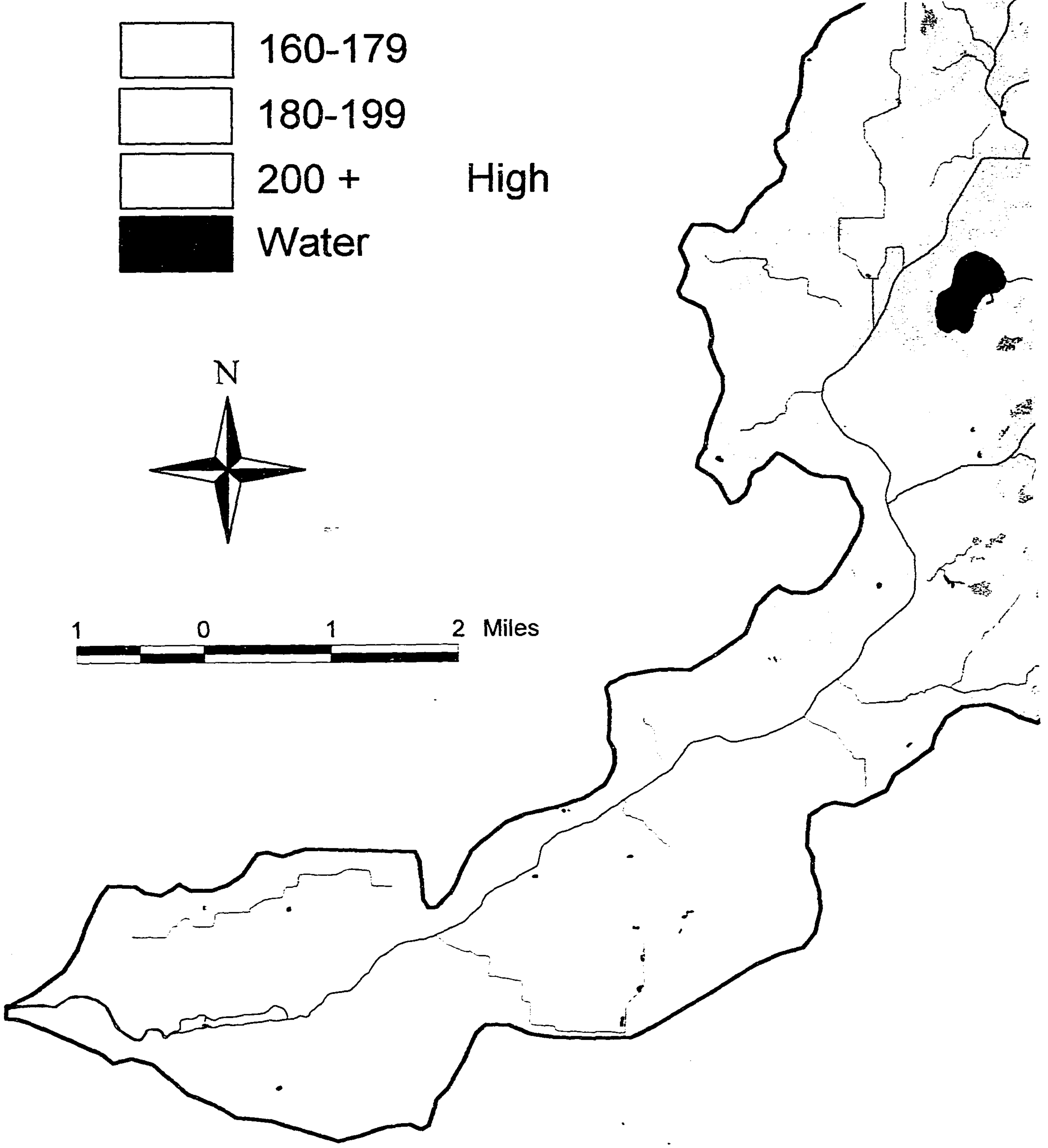

Pollution Potential Index
100-119 Low
120-139
140-159
160-179
180-199
200 + High
Water
N
1 0 1 2 Miles

(PLATE II)

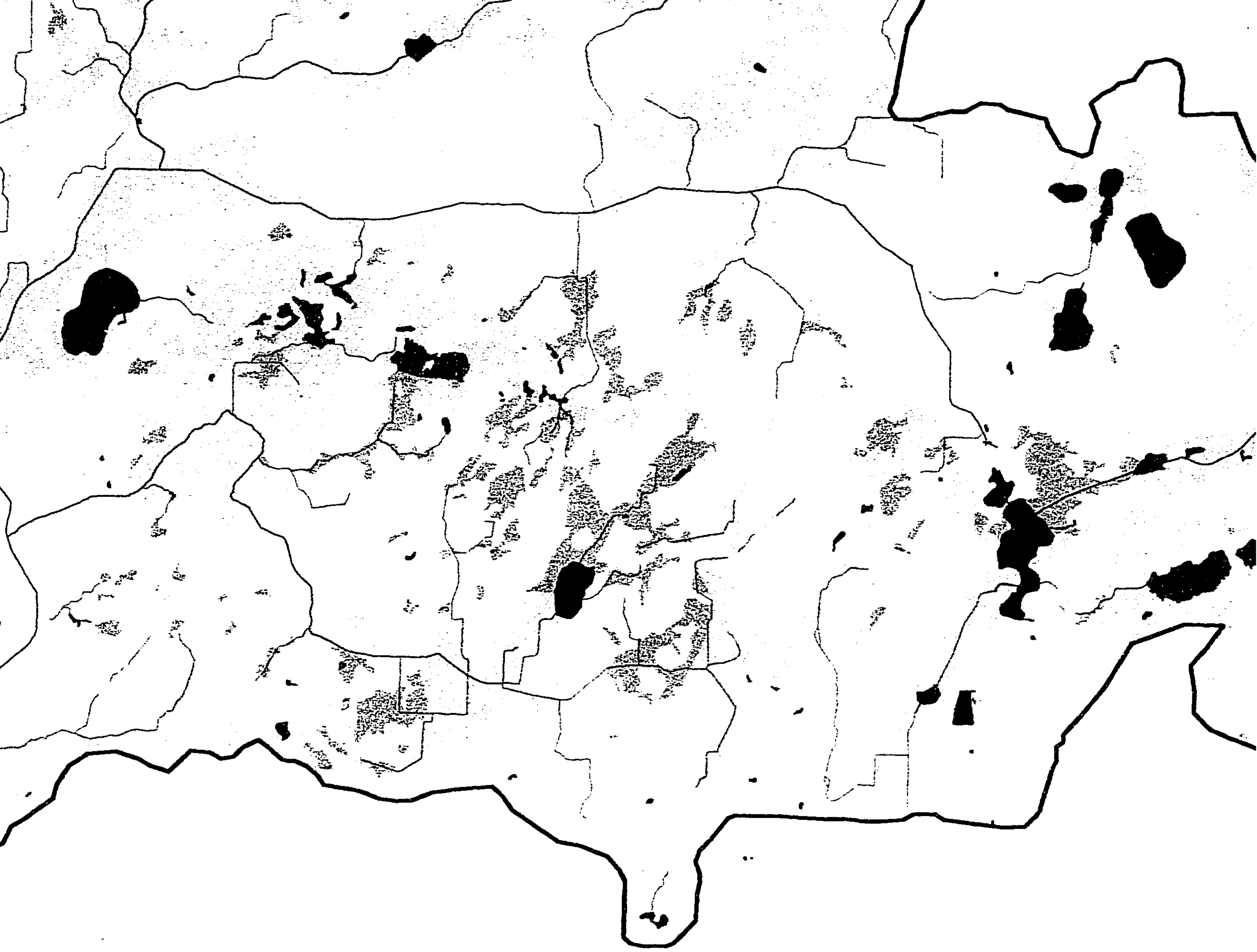
Groundwater Pollution Potential Ma
of Nottawa Creek Watershed, Cal

