Modeling the Risk of Groundwater Contamination Using DRASTIC and Geographic Information Systems in Houston County, Minnesota

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Abstract

Groundwater plays an important role in the environment as it contributes to irrigation, streams and rivers, and wetland habitats affecting many species of plants and animals. Groundwater provides over half the drinking water for the nation; it is important to protect such an important resource. Groundwater contamination, though almost impossible to stop in some areas, can be minimized by delineating vulnerable areas. The use of modeling with Geographic Information Systems (GIS) contributes significantly to the delineation of vulnerable areas. The DRASTIC model, introduced by the U.S. Environmental Protection Agency (EPA), studied several key hydrogeologic characteristics that affect groundwater infiltration. DRASTIC is an acronym standing for **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone, and hydraulic **C**onductivity. Well test results have shown that areas of Houston County, Minnesota may be contaminated and that further research is needed. Data was collected, processed, and presented in GIS to spatially represent the DRASTIC parameters. Models were produced to show the susceptibility to contamination of groundwater in Houston County. Maps indicate areas of high risk to be further researched to resolve issues of groundwater contamination.

Introduction

In recent years, groundwater contamination has been discussed continuously by water quality agencies of all levels of government (Dixon, 2005). The quality of groundwater is important because it is the primary source of drinking water for over half of the nation. Groundwater is an important contributor to irrigation, streams and rivers, and wetland habitats affecting many species of plants and animals. Groundwater may be a reliable resource in many places today, but to keep the groundwater supply sustainable, risk assessments need to be conducted to keep groundwater a renewable resource (Twarakavi and Kaluarachchi, 2006).

Groundwater contamination can be minimized by delineating and monitoring vulnerable areas. Determining how to delineate areas susceptible to contamination is difficult due to the many variables that may or may not affect groundwater contamination in certain areas (Dixon, 2005). Hydrogeologic factors are used to determine groundwater susceptibility. These factors are integrated into

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groundwater models using multiple methods to predict likely susceptible areas (Sunil Raj Kiran, Santhosh Kumar, Stalin, Archana, Sridevi, and Selva Radha, n.d.). The Environmental Protection Agency (EPA) introduced the widely used DRASTIC model. The DRASTIC model accounts for the most significant hydrogeologic factors that contribute to groundwater contamination and applies a series of ratings and weights based on the overall importance to water infiltration (Aller, Bennett, Lehr, Petty, and Hackett, 1987; Sunil Raj Kiran et al., n.d.; Babiker, Mohamed, Hiyama, and Kato, 2005). The DRASTIC model supplies a standard method to assess the risk of groundwater contamination. The results are adamant as to whether an area is designated as susceptible to pollution (Afshar, Marino, Ebtehaj, and Moosavi, 2007).

Combining the DRASTIC model with GIS creates a powerful tool. Watkins, McKinney, Maidment, and Lin (1996) suggest ground water models integrated into GIS can visually represent the spatial aspects of ground water data as well as execute spatial calculations on data enabling further inferences to be made about susceptible areas.

Recent flooding has sparked interest in well testing in Houston County. As expected, many wells in or near low-lying areas were found to be contaminated. Yet, wells outside the flooded region also had failed tests. These wells were not affected by the flooding but by other sources of contamination. The goal of this project was not to pinpoint sources of contamination, but to analyze characteristics that affect groundwater contamination and produce a map showing areas that are more susceptible to contamination. By integrating the DRASTIC model into GIS, the hydrogeologic parameters were mapped and processed to delineate areas susceptible to contamination producing a risk assessment map of Houston County, MN.

Study Area

Houston County, MN is located in the southeastern corner of Minnesota and is the only county that shares a border with both Wisconsin and Iowa. The county spans approximately 568 square miles with elevation ranging from 623 feet above mean sea level in the east to 1342 feet in the southwest. The county encapsulates terrains ranging from nearly flat agricultural lands to steep bluffs to marshlands and riverbeds.

Data Collection

The data used for this project was retrieved from multiple sources. Shapefiles of well points were downloaded from the Minnesota Geospatial Information Office with links to further information from the Minnesota Geological Survey's (MGS) County Well Index (CWI). The well points were available in two files consisting of wells that were located with a Global Positioning System (GPS) and well locations that were calculated from the description on the well log. The MGS supplied a bedrock geology shapefile that mapped the boundaries of the bedrock layers within Houston County. The Minnesota Department of Natural Resources (DNR) provided, from their Data Deli, files consisting of Minnesota counties, streams, roads, and a 30-meter digital elevation model

(DEM). The soils layer was collected from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) Database. Lastly, the 2008-2009 precipitation information from the Root River Soil and Water Conservation District (SWCD) came in the form of a spreadsheet. All data was converted, when necessary, into spatial layers that were further viewed and processed using Environmental Systems Research Institute's (ESRI) ArcGIS Suite, version 9.2. A 30-meter cell size was used for all raster manipulation in the project. Thirty meter cell size was the scale of the DEM. This best fit the scale of the study area based on the accuracy of the 30-meter DEM, which was the smallest cell size of available data.

The DRASTIC Model

In 1987, an EPA funded effort to research and develop a method for evaluating pollution potential anywhere in the United States successfully produced the DRASTIC model (Aller et al., 1987). DRASTIC was used to evaluate the relative vulnerability of areas to groundwater contamination by focusing on hydrogeologic factors that influence pollution potential (Aller et al., 1987). The hydrogeologic factors include **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone, and hydraulic **C**onductivity that make up the acronym DRASTIC. A combination of ratings and weights were assigned to these factors based on how significantly they influenced pollution potential. Each DRASTIC factor was assigned a DRASTIC weight ranging from 1 to 5. Each DRASTIC factor was further assigned a rating, typically from 1 to 10, based on a range of information within the parameter. Higher ratings and weights indicated higher risk of vulnerability. Because of the influence of chemically enhanced agricultural areas, a series of pesticide weights were also produced to be used in calculating pollution potential for groundwater contamination (Table 1).

Table 1. DRASTIC parameters with the associated DRASTIC weight and the Pesticide DRASTIC weight, provided by the DRASTIC model, used in calculating the DRASTIC Index.

Parameter	DRASTIC Weight	Pesticide DRASTIC Weight
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
Hydraulic Conductivity	3	2

The values of the ratings and weights for each parameter are plugged into an equation to determine the pollution potential known as the DRASTIC Index. The equation for the DRASTIC Index is as follows (Aller et al., 1987):

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

where:

R = Rating
W = Weight

The DRASTIC index is the computed value that makes it possible to identify areas more susceptible to groundwater contamination. The higher the DRASTIC index means the higher the susceptibility.

Because DRASTIC was created for the purpose of evaluating features throughout the United States, the ranges and ratings are generalized to fit many landscapes. Therefore, the DRASTIC ranges and ratings had to be modified to fit local hydrogeologic settings. DRASTIC and Pesticide DRASTIC were developed using the following assumptions (Aller et al., 1987):

1) the contaminant is introduced at the ground surface;
2) the contaminant is flushed into the groundwater by precipitation;
3) the contaminant has the mobility of water and;
4) the area evaluated is 100 acres or larger.

Deviations from the assumed characteristics would need to be determined with further studies and were not included in the scope of this project.

The Modified DRASTIC Model

The Modified DRASTIC Model consisted of using the same methods for assigning ratings and weights to each of the parameters. The ranges for some factors were modified to more closely relate to local hydrogeologic settings.

Depth to Water

The depth to water factor refers to the actual depth from the ground surface to the water table. The depth of water is important because it determines the thickness of material that a contaminant would have to pass through to reach the aquifer. Generally, the thicker the material between the surface and the water table provides a higher chance of the contaminant breaking down before it can affect the aquifer.

Finding the depth to water with the available data took multiple steps involving the streams layer, the GPS located wells layer, and the calculated wells layer. The well layers were queried to find well points with attributes where the uppermost bedrock was the same as the aquifer from where it was fed, meaning the aquifer was at or near the surface. The streams layer was queried to find the perennial streams and rivers, meaning the water table is constantly contributing water at the surface. Both the streams and wells layers were converted to rasters and combined into one raster layer. This raster was then used to extract the elevation values from the DEM using the Extract by Mask command in Spatial Analyst. The raster was converted to elevation points in order to interpolate a raster surface. The Inverse Distance Weighted technique was used to interpolate the depth to water raster.

The Inverse Distance Weighted (IDW) interpolation uses a linearly weighted method of assigning values based on the inverse distance from the actual data value (ESRI, 2007). Simply, values closer together have more influence on the values assigned to a raster than values farther away. Although multiple interpolation methods were available and some even recommended for creating certain surfaces, the IDW technique provided better fitting data for use in this project by producing only the value ranges found within the data attributes. The IDW raster was then subtracted from the DEM using the Minus function in Spatial Analyst resulting in the depth to water raster. The values were then reclassified into values based on the ranges set in the Modified DRASTIC model as shown in Table 2.

Net Recharge

"The primary source of groundwater typically is precipitation which infiltrates through the surface of the ground and percolates to the water table. Net recharge represents the amount of water per unit area of land which penetrates the ground surface and reaches the aquifer" (Aller et al., 1987). Net recharge is calculated by the following equation:

Net Recharge = Precipitation – Evaporation – Run Off

Table 2. Depth to water table ranges, in feet, and associated ratings according to the Modified DRASTIC model.

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

Although precipitation data from the SWCD for 2008-2009 was available, evaporation and run off data was not. The United States Geological Survey (USGS) states recharge rates are typically about 20-25% for unconfined aquifers in Minnesota (USGS, 2007).

Precipitation data was submitted monthly to the SWCD by approximately ten volunteers within Houston County. The locations reported were random and very sparse in some areas. There was no information submitted for some months at random locations. That could have meant that there was no precipitation at that location or that there was nothing submitted. It was assumed that nothing was submitted and an average precipitation amount was used to fill the void.

The annual precipitation was calculated for each location. The net recharge was then calculated by taking 25% of the annual precipitation for each location and the net recharge points were applied to the map. The IDW interpolation technique was again used to create a raster of net recharge values. The values were reclassified based on the ranges set in the Modified DRASTIC model and are shown in Table 3.

Table 3. The net recharge, in inches, was estimated as 25% of annual precipitation to account for runoff and evaporation. The range and ratings were established by the Modified DRASTIC model.

Net Recharge (Inches)	
Range	Rating
8-9	3
9-10	6
10-11	8
11+	9

Aquifer Media

Aquifer media refers to the characteristics of the bedrock that serve as an aquifer. An aquifer is rock below the surface that has capacity to hold water for use. The water is contained within pour spaces and cracks in the rock layer. The media of the rock affects the flow of water through the rock which also affects the rate and direction that a contaminant flows.

Finding the aquifer media posed a challenge because there was no geologic atlas available for Houston County. Well information and the bedrock geology files were the sources used to generalize what aquifers were used and therefore, determine the media of each aquifer.

The geology of Houston County is unique in that it ranges from karst limestone in the southwest region to bluffs and steep slopes overlooking the Mississippi River. Runkel, Tipping, Alexander, Green, Mossler and Alexander (2003) provided the background information necessary to generalize media types and aquifer usage to influence the Modified DRASTIC ratings (Table 4).

Table 4. The properties of the materials within the aquifer are known as the aquifer media and were rated by movement of water through the materials according to the modified DRASTIC model.

Aquifer Media	
Range	Rating
Limestone	10
Dolostone	9
Sandy Dolostone	8
Sandstone, medium to coarse grained	7
Sandstone, fine to medium grained	6
Sandstone, very fine to fine grained	5
Shaly Sandstone	4
Siltstone	3
Shale	2

Many of the well attributes contained aquifer information from where they were pumping water. Although 524 wells were listed as using water from numerous aquifers, there was no way to determine aquifer boundaries based on well information. To determine general boundaries for aquifer media, an assumption was made that the majority of the wells would determine the source aquifer. That said, wells were grouped by location within the bedrock geology layer. Geology layers were grouped based on media characteristics and relationships to confining layers as shown in Table 5.

The DRASTIC ratings were modified to better fit local hydrogeologic settings and the major rock characteristics within each aquifer were very similar and therefore were rated with little difference. Group 1 characteristics represented fine to medium grained sandstone and was assigned a rating of 6. Group 2 characteristics represented very fine to fine grained sandstone and was assigned a rating of 5. Group 3 characteristics represented shaly sandstone and was assigned a rating of 4.

Table 5. Bedrock layers were combined to form aquifer groups based on the primary water source of most wells. The groups were classified according to the aquifer media rating of the modified DRASTIC model.

AQUIFER GROUPS	
GROUP 1	*Shallow*
Galena Group	
Decorah Shale	
St. Peter Sandstone	
Prairie Du Chien Group	
GROUP 2	
Jordan Sandstone	*to*
St. Lawrence Formation	
Franconia Formation	
Ironton and Galesville Sandstone	
GROUP 3	
Eau Claire Formation	
Mt. Simon Sandstone	*Deep*

Soil Media

Soil media refers to the portion of the earth located between the surface and the uppermost bedrock. This area contains significant biologic activity and organic material at the surface. The type and size of the soil media directly affects the rate of infiltration of pollution (Aller et al., 1987).

Soil classification was broken down by the Soil Conservation Service within the DRASTIC model. However, the information collected from the SSURGO database was subset by other standards. Comparisons were made between different classifications involving the soils within Houston County. The soils were classified in regards to local soil characteristics with influence from both classifications and were rated accordingly within the Modified DRASTIC model (Table 6).

Table 6. The type and size of the soil media directly affects the rate of infiltration and is rated according to the modified DRASTIC model.

Soil Media	
Range	Rating
Silty Clay	1
Silty Clay Loam	2
Peat	3
Silt Loam	4
Loam	5
Sandy Loam	6
Loamy Sand	7
Sand	8
Riverwash	9
Rock	10
Water	10

Topography

Topography is variability of the slope, or gradient, of the ground surface. Slope affects the type and amount of soil at the surface of the land as well as the rate and quantity of runoff. A contaminant introduced on a steep slope has less chance of infiltrating into the surface and would likely flow downward leaving concentrated pollution at the base of the slope near a groundwater source. Slope is also used to determine gradient and flow of the water table since the water table similarly follows the contour of the surface (Aller et al., 1987).

The Slope tool from the Surface toolset in the Spatial Analyst extension was used to generate the slope of Houston County. The tool used the 30-meter DEM to calculate a grid layer showing percent slope. The slope layer was then reclassified to rating values according to the percent ranges recommended in the DRASTIC model (Table 7).

Table 7. Topography is the variability of the slope of the ground surface. The slope affects the rate and quantity of runoff and was rated accordingly by the modified DRASTIC model.

Topography (Percent Slope)	
Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1

Impact of the Vadose Zone

The vadose zone is defined as the unsaturated zone above the water table. The vadose zone consists of the material existing as the surface soil, as well as the bedrock layers without a holding capacity for ground water. The impact of pollution on the vadose zone is measured based on the thickness, porosity, and permeability of all material within the vadose zone. The ratings are assigned per the influence of the least impervious material, taking into account all types of material toward the surface.

The techniques for determining ratings for the vadose zone ventured from the DRASTIC model and leaned more upon the results from the aquifer media and relative depth of the water table. In review, it was determined the three aquifer groups that were primarily drilled for use were the Prairie Du Chien Group, Ironton-Galesville, and Eau Claire-Mt. Simon (Table 5). The water table generally follows the contour of the land within the three aquifers. The rating value for the vadose zone parameter took into account the material that made up each bedrock layer above each specific aquifer, or estimated water table, as found in Runkel et al. (2003). The ratings were assigned as follows in Table 8.

Table 8. The vadose zone is defined as the unsaturated zone above the water table. Material, thickness, porosity, and permeability impact infiltration in the vadose zone. The bedrock layer characteristics were used for rating in the modified DRASTIC model.

Impact of the Vadose Zone	
Range	Rating
Galena/Cummingsville Mbr	10
Decorah-Platteville-Glenwood Fm	1
Prairie Du Chien Group	9
St. Peter Sandstone	7
Jordan Sandstone	6
St. Lawrence/Franconian Fm	5
Ironton/Galesville Sandstones	5
Eau Claire Fm	4
Mt. Simon Sandstone	1

To briefly explain an example of how the modified rating system was determined, in the report, Runkel et al. (2003) defined the material in each bedrock layer above the estimated water table. Therefore, in the southwest region of the county, there are portions of the Galena/Cummingsville Member. This bedrock layer consists of karst limestone meaning that it very susceptible to pollution and rated as 10. The bedrock layer beneath acts as a confining unit known as the Decorah Shale. With little porosity, the Decorah Shale, rated as 1, is able to hold some groundwater and therefore the water table is present at that location. Because there is very little material available between the karst limestone and the water table, the groundwater at that point is very susceptible to pollution and is a great risk for regular use. However, the majority of water in that area is pumped from the Prairie Du Chien Group which is beneath the Decorah-Platteville-Glenwood Formation and the St. Peter Sandstone. The area where both Decorah Shale and St. Peter Sandstone protect the Prairie Du Chien aquifer was rated as 1, whereas the area protected only by the St. Peter Sandstone was rated as 7 because it is only protected by the medium-to-coarse grained sandstone rather than a shale confining unit. The least porous material has a greater impact on the vadose zone rating as well as the thickness of material.

Hydraulic Conductivity

Hydraulic conductivity refers to the rate at which the aquifer materials transmit water. The rate is affected by the material, porosity, and gradient of the aquifer. Hydraulic conductivity is important because it determines the rate of movement through the aquifer of a contaminant from the point of contact. Higher rates represent higher susceptibility to contamination (Aller et al., 1987).

Runkel et al. (2003) suggests hydraulic conductivity rates for both shallow and deep bedrock conditions. Both conditions are tested and reported because they vary in character. Shallow bedrock conditions typically have higher rates of movement due to relatively high density of large fractures and cavities. Deep bedrock conditions, although evidence is scarce in this area, seem to transmit water slower due to significantly fewer fractures and cavities (Runkel et al., 2003).

Although Runkel et al. (2003) suggested general depth and thickness of bedrock types, determining the conductivity rates posed a challenge because depth or thickness was not linked spatially to bedrock layers. Shallow bedrock conditions were determined by the areas of that bedrock layer that was exposed to the surface. Therefore, deep bedrock conditions were used in the areas where the bedrock layer was covered by at least one other bedrock layer. The rates suggested by Runkel et al. (2003) were applied to the bedrock layers in the bedrock geology shapefile. The bedrock layers were then converted to a raster and reclassified based on the DRASTIC model ranges (Table 9).

Table 9. Hydraulic conductivity refers to the rate, in GPD/FT^2, at which the aquifer materials transmit water and is rated according to the modified DRASTIC model.

Hydraulic Conductivity (GPD/FT^2)	
Range	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10

DRASTIC Index

The final step in the modified DRASTIC model was to apply the weight factors to each of the seven parameters (Table 1). Each parameter was weighted by multiplying the rating of each cell value and the DRASTIC weight using the Math toolset's Times tool in the Spatial Analyst extension. The resulting cell values for all parameters were added together using the Plus tool from the same toolset (Figure 1). The final raster represented the DRASTIC Index showing the risk of susceptibility to contaminants in Houston County. The same procedure was executed using the Pesticide DRASTIC weights.

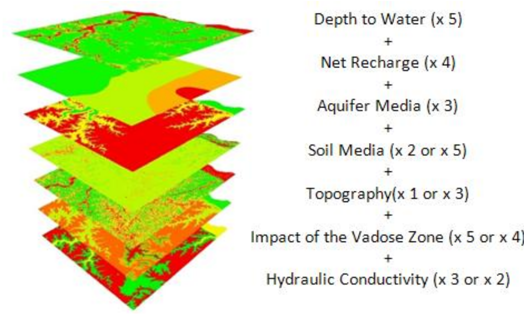

Figure 1. The procedure for calculating the DRASTIC index and the Pesticide DRASTIC index is multiplying the values of the raster layer by the weight and adding the weighted results.

Results/Discussion

The DRASTIC index indicates the relative level of susceptibility to groundwater contamination. The DRASTIC model represents general ratings and weights to be used for the entire United States. The application of the model to Houston County would produce a result showing the entire county as susceptible in comparison to the state or nation. Therefore, the DRASTIC model was modified to better fit local hydrogeologic settings.

Houston County constitutes varying landscapes that affect groundwater infiltration. Within the variability, agricultural areas coincide with deep river valleys and steep slopes. Because cropland is dispersed throughout the county, both the DRASTIC model weights and the

Pesticide DRASTIC model weights were used in creating separate groundwater vulnerability maps. The maps produced show a variety of relative susceptibility throughout Houston County using a red to green color scale. The red color represents higher susceptibility and the green color represents lower susceptibility (Figure 2).

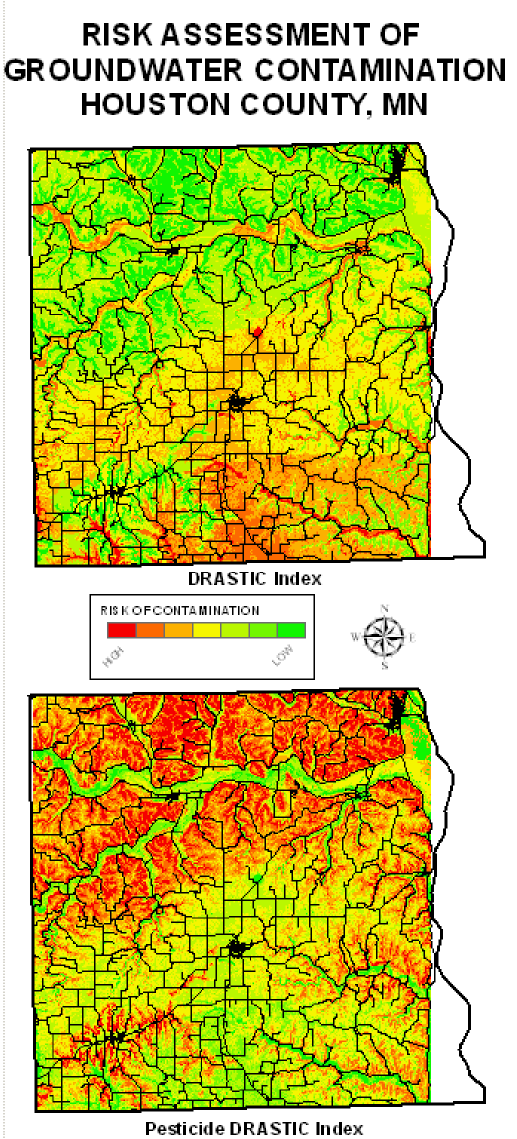

Figure 2. The risk assessment of groundwater contamination using the DRASTIC index and the Pesticide DRASTIC index. Red refers to areas of high risk. Green refers to areas of low risk.

The DRASTIC map showed higher risk areas mostly in the southeastern part of the county with some widely dispersed high risk areas throughout the county. Much of the area in the southeast consists of cropland encroaching Winnebago Creek and Crooked Creek. The southwest portion of the county would have been the highest risk area because of the karst characteristics, but the expected high DRASTIC ratings for that region were negated with the underlying confining unit protecting groundwater below from which most water is pumped.

The Pesticide DRASTIC map showed many more dominant high risk areas in many of the same parts of the county that were low risk with the DRASTIC map. The north and southwest regions of Houston County were labeled as high risk where the southeast region was lower risk. The high risk regions seemed to be related to areas of abrupt slope change. The prominent difference was the different weights applied to the topography and soil media parameters for the DRASTIC model versus the Pesticide DRASTIC model.

Conclusions/Limitations

The project was designed to assess the risk of groundwater contamination in Houston County, MN. Modifying the DRASTIC model to accommodate local hydrogeological settings and combining the use of GIS made it possible to create a visual tool representing areas of risk. Many of the methods used for calculating the DRASTIC parameters typically rely on information provided by a geologic atlas. Unfortunately, a geologic atlas was unavailable. Therefore, other sources of information had to be used to best estimate and calculate the DRASTIC parameters. The use of the DRASTIC model and the Pesticide DRASTIC model provided values used in the GIS to contribute hydrogeological information in a spatial context. The maps produced, though reliable to the level of information used, should be used only as reference for further research. This project serves as a foundation to build upon and provide techniques that may be used for future groundwater research.

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References

Afshar, A., Marino, M. A., Ebtehaj, M., and Moosavi, J. 2007. Rule-Based Fuzzy System for Assessing Groundwater Vulnerability. *Journal of Environmental Engineering , 133* (5), 532-540.

Aller, L., Bennet, T., Lehr, J. H., Petty, R. J., and Hackett, G. 1987. "DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings." *US EPA Report 600/2-87/035*, U.S. Environmental Protection Agency. Retrieved on July 14, 2009, from http://www.epa.gov/nscep.

Babiker, I. S., Mohamed, M. A., Hiyama, T., and Kato, K. 2005. A GIS-Based DRASTIC Model for Assessing Aquifer Vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan. *Science of the Total Environment* (345), 127-140.

Dixon, B. 2005. Applicability of neuro-fuzzy techniques in predicting ground-water vulnerability: a GIS-based sensitivity analysis. *Journal of Hydrology* (309), 17-38.

ESRI. 2007. Environmental Systems Research Institute. ArcGIS 9.2 Desktop Help. Retrieved on October 12, 2009, from http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=How_Inverse_Distance_Weighted_%28IDW%29_interpolation_works.

Runkel, A. C., Tipping, R. G., Alexander, E. C. Jr., Green, J. A., Mossler, J. H., and Alexander, S. C. 2003. Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey Report of Investigations 61, 105 p., 2 pls. Retrieved on September 16, 2009 from ftp://mgssun6.mngs.umn.edu/pub3/ri-61.

Sunil Raj Kiran, P., Santhosh Kumar, R., Stalin, K., Archana, P., Sridevi, L., and Selva Radha, A. n.d. *GIS Techniques for Groundwater Contamination Risk Mapping.* Retrieved on June 5, 2009, from GISdevelopment.net: http://gisdevelopment.net/application/nrm/water/ground/mi08_151pf.htm

Twarakavi, N. K., and Kaluarachchi, J. J. 2006. Sustainability of ground water quality considering land use changes and public health risks. *Journal of Environmental Management* (81), 405-419.

USGS. 2007. United States Geological Survey. Ground-Water Recharge in Minnesota. Retrieved on October 14, 2009, from Google.

Watkins, D. W., McKinney, D. C., Maidment, D. R., and Lin, M. D. 1996. Use of Geographic Information Systems in Ground-Water Flow Modeling. *Journal of Water Resources Planning and Management , 122* (2).