An-Najah National University
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Assessment of Groundwater Vulnerability to Contamination in the West Bank, Palestine

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This Thesis is dedicated to my beloved Homeland

and to all the Palestinian People.

Ne'mat

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Ne'mat Sadeq Qamhieh.

Nablus, 2006.

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ABSTRACT

This study assesses the groundwater pollution risk in the West Bank, Palestine. The combined use of DRASTIC model and geographic information system (GIS) was adopted for this purpose. Seven thematic maps of the DRASTIC model were developed in order to asses the vulnerability of groundwater to contamination and these include the depth to water table, recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. The GIS technology was used to create an integrated vulnerability map of the West Bank to demarcate vulnerable zones. The result shows that 90% of the study area is at low risk of pollution while 10% is at moderate risk. This indicates that our groundwater resources are safe. The study demonstrated that GIS technology is an efficient environment for analyses and precise processing of spatial data. The thesis also included a comprehensive literature review regarding the different concepts and approaches for assessing groundwater vulnerability to contamination

CHAPTER I

INTRODUCTION

INTRODUCTION

1.1 General

Groundwater resources are highly essential to the survival of human beings, particularly in areas where other sources of potable water are lacking. However, many sources of contamination contribute to the impairment of this precious resource. For instance, agricultural activities are the main source of elevated nitrate concentrations in groundwater (Mclay et al., 2001). These agricultural activities include the use of fertilizers, manure application, and leguminous crops. The extensive use of fertilizers on row crops is considered as a main source of nitrate leaching to groundwater particularly in sandy soils. Elevated nitrate concentrations in groundwater are common around dairy and poultry operations, barnyards, and feedlots (Almasri et al., 2004). In addition to agricultural practices, non-point (widespread) sources of nitrogen involve precipitation (rainfall), irrigation with groundwater containing nitrogen, and dry deposition. Point sources of nitrogen are shown to contribute to nitrate pollution of groundwater. The major point sources include septic tanks and dairy lagoons where high concentrations of nitrate in groundwater are observed in areas with septic tanks and dairy lagoons (Almasri et al., 2004). In high-density residential areas with no sewer systems, septic systems and cesspits produce a significant source of nitrogen to the subsurface especially in the form of ammonium and organic nitrogen. This form of nitrogen pollution is a concern to rural homeowners who use shallow groundwater wells for drinking water that can be easily contaminated with septic tanks.

1.2 Problem identification

Water samples from various wells in the West Bank have demonstrated elevated nitrate concentrations. Therefore, I have conducted this research work to evaluate the groundwater vulnerability to pollution through the groundwater vulnerability map produced by this study.

It is essential to prevent the pollution of groundwater aquifers from nitrate contamination because these aquifers are generally the main source of potable water. Prevention of the pollution of the groundwater resources of the West Bank from anthropogenic sources such as nitrate contamination is understandably a crucial issue since remediation is prohibitively expensive and in fact impractical. Protection and maintenance of an adequate and safe water supply for Palestinians is a fundamental part of our struggle for survival in our own homeland. Nitrate concentration was chosen as an indicator of groundwater pollution because nitrate is a major widespread contaminant and is associated with various land use practices such as agriculture. Management alternatives to protect the aquifer resources, in terms of groundwater quality, are improvements to agricultural practices, land use changes, and designation of protection areas which need monitoring. These alternatives are effective preventative measures and very suitable for the maintenance of safe groundwater resources.

The assessment of groundwater contamination should account for areas of high vulnerability of groundwater. Vulnerability assessment is imperative to direct the modeling efforts and to give clues to decision makers and stakeholders regarding the areas where management options and protection alternative measures should be introduced (National Academy of Sciences, 1993).

Groundwater vulnerability maps are designed to show areas of greatest potential for groundwater contamination on the basis of hydrogeological and human factors (National Academy of Sciences, 1993). Groundwater vulnerability is usually determined by assigning point ratings to the individual data layers and then adding the point ratings together when those layers are combined into a vulnerability map (National Academy of Sciences, 1993). The methods used to assess groundwater vulnerability are divided as follows: process-based models, statistical methods, and overlay and index methods (National Academy of Sciences, 1993).

DRASTIC was developed to be a standardized system for evaluating groundwater vulnerability to pollution. The primary purpose of DRASTIC is to provide assistance in resource allocation and prioritization of many types of groundwater-related activities and to provide a practical educational tool (National Academy of Sciences, 1993). DRASTIC is an acronym for the seven factors considered in the method: **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 DRASTC method has been used to develop groundwater vulnerability maps in many parts of the world; however, the effectiveness of the method has shown mixed success (Rupert, 2001). DRASTIC maps are usually not calibrated to measure contaminant concentrations (Rupert, 1997). It gives indication to the vulnerability of groundwater to contamination regardless of the contaminant itself. The DRASTIC groundwater vulnerability mapping method was improved by calibrating the point rating scheme to measured nitrate concentrations in groundwater on the basis of statistical correlation between these concentrations and land use, soils, and depth to water (Rupert, 1997).

In the assessment of groundwater vulnerability, spatial analysis techniques are needed in estimating, evaluating, and managing data. In addition, GIS is a sound approach to evaluate the outcomes of various management alternatives. GIS technology is also helpful in facilitating data input and output processing especially in watersheds where field data are regularly updated from frequent monitoring and allows rapid visualization of raw data. In this work, data analysis and model implementation were performed using the GIS software.

1.3 Research objectives

This research project aims at developing a groundwater vulnerability map for the West Bank groundwater resources through the utilization of the well-known DRASTIC model (Aller et al., 1985). The entire study will be conducted through the utilization of GIS techniques in data visualization and spatial analysis. Another objective of this research work is to conduct a literature review for the current vulnerability assessment approaches. The vulnerability map will be used to locate the areas that are highly vulnerable to contamination and thus the areas that will be possibly targeted by land use restrictions or target these areas for greater attention in order to prevent further contamination of the underlying groundwater.

1.4 Why do we need groundwater vulnerability maps?

Groundwater vulnerability maps are designed to show areas of greatest potential for groundwater contamination on the basis of hydrogeologic and anthropogenic (human) factors. Vulnerability maps could be used as a meaningful tool in the environmental decision-making process. Methods applied to obtain groundwater vulnerability maps, have to portray a correct view on the site vulnerability and subsequent site-specific investigations are essential in many cases. A groundwater vulnerability maps can be useful for land-use planners, hydrogeologists and water managers. Based on the produced vulnerability map, it is possible to point out priority areas where there is a significant risk of groundwater contamination taking into account the location of different forms of land-use classes.

1.5 Contribution of the research

This vulnerability assessment can highlight the need for financial and human resources to be directed to the control of potential groundwater contamination and/or the protection of groundwater resources. Moreover, it could be used to establish routine groundwater monitoring programs, to establish databases, or to ensure compliance with standards or other protection requirements.

Scarce and irregular financial resources of the Palestinian National Authority prevent uniform and high levels of spending. The product of this assessment is a map depicting areas where groundwater has the potential to be contaminated. Hence, this assessment can be used in management programs to guide allocation and targeting of resources to areas where the greatest levels of effort are warranted and resources are not wasted.

The intended assessment can be used in the policy analysis and development process to identify the potential for groundwater contamination and the need for protection and to aid in examining the relative impacts of alternative ways to control contamination. Moreover, it can be used to aid decision makers where to alter land use activities to minimize the potential for groundwater contamination, or voluntary changes in behaviors of land owners as they become more aware of the impacts of their land-based activities on groundwater. General education of the people about the vitality of preserving water resources and protecting them from contamination may be stimulated by such study. In other words, this study will promote public awareness in this regard.

1.6 Thesis main output

The main output of this research project is a qualitative vulnerability map for the groundwater resources of the West Bank. This map will hopefully demarcate the more vulnerable zones to which active protective measures ought to be directed. To achieve this goal, the combined use of DRASTIC model and GIS technique will be utilized.

1.7 Thesis outline

Chapter one is the introduction followed by Chapter 2 where a general background is provided. Chapter 3 furnishes an overall description of the DRASTIC method. Chapters 4, 5, and 6 provide the literature review, methodology, and description of the study area. The development of the vulnerability map for the groundwater of the West Bank is furnished in Chapter 7. Conclusions and recommendations are provided in Chapter 8.

CHAPTER II

GENERAL BACKGROUND

GENERAL BACKGROUND

This chapter is divided into sections that cover the health impacts associated with contamination of drinking water (mainly from nitrate), vulnerability of groundwater resources to contamination, and approaches to quantify the groundwater vulnerability to contamination.

2.1 Health impacts associated with nitrate-contaminated drinking water

Since nitrate (NO_3) is a major widespread contaminant and is associated with land use practices, it is vital to demonstrate the health impacts linked to the use of nitrate-contaminated drinking water. The potential major health effect of NO_3 in drinking water is clinical methemoglobinemia (Schwartz et al., 1988). Clinical methemoglobinemia is fully discussed in Rapaport's Introduction to Hematology (1987). The following summary is derived from his textbook. Nitrate, a highly mobile form of nitrogen, can leach through the root zone and eventually into groundwater (Navulur, 1996). When ingested, NO_3 is absorbed in the blood stream from the stomach and the upper intestine. Most is excreted in the urine but some can be reduced, especially in the intestine, to nitrite (NO_2). Nitrite oxidizes the ferrous iron in hemoglobin to ferric iron to form methemoglobin. The methemoglobin level of normal blood cells does not exceed 1% of total hemoglobin because the methemoglobin is rapidly reduced back to hemoglobin, primarily by the reducing enzyme NADH dehydrogenize.

Met hemoglobin cannot carry oxygen; therefore, the patient with clinical methemoglobinemia is cyanotic. If more than 10% of hemoglobin is converted to methemoglobin, the oxygen carrying capacity of the blood is sufficiently reduced such that symptoms of anoxia develop.

Concentrations of 20% to 30% cause cyanosis but require no treatment. Higher concentrations, however, may lead to brain damage, stupor and even death from anoxia.

In infants under the age of 3 months, in whom the red cell's methemoglobin-reducing capacity is not yet fully developed, nitrates in well water used to prepare infant formula (which are reduced by intestinal flora to nitrites) and oxidant material in disinfectants used to wash diapers or in dyes used to mark diapers have been implicated in acquired methemoglobinemia in the newborn.

Nitrates and nitrites have also been linked to cancer as possible etiological factors, but the evidence thus far is inconclusive (Navulur, 1996). Nitrates are not just a problem for human health; domestic animals may also be adversely affected by high NO_3 concentrations in drinking water. Many plants and feeds are naturally high in NO_3. If well water contaminated with NO_3 is also given to animals, NO_3 poisoning is possible, particularly in ruminants such as cows or sheep (Navulur, 1996).

2.2 Definition of vulnerability of groundwater resources

Vulnerability is a nonspecific term since it implies different concepts to different people. Many consider it as an inherent property of soils along with other components of the natural environment. Others reckon that vulnerability depends on the characteristics of individual contaminants or groups of contaminants; however, it is independent of specific land-use or management practices (e.g. the quantity of pesticide applied). Yet others relate vulnerability to a specific set of anthropogenic activities at the land surface. Many authors attempted to avoid the term vulnerability altogether and have substituted terms such as sensitivity (National Academy of

Sciences, 1993). Quotations included in Appendix A (Table A.1) illustrate the diversity in terminology.

2.3 Types of vulnerability assessments

Vulnerability assessments may or may not account for the different behavior of different contaminants in the environment. Thus, there are two general types of vulnerability assessments. The first addresses specific vulnerability, and is referenced to a specific contaminant, contaminant class, or human activity and called specific vulnerability. The second addresses natural vulnerability and is for vulnerability assessments that do not consider the attributes and behavior of specific contaminants and thus named intrinsic vulnerability (National Academy of Sciences, 1993).

2.4 Approaches to vulnerability assessment

The following sections summarize the general methods used to assess groundwater vulnerability. These methods are discussed in detail in the executive summary issued by the National Academy of Sciences (1993). The methods used to assess groundwater vulnerability range from simple overlay and index methods to more complicated process-based simulation models. Each method has advantages and limitations, and none is best for all situations.

2.4.1 Process-based models:

These models at the appropriate scale would be ideal in a perfect world, since they attempt to capture the true physical, chemical, and biological reactions that occur from the surface through the groundwater regime. Process-based models, however, have not been demonstrated to be more effective than other techniques. The limitations of process-based models are derived from model structure such as lack of knowledge of how to formulate processes mathematically and limitations in data availability and quality. Furthermore, limited field experimentation with simulation models suggests that models based on simplified process representation may be more useful for many vulnerability assessments than more complicated models. Most approaches for groundwater vulnerability assessment assume undisturbed surficial deposits with spatially uniform percolation. Preferential flow paths, such as roots and worm holes, cracks, joints, and solution channels, are ignored. Yet these may well be the fundamental pathways affecting vulnerability, providing more direct and rapid paths for contaminants to reach groundwater than they would otherwise have. Examples of process-based simulation models are GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) and PRZM (Pesticide Root Zone Model).

2.4.2 Statistical methods:

These methods incorporate uncertainty and attempt to explicitly minimize error, but require observations of surrogates for vulnerability such as groundwater samples from shallow wells. Using these surrogates, the methods directly derive parameter coefficients instead of assigning weights to attributes based on expert judgement. Parameters from simple process-based indices (e.g., travel times) could be used in statistical methods, making for a sort of hybrid approach. However, the results of these methods can only be applied to the geographic areas in which the data were collected to regions where similar factors are associated with the likelihood of groundwater contamination. Examples of statistical methods include regression analysis.

2.4.3 Overlay and index methods:

These methods were developed because of limitations in process-based models and because of lack of monitoring data required for statistical methods. Overly and index methods are based on assumptions that a few major factors largely control groundwater vulnerability and that these factors are known and can be weighted. These assumptions have not been demonstrated, particularly with respect to assigning weights to different factors. Examples of overlay and index methods include DRASTIC model and SEEPAGE (System for Early Evaluation of Pollution Potential from Agricultural Groundwater Environments)

R.C. Gogu and A. Drassargues (2000) discussed the current methods used for groundwater vulnerability assessment. Most often these methods were based on overlay and index techniques. They ranged from sophisticated numerical models, to techniques using weighting factors affecting vulnerability and also to statistical methods.

Hydrogeological Complex and Settings methods (HCS) imply a qualitative assessment. First, one must decide the hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Then the entire area is analyzed and divided following the criteria established (Albinet and Margat, 1970). Generally, a map overlay procedure is used. Large areas with various hydrographical and morphostructural features are best suited for assessment through these methods.

Parametric system methods are the Matrix Systems (MS) and Rating Systems (RS) methods and the Point Count System Models (PCSM) for the groundwater vulnerability assessment.

Matrix Systems (MS) methods are based on a restricted number of carefully chosen parameters. Examples are the method selected for the Flemish Region of Belgium (Goossens and Van Damme, 1987) and the system used by Severn-Trent water Authority in some areas of Central England (Carter and others, 1987).

Rating Systems (RS) methods provide a fixed range of values for any parameter considered to be necessary and adequate to assess the vulnerability. Examples are GOD method (Foster, 1987), AVI method (Van Stempvoort and others, 1993), and the ISIS method (Civita and De Regibus, 1995).

In Point Count System Models (PCSM) or Parameter Weighting and Rating Methods, an additional multiplier, identified as a weight, is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are added to obtain the final score. Examples are the DRASTIC method (Aller and others, 1987), SINTACS method (Civita, 1994), and the EPIK method (Doerfliger and Zwahlen, 1997).

Process-based models require sophisticated mathematical analyses, data required are not available, and they may not necessarily provide more valuable results. Statistical methods include multiple independent variables. Overlay and index methods are simple, easy to do, and quantitative. In this study, I chose to use one of the overlay and index methods.

CHAPTER III

THE DRASTIC METHOD

THE DRASTIC METHOD

3.1 Introduction

DRASTIC is one of the widely used methods for the assessment of the intrinsic vulnerability of groundwater to contamination (Rupert, 1999). It was developed by the US Environmental Protection Agency (EPA) to be a standardized system for evaluating groundwater vulnerability to pollution (Aller et al., 1985).

DRASTIC is a Point Count System Model (PCSM) or a Parameter Weighting and Rating Method. A multiplier, identified as a weight, is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are summed up to obtain the final score. This score provides a relative measure of groundwater vulnerability degree of one area. The vulnerability degrees of the different areas are compared to each other, and the higher the score, the greater the sensitivity of the area or in other words, the higher the vulnerability to contamination. One of the most difficult aspects of this method remains distinguishing different classes of vulnerability (high, moderate, low, etc.) on basis of the final numerical score. The qualitative categories or classes of vulnerability are then displayed on a map (Gogu and Dassargues, 2000).

DRASTIC is one of the most widely used models to assess groundwater vulnerability as it was utilized in the US and different countries worldwide: Evans and Mayers, 1990; Rundquist et al., 1991; Knox et al., 1993; Secunda, Collin, and Melloul, 1998; Fritch, McKnight, Yelderman, and Arnold, 2000; Piscopo, 2001 (Al-Admat et al, 2003).

3.2 The parameters of the DRASTIC method

In the DRASTIC method, spatial datasets on **D**epth to groundwater, **R**echarge by rainfall, **A**quifer type, **S**oil properties, **T**opography, **I**mpact of the vadose zone and the aquifer's hydraulic **C**onductivity are combined (Navulur, 1996). DRASTIC is an acronym name for the above seven parameters considered in this method. Each of the aforementioned hydrogeologic factors is assigned a rating from 1 to 10 based on a range of values. The ratings are then multiplied by a relative weight ranging from 1 to 5, Table 3.1. Weights reflect the relative importance of each parameter in contributing to the overall objective. The most significant factors have a weight of 5 while the least significant ones have a weight of 1.

Table 3.1: Assigned weights for DRASTIC hydrogeologic factors

Hydrogeologic factors	Weights
D - Depth to Water Table	5
R - Net Recharge	4
A - Aquifer Media	3
S - Soil Media	2
T - Topography	1
I - Impact of the Vadose Zone Media	5
C - Aquifer Hydraulic Conductivity	3

The governing equation for the computation of the DRASTIC index (DI) is the following:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \qquad (1)$$

where D, R, A, S, T, I, C represent the above mentioned seven hydrogeological factors, and the subscripts "r" and "w" refer to the rating and weights, respectively. The resulting DRASTIC index represents a relative measure of groundwater vulnerability to contamination. The higher the DRASTIC index, the greater the vulnerability of the aquifer to contamination. A site with low DRASTIC index is not free from groundwater contamination, but it is less susceptible to contamination when compared with the sites having high DRASTIC indices. The DRASTIC index results can be converted into qualitative risk categories using Table 3.2.

Table 3.2: DRASTIC index ranges for qualitative risk categories

DRASTIC qualitative category	**Low**	**Moderate**	**High**	**Very high**
DRASTIC index	1 - 100	101 - 140	141 - 200	> 200

These ranges are arbitrary and the corresponding categories vary and depend on the personal judgment of the author.

3.3 Description of the DRASTIC method parameters

The seven hydrogeological factors that comprise the basis of the DRASTIC method are described briefly in the following subsections (Aller et al., 1987)

3.3.1 Depth to water (D):

The depth to water is the distance from the ground surface to the water table. It determines the depth of the soil material through which a contaminant must travel before reaching the aquifer. Thus, the shallower the water depth, the more vulnerable the aquifer is to pollution. Table 3.3 summarizes the rating scheme for this parameter.

Table 3.3: Rating scheme for different ranges of depth to water.

Depth to water (feet)	Rating
0 – 5	10
5 – 15	9
15 – 30	7
30 – 50	5
50 – 70	3
75 – 100	2
100+	1

3.3.2 Net recharge (R):

The primary source of recharge is precipitation, which infiltrates through the ground surface and percolates the soil to the water table. Net recharge is the total quantity of water per unit area, which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the water table. The more the recharge, the greater the chance for contaminants to reach the water table. Table 3.4 summarizes the rating scheme for this parameter.

Table 3.4: Rating scheme for different ranges of annual recharge to groundwater.

Recharge (inch)	Rating
0 – 2	1
2 – 4	3
4 – 7	6
7 – 10	8
10 +	9

3.3.3 Aquifer media (A):

Aquifer media refers to the consolidated or unconsolidated rock that serves as an aquifer. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability, and thus the vulnerability of the aquifer. Table 3.5 summarizes the rating scheme for this parameter.

Table 3.5: Rating scheme for the different aquifer media.

Aquifer media	Rating range	Rating
Massive shale	-	2
Metamorphic/igneous	2 – 5	3
Weathered metamorphic/igneous	3 – 5	4
Glacial till	4 – 6	5
Bedded sandstone, limestone, and shale sequences	5 – 9	6
Massive sandstone	4 – 9	6
Massive limestone	4 – 9	8
Sand and gravel	4 – 9	8
Basalt	2 – 10	9
Karst limestone	9 - 10	10

3.3.4 Soil media (S):

Soil media is the upper weathered zone of the earth. Soil has a significant impact on the amount of recharge that can infiltrate into the ground. In general, the less the clay shrinks and swells and the smaller the grain size of the soil, the less likely contaminants will reach the water table. Table 3.6 summarizes the rating scheme for this parameter.