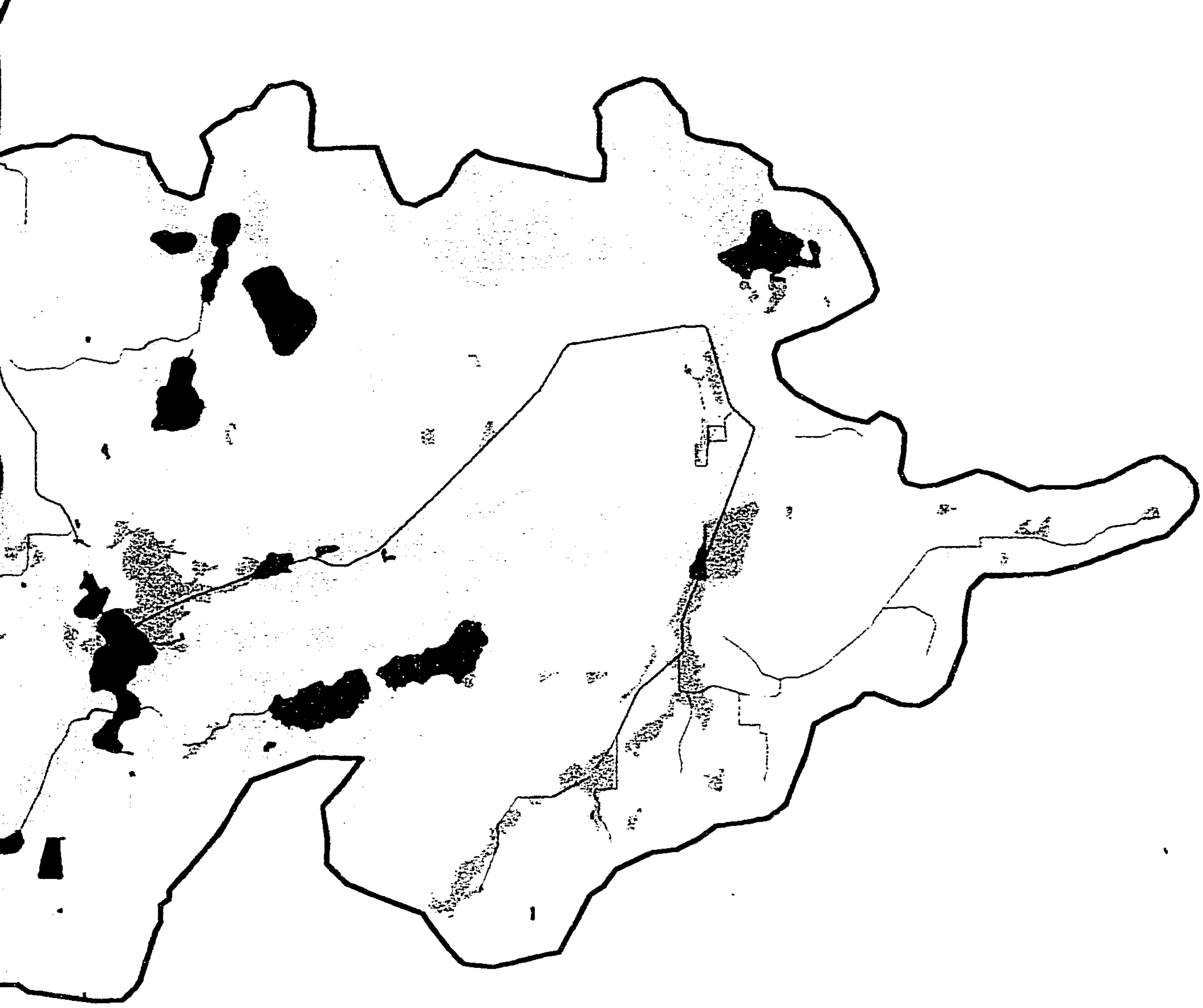


(PLATE II)
ᑦotential Map (Pesticide DRASTIC)
ershed, Calhoun County, Michigan



160-179
180-199
200 +
High
Water
N
1
0
1
2
Miles





PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

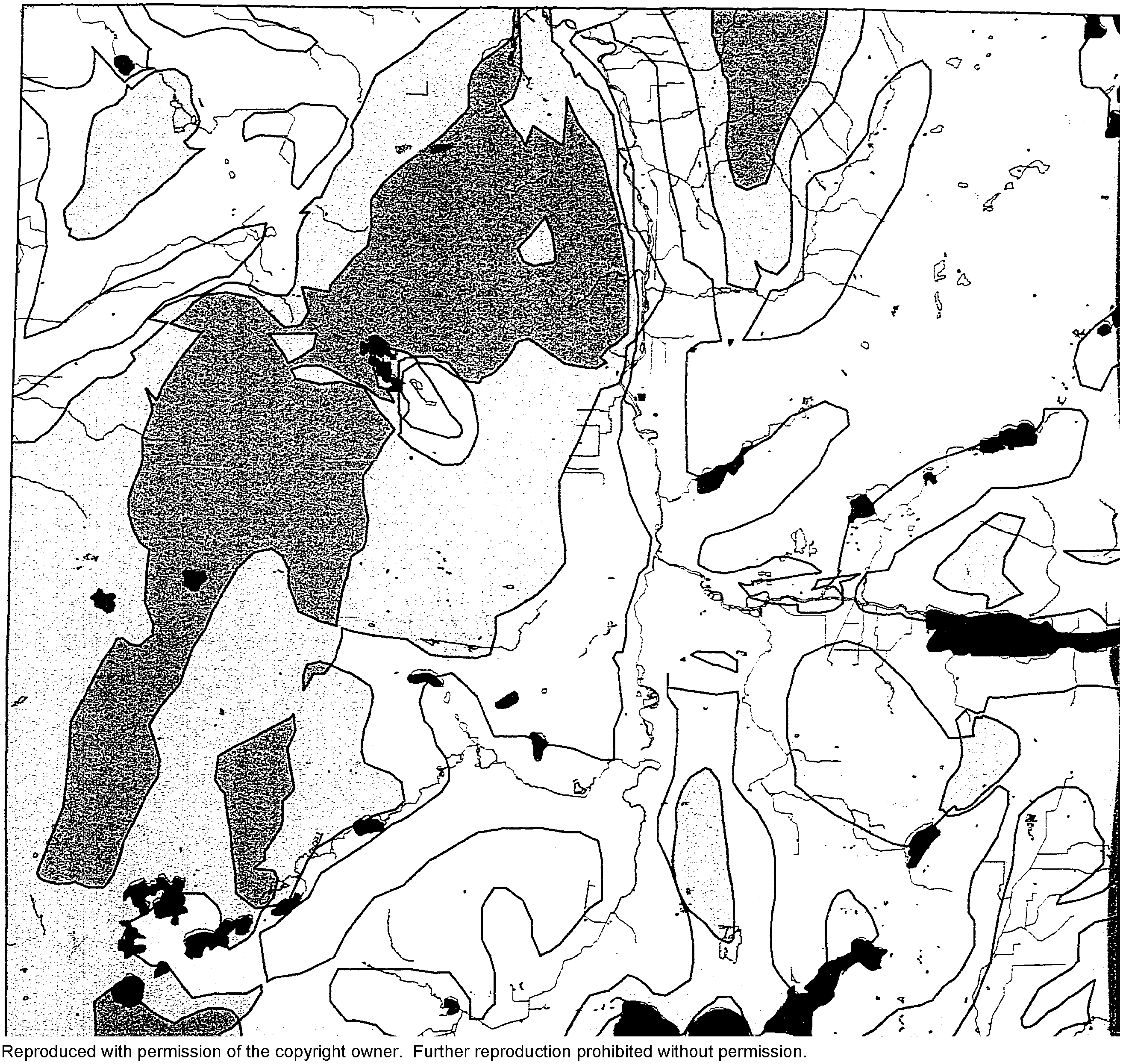
Pollution Potential Index

125-150	Low
151-175	
176-200	
201	High
Water	

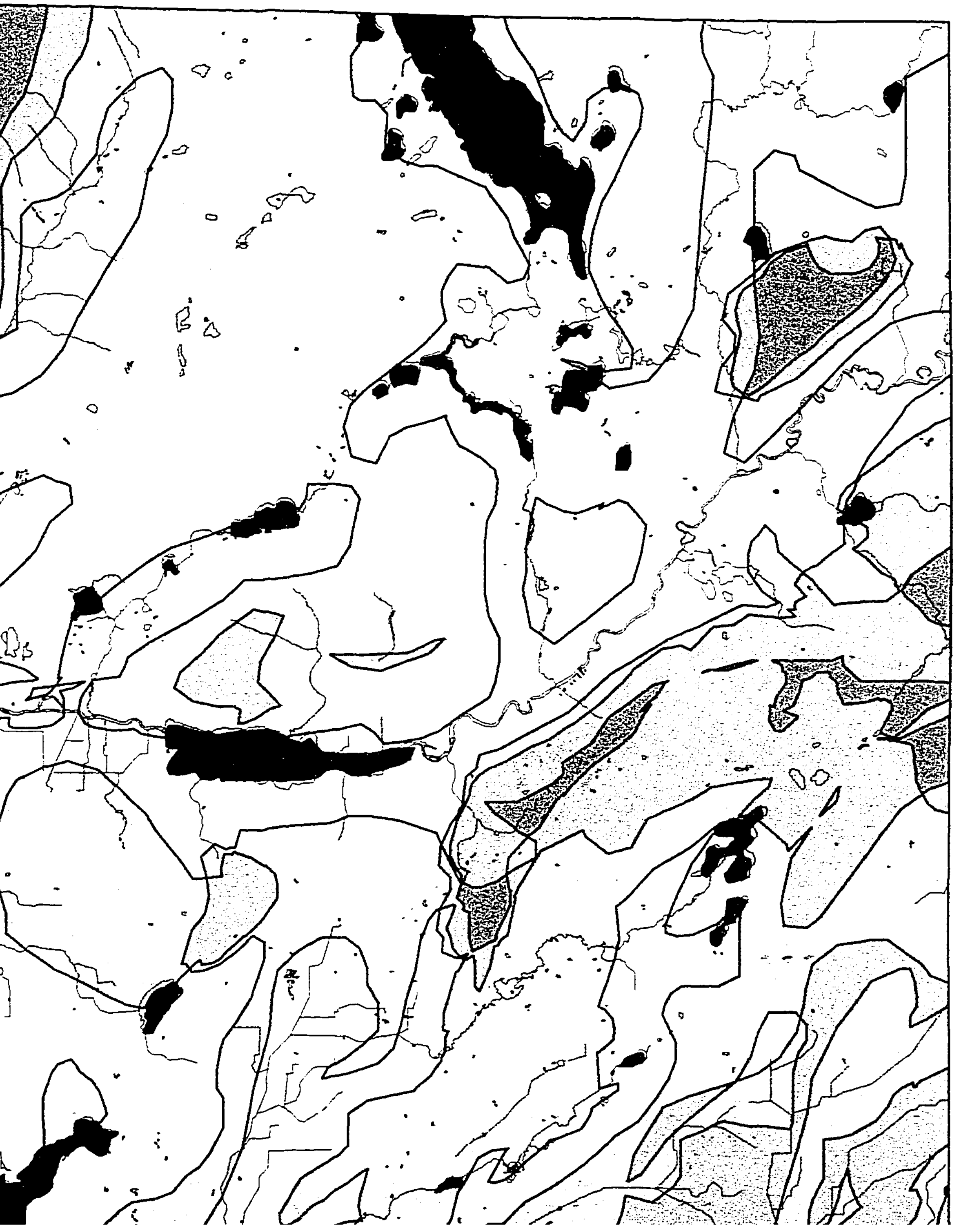
