An-Najah National University
Faculty of Graduate Studies

Assessing and Mapping of Groundwater Vulnerability to Contamination Using the Protective Cover and Infiltration Conditions (PI) Method for the West Bank / Palestine

By
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This Thesis was defended successfully on 11/11/2010 and approved by

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Dedication

I humbly dedicate this thesis to my family, namely my parents, who taught me to keep my head up and my eyes focused on the road that links me to my goal, my brothers and sisters, for filling my life with smiles and my dear husband for encouraging me to spread my wings and fly, and for his invaluable support.

Thank you all for your unconditional love and guidance. Thank you for all that you did and all that you are doing.

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First, I thank Allah the Almighty who gave me health, inspirations and co-operative people to enable me achieve this goal.

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Special thanks go to my teachers everywhere, especially in the Civil Engineering Department at An-Najah National University and the staff of the Water and Environmental Studies Institute (WESI) for their support and encouragements.

Finally, I would like to express my respect to my family and friends.

الإقرار

أنا الموقعة أدناه مقدمة الرسالة التي تحمل العنوان:

Assessing and Mapping of Groundwater Vulnerability to Contamination Using the Protective Cover and Infiltration Conditions (PI) Method for the West Bank / Palestine

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Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

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Assessing and Mapping of Groundwater Vulnerability to Contamination Using the Protective Cover and Infiltration Conditions (PI) Method for the West Bank / Palestine

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Abstract

Groundwater resources, especially from karst aquifers, provide vital freshwater supplies for Palestinians. Both, quantity and quality stresses on groundwater have increased in the past decades to a level that poses a contamination threat to drinking water sources due to human exploitation. Optimal protection and management of groundwater resources in karst aquifers is a priority and a goal in the developed and developing countries. Protection of groundwater starts with the evaluation of the sensitivity of its environment. This thesis attempts to produce a groundwater vulnerability map for the West Bank, which is intended to highlight the areas of greatest potential for groundwater contamination on the basis of hydro-geological conditions. The research uses a GIS-based approach called the PI method, which takes into consideration the nature of karst aquifers. Inherent geological, hydrological, hydrogeological, climatological and vegetation data, in terms of thematic layers, were collected and used in the creation of the groundwater vulnerability map of the West Bank. The results obtained from this study indicate that about 47% of the West Bank is under extreme to high groundwater vulnerability, 32% is under moderate vulnerability and 21% is under low to very low vulnerability.

CHAPTER ONE

INTRODUCTION

1.1 General Background

Groundwater resources, especially from karst aquifers, provide very important freshwater supplies for both humans and ecosystems (Dimitriou and Zacharias, 2006).

Both, quantity and quality pressures on groundwater have increased in the past decades to a level that poses a contamination threat to drinking water sources and sensitive ecosystems due to human exploitation. Growing water demand, increasing use of agricultural activities, atmospheric deposition and many point sources of pollution threat the quality of groundwater (Lindström, 2005; Vías et al., 2005; Almasri, 2007; Liggett and Talwar, 2009; Kattaa et al., 2010).

Optimal protection and management of groundwater resources in karst aquifers is a priority and a goal in the developed and developing countries (Cucchi et al., 2007). Protection of groundwater starts with the evaluation of the sensitivity of its environment. Different techniques and methodologies have been developed to assess the environmental impacts associated with groundwater pollution, among which, the concept of aquifer vulnerability (Margane, 2003; Ritta Lindström, 2005; Frind et al., 2006; Kouli et al., 2007; Almasri, 2007; HWE, 2007).

The term “Aquifer Vulnerability” came to light in 1968 to expresses the degree of protection provided by the natural environment against the pollutants leakage into groundwater (Margat, 1968). Since that time, many definitions for vulnerability have been suggested (Zwahlen, 2004).

According to Vrba and Zaporozec (1994), for instance, the term represents "*the intrinsic properties of aquifer systems as a function of their sensitivity to human and natural activities*". It can be also defined as "*the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system*" (Kouli et al., 2007). Groundwater vulnerability includes two particular notions: intrinsic vulnerability and specific vulnerability (Kouli et al., 2007). The former takes into account the hydrogeological characteristics of aquifers, while the latter describes the potential impacts of land use and contaminants, as well as the hydrogeological factors (Frind et al., 2006).

In general, karst aquifers, which are among the most important drinking water resources in the West Bank, are considered to be significantly vulnerable to pollution, due to their unique structure which is highly heterogeneous (HWE, 2007). The structure is considered as a network of high permeable channels surrounded by large volumes of low permeable rocks. As water recharge occurs by both concentrated and dispersed entry, a fair amount will directly enters the network of channels, as a result, attenuation of pollutants does not occur effectively as in the case of porous aquifers (Doerfliger et al., 1999).

The implementation of the vulnerability concept is based on classifying a geographical area according to its susceptibility to groundwater contamination (Knox et al., 1993).

The origin-pathway-target model is the base of vulnerability assessment. The origin describes the location of pollutant release. The pathway represents the passage of the pollutant from the origin to the target, i.e. the water that is to be protected (Kouli et al., 2007).

Despite the existence of different approaches, there is no universal methodology concerning vulnerability assessment for groundwater. Generally, the available methods are grouped into three main categories: (1) index and overlay method, (2) process-based simulation models and (3) statistical models (Lindström, 2005).