Table 3.6: Rating scheme for different types of soil media.

Soil media	Rating
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Nonshrinking	1

3.3.5 Topography (T):

Topography refers to the slope of the land surface. Topography helps control the likelihood that a pollutant will run off or remain long enough to infiltrate through the ground surface. Where slopes are low, there is little runoff, and the infiltration potential is greater. Conversely, where slopes are steep, runoff capacity is high and the potential for pollution of groundwater is low. The United States Geological Survey (USGS) uses a digital elevation model (DEM) to calculate percent slopes. Table 3.7 summarizes the rating scheme for this parameter.

Table 3.7: Rating scheme for the different ranges of slope.

Slope (percent)	Rating
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
18 +	1

3.3.6 Impact of the vadose zone media (I):

The vadose zone is the unsaturated zone above the water table. The texture of the vadose zone determines the time of travel of the contaminant through it. In surficial aquifers, the ratings for the vadose zone are generally the same as the aquifer media. Sometimes a lower rating is assigned if the aquifer media are overlain by a less permeable layer such as clay. Table 3.8 summarizes the rating scheme for this parameter.

Table 3.8: Rating scheme for the different types of vadose zone material.

Vadose zone material	Rating range	Rating
Confining layer	1	1
Silt/clay	2 – 6	3
Shale	2 – 6	3
Limestone	2 – 5	3
Sandstone	2 – 7	6
Bedded limestone, sandstone, and shale	4 – 8	6
Sand and gravel with significant silt and clay	4 – 8	6
Sand and gravel	4 – 8	8
Basalt	2 – 9	9
Karst limestone	8 – 10	10

3.3.7 Hydraulic conductivity of the aquifer (C):

Hydraulic conductivity of the aquifer refers to the rate at which water flows horizontally through an aquifer. The higher the conductivity is, the faster the velocity of groundwater flow will be and the contaminant will spread out through the aquifer more quickly. Conductivity values for the aquifers are usually derived from groundwater flow models and represent averages over large areas. Table 3.9 summarizes the rating scheme for this parameter.

Table 3.9: Rating scheme for the different ranges of aquifer hydraulic conductivity values.

Hydraulic conductivity (gpd/ft^2)	Rating
1 – 100	1
100 – 300	2
300 – 700	4
700 – 1000	6
1000 – 2000	8
2000 +	10

3.4 Why DRASTIC?

As mentioned earlier, DRASTIC is one of the most widely used groundwater vulnerability mapping methods. Having a good precision and flexibility, DRASTIC model is much used in detailed studies (Gogu and Dassargues, 2000). The DRASTIC technique produces a standardized methodology which provides suitable results for evaluating a region with respect to groundwater protection, monitoring, and clean-up plans.

DRASTIC has frequently been adapted to situations other than those it was designed for. DRASTIC coupled with other factors such as application methods may help delineate areas where aquifer vulnerability is higher and land use suggests a potential source of pollution.

As detailed site-specific analyses are costly and time consuming, regional vulnerability assessment using the DRASTIC method with modifications can be used as an economical tool to identify the zones of concern and as a tool to overcome problems of haphazard, uncontrolled development of land and of undesirable activities having an impact on groundwater quality (Thirumalaivasan, 2003).

DRASTIC was originally developed as an easy-to-use method for aquifer vulnerability assessment, encompassing diverse hydrogeologic settings, based on vulnerability index. The DRASTIC model defines ranges of model parameters, which at times warrants modifications for better addressing of local issues and for refined representation of local hydrogeologic settings. Thus the DRASTIC is flexible.

Numerous assessment studies demonstrated that the groundwater vulnerability maps can be improved by calibrating the point ratings on the basis of statistical correlations between groundwater quality and human (anthropogenic) variables (Rupert, 2001). This also can be done with DRASTIC.

Since DRASTIC index provides only a relative evaluation tool and is not designed to provide absolute answers, many users have tried to divide the final index into vulnerability classes such as: low, moderate, high, and very high potential (Gogu, 2000). Thus, the output of DRASTIC method can be easily processed to extract more representative and informative results.

The DRASTIC model, which falls under the overlay and index category is the most widely used for vulnerability assessment studies at regional scales (National Academy of Sciences, 2003).

We chose to utilize DRASTIC method because our study is focused on a region and not on a specific local field. Moreover, it is economic and suits our scarce financial resources in the essence that no detailed data is needed to carry out the work but just the literature-based data that are available in reports and past studies.

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CHAPTER IV

LITERATURE REVIEW

LITERATURE REVIEW

4.1 Introduction.

The DRASTIC model was adopted in all of the following studies. It was calibrated by some authors, modified by others. Moreover, it was compared with other indices. Yet some researches modified the DRASTIC model parameters. Sensitivity analysis of this model was also performed. Anthropogenic impact was added to intrinsic vulnerability parameters in some studies.

4.2 Original DRASTIC

Witkowski et al. (2002) produced a groundwater vulnerability map of the Chrzanow Karst-fissure Triassic aquifer in the southern part of Poland. The study area included Karst-fissured Triassic aquifers which are the most important and valuable source of potable water for upper Silesia, the most urbanized and industrialized part of Poland. Taking into consideration the specific character of this aquifer for its groundwater vulnerability assessment, special methods of karstic aquifers (Doerfliger and Zwahlen 1997; Witkowski and others 1997; Malik and Svasta 1999) could not be effectively used. In that case, a modification of a standard DRASTIC method (Aller et al. 1987) was applied. The proposed method was tested on the isolated Chrzanow Triassic aquifer, which has well-defined borders.

The researchers assumed that six factors considerably influence the vulnerability of groundwater in the study area to pollution. These are depth to groundwater table in the Triassic carbonate series, lithology of the unsaturated zone, net recharge, hydraulic conductivity of the Triassic aquifer, groundwater flow velocity within the Triassic aquifer, and thickness of the Triassic aquifer.

Data showed that a general concept of a vulnerability map is analogous to the DRASTIC system (Aller and others 1987). However, as opposed to the original DRASTIC, the following factors were not taken into account: (1) aquifer factors due to lack of changeability of this factor (vulnerability assessment concerns only the Triassic aquifer of limestone and dolomite); (2) soil media considering a specific geology and cover of the Triassic aquifer that includes poorly permeable sediments of various thickness (from 0 to over 170 m); and (3) the factor topography was included in the factor concerning recharge derived by model calibration.

Taking into account a specific character of the studied karst-fissured aquifer and its intensive drainage, two other factors were included, groundwater flow velocity within the aquifer and its thickness. Flow velocity, which determines the rate of movement of potential pollution in the aquifer, varies widely from 0.00081 to 8.293 m/day. Also, the thickness of the aquifer determines its vulnerability. The areas of small thickness are more vulnerable to pollution than areas of large thickness. Construction of the final vulnerability map was based on six geological and hydrogeological factors, which, in the researchers' opinion, have a crucial impact on potential groundwater contamination in the studied aquifer.

As a result of computer-based overlays of six hydrogeological and geological factor maps, the final groundwater vulnerability map for the considered aquifer was compiled. The final version of the vulnerability map was produced as a result of numerous simulations, including the different range of the vulnerability index for the six individual classes of vulnerability shown in Table 4.1.

Table 4.1: Classes of the relative groundwater vulnerability to pollution based on the vulnerability index

Classes of relative vulnerability	Vulnerability index
Extremely high	151-182
Very high	121-150
High	91-120
Medium	63-90
Low	43-62
Very low	21-42

The DRASTIC-type parametric system used in this research for intrinsic (natural) vulnerability assessment, based mainly on hydrogeological and geological evaluation, gave reliable and clear information on the relative degree of groundwater protection. Application of the combined methods, i.e. the aquifer simulation model and geographical information system, gave very good results.

4.3 Modified DRASTIC.

Adamat, Foster, and Baban (2003) produced a groundwater vulnerability and risk map for the basaltic aquifer of the Azraq basin of Jordan using GIS, remote sensing, and DRASTIC. Their study area is in a region recognized to form a transition zone between the climatic environment of the Jordan Valley and the arid interior desert of eastern Jordan. The basalt plateau, in which the aquifer is located, is part of a lava plateau stretching from Syria to Saudi Arabia through Jordan.

The GIS coverage were all in raster format and values for each overlay were summed in ArcView GIS according to the pixel value of each area that resulted from multiplying the rating with its appropriate DRASTIC weight. A fixed number of 68 was added to the final raster grid coverage. This number represents: $(D_r D_w) + (A_r A_w) + (I_r I_w)$.

In order to introduce a land use factor into the DRASTIC index, the land use map was rated. This map was converted into a raster grid and multiplied by the weight of the parameter. The resultant grid coverage was then added to the DRASTIC index based on the following equation modified from Secunda, Collin and Melloul (1998):

$$MD_{(i)} = DI_{(i)} + L_r L_{w(i)} \qquad (2)$$

Where $MD_{(i)}$ is the modified DRASTIC index and (i) refers to each work unit in the grid. Whereas, DI is the DRASTIC index and $L_r L_w$ is the multiplication of rating and weight of land use.

In order to check if there was a spatial relationship between land use and groundwater vulnerability of the study area, the land use map was overlaid on the groundwater vulnerability map. This operation proved that less than 1% of the study area had a low vulnerability and possible source of contamination which corresponded with the modified DRASTIC index.

The researchers investigated the relationship between groundwater vulnerability and nitrate concentrations in groundwater. They overlaid the well location map on the modified DRASTIC map and the *"assign data by location"* operation in ArcView GIS was used to spatially join the two maps. In this operation, the attribute file of the wells map was updated with the data from the attribute file of the modified DRASTIC map based on the spatial relationship between the features in the two maps.

It was found that the introduction of land use only increased the potential for moderate groundwater vulnerability by about 1% which appeared to be explained by the fact that many settlements and/or irrigated agricultural areas lied within the low vulnerability zone. Nitrate concentrations in wells that exist inside the low vulnerability zones, as defined by the modified DRASTIC index, varied between 8.11 mg/l to 11.64 mg/l with an average concentration of 9.99 mg/l. Whereas, nitrate concentrations in the moderate vulnerability zones varied between 7.03 mg/l to 21.01 mg/l with an average concentration of 10.52 mg/l. Nitrate concentrations in six wells inside the moderate vulnerability zones were much higher than those in the low vulnerability zones, although some wells inside the low vulnerability zones had nitrate concentrations higher than those recorded in wells in the moderate vulnerability zones. Overall, it was encouraging to find that no well with very high nitrate concentrations was found within the low vulnerability zones suggesting that the model may be conservative in identifying those areas at low risk of contamination.

Although the groundwater is relatively deep, the results suggest that great care should be taken when siting development in the moderate vulnerability zones due to importance of the basalt aquifer as a groundwater resource for drinking water supply for the local population and for the major cities in Jordan. While the vulnerability maps produced by this study could be used as a general guide to groundwater vulnerability and risk, local conditions on the ground must be taken into account by local managers and planners. Further investigations were clearly required in order to understand the mechanisms of groundwater recharge and contaminant transport in this aquifer, especially in relation to the spatial distribution of potentially important geological features such as faults and the role that wadis play in relation to groundwater recharge, neither of which have been included in this study.

Shadid (2000) evaluated the vulnerability of shallow groundwater in and around two towns in India using the DRASTIC method and GIS. The study area is a part of Midnapur district, West Bengal, India. Climatically, it falls in the Gangetic West Bengal region with an annual average rainfall of 152 cm and temperature of 31^0C. Geologically, the area is a soft rock area. From various geological and geophysical investigations the area has good potential for shallow groundwater contamination. All the thematic maps were digitized in continuous mode and in the vector format. The digitized values were edited to get error free thematic maps. Average depth of the groundwater table was estimated from the soil map, geological map, and water table data collected from different sites of the area.

The study area is mainly flat. Except for the calcareous sticky clayey soil over older deltaic formation, the other types of soil in the area are moderately pervious. The net recharge in the study area is assumed to be more than 10 inches per year.

Aquifer media were identified from the Vertical Electrical Sounding (VES) and borehole data. Data points were interpreted using an inversion technique called Evolutionary Programming (EP). Medium to coarse sand with gravel was found as the groundwater bearing zone in the study area.

The vadose zone map of the study area was prepared from the lithologic section obtained from geophysical data. Aquifers situated in the deltaic formations are unconfined, whereas the aquifers in the lateritic formation are confined. Since the vadose zone for an unconfined aquifer system is the same as the aquifer media, sand and gravel was considered as the vadose zone for the area under deltaic formations and was rated with a value of 8. In the lateritic zone the aquifers are underlain by clayey or silty clay layers. This zone was considered as the vadose zone and was rated with a value of 3. The aquifer media of this area are medium to coarse sand with gravel which has a hydraulic conductivity of 1,000 to 2,000 gpd/ft^2. Four types of soil were mapped from aerial photographs: (1) a lateritic soil of hardcrust horizon; (2) a lateritic soil of mottled clay horizon; (3) a sandy loamy soil; and (4) a grayish sticky calcareous soil. The slope map was generated from elevation contours given in the topsheet of the Survey of India by linking a FORTRAN program with the GIS.

After preparation of all thematic maps, different polygons in the maps were labeled with DRASTIC ratings and then scaled with the weights. The ratings were scaled with both the DRASTIC weights for generic industrial and municipal pollutants separately to generate the vulnerability maps of both classes. The thematic maps were registered with one another using ground control points and integrated using the weighted aggregation model. The integration was done step by step and a maximum of two layers were integrated at a time. The polygons of the final integrated layers contained the composite details of all the thematic layers together numerically, and the DI score of each polygon indicated the groundwater vulnerability of that zone.

The DI values in the final integrated maps were classified and pollution vulnerability maps for industrial, municipal and pesticide pollutants were developed. The area under each zone was displayed by a graph. It was noted that almost 50% of the area was highly vulnerable to industrial and municipal pollutants and more than 81% of the area was highly vulnerable to pesticide pollutants.

From the pollution vulnerability maps, it could be concluded that the areas near the Ksai River were more vulnerable to pollutants. These are the main groundwater supply zones of Midnapur-Kharagpur towns of the study area. Therefore, it was recommended that proper management approaches are essential to provide a long term pollution – free groundwater supply in the area.

AL-Zabet (2002) carried out an evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. The study area was the Eastern District of Abu Dhabi Emirate in the United Arab Emirates. It occupies the physiographic transition zone between the extensive sand dune covering most of Abu-Dhabi Emirate and the western flank of the Oman Mountains. The topographic maps and satellite images enabled recognition of the following geomorphic features within the study area (Menges and others, 1993):

(1) mountains of exposed bedrock;

(2) piedmonts, alluvial plains and piedmonts related to ephemeral streams on the western flank of the Oman Mountains;

(3) a wide alluvial plain and valley near the Al-Ain urban area; and

(4) a nearly continuous expansion of aeolian sand and associated dune landforms divided into the northern and southern dunes area.

In this study, the depth to water level was obtained by subtracting the ground surface elevation from the water level. The ground surface elevation data were obtained from the DEM. The area under consideration was selected using Microdem (2001) software and then the topographic model was converted into xyz data to be imported into Surfer (2000) software. The water level map of the study area was obtained from a report published by the USGS in cooperation with the National Drilling Company.

The 50–year average precipitation map prepared by the Ministry of Agriculture and Fisheries (1993) was used in this study. In the previous studies which were done in the eastern area to measure direct recharge using the water balance method, an infiltration rate of 10% of the total precipitation per year was estimated. This percentage of annual precipitation was used in this study as the average recharge rate.

The main aquifer which is being exploited and the one most vulnerable to contamination is the unconfined shallow Quaternary alluvial Al-Ain aquifer. It is relatively thin, composed of a sequence of relatively uncemented coarse-grained gravel and sand with interbeds of silt and clay of small to moderate permeability overlying a thick basalt unit of very low permeability. The predominant soil types are:

(1) the coarse gravel and sand in the piedmont and alluvial plains to the east of Jabal Hafit;

(2) the sandy soil to the west of Jabal Hafit in the north and south sand dune area; and

(3) the bare bedrock in the mountain areas in Oman and Jabal Hafit.

The digital elevation model (GTOPO30 – DEM) was used to extract the slope of the study area. Within the study area most of the areas have a gentle and smooth slope in the range of 1-5%. The areas in the extreme southeast represent the ridges of sand dunes which may reach an elevation of 660 ft.

The vadose zone is composed of unconsolidated gravel and sand except in the mountain areas where the vadose zone is composed of igneous metamorphic rocks in the Oman Mountains and of limestone in the

Jabal Hafit. The hydraulic conductivity survey performed by the National Drilling Company for the Al-Ain aquifer was used in this study.

After the preparation of the hydrogeological layers, the digitized maps and digital elevation model data were converted to xyz format. The coordinates were converted from the UTM coordinate projection to the World Geologic System projection (WGS84). The grid size was 100 rows by 66 columns, each cell measuring 0.97 square mile.

The final vulnerability DRASTIC pesticide map was produced using the national color code scheme. The resulting vulnerability map indicated the highest potential areas for contamination are where the DRASTIC index ranged between 150 and 180. Elsewhere, a low to medium DRASTIC index range was observed (100-130) indicating areas of relative low vulnerability potential.

The procedure for generating the DRASTIC map was identical to that described for the pesticide DRASTIC map. Comparing the pesticide DRASTIC index map with the general DRASTIC index map indicated that the potential for polluting groundwater with pesticides is greater than with general pollutants. As a result, Al-Zabet (2002) suggested that more attention must be given to vulnerable areas which are areas currently of extensive agricultural activities.

Secunda, Collin and Melloul (2002) carried out a groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in the study area.

The study area is approximately 700 square kilometers. Its southern border being the municipality of Ramat Hasharon, its northern border coinciding with the Netania Metropolitan area, the western border the Mediterranean Sea coast and the eastern border the "green line" bordering the West Bank. The study area is underlain by a Pleistocene sandstone and calcareous sandstone coastal aquifer. An aquifer thickness of 200 m decreases eastwards from the coastline feathering out to a few meters in the foothills of the mountains to the east.

The study region was chosen according to criteria including urbanization, industrialization, a high level of agricultural activities and extensive available data. From a hydrological point of view, the area involves significant local abstraction of groundwater resources for drinking, irrigation and industry. As such it can be considered a suitable validation region for trying the DRASTIC and the Composite DRASTIC Indices with land use data.

Each DRASTIC parameter has been evaluated with respect to the others in order to determine the relative importance of each. Certain adaptations for application to the study area were required for original DRASTIC ratings. Local modification of DRASTIC to the study area accommodates corresponding weights and ratings as based upon specific regional data, utilizing input of local expertise regarding evaluation. To map each unit or polygon, a rating was assigned. In the assessment of the study area, the DRASTIC parameters were processed using GIS as vector map layers.

Cell ratings for each parameter were determined by a union between the original polygon layer of the parameter and the map layer of the cells. A rating for each cell was then obtained, based upon the percentage of each polygon location within the given cell. When insufficient data were available, as with localized conductivity data, no attempt was made to map such parameters over the study area.

After the processing of the seven DRASTIC parameters into cell vector map layers using ARC/INFO, the layers were converted to ERDAS GIS raster format. A model using DRASTIC Index formulation was designed in ERDAS using the different raster layers and their respective weights to produce final vulnerability map. The ultimate result was a numerical value, the DRASTIC Index, DI, for each geographic unit, or cell, as calculated using the following additive equation :

$$DI = D_r D_w + R_r R_w + A_r A_w + S_w S_w + T_r T_w + I_r I_w + C_r C_w \qquad (3)$$

Extensive land use (L) was incorporated as an eighth parameter. The resultant land use rating (L_r) and weighting (L_w) can then characterize such extensive land uses including effluent irrigation of crops as potential sources of groundwater pollution. Assigned ratings and weightings for the extensive agricultural land use parameter are then added to the final DRASTIC Index equation to produce a Composite DRASTIC-Extensive Land use Index of groundwater vulnerability (CDI) for each work unit (i):

$$CDI_{(i)} = DI_{(i)} + L_r L_{w\,(i)}. \qquad (4)$$

By comparing DI and CDI maps, cells having highest DI levels and in which CDI is significantly larger than DI can be delineated.

In this study, nitrates were used as a fingerprint parameter to assess the impact of agriculture, domestic sewage and irrigation with treated effluents upon groundwater quality Composite DRASTIC Index results in order to calibrate DRASTIC models.

In intensive agricultural areas, continuous recharge of treated effluents and the water used for irrigation can change the configuration of the soil and the subsoil media, leading to higher recharge and thus higher percolation to groundwater for pollutants. The CDI values indicated that these areas where long-term land use activities increased natural potential vulnerability to groundwater pollution as assessed by DI. The indices in fact delineate areas where anthropogenic potential compounds exist.