Water

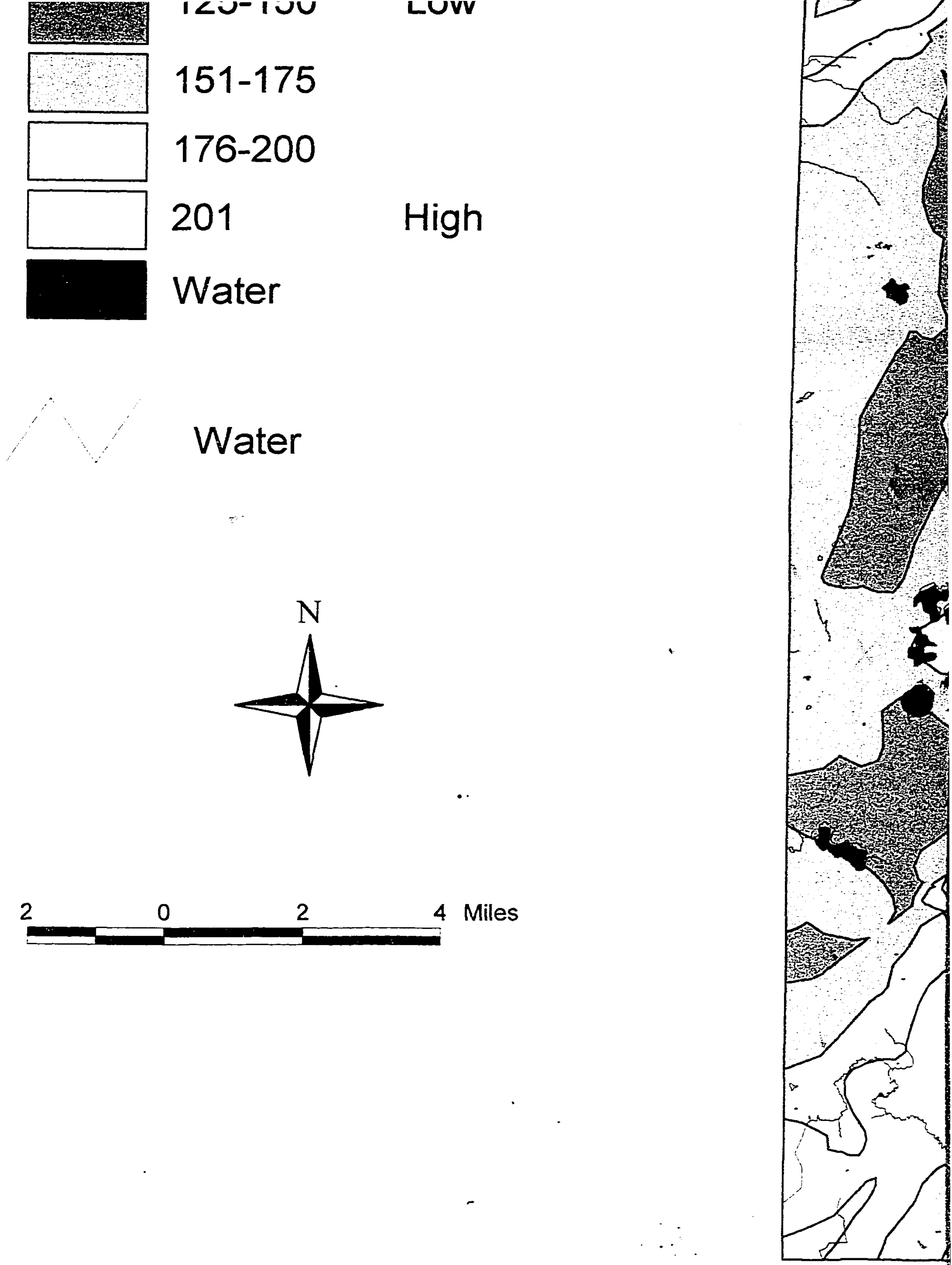
N

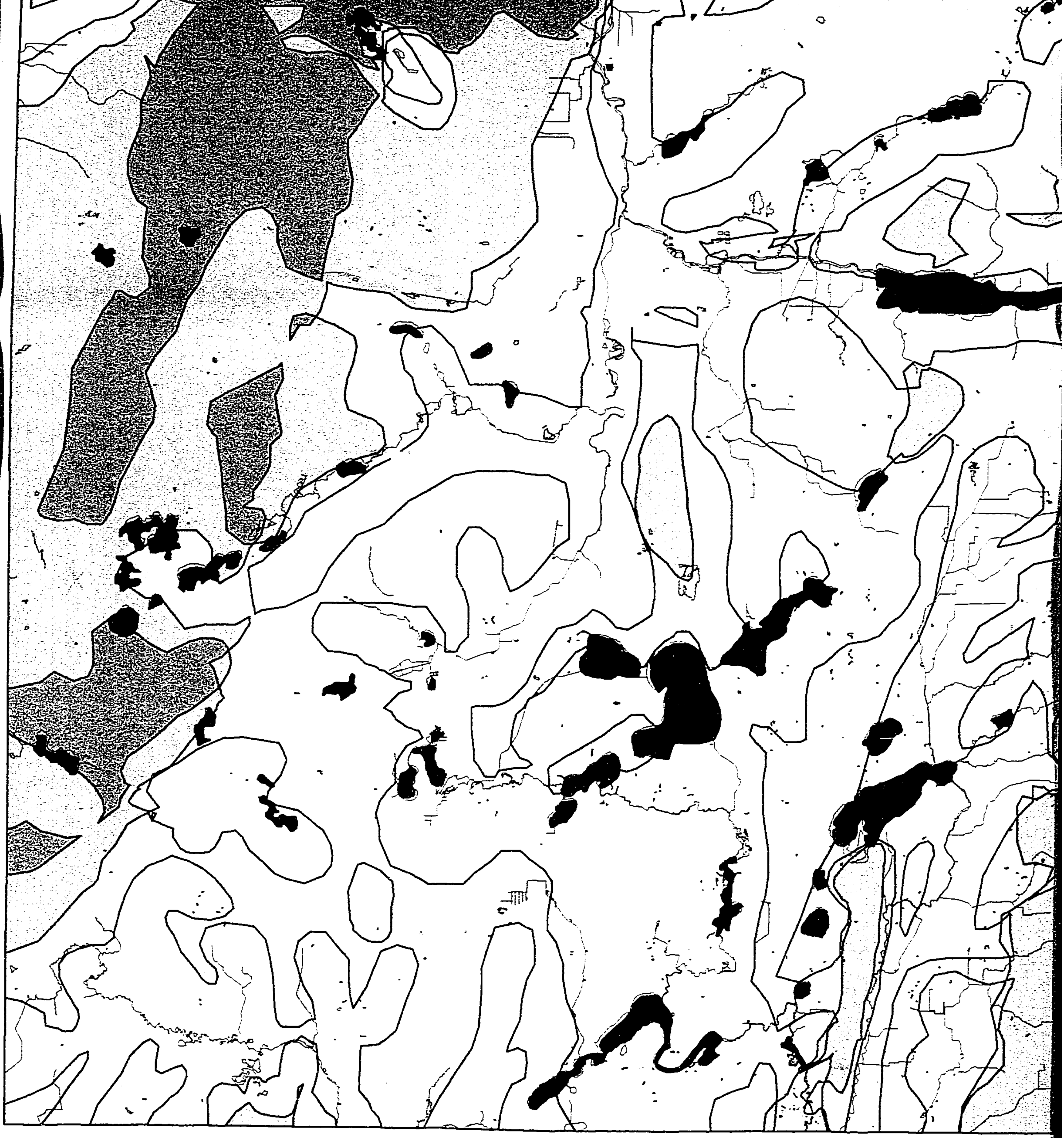
(PLATE III)
Groundwater Pollution Potential Map of Kalamazoo County, Michi

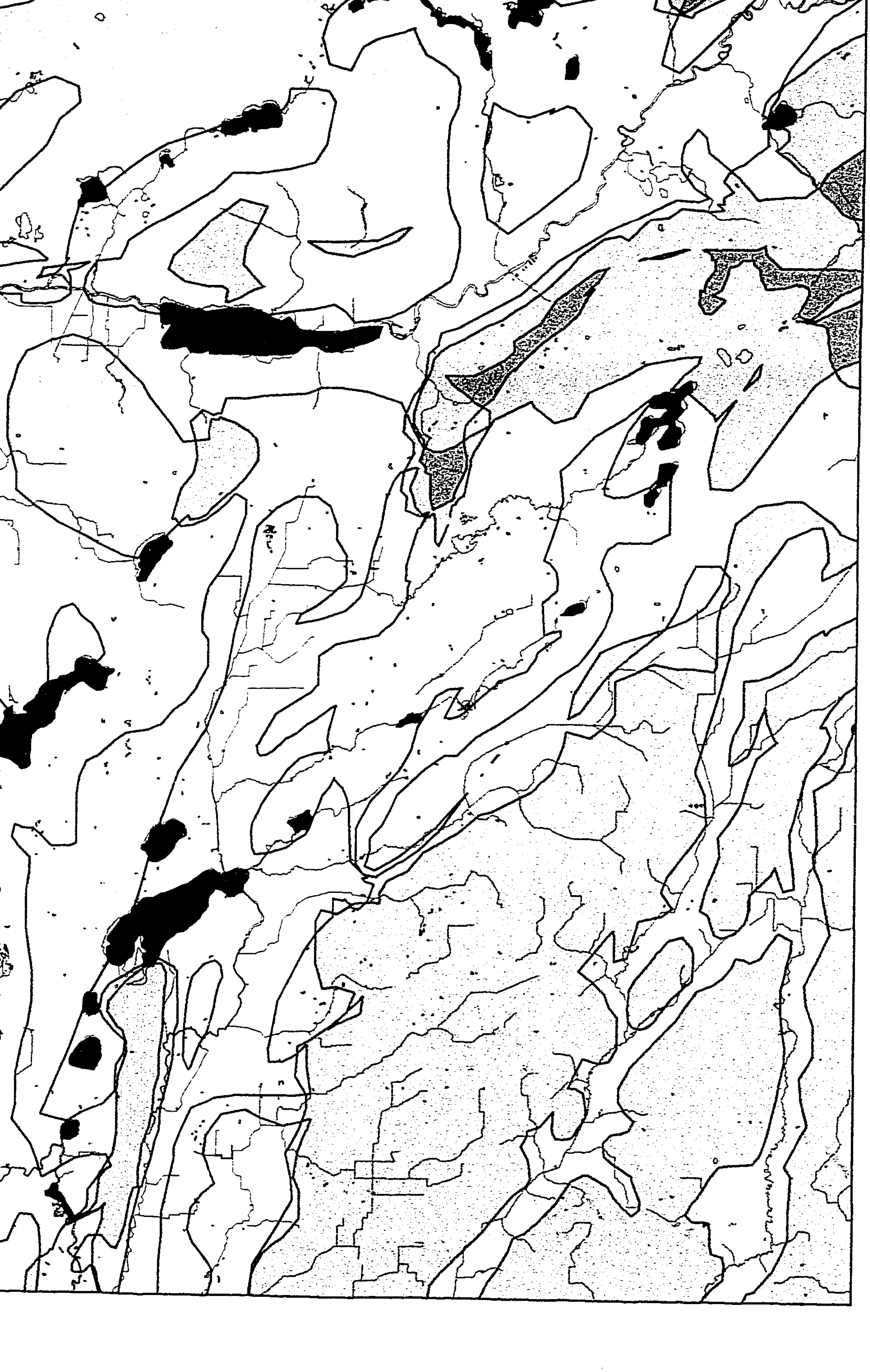


TE III)
Potential Map (DRASTIC)
County, Michigan




151-175
176-200
201
High
Water
Water
N
2
0
2
4
Miles





PLEASE NOTE:

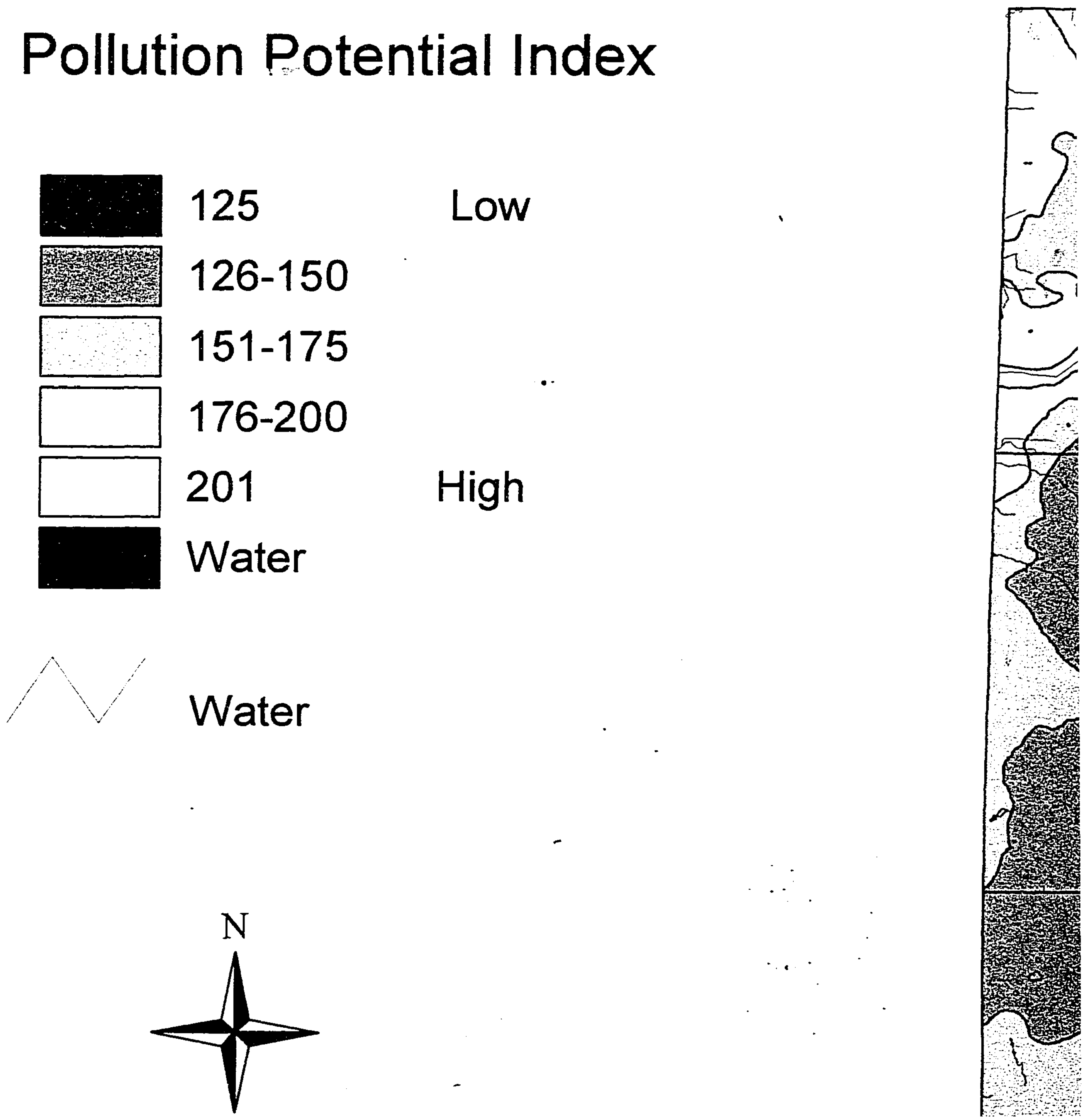
Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