Although the overlay and index method is empirical, it is considered the only meaningful technique in delineating the zones that are most vulnerable to contamination in karstic aquifers (Gogu and Dassargues, 2000).

Groundwater vulnerability mapping is a new scientific approach that simplifies planning and decision making processes for the protection of this valuable resource (Dimitriou and Zacharias, 2006). It is based on the idea that some land areas are more vulnerable to groundwater pollution than others (Piscopo, 2001). Maps can be presented with the aid of GIS, which has the advantages of both spatial data gathering and meaningful processing (Burrough and McDonnell, 1998).

The PI method, which is a GIS-based approach, is generally used for mapping the intrinsic vulnerability of groundwater resources (Goldscheider et al., 2000). It can be applied to all aquifer types, and gives special methodological tools for karstic ones. The vulnerability in the PI method is evaluated on the basis of two factors: Protective cover (P) and Infiltration conditions (I) (Goldscheider et al., 2000). The vulnerability map generally shows the spatial distribution of the protection factor ($\prod$), obtained by multiplying the two factors. The areas on each of the three maps, i.e. P map, I map and $\prod$ map are assigned to one of five classes, symbolized by five colors: from red for high vulnerability to blue for low vulnerability. Thus, one legend can be used for the three maps (HWE, 2007). This in essence improves the readability of the map and enhances a quick decision.

1.1 Research Objective

The main objective of this research is to conduct an intrinsic vulnerability assessment to contamination for the West Bank's aquifers using the PI method.

1.2 Research Motivations

The following are the research motivations:

1. Groundwater is the main water source in the West Bank and thus understanding the issues related to its quality is needful.
2. Identifying areas with high vulnerability to contamination is essential to prioritize areas for land use management.

1.4 Research Question

The following is the research question:

1. What are the locations and the portions of the aquifers in the West Bank that are under conditions of high vulnerability to contamination?

1.5 Methodology

The methodology of the research is divided into three main phases: Inception Analysis, Data Analysis and Decision Analysis. These phases are summarized in figure (1).

The first phase consists of the data collection mainly from the Water and Environmental Studies Institute (WESI) and the House of Water and Environment (HWE), carrying out literature review, and understanding the concept of the groundwater vulnerability assessment and mapping.

The second phase includes data processing and the development of a calculation method for the vulnerability assessment with the aid of MS Excel and GIS. The whole area of the West Bank is converted to a grid of cells which have the same dimensions. Each cell will carry a specific weighting and rating value depending on the data of each parameter. The output of this coding system will take a grid shape of the vulnerability map in the ASCII form. This step also includes the GIS visualization of the vulnerability map.

The third phase entails analysis of the vulnerability map, which takes the form of determining the percentages of the West Bank areas that are under low, moderate and high vulnerability classes to groundwater contamination, checking for the impacts of different land use activities on the groundwater vulnerability and conducting a comparison between these results and the results obtained from another research for the same area using a different assessment method. The decision analysis stage also covers the conclusions and recommendations.