Comparing the final DI map with that of the CDI values, heightened ratings were noted in the vicinity of areas characterized by extensive agriculture as well as significant urbanization. Comparing the maps of CDI with that of nitrate values in the study area, the correspondence of cells having high nitrate levels and cells assigned the highest CDI is readily apparent in some areas. The uncertainties in this study were around 20%

4.4 Calibrated DRASTIC

Rupert (2001) improved the DRASTIC groundwater vulnerability method by calibrating the point rating scheme to measured nitrite plus nitrate (NO_2+NO_3) concentrations in groundwater. Statistical correlations between NO_2+NO_3 concentrations and land use, soils, and depth to water were used. The study area was the upper Snake River Basin which extends from western Wyoming to south–central Idaho, US. The eastern Snake River Basin is underlain by a series of highly vesicular and fractured quaternary olivine basalt flows. These flows are highly transmissive to groundwater. Paleozoic sedimentary and tertiary volcanic rocks predominate north, east, and south of the plain. About 50% of the basin is forest and rangeland, about 30% is irrigated agricultural land, and the remaining area is mostly composed of basalt areas which are sparsely vegetated. With the exception of precipitation, there are no known major sources of naturally occurring nitrate in the upper Snake River Basin (Rupert, 1996). The majority of nitrogen in the basin comes from anthropogenic sources.

Rupert et al. (1991) used a modified form of uncalibrated DRASTIC model to develop the first published groundwater vulnerability map in Idaho, US. Three factors were used; depth to groundwater, net recharge, and soil type. Land use was used as a surrogate for net recharge because irrigated agricultural areas provide the largest amount of recharge in the study area. The point ratings were different from those used by DRASTIC but were obtained in the same manner. The authors determined the point ratings on the basis of best professional judgment. The resultant map was termed relative groundwater vulnerability because the vulnerability ratings (low, medium, high, and very high) were determined to each other and were not based on actual groundwater quality data.

The above vulnerability map was updated 10 years later by Rupert (2001). He calibrated the point rating scheme based upon correlations of NO_2+NO_3 concentrations in groundwater with data of land use, soils, and depth to water. Statistical techniques and GIS were used to quantify the relations. Based upon these relations, a point rating scheme that predicts the probability of elevated NO_2+NO_3 concentrations was then developed. That point rating scheme was then processed by GIS, and the probability maps were produced. This test determines if statistically significant differences in NO_2+NO_3 concentrations exist between the various data groups. This test calculates a p-value. However, Rupert (2001) used the 95% confidence level as the cutoff value for determining whether differences between data sets were statistically significant or not.

A map showing the probability of groundwater contamination by NO_2+NO_3 was developed. The map was termed a probability map instead of a vulnerability map because the probability categories were based on the results of statistical comparisons of NO_2+NO_3 in groundwater and because the term probability more accurately described what the maps portrayed whether an area had a high or low probability for NO_2+NO_3 contamination in groundwater.

The effectiveness of groundwater probability map produced by this study to predict elevated NO_2+NO_3 concentrations in groundwater was compared to the effectiveness of the relative groundwater vulnerability map produced by the uncalibrated DRASTIC method. Comparisons were made by correlating those maps with an independent set of NO_2+NO_3 data which were retrieved from the USGS National Water Information System database for the years 1980–1991. A direct comparison was possible because the same land use, soils, and depth to water data layers were used to develop both maps.

The relative groundwater vulnerability map produced by Rupert et al. (1991) had poor correlations with NO_2+NO_3 concentrations in groundwater. There was no statistically significant difference ($p>0.05$) in NO_2+NO_3 concentrations in groundwater between the low and medium, low and very high, and high and very high relative groundwater vulnerability categories. Thus, the relative vulnerability map is not effective in predicting elevated NO_2+NO_3 concentrations in groundwater.

The probability map developed by Rupert (2001) had good correlations with NO_3+NO_2 in groundwater. The mean and median NO_2+NO_3 concentrations increased in all categories as the probability rating increased. Rupert (2001) demonstrated that the effectiveness of probability maps can be improved by calibrating the point ratings on the basis of the results of statistical correlations between groundwater quality and hydrogeologic and anthropogenic variables. This study suggests that groundwater vulnerability and probability maps can be used to focus pollution prevention programs on areas of high potential for contamination.

Mclay et al. (2001) carried out a study to compare three approaches for predicting groundwater nitrate concentrations in a region of mixed agricultural land use in New Zealand. The study area was the Waikato Region of New Zealand which has different land uses ranging from intensive grazing, market gardening and horticulture to extensive sheep and beef grazing.

The aim of the study was to use an existing groundwater nitrate monitoring database to establish the variation in NO_3-N concentration in shallow groundwater (<30m depth from surface) in a region of mixed agricultural land uses, which is not influenced by high density housing, and to investigate whether the variation could be explained by: (1) the dominant land use where groundwater was sampled; (2) the easily measurable topsoil properties that affect nitrogen cycling in the soil; or (3) the risk of solute leaching at a site (as predicted by a site "leaching risk" assessment model). The leaching risk at each site was assessed using the hydrogeological setting categories of the leaching risk assessment model DRASTIC.

There was considerable temporal variability in NO_3-N concentration at some sites. Within each land use, the average groundwater NO_3-N concentrations were not normally distributed and required logarithmic transformation. Two-way analysis of variance, correlation and regression analysis of log transformed data was performed at the 95% level of significance.

The buffer area data were considered in two ways. Firstly, two-way analysis of variance was used to assess if the buffer area land use affected average groundwater NO_3-N concentration. Secondly, the areas of each type of land use within the buffer area were expressed as a proportion of the total area of the buffer area. The proportion of the buffer areas under each of the land uses was then examined for correlation between land use and the groundwater NO_3-N concentration.

The data from the biochemical assays, inorganic N extractions, total N and total C determinations were not normally distributed and required logarithmic transformation for statistical analysis. Spearman rank-order correlations were used to determine the non-parametric correlations, as it could not necessarily be expected that correlations would be linear, and the rank-order correlation is applicable to both linear and non-linear relationships. Furthermore, the assays being used were designed to rank sites according to potential activity rather than give absolute values. All statistical tests were performed at the 95% level of significance.

The DRASTIC indices ranged from a minimum of 73 to a maximum of 170 across sites. The individual DRASTIC components: depth to groundwater, impact of the vadose zone, aquifer media and topography data were all significantly ($p<0.05$) and positively correlated with groundwater nitrate concentration on a rank-order basis, and recharge was significantly ($p<0.05$) but negatively correlated with groundwater nitrate concentration. The positive relationship between depth and groundwater nitrate concentration was because the depth variable used was the DRASTIC depth index, which assigns a larger rating (i.e. greater risk) to shallower groundwater. Therefore, the positive relationship shown is between the groundwater nitrate concentration and the "riskness" of the depth, and shows that generally NO_3-N concentrations are less in the deeper wells. Although the combined DRASTIC index showed the strongest rank-ordered correlation with groundwater nitrate concentration, the influence of the vadose zone accounted for most of the correlation.

The general trend was that groundwater nitrate concentration increases as the DRASTIC index increases. None of the three approaches used (dominant land use at or surrounding the sites where groundwater was sampled, topsoil properties which reflect N cycling or the leaching risk assessment model) was highly suitable for predicting groundwater nitrate concentrations. Site-specific factors (e.g. local climate, hydrogeology, soils, policy management) may override general land use effects. Consequently, it was suggested that models such as DRASTIC that assess the risk of solute leaching to groundwater at a site, perhaps with a land management index included, may be useful for predicting areas for more intensive monitoring of groundwater. The results also emphasized that there is a need to test the link between measurements of nitrate leaching from a variety of land use activities with measurements of groundwater nitrate concentrations below these activities.

4.5 DRASTIC compared with others

Melloul and Collin (1998) proposed an index for aquifer water quality assessment. The study area was the coastal aquifer of historic Palestine. The groundwater basins of this region belong to the granular pleistocene coastal plain aquifer. The aquifer extends from the Mount Carmel in the north to Gaza Strip in the south, and from the seashore on the west to the mountainous aquifer in the east.

The aquifer in this area is composed of layers of dune sand, sandstone, calcareous sandstone, silt, intermittent loams and clay lenses which generally begin at the coast and punch out between 2-5 km from the sea and effectively separating the western portion of the aquifer into subaquifers. The aquifer rests upon sea clays of Neogene age. Further eastward, the aquifer rests upon limestone deposits of Eocene, Senonian, Turonian and Cenomanian Age (Tolmach, 1979).

Rainfall in the study area varies between 50-800 mm per year and occurring mostly between October to April. Around 40% appear to percolate to the aquifer. Groundwater abstraction has been set at around 80 million cubic meter (MCM) per year for the study area, but can reach 130 MCM per year (Melloul and Bibas, 1990).

A key objective of their study was the development of a formula to estimate an Index of Aquifer Water Quality (IAWQ) for assessing empirical regional groundwater quality, simultaneously utilizing data values of a number of chemical parameters characterizing salinity and pollution. This index, in their opinion, can act as a means of relating theoretical DRASTIC results to field realities.

In order to relate data to global norms, each value of a parameter, P_{ij} (field data value parameter i in cell j where the study area is divided into a grid of squared cells of uniform sizes), is related to its desired standard value (P_{id}) regarding drinking, irrigation, and other water purposes (WHO, 1993).

The proposed IAWQ formula, to numerically assess any groundwater quality situation could be stated as a summation of weights multiplied by respective ratings of various parameters for each cell. Thus, to pinpoint a source of contamination in areas rated by the DRASTIC model as poterntially vulnerable to pollution, applicable fingerprint chemical parameters were utilized to identify such specific sources of pollution as industrial and solid-waste sites. They used both the DRASTIC values and the IAWQ results. Certain cells revealed similarities in their index values indicating conformity of actual groundwater quality to DRASTIC assessment.

Utilizing data from the study area, evidence of groundwater salinization/pollution from the ground surface by means of vertical chloride (Cl) and NO_3 profiles was sought in inland regions of the aquifer far enough from the influence of seawater. Nitrate values exceeded 1 in many of the cells, indicating that the ratio of mean NO_3 values to the recommended desired drinking-water standard of 45 mg/l NO_3 (10 mg/l as NO_3-N) is generally exceeded throughout the study area. On the other hand, the ratio of mean Cl values to the recommended desired drinking water standard of 250 mg/l remained below l in most of the cells.

In such cells located in areas with high levels of anthropogenic activities, DRASTIC and IAWQ indices both reported high values. The authors concluded that this would be an evidence that these cells were indeed in areas having a high potential of vulnerability to groundwater pollution and that the aquifer is already polluted.

Mapping of IAWQ values, as the authors suggested, could lead to development of a prioritized register of chemical parameters required to properly identify the effects of specific sources of pollution upon groundwater quality. However, owing to the dynamic nature of pumpage, recharge, and other water management factors characterizing each area, such maps should be continuously updated.

Under certain ecohydrological conditions similarities between the two indices point to the dominant influence of vertical leaching. On the other hand, discrepancies between IAWQ and DRASTIC can point to lateral groundwater flow as the controlling factor of pollution.

Thus, the IAWQ is a tool to delineate areas where special attention may be required with specific types of land usage and related activities. This tool can be used to validate DRASTIC data as well as to assess the actual sensitivity of groundwater quality to anthropogenic impact. As such, this tool can furnish management decisions regarding water resource management and land use planning.

Navulur (1996) carried out a regional scale assessment of the vulnerability of Indiana's groundwater systems to nitrate contamination from non-point sources. The assessment was conducted using the conventional DRASTIC and SEEPAGE (System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments) analyses (Richert et al., 1992).

The models were integrated within the ARC/Info GIS environment, and a GUI was developed to implement the analyses. The data required for the models were extracted from various sources including the State Soils Geographic Database (STATGO).

DRASTIC classified 24% of the state area as under high and very high vulnerability. SEEPAGE predicted that 28% of groundwater systems in Indiana are in high and very high vulnerability areas. The predictions of these models were statistically evaluated using a USGS water quality database. Spatial statistics were utilized to eliminate some detections from point source pollutants. The comparison showed that approximately 80% of nitrate detections >2 mg/l were within high and very high vulnerability areas as predicted by the models.

Since the DRASTIC and SEEPAGE models are empirical models, a Bayesian probability map of risk areas was built using DRASTIC and SEEPAGE data layers as factors of evidence for computing probabilities of occurrence of nitrate detection. The Bayesian map using DRASTIC factors as evidence classified 26% of the state with a probability of nitrate detection > 50%, whereas the Bayesian map using SEEPAGE factors as evidence predicted 21% of the state with a probability of nitrate detection > 50%. The patterns of nitrate vulnerability predictions, based on weights of evidence, were similar to those predicted by DRASTIC and SEEPAGE validating the choice of DRASTIC and SEEPAGE factors for regional scale groundwater quality assessment. When compared with the water quality database, 76% of the nitrate detections were within areas with probability of detection > 50% as predicted by the Bayesian model. The results suggested that these statistical techniques can be used to develop regional scale risk maps when limited data is available.

To further investigate various processes affecting nitrogen transformations at the field scale level, the Nitrogen Leaching and Economic Analysis Package (NLEAP) model was selected for simulating nitrate leaching beneath the root zone (Follet et al., 1991). The model was validated for a field site named SEPAC (Southeast Purdue Agricultural Center) in southeastern Indiana, US. The model results were compared with the observed nitrate loadings from subsurface drainage flow in the field. The results showed that, following calibration, NLEAP performed satisfactorily in simulating NO_3 leaching. The model annual indices (leaching index, nitrate leached, and annual leaching risk potential) were also computed for Indiana. The model was integrated with the ARC/info GIS to facilitate this part of the study. The results of comparison of the annual indices with the water quality database showed that these indices might be useful as additional data layers for regional scale analyses of groundwater vulnerability.

A new technique was developed for assessing groundwater vulnerability at a regional scale to non-point source pollutants. The technique improved upon the limitations of conventional DRASTIC and SEEPAGE analyses. This technique uses the data layers: land use, aquifer recharge, soil media, aquifer media, slope, hydraulic conductivity, and nitrate leaching as calculated by NLEAP for predicting the vulnerable areas. Then data layer of nitrate leaching was computed using NLEAP annual simulations. The new technique employs a weighting scheme for computing the pollution potential of a region. A graphical user interface was developed to integrate the new model within the ARC/Info GIS environment. The new technique predicted that 57% of the state is under high and very high vulnerability areas. The results from this technique were statistically evaluated using a water quality database. 92% of nitrate detections fell within the high and very high vulnerability areas as predicted by the new method. Comparison of the results with the predictions from conventional techniques showed that the new model improved upon the DRASTIC and SEEPAGE analyses. Also a Bayesian risk map of the factors validated the choice of the parameters for predicting groundwater quality assessment at a regional scale.

DRASTIC performed better than SEEPAGE in predicting areas which are vulnerable to groundwater nitrate contamination from non-point sources.

4.6 DRASTIC with modified parameters

Thirumalaivasan, Karmegam, and Venugobal (2003) developed a software called AHP-DRASTIC to carry out specific vulnerability assessments using DRASTIC model and GIS. These researchers believe that the DRASTIC model is rigid in the assignment of ratings and wieghts to the model parameters. However, to better address local issues for a refined representation of local hydrogeologic settings, they envisaged a modification of the original DRASTIC model.

In their study, the modifications to the DRASTIC model were in the form of modifying ranges of four specific parameters, namely: (1) depth to water table; (2) topography; (3) hydraulic conductivity and (4) impact of vadose zone. As the model parameter ranges have been modified in this study, they decided to use the Analytic Hierarchy Process (AHP) which is a powerful Multi Criteria Evaluation (MCE) process. The AHP was used in this study in conjunction with DRASTIC to construct "pair-wise comparison" matrices which compare all the criteria to one another. This is done to estimate a rating or weighting of each of the criteria which describes the importance of each of these criteria in contributing to the overall objective. Needless to say, uncalibrated DRASTIC index is a poor predictor of groundwater vulnerability to contamination and the use of AHP can validate the DRASTIC index.

The study area was a sub-watershed in the North Arcot district of Tamil Nadu, India. This area is underlain by crystalline metamorphic gneiss of Archaean complex of peninsular India with a wide range of mineral and rock composition and bound in the east and southeast by alluvial plain of Plalar River. Land use in the study area is chiefly agricultural cropland and plantations covering the alluvial spread and the plains with coconut, sugarcane, paddy, groundnut and pulses. Extensive agricultural activities in the alluvial aquifer coupled with increased usage of fertilizers with different application rates have led to high levels of nitrate contamination in groundwater.

All the DRASTIC model parameters were developed as raster thematic maps in ArcView GIS with a 50 m uniform cell size. The ranges of depth to water table, topography, impact of vadose zone and hydraulic conductivity parameters were modified for refined representation of these parameters in the study area. All the other parameters were not modified and used as such. The researchers developed a Graphical User Interface (GUI) using Visual Basic Application for implementing the AHP methodology. The GUI facilitated the creation of Pair-Wise Comparison Matrices (PCMs) and evaluation of ratings, weights, Consistency Index (CI) and Consistency Ratio (CR) in a user friendly manner. The user is prompted with relevant details while deciding the relative importance of criteria and sub-criteria. The GUI gave the output of ratings and weights in the form of a Microsoft Access database file (MDB).

In order to determine the Specific Vulnerability Index (SVI) through spatial modeling, the GUI was integrated with the ArcView GIS software. The GIS software was customised using Avenue scripting language, which accesses the MDB database file and automatically transfers the ratings and weights to the corresponding criteria and sub-criteria by the table join operation supported by GIS. The ratings and weights derived from AHP would sum up to one for any given sub-criteria and criteria and they are fractional numbers. Hence, these ratings and weights were multiplied by a common scaling factor so that the range of vulnerability index would be similar to what could be obtained using conventional DRASTIC model ranges and ratings. The ratings and weights were transferred to ArcView model parameter coverages using Avenue scripts, and these model parameters were combined linearly to calculate the DRASTIC Specific Vulnerability Index (DSVI). The natural breaks method available in ArcView GIS (Jenks, 1977) captured the natural groupings of DSVI into the proposed three vulnerability categories, namely low, moderate and high vulnerability category.

The DRASTIC model assumes that the contaminant has the mobility of water. Nitrate, being completely soluble in water, almost satisfies this assumption. Moreove, their study area has a known problem of nitrate contamination, especially in the river alluvium due to very high rate of use of nitrogenous fertilizers.

The results have shown that the predominant portion of the alluvial aquifer has a high vulnerability to nitrate. The methodology was verified by comparing nitrate concentrations from well samples in the field. The results have indicated a strong relationship between DSVI and nitrate concentrations. Contingency table analysis results have shown that the model results are quite consistent with field observations. The study produced vulnerability assessment maps helpful in decision-making with regard to water polluting industries.

Lake et al. (2003) carried out a study on evaluating factors influencing groundwater vulnerability to nitrate pollution through developing the potential of GIS. They developed a methodology to identify all areas of England and Wales at risk from groundwater nitrate pollution. In addition, the original Nitrate Vulnerable Zones (NVZs) were defined through steady state groundwater modelling (Palmer et al., 1995) which did not include information pertaining to soil or nitrogen leaching mechanisms.

This study combined these factors with geological characteristics in an assessment of groundwater vulnerability to diffuse sources of agriculturally derived nitrate. Furthermore, the results were rigorously verified against actual borehole nitrate concentrations and by comparing different methods of estimating groundwater vulnerability. They described the creation of models of groundwater vulnerability using a GIS to combine spatial information on surface leaching, soil characteristics, low permeability superficial (drift) deposits and aquifer type. These were then converted into a measure of vulnerability. Overlay procedures were implemented within a GIS environment to produce the three models. The details of these and a brief summary of each layer are shown in Table 4.2 and Table 4.3 respectively.

Table 4.2: Components of the three nitrate vulnerability models.

Layer	Models		
	Risk	**Specific**	**Intrinsic**
Leaching	Leach 1	Leach 2	Leach 3
Soil	Soil 2	Soil 2	Soil 1
Drift	Drift	Drift	Drift
Aquifer	Aquifer	Aquifer	Aquifer

Table 4.3: A brief summary of four spatial data layers.

Leaching layers	**Leach 1**	Simulated mean nitrate concentrations in land drainage (mg/l) using current land use
	Leach 2	Simulated mean nitrate concentrations in land drainage (mg/l) assuming 100 kg N/ha applied to all land
	Leach 3	Simulated mean annual soil drainage from all land (mm)
Soil layers	**Soil 1**	This layer contains the seven soil categories present on the Environment Agency GVMs. (GVM refers to Groundwater Vulnerability Maps)
	Soil 2	Soil reclassified to remove specific information about the soil's ability to attenuate. Consists of two classes HI (High + Intermediate) and L (low).

Drift layer	**Drift**	Low permeability drift taken from the GVMs to indicate the presence or absence of drift material.
Aquifer layers	**Aquifer**	Aquifer classification from the GVMs consisting of three classes, namely: Major aquifer, Minor aquifer and non-aquifer.

The vulnerability patterns generated by the model variants were compared using an extensive database of over 3,700 sites for monitoring nitrate concentrations in groundwater.

It was found that all the models were similar to each other in terms of the geographical distribution of vulnerability categories. Furthermore, the patterns of vulnerability could be explained by referring to the geology, climate and land use of England and Wales.