UMI

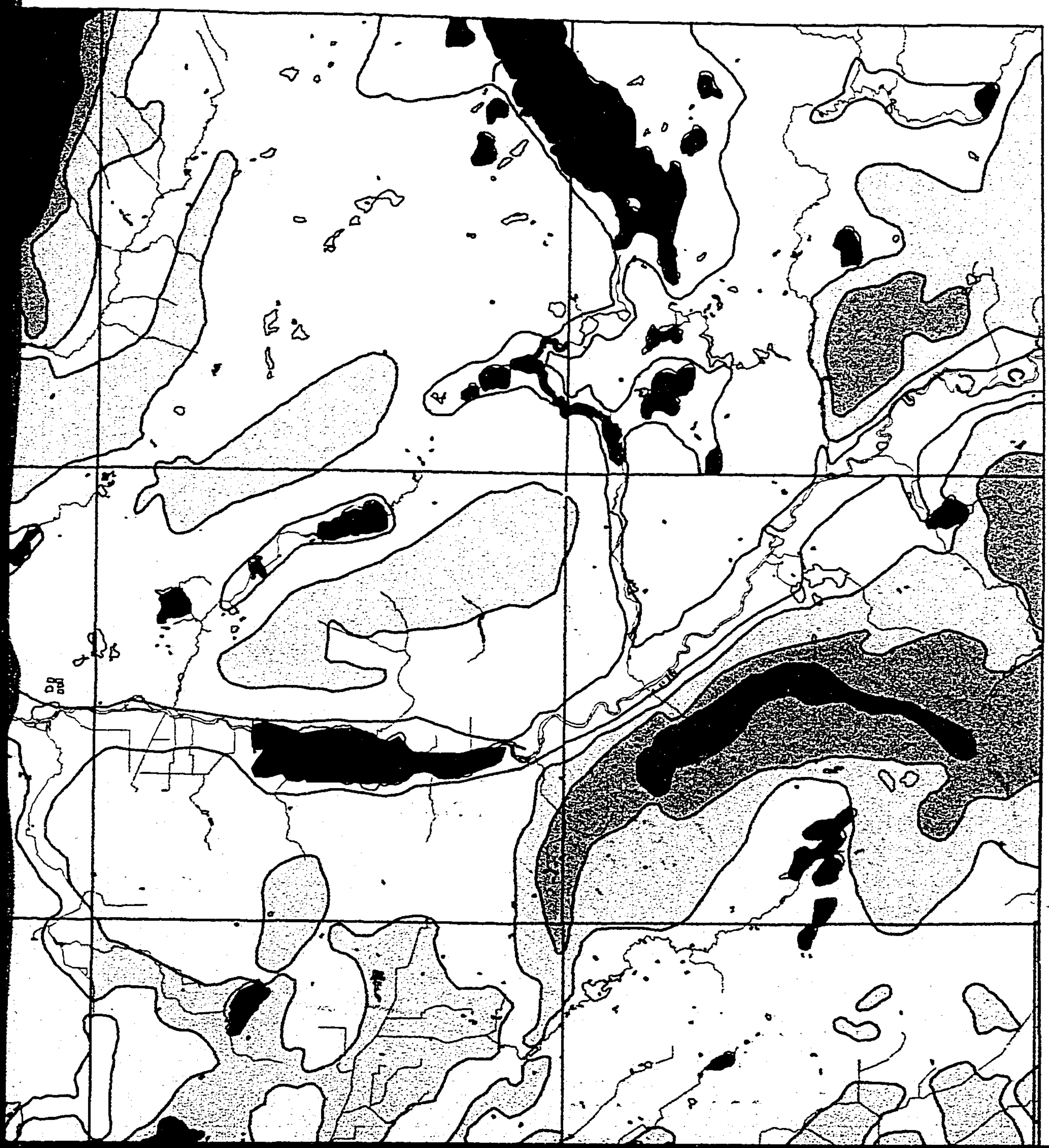

Pollution Potential Index
125
Low
126-150
151-175
176-200
201
High
Water
Water
N

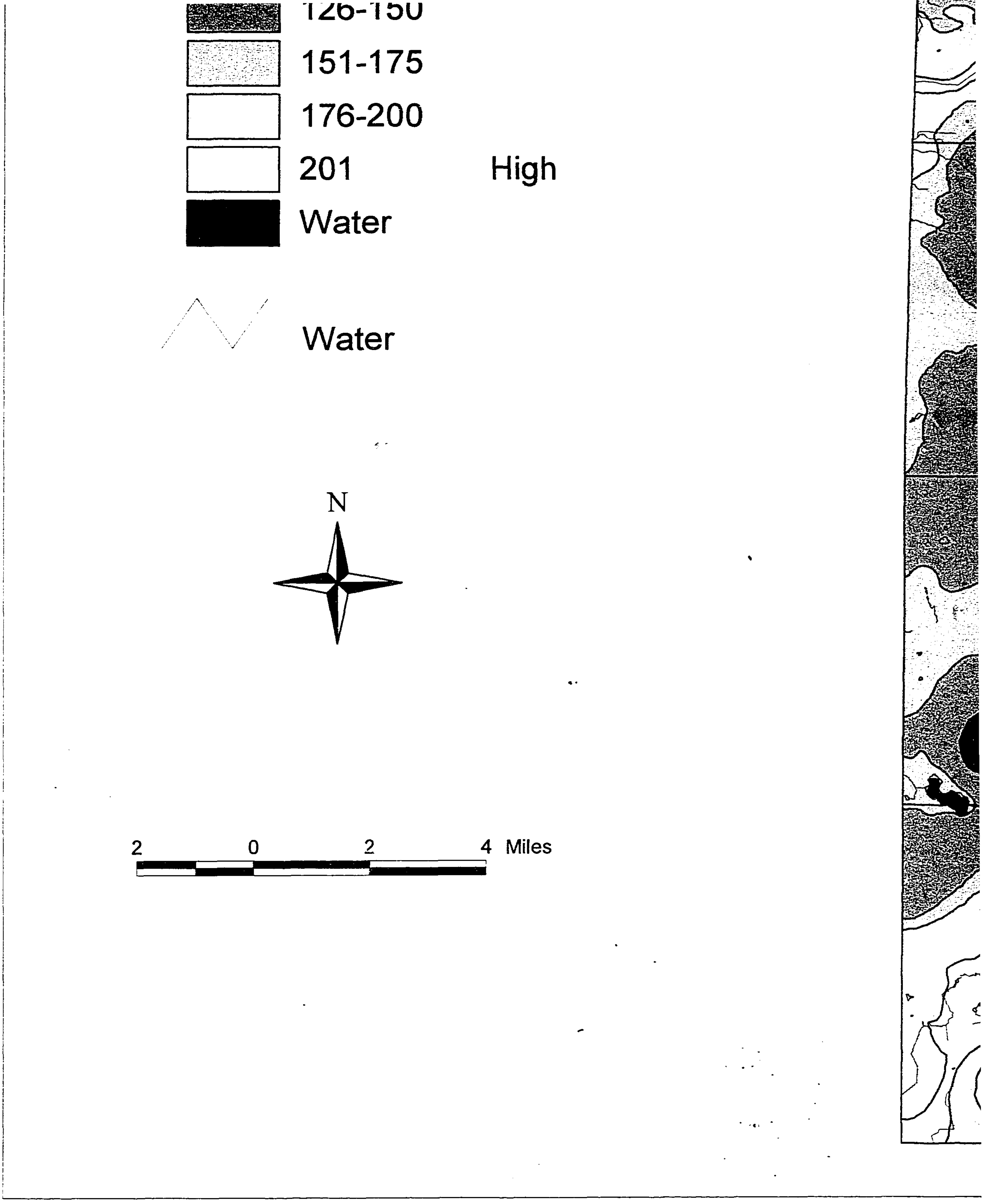
(PLATE IV)
Groundwater Pollution Potential
DRASTIC) of Kalamazoo Cou

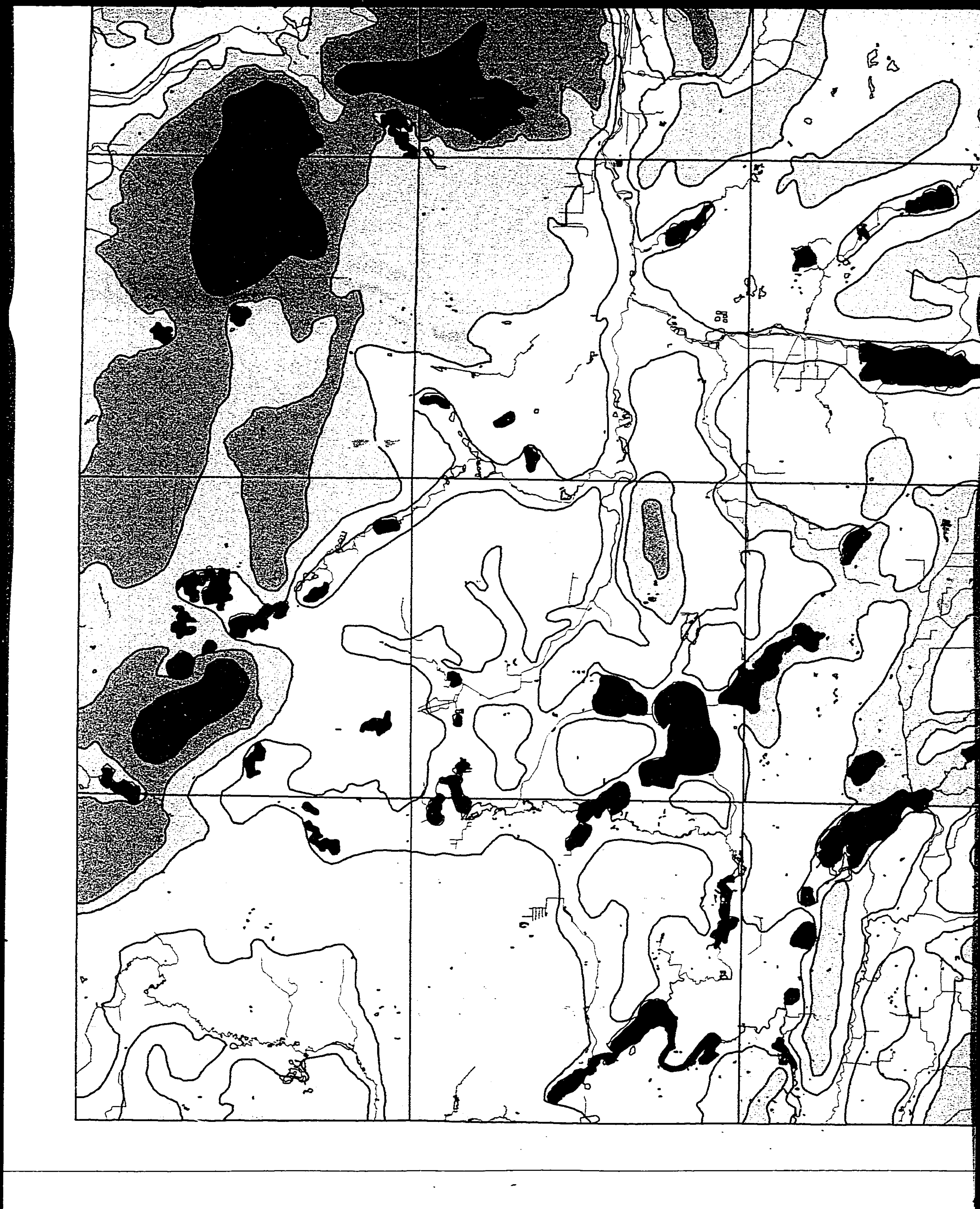
PLATE IV)

