King Fahd University of Petroleum and Minerals

Term Paper

On

Groundwater Vulnerability Assessment Using GIS-Based DRASTIC Model

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Abstract

Assessment of groundwater pollution vulnerability using the DRASTIC model in a GIS environment has become more widespread for effective groundwater planning and management. Groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against contamination entering the subsurface environment. Groundwater pollution vulnerability maps are useful for groundwater quality monitoring, and to identify areas that need more detailed analysis for land use planning. The DRASTIC standardized system for evaluating groundwater pollution potential is based on different parameters, such as ***D****epth to water*; *net* ***R****echarge*, ***A****quifer media*, ***S****oil media*, ***T****opography*, ***I****mpact of vadose zone and hydraulic* ***C****onductivity*. The thematic layers of each parameter have been prepared and integrated through the DRASTIC model within a GIS environment to demarcate vulnerable zones. DRASTIC indices for both normal and agricultural pollutants have been derived to prepare groundwater vulnerability maps.

1. Introduction

Information about subsurface conditions is needed for the area of investigation, which may be a complete catchment, the outcrop or recharge area of an aquifer or the part of the aquifer contributing water to individual public supply sources or well fields. The information required is that which will enable assessments to be made of both the vulnerability of the aquifer to pollution and its susceptibility to the impacts of heavy or even excessive abstraction of groundwater.

The groundwater system responds slowly to contamination events and the travel times to reach the groundwater zone are often long. Cleaning and restoring contaminated groundwater is often technically problematic and expensive. Moreover, finding alternative sources for water supply is not always possible. Therefore, the most effective and realistic solution is to prevent the contamination of groundwater.

Groundwater vulnerability is considered an intrinsic property of groundwater and can be defined as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system.

A **DRASTIC** model applied in a GIS environment was used to evaluate the vulnerability of the aquifer using **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, and hydraulic **C**onductivity by computing the relative vulnerability of groundwater to contamination from surface sources of pollution. A series of easy-to-understand color maps was produced, which can be used to provide assistance in resource allocation and prioritization of groundwater-related activities.

2. Background

The concept of groundwater vulnerability is derived from the assumption that the physical environment may provide some degree of protection of groundwater against natural and human impacts, especially with regard to pollutants entering the subsurface environment. The term ‘vulnerability of groundwater to contamination’ was probably first introduced in France in the late 1960s.

The general intention was to show that the protection provided by the natural environment varied from place to place. This would be done by describing in map from the degree of vulnerability of groundwater to pollution as a function of the hydrogeological conditions. Thus the fundamental principle of groundwater vulnerability is that some land areas are more vulnerable to pollution than others, and the goal of a vulnerability map is to subdivide an area accordingly. The differentiation between mapped units was considered arbitrary because the maps showed the vulnerability of certain areas relative to others, and did not represent absolute values. The maps, however, would provide information from which land use and associated human activities could be planned and/or controlled as an integral part of an overall policy of groundwater protection at national, sub-national (province or state) or catchment scale.

"DRASTIC is an index model designed to produce vulnerability scores for different locations by combining several thematic layers. It was originally developed for manual overlay of semi quantitative data layers however the simple definition of its vulnerability index as a linear combination of factors shows the feasibility of the computation using GIS. GIS are designed to collect diverse spatial data to represent spatially variable phenomena by applying a series of overlay analysis of data layers that are in spatial register"(Babiker et al., 2005).

3. Classifying Aquifer Vulnerability

Vulnerability assessment involves evaluating likely travel times from the ground surface to the water table, or to the aquifer in the case of confined conditions. The greater the travel time, the more potential there is for pollutant attenuation. Aquifer vulnerability can be subdivided simply into five broad classes (Table.1). Extreme vulnerability is associated with aquifers having a high density of open fractures and with shallow water tables, which offer little chance for pollutant attenuation.

