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EVALUATION OF GROUNDWATER SUSCEPTIBILITY ASSESSMENT SYSTEMS IN DANE COUNTY, WISCONSIN

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ABSTRACT

Groundwater susceptibility assessment systems rate land areas by their relative potential for groundwater contamination based on hydrogeologic or physical factors that affect groundwater flow and/or contaminant attenuation. Assessment system results are being used in policy analysis and development, in program management, in making land-use decisions, and in providing general education about hydrogeologic resources. Although agencies are using or promoting the results of different types of groundwater susceptibility assessment systems, very little research has been done to test the results of these systems.

System validation can be difficult because there is a general lack of widespread groundwater monitoring data. Even so, system susceptibility scores are frequently compared to contaminant concentrations in wells. However, assessment systems generally determine only the susceptibility of the water table to contamination and may not account for groundwater flow, saturated subsurface, or well conditions that could affect contaminant concentrations in wells. Therefore, comparison of system results to contaminant concentrations in drinking-water wells (after accounting for land-use practices) will not validate the system, but this comparison will evaluate a system's ability to assess the contamination of drinking-water wells.

For this study, we determined whether groundwater susceptibility assessment systems could predict atrazine contamination of rural drinking-water wells in Dane County, Wisconsin. The systems selected include the following: DRASTIC, Wisconsin Susceptibility Model (WISM), Soil Contaminant Attenuation Model (SCAM3), Farm-A-Syst, and SEEPPAGE. The results of two other systems, Pesticide DRASTIC and a county-scale version of WISM, known as WISM-CO, were also evaluated. The objectives of this study were to 1) use GIS techniques and databases to calculate susceptibility scores for the seven assessment systems, 2) compare the results of the systems with each other, 3) compare the results of the seven assessment systems with atrazine concentrations to assess their ability to predict atrazine contamination in drinking-water wells, and 4) identify the causes for differences in the various systems' predictions.

We calculated assessment system susceptibility scores using hydrogeologic characteristics over the zones of contribution (ZOCs) of 325 drinking-water wells. The geographic information system (GIS) PC ARC/INFO was used to summarize each system's land-use and hydrogeologic parameter information over each ZOC and to calculate system susceptibility scores. We evaluated assessment system results by comparing each system's scores, atrazine concentrations in wells, and total atrazine applications in associated ZOCs. Finally, we examined the ability of systems to assess the atrazine contamination of drinking-water wells in regions with specific geologic or hydrogeologic characteristics.

We concluded that, in general, none of the seven susceptibility systems were successful in predicting rural drinking-water well contamination by atrazine in Dane County.

After accounting for atrazine application rates in each ZOC, we found no consistent relationships between assessment system scores and atrazine detections.

Higher rates of atrazine application increased the number of atrazine detections irrespective of the system susceptibility categories. We also found that the systems rate ZOCs in regional discharge areas as more susceptible than average, based on the types of surface and subsurface materials generally found in discharge areas. However, discharge areas have been found to have fewer atrazine detections (and presumably lower susceptibility) than other areas. We also found more atrazine detections for ZOCs located in moraines, and suggest that this is caused by increased internal drainage and thus greater groundwater recharge. Therefore, the prediction of drinking-water susceptibility to contamination, and possibly groundwater susceptibility to contamination, may be improved by incorporating information about the groundwater flow system.

The delineation of regional hydrogeologic flow systems, as an alternative to or in conjunction with susceptibility assessment systems, may be useful in determining a region's susceptibility to groundwater contamination. In addition, vulnerability analyses that identify potential sources of groundwater contamination may improve predictions of the contamination of drinking-water wells. Finally, accounting for atrazine application amounts to ZOCs may be more useful than using susceptibility scores in predicting atrazine detections.

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INTRODUCTION

Project Background

Groundwater is an important source of drinking water in the United States; in 1984, it was estimated that over ninety percent of public-water supplies obtained their water from groundwater (Aller *et al.*, 1987). In Wisconsin, seventy-five percent of residents depend on groundwater for drinking water (WDATCP and WDNR, 1989). Over the last two decades, concern for maintaining contaminant-free groundwater has grown. Human activities have introduced chemicals or contaminants in groundwater from both point source releases (such as municipal landfills and underground storage tanks) and from non-point contamination sources (such as pesticide applications). Several state-wide studies have been conducted to examine the extent of contamination in drinking-water wells. A study by Illinois state agencies found that the occurrence of agricultural chemicals in private rural wells averaged 23% (Schock *et al.*, 1992). A study in Wisconsin determined that 29% of wells sampled in the south central agricultural reporting district had detectable concentrations of the herbicide atrazine (LeMasters and Doyle, 1989). Because contaminated groundwater clean-up is very expensive and may take a long time (National Research Council, 1993), strategies have been developed to protect drinking-water supplies by preventing contamination.

One component of such strategies is the identification of the relative susceptibility of different land areas to groundwater contamination. Groundwater susceptibility, also called contamination potential or sensitivity of groundwater to contamination, refers to the ease with which contaminants can move from the land surface to the water table and is based on the types of surface and/or subsurface materials in the area. Although susceptibility is not an absolute measurable property, it is assumed to provide an indication of the relative likelihood that a contaminant applied at the land surface will reach the groundwater. The terms susceptibility and vulnerability have been used interchangeably in some studies; however, in this document, we define vulnerability to be the relative likelihood that groundwater could become contaminated after accounting for land-use information in addition to susceptibility conditions.

By 1990, forty-four states have, or were in the process of adopting, groundwater protection strategies; 38 states have programs to classify or map groundwater supplies that are susceptible to contamination (U.S. EPA, 1990). Presently, the United States Environmental Protection Agency (U.S. EPA) is helping individual states to develop Comprehensive State Ground Water Protection Programs as well as State Management Plans to protect groundwater from pesticide contamination. Both programs require a state to assess sources of potential groundwater contamination. State Management Plans require that information should be obtained about both hydrogeologic characteristics and the potential for contaminant leaching; this information may be determined, in part, with the use of groundwater susceptibility assessment systems (U.S. EPA, 1993).

Groundwater susceptibility assessment systems have been used to rate land areas by their relative potential for contamination based on hydrogeologic or physical factors that affect groundwater flow and/or contaminant attenuation. The systems intend to provide information about a region's hydrogeologic characteristics and contamination susceptibility on a general, non site-specific basis. Their results can be used in policy analysis and development, program management, making land-use decisions, and providing general education about hydrogeologic resources (National Research Council, 1993). Although agencies are using or promoting the results of different types of groundwater susceptibility assessment systems for decision-making, very little research has been done to test or compare the various systems.

System validation requires the comparison of assessment system results with field measurements. Although field validation for assessment systems is not possible for every location, it can increase confidence that system results are reliable (U.S. EPA, 1993). In general, system testing can help identify a level of confidence in the form and structure of the system and will be able to provide insight into an assessment system's appropriate use (National Research Council, 1993). System validation can be difficult because there is a general lack of widespread groundwater monitoring data. Even so, system scores are often compared to contaminant concentrations in wells. However, assessment systems generally determine only the susceptibility of the water table to contamination and may not account for groundwater flow, saturated subsurface, and well conditions that could affect contaminant concentrations in wells. Therefore, comparison of system scores to contaminant concentrations in drinking-water wells (after accounting for land-use practices) will not validate the system, but this comparison will evaluate a system's ability to predict the contamination of drinking-water wells.

Groundwater susceptibility assessment systems use different methods to assess the susceptibility of groundwater to contamination. The assessment systems selected for analysis in this study primarily use parameter weighting/rating methods to calculate relative numerical scores for susceptibility. These systems are based on hydrogeologic parameters that were selected by system developers, depending on the availability of hydrogeologic information or according to the opinions and knowledge of experts or groups of experts. The systems provide numerical scores for different types or values of hydrogeologic parameters and these parameter scores, along with multiplicative weighting factors, are used to calculate final numerical values for contamination potential. Assessment system results, determined from parameter weighting/rating methods, can be developed relatively easily using a geographic information system (GIS) to manipulate, store, and retrieve information from a variety of sources and map scales. The five groundwater assessment systems selected for evaluation were: DRASTIC (Aller *et al.*, 1987), WISM (Schmidt, 1987), SCAM3, which was modified in this study after SCAM from Zaporozec (1985) and Sutherland and Madison (1987), Farm-A-Syst (Cates and Madison, 1991), and SEEPPAGE (Moore, 1989). The results of two other systems (related to DRASTIC and WISM), Pesticide DRASTIC (Aller *et al.*, 1987), and a county-scale version of WISM, known as WISM-CO (developed in this study), were also evaluated. These systems were selected because federal agencies are promoting the use of some (DRASTIC, Pesticide DRASTIC, Farm-A-Syst, and SEEPPAGE); others (WISM, SCAM3, and Farm-A-Syst) were developed, at least in part, by organizations in Wisconsin and, therefore, are being promoted locally.

DRASTIC and Pesticide DRASTIC, developed by the National Water Well Association and promoted by the U.S. EPA, have been used to create maps displaying relative groundwater contamination potentials for states and counties. DRASTIC results are intended to be used as a screening tool or to develop hydrogeologic zoning maps that determine whether certain facilities are, or may be, located in areas which are generally susceptible to the release of surface contaminants. One study in Nebraska examined the frequency of VOC (volatile organic chemical) contamination of community water wells as compared to DRASTIC contamination potential categories. They found a positive correlation between the frequency of VOC contamination incidents and the DRASTIC susceptibility categories of surficial aquifers (Kalinski *et al.*, 1994). However, a study by Curry (1987) found no statistical correlation between DRASTIC scores at specific sites and water-quality data for a drainage basin in karstic terrain. A study by the U.S. EPA (1992) examined whether DRASTIC scores for either counties or sub-county areas were associated with detections of pesticides or nitrate in drinking-water wells. Their study concluded that DRASTIC scores generally had not identified drinking-water wells with a greater likelihood of detections (U.S. EPA, 1992).

The WISM, or Wisconsin Susceptibility Model, developed by the Wisconsin Department of Natural Resources (WDNR) and the Wisconsin Geological and Natural History Survey (WGNHS), was used to create a 1:1,000,000-scale groundwater susceptibility map for the state of Wisconsin (WDNR and WGNHS, 1987). The map was developed as an educational product to provide information about groundwater susceptibility to contamination on a general non-site specific basis. The WISM-CO system, developed in this project, uses the same susceptibility ranking scheme as the WISM system; however, WISM-CO is based on county-scale sources for the same hydrogeologic information.

The Soil Contamination Attenuation Model (SCAM), originally developed by F. Madison (Zaporozec, 1985), (Sutherland and Madison, 1987), was designed specifically to rank the contaminant attenuation potential of soil. SCAM has been used to create soil contaminant attenuation maps for some counties in Wisconsin and is presently being used to site septic systems in Pennsylvania. We included SCAM in the evaluation of groundwater susceptibility assessment systems, although some contaminant attenuation processes may occur below the soil solum. SCAM3, the third version of SCAM, was created during this project to refine some of the parameter definitions in SCAM.

Farm-A-Syst, based in part on soil parameters in the SCAM system, was jointly developed by University of Wisconsin-Extension, Minnesota Extension Service, and U.S.

EPA. Farm-A-Syst worksheet evaluations are used to summarize groundwater susceptibility assessments and to develop voluntary action plans to reduce identified high groundwater contamination risks for farmsteads. In addition, the worksheet also educates owners about the surface and subsurface materials underlying their farmstead. Presently, worksheets have been, or are being, developed by 21 states (National Farm-A-Syst, 1993).

SEEPPAGE, developed by the United States Department of Agriculture Soil Conservation Service (SCS), includes hydrogeologic parameters similar to DRASTIC and soil parameters similar to SCAM. It was intended to be used by SCS technicians so that they could provide farmstead owners with groundwater susceptibility assessments.

Evaluation of the susceptibility assessment systems was made possible by efforts from a previous Dane County atrazine study conducted at the WGNHS. The results of that study are summarized in an open-file report titled *Hydrogeologic and Land-Use Controls on Atrazine Detections in Dane County, Wisconsin* (Muldoon *et al.*, 1994). That study developed the geographic information system (GIS) database that provided information necessary for assessment system testing.

Project Objectives

The objectives of this study were to 1) use GIS techniques and databases to calculate susceptibility scores for seven assessment systems, 2) compare the results of the systems with each other, 3) compare the results of the seven groundwater susceptibility assessment systems with atrazine concentrations to assess their ability to predict atrazine contamination in drinking-water wells, and 4) identify the causes for differences in the various systems' predictions. The project was conducted in three steps.

1. Summarize hydrogeologic information for each assessment system in the zones of contribution (ZOCs) of atrazine-sampled wells.
2. Calculate the seven assessment susceptibility scores using information from the previous step.
3. Examine the relationships among system scores, atrazine concentrations in wells, and atrazine application amounts in ZOCs.