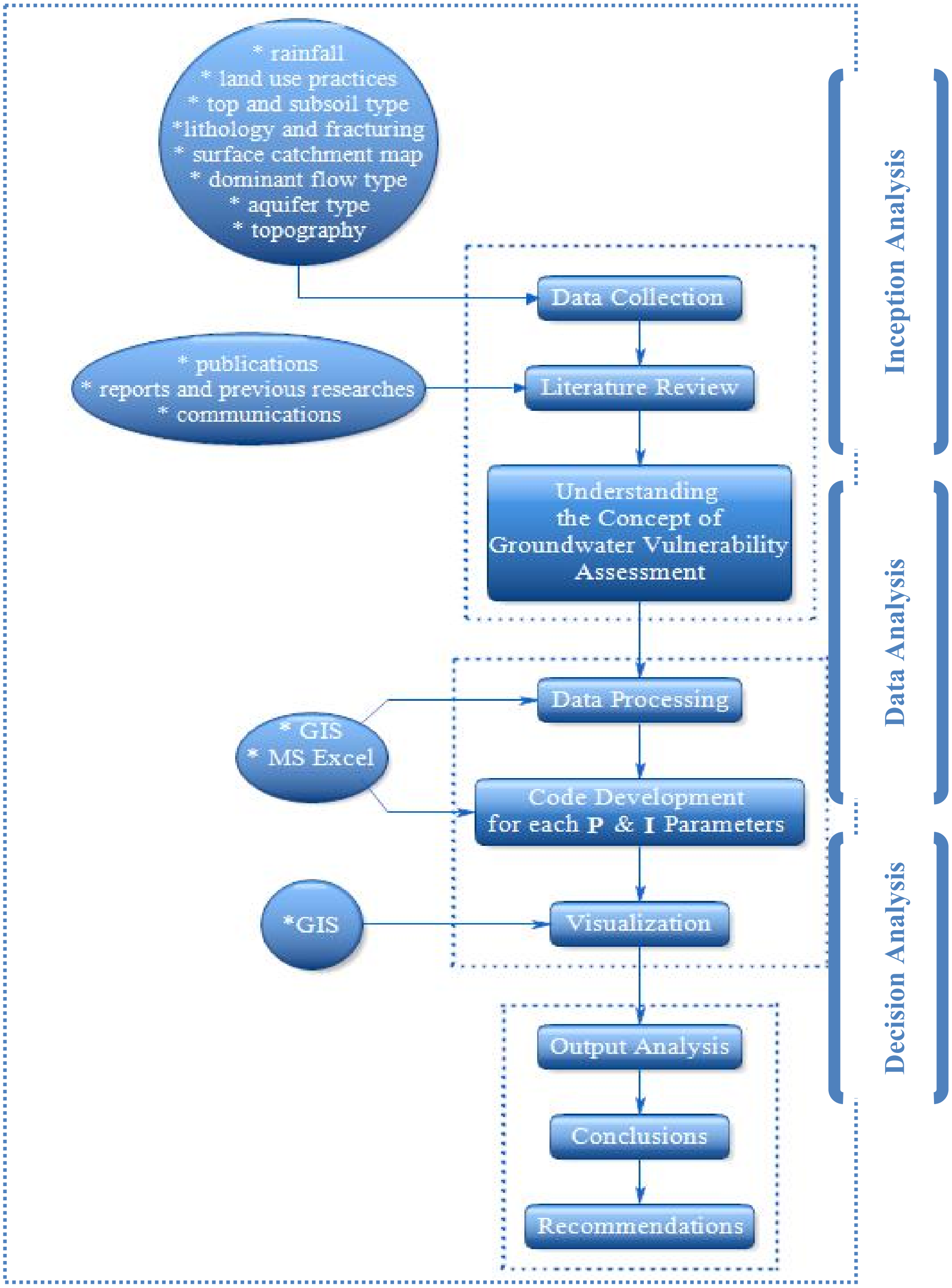


Figure (1): A flowchart that depicts the overall methodology for the research.

1.6 Thesis Outline

This thesis consists of six chapters. Chapter 2 covers the literature review. Chapter 3 consists of brief details about the general and physical characteristics of the West Bank. A detailed description of the PI method is presented in Chapter 4. Chapter 5 illustrates the results, the corresponding maps of the vulnerability of the West Bank's aquifers and the analysis of the results. Finally, conclusions and recommendations are provided in Chapter 6.

CHAPTER TWO

LITERATURE REVIEW

2.1The Concept of “Groundwater Vulnerability”

In Hydrogeology, the term “vulnerability” was first introduced in 1968 by the French hydrogeologist J. Margat; and since then the concept was adopted all over the world (Adams and Foster, 1992).

Scientists have proposed a number of definitions for groundwater vulnerability, many are quite similar, however there is no common definition that has been accepted yet (Samey and Gang, 2008).

Groundwater vulnerability was defined as “*the sensitivity to a contamination generated by human activity applied on the subsurface environment.*” (Daly and Warner, 1998).

“Aquifer Pollution Vulnerability” was defined as “*the intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load*” (Foster and Hirata, 1988).

According to The US National Research Council (1993), the groundwater vulnerability is “*the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer*”.

US EPA distinguishes between “Aquifer Sensitivity” and “Groundwater Vulnerability”. The former is defined as “*the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest*”. The sensitivity is a function of the characteristics of the aquifer and the overlying layers. On the other hand, “Groundwater Vulnerability” is “*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*” (Margane, 2003).

The groundwater vulnerability term integrates both the concepts of intrinsic and specific aquifer’s vulnerability (Dimitriou and Zacharias, 2006). “Intrinsic Vulnerability” is used to represent the inherent geological, hydrological and hydrogeological characteristics which reflect the sensitivity of groundwater to pollution (Zwahlen, 2003). David Drew et al (2002) widened this term to include climatological and vegetation characteristics. It is independent of the nature of human activities and invariant in time (Gogu and Dassargues, 2000). On contrast, “Specific Vulnerability” is the term that takes into account the fluxes, concentrations and contaminant’s characteristics and their relationship with the various components of the intrinsic vulnerability (Zwahlen, 2003).

2.2Groundwater Vulnerability Assessment

Groundwater vulnerability assessment is used to estimate the probability of groundwater pollution at different scales and on different administrative levels (Neukum and Hötzl, 2007).

The adoption of such assessment is recommended as an initial step in groundwater protection strategy (US EPA, 1993). It is used to direct regulatory, inspection, educational and policy development efforts to those areas of greatest protection need. Additionally, it facilitates the distinction between areas where contaminating activities pose insignificant threats to groundwater, and areas that need protection against these activities (Lindström, 2005).

The "Committee on Techniques for Assessing Groundwater Vulnerability" of the US National Research Council outlined three "groundwater vulnerability laws" that should be taken into account in every assessment process. First law: "*all groundwater is vulnerable*", second law: "*uncertainty is inherent in all vulnerability assessments*" and third low: "*there is risk that the obvious may be obscured and the subtle indistinguishable*" (US NRC, 1993).

Depending on their hydrogeological characteristics and attenuation capacities, aquifers provide different degrees of natural protection against anthropogenic pollution. Therefore, some land areas are more vulnerable to groundwater contamination than others (Vrba and Zaporozec, 1994).

The vulnerability of an area can be evaluated either as an effect of the vertical transportation of pollutants in the unsaturated zone, or may also include the horizontal transportation in the saturated zone (Johansson et al., 1993).

The impacts of the factors controlling the groundwater vulnerability i.e. the potential pollution, the mode of transportation and the contaminated resource are pointed out clearly by the origin-pathway-target conceptual model which is considered as the foundation of the assessment process. See figure (2) (Vlaicu and Munteanu, 2008).