When verified by comparison with trend data derived from monitored nitrate concentrations, all the models were statistically significant predictors of groundwater nitrate concentrations. The best predictive model contained a model of nitrate leaching without land use information, implying that changes in land use will not affect designations based upon this model. The relationship between nitrate levels and borehole intake depths was investigated since there was concern that the observed contrasts in nitrate levels between vulnerability categories might be reflecting differences in borehole intake depths and not actual vulnerability. However, this was not found to be statistically important. The researchers' preferred model provides, they believe, the basis for developing a new set of groundwater Nitrate Vulnerable Zones that should help decision makers in England and Wales to comply with the EU Nitrate Directive.

Babiker et al. (2004) developed a GIS – based DRASTIC model for assessing aquifer vulnerability in Kakamighara heights, central Japan.

Their study aimed at estimating aquifer vulnerability by applying the DRASTIC model as well as utilizing sensitivity analyses to evaluate the relative importance of the model parameters for aquifer vulnerability in the study area. An additional objective was to demonstrate the combined use of the DRASTIC and GIS as an effective method for groundwater pollution risk assessment.

The study area is composed of low hills 20 to 60 m above sea level. The area is characterized by a warm and mild climate with an average annual temperature of 15.5 ^{0}C and a rainfall of 1915 mm (mean of 30-year records from Giftu City rainfall station, Japan Meteorological Agency).

Several types of data were used to construct thematic layers of seven model parameters to characterize the hydrogeological setting and evaluate aquifer vulnerability.

The researchers attempted to evaluate whether it was really necessary to use all of the seven DRASTIC parameters to assess the Kakamighara aquifer vulnerability by performing model sensitivity analysis. The rated DRASTIC parameters were first evaluated for interdependence and variability. According to Rosen (1994), the independency of DRASTIC parameters decreases the probability of misjudgment. In fact, most of the DRASTIC parameters are naturally closely related. Two sensitivity tests were performed; the ***map removal*** sensitivity analyses introduced by Ludwick et al. (1990) and the ***single-parameter*** sensitivity analysis introduced by Napolitano and Fabbri (1996). The map removal sensitivity measure identifies the sensitivity of the vulnerability map towards removing one or more maps from the vulnerability analysis. Whereas, the single-parameter sensitivity measure evaluates the impact of each of the DRASTIC parameters on the vulnerability index. The implementation of sensitivity analysis required a well-structured database and a GIS capable of manipulating large tables.

The statistical summary of the seven rated parameter maps used to compute the DRASTIC index is provided in Table 4.4.

Table 4.4: A statistical summary of the DRASTIC parameter maps

Measure	**D**	**R**	**A**	**S**	**T**	**I**	**C**
Minimum	1	8	2	1	1	2	1
Maximum	7	9	8	10	10	8	10
Mean	4	9	4	5	6	5	5
SD	2	1	3	3	4	2	3
CV(%)	50	11.1	75	60	66.7	40	60

SD stands for standard deviation and CV for coefficient of variation.

The rank-order correlation analysis (a summary of the result is provided in Table 4.5) between the seven DRASTIC parameters indicated that a relatively strong relationship exists between aquifer media and impact of vadose zone.

Table 4.5: A summary of the rank-order analysis results for the seven DRASTIC parameters

Correlated parameters	**Correlation Coefficient, r**	**Significance level, p**
Aquifer media and impact of vadose zone	0.81	<0.0001
Aquifer media and topography	0.73	<0.0001
Impact of vadose zone and topography	0.56	<0.0001
Net recharge and soil media	0.46	<0.0001
Aquifer media and hydraulic conductivity	0.30	<0.001
Depth to water and topography	0.29	<0.001

Only statistically significant (confidence level at/or more than 95%) interrelations are tabulated. Because of the relatively few significant correlations at 95% confidence level Table 4.5, the DRASTIC parameters in the study area were generally considered independent. Table 4.6 displays the variation of the vulnerability index as a result of removing only one layer at a time.

Table 4.6: Statistics of the map removal sensitivity analysis

Parameter removed	**Variation index (%)**			
	Mean	**Minimum**	**Maximum**	**SD**
D	7.9	0	16.3	4
R	15.1	4	41.7	7.5
A	4.5	0	11.3	3.3
S	11.6	3	15.4	2.8
T	11.2	2.3	16	3.3
I	10.7	0.5	24.3	5.2
C	7.2	0	24	4.9

One parameter is removed at a time. Total of 633 subareas (≥ 10 pixels in size) were considered. In Table 4.7, the variation of the vulnerability index due to the removal of one or more layers at a time from the model computation is presented.

Table 4.7: Statistics of the map removal sensitivity analysis.

Parameters used	**Variation index (%)**			
	Mean	**Minimum**	**Maximum**	**SD**
D, R, S, T, I, C	4.5	0	11.3	3.3
D, R, S, T, and I	7	0	19.1	4.2
R,S,T and I	10.1	0	33.9	8
R,S and T	21	0	50.2	11
R and S	18.7	0	93.4	18.5
R	52.4	12.5	69.1	11.3

One or more parameters are removed at a time. Total of 633 subareas (≥ 10 pixels in size) were considered. The map removal sensitivity analysis indicated that the vulnerability index is highly sensitive to the removal of net recharge, soil media, and topography layers but is least sensitive to the removal of the aquifer media layer. Therefore, considerable variation in the vulnerability assessment is expected if a lower number of data layers have been used. The single-parameter sensitivity analysis has shown that net recharge and hydraulic conductivity are the most significant environmental factors which dictate the high vulnerability of the Kakamighara aquifer. This highlights the importance of obtaining accurate, detailed, and representative information about these factors.

Meinardi et al. (1995) carried out a study on vulnerability to diffuse pollution and average nitrate contamination of European soils and groundwater. They thought that from an environmental viewpoint, it was useful to consider soil as the solid parts of the subsurface, in combination and inseparable from the fluids, gases and biota within the solid matrix. The soil includes the deeper strata of the subsurface and groundwater forms part of it. Soil and groundwater are affected by various sources of pollution.

The effects of point sources may be serious at the affected locations but diffuse sources also represent an important threat to the environment because of their widespread occurrence. Subsurface water flow is the main transport mechanism, bringing pollution to deeper soil layers, to the draining surface water and ultimately to the sea.

Although a type of soil is present in every region of Europe, the groundwater in that soil is not exploitable everywhere, nor is it even flowing at a significant rate. Hence, the vulnerability to diffuse pollution should be distinguished as vulnerability of the topsoil layers (affecting agricultural production and ecological conditions) and vulnerability of the groundwater in exploitable aquifer systems (water extraction and ecological conditions downstream).

The following factors play a role in the mapping of both types of vulnerability: definition of elementary areas; hydrogeological mapping of the subsurface; the texture of the topsoil; land cover; net precipitation; groundwater recharge; and groundwater age.

The following factors that determine the vulnerability of the topsoil were taken into consideration: land cover; net precipitation; topsoil features; leaching of contaminants from the topsoil; thickness of the unsaturated zone; groundwater recharge; and aquifer characterization.

The study produced four important maps each of which covers the entire continent of Europe, vulnerability of European topsoils, vulnerability of European groundwater, leaching of nitrate from the topsoil and average nitrate concentrations in groundwater.

Investigations in northwest Europe (Kolenbrander, 1981) made it plausible that the average leaching of nitrates to a level of 1 m below land surface is a function of nitrogen dose, crop type, soil features (texture) and groundwater level. Concentrations can be calculated if the net precipitation and/or groundwater recharge are also known. Nitrogen doses were derived from national data. The various crop types were derived from the land-use map by Van De Velde et al. (1994). Soil features including an indication of groundwater levels, were derived from the FAO soil map of the world. Net precipitation and groundwater recharge were calculated for the vulnerability mapping. The leaching of part of the nitrogen dose also depends on its form as fertilizer (100% effective) or as manure (only 60% of the nitrogen available for leaching). The elaboration of all data was realized with the help of GIS. The produced map shows that the leaching of nitrate into the soil layers is deeper than 1 m below land surface.

The input of nitrogen compounds in groundwater of the saturated zone consists of the leached quantities from the topsoil. Assuming that the dose at land surface has exponentially increased with time from a constant load before 1980 to the actual load per region, the time-variable input to levels deeper than 1 m below land surface can also be estimated.

The determined vulnerabilities depicted the situation of the topsoil and of groundwater in relatively large areas, thus ignoring much of the local details. Nevertheless, the method could be easily adapted to smaller regions if necessary. Furthermore, it is assumed that the different elements of diffuse pollution all behave in the same way. An adaptation of the method to attain a more specific representation of the vulnerability to a selected pollutant is possible.

CHAPTER V

METHODOLOGY

METHODOLOGY

This chapter provides a brief illustration of the methodology followed in carrying out the research work described herein. Figure 5.1 depicts the flowchart of the methodology.

The methodology begins with the identification of the research objectives. This step was important since the objectives dictate the entire pathway of the work. That is, literature review that I carried out relied mainly on the objectives and the selection of the vulnerability method was based on the literature review. I made sure that the selected vulnerability method once applied can address successfully the articulated objectives and thus the expected research outcomes would be as planned.

After that and since we are considering the entire West Bank as a case study, data collection was commenced. Again, in data collection, we concentrated on the data pertaining to the implementation of the DRASTIC method. Data were obtained from different sources including the Palestinian Water Authority (PWA), the Water and Environmental Studies Institute (WESI) at An-Najah National University, along with other sources.

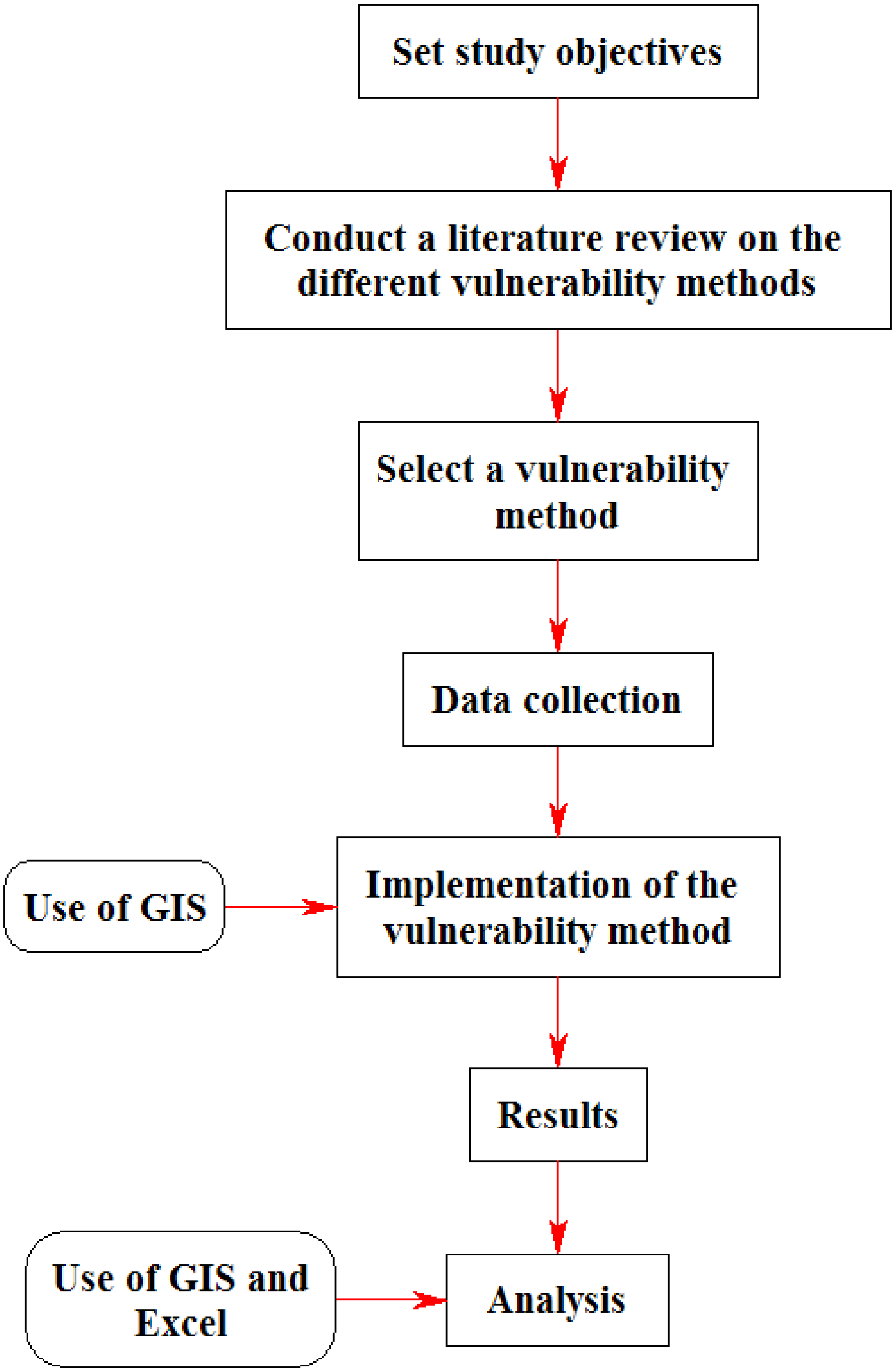


Figure 5.1: Methodology flow chart

I implemented the DRASTIC method with a great utilization of GIS in data preparation, processing, and implementation. The use of GIS is essential to efficiently account for the spatiality in the properties of the different factors considered in the DRASTIC method. After applying the DRASTIC method, results of the vulnerability indices for the entire West Bank were obtained and later analyzed using GIS and EXCEL.

CHAPTER VI

DESCRIPTION OF THE STUDY AREA

DESCRIPTION OF THE STUDY AREA

6.1 The study area

6.1.1 Geography:

The West Bank area of Palestine Figure 6.1 has a varied topography which consists of central highlands, semi-arid rocky slopes, an arid rift valley and rich plains in the north and west (UNEP, 2003). The West Bank is mostly composed of limestone hills between 600 to 900 meters high. The lowest point of the area is the Dead Sea at 410 meters below sea level, and the highest, the Tall Asur, at 1,022 meters above sea level.

Brown lithosols and loessial arid brown soils cover the eastern slopes and grassland, with pockets of cultivation spreading over the steep slopes. Soil cover is generally thin and rainfall is erratic. About 12 percent of the land is desert, eroded or saline.

6.1.2 Vegetation:

The dry southern West Bank, eastern slopes and central Jordan valley are composed of Mediterranean savanna grading into land dominated by steppe brush and spiny dwarf shrubs. The southern Jordan valley around Jericho and the Dead Sea is also influenced via the Wadi Araba by Sudanian vegetation.

Figure 6.1: West Bank map (UNEP, 2003)

6.1.3 Climate:

The climate is hot and dry during the summer and cool and wet in winter. The central highlands have occasional frost, snow and hail. The Jordan Valley is warm and very dry in the south. The mean summer temperatures range from 30°C at Jericho to 22°C at Hebron, whereas the mean winter temperatures range from 13°C at Jericho to 7°C at Hebron. The average annual precipitation is 450-500 mm, decreasing from north to south and from high to low altitude. Rain tends to fall in intense storms. Evaporation is high in summer when there is a water deficit. Winds prevail from the northwest but come from the southwest in winter. Land and sea breezes occur, and in late spring the hot dry khamsin blows from the desert in the south (UNEP, 2003).

6.1.4 Water resources:

The principal water resources include groundwater, springs and harvested rainwater. The Palestinians in the West Bank are deprived from their natural rights in the Jordan River. The West Bank lies over a Mountain Aquifer which is divided into the Western Aquifer, the Northeastern Aquifer, and the Eastern Aquifer. The Eastern Aquifer and part of the Northern Aquifer flow east towards Jordan River. The Western Aquifer and part of the Northern Aquifer flow west towards the Mediterranean Sea.

6.1.5 Governerates:

The West Bank is divided into eleven governorates which are subdivided into 89 municipalities. Local councils have also been formed to manage all basic services and infrastructure.

6.1.6 Population:

About 2 million Palestinians live in the West Bank. Forty percent of these are refugees since 1948. Around 65% of the population lives in urban areas. Annual population growth is estimated at 4.8%. The Israeli settler population living in the West Bank is 203,067.

6.2 Water resources assessment

6.2.1 The resource base:

In the West Bank territories, water is a precious natural resource and its relative scarcity is a major obstacle to economic development. Global climate change may further aggravate the situation through increased temperatures and evaporation rates and lower and more erratic rainfall. In the West Bank, rainfall averages 450 mm per year. Since the West Bank area is 5,879 km^2, this gives an average total of about 2,600 million m^3 of rain per year. It is estimated that around 680 million m^3 of this infiltrates into the soil to replenish aquifers and the remainder becomes surface runoff or lost through evapotranspiration. Groundwater is the major source of fresh water. Small perennial or seasonal streams, fed by springs, constitute the only source of surface water.

6.2.2 The mountain aquifer system:

This aquifer system underlies and largely recharged from the West Bank in which it is by far the most important source of water. This aquifer system is highly permeable due to its geological nature.

The groundwater in the Mountain Aquifer system flows in three main directions, according to which three main groundwater basins can be identified; namely, the Western, North-eastern and Eastern Aquifer Basins Figure 6.2.

Figure 6.2: the mountain aquifer system (UNEP, 2003)

The Western Aquifer Basin extends from Beer As-Sabi' northwards to the Carmel Mountain foothills, and from near the center of the Mountain Belt to the Coastal Belt. This aquifer discharges outside the West Bank through springs flow diversion and groundwater abstraction through deep boreholes (UNEP, 2003).

The Northeastern aquifer is located in the northernmost part of the Mountain Belt in an area that is generally flat with rolling hills and no obvious topographic features to delineate its boundaries.

The groundwater potential of the aquifer system in this basin is about 145 million m^3 per year, and it generally flows northeast. The aquifer has a total natural discharge of around 140 million m^3 per year from four main groups of springs (Beisan, Jenin, Gilboa and Wadi al Fara’a) (UNEP, 2003).

The Eastern Mountain Aquifer includes the eastern part of the Mountain Belt and the steep Western Escarpment of the Jordan Rift Valley. The aquifer is recharged from the high precipitation areas in the mountainous part of the aquifer basin at an estimated average volume of 172 million m^3 per year. It flows generally south-east towards the Jordan Rift valley (UNEP, 2003).

About 300 springs are distributed throughout the West Bank. The total average annual yield of these springs is around 60 million m^3.

The average annual recharge for the Western, North-eastern and Eastern Aquifers is 362, 145 and 172 million m^3 per year, respectively. This means a total average annual recharge of 679 million m^3 per year for the West Bank (UNEP, 2003).

6.3 Soil and groundwater pollution in the West Bank

Groundwater in most areas of the West Bank is generally considered to be of good quality, though easily contaminated in some regions, depending on land use and local soil and geological conditions. The region’s geology is limestone that allows substances to penetrate easily. The aquifers are vulnerable to contamination because the attenuation of nutrients and pollutants in wastewater are low. In some areas, groundwater is unsuitable for drinking because of high salinity partly due to natural factors. This problem will worsen since over-abstraction of freshwater leads to intrusion of salty water from deeper levels.

Pesticide contamination of both soil and groundwater is a major environmental issue in the West Bank, but data are scarce, given that resources and laboratory capacity are limited.

A detailed study (Marei and Haddad, 1998) found nitrate levels above WHO standard guideline values for drinking water (i.e. > 50 mg/L) in up to one-third samples from wells in Jordan Valley, Nablus, Jenin, and Tulkarm (UNEP, 2003).

Figures 6.3 to 6.5 depict nitrate concentrations time series for three different wells located in the groundwater of Qalqilya, Tulkarm, and Jenin.

The Palestinian Ministry of Health had published data in 2001 indicated that 600 out of 2,721 samples, including water from both wells and tanks, failed to meet WHO bacteriological guideline values for drinking water. This explains the frequent outbreaks of diarrhea among the Palestinian population.

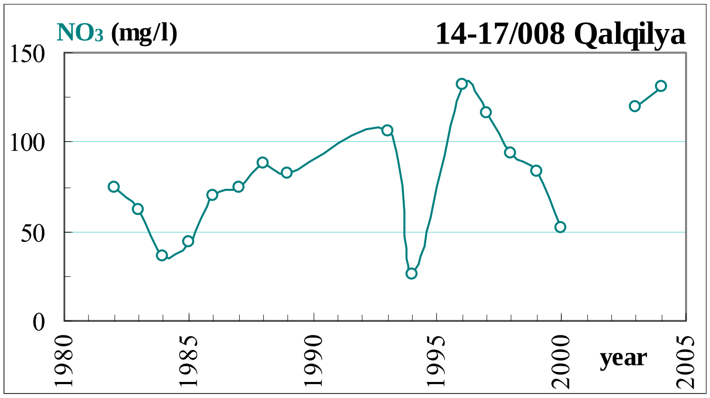


Figure 6.3: Nitrate time series for well 14-17/008 located in Qalqilya

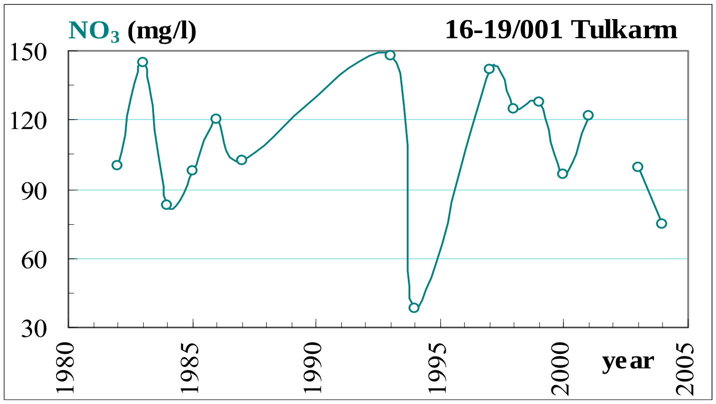


Figure 6.4: Nitrate time series for well 16-19/001 located in Tulkarm

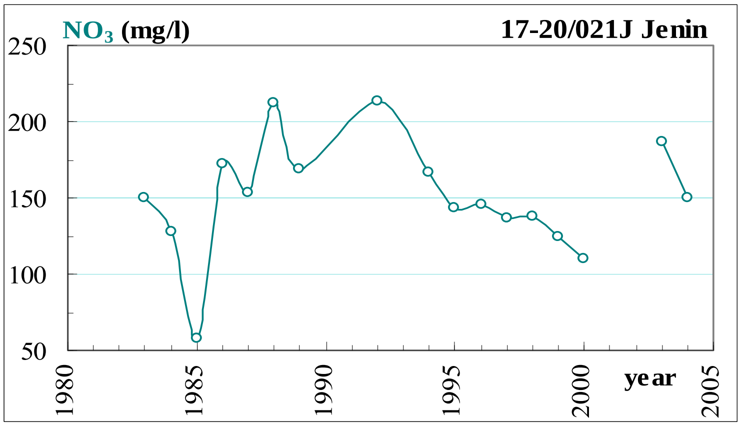


Figure 6.5: Nitrate time series for well 17-20/021 located in Jenin

CHAPTER VII

DEVELOPMENT OF THE VULNERABILITY MAP FOR THE WEST BANK AQUIFERS

DEVELOPMENT OF THE VULNERABILITY MAP FOR THE WEST BANK AQUIFERS

As mentioned earlier in this thesis, the DRASTIC method relied on seven parameters in the development of the vulnerability map. Since the method involves the evaluation and characterization of highly distributed input data, GIS was heavily utilized in data development and processing. This chapter describes the development and preparation of the necessary input parameters for the DRASTIC method along with the development of the vulnerability map of the West Bank and the associated results and analysis. Appendix B illustrates the computation of the DRASTIC index and the corresponding development of the vulnerability map (hypothetical example).

7.1 Preparation of DRASTIC input data

7.1.1 Depth to groundwater

Depth to groundwater was obtained from the water table elevation data of the individual wells as maintained by the PWA and the ground surface elevation data at well location. Ground surface elevation at each well location was obtained from the digital elevation model (DEM) of the West Bank. GIS capability in interpolation was used to map the depth to groundwater everywhere for the study area and Figure 7.1 was obtained. The database of the PWA contains information on the water table elevation on monthly basis for different years. The average of these values was used in the estimation of the depth to water table.

The values of the depth to groundwater were later utilized to compute the rates based on the categories summarized earlier in Table 3.3. To efficiently use GIS in data processing, raster data format was utilized here such that each cell that represents the depth to groundwater was given the proper rate. A uniform cell size of $100 \times 100\ m^2$ was used where this resolution was sufficient to capture the variability in the different properties without major aggregation or averaging.

7.1.2 Recharge

Groundwater recharge was estimated using the equations developed by Guttman (1998) for the Eastern Aquifer. These are the following:

For rainfall < 300 mm/yr → recharge $= 0.15 \times$ [precipitation]

For rainfall ≥ 300 and ≤ 650 mm/yr → recharge $= 0.534 \times$ [precipitation – 216]

For rainfall > 650 mm/yr → recharge $= 0.8 \times$ [precipitation – 360]

In order to implement the above equations, rainfall data was prepared for the different stations in the West Bank. A shapefile of the rainfall stations was obtained and for each station the average long-term rainfall was computed. Thereafter, Thiessen polygons were created for the stations to develop the areas of constant rainfall. Once these polygons are developed using a GIS extension, each polygon was processed using one of the above equations based on rainfall data ending up with a single representative recharge value for each polygon. The attribute table of the Thiessen polygons of the recharge was rated based on Table 3.4.

7.1.3 Aquifer Media

In order to assess the impact of the aquifer media on the vulnerability to groundwater resources, a GIS shapefile was obtained from the PWA that provides the distribution of the subsurface media lithology. Unfortunately, the shapefiles does not include any data to characterize the different properties of each polygon. In order to overcome this oversight, I utilized the hydrogeology map that was recently developed by the PWA in collaboration with the British Geological Survey (BGS). Although there were noticeable differences between the GIS shapefile that we acquired and the hydrogeology map, I did my best in matching between the areas. Accordingly, the shapefile's attribute table was edited; a new field representing the media characteristics was created and filled in with the matched information, and finally an additional new field was also added to represent the rate assigned to each polygon based on Table 3.5

7.1.4 Soil Media

The soil map of the Applied Research Institute – Jerusalem (ARIJ, 2002) for the West Bank was utilized for the assessment of the soil impact on the overall vulnerability of groundwater resources to contamination. The map includes eight major soil classifications. However, additional work was performed to convert the scientific names of each soil category into soil texture for easiness of comparing with Table 3.6 in order to assign the rates. For the attribute table of this soil shapefile, a new field was added to represent the soil texture; another new field was also added to account for the rates that were assigned according to each record representing the soil texture.

7.1.5 Topography

As mentioned earlier, the topography in the DRASTIC method implies the slope of the ground surface in percentage. In order to compute the slope, the DEM of the West Bank was used within the GIS environment. There is a readily available option in the Spatial Analyst of GIS where it is straightforward to compute the slope of the ground surface from the grid of the DEM. After computing the slope, the resulting grid was processed to find out the ratings based on Table 3.7.

7.1.6 Impact of Vadose Zone

As furnished earlier, the impact of vadose zone represents the influence of the unsaturated zone on the vulnerability of groundwater resources to contamination. Since we do not have specific information regarding the media of the vadose zone, it was assumed that the unsaturated zone is a continuation and extension of the aquifer media and thus the same GIS shapefile used earlier in characterizing the impact of the aquifer was also used herein. However, a close look at Table 3.8 indicates that there is a different rating convention when considering the impact of the vadose zone compared to that of the aquifer.

7.1.7 Hydraulic Conductivity

In order to assess the impact of aquifer hydraulic conductivity on the overall groundwater vulnerability to contamination, the GIS shapefile of the aquifer media was utilized. For each polygon that represents an aquifer medium, a hydraulic conductivity value was assigned based on published information that corresponds to the each polygon medium. I used tabulated hydraulic conductivity values for different aquifer media published in the literature Groundwater Hydrology, (Todd, 1980). These data were added to the GIS shapefile and the corresponding rates were assigned based on Table 3.9.

Figures 7.1 through 7.7 depict the different parameters (ratings multiplied by weights) used in the development of the overall DRASTIC map.

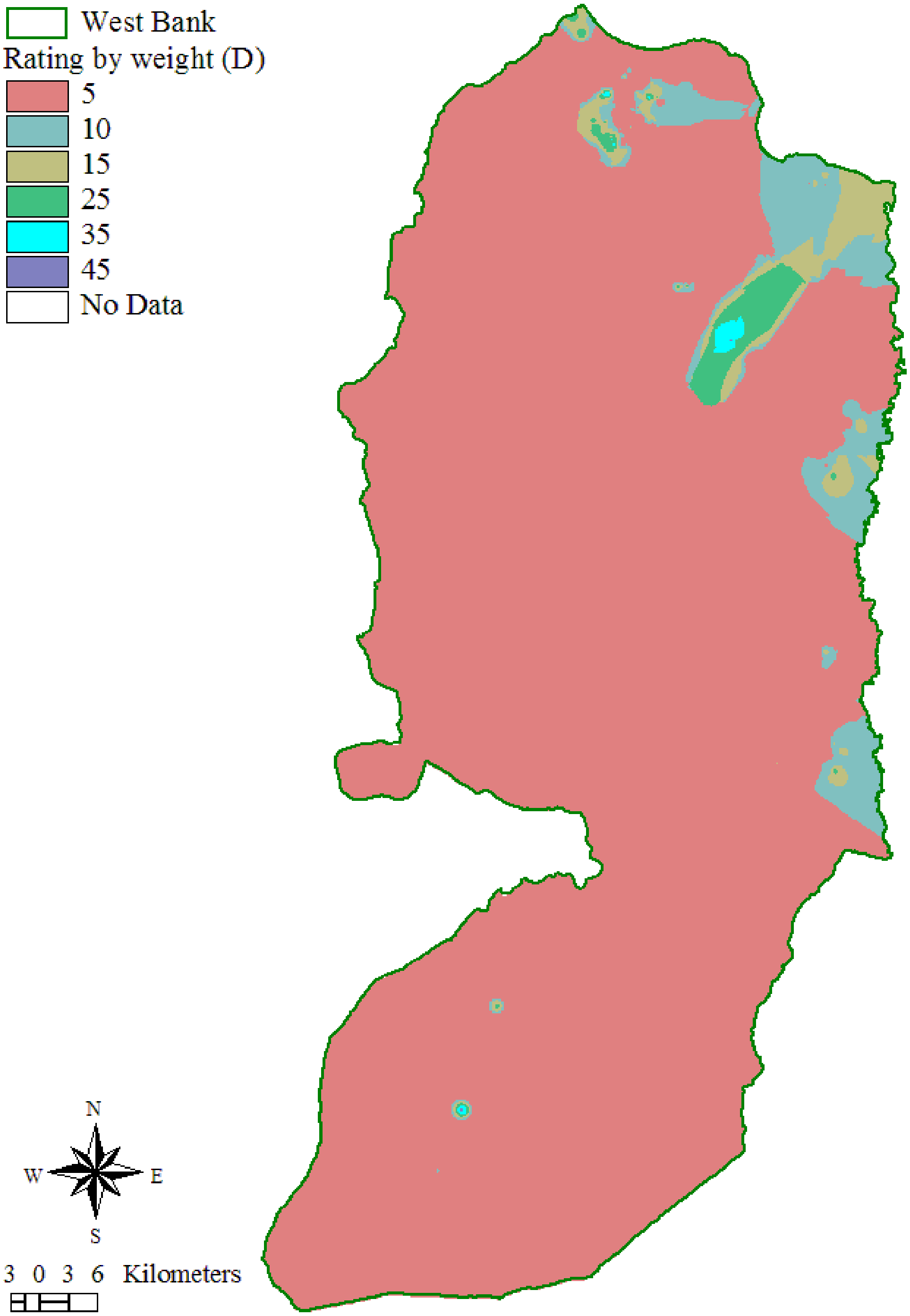


Figure 7.1: The multiplication of the rate and weight for the depth to water ($D_r \times D_w$) for the West Bank.

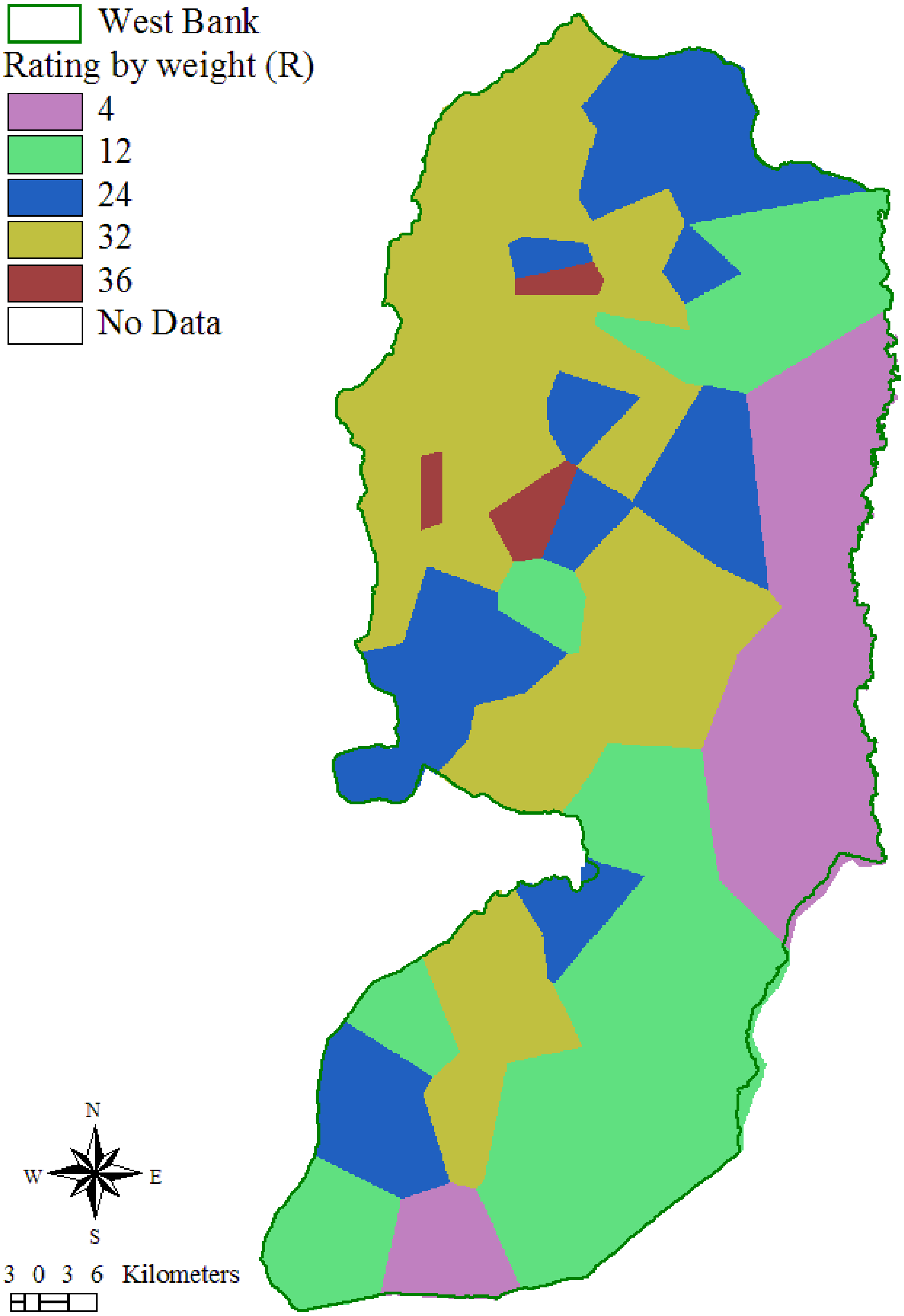


Figure 7.2: The multiplication of the rate and weight for the groundwater recharge ($R_r \times R_w$) for the West Bank.

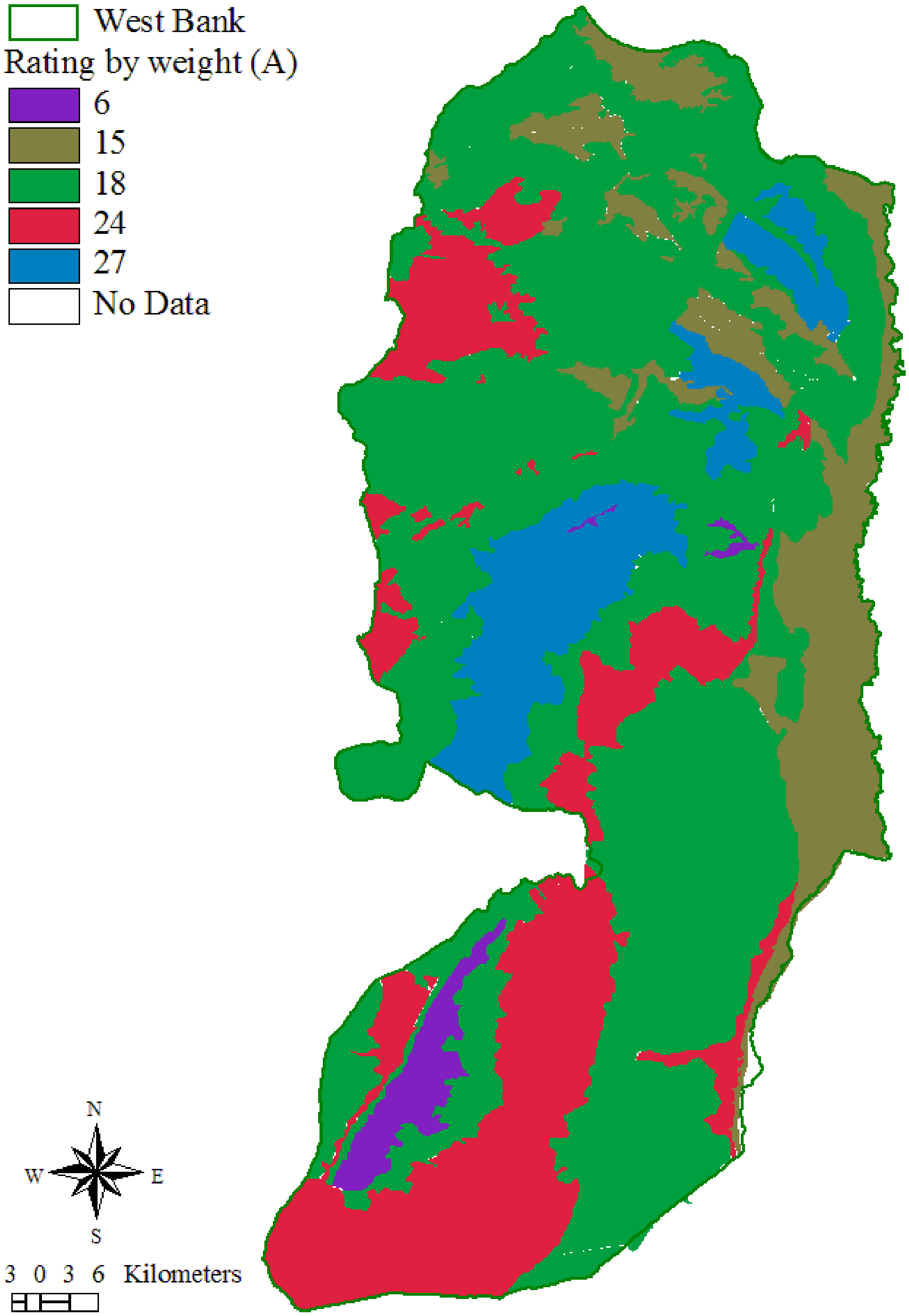


Figure 7.3: The multiplication of the rate and weight for the aquifer media ($A_r \times A_w$) for the West Bank.

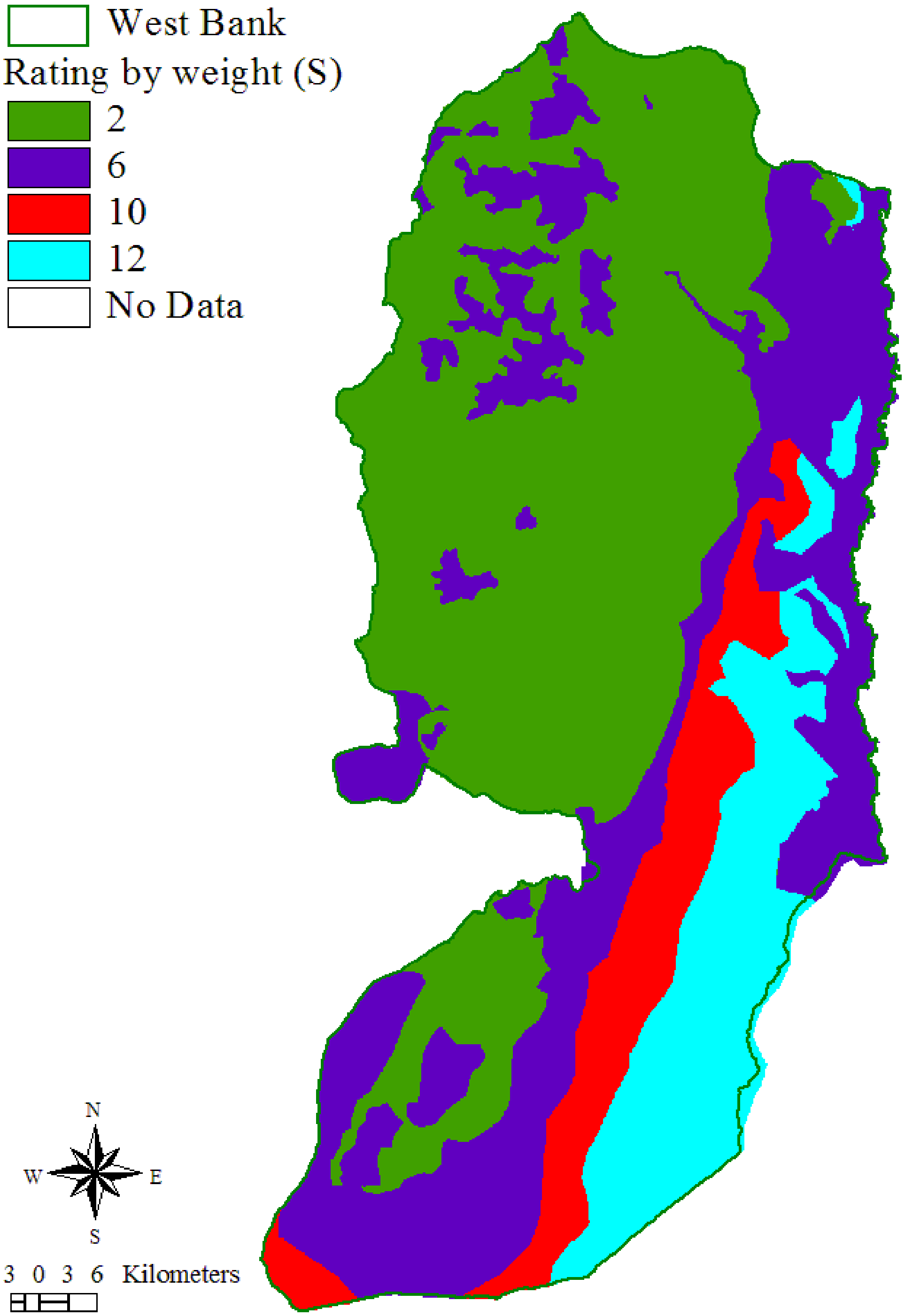


Figure 7.4: The multiplication of the rate and weight for the soil media ($S_r \times S_w$) for the West Bank.

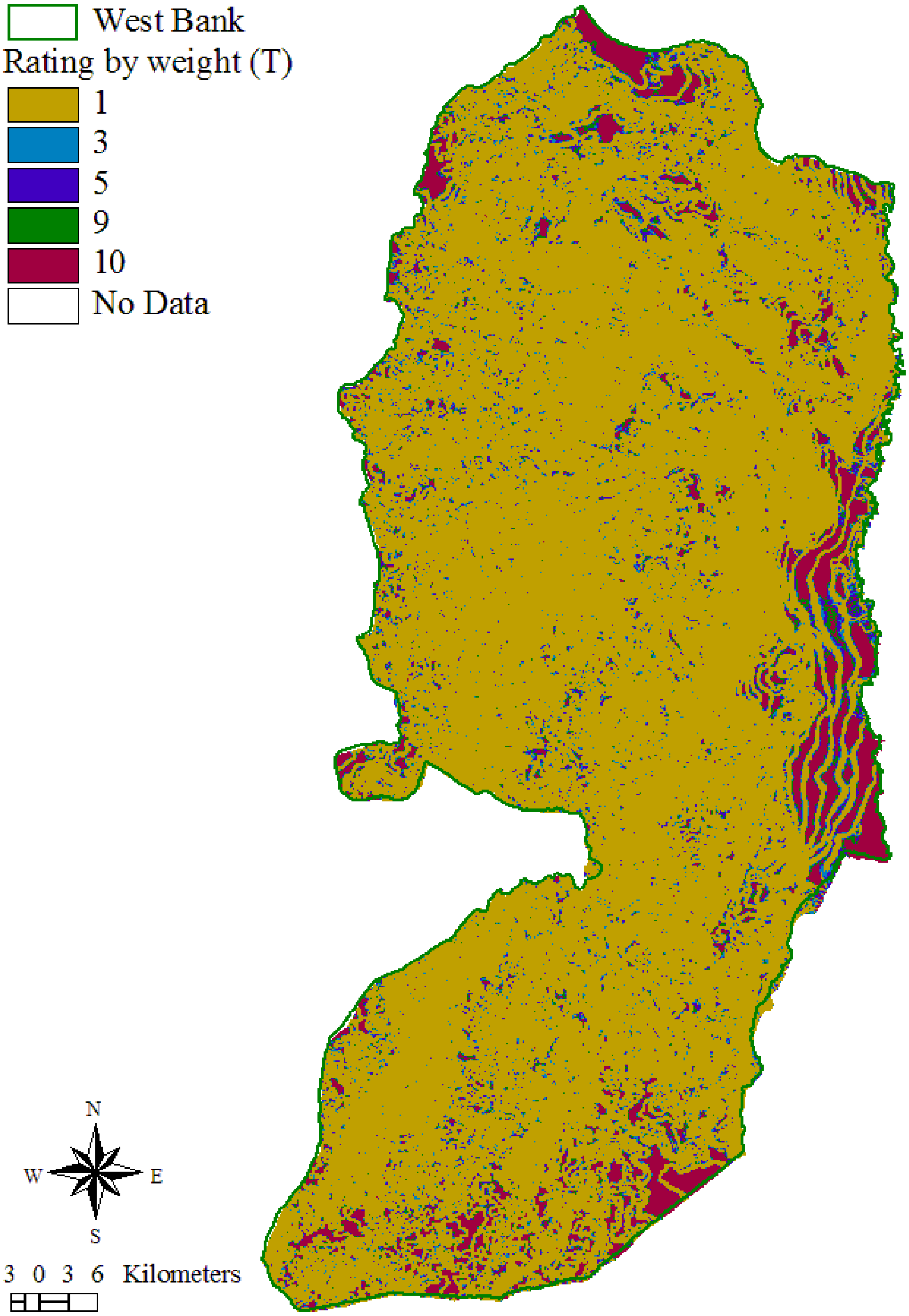


Figure 7.5: The multiplication of the rate and weight for the topography ($T_r \times T_w$) for the West Bank.

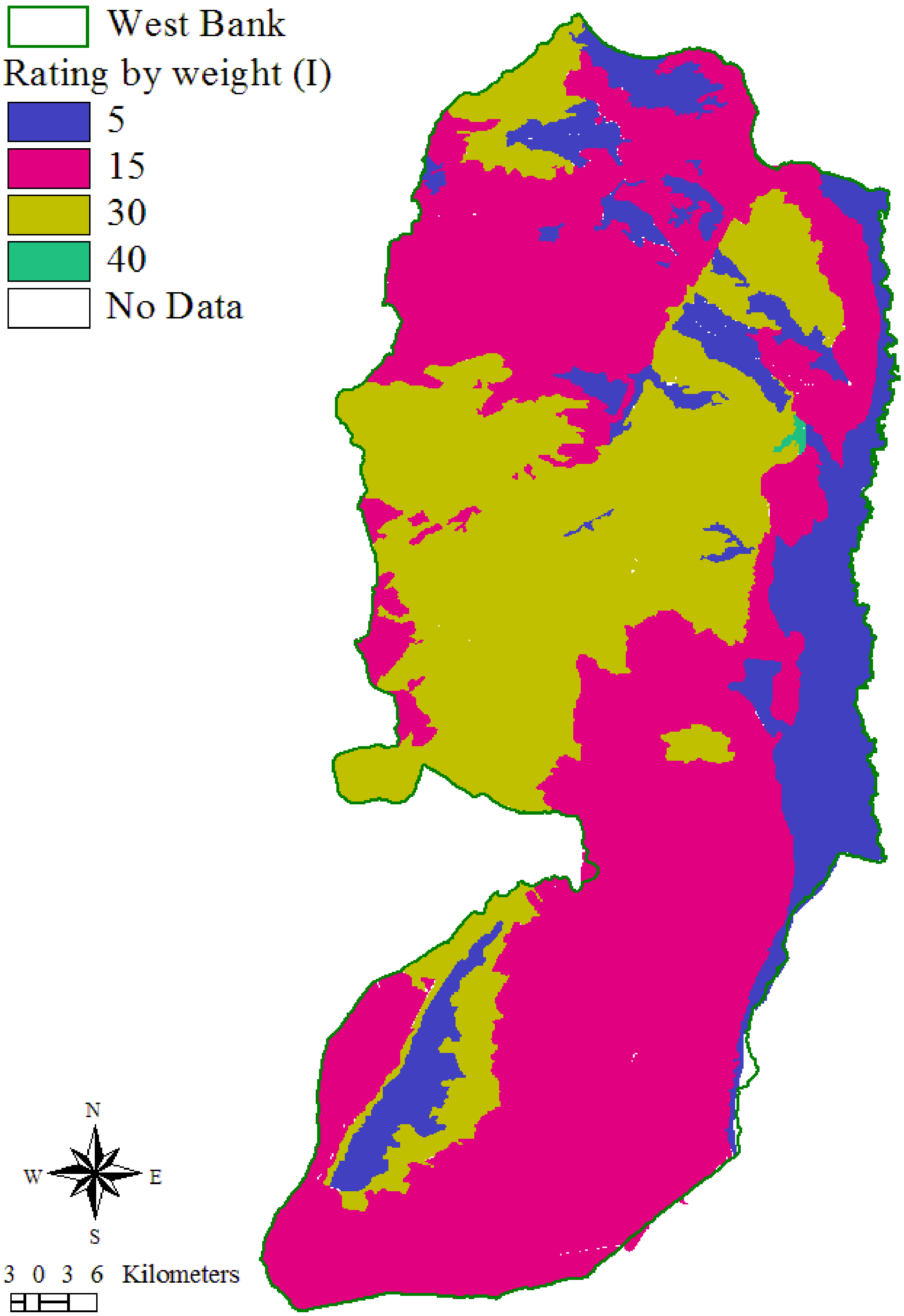


Figure 7.6: The multiplication of the rate and weight for the impact of vadose zone ($I_r \times I_w$) for the West Bank.

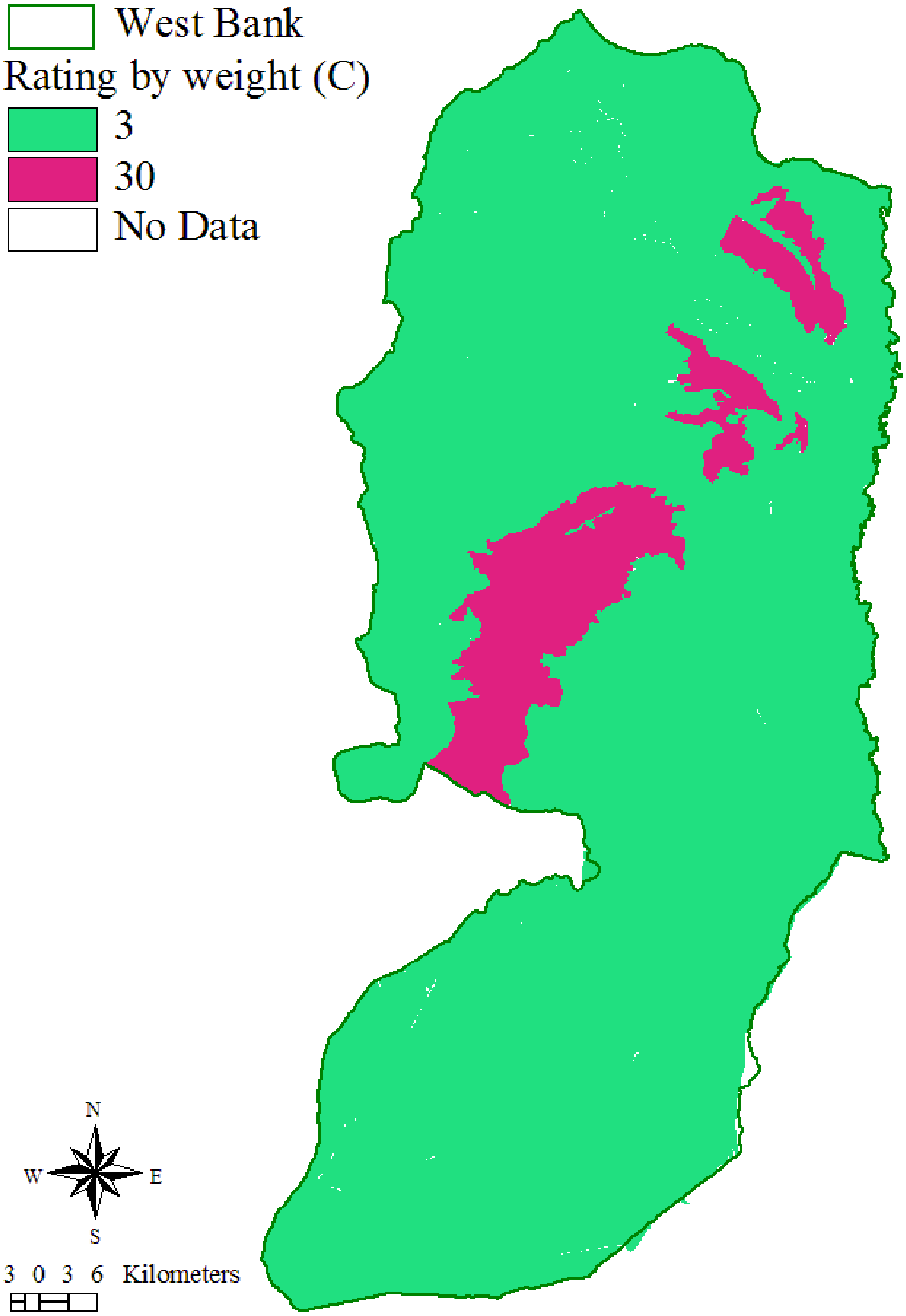


Figure 7.7: The multiplication of the rate and weight for the hydraulic conductivity ($C_r \times C_w$) for the West Bank.

7.2 Results and analyses

Rate grids for the seven hydrogeological parameters of the DRASTIC model were obtained. The values in the cells of each grid were multiplied by the weight of each parameter. Thus seven grids representing the relevant multiplications were obtained. The final DRASTIC index grid Figure 7.8 was computed by summing up the seven grids using GIS to delineate the vulnerability.

Figure 7.9 demonstrates the variability of DRASTIC index values with the corresponding areas. 600 km^2 of the West Bank area have a DI around 90. Almost 510 km^2 have a DI about 66. Yet, 320 km^2 have a DI 82 approximately. Apart from the above three indices, values from 34 to 149 were roughly evenly distributed among the remaining area (74%) of the West Bank. A qualitative vulnerability map Figure 7.10 was developed by the conversion of DI values into different categories each of which having a given color according to the corresponding range of DI. The resulting vulnerability map shows that groundwater in most areas of the West Bank is generally considered to be of reasonable safety. The hydraulic conductivity layer map Figure 7.7 and the groundwater qualitative vulnerability map Figure 7.10 are almost identical. This indicates the predominant role of hydraulic conductivity in contributing to the final sum of DRASTIC index. The areas having the highest DI indices simultaneously have the highest $C_r \times C_w$ values suggesting that the aquifer in this area is mainly composed of sandstone.

Figure 7.11 shows that 5,000 km^2 out of 5,500 km^2 have a low vulnerability index denoting a low potential for groundwater contamination, whereas the remainder 500 km^2 have a moderate potential for pollution. This result could be attributed to the fact that depth to water was generally rated as 1 because the majority of wells in the West Bank usually exceed 100 feet in depth. Almost, location with high potential for contamination was detected. Figure 7.12 depicts the overall percentage of the area occupied by each qualitative vulnerability index. Percentages for low, moderate and high potential were 90%, 10% and 0%, respectively.

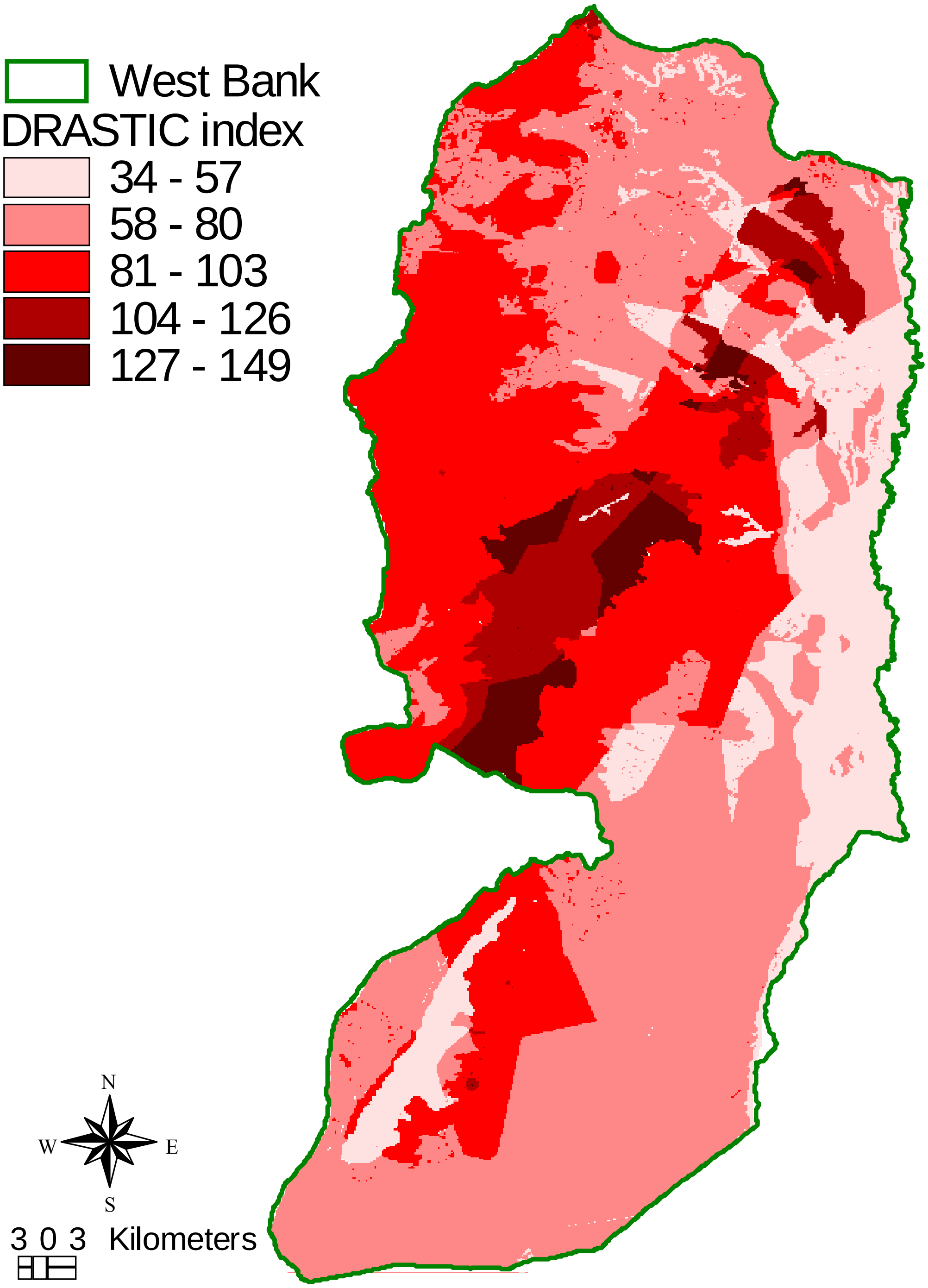


Figure 7.8: The map of the groundwater vulnerability to contamination for the West Bank.

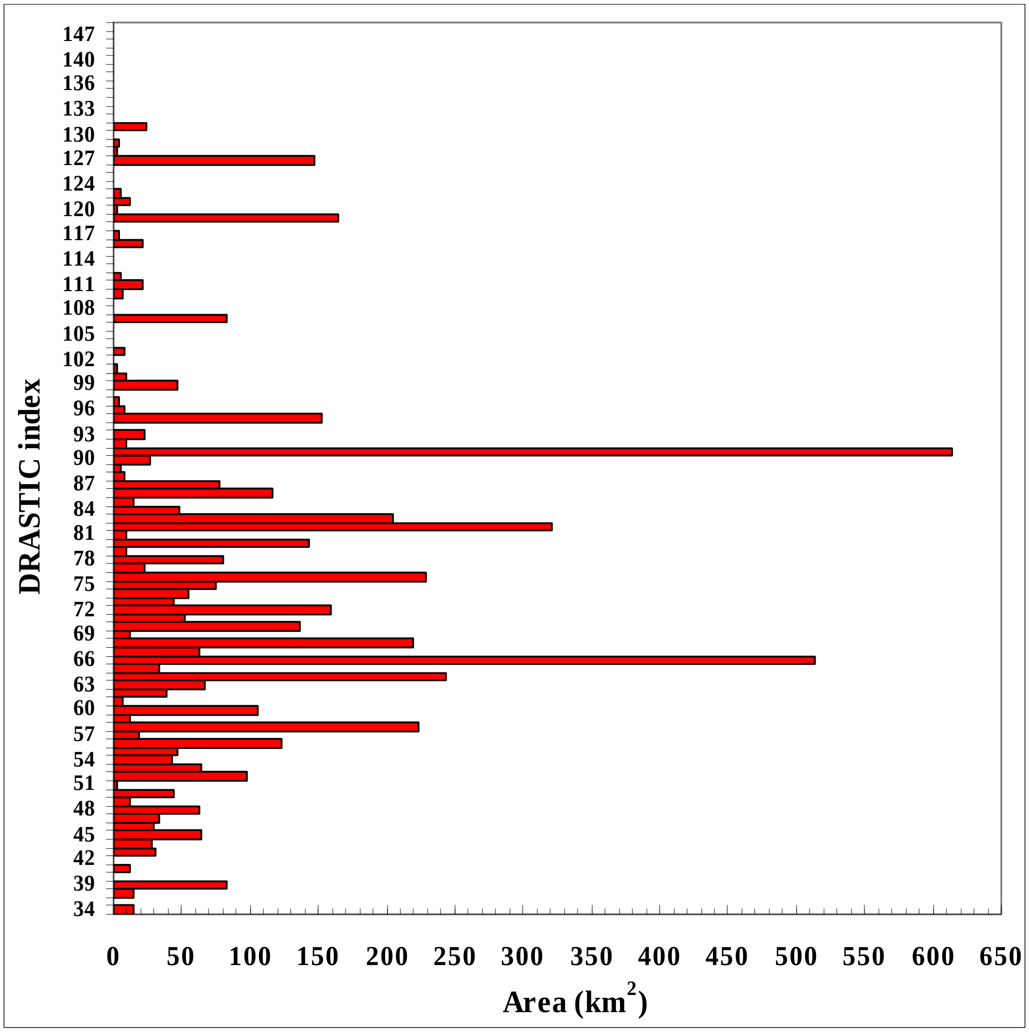


Figure 7.9: The variability of DRASTIC index values with the corresponding areas for the West Bank.

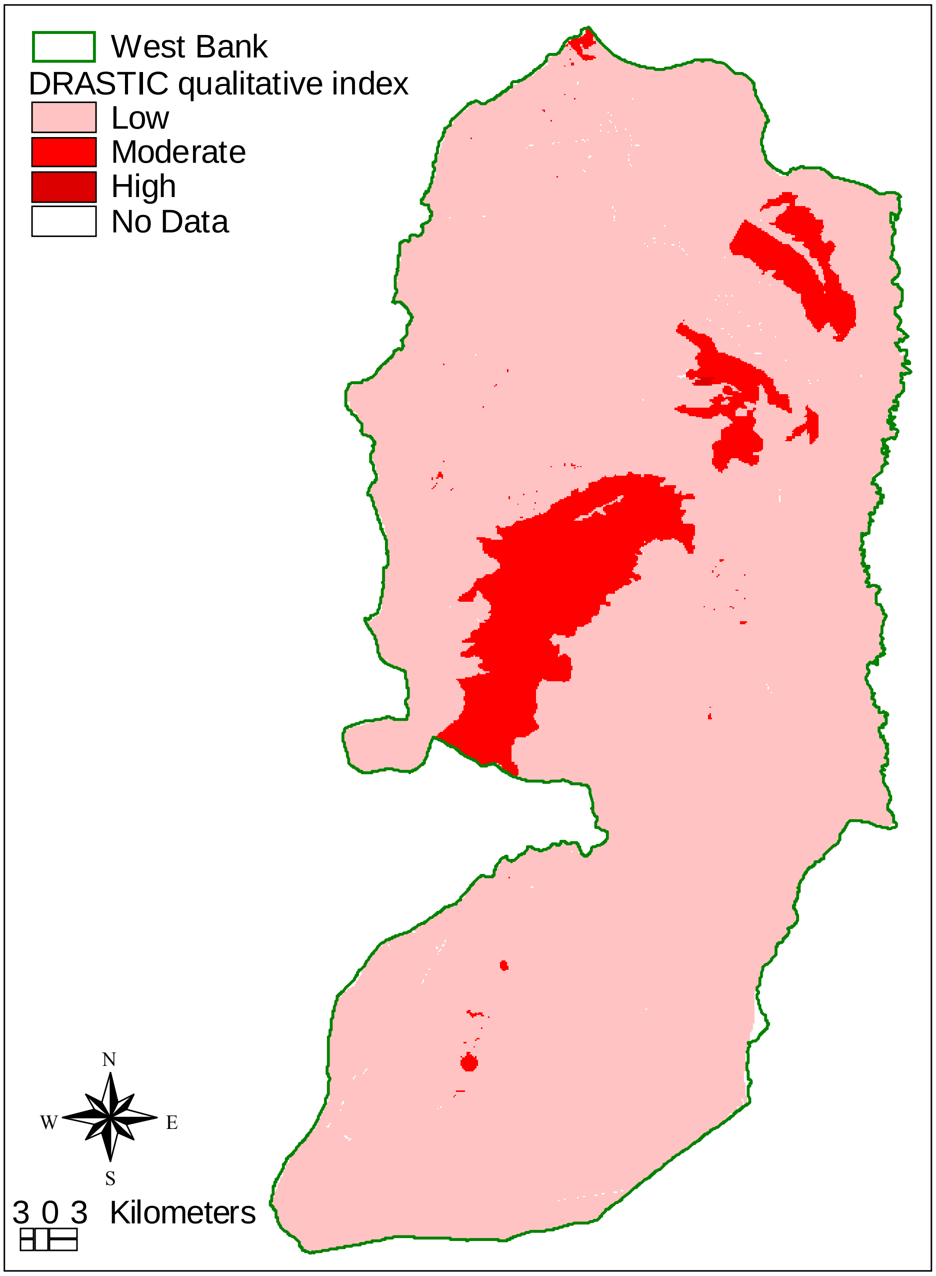


Figure 7.10. The map of the groundwater qualitative vulnerability indices for the West Bank.

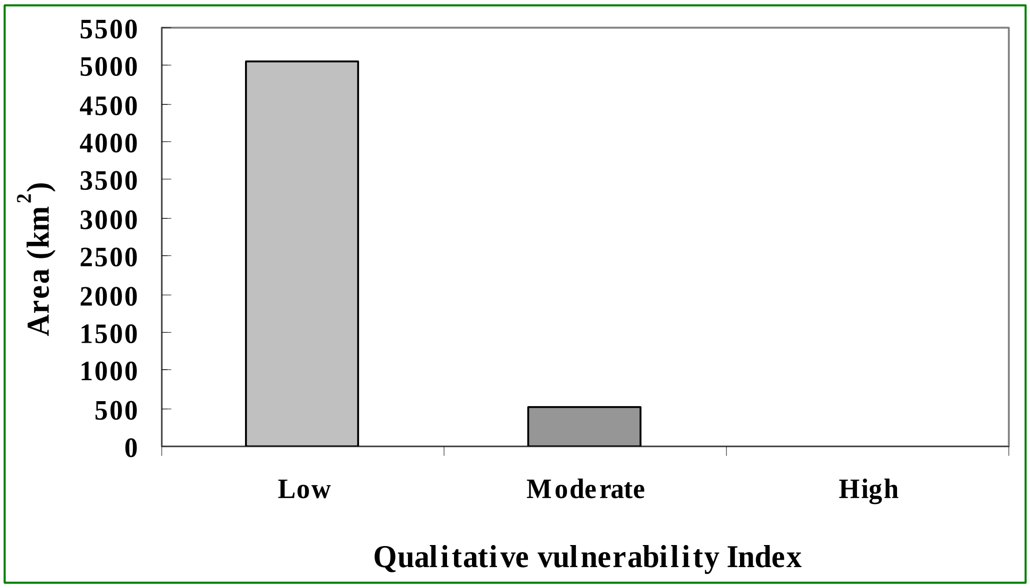


Figure 7.11: The overall area occupied by each qualitative DRASTIC vulnerability index for the West Bank.

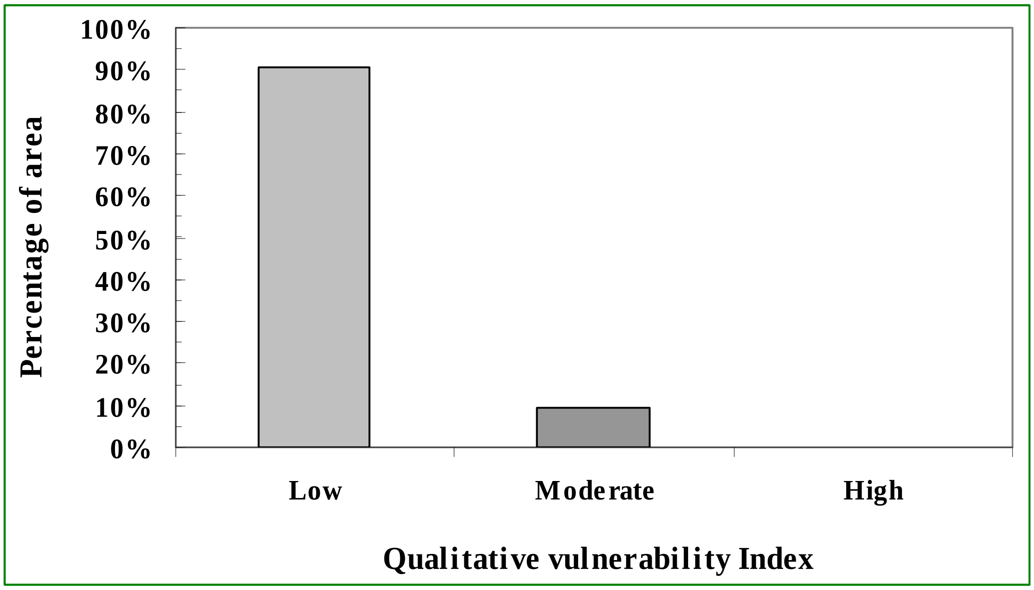


Figure 7.12: The overall percentage of area occupied by each qualitative DRASTIC vulnerability index for the West Bank.

Groundwater vulnerability analysis was also carried out for governerates of the West Bank Figure 7.13. The highest average DFRASTIC indices were observed in Ramallah and Al-Bireh, Salfit, Qalqilya, and Nablus as portrayed in Figure 7.14

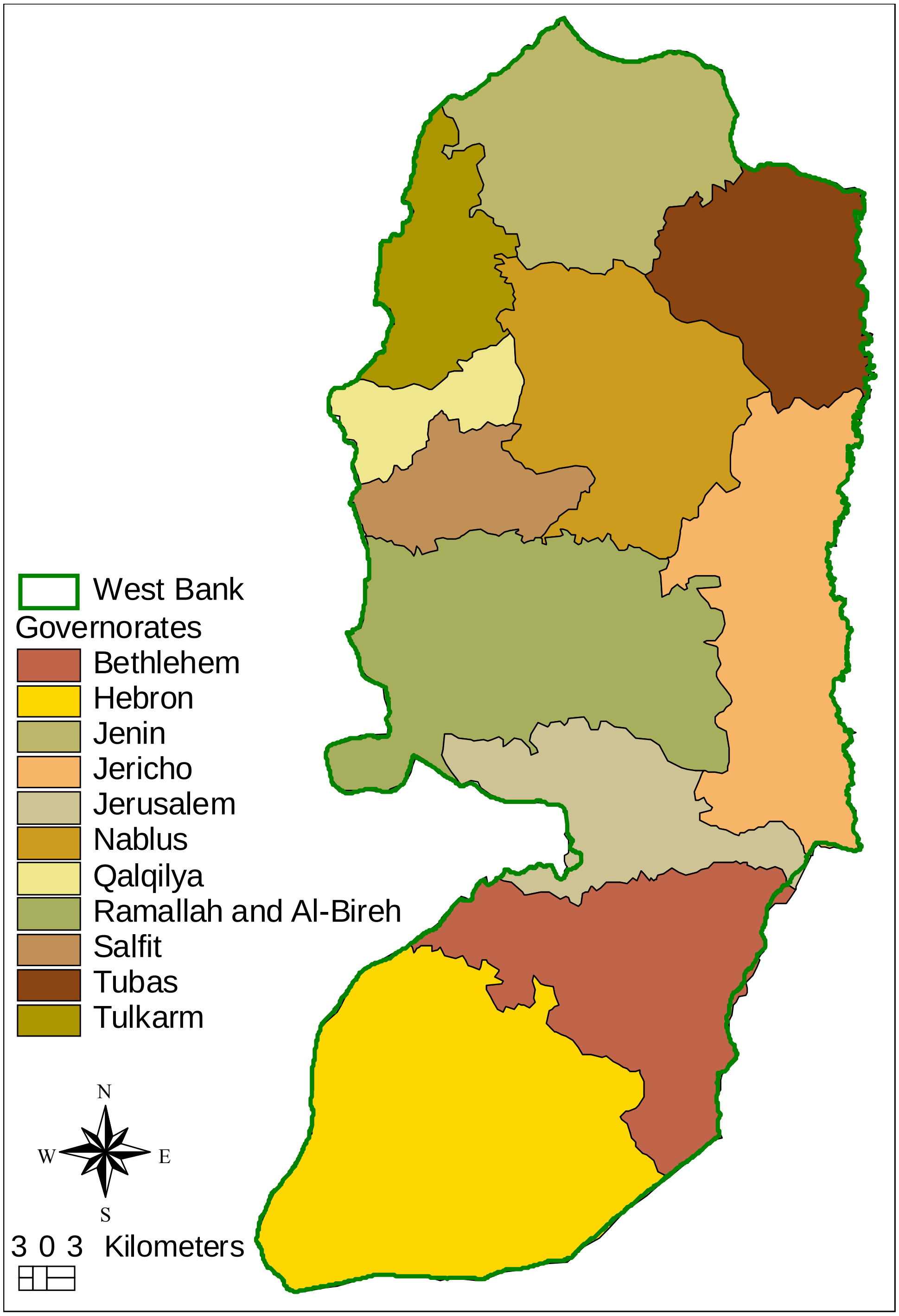


Figure 7.13: West Bank governerates.

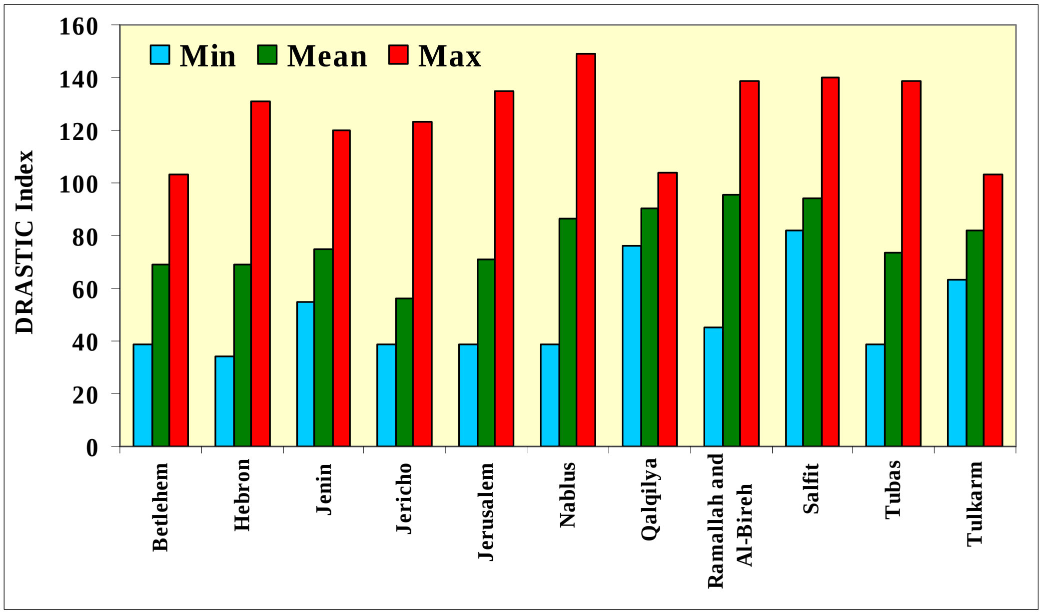


Figure 7.14: Statistics of DRASTIC indices in the West Bank governerates.

Vulnerability analysis based on groundwater basins Figure 7.15 showed that the Western groundwater basin has the highest mean DRASTIC index compared to the other two basins Figure 7.16. This presumably due to the facts that Western basin has the highest recharge and the lowest slope among the West Bank basins.

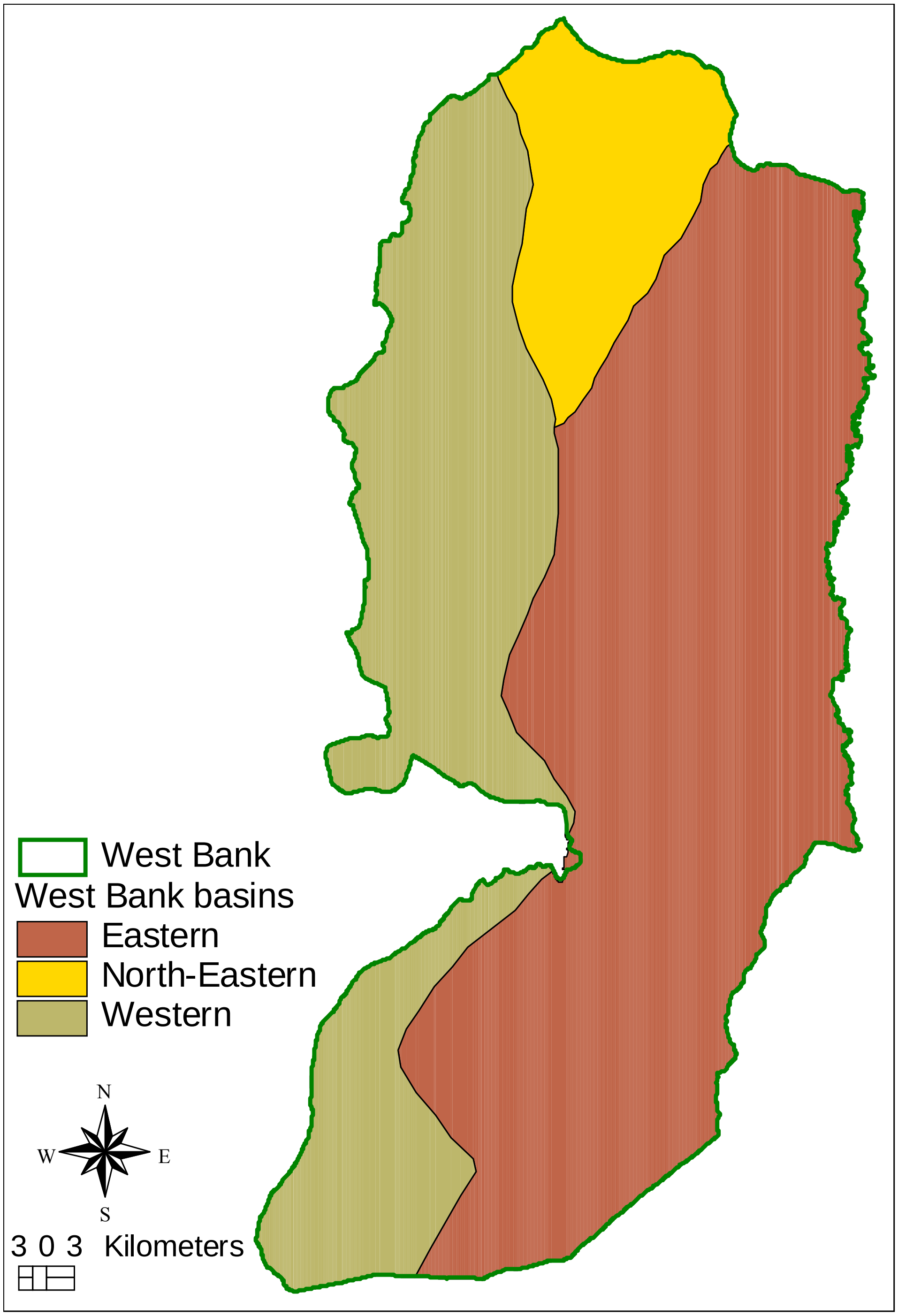


Figure 7.15: Distribution of groundwater basins in the West Bank.

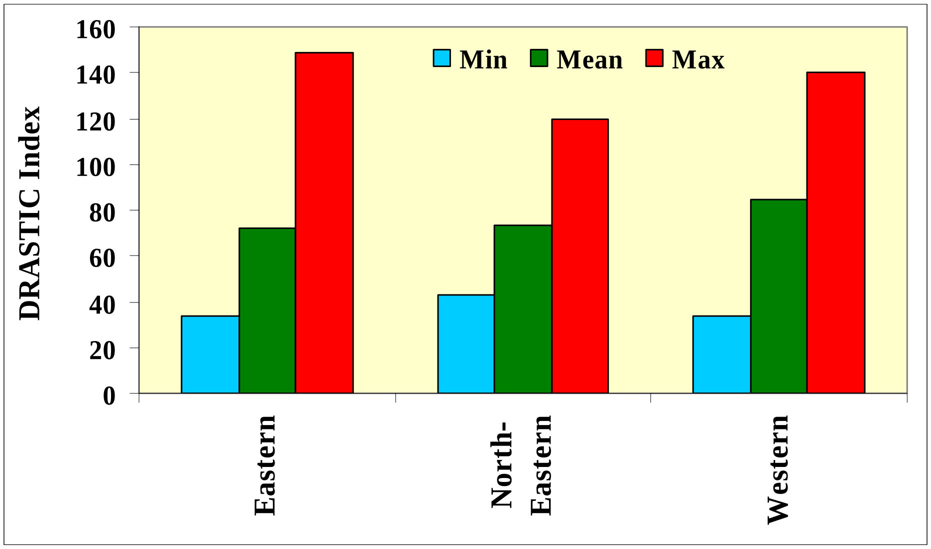


Figure 7.16: Statistics of the DRASTIC indices in the groundwater basins.

7.3 Research impediments

1- Data monopoly : A great deal of time was allocated for data collection, I have been promised to get data but never got it, and data given was not in a processable digitized format

2- The research needs a good knowledge in GIS. A lot of time was allocated to learn GIS

3- The research requires a good understanding and characterization of the geology of the West Bank and limited data on this was available to me

7.4 Research limitations.

As such, there are few limitations regarding the methodology and its application that ought to be considered in the future and these are summarized as in the following:

1- This study considered intrinsic vulnerability. In fact, a more precise specific vulnerability map for certain contaminants should be developed, The very early objective of this work was to modify DRASTIC method to account for the impact of land use related activities on the vulnerability index. I intended to consider the inclusion of the on-ground nitrogen loadings, yet the unavailability of land use map for the West Bank prevented this modification which I deem is of great importance to enhance the methodology.

2- Since the DRASTIC method requires the hydraulic conductivity values, I did use published data from the literature as per each medium though such values of hydraulic conductivity values ought to be based on aquifer tests for the site of concern.

3- For the depth to water table, I did not distinguish between the actual water table and the potentiometric head. This is because I do not have data to characterize the vertical distribution of the geologic formations and thus I was unable to make the distinction between layers under confined conditions from those under unconfined ones.

4- Rainfall data that was used did not cover uniform time periods and thus the average values used in recharge computation may not be relatively representative.

5- Net recharge was computed merely from rainfall. However we know that recharge comes from: Irrigation return flow, water leakage from networks, wastewater leakage from sewerage systems, infiltration from wastewater wadis, and infiltration from cesspits.

6- No calibration was carried out to verify that the vulnerability map is in full compliance with the monitored contamination occurrences. It is common to carry out a calibration exercise such that DRASTIC indices are correlated with sampled groundwater concentrations. That is the weights are tuned to get the maximum correlation between for instance high vulnerability zones and corresponding high contaminant concentration.

7- No Sensitivity analysis of DRASTIC indices after removing the parameters one at a time was carried out. This is important to reliably evaluate the relative importance of these parameters for aquifer vulnerability and thus we can justify the different vulnerability values.

The resulting vulnerability map shows that groundwater in most areas of the West Bank is generally safe. However, this is subject to the following: The ranges used in defining the qualitative indices, the map does not account for the accumulated effects of contaminants, the map did not take into account the land use distribution in the West Bank

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions:

This study demonstrated the combined use of the DRASTIC model and GIS as an effective method for groundwater pollution vulnerability assessment. The GIS technology has provided an efficient environment for analyses and high capabilities of handling spatial data in the study area. As mentioned earlier, it seems that groundwater resources are considerably palatable in the West Bank area of Palestine for the time being. The present study hopefully demonstrates a cost-effective method to develop, improve and verify groundwater vulnerability maps.

8.2 Recommendations:

This study has dealt with intrinsic vulnerability to groundwater contamination. Futuristic specific vulnerability assessments are recommended in order to delineate areas with high potential for specific contamination. The identification of such foci will be critical for the maintenance of groundwater quality through establishing monitoring networks required for surveillance of potential pollution sites. Special attention should be paid to the areas with moderate pollution potential as shown in the qualitative vulnerability map of the West Bank which has been developed in this study. Palestinian decision makers can make use of this map in determining areas where groundwater monitoring is highly advisable. Adoption of a composite DRASTC model to develop a modified DRASTIC groundwater vulnerability map will be mandatory if a specific contamination ensues. Sensitivity analysis of GIS-based DRASTIC model indices after removing hydrogeological parameters one at a time, can reliably evaluate the relative importance of these parameters for aquifer vulnerability. Studies to come must take these sensitivity analyses into account. Palestinian decision makers can use the vulnerability map, developed in this study, as a tool to determine areas where meticulous groundwater monitoring is highly advisable. Remediation of contaminated groundwater is prohibitively expensive and time-consuming. Prevention is always better than cure and is particularly critical in effective groundwater management. For this purpose, composite groundwater vulnerability maps must be produced every now and then on a regular spatial and temporal basis to anticipate any possible impending pollution in good time.

REFERENCES

REFERENCES.

Al-Admat, R.A.N, Foster, I.D.L., and Baban, S.M.J. (2003).Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq basin of Jordan using GIS, Remote sensing and DRASTIC (2003).*Applied Geography, 23*, 303-324.

Aller, R., Bennet, T., Lehr, J.H., and Petty, R.J. (1985). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings, *U.S. EPA, Robert S. Kerr Environmental Research Laboratory, Ada, OK, EPA/600*,2-85, *0108*, 163 pp.

Aller, R., Bennet, T., Lehr, J.H., and Petty, R.J. (1987). DARASTIC: A standardized system for evaluating groundwater pollution using hydrogeologic settings, *EPA-600*/2-87-035.

Almasri, M.N. and Kaluarachchi, J.J. (2004). Assessment and management of long-term nitrate pollution of ground water in agriculture-dominated watersheds. *Journal of Hydrology*, *295*, 225-245.

Almasri, M.N: and Kaluarachchi, J.J. (2004). Implications of on-ground nitrogen loading and soil transformations on groundwater quality management. *Journal of the American Water Resources Association*, *40(1)*,165-186.

Almasri, M.N., Kaluarachchi, J.J., Ghabayen, S., Jarrar, A., Mckee, M., Jayyousi, A., and Aliewi, A. (2004). *Assessment of groundwater vulnerability to nitrate contamination in Gaza strip, Palestine*. Unpublished paper.

Al-Zabet, T. (2002). Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. *Environmental Geology, 43*, 203-208

Babiker, I.B., Mohamed, M.A., Hiyama, T. and Kato,K. (2004). A Kakamigahra Heights, Gifu Prefecture, central Japan. *Science of the Total Environment,* STOTEN-08619; No of pages 14.

Civita, M. (1994). *Aquifer vulnerability maps to pollution*. Pitagora, Bologna.

Collin, M.L. and Melloul, A.J. (2003). Assessing groundwater vulnerability to pollution to promote sustainable urban and rural development. *Journal of Cleaner Production, 11*, 727-736.

Doerfliger, N. and Zwahlen, F. (1997). EPIK: a new method outlining of protection areas in karstic environment. In Gunay,G.,Johnson,AI. (Eds), *Antalya international symposium and field seminar on karst waters and environmental impacts* (pp. 117-123).

Follet, R.F., Keeny, D.R., and Cruse, R.M. (1991). *Managing nitrogen for groundwater quality and farm profitability*. Technical report, SSSA.

Gogu, R.C. and Dassargues, A. (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods.*Environmental Geology, 39(6)*, 549-559.

Goodchild, R.G. (1998). EU policies for the reduction of nitrogen in water: the example of the nitrate directive. *Environmental Pollution, 102*, 737-740.

Hasler, B. (1998). Analysis of environmental policy measures aimed at reducing nitrogen leaching at farm level. *Environmental Pollution, 102*, 749-754.

Joosten, L.T., Buijze, S.T., and Jansen, D.M. (1998). Nitrate in sources of drinking water? Dutch drinking water companies aim at prevention. *Environmental Pollution, 102*, 487-492.

Kim, K., Chae, G.T., Yun, S.T., Kim, K.H., Kim, S.O., Choi, B.Y., Kim, H.S., and Rhee, C.W. (2004). Hydrogeochemistry of alluvial groundwater in an agricultural area: an implication for groundwater contamination susceptibility. *Chemosphere, 55*, 369-378.

Lake, I.R. et al. (2003). Evaluating factors influencing groundwater vulnerability to nitrate pollution: developing the potential of GIS. *Journal of Environmental Management, 68*, 315-328.

Marei A., Haddad M. (1998). *Nitrate Concentration in Groundwater in Northern West Bank.* Al-Quads University.

Mclay, C.D., Dragten, R.,Sparling, G., and Selvarajah, N. (2001). Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. *Environmental Pollution, 115*, 191-204.

Meinardi, C.R., Beusen, A.H., Bollen, M.J,. Klepper, O., and Willems, W.J. (1995). Vulnerability to diffuse polution and average nitrate contamination of European soils and groundwater. *Wat. Sci. Tech., 8*,159-165.

Melloul, A.J. and Collin, M. (1998). A proposed index for aquifer water quality assessment: the case of Israel's Sharon region. *Journal of Environmental Management, 54*,131-143.

National Academy of Sciences. (2003). *Ground water vulnerability assessment*. Executive summary. Washington DC: Author.

Navulur, K.C. (1996). *Groundwater vulnerability evaluation to nitrate pollution on a regional scale using GIS*. Unpublished Doctoral dissertation, Purdue University, Indiana, US.

Rapaport, S.I.. (1987). *Introduction to Hematology* [2nd ed.]. Philadelphia: J.B. Lippincott. Company.

Richert, S.E., Young, S.E., and Johnson, C. (1992). SEEPAGE: A GIS model for groundwater pollution potential, ASAE 1992. *International Winter Meeting. Number 92*, 2592.

Rigina, O. and Baklanov, A. (2002). Regional radiation risk and vulnerability assessment by integration of mathematical modeling and GIS analysis. *Environment International, 27*, 527-540.

Robert S. Kerr Environmental Laboratory (1987). *DRASTIC User Manual*. US. Environmental Protection Agency, ADA OK.

Rupert, M.G. (1989). *Improvements to the DRASTIC groundwater vulnerability mapping method*. US Geological Survey USGS fact Sheet FS-066-99.

Rupert, M.G. (1999). Improvements to the DRASTIC groundwater vulnerability mapping method. *USGS science for changing world, 66*,1-6.

Rupert, M.G. (2001). Calibration of the DRASTIC groundwater vulnerability mapping method. *Ground Water, 39(4)*, 625-630.

Schwartz, J.M. (1983). *The Metabolic Basis of Inherited Disease.* (5th ed.). New York: Mc Graw-Hill.

Secunda, S., Collin, M.L., and Melloul, A.J. (1998). Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Isael's Sharon region. *Journal of Environmental Management, 54*, 39-57.

Shadid, S. (2000). A study of groundwater pollution vulnerability using DRASTIC/GIS, West Bengal, India. *Journal of Environmental Hydrology, 8*, 1-9.

Shukla, B.D., Misra, A.K., and Gupta, R.K. (1998). Application of nitrogen in production and post-production systems of agriculture and its effect on environment in India. *Environmental Pollution, 102*, 115-122.

Thapinta, A. and Hudak P.F. (2003). Use of geographic information systems for assessing groundwater pollution potential by pesticides in Central Thailand. *Environment International, 29*, 87-93.

Thirumalaivasan, D. and Karmegam, M. (2001). *Aquifer vulnerability assessment using analytic hierarchy process and GIS for upper Palar watershed*. Paper presented at the 22nd Asian Conference on Remote Sensing, Singapore.

Thirumalaivasan, D., Karmeagam, M., and Venugopal, K. (2003). AHP-DRASTIC: software for specific aquifer vulnerability assessment using DRASTIC model and GIS. *Environmental Modeling & Software, 18*, 645-656.

Tood, D.K. (1980). *Groundwater Hydrology.* (2nd ed). New York: John Wily and Sons.

United Nations Environment Programme (UNEP). (2003). *Desk Study on the Environment in the occupied Palestinian Territories.* Switzer Land: UNEP.

USGS. (1999). *NATIONAL WATER-QUALITY ASSESSMENT PROGRAM-NAWQA.* Improvements to the DRASTIC ground-water vulnerability mapping method. USGS Fact Sheet FS-066-99.

Withowski, A.J., Rubin, K., kowalezyk, k., Rozkowski, A., and Wrobel, J. (2003). Groundwater vulnerability map of the Chraznow karst-fissured Triassic aquifer (Poland). *Environmental Geology, 44*,59-67.

APPENDICES

Appendix A: Diverse definitions of groundwater vulnerability

Table A1: The many ways of defining groundwater vulnerability.

Name	Definition	Reference
Groundwater vulnerability to contamination	The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer	National Academy of Sciences, 1993
Aquifer pollution vulnerability	The intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load	Foster, 1987
Groundwater pollution risk	The interaction between the natural vulnerability of the aquifer, and the pollution loading that is, or will be, applied on the subsurface environment as a result of human activity	Foster, 1987
Hydrogeologic vulnerability	A function of geologic factors such as soil texture and depth to groundwater	US General Accounting Office, 1991
Total vulnerability	A function of these hydrogeologic factors, as well as the pesticide use factors that influence the site's susceptibility	Pettyjohn, 1991
Total risk	This last approach is even broader, for it incorporates the size of the population at risk from potential pesticide contamination that is, the number of people who obtain their drinking water from groundwater in the area	Pettyjohn, 1991
Aquifer vulnerability and Sensitivity	The geology of the physical system determines vulnerability Aquifer sensitivity is related to the potential for contamination. That is, aquifers that have a high degree of vulnerability and are in vulnerability and in areas of high population density are considered to be the most sensitive The relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials of interest, and overlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or contaminant characteristics	US EPA 1993
Groundwater vulnerability	The relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics and hydrogeologic sensitivity conditions	US EPA 1993

Appendix B: Computation of DRASTIC index-hypothetical example.

The following hypothetical example illustrates the computation of the DRASTIC index (DI) and the corresponding development of the vulnerability map through the utilization of MS Excel. DI is determined according to equation (1). In order to facilitate the computation of DI, the study area is divided into a grid of uniform squared cells, where each cell carries a parameter value. Therefore, seven layers of such grids (Figures B.3 through B.9) will be overlaid one on top of the other.

Since depth to water data are not available, we subtracted the value of the water table elevation in each cell from the value shown in the corresponding cell in the ground surface elevation grid. Consequently, a depth to water grid was obtained, (see Figures B.1 to B.3).

100	98	96	94	90
95	92	89	83	75
89	80	78	78	73
85	79	82	73	69

Figure B.1: Ground surface elevation grid (feet)

85	95	89	91	78
92	65	86	81	72
51	76	63	68	70
49	75	61	57	62

Figure B.2: water table elevation grid (feet)

15	3	7	3	12
3	27	3	2	3
38	4	15	10	3
36	14	21	16	7

Figure B.3: Depth to water grid (feet)

The first layer, depth to water, was thus prepared.

3	6	3	1	0
8	3	5	6	10
3	1	6	9	14
6	5	1	0	11

Figure B.4: Ground water recharge grid (inches)

10	8	6	1	10
6	3	2	5	9
10	9	8	2	3
7	8	10	1	1

Figure B.5: Aquifer type grid

11	10	11	3	8
4	10	9	6	2
3	5	8	11	7
3	2	7	1	2

Figure B.6: Soil type grid

1	10	8	6	5
2	9	3	4	2
10	9	8	2	1
4	7	6	3	10

Figure B.7: Vadose zone type grid

2.7	3.4	4.4	6.6	4.6
5.4	8.7	9.2	9.6	7.8
5.1	6.6	5.2	6.2	3.7
2.1	2.5	2.4	4.3	3.0

Figure B.8: Topography grid (percentage)

50	150	450	950	1100
800	110	160	90	80
600	310	900	200	2500
750	500	50	600	480

Figure B.9: Hydraulic conductivity grid (gpd/ft^2)

All the values in the cells of each grid were given rates corresponding to the range in which each value lies. Such rating is derived from the tables which have been demonstrated beforehand. Thus, processing starts by preparing seven rate grids derived from the previous grids as depicted in Figures B.10 through B.16.

7	10	9	10	9
10	7	10	10	10
5	10	7	9	9
5	9	7	7	9

Figure B.10: Depth rate grid (D_r)

3	6	3	1	1
8	3	6	6	9
3	1	6	8	9
6	6	1	1	9

Figure B.11: Recharge rate grid (R_r)

10	6	6	2	10
6	4	3	6	10
10	10	6	3	4
8	8	10	2	2

Figure B.12: Aquifer rate grid (A_r)

11	10	11	3	8
4	10	9	6	2
3	5	8	11	7
3	2	7	1	2

Figure B.13: Soil rate grid (S_r)

1	10	8	6	6
2	9	3	4	2
10	9	8	2	1
4	7	6	3	10

Figure B.14: Vadose zone rate grid (I_r)

9	9	9	5	9
9	5	5	5	5
9	5	9	5	9
9	9	9	9	9

Figure B.15: Topography rate grid (T_r)

1	2	4	6	8
6	2	2	1	1
4	4	6	4	10
6	4	1	4	4

Figure B.16: Hydraulic rate grid (C_r)

The values in the cells of each rate grid are multiplied by the weight of each parameter; for instance 5 for depth to water, 4 for recharge, 3 for aquifer media type, 2 for soil media type, 1 for topography, 5 for the impact of vadose zone and 3 for hydraulic conductivity. Thus seven grids representing the multiplication of rate by weight were obtained as in Figures B.17 through B.23.

35	50	45	50	45
50	35	50	50	50
25	50	35	45	45
25	45	35	35	45

Figure B.17: $D_w \times D_r$ grid

12	24	12	4	4
32	12	24	24	36
12	4	24	32	36
24	24	4	4	36

Figure B.18: $R_w \times R_r$ grid

30	18	18	6	30
18	12	9	18	30
30	30	18	9	12
24	24	30	6	6

Figure B.19: $A_w \times A_r$ grid

22	20	22	6	16
8	20	18	12	4
6	10	16	22	14
6	4	14	2	4

Figure B.20: $S_w \times S_r$ grid

5	50	40	30	25
10	45	15	20	10
50	45	40	10	5
20	35	30	15	50

Figure B.21: $I_w \times I_r$ grid

9	9	9	5	9
9	5	5	5	5
9	5	9	5	9
9	9	9	9	9

Figure B.22: $T_w \times T_r$ grid

3	6	12	18	24
18	6	6	3	3
12	12	18	12	30
18	12	3	12	12

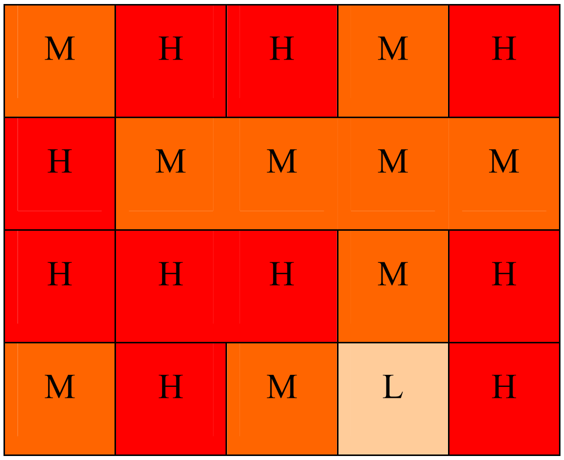
Figure B.23: $C_w \times C_r$ grid

The final DRASTIC Index (DI) grid was computed by summing up the seven (weight × rate) grids as shown in Figure B.24.

116	177	158	119	153
145	135	127	132	138
144	156	160	135	151
126	153	125	83	162

Figure B.24: DRASTIC Index grid or the vulnerability map

The value in each cell represents the DI for that particular location. A qualitative vulnerability map was obtained as shown in Figure B.25 by converting DI values into different categories each of which falling into a category as explained before. These categories are: low, moderate, high and very high having the ranges 1-100, 101-140, 141-200 and > 200, respectively.



M	H	H	M	H
H	M	M	M	M
H	H	H	M	H
M	H	M	L	H

Figure B.25: The vulnerability map

جامعة النجاح الوطنية
كلية الدراسات العليا

تقييم قابلية المياه الجوفية للتلوث في الضفة الغربية، فلسطين

اعداد
نعمت صادق عبد الرحمن قمحية

باشراف
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قدمت هذه الأطروحة استكمالا لمتطلبات درجة الماجستير في العلوم البيئية بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

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تقييم قابلية المياه الجوفية للتلوث
في الضفة الغربية، فلسطين

اعداد

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الملخص

تستهدف هذه الدراسة الرائدة تقييم خطر تلوث المياه الجوفية في منطقة الضفة الغربية من فلسطين. ولتحقيق هذا الغرض فقد تم تبني اللأستعمال المشترك لنموذج DRASTIC ونظام المعلومات الجغرافية (GIS).

تم انتاج سبع خرائط للمعايير الجيولوجية المائية السبعة التالية: عمق المياة الجوفية عن سطح الأرض واعادة الامتلاء وأوساط الخوض المائي وأوساط التربة ودرجة الميلان وأثر المنطقة فوق المياة الجوفية (المنطقة غير المشبعة بالماء) وحركة المياه داخل الحوض المائي (التوصيل المائي)

جمعت تلك الخرائط السبع السابقة باستخدام تقنية ال GIS في خارطة واحدة توضح قابلية تلوث المياه الجوفية في منطقة الضفة الغربية وكشفت هذه الخارطة عن أن احتمال التلوث ضئيل في 90% من منطقة الدراسة وأن 10% المتبقية احتمال التلوث فيها متوسط.

تشير هذه النتائج الى أن مصادر مياهنا الجوفية امنة تقريبا.

أثبتت الدراسة أن تقنية GIS تشكل بيئة فعالة لعمليات التحليل والمعالجة الدقيقة للبيانات المكانية تضمنت الأطروحة ايضا مراجعة شاملة لما كتب حول قابلية المياه الجوفية للتلوث.