Chapter II

ASSESSING GROUNDWATER SUSCEPTIBILITY

General Groundwater Susceptibility Assessment Methods

There are several general categories of methods that have been used to assess the susceptibility of groundwater to contamination. Parameter weighting/rating methods generalize existing data by assigning numerical rates or scores to different types or values of hydrogeologic parameters, such as depth to groundwater. These systems then calculate a final numerical value for contamination potential from a combination of the parameter scores. Other systems that assess groundwater susceptibility rely on hydrogeologic-setting classification methods, empirical models, and simulation models. Hydrogeologic-setting classification methods compare the hydrogeologic conditions of a study area with the hydrogeologic conditions of areas that have been found to be sensitive to contamination. These methods are based on the assumption that areas with hydrogeologic conditions would be equally sensitive to contamination. Empirical models involve the development of a formula that relates the observed concentration or occurrence of contaminants in soil and/or groundwater to various physical parameters. Simulation models develop mathematical expressions of processes related to the transport of contaminants to an aquifer in order to predict contaminant concentrations.

Hydrogeologic Influences on Susceptibility

The groundwater susceptibility assessment systems selected for analysis in this study primarily use parameter weighting/rating methods to calculate numerical scores for contamination potential. The DRASTIC system also provides general hydrogeologic parameter scores for areas with similar hydrogeologic settings. The assessment systems differ from each other in hydrogeologic information used (Table 1) and the numerical ranking schemes used to calculate final contamination potential numbers. In general, groundwater susceptibility assessment systems calculate scores based on hydrogeologic or physical factors that affect groundwater flow and/or contaminant attenuation, according to expert opinion and knowledge. However, some hydrogeologic parameters are included based on the availability of information rather than the importance of predicting the occurrence of contamination. The following sections define each of the general hydrogeologic factors in Table 1 and discuss the affect each factor is assumed to have on the movement of a contaminant to the water table.

Soil Characteristics

Soil characteristics affect biological, physical, and chemical processes (such as adsorption or degradation) in soils that act on a pollutant. Soil characteristics may also affect the amount of infiltration and thus the ability of a contaminant to move vertically into the vadose zone. In general, soils with higher porosity (sandy soils) provide less surface area for sorption than less porous soils such as clay. Soils with large pore spaces also tend to have high contamination potentials because large amounts of water, and thus contaminants, can move rapidly down through the soil and into groundwater. In addition, chemical and biological breakdown of contaminants that are attached to soil particles, occur mostly in soils that tend to be warm, moist, high in organic matter, and well aerated (Cates and Madison, 1991). Thus, soils that are well drained, fine textured, and have high amounts of organic matter are assumed to have low contamination potentials.

Table 1. Summary of hydrogeologic factors used in each groundwater susceptibility assessment system.

HYDROGEOLOGIC FACTORS	DRASTIC	WISM	SCAM3	Farm-A Syst	SEEPPAGE
Soil Characteristics	X	X	X	X	X
Geologic Materials		X		X	
Depth to Water	X	X		X	X
Vadose Zone Characteristics	X				X
Aquifer Characteristics	X				X
Recharge	X				
Land Slope	X				X
Horizontal Distance to Contaminants					X

Geologic Materials

Geologic materials used by the assessment systems can be described by two types of hydrogeologic parameters: 1) the type and thickness of both unlithified or lithified materials that underlie the soil or 2) just the type of and depth to the lithified material (bedrock) that underlies the soil and surficial deposits. Geologic materials can either be saturated or unsaturated. Bedrock type refers to the lithology of the uppermost rock layer, while depth to bedrock is the distance from the land surface to the top of the bedrock. The type and thickness of geologic materials affect both groundwater (and contaminant) flow paths and rates. In general, high permeability (which is increased by fractures in the material) and small depth to bedrock indicate higher contamination potential because there is potentially less time for attenuation processes to occur.

Depth to Water

The depth from the land surface to the water table is the vertical distance a contaminant must travel to reach the water table. The assumption is that the greater the depth, the greater the opportunity for contaminant attenuation processes to occur and thus the lower the contamination potential.

Vadose Zone Characteristics

The vadose zone is the unsaturated (or discontinuously saturated) unlithified or lithified subsurface material located above the water table. High permeability and thin zone thickness indicate high contamination potential because there is potentially less time for attenuation processes to occur.

Aquifer Characteristics

An aquifer is the saturated subsurface material that will yield sufficient quantities of water for use. Both the lithologic composition of the aquifer and its hydraulic conductivity can affect groundwater movement. Groundwater (and thus contaminants) can be transmitted through pore spaces (primary porosity) or through fractures developed after the material was formed (secondary porosity). The aquifer lithology affects the flow path that contaminants follow. In general, the larger grain sizes and the more fractures within an aquifer, the higher the permeability and hydraulic conductivity and, therefore, the lower the attenuation capacity of the aquifer.

Recharge

Net recharge is the amount of water per unit area of land that infiltrates and percolates to the water table. Recharge is the primary vehicle for leaching and transporting contaminants to the water table. In general, the greater the recharge, the greater the contamination potential. This statement is true until the amount of recharge is great enough to cause dilution of the contaminant; however, net recharge ranks for DRASTIC (the only assessment system that uses net recharge) do not include a dilution factor.

Land Slope

The land slope is a measure of the average slope (in percent) of the ZOC land surface. The slope of the land surface affects the amount of runoff. In general, flatter the slope, the less runoff or the greater amount of recharge and thus the higher contamination potential.

Horizontal Distance to Contaminants

The horizontal distance to contaminants is defined as the horizontal distance from the point of interest (which could be a well) to the site of contamination. Distance affects the amount of time available for attenuation processes to occur. In general, the greater the distance, the greater the opportunity for attenuation processes to work and thus the lower the contamination potential.

Chapter III

GENERAL METHODS

This chapter provides a brief description of the methods used to calculate assessment system scores, acquire atrazine concentrations in wells, and estimate atrazine application amounts in ZOCs. Several methods were developed and completed by other studies, while others were developed from this project.

Use of a GIS

Geographic information systems (GIS) are used to analyze, display, manipulate, and retrieve spatially related data. The atrazine study by Muldoon *et al.* (1994) compiled soils, geologic, hydrogeologic, and cartographic data in Dane County in a GIS using PC ARC/INFO software (Environmental Systems Research Institute, 1990). Information about the location of domestic drinking-water wells and atrazine concentrations in those wells was also incorporated in the GIS. The study used the GIS to estimate the area of land contributing water (called zones of contribution, or ZOCs) to the atrazine-sampled wells and to estimate historical rates of atrazine applications in each ZOC. In our study, the GIS was used to access and analyze these data, develop new information to calculate groundwater susceptibility assessment scores, and display results.

Atrazine Sampling and Testing

Muldoon *et al.* (1994) obtained results from water-quality tests for 397 private water supply wells in Dane County (see Figure 1). Water-quality data were used from three different studies: the Grade A Dairy Farm Well Water Quality Survey (LeMasters and Doyle, 1989), the Rural Well Survey (LeMasters, 1990), and a study by Bradbury and McGrath (1992). Each water-quality study noted the concentration of one contaminant found in Wisconsin wells – the agricultural herbicide atrazine.

The laboratory analysis technique for atrazine varied with each study and sampling frequency was not consistent. While most wells were sampled only once, some were sampled multiple times. Most samples collected as part of the Rural Well Survey were analyzed using the inexpensive immunoassay procedure that measures concentrations of selected triazine-based compounds. The detection limit for this analysis method was 0.1 μg/l. Samples collected as part of the Grade A Dairy Farm Survey were analyzed by the Wisconsin Department of Agriculture, Trade and Consumer Protection (WDATCP) Bureau of Laboratory Services using the neutral extractable method developed by the State Laboratory of Hygiene (method 1200). The detection limit for atrazine was 0.15 μg/l. The samples used by Bradbury and McGrath were analyzed by the WDATCP Bureau of

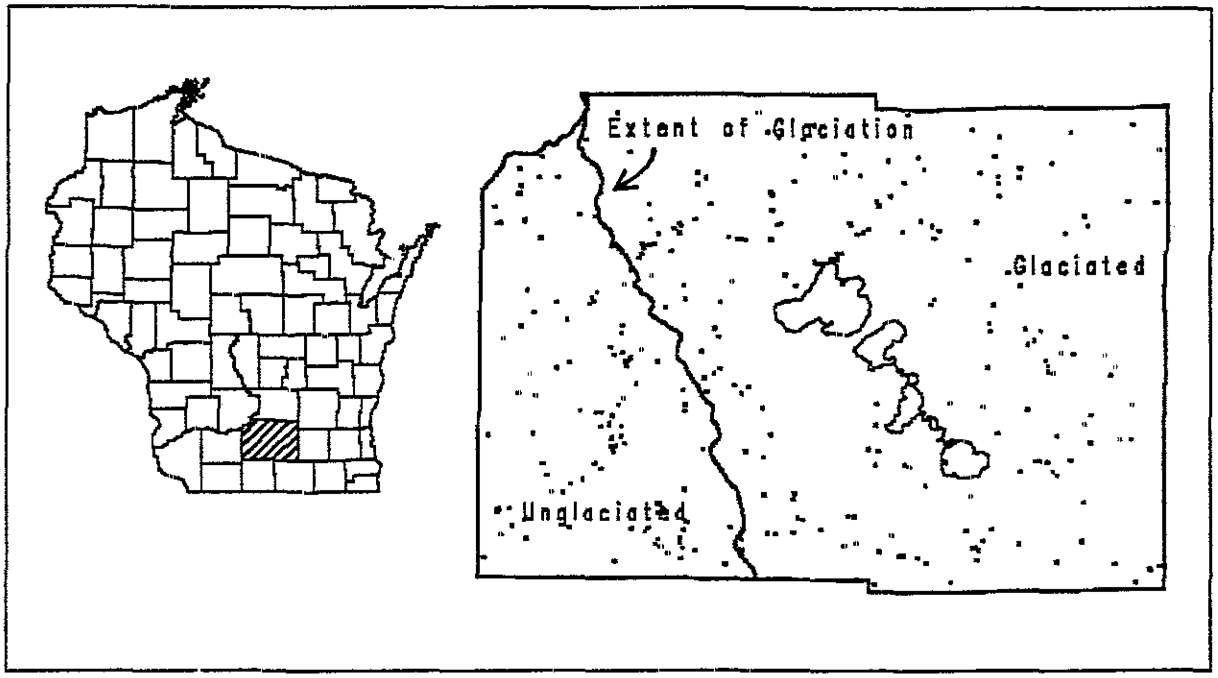

Figure 1. The location of Dane County in Wisconsin and the extent of glaciation. Points show the location of 325 wells; the position of the largest lakes are shown in the center of the county (modified from Muldoon *et al.*, 1994).

Laboratory Services using method 1200; results included measures of atrazine and metabolite concentrations. Again, the detection limit for parent atrazine was 0.15 µg/l. As part of the Rural Well Survey, WDATCP analyzed replicate samples in order to compare results from different analysis techniques. In general, the immunoassay technique provided reliable estimates of atrazine concentration except for samples with high atrazine concentrations; in these cases, the method underestimated atrazine values (LeMasters, 1990). Since the different analysis methods do not provide directly comparable measures of atrazine concentrations, the investigators selected which values to use: for samples analyzed by the neutral extractable method, they chose to use parent atrazine concentrations, for samples analyzed by the immunoassay procedure, they used the concentration of triazine-based compounds, and if more than one analysis result was available for a given well (either total triazine concentration or parent atrazine concentration), they chose to use the highest value for their analyses. As a simplification they refer to all sampling results as "atrazine values" or "atrazine concentrations" (Muldoon *et al.*, 1994).

ZOC Delineation and Selection

Muldoon *et al.* (1994) estimated the land area of the ZOC around each atrazine-sampled well that contributed water to the well (*see* Figure 2 for an example of ZOCs). The ZOCs for each well were calculated using the U.S. EPA Wellhead Protection Area (WHPA) model (Blandford and Huyakorn, 1990), a two-dimensional, groundwater flow model that assists with Wellhead Protection Area delineation. The GPTRAC module, which tracks particles through the groundwater flow system, was used to delineate the ZOCs. They used hydrogeologic parameters (hydraulic head, aquifer transmissivity, porosity, and aquifer thickness) to execute GPTRAC and calculate ZOCs for the selected time period of 15 years. Finally, they edited the ZOC boundaries and digitized them into PC ARC/INFO.

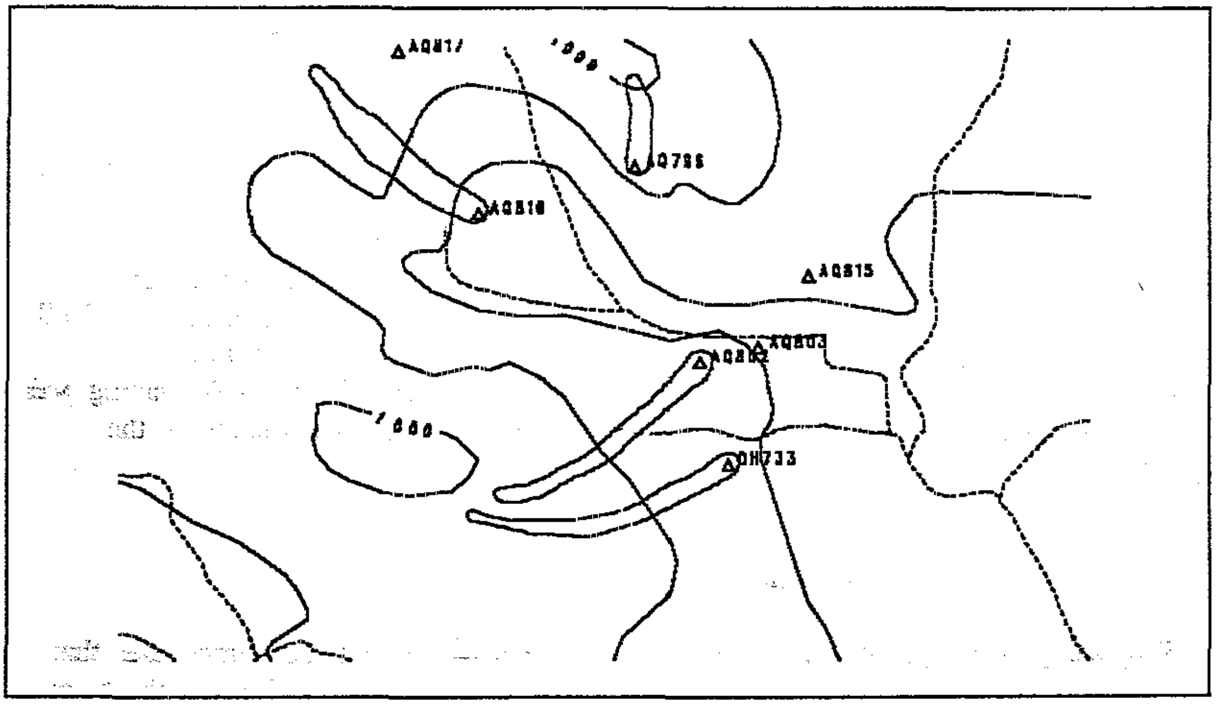

Figure 2. Example of calculated ZOC delineations (with water-table contours) in Dane County. Triangles represent wells; the polygon around each triangle is the ZOC (modified from Muldoon *et al.*, 1994).

Within each ZOC boundary, Muldoon *et al.* (1994) identified and delineated agricultural fields and crop types (from 1979 to 1990) using air photos and rural land-use information. The land-use practices were used to estimate a total atrazine application load in each ZOC over 1979 to 1990. Atrazine applications were calculated from crop rotations by estimating typical rates of atrazine for a variety of crops. From the original 397, 325 wells were selected in order that all had a ZOC with medium to high confidence in ZOC delineation, an atrazine application load greater than zero, and a ZOC without identified point sources of atrazine contamination. Thus, wells with ZOCs that were composed of entirely forested or urban areas for the 12 years, or areas having no atrazine applied, were not selected. The points on Figure 1 show the location of these 325 sampled wells.

Our study used the ZOC delineations, atrazine concentrations in wells, total atrazine applications in ZOCs as well as other resource data developed in the Dane County atrazine study by Muldoon *et al.* (1994). For each assessment system, susceptibility scores were calculated using hydrogeologic parameters in the ZOC around each sampled well. We hypothesized that the calculation of each system's final scores for the area in the ZOC would provide the most accurate prediction of the contamination potential of the ZOC.

Methods Used to Acquire Assessment System Results

The groundwater susceptibility assessment scores were calculated for each of the 325 ZOCs delineated around atrazine-sampled wells. In order to calculate these scores, PC ARC/INFO was used to help summarize, store, manipulate, and retrieve hydrogeologic information for each ZOC, including data on soils and subsurface characteristics, depth to water, recharge amounts, and distance from wells to fields with atrazine applications. Well constructor's reports were available for 137 of the selected wells. Geologic and hydrogeologic data for the other 188 wells were interpolated from adjacent wells having well constructor's reports. Over 3,000 well constructor's reports were computerized in the project GIS.

Limitations and Assumptions

This study evaluates the assessment systems using assumptions and procedures that could affect the calculation of contamination potential scores and may limit applicability of study results. Major procedural limitations, listed below, are discussed in following paragraphs.

1. Groundwater susceptibility and susceptibility of drinking-water wells to contamination are not equivalent.
2. There are limitations with using generalized hydrogeologic data.
3. ZOC boundaries have limited accuracy.
4. There are limitations with the use of atrazine as a contamination indicator.

Groundwater Susceptibility versus Susceptibility of Drinking Water

The assessment systems were designed to determine the susceptibility of the water table to contamination, not to predict the contamination susceptibility of domestic-well water. However, because of a general lack of widespread groundwater monitoring data, assessment system scores are compared to contaminant concentrations in wells, which produce water from below the water table. In this study, we examined the ability of the systems to predict atrazine contamination in private wells after estimating atrazine application rates in the ZOCs. Depending on assessment system design, systems are more likely to reflect contamination susceptibility for shallow wells finished near the water table than for deeper wells finished far below the water table. Therefore, comparison of systems and contaminant concentrations in wells (which may be affected by groundwater flow, saturated subsurface or well conditions) will not validate the results of the systems, but this comparison will evaluate the ability of the systems to predict the contamination of drinking-water wells.

Generalized Data

This study sometimes used more detailed information for the soil materials than the systems required. We evaluated soil characteristics using soil map units and a soil score was then calculated from the scores of the individual soil map units in the ZOCs. However, some systems (DRASTIC, WISM) were developed to use soil associations and thus our generalized soil score, based on soil map units, could alter the calculated system scores or change the results of statistical analyses.

The assessment system scores were calculated for some ZOCs without well constructor's reports. Hydrogeologic parameter data for wells without well constructor's reports were interpolated from nearby wells having well constructor's reports. Depending on the variability of the surface and subsurface materials, the interpolation process should be more accurate where wells without well constructor's reports were close by and at similar elevations. Because these conditions could not always be met, hydrogeologic parameter information for wells without a well constructor's report is of variable quality. Therefore, the use of these data may affect assessment system susceptibility analyses.

ZOC Assumptions

The Zone of Contribution, or ZOC, is defined as an estimation of the land area that contributes water to the well. The ZOCs were delineated based on two-dimensional, homogeneous, isotropic groundwater flow and a 15-year travel time for water (Muldoon *et al.*, 1994). As some of these assumptions were not always met, we have different confidences in the ZOCs delineations.

In addition, we assumed that the ZOC was an estimate of the land area that contributes water (and thus contaminants) to the well. We did not include well construction information, such as the placement of casing depth in relation to water-table depth or the condition of well casings and seals. However, experience and studies indicate that well construction can influence the occurrence of pesticide contamination in domestic wells (Hallberg *et al.*, 1992; Schock and Mehnert, 1991). We did not separate wells based on similar well construction characteristics (such as age and depth) because we did not have well constructor's reports for over half of the wells and preliminary analyses suggested that the sample sizes of the remaining wells were too small to use in statistical analyses.

The Use of Atrazine as a Contamination Indicator

Atrazine was registered for use on corn in Wisconsin in 1960 (Baldock *et al.*, 1993). It has been the most widely used herbicide in Wisconsin (Wollenhaupt *et al.*, 1990), although atrazine is classified as a possible human carcinogen. In 1989, it was used on 80% of Wisconsin's land used for corn production (WDATCP and WDNR, 1989). In Dane County, atrazine use was widespread and atrazine residues have been found to persist in groundwater for at least 10 years (Bradbury and McGrath, 1992); in another region of the United States, atrazine metabolites have been detected in groundwater that is at least 25 years old (Denver and Sandstrom, 1991).

Because atrazine use was widespread across Dane County, this study was able to use wells that had at least some atrazine application in their associated ZOCs. We used atrazine concentration data from a large number of well samples, collected during a relatively short time period, that were distributed across Dane County. In addition, we were able to use only wells contaminated through non-point application to cropland because the study by Muldoon *et al.* (1994) eliminated the wells that were most likely contaminated through atrazine point sources (such as mixing and loading sites). Our information about land-use practices in each ZOC was used to estimate the amount of atrazine applied over a period of time. The atrazine application estimates could then be taken into account when comparing the assessment system susceptibility scores to atrazine contamination in wells.

However, there are problems with using atrazine concentrations as a contamination indicator. Atrazine is non-conservative (that is, it is chemically active) and can be transformed by chemical and biological processes into 11 metabolites, including desethylated atrazine, and concentrations may vary temporally. In a study by Bradbury and McGrath (1992), desethylated atrazine was frequently detected in wells at greater concentrations than the parent compound and was occasionally found in well-water samples where the parent was not detected. Therefore, analyzing parent atrazine concentrations alone could significantly underestimate the extent of atrazine contamination in a given area. However, the majority of the atrazine concentrations in this study were based on triazine analyses, which include some metabolites. Furthermore, atrazine concentrations may be an inconsistent indicator of contamination because 1) well-water atrazine concentrations used in this study were not analyzed by the same analytical method (some were sampled multiple times, and some used different analysis procedures) and 2) the potential for sampling error is large because atrazine is present only in trace amounts.

Potential sources of contamination that are dispersed and not used extensively across the county would not be useful contamination indicators for county-wide contamination comparisons. Nitrate and chloride could provide a better indication of contamination. The travel time and attenuation of chloride are not affected by biological processes and thus it reflects actual groundwater movement through the environment; also, it is relatively inexpensive to determine its presence and concentrations. The nitrogen cycle is well understood and nitrate is conservative and easy to analyze. For both chloride and nitrate, however, it is more difficult (and not always possible) to estimate contaminant sources in the ZOCs and the application amounts from each source than it is to do so with atrazine.

Chapter IV

GENERAL DATA SOURCES

This chapter provides a brief discussion of the data sources and methods used to obtain hydrogeologic information for each general hydrogeologic factor defined in Chapter II. The purpose of this chapter is to decrease redundancy in descriptions of data sources and methods for assessment systems that acquire parameter information from either the same sources and/or by the same methods. Chapter V details each system specifically by providing each assessment system's parameters, parameter definitions, data sources, and methods used to calculate final scores. Information in Chapter V that would be the same as in the general category discussions (in this chapter) is referenced and differences are mentioned and discussed.

Soil Characteristics

We obtained soil information from the Soil Survey of Dane County, Wisconsin (Glocker and Patzer, 1978). Each soil map unit was examined and either the most significant soil textural layer affecting contamination potential or the entire soil map unit was evaluated. The Soil Survey contains information about 148 soil map units and 5 miscellaneous land types including: alluvial land, wet; cut and fill land; made land; marsh; and stony and rocky land. Muldoon *et al.* (1994), added three land types - gravel pits, quarry, and water, and overlayed digital soils information with each ZOC polygon in order to identify the soil map units in each ZOC.

Geologic Materials

The geologic materials were evaluated, in part, by examining either the thickness or type, or both, of the lithified and unlithified materials, regardless of saturation. For the Farm-A-Syst evaluation, a degree of fracturing for each lithologic unit was also estimated in order to fully characterize the bedrock deposits. Wells penetrating any dolomitic formations, except for the St. Lawrence Formation, were evaluated as having ZOCs with fractured bedrock; all other wells passing through bedrock were evaluated as having ZOCs with unfractured bedrock (R. Peters and B. Brown, verbal communication, 1993) .

Bedrock characteristics were interpreted from geologic maps, well constructor's reports and soil survey information. The Soil Survey of Dane County, Wisconsin (Glocker and Patzer, 1978) identifies soil map units having rock within 5 feet. For wells that did not have well constructor's reports, and for wells that had well constructor's reports but did not reach bedrock, bedrock characteristics were interpolated from the well constructor's reports of surrounding wells that were drilled into bedrock. In addition, the 1:62,500-scale bedrock geology map of Dane County (Olcott, 1972) and the 1:62,500 depth-to-bedrock map (Olcott, 1973) were used in determining bedrock characteristics.

Unlithified materials were classified as silts, lacustrine deposits, organic materials, alluvium, outwash, or till on the bases of soil parent material information from the Soil Survey of Dane County. For wells with bedrock identified as the parent material and bedrock depth greater than 10 feet, the unlithified materials were classified as *weathered* bedrock. A second, deeper unlithified material type was sometimes assigned to wells with a bedrock depth of greater than 10 feet. In general, we assumed that unlithified materials more than approximately 10 feet thick that were identified as either silts, lacustrine, organic or alluvium, were most likely underlain by till or outwash. We examined each of these wells and, where necessary, used our best judgement to select outwash or till as the second unlithified material. For analyses in our study, when two types of unlithified materials were assigned to a well, the second material type was always evaluated.

Depth to Water

Depth to water was calculated by subtracting water-table elevations from land-surface elevations for each of the 325 wells. Water-table elevations were determined by overlaying unpublished WGNHS 1:100,000-scale water-table elevation maps (with 20-ft. contour intervals) with the locations of each of the 325 wells mapped on 7.5 minute topographic quadrangle base maps. The water-table elevations for the well locations were interpolated from the water-table elevation contours. Land-surface elevation for well locations were interpolated from the 7.5 minute topographic quadrangle maps (with either 10-ft. or 20-ft. contour intervals).

Vadose Zone Characteristics

In order to evaluate the materials in the vadose zone, several types of information were used to select vadose zone material types: well depth, water-table depth, bedrock depth, and types and thicknesses of materials penetrated by the well. Well constructor's reports provided information about well and bedrock depths; for wells that did not have these reports, information was interpolated from nearby wells with well constructor's reports. Water-table depths were determined using the method described above. Unlithified and lithified materials penetrated by the well were determined using the methods described in the "Geologic Materials" section. Well, water-table, and bedrock depths were used to create a file that contained the thicknesses of unlithified and lithified vadose zones.

The assessment systems do not require detailed lithologic information for completely lithified vadose zones because different lithologies (such as sandstone and shale, dolomite, and sandstone) are assigned the same typical numerical score. Entirely unlithified vadose zones, however, were evaluated by examining the type of the unlithified vadose material.

For ZOCs having *both* unlithified and lithified vadose zone materials, one material was selected for evaluation based on the thicknesses of both. If the unlithified material was either alluvium, silts, or lacustrine deposits with a thickness that was greater than or equal to 25% of the total vadose zone thickness, then the vadose zone was evaluated using that type of unlithified material. If the unlithified material was weathered dolomite (clay) with a thickness that was greater than or equal to 15% of the total vadose zone thickness, then the vadose zone was evaluated using the score for clay. When the unlithified material was outwash with a thickness that was greater than or equal to 25% of the total vadose zone thickness, the vadose zone was evaluated using the score for sand and gravel. These evaluations and percentage amounts were based on using our best judgement and on how thick the vadose zone material type must be, compared to the total vadose zone thickness, before it began to affect attenuation of contaminants.

Aquifer Characteristics

The lithologic types of the aquifers were identified using well constructor's reports to determine which wells were completed in rock. In addition, well depth, water-table depth, bedrock depth, and types and thicknesses of materials penetrated by the well were used to identify the saturated lithologies. For wells that did not have well constructor's reports, information was interpolated from nearby wells with well constructor's reports and from the Soil Survey of Dane County information identifying soil map units having rock within 5 feet. The lithology of the aquifers was determined by examining well constructor's reports, extent of glaciation in the county, and/or Dane County Soil Survey information. The composition of unlithified aquifers was evaluated as either till or outwash. We did not need to determine the type of lithologic materials in lithified aquifers because the typical system scores for each lithologic material (sandstone and shale, dolomite, and sandstone) were the same.

The hydraulic conductivity of the aquifer for each ZOC was calculated by Muldoon *et al.* (1994) from specific capacity test data for wells with well constructor's reports. For wells with no constructor's reports, aquifer parameters were estimated from the geometric mean hydraulic conductivity of surrounding wells completed at similar elevations. The hydraulic conductivity units were converted from meters/day to gal/day/ft^2, the units used by DRASTIC (the only assessment system that uses hydraulic conductivity).

Recharge

One suggested net recharge value for Dane County was calculated from the discharge of the groundwater reservoir (which is equal to groundwater recharge) and was estimated to be 6 inches/year or about one-fifth of the average annual precipitation of 31 inches (Cline, 1965). Another net recharge value for Dane County (K. Bradbury, verbal communication, 1993), is 10 inches/year. The latter value was selected for use in this study.

Land Slope

The Soil Survey of Dane County, Wisconsin (Glocker and Patzer, 1978) lists ranges of land slope percentages for most of the 153 soil map units and miscellaneous land types categories. For land types that were not listed, we assigned the flattest slope system scores to water, marsh, and alluvial lands and the steepest slope system scores to the stony and rocky lands. Other land type categories (cut and fill land, gravel pits, made land, and quarry) were not used to determine a slope because of possible slope variability. An average slope score was obtained for each ZOC based on area-weighted slope scores.

Horizontal Distance to Contaminants

The horizontal distance to contaminants is the horizontal distance from the atrazine-sampled wells to the farm fields in which atrazine was applied. In the Dane County atrazine study (Muldoon *et al.*, 1994), field boundaries within each ZOC were created by spatially overlaying farm fields with the ZOC boundaries. Twelve-year cropping and land-use histories were used to estimate atrazine loads for each field.

In order to calculate the horizontal distance from the wells to the fields with atrazine applications, the centroid for each polygon with an atrazine application amount greater than zero was determined and the distance from the closest centroid to each well was calculated.

Chapter V

DESCRIPTION OF ASSESSMENT SYSTEMS

Hydrogeologic parameter descriptions, scores, and data sources have been defined differently in various assessment systems. Although some systems share similar parameters, the systems may differ in the specific methods used to obtain parameters. In order to explain each system in detail, this chapter discusses the parameter definitions and formulas used to calculate groundwater susceptibility scores for each system. Two systems (DRASTIC and SEEPPAGE) provide ranges for some parameter scores. The variable scores allow a user to chose either a typical score or an adjusted value that is based on more specific knowledge. For this study, typical scores were always selected.

Assessment System Assumptions

Assumptions regarding either the physical or chemical processes involved in groundwater and contaminant movement or the size of areas analyzed may affect susceptibility analyses if all assumptions are not met. All assessment systems assume the contaminant is introduced at the soil surface and flushed into the groundwater by precipitation. Some ZOCs located in heavily irrigated land areas probably have different recharge amounts than ZOCs without irrigation. A preliminary analysis found that the susceptibility scores for the 13 irrigated ZOCs were similar to the non-irrigated ZOCs; therefore, we used the same recharge score for all ZOCs. All assessment systems also assume that the contaminant has the mobility of water. The literature suggests that the mobility of atrazine is highly variable, as is reflected by the triazine (includes atrazine) organic carbon partition coefficient (K_{OC}) that ranges from 41-200 μg/g (U.S. EPA, 1993). Finally, the assessment systems assume that soils are basically undisturbed except for disturbances resulting from tillage.

Some assumptions are specific to one assessment system; for example, DRASTIC assumes that the area evaluated is 100 acres or larger. In this study, almost all 325 ZOCs (except for six) are smaller than 100 acres, with an average size of 27 acres; however, the affect of area size on susceptibility assessment results is not clear. Also, SEEPPAGE is best used where the aquifer evaluated is a water-table aquifer.

DRASTIC

DRASTIC is a groundwater susceptibility assessment system developed by the National Water Well Association and promoted by the U.S. EPA (Aller *et al.*, 1987). The system was originally designed for county-wide susceptibility assessments. The developers of the DRASTIC system selected the types of hydrogeologic parameters used and assigned numerical scores to parameters and weighting factors. The system evaluates groundwater contamination potential using seven hydrogeologic parameters selected as the most important mapped factors that control the groundwater contamination potential. These factors were arranged to form the acronym, DRASTIC, for ease of reference.

Numerical Score for Contamination Potential

$$= D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

where: D,R,A,S,T,I,C represent hydrogeologic parameters (defined below);
subscript R = rating (numerical score for each parameter type or range);
subscript W = weight (numerical multiplier for each parameter).

Parameters

D: Depth to Water (feet) is defined as either the depth to water table for unconfined aquifers or the depth to the piezometric surface for confined aquifers. Semi-confined aquifers must be evaluated as either unconfined or confined.

R: Net Recharge (inches) is the amount of water per unit area of land which percolates through the ground surface and reaches the water table. It is calculated by adding the amounts of precipitation, irrigation, and/or artificial recharge and subtracting amounts lost to surface runoff, evaporation, and transpiration.

A: Aquifer Media (lithology) is the unlithified or lithified material that serves as an aquifer - geologic materials that yield sufficient quantities of water for use.

S: Soil Media (texture) is considered to be the upper weathered zone of the earth which averages 0-6 feet from the ground surface. Soil characteristics are be ranked by selecting the most significant textural layer (based on thickness and texture) affecting contamination potential. Soils with a depth of less than or equal to 10 inches are be ranked as "thin or absent".

T: Topography (percent slope) is the slope and slope variability of the land surface. Percent slopes are determined from published soil surveys and 7.5 minute and 15 minute topographic quadrangles.

I: Impact of the Vadose Zone Media (lithology) is evaluated by determining the type and thickness of materials in the zone above the water table that are unsaturated or discontinuously saturated. For unconfined aquifers, all unsaturated media below the soil and above the water table are examined to determine the most significant layer affecting contamination potential; the category "confining layer" must be selected for confined aquifers.

C: Hydraulic Conductivity of the Aquifer (gal/day/ft^2) is a measure of the ability of the aquifer to transmit water and is calculated from aquifer pumping tests or well yields or obtained from published hydrogeologic reports and unpublished theses.

Table 2. Weighting factors for hydrogeologic parameters in the DRASTIC and Pesticide DRASTIC assessment systems.

HYDROGEOLOGIC PARAMETERS	DRASTIC Weighting Factors	Pesticide DRASTIC Weighting Factors
Depth to Water	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of Vadose Zone	5	4
Aquifer Hydraulic Conductivity	3	2

Methods

Final scores for this system were calculated using two different methods. Each method uses different numerical weights (*see* Table 2), although both use the same parameter information and formulae for calculating contamination potential. Higher soil and topography weighting factors were used in Pesticide DRASTIC because these factors were considered to be more important than other factors in determining the leaching of pesticides to groundwater. The use of each group of numerical weights depends on the type of contamination, either general contamination sources or pesticide applications. For this study the final scores for contamination potential were calculated using numerical weights for both the general and pesticide contamination sources. In following chapters these system scores will be referred to as DRASTIC (general contamination assessment system) and Pesticide DRASTIC (pesticide contamination assessment system).

Depth to water was determined by the method detailed in the Chapter IV. For this study, all aquifers (including possibly some semi-confined aquifers) were evaluated as unconfined, because of the lack of information about the existence of confined aquifers in Dane County. Net recharge, aquifer media, hydraulic conductivity, vadose media, and topography were evaluated by the methods described by sections in Chapter IV.

Soil characteristics were evaluated by selecting the most significant soil textural layers affecting contamination potential. Because of the way soils have formed in Dane County's humid climate, the B horizon usually contains the most significant textural layer, often the finest-textured layer. However, when it was difficult to identify the most significant textural layer in the B horizon, the texture of the C horizon was also examined. Although the documentation ranks soils with a depth less than or equal to 10 inches as "thin or absent", it was decided that no soil map units in Dane County, except for stony and rocky land, should be ranked this way because all contribute to contamination attenuation. Once a numerical rank was obtained for each soil map unit in Dane County, a soil rank for each ZOC was determined by selecting the DRASTIC soil texture score of the soil texture with the largest areal extent in each ZOC.

WISM

The Wisconsin Susceptibility Model, also called WISM (Schmidt, 1987), was used to create a 1:1,000,000-scale groundwater contamination susceptibility map for the state of Wisconsin based on five parameters. WISM developers selected the types of resource characteristics and assigned numerical scores to parameters and weighting factors. The resource characteristics were selected according to their importance in controlling water movement to the water table or according to their availability in mapped data on a statewide basis.

Numerical Score for Contamination Potential = $S_R S_W + Sd_R Sd_W + W_R W_W + T_R T_W$

where: S, Sd, W, T represent hydrogeologic parameters (defined below);
subscript R = rating (numerical score for each parameter type or range);
subscript W = weight (numerical multiplier for each parameter based on depth to bedrock).

Parameters

S: Soil characteristics are evaluated by assigning each soil association to one of four categories based on permeability (inches/hour), texture, and water holding capacity (inches) of the upper 5 ft of materials. Scores are based on the characteristics of the predominant soils in the association, with lesser consideration given to the minor soils.

Sd: Surficial deposits (texture) are the unconsolidated materials between the soil and the top of the bedrock. The surficial deposits primarily represent the top of the unlithified material between the soil layer and the bedrock, since more information has been collected for shallower deposits.

W: Depth to water table (feet) is the distance between the land surface to the water table.

T: Type of bedrock (lithology) is the consolidated material that underlies the soils and surficial deposits.

Depth to bedrock (feet) is the distance from the land surface to the top of the bedrock or uppermost lithified deposit. Five ranges of depth to bedrock are used to determine weights for each of the four parameters listed above.

Methods

This system was evaluated using final scores calculated by different methods. First, the final numerical scores for areas in Dane County were obtained from the WDNR's final coverage of groundwater susceptibility scores for the entire state; final scores from this method will be referred to as WISM-ST scores, where "ST" refers to State. The system was also evaluated by using county-scale data for the same parameter information as WISM-ST, and using the same numerical scores and ranking methods to calculate final scores; the final scores for this evaluation will be referred to as WISM-CO, where "CO" refers to county, to indicate the use of county-scale data.

WISM-ST

The final numerical scores for WISM-ST were obtained from the WDNR's coverage of groundwater susceptibility scores for the entire state. The scores (developed by Schmidt, 1987), were created by combining the GIS information for the five parameters from the following sources, respectively: *Soil Association Map of Wisconsin at a scale of* 1:250,000 (Hole, 1968), U.S. Geological Survey (USGS) Quaternary geology maps at a scale of 1:500,000, USGS compiled water-table depth map created from well log information and from other sources such as county reports and county solid waste plans (1:250,000-scale), and compilation sheets of the Bedrock Geology of Wisconsin map at a scale of 1:500,000 (WGNHS, 1981). An overlay of the WDNR's final scores and our well locations was developed in order to assign final groundwater susceptibility scores to each of the 325 wells. The susceptibility scores obtained from this overlay will be referred to as the WISM-ST scores. We did not use susceptibility scores that were area-weighted over each ZOC because the ZOCs did not extend over many different susceptibility rankings.

WISM-CO

The final numerical scores for WISM-CO were calculated from county-scale sources of the same parameter information as WISM-ST, using the same numerical scores and ranking methods to calculate contamination potential scores. The scores were created by combining the information for the five parameters from the following sources. Soil information was obtained by ranking the 156 soil map units. Although WISM-ST documentation states that soils were previously ranked by permeability, texture, and water holding capacity (Schmidt, 1987), we were not able to determine which soil categories contained which ranges of parameters (J. Cain, verbal communication, 1993); therefore, we derived a method for ranking the soil map units that best approximated the original. We decided to only rank the soils based on permeability and texture because permeability, texture, and water holding capacity are, for the most part, directly related. We first obtained permeability ranges for the least permeable unit in the B horizon from the Soil Survey of Dane County (Glocker and Patzer, 1978) and separated them into the four WISM-ST permeability categories: 0.0 - 0.2 inches/hour (low), greater than 0.2 - 0.63 inches/hour (medium), greater than 2.0 - 6.3 (high-medium) inches/hour, and greater than 6.3 inches/hour (high). Then, the soil map units in each permeability category were compared with the textures of the B horizon determined by SCAM3 and the following changes were made. The low permeability category had the above permeability ranges and those soil map units whose texture of the B horizon was either organic materials, clay or silty clay. The high-medium permeability category had the above permeability ranges and those soil map units whose texture of the B horizon was either loam or sandy loam. The high permeability category had the above permeability ranges and those soil map units whose texture of the B horizon was sand.

Surficial deposit scores were obtained by evaluating the unlithified materials outlined by the Geologic Materials section in Chapter IV. Unlithified materials were evaluated as the following WISM-ST categories: outwash was evaluated as sand and gravel; weathered sandstone and till were evaluated as sandy; alluvium, silts, weathered sandstone/shale, and lacustrine were evaluated as loamy; and weathered dolomite was evaluated as clayey. Depth to water, type of bedrock, and depth to bedrock parameters were evaluated by the methods described in Chapter IV sections.

SCAM3

The Soil Contaminant Attenuation Model or SCAM (Zaporozec, 1985), (Sutherland and Madison, 1987), evaluates the ability of the soil map units to attenuate the movement of contaminants introduced at the land surface, based on seven soil physical and chemical characteristics (obtained from county soil survey reports). The third iteration of SCAM, SCAM3, was created during this project to refine some of the some of the parameter definitions in SCAM. Only the SCAM3 system results were selected for analysis in this study.

Numerical Score for Contamination Potential

$$= Ta_R + Tb_R + pH_R + D_R + Dr_R + P_R + O_R$$

where: Ta, Tb, Ph, D, Dr, P, O represent soil characteristics (defined below); subscript R = rating (numerical score for each parameter type or range).

Parameters

Ta: Texture of Surface (A or O) horizon.

Tb: Texture of Subsoil (B) horizon is the finest textured material that exceeds 30% of the total thickness of the B horizon. If one texture does not exceed 30%, then the texture of the subsoil is the most significant textural layer affecting contamination potential. If there is no B horizon, then the subsoil texture is the texture of the materials approximately 2 feet below the surface.

pH: pH of Surface (A or O) horizon.

D: Depth of Soil Solum is the depth from the surface to the top of the C or R horizons whichever comes first. *For soils with the subordinate distinction b (indicating buried* horizons) soil depth is the distance from the surface to the bottom of the 2O, Ab, Bb, Eb or the top of the Cb whichever is deeper. For alluvial soils (Entisols) without buried horizons, soil depth is from the surface to the top of the C horizon. For Histosols, soil depth will be from the surface to the bottom of the last O horizon. If the soil is eroded and the erosion losses are not considered in the soil profile description, then soil depth for moderately eroded soils (soil map unit names with a "2") are calculated by subtracting 4 inches from the depth to the top of the C or R horizons whichever comes first. For extremely eroded soils (soil map unit names with a "3") the soil depth is calculated by subtracting 6 inches from the depth to the top of the C or R horizons whichever comes first.

Dr: Soil Drainage Class refers to the frequency and duration of periods of saturation or partial saturation that existed during the development of the soil (Glocker and Patzer, 1978). The classes are found in soil series descriptions.

P: Permeability of Subsoil Horizon is evaluated by one score if soil series description indicates that bedrock is found within 20 inches of the surface, or if bedrock is present in the soil mapping unit within 40 inches of the surface. For other soils, the subsoil permeability is determined from the particle-size class in the "family" column of the "Classification of Soil Series" in the Soil Survey; subsoil permeability is evaluated using the underlying material if there is more than one particle-size class.

O: Organic Matter Content of Surface Horizon or 0-6" depth from surface. The organic matter content for Histosols, Aquic suborder, or Lithic, Aquollic, and Aquic subgroup are evaluated as one score. For other soils that have been tested for organic matter content, use the percent of organic matter content from the test. For other soils that have not been tested, the organic matter content is evaluated using the soil order from the "Classification of Soil Series" table in the Soil Survey; the organic matter content score is lowered by one level if the soil mapping unit indicates an eroded soil.

Methods

SCAM3 was created during this project to refine some of the parameter definitions in SCAM. Refinements were made for the following parameters: textures of surface and subsoil, depth of soil solum, and permeability of subsoil horizon. A SCAM3 score was obtained for each of the 153 soil map units and miscellaneous land types, based on the above parameter definitions while a final numerical score for each ZOC were calculated based on the area-weighted SCAM3 scores for the soil map units in each ZOC.

Farm-A-Syst

Farm-A-Syst, or Farmstead Assessment System (Cates and Madison, 1991), was developed as part of an educational effort designed to help protect the quality of groundwater at individual farmsteads. The system consists of 12 worksheets that examine both farmstead practices and physical characteristics of a farmstead site. Worksheet #11 is used to calculate a level of groundwater contamination risk associated with the soils and geologic characteristics at each farmstead. Numerical susceptibility scores are determined for both soils and geologic characteristics and a final susceptibility score is selected from the combination of the two numbers. Farm-A-Syst was developed, in part, by the creators of SCAM and, thus, the seven soils-characteristic definitions and numerical rankings used for both assessment systems are exactly the same. However, for this study we used SCAM3 to obtain soil characteristics for Farm-A-Syst. Farm-A-Syst differs from SCAM because a subsurface materials and depth to water table score is also used to determine a farmstead's contamination potential.

Numerical Score for Contamination Potential = based on Sl_R , Sb_R

where: Sl, Sb represent hydrogeologic parameters (defined below);
subscript R = rating (numerical score for each parameter type or range).

Parameters

Sl: Soils Characteristics (see SCAM3 parameter descriptions).

Sb: Subsurface and Geologic Materials are evaluated by obtaining one score relating to both the lithology (and sometimes thickness) of materials and the depth to groundwater at each site.

Methods

The Soil Characteristics score was obtained by the method outlined by SCAM3; the Subsurface and Geologic Materials were evaluated by the process described in Chapter IV sections. Some additional assumptions were made about the geologic materials, such as till was evaluated as medium-coarse textured and outwash as sand and gravel containing less than 12% silt or clay. Unlithified materials such as alluvium, silts, weathered dolomite, weathered sandstone/shale, and lacustrine deposits were evaluated as medium-fine textured unconsolidated materials; outwash (less than 45 feet thick), till, and weathered sandstone were evaluated as coarse-textured materials.

SEEPPAGE

SEEPPAGE, developed by the U.S. Department of Agriculture's Soil Conservation Service, is an acronym for: a **S**ystem for **E**arly **E**valuation of the **P**ollution **P**otential of **A**gricultural **G**roundwater **E**nvironments. The seven parameters used by this system were primarily selected by their ease-of-use, as information that was not readily available or not easily developed was not considered in devising the system (Moore, 1989). SEEPPAGE, in part, is a combination of selected parameters from the DRASTIC and SCAM systems. Final scores for SEEPPAGE can be calculated using two different methods. Each method uses different numerical weights, although both use the same parameter information and formulae for calculating contamination potential. The use of each weight depends on the source of contamination, either point contamination sources (from site-specific, readily observable origins) or dispersed contamination sources (from nonspecific, diffuse origins) (Moore, 1989). For this study only the numerical weights for a dispersed contamination source were used to calculate final scores for contamination potential.

Numerical Score for Contamination Potential

$$= D_R D_W + L_R L_W + W_R W_W + V_R V_W + A_R A_W + Sd_R Sd_W + At_R At_W$$

where: D, L, W, V, A, Sd, At represent hydrogeologic parameters (defined below);
subscript R = rating (numerical score for each parameter type or range);
subscript W = weight (numerical multiplier for each parameter).

Parameters

D: Distance Between Site and Point of Water Use (feet) is the horizontal distance between the site and the point of water use or point of concern such as a property line.

L: Land Slope (percent slope) is the slope of the land surface at the site.

W: Depth to Water Table (feet) is determined by estimating the shallowest depth to the water table that is below the elevation of the base or proposed base of the site more than 5% of the year.

V: Vadose Zone Material (lithology) is defined as the unsaturated or discontinuously unsaturated material that is above the water table and below the surface soil.

A: Aquifer Material (lithology) is defined as the saturated geologic material that will yield useable quantities of water.

Sd: Soil Depth (inches) values are determined consistent with the standards used by the U.S. Department of Agriculture for the mapping of soils (USDA, 1990).

At: Attenuation Potential of Soils rating is based on numerical scores for six physical and chemical soil characteristics (that can be obtained from county soil surveys) for each soil map unit. The characteristics include: [Ta] Texture of Surface (A) Horizon (if A is absent, score equals 0); [Tb] Texture of Subsoil (B, or if absent, C) Horizon - for evaluation of B horizons having textural changes, Moore (written communication, 1993) recommends rating the stratum that tends to dominate the attenuation process, using best professional judgement; [pH] pH of the Surface (A) Horizon (if absent, use uppermost soil horizon); [O] Organic Matter Content (percent) of Surface Layer of Mineral Soils; [P] Permeability (inches/hour) of Least Permeable Horizon in Profile (below the A); and [Dr] Soil Drainage Class.

Numerical Score for Attenuation Potential of Soils (At_R)

$$= Ta_R + Tb_R + pH_R + O_R + P_R + Dr_R$$

where: Ta, Tb, pH, O, P, Dr represent soil characteristics (defined above);
subscript R = rating (numerical score for each parameter type or range).

Methods

We contacted the author (J.S. Moore, written communication, 1993) to clarify some of the SEEPPAGE parameter definitions. Moore mentioned that SEEPPAGE was written for application throughout the United States; therefore, the documentation provided is general so that it could apply to many types of physiographic provinces and, as a result, professional judgement may be needed in order to make some of the rating determinations. The following parameters were obtained by methods outlined in Chapter IV sections: distance between site and point of water use, land slope, depth to water table, vadose zone materials, and aquifer materials. Soil depth was determined by the same method outlined by SCAM3. The organic matter content and permeability scores for SEEPPAGE are based on ranges from the county soil survey reports. SEEPPAGE did not provide a score for a combination soil drainage class "well to moderately well drained" used in soil series descriptions, so the score between the well and moderately well drained classes was selected.

Chapter VI

ANALYSES

Susceptibility scores were calculated for each well's ZOC for each groundwater susceptibility assessment system. These scores were compared to atrazine concentrations in wells, after accounting for estimates of total atrazine application amounts in ZOCs. Our hypothesis was that for similar amounts of atrazine applied to ZOCs, higher atrazine concentrations would be found in wells in areas assessed as more susceptible to groundwater contamination and lower atrazine concentrations would be found in wells in areas assessed as less susceptible to groundwater contamination.

We first determined system score distributions, correlations between each system's scores, and how the systems evaluated the contamination susceptibility for the 325 ZOCs in Dane County, Wisconsin. We then analyzed the relationships between the system scores and atrazine concentrations. After accounting for different atrazine application amounts in ZOCs, we examined the score/atrazine concentration relationships. All statistical analyses were completed using SPSS statistical software for Windows (Norušis, 1992).

Assessment System Score Distributions

After the final scores for the seven assessment systems were calculated for each of the 325 ZOCs by methods described in previous chapters, we obtained final score summary statistics and determined distribution types. Summary statistics included mean, median, standard deviation, and skewness, as well as the type of score distribution (Table 3). Log-normal or cubic transformations of assessment system scores were performed where statistical analyses required normally distributed data. DRASTIC and Pesticide DRASTIC scores both had log-normal distributions; SCAM3 had scores that were transformed to a more normal distribution by a cubic function. The other assessment systems, WISM-ST, WISM-CO, and SEEPPAGE, had normally distributed scores. Farm-A-Syst scores do not appear in Table 3 because this system generates categorical, non-continuous data.

It was important to keep in mind that some of the assessment systems use high scores to show greater susceptibility, while others use low scores to indicate greater susceptibility. For DRASTIC, Pesticide DRASTIC, and SEEPPAGE, *high* scores show areas that are the most susceptible to groundwater contamination. The other assessment systems, WISM-ST, WISM-CO, SCAM3, and Farm-A-Syst, use *low* scores to depict areas having the highest susceptibility to groundwater contamination.

Table 3. Assessment system score summary statistics for 325 ZOCs.

Assessment System	SUMMARY STATISTICS					
	Mean*	**Median**	**Std. Dev.**	**Minimum**	**Maximum**	**Distrib****
DRASTIC	122.7	119.0	—	93.0	193.0	L
Pesticide DRASTIC	136.3	133.0	—	101.0	214.0	L
WISM-ST	54.6	52.0	22.1	15.0	104.0	N
WISM-CO	51.3	52.0	16.3	19.0	116.7	N
SCAM3	41.5	44.4	—	16.0	53.9	O
SEEPPAGE	139 .2	138.0	17.9	100.0	187.0	N

* Indicates geometric mean for non-normal distributions.

** L = Log-Normal Distribution, N = Normal Distribution, O = Other Distribution.

Assessment System Score Comparisons

In order to compare relative results of the different systems, a Spearman rank correlation coefficient was calculated between each system's scores. The Spearman rank correlation coefficient can be used to measure correlation between two ordinal variables and can be used for data that do not satisfy a normality assumption. The values of each system's scores were ranked from smallest to largest, and the Pearson correlation coefficient was computed on the ranks. The Pearson correlation coefficient, ranging from -1 to +1, measures the strength of the negative or positive linear relationship.

The highest score correlation (0.9737) was between the DRASTIC and Pesticide DRASTIC assessment systems. Both systems use the same seven hydrogeologic parameters and parameter scores; the only difference is in four of the seven weighting factors. The Pesticide DRASTIC scores tend to be a little higher than the DRASTIC scores because, overall, the different Pesticide DRASTIC weights tend to be higher.

We also found correlations between other systems which were the result of systems using similar data. The SEEPPAGE system is a combination of some of the parameters from both DRASTIC and SCAM (see Chapter V for more information). Thus, SEEPPAGE scores showed moderate correlations with DRASTIC and Pesticide DRASTIC (0.5345 and 0.5976, respectively), since all share some of the same hydrogeologic parameters and weighting factors. In particular, the DRASTIC systems and SEEPPAGE share similar topography, depth to water, vadose zone, and aquifer parameters. A strong negative correlation (-0.7671) was observed between SEEPPAGE and SCAM3. This was primarily the result of SEEPPAGE using the same soils information as the SCAM3 system. This correlation is negative because SEEPPAGE uses higher numbers while SCAM3 uses lower numbers to represent greater susceptibility. The soils portion of the Farm-A-Syst score is exactly the same as SCAM3 scores; therefore, as expected, the Farm-A-Syst scores showed a moderate correlation with SCAM3 (0.5499) and thus with SEEPPAGE (-0.5251). Farm-A-Syst is the only system that combines two susceptibility scores, one for soil and the other for subsurface characteristics, to create a final score. Depending on the subsurface score, the final susceptibility score can be very different from the soil susceptibility score. For example, a SCAM3 score ranking the soils in a ZOC as having moderate-low susceptibility would change to a Farm-A-Syst score indicating *high* susceptibility for that same ZOC, if the subsurface score indicated high susceptibility. Other assessment system correlations ranged between -0.3709 and -0.0069, indicating weak to no correlation of scores.

Assessment System Score Categorization

We grouped different numerical ranges of system scores into susceptibility categories, because computed score values are not as important as relative score magnitudes. For some assessment systems, ranges or categories, not raw final scores, are used to define susceptibility. Each of the assessment systems provide numerical ranges that separate final scores into susceptibility categories. With the exception of SCAM3 and Farm-A-Syst, the system categories have equal interval ranges. The relative number of ZOCs in each susceptibility category is shown graphically in Figure 3 and displayed in tabular form in Tables 4, 5, and 6. The systems based entirely or predominantly on soils (SCAM3 and Farm-A-Syst) have data in all possible susceptibility categories. The other systems, which use more hydrogeologic parameters, have more scores in the susceptibility categories in the middle with few (or no) scores in the extreme susceptibility categories.

DRASTIC uses equal interval ranges to separate DRASTIC and Pesticide DRASTIC final scores into eight susceptibility categories. Table 4 displays the frequency of scores in each category out of 325 total scores; note that no final scores calculated by either the DRASTIC or Pesticide DRASTIC systems fall into the lowest susceptibility category. Therefore, according to the DRASTIC systems, none of the ZOCs we examined had hydrogeologic settings with the lowest susceptibility. Note also that the Pesticide DRASTIC system has more scores in the higher susceptibility categories than the DRASTIC system. This is the result of higher weighting factors used in the Pesticide DRASTIC system. Although the Pesticide DRASTIC weights for both vadose and aquifer hydraulic conductivity parameters are smaller, the weights for the soil and topography parameters are larger.

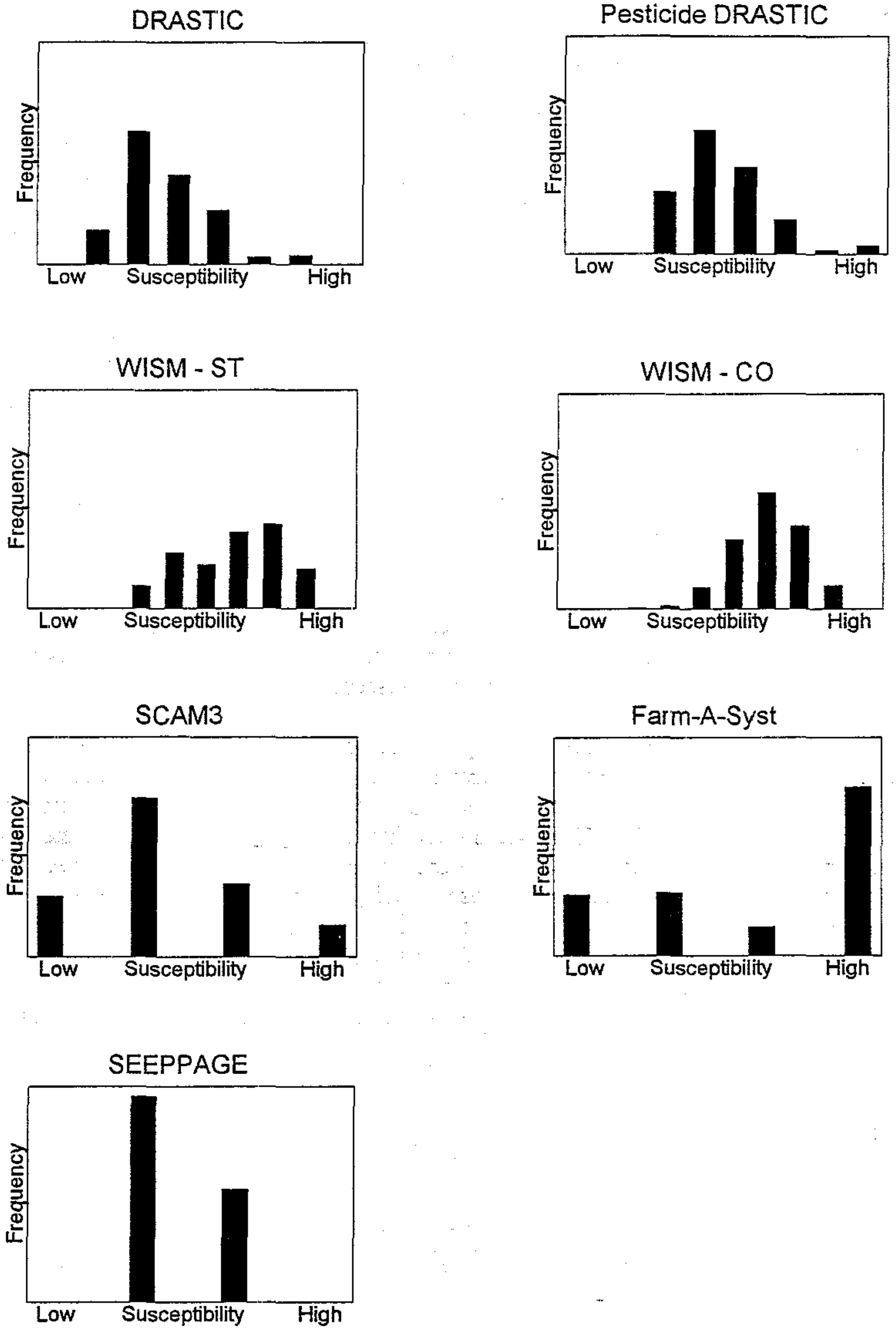

Figure 3. Distribution of scores by susceptibility assessment system category.

Table 4. Distribution of scores in the eight DRASTIC groundwater susceptibility categories.

Assessment System	Groundwater Susceptibility to Contamination							
	least susceptible							**most susceptible**
DRASTIC	----	34	132	89	54	7	9	----
Pesticide DRASTIC	----	----	63	126	88	35	4	9

For development of the Wisconsin groundwater susceptibility map, WISM-ST designers provided 20 numerical ranges of susceptibility categories; the susceptibility map displayed these ranges by using a color gradation from red to green. In order to simplify subsequent analyses, we reduced these 20 categories to 10 categories. The number of scores in each of 10 categories, for both the WISM-ST and WISM-CO systems, are displayed in Table 5. Note that none of the ZOCs in Dane County had final scores in either the two lowest susceptibility categories or highest susceptibility categories. The final score distributions in both assessment systems are similar but perhaps the most distinct difference is the lack of scores in the lower susceptibility category for the WISM-CO system compared to the WISM-ST system. This is primarily the result of using more detailed information because we were able to select the majority of bedrock as sandstone (instead of carbonate) when it occurred in a ZOC.

Table 5. Distribution of scores in each of the 10 WISM-ST categories.

Assessment System	Groundwater Susceptibility to Contamination									
	least susceptible									**most susceptible**
WISM-ST	----	----	----	23	56	44	77	85	40	----
WISM-CO	----	----	1	1	22	66	119	90	26	----

Table 6 presents the categorized scores for SCAM3, Farm-A-Syst, and SEEPPAGE. Both SCAM3 and Farm-A-Syst separate final scores into four categories; SEEPPAGE final scores fall into two categories. While SCAM3 and Farm-A-Syst share the same soils information, Farm-A-Syst scores are also based on a subsurface materials score. Farm-A-Syst frequently evaluated subsurface materials as more susceptible; thus, there are more scores in Farm-A-Syst's higher susceptibility category than in SCAM3's higher susceptibility category. The SEEPPAGE scores assigned to ZOCs in Dane County fall into only two susceptibility categories and thus may not be sufficiently different to be used effectively in a susceptibility assessment.

Table 6. Distribution of scores in SCAM3, Farm-A-Syst, and SEEPPAGE categories.

Assessment System	Groundwater Susceptibility to Contamination			
	least susceptible			most susceptible
SCAM3	61	159	73	32
Farm-A-Syst	62	64	29	170
SEEPPAGE	----	210	115	----

From our examination of score distributions in susceptibility categories alone, all assessment systems tested (except for SEEPPAGE) separate the ZOC scores into enough susceptibility categories to be useful in a susceptibility assessment. In general, DRASTIC, DRASTIC pesticide, SCAM3, and SEEPPAGE indicate that the ZOCs tested in Dane County are of medium susceptibility; WISM-ST, WISM-CO, and Farm-A-Syst indicate that the same ZOCs are of medium to high susceptibility.

Comparison of System Scores and Atrazine Concentration

We analyzed the relationships between the system scores and atrazine concentrations in wells, without accounting for atrazine application to ZOCs. Again, we assumed that a ZOC is a delineation of the land area which contributes water to the well and that groundwater and drinking well-water have similar contamination susceptibilities. For each assessment system, relationships between ZOC raw and normalized scores and atrazine concentrations were examined with the use of scatter plots in order to identify possible trends. In general, scatter plots can help identify relationships when data points fall on straight or curved lines. However, for each of the seven assessment systems we could not identify trends in any of the scatter plots because there was too much variability in the data.

Categorized susceptibility scores were then compared to categories of atrazine concentration. Table 7 shows the frequency of wells in the atrazine concentration categories. For these analyses, final scores for each assessment system were separated into susceptibility groups based on system design or into four susceptibility groups using approximate quartiles of the score population. Quartiles were used either to aggregate category ranges when there were a limited number of scores in each system category or to expand the category ranges of SEEPPAGE that had only two susceptibility categories. DRASTIC, Pesticide DRASTIC, WISM-CO, WISM-ST, and SEEPPAGE scores were separated into both system categories and quartiles while the only four ranges used to group SCAM3 and Farm-A-Syst scores were the ones provided for in each system's design.

Relationships between assessment system score categories and atrazine concentration categories were examined with cross-tabulation analysis. We hypothesized that higher atrazine concentrations would occur in the most susceptible categories and lower concentrations would be found in the least susceptible category. However, we did not find these trends.

Table 7. Descriptive statistics for atrazine concentration categories (Muldoon *et al.*, 1994).

Atrazine Concentration Categories ($\mu g/l$)	SUMMARY STATISTICS	
	Frequency	**Percent**
Five Categories		
Below detection	156	48.0
> 0 - 0.2	39	12.0
0.2 - 0.2999	51	15.7
0.3 - 0.4999	30	9.2
= > 0.5	49	15.1
Detection		
No detect	156	48.0
Detect	169	52.0

System Categories and Atrazine Detections

Assessment system score categories were then compared to the occurrence of atrazine detections (detect/no detect). We hypothesized that relatively higher percentages of detects would be found in the categories most susceptible to contamination and relatively lower percentages of detects would occur in the categories least susceptible to contamination. The relative number of ZOCs and the distribution of atrazine detections in each susceptibility category is shown graphically in Figure 4 and displayed in tabular form in Tables 8,9, and 10. In Figure 4, the dark portion of each bar shows the distribution of atrazine detections (the lighter portion shows the distribution of no detects) that are associated with the ZOCs in each susceptibility category. The figure shows that for each assessment system, there are no consistent changes between the proportion of detects and greater or lesser susceptibility. This observation is reinforced through examination of Tables 8, 9, and 10.

Figure 4. Distribution of scores and Atrazine detections by susceptibility assessment system category.

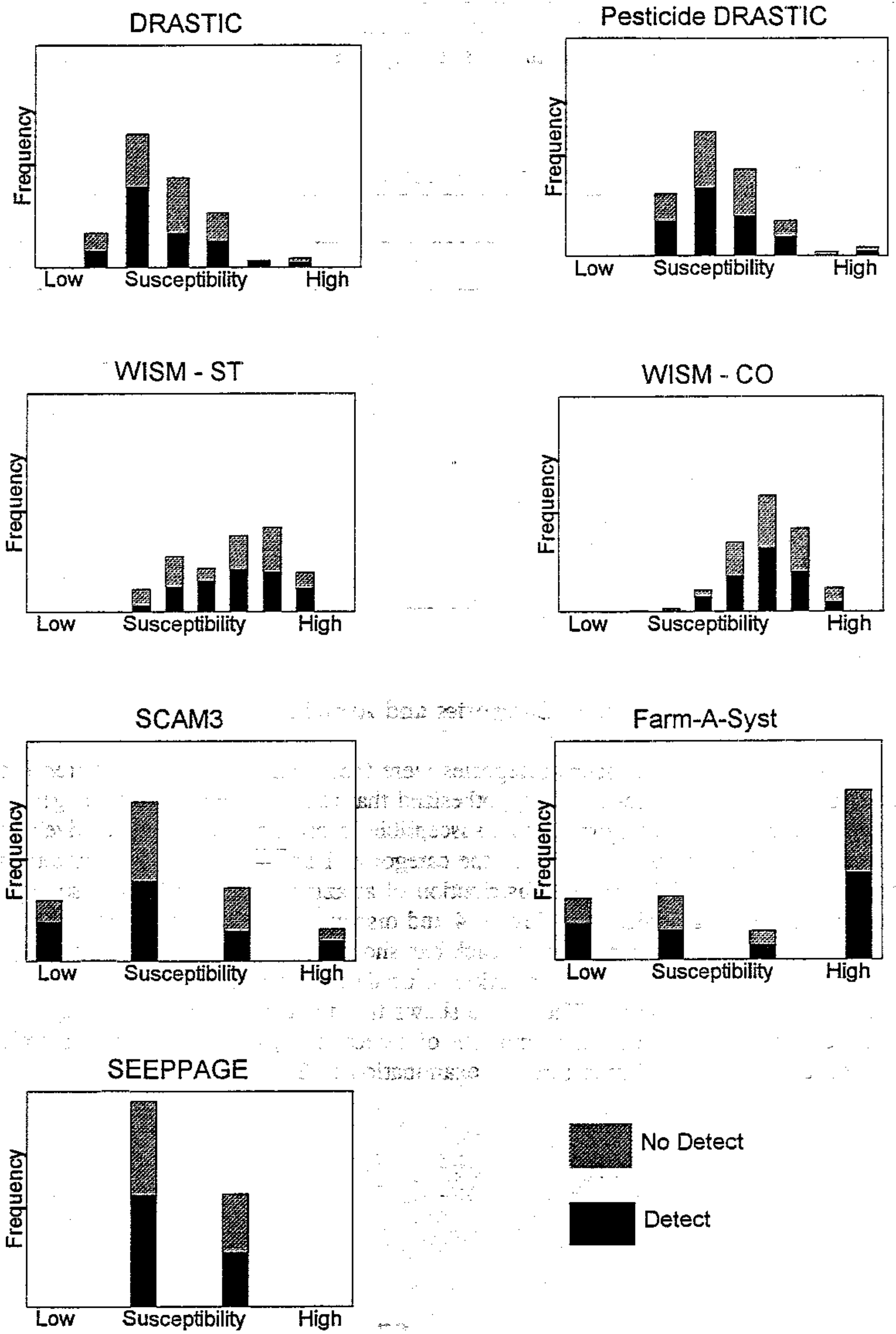

Table 8 shows percentages of atrazine detections in each of 8 susceptibility categories for DRASTIC and Pesticide DRASTIC. Both DRASTIC and Pesticide DRASTIC did not show trends across eight contamination susceptibility categories; higher percents of detects did not necessarily occur in the most susceptible categories and lower percents of detects did not necessarily occur in the least susceptible categories.

Table 8. Distribution of atrazine detections for the DRASTIC and Pesticide DRASTIC assessment systems.

Assessment System	DRASTIC Groundwater Susceptibility Categories															
	least susceptible												most susceptible			
	n	D	n	D	n	D	n	D	n	D	n	D	n	D	n	D
DRASTIC	0	0	34	17	132	80	89	34	54	26	7	7	9	5	0	0
		(0)		(50.0)		(60.6)		(38.2)		(48.1)		(100)		(55.6)		(0)
Pesticide DRASTIC	0	0	0	0	63	35	126	69	88	40	35	19	4	1	9	5
		(0)		(0)		(55.6)		(54.8)		(45.5)		(54.3)		(25.0)		(55.6)

*n = # of scores in each category, D = # of detects, ( ) = percentage of detects.

The percentages of atrazine detections in 10 susceptibility categories for WISM-ST and WISM-CO are shown in Table 9. While both systems did not show consistent trends in atrazine detections across the susceptibility categories, WISM-ST did have the lowest percent of detections in the lower susceptible category. However, WISM-CO had the lowest percent of detections in the more susceptible category.

Table 9. Distribution of atrazine detections for WISM-ST and WISM-CO.

Assessment System	Groundwater Susceptibility to Contamination									
	least susceptible									most susceptible
WISM-ST										
n	----	----	----	23	56	44	77	85	40	----
D				6	25	31	43	40	24	
(%D)				(26.1)	(44.6)	(70.4)	(55.8)	(47.1)	(60.0)	
WISM-CO										
n	----	----	1	1	22	66	119	90	26	----
D			0	1	15	33	65	44	11	
(%D)			(0)	(100)	(68.2)	(50.0)	(54.6)	(48.9)	(42.3)	

* n = # scores in each category, D = # of detects, (%D) = percentage of detects.

Table 10 shows the percentages of atrazine detections in each of 4 susceptibility categories for SCAM3, Farm-A-Syst, and SEEPPAGE. All three systems had no consistent trends between atrazine detections and susceptibility categories. SCAM3 and Farm-A-Syst had the highest percent of detections in the least susceptible category, which is opposite from what we hypothesized. SEEPPAGE also had a detection pattern that was opposite from hypothesized trends, as the moderate susceptibility category had a slightly higher percent of atrazine detections than the high susceptibility category.

Table 10. Distribution of atrazine detections for the SCAM3, Farm-A-Syst, and SEEPPAGE assessment systems.

Assessment System	Groundwater Susceptibility to Contamination							
	least susceptible						**most susceptible**	
	n	Detects	n	Detects	n	Detects	n	Detects
SCAM3	61	39 (63.9)	159	80 (50.3)	73	30 (41.1)	32	20 (62.5)
Farm-A-Syst	62	37 (59.7)	64	30 (46.9)	29	15 (51.7)	170	87 (51.2)
SEEPPAGE	0	0 (0)	210	114 (54.3)	115	55 (47.8)	0	0 (0)

* n = # of scores in each category, Detects = # of detects, ( ) = percentage of detects.

In case atrazine detection trends were masked by previously used susceptibility categories, we decided to re-examine the scores after grouping them into one of four categories ranging from least susceptible to most susceptible. Therefore, assessment system score quartiles were used for DRASTIC, Pesticide DRASTIC, SEEPPAGE, WISM-ST, and WISM-CO while system categories were used for SCAM3 and Farm-A-Syst. Results for all the systems are presented in Table 11. Again, we hypothesized that relatively higher percentages of detects would occur in the categories most susceptible to contamination and relatively lower percentages of detects would be found in the categories least susceptible to contamination. However, no significant trends were found between the four contamination susceptibility groups of system scores and atrazine detections. None of the systems had the highest percent of detects in the most susceptible category while four of the seven assessment systems (Pesticide DRASTIC, SCAM3, Farm-A-Syst, and SEEPPAGE) had the highest percent of detects in the least susceptible category.

Table 11. Distribution of atrazine detections for all assessment systems across four groundwater contamination susceptibility categories.

Assessment System	Groundwater Contamination Susceptibility Categories							
	least susceptible						**most susceptible**	
	n	Detects	n	Detects	n	Detects	n	Detects
DRASTIC	86	44 (51.2)	80	53 (66.3)	89	34 (38.2)	70	38 (54.3)
pest. DRASTIC	91	55 (60.4)	76	40 (52.6)	82	37 (45.1)	76	37 (48.7)
WISM-ST	79	31 (39.2)	83	50 (60.2)	78	43 (55.1)	85	45 (52.9)
WISM-CO	83	46 (55.4)	96	53 (55.2)	61	32 (52.5)	85	38 (44.7)
SCAM3	61	39 (63.9)	159	80 (50.3)	73	30 (41.1)	32	20 (62.5)
Farm-A-Syst	62	37 (59.7)	64	30 (46.9)	29	15 (51.7)	170	87 (51.2)
SEEPPAGE	86	50 (58.1)	77	39 (50.6)	82	38 (46.3)	80	42 (52.5)

* n = # of scores in each category, Detects = # of detects, ( ) = percentage of detects.

The majority of the wells did not have well constructor's reports, requiring us to use information from adjacent wells with well constructor's reports. To explore the possible effects of using data from wells without well constructor's reports, we examined the distribution of ZOC scores using only the 137 ZOCs with wells with constructor's reports. These results were then compared to the results from all 325 ZOCs. For each assessment system, we found no significant differences in the distributions of susceptibility scores.

System Categories, Atrazine Detections, and Atrazine Applications

The percents of atrazine detections in Table 11 could have been affected by the total amount of atrazine applied in a ZOC. In general, regardless of the susceptibility category, ZOCs with higher atrazine applications might tend to show higher percents of atrazine detections. Muldoon *et al.* (1994) obtained a value for the mean annual atrazine application rate for ZOCs or the total atrazine load (lbs) per 12 years over the area of the ZOC by estimating typical application rates of atrazine for a variety of crops. They did not find a strong linear relationship between mean annual atrazine application rate in the ZOC and atrazine concentration. They did find a trend of higher percentages of atrazine detections in ZOCs with higher application rates. Table 12 presents the number of ZOCs summarized by mean annual application rate.

Table 12. Descriptive statistics for atrazine application categories (Muldoon *et al.*, 1994).

Mean Annual Application Rate for ZOC (lbs/acre)	SUMMARY STATISTICS	
	Frequency	**Percent**
Four Categories		
> 0 - 0.3	81	24.9
0.3 - 0.5	66	20.3
0.5 - 0.8	91	28.0
> 0.8	87	26.8

Table 13 presents the relationship between susceptibility category and atrazine detection, stratified by atrazine application rate. The percentage of atrazine detections in each susceptibility category was calculated across the four categories of atrazine application. Stratification by atrazine application rate does indicate a few relationships between assessment system susceptibility results and the occurrence of atrazine detections. For example, the WISM-ST system shows increased atrazine detections with increased susceptibility in the 0.5 - 0.8 lbs/acre application category; the SEEPPAGE system has a similar trend in the > 0.8 lbs/acre application category. These trends do not occur at lower atrazine application rates.

For each assessment system, within a given susceptibility category, we found that the higher application categories (0.5 - 0.8 and > 0.8 lbs/acre) had the majority of the highest detection percentages. From these percentages, as was determined by Muldoon *et al.* (1994), it is evident that the total application amount in a ZOC is related to the detection of atrazine in the well. Accounting for atrazine application amounts to ZOCs may be more useful than using susceptibility scores in predicting atrazine detections.

We then determined the mean annual atrazine application for the ZOCs in each of the four susceptibility categories and found that the four application means were significantly different across susceptibility categories for five of the systems (DRASTIC, Pesticide DRASTIC, WISM-ST, WISM-CO, SCAM3). Each of these systems showed higher atrazine applications in the most susceptible category while SCAM3 also had a high application rate in the least susceptible category. This also suggests that atrazine applications and system susceptibility categories are not entirely independent. For the SCAM3 system, ZOCs in the least susceptible category often contained fertile soils which are intensively-farmed and thus have high atrazine applications. The increase in the percent of atrazine detections in the least susceptible SCAM3 category (Table 13) could then be explained, in part, by high atrazine applications.

Table 13. Distribution of atrazine detections by mean annual atrazine rate across four groundwater contamination susceptibility categories. All systems scores, except for SCAM3 and Farm-A-Syst, are grouped by quartiles.

Assessment System by mean annual rate for ZOC (lbs/acre)	Four Groundwater Contamination Susceptibility Categories							
	least susceptible						most susceptible	
	n	Detects	n	Detects	n	Detects	n	Detects
DRASTIC								
< 0.3	21	11 (52.4)	23	14 (60.9)	21	8 (38.1)	16	6 (37.5)
0.3 - 0.5	19	9 (47.4)	20	13 (65.0)	16	4 (25.0)	11	4 (36.4)
0.5 - 0.8	26	12 (46.2)	20	13 (65.0)	30	13 (43.3)	15	9 (60.0)
> 0.8	20	12 (60.0)	17	13 (76.5)	22	9 (40.9)	28	19 (67.9)
pest. **DRASTIC**								
< 0.3	23	14 (60.9)	22	11 (50.0)	13	6 (46.2)	23	8 (34.8)
0.3 - 0.5	18	12 (66.7)	19	9 (47.4)	18	7 (38.9)	11	2 (18.2)
0.5 - 0.8	28	15 (53.6)	18	9 (50.0)	27	13 (48.1)	18	10 (55.6)
> 0.8	22	14 (63.6)	17	11 (64.7)	24	11 (45.8)	24	17 (70.8)
WISM-ST								
< 0.3	27	10 (37.0)	13	9 (69.2)	23	12 (52.2)	18	8 (44.4)
0.3 - 0.5	17	6 (35.3)	13	9 (69.2)	16	6 (37.5)	20	9 (45.0)
0 5 - 0.8	23	9 (39.1)	29	14 (48.3)	21	12 (57.1)	18	12 (66.7)
> 0.8	12	6 (50.0)	28	18 (64.3)	18	13 (72.2)	29	16 (52.2)
WISM-CO								
< 0.3	31	19 (61.3)	19	11 (57.9)	16	5 (31.3)	15	4 (26.7)
0.3 - 0.5	16	7 (43.8)	14	10 (71.4)	10	5 (50.0)	26	8 (30.8)
0.5 - 0.8	24	11 (45.8)	37	18 (64.7)	17	11 (64.7)	13	7 (53.8)
> 0.8	12	19 (75.0)	26	14 (53.8)	18	11 (61.1)	31	19 (61.3)
SCAM3								
< 0.3	14	10 (71.4)	41	18 (43.9)	19	7 (36.8)	7	4 (57.1)
0.3 - 0.5	8	6 (75.0)	31	14 (45.2)	18	5 (27.8)	9	5 (55.6)
0.5 - 0.8	15	7 (46.7)	48	27 (56.3)	21	8 (38.1)	7	5 (71.4)
> 0.8	24	16 (66.7)	39	21 (53.8)	15	10 (66.7)	9	6 (66.7)
Farm-A-Syst								
< 0.3	20	14 (70.0)	14	4 (28.6)	9	5 (55.6)	38	16 (42.1)
0.3 - 0.5	13	8 (61.5)	8	2 (25.0)	5	2 (40.0)	40	18 (45.0)
0.5 - 0.8	16	4 (25.0)	18	13 (72.2)	6	4 (66.7)	51	26 (51.0)
> 0.8	13	11 (84.6)	24	11 (45.8)	9	4 (44.4)	41	27 (65.9)
SEEPPAGE								
< 0.3	22	13 (59.1)	18	11 (61.1)	21	7 (33.3)	20	8 (40.0)
0.3 - 0.5	11	7 (63.6)	18	8 (44.4)	16	7 (43.8)	21	8 (38.1)
0.5 - 0.8	26	14 (53.8)	16	7 (43.8)	30	14 (46.7)	19	12 (63.2)
> 0.8	27	16 (59.3)	25	13 (52.0)	15	10 (66.7)	20	14 (70.0)

* n = # of scores in each category, Detects = # of detects, ( ) = percentage of detects

In general, none of the susceptibility systems tested could predict drinking-water well contamination by atrazine in Dane County. After accounting for atrazine application rates in each ZOC, we did not find any consistent positive relationships between assessment system scores and atrazine detections. Although the results in this study indicate that the systems are not very reliable predictors of drinking-water well contamination by atrazine, they do not mean that the systems fail to predict groundwater susceptibility to contamination.

Stratification

We examined the assessment systems ability to predict drinking-water susceptibility in regions with characteristics identified by Muldoon *et al.* (1994) as important predictors of atrazine detection. Muldoon *et al.* (1994) evaluated atrazine detections for ZOCs stratified by geologic or hydrogeologic characteristics and found that the existence of fine-grained materials in a ZOC, the location of a ZOC in a regional discharge area, or the location of a ZOC in the Wisconsin River Valley were important predictors of atrazine detections (Table 14). We also stratified based on the location of ZOCs in moraines (prominent ridges formed along the margin of a glacier).

Table 14. Distribution of atrazine detections in hydrogeologic categories.

HYDROGEOLOGIC CATEGORY	n	Detect	Percentage of Detects
Fine-Grained Materials	121	45	(37.2)
Regional Discharge Areas (excluding the Wis. River Valley)	59	25	(42.4)
Wisconsin River Valley	13	9	(69. 2)

* n = # of scores in each category, Detect = # of detects.

We first examined the relationships between assessment system susceptibility scores and the three hydrogeologic categories. In each hydrogeologic category, the mean of the ZOC scores was calculated and compared to the score mean of the remaining ZOCs, by using a t-test for equality of means (at 95% confidence). A significant difference between the score means would indicate that the system could be sensitive to the hydrogeologic characteristics that had been found to be important factors in atrazine detection by Muldoon *et al.* (1994).

Existence of Fine-Grained Materials

Muldoon *et al.* (1994) found that the ZOCs with fine-grained materials had fewer atrazine detections than the other ZOCs. The assessment systems evaluated in this study do not specifically account for thin layers of fine materials, even though some fine-grained materials may be accounted for by soil characteristic evaluations. ZOCs were identified as having "fine-grained materials" present by using well constructor's reports to identify ZOCs with shale or clay layers. Additional ZOCs were added to this category that had the Sinnipee Group dolomite as the uppermost bedrock unit, because this factor was identified as having an influence on atrazine detections. The existence of fine-grained materials can limit the movement of water from the ZOC into the well and thus affect the occurrence of atrazine detections. Across the assessment systems, the means of the ZOC scores in the "fine-grained materials" category were not significantly different than the means of the scores of the remaining ZOCs. Therefore, in geologic environments similar to Dane County, consideration of thin layers of fine-grained materials could improve the assessment of drinking water, and possibly groundwater susceptibility to contamination.

Regional Discharge Areas

Muldoon *et al.* (1994) found fewer atrazine detections in ZOCs in regional discharge areas (with the exception of the Wisconsin River Valley). Much of the water reaching the well in ZOCs located in regional discharge areas could originate from outside the ZOC and thus land uses adjacent to these wells would have less influence on the water quality of these wells than for wells that were not in regional discharge areas. Because water reaching these wells would have a longer path and travel time to reach the well, there would be a longer time for physical and chemical attenuation processes to act and, therefore, one would expect fewer contaminant detections.

All assessment systems showed differences (at the 95% confidence level) between the mean of the ZOC scores in regional discharge areas and the mean of ZOCs outside of regional discharge areas. However, the score means in regional discharge areas indicated *more* susceptibility instead of less susceptibility. In general, regional discharge areas in Dane County tend to have shallow water tables and sandy surface and subsurface materials and thus would be evaluated by these assessment systems as more susceptible. Therefore, the assessment systems are not accurate indicators of the susceptibility of drinking water to atrazine contamination in regional discharge areas. The systems could incorporate a regional hydrogeologic flow component, which might improve the evaluation of the susceptibility of drinking water to contamination in regional discharge areas.

Wisconsin River Valley

The wells in the Wisconsin River Valley are an exception to the trend of observing fewer atrazine detects in regional discharge areas. Although the wells, located in the terrace system of the Wisconsin River, are in a regional discharge area, the ZOCs seem different from other ZOCs in regional discharge areas because of the intensive-irrigated farming. We think that the higher percent of atrazine detections in this area is caused by consistent atrazine use, intensive irrigation, and surface and subsurface materials that do not afford groundwater much protection from contamination.

All assessment systems showed differences (at the 95% confidence level) between the mean of the Wisconsin River Valley ZOC susceptibility scores and the other ZOCs. Each assessment system had a score mean reflecting higher susceptibility for these wells, which is similar to the scores for wells located in other regional discharge areas. Although these wells are located in a regional discharge area, they have a strong local groundwater flow system resulting from irrigation. Therefore, in addition to incorporating a regional groundwater flow component, assessment systems may be improved by considering land-use practices, such as irrigation, that influence the local groundwater flow system.

Moraines

Dane County has two moraines known as the Milton Moraine and the Johnstown Moraine (Mickelson, 1983). The assessment systems evaluate the ZOCs in these moraines as having primarily lower susceptibility. We examined the percentage of atrazine detections for wells with the majority of the ZOC located in either of the two morainal areas. Seven wells were located in the two moraines and *all* of these had atrazine detections. The morainal area has blocked surface drainage so that most of the surface water infiltrates. This increases recharge and thus can increase the amount of atrazine that reaches the groundwater. Again, our analyses suggest that a local hydrogeologic flow component may be helpful in assessing susceptibility.

Summary

After examining the ability of the assessment systems to predict drinking-water susceptibility in regions with similar geologic or hydrogeologic characteristics, we found that the assessment system results may be improved by considering additional information. This information includes: determining the existence of thin layers of fine-grained materials, accounting for regional and local hydrogeologic flow systems, and accounting for the historical application of atrazine.

Chapter VII

CONCLUSIONS

None of the seven susceptibility systems were successful in predicting drinking-water well contamination by atrazine in Dane County. After accounting for atrazine application rates in each ZOC, there were no consistent relationships between assessment system scores and atrazine detections. A few trends were observed between greater susceptibility and more atrazine detections at higher atrazine application rates. Although the results in this study indicate that the systems are not very reliable predictors of drinking-water well contamination by atrazine, they do not mean that the systems fail to be predictors of groundwater susceptibility to contamination.

From our examination of score distributions in susceptibility categories alone, all assessment systems tested (except for SEEPPAGE) separate the Dane County ZOC scores into enough susceptibility categories to be useful in a susceptibility assessment. In general, DRASTIC, DRASTIC pesticide, SCAM3, and SEEPPAGE indicate that the ZOCs tested in Dane County are of medium susceptibility; WISM-ST, WISM-CO, and Farm-A-Syst indicate that the same ZOCs are of medium to high susceptibility.

A geographic information system (GIS) was extremely useful in determining assessment system parameter data for ZOCs and in examining the relationships between susceptibility scores and atrazine concentrations. The compilation of system parameter information in relational databases allowed system scores to be calculated relatively easily.

Higher rates of atrazine application increased the number of atrazine detections irrespective of the system susceptibility categories. We also found that the systems rate ZOCs in regional discharge areas as more susceptible than average, based on the types of surface and subsurface materials generally found in discharge areas. However, discharge areas have been found to have fewer atrazine detections (and presumably lower susceptibility) than other areas. We also found more atrazine detections for ZOCs located in moraines, and suggest that this is caused by increased internal drainage and thus greater groundwater recharge. Therefore, the prediction of drinking-water susceptibility to contamination, and possibly groundwater susceptibility to contamination, may be improved by incorporating information about the groundwater flow system.

The delineation of regional hydrogeologic flow systems, as an alternative to or in conjunction with susceptibility assessment systems, may be useful in determining a region's susceptibility to groundwater contamination. In addition, vulnerability analyses that identify potential sources of groundwater contamination may improve predictions of the contamination of drinking-water wells. Finally, accounting for atrazine application amounts to ZOCs may be more useful than using susceptibility scores in predicting atrazine detections.

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