Table.1. Broad classification of aquifer vulnerability (based on Foster et al., 2002)

Vulnerability Class	Definition
Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	Vulnerable to many pollutants, except those highly absorbed and/or readily transformed, in many pollution scenarios
Moderate	Vulnerable to some pollutants, but only when continuously discharged or leached
Low	Only vulnerable to the most persistent pollutants in the long term, when continuously and widely discharged or leached
Negligible	Confining beds are present and prevent any significant vertical groundwater flow

Thus for preliminary assessment purposes, it is instructive to note that the hydrogeological environments differ greatly in the time taken for recharge entering at the land surface to reach the water table surface of the aquifer (Table.2). Table.1 also indicates the likely vulnerability class for each environment, and the general vulnerability of some common soils and rocks is summarized in (Figure.1), in which the arrows indicate increasing vulnerability, and the three classes used in this earlier attempt at classification roughly correspond to the three middle classes in (Table.1)

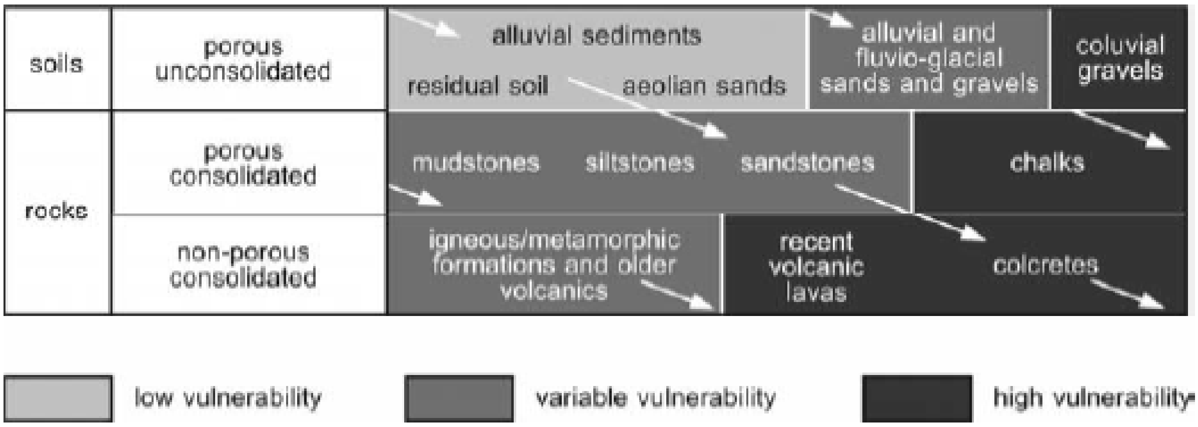

Figure.1. Vulnerability of soils and rocks to groundwater pollution (modified from Lewis *et al*., 1980)

Table.2. Hydrogeological environments and their associated groundwater pollution vulnerability (based on Morris *et al*., 2003)

Hydrogeological environment		Typical travel times to water-table	Attenuation potential of aquifer	Pollution vulnerability
Alluvial and coastal plain sediments	unconfined semi-confined	weeks-months years-decades	high-moderate High	moderate low
Intermontane valley-fill and volcanic systems	unconfined semi-confined	months-years years-decades	moderate moderate	moderate moderate-low
Consolidated sedimentary aquifers	porous sandstones karstic limestones	weeks-years days-weeks	high low	moderate-high extreme
Coastal limestones	unconfined	days-weeks	low-moderate	high-extreme
Glacial deposits	unconfined	weeks-years	moderate-low	high-moderate
Extensive volcanic sequences	lavas ash/lava sequences	days-months months-years	low-moderate high	high-extreme low
Weathered basement	unconfined semi-confined	days-weeks weeks-years	low moderate	high-extreme moderate
Loessic plateaux	unconfined	days-months	low-moderate	moderate-high

Unsaturated zone travel time and aquifer residence time are important factors in any aquifer assessment because they affect the ability of the aquifer in question to protect against pollution. For instance, a residence period of a month or so is adequate to eliminate most bacterial pathogens.

The soil zone is usually regarded as principal factors in the assessment of groundwater vulnerability and the first line of defense against pollution. The soil layer is usually continuous, but the spatial variability of its physical, chemical and biological properties can be very great, and generalizations of soil parameters have to be undertaken with some care. Because of its potential to attenuate a range of pollutants, it plays a critical role when considering specific vulnerability to diffuse sources of pollution such as agricultural fertilizers, pesticides and acid deposition. Not all soil profiles and underlying materials are equally effective in attenuating pollutants, and the degree of attenuation will vary widely with the types of pollutant and polluting process in any given environment.

The soil has a particularly important position amongst vulnerability factors because the soil itself is vulnerable. The soil’s function as a natural protective filter can be damaged rather easily by such routine activities as cultivation and tillage, irrigation, compaction and drainage. Human activities at the land surface can greatly modify the existing natural mechanisms of groundwater recharge and introduce new ones, changing the rate, frequency and quality of groundwater recharge. This is especially the case in arid and semi-arid regions where there may be relatively little and infrequent natural recharge, but also applies to more humid regions. Understanding these mechanisms and diagnosing such changes are critical, and the use of soil properties in vulnerability assessment should always take into consideration whether the soils in the area of interest are in their natural state. Further, there are many potentially polluting human activities in which the soil is removed or otherwise by-passed and for these the component of protection provided by the soil does not apply.

Below the soil, the unsaturated zone is very important in protecting the underlying groundwater, especially where soils are thin and/or poorly developed. The character of the unsaturated zone and its potential attenuation capacity then determine the degree of groundwater vulnerability. The main unsaturated zone properties that are important in vulnerability assessment are the thickness, lithology and vertical hydraulic conductivity of the materials. The thickness depends on the depth to the water table, which can vary significantly due to local topography and also fluctuates seasonally, and both these have to be taken into account when determining thickness. The importance of hydraulic conductivity, its distribution and its role in determining groundwater flow rates should be particularly emphasized. Porosity, storage properties, and groundwater flow direction may also be important, and another supplementary parameter in some types of aquifers and circumstances may be the depth and degree of weathering of the upper part of the unsaturated zone.

Degree of confinement is also an important factor in determining vulnerability. Concern about groundwater pollution relates primarily to unconfined aquifers, especially where the unsaturated zone is thin because the water table is at shallow depth. Significant risk of pollution may also occur in semi-confined aquifers, if the confining aquitards are relatively thin and permeable. Groundwater supplies drawn from deeper and more fully confined aquifers will normally be affected only by the most persistent pollutants and in the long term. Data requirements are summarized in (Table.3) below.

Additional attributes that can be considered as of secondary importance to those in Table.3 include topography, surface water features and the nature of geological formations beneath the aquifer of interest. Some of these may have only local significance. Topography influences the location of recharge, soil development, properties and thickness and local groundwater flow. The interaction between surface water and groundwater, i.e. in which direction water is moving, may be important locally.

Table.3 Data requirements for principal factors contributing to vulnerability assessments (modified from Foster *et al.*, 2002)

Component of vulnerability	Ideally required	Normal availability and source
Hydraulic inaccessibility (ease and speed of water movement)	Degree of aquifer confinement (incl. partial or semi-confined)	Simple division between confined and unconfined from geological maps
	Soil thickness and permeability	Soil classes in map form and their accompanying descriptions
	Depth to groundwater table or potentiometric surface in map form (gives thickness of unsaturated zone)	Varying amounts of water table data from individual wells
	Unsaturated zone moisture content and vertical hydraulic conductivity of strata in unsatu-rated zone or confining layers	Little or no data: typical values inferred from existing studies or literature
Attenuation capacity	Mineral and organic matter content of soil, and its thickness	Soil classes in map form and their accompanying descriptions
	Grain size and/or fracture distri-bution of strata in unsaturated zone or confining layers	General distinction between intergranular and fracture flow from geological maps
	Mineralogy of strata in unsaturated zone or confining beds, including organic content	Maybe found in descriptive memoirs or reports accompanying maps, or from existing studies or literature

4. Mapping Aquifer Vulnerability

A vulnerability map shows in a more or less subjective way the capacity of the subsurface environment to protect groundwater. Like all derivative or interpreted maps, it is somewhat subjective because it must meet the requirements of the user. The maps should provide the user with the most accurate and informative assessment of the sensitivity to impacts, allowing comparison between aquifers and between different locations and different parts of the same aquifer.

Preparation of the maps usually involves combining or overlaying several thematic maps of selected physical factors that have been chosen to depict vulnerability. These are discussed below, but have been grouped by into those associated with:

- the hydrogeological framework – the characteristics of the soils and underlying geological materials;
- the groundwater flow system – the direction and speed of groundwater movement;
- the climate – the amount and type of recharge.

One of the best known point count systems is DRASTIC, developed by the US EPA, this has been widely tested. The method employs seven hydrogeological factors to develop an index of vulnerability:

- **D**epth to water table
- net **R**echarge
- **A**quifer media
- **S**oil media
- **T**opography (slope)
- **I**mpact on the vadose zone
- hydraulic **C**onductivity

An index is generated by applying a weight to each hydrogeological factor that is represented numerically. As the hydrogeological factors vary spatially, the DRASTIC index provides a systematic way of mapping the relative vulnerability of groundwater to contamination and can be readily incorporated into a GIS. However, the large number of parameters included means that data requirements are invariably difficult to meet. Further, the large number of variables factored into the final index number may mean that critical parameters may be subdued by other parameters having little or no bearing on vulnerability in that particular setting. Some DRASTIC parameters, such as aquifer and soil media and hydraulic conductivity, are not fully independent but interact with each other.

Whichever system is used, the primary sources of data for assessing aquifer vulnerability are soil and geological maps and cross-sections, data or maps of depth to groundwater, supplemented by information from existing hydrogeological investigations that can provide additional information on subsurface transport and attenuation properties (Table.3).

Overall, allowing for the cautionary words at the beginning of this discussion, the concept of groundwater vulnerability has become both broadly accepted and widely used Vulnerability maps should not be used to assess hazards where pollutants are discharged deeper into the subsurface, for example leaking tanks and landfills. A further note of warning is that for most methods the resulting assessment of vulnerability applies only to the aquifer closest to the ground surface if there is more than one aquifer in a vertical sequence. While this is often the most important for local water supply, deeper aquifers may also be exploited. At first sight, such aquifers may appear to be more than adequately protected from pollution, but they may in fact be vulnerable to downward leakage of pollutants, which can be induced by pumping from the deeper horizons, or to pollutants moving laterally from a more remote source.

5. Case Study: A GIS-based DRASTIC Model for Assessing Aquifer Vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan :(Babiker et al., 2005)

The Kakamigahara aquifer, located in the southern part of Gifu Prefecture, central Japan, provides a source of water for domestic, industrial and agricultural use. High nitrate levels encountered exceeding the 13 mg/l concentration while the acceptance level (44 mg/l NO^{-3}) according to Japan regulations (Babiker et al., 2004). The main source of nitrate contamination has been identified as agricultural land use, with some possibility of urban sources (residential, commercial, and industrial). To ensure that this aquifer can remain as a source of water for the Kakamigahara area, they evaluate the Kakamigahara aquifer vulnerability using **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, and hydraulic **C**onductivity (DRASTIC), the empirical model of the U.S. Environmental Protection Agency (EPA, US, 1985), using a combination of DRASTIC and geographical information system (GIS) as an effective method for groundwater pollution risk assessment and water resource management.

5.1 Methods

The model yields a numerical index that is derived from ratings and weights assigned to the seven model parameters (Table.4). The significant media types or classes of each parameter represent the ranges, which are rated from 1 to 10 based on their relative effect on the aquifer vulnerability.

The seven parameters are then assigned weights ranging from 1 to 5 reflecting their relative importance. The DRASTIC Index is then computed applying a linear combination of all factors according to the following equation:

$$\textbf{DRASTIC Index} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (1)$$

Where D, R, A, S, T, I, and C are the seven parameters and the subscripts **r** and **w** are the corresponding *rating* and *weights*, respectively.

Table .4: The DRASTIC model parameters (Babiker et al., 2005)

Factor	Description	Relative weight
Depth to water	Represents the depth from the ground surface to the water table, deeper water table levels imply lesser chance for contamination to occur.	**5**
Net **R**echarge	Represents the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants.	**4**
Aquifer media	Refers to the saturated zone material properties, which controls the pollutant attenuation processes	**3**
Soil media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	**2**
Topography	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	**1**
Impact of vadose zone	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone	**5**
Hydraulic **C**onductivity	Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system	**3**

DRASTIC uses a relatively large number of parameters (seven parameters) to compute the vulnerability index, which ensures the best representation of the hydrogeological setting. The numerical ratings and weights, which were established using the Delphi technique, are well defined and are used worldwide. This makes the model suitable for producing comparable vulnerability maps on a regional scale. Data analyses and model implementation were performed using the GIS software.

5.2 Results

(Figure.2) shows the rated parameter maps used to obtain the DRASTIC aquifer vulnerability index

- **D**epth to water table
- net **R**echarge
- **A**quifer media
- **S**oil media
- **T**opography (slope)
- **I**mpact on the vadose zone
- hydraulic **C**onductivity

by using several map calculation functions of GIS software for each single parameter to get a rated value out of 10 according to the properties of the parameters. Overlying all these seven parameters, aquifer vulnerability map obtained.

The DRASTIC aquifer vulnerability map clearly shows the dominance of "High" vulnerability classes (shades of red) in the western part of Kakamigahara Heights while the eastern part is characterized by "Moderate" vulnerability (shades of green)(Figure. 3).

Integrated vulnerability map shows that the eastern part of the Kakamigahara aquifer is under a higher risk of contamination despite its moderate intrinsic vulnerability (Figure. 4). The more vulnerable western part of the aquifer is, however, under a lower contamination risk. This is mainly due to the high pollution risk associated with vegetable cultivation.

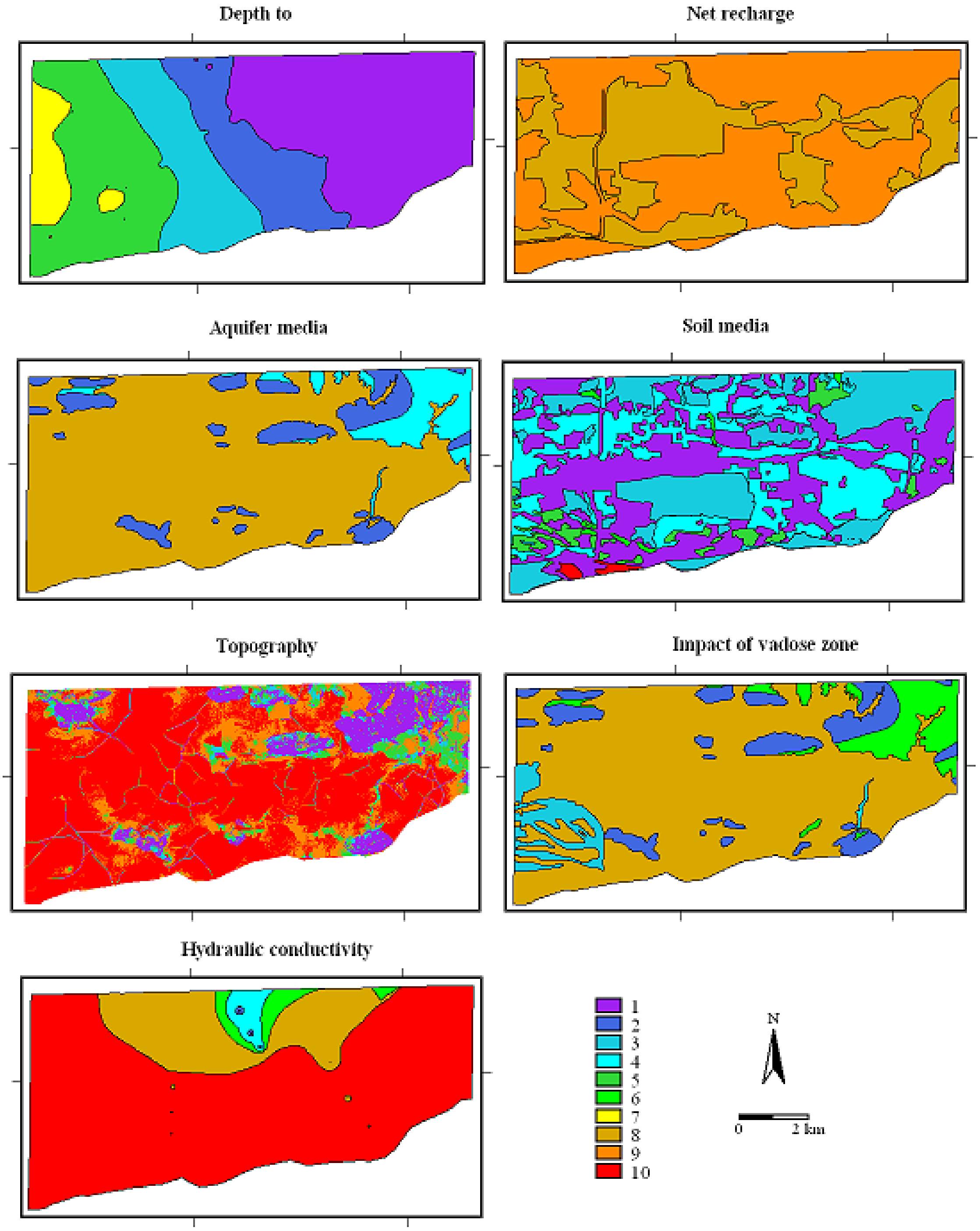

Figure.2. Rated maps used to compute the DRASTIC vulnerability index. The rating score 1 implies a minimum impact on vulnerability while the score 10 indicates the maximum impact (Babiker et al., 2005)

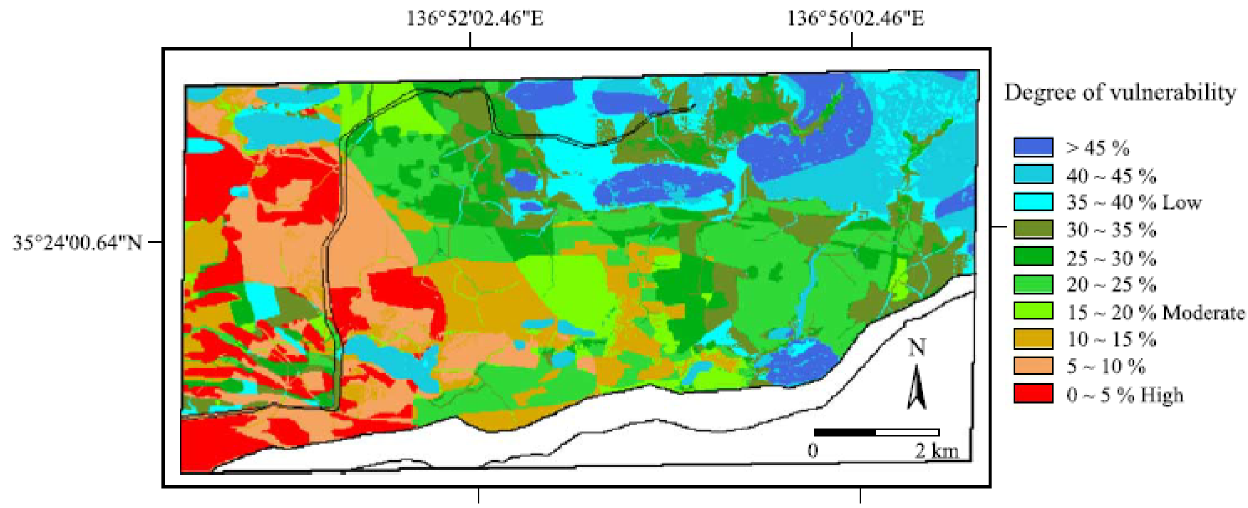

Figure.3. **Aquifer vulnerability map of Kakamigahara Heights (Babiker et al., 2005).**

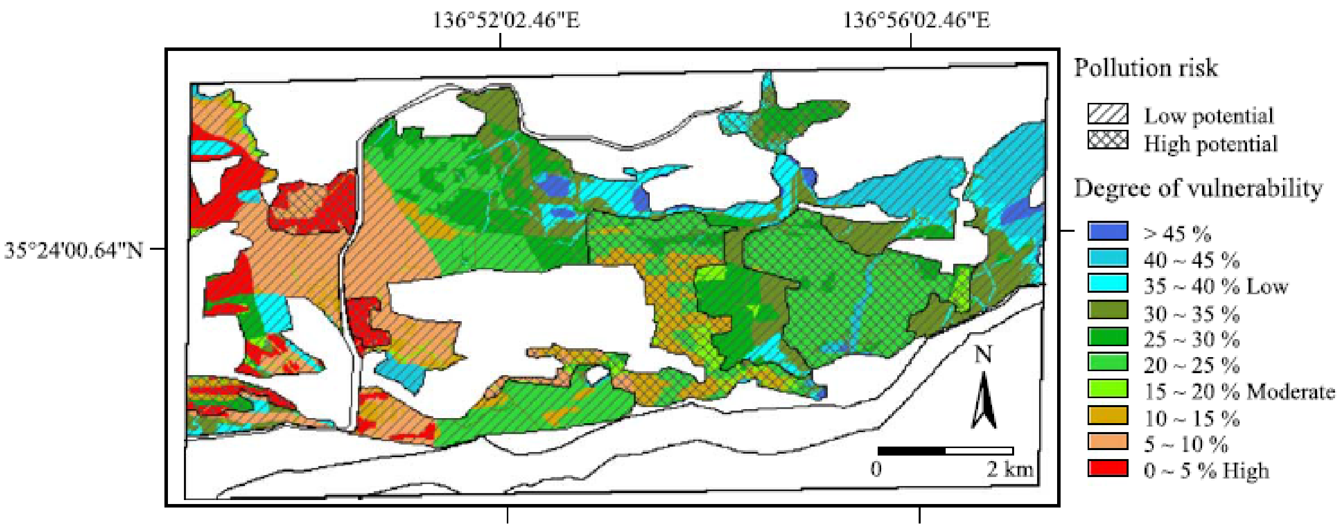

Figure.4. Integrated vulnerability map combining the aquifer vulnerability with the potential pollution sources in Kakamigahara Heights (Babiker et al., 2005).

6. Summary and Recommendations

Representation of the vulnerability of groundwater to pollution by means of maps has become an important tool by which hydrogeologists can assist the planning community. Vulnerability maps have been demonstrated to play a useful part in groundwater protection, can allow for improve communication about risks and what is threatened, for better visual presentations and understanding of the risks and vulnerabilities so that decision makers can see where resources are needed for protection of these areas. The vulnerability maps will allow them to decide on mitigating measures to prevent or reduce loss of life.

The GIS technique has provided an efficient environment for analyses and high capabilities in handling a large quantity of spatial data. The seven model parameters were constructed; classified and encoded employing various map and attribute GIS functions. The incorporation of the GIS enabled the results to be presented in the form of maps. Each contributing parameter in the system could be presented individually or as part of the whole system. The maps were highly visual and easy to interpret especially by non-specialists who may be using the tool. Furthermore, the maps could be analyzed to various degrees of complexity depending on user ability.

Finally, I highly recommend each municipality to develop a GIS data base system for risk assessment and management, containing the following types of information:

- Hazard maps indicating the probability and potential damage within a given time period.
- A database of elements of vulnerability, concentration…etc.
- Analysis of vulnerability of the elements at risk, taking into account the intensities of events as indicated in the hazard maps.

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Appendices

Appendix A: Case Study Paper

Appendix B

PPT Presentation Slides