on Potential Map (Pesticide

amazoo County, Michigan




126-150
151-175
176-200
201
High
Water
Water
N
2
0
2
4
Miles



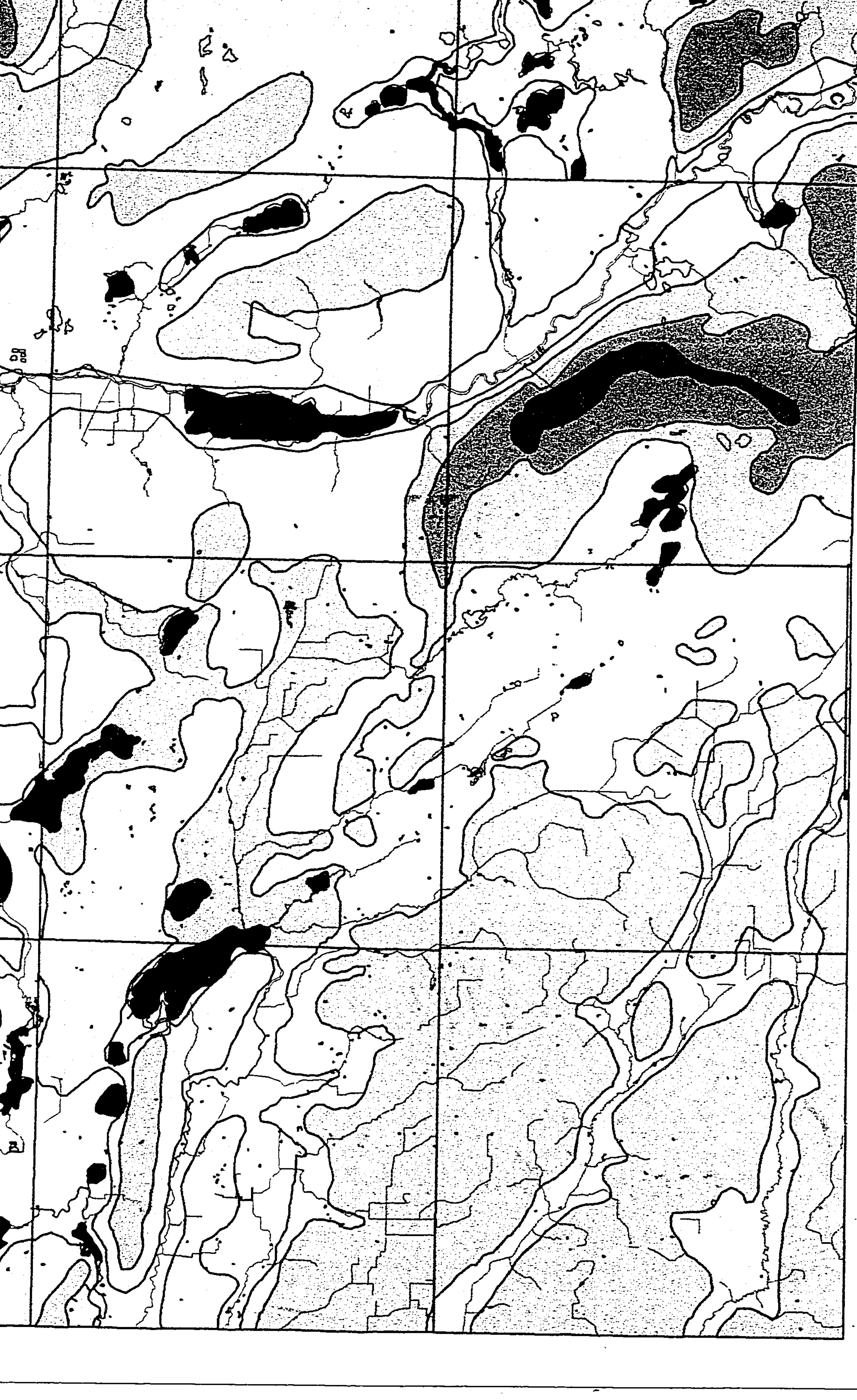
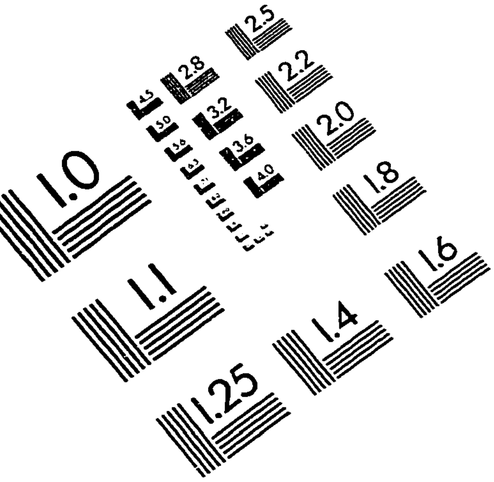
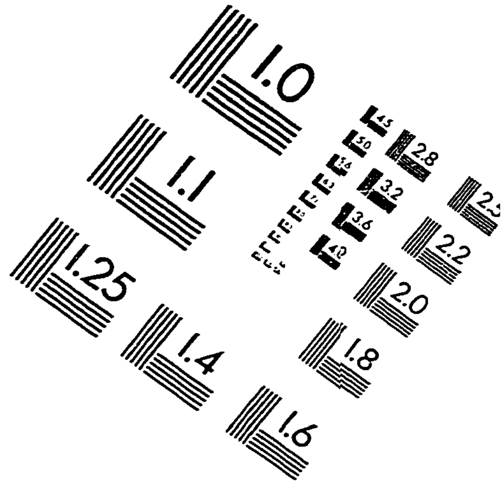
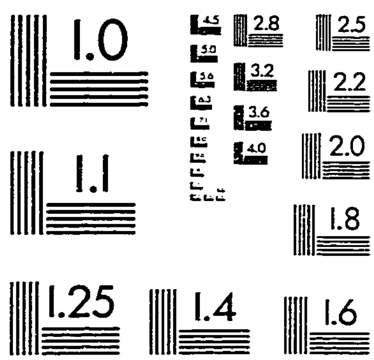
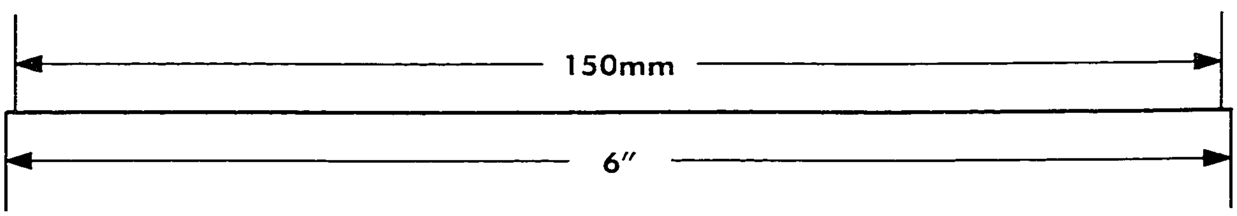


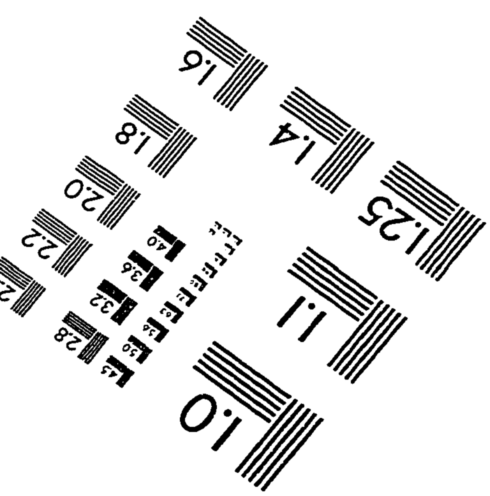
IMAGE EVALUATION TEST TARGET (QA-3)

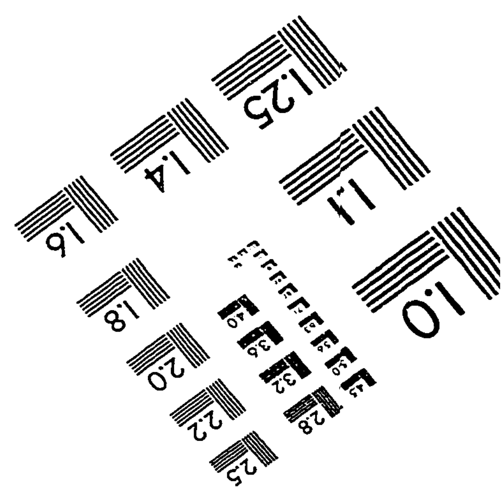












APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989