When considering the resource protection, the groundwater table is set to be the target and the pathway will take the form of vertical transport from the ground surface to the groundwater table. For the source protection, the water in the spring or well is the target while the pathway additionally **includes the horizontal flow path in the aquifer (Zwahlen, 2003).**

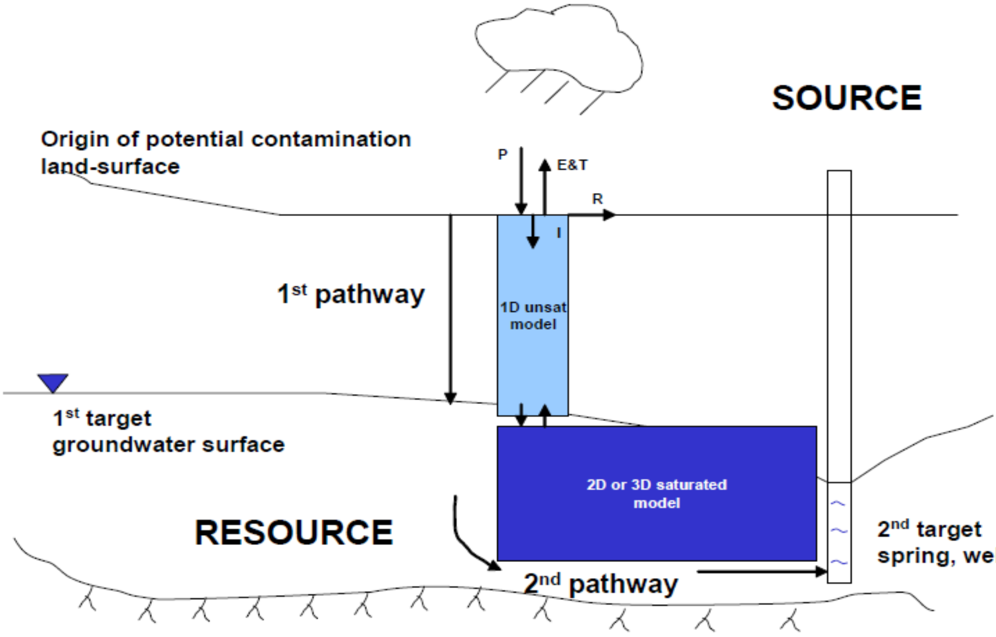


Figure (2): The origin-pathway-target conceptual model, showing the main conceptual processes affecting transportation of dissolved contaminants from the land surface to the spring or pumping well (Lindström, 2005).

2.3 Approaches to Vulnerability Assessment

Despite the development of different approaches since 1970s (Malik and Vojtkova, 2009), there is no universal methodology concerning vulnerability assessment for groundwater. Generally, the available methods are grouped into three main categories: (1) index and overlay method, (2) process-based simulation models and (3) statistical models (Lindström, 2005). Each method has its benefits and limitations that affect its suitability for proper applications (Samey and Gang, 2008).

1. ***Overlay and Index Methods*** The existence of a number of key arameters that play a significant role in controlling the vulnerability of groundwater is the basic assumption for these methods (Lindström, 2005). Overlay and index methods need limited basic data and are typically used in regional studies (Lindström and Scharp, 1995). The evaluated vulnerability is qualitative and relative. The simplest overlay systems use equal weights for all the parameters. More sophisticated systems assign different numerical weights and scores for these parameters based on their contribution to vulnerability (Samey and Gang, 2008). These methods integrate a large amount of spatial information into maps of vulnerability classes. An example of such methods is represented in figure (3), which shows that each physical parameter is mapped spatially in a geographic information system with existing data sets or field data. Each map is then rated according to its effect on vulnerability and the subsequent parameter maps are all combined into a final map. In this example the scores are grouped into five vulnerability categories ranging from high to low. The number of categories used to display the result can vary from one method to

2. **another.**

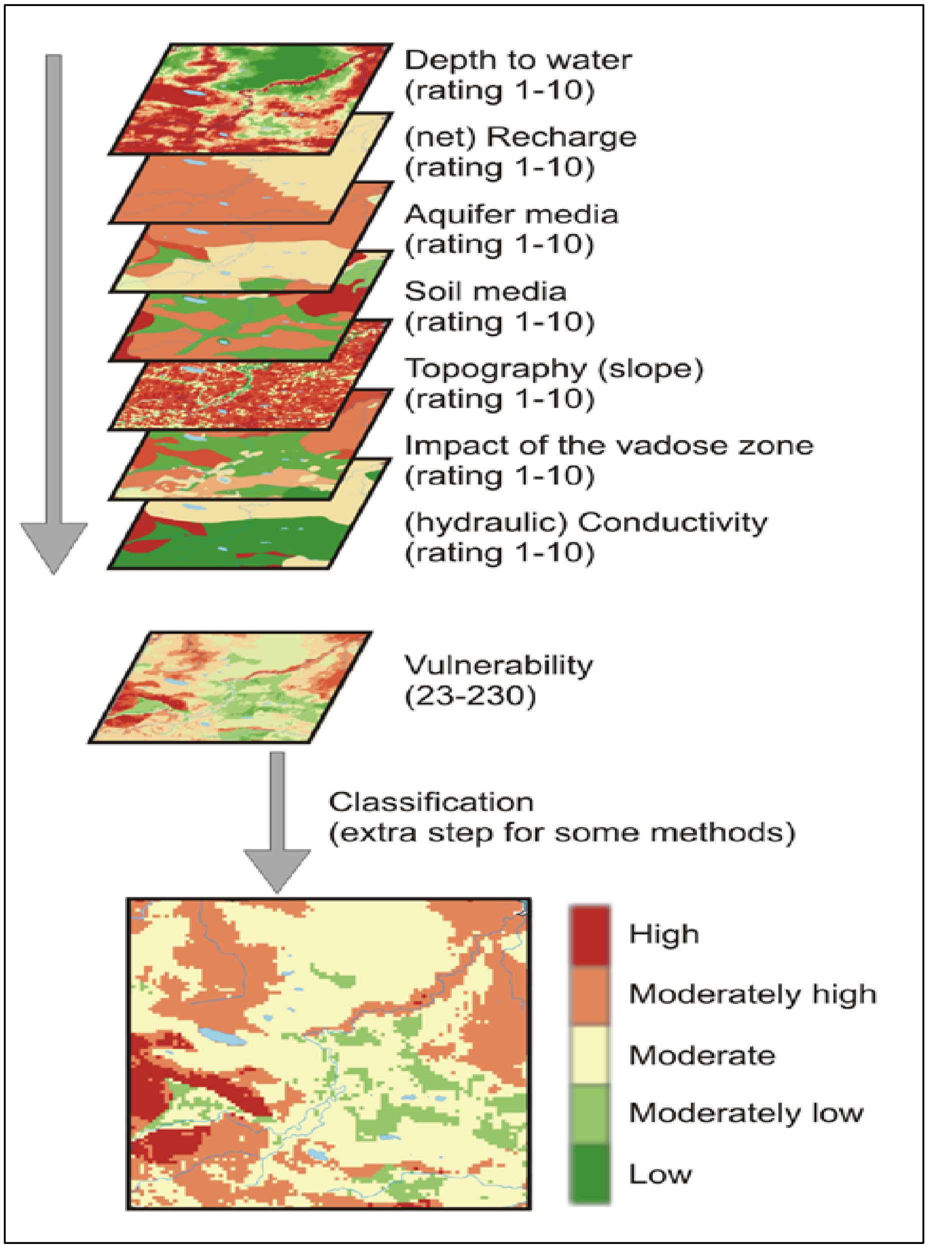


Figure (3): An example of overlay and index methods (Liggett and Talwar, 2009).

3. *Process-based Simulation Models*

They are used to test the vulnerability quantitatively and put referential standards for quantification, comparison and validity of purposes. They rely on scientific understanding, use water flow equations and compute the concentrations and travel time of contaminants in the unsaturated and saturated zones (Lindström, 2005). Figure (4) depicts a schematic diagram of process-based methods of assessing the vulnerability of a well. Process-based models are more complex than the overlay and index methods, but the results are not more accurate (Tesoriero et al., 1998) as the needed data are rarely available and must be indirectly estimated (Samey and Gang, 2008).

4. *Statistical Methods*

They are the least common methods used for vulnerability assessment because of the difficulty of their development. The contamination probability can be assessed after developing statistical relationships between the observed contamination, environmental conditions and land uses (Lindström, 2005). They usually start with mapping and analysis of water quality from known sites (e.g., samples from wells and soil). These maps can then be integrated into linear regression models in which the concentration of pollutants is related to series of factors as depicted in figure (5) (Liggett and Talwar, 2009). The vulnerability is stated as contamination probability rather than categorized ranking; the higher the probability, the higher the vulnerability (Lindström, 2005).

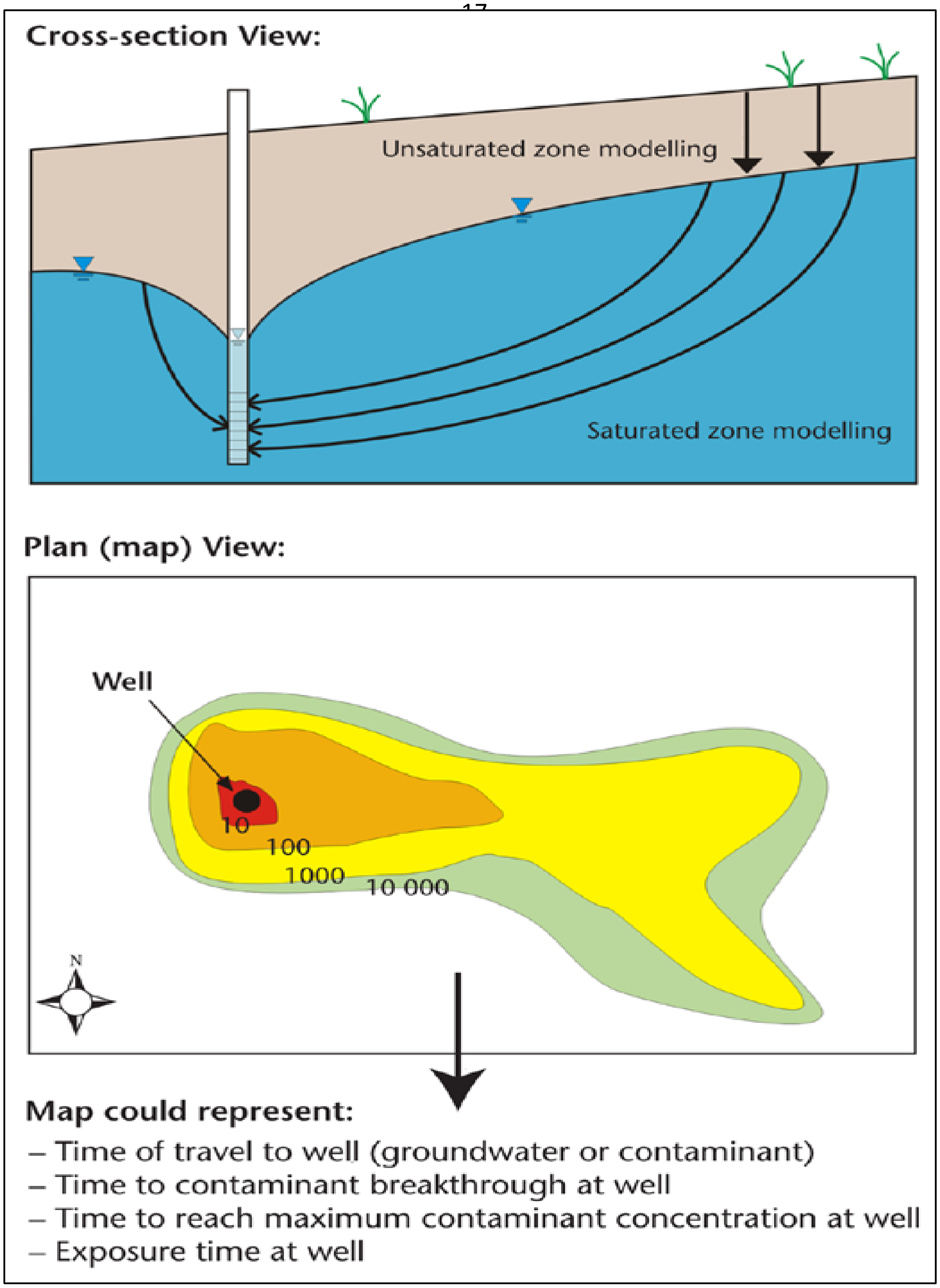


Figure (4): Schematic diagram of process-based methods. Top: numerical modeling can show the direction, magnitude and timing of water or contaminant flow into a well. The plan view of the same system shows the well capture zone outlined on the surface for the purpose of well-head protection planning. Contours may represents time of travel, time to reach maximum contaminant concentration, etc (Liggett and Talwar, 2009).

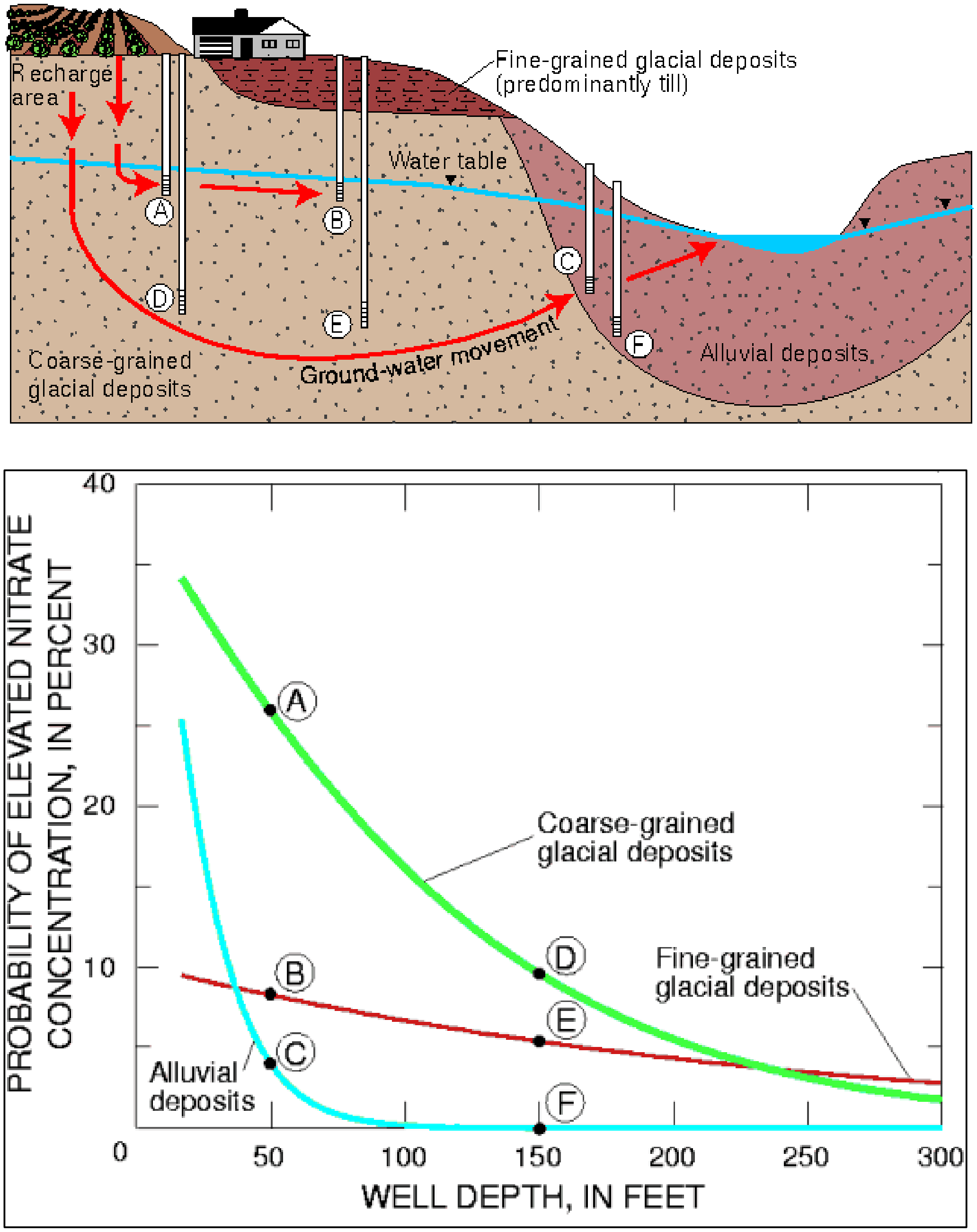


Figure (5): The probability of elevated nitrate concentration of a well in relation to well depth and surficial geology of a basin. Shallow wells with coarse-grained surficial deposits (well A for example) are most susceptible to elevated nitrate concentrations (Erwin and Tesoriero, 1997).

It is common to use the overlay and index and statistical methods for evaluating the intrinsic vulnerability and the process-based models for assessing specific vulnerability (Kouli et al., 2007).

2.4 Groundwater Vulnerability Mapping

Groundwater Vulnerability Mapping is a relatively new scientific technique emerged initially in the late 1960s (Dimitriou and Zacharias, 2006). It is developed to reinforce land use planning, decision-making and groundwater protection measures and resource management (Samey and Gang, 2008).

Mapping intrinsic vulnerability is strongly connected to managerial and political purposes and can form a base for further investigations. In contrast, specific vulnerability mapping is connected to scientific objectives and needs additional explanations for decision makers (Margane, 2003).

The most common methods used for vulnerability mapping are (Margane, 2003):

- The DRASTIC method, which is mainly used in the US,
- The GLA method and its modified form; the PI method, used by the German States and Federal Government authorities,
- The EPIK method, used by the Swiss authorities and
- The COP method, which may be adopted by all European authorities for karst areas.

The choice of the most appropriate method for vulnerability mapping depends on a number of factors such as the scale of the map, amount and quality of data available, spatial data distribution and the purpose of the map (Tesoriero et al., 1998). Generally, mapping scales have the range of 1:50,000 – 1:100,000 depending on data availability and their spatial distribution. The availability of more data will increase the details of the map and so the scale will be larger (Margane, 2003).

The application of DRASTIC method is suitable for areas with general hydrogeological setup and low data availability. It is suggested to use an even more simple method; GOD if the required parameters are not all known (Foster and Hirata, 1988).

The rating system of the GLA and its modification, the PI method, is more founded on scientific considerations and less subjective than DRASTIC. For karst environments (limestone, dolomite, dolomite limestone), the GLA has some shortages which are taken into account in the modified PI method, so this method may be fundamentally applied for all hydrogeological settings. It is recommended to use either the GLA or the PI method in areas having dissimilar lithological units (Margane, 2003).

The EPIK-Method is recommended to be applied for pure karst environments as they are specially designed for this purpose. Till now, The COP is not adopted as a standard vulnerability mapping method for karst areas (Margane, 2003).

Some examples on vulnerability mapping methods are provided in table (1). Grey boxes indicate parameters included in a given method; white boxes indicate parameters that are not included. Black boxes indicate possible inclusion of parameters, which will depend on the actual study.

Table (1): Selected examples of vulnerability mapping methods (Liggett and Talwar, 2009).

Name	Type[a]	Examples	Parameters[b]					
			D	R	A	S	U	O
Index Methods								
DRASTIC	INV	Al-Adamat et al., 2003; Almasri, 2007; Al-Hanbali and Kondoh, 2008.	▨	▨	▨		▨	▨
GOD	INV	Neukum and Hötzl, 2007; Afonso et al., 2008.	▨				▨	▨
EPIK	INV	Vías et al., 2005; Neukum and Hötzl, 2007.	▨				▨	▨
Aquifer Vulnerability Index (AVI)	INV	Alberta Land Resource Atlas of Alberta, 2009.	▨				▨	
PI	INV	Goldscheider et al., 2000; Margane, 2003; Werz and Hötzl, 2005;	▨	▨	▨		▨	▨
Process Methods								

Surface to Aquifer/Well Advection Time (SAAT/SWAT)	INV	N/A	▨	▨		■	▨	
Numerical Models (e.g., MODFLOW, FEFLOW)	INV or SPV	Frind et al., 2006; Butscher and Huggenberger, 2008.	■	▨	▨	▨	■	■
Statistical Methods								
Logistic Regression	SPV	Erwin and Tesoriero, 1997; Tesoriero et al., 1998; LaMotte and Greene, 2007.	■	■	■	■	■	■

A: INV= intrinsic vulnerability; SPV= specific vulnerability.

B: D= depth to water; R= recharge/infiltration; A= aquifer characteristics (material conductivity, etc.); S= saturated zone characteristics (e.g., flow patterns, layering hydraulic gradient); U= unsaturated zone characteristics (materials, hydraulic conductivity, soil moisture); O= other characteristics (e.g., explicit level of confinement, karst aquifers, permeable pathways).

2.5 GIS Use in Vulnerability Assessment

GIS has powerful functions that play a significant role in planning and decision making (Mahamid and Thawaba, 2007). It can support vulnerability mapping by allowing spatial data handling, processing, analysis, and visualization (Burrough and McDonnell 1998).

GIS has been used in many areas of groundwater vulnerability assessment: (1) integrating data layers involved in the assessment, (2) supporting modeling and analysis of physical and spatial interactions of critical environmental parameters and (3) displaying the results in a map form (Al-Adamat et al., 2003; Lindström, 2005; Dimitriou and Zacharias, 2006; Almasri, 2007; Mahamid and Thawaba, 2007; Afonso et al., 2008; Samey and Gang, 2008; Kattaa et al., 2010).

2.6Groundwater Vulnerability Mapping for Karstic Aquifers

Groundwater from karst aquifers is among the most valuable resources of drinking water for the growing population of the globe (Ford and Williams, 1989). About 25% of the global population drinks karst water. This share is predicted to reach 80% in 2025 (http://www.ung.si/en/academic-programmes/121557/151992, Feb, 2010).

Karst aquifers are extremely vulnerable to contamination. Due to their unique characteristics, like thin covering layers and point recharge via dolines, shafts and swallow holes, contaminants can easily reach the groundwater, where they are transported rapidly and turbulently in karst conduits over large distances (Kouli et al., 2007). The residence times of contaminants are often short, and the attenuation process to contaminants often does not work effectively in karst systems (Goldscheider, 2004), see figure (6).

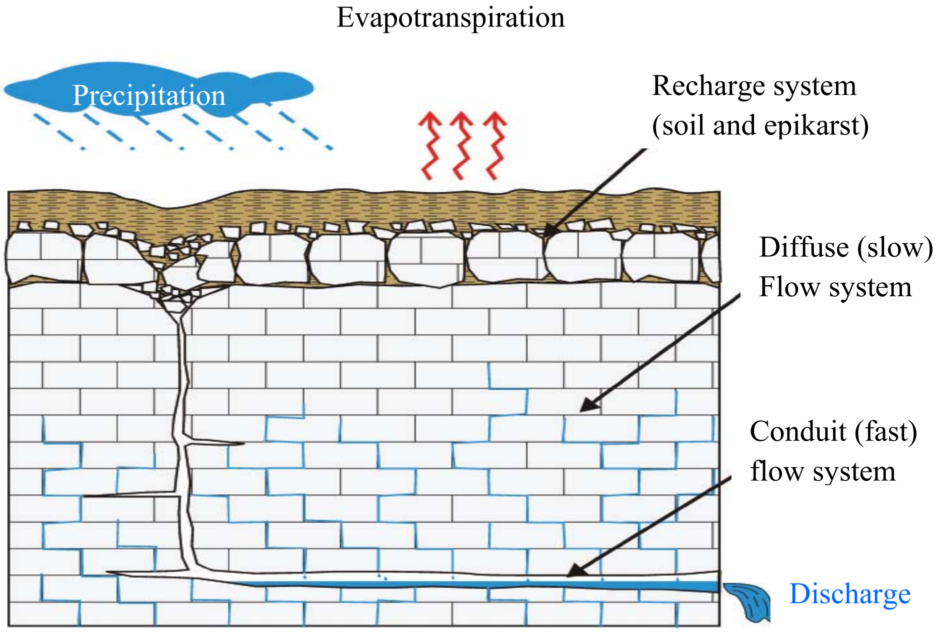


Figure (6): Conceptual model of a karst aquifer (Butscher and Huggenberger, 2009).

Having these issues in mind, the COST Action 620 (COST is a French acronym standing for “Cooperation in the field of Scientific and Technical research”) was developed by the European scientists to provide a conceptual framework for “Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers” (DoELG/EPA/GSI 1999).

The assessment of karst aquifer system with respect to the factors governing the percolation of recharge water is necessary in mapping intrinsic vulnerability (Zwahlen, 2003). Geological, geomorphological, pedological and hydrological mapping give the data base required for the assessment (Witkowski et al., 2004).

Although the overlay and index method is empirical, it is considered the only meaningful technique in delineating the zones most vulnerable to contamination in karstic aquifers (Gogu and Dassargues, 2000).

Hydrologists developed methods that take into consideration the nature of karst. (Kouli et al., 2007). Among the followed approaches are the development of the EPIK method that is dedicated only to karst (Doerfliger et al., 1999) and the PI method that can be used for all types of aquifers, but provides special tools for karst (Goldscheider et al., 2000).

Four main factors are taken into account within the international approach for mapping the intrinsic groundwater vulnerability in karst aquifers. The overlying layers, which to somehow provide a natural protection to groundwater, may be bypassed by anthropogenic recharge in karst areas. The flow concentration also has to be considered. The precipitation regime plays a significant role when comparing groundwater vulnerability in different climatic regions, but it is of less significance at local scale mapping. The last factor describes the hydraulic properties of the karst aquifers. The first three factors are combined to create the resource vulnerability maps. Source vulnerability maps additionally consider the fourth factor (Goldscheider and Popescu, 2004).

2.7 Previous Studies on Groundwater Vulnerability in the West Bank

The studies concerning the groundwater vulnerability mapping for the West Bank area are:

- The Ministry of Planning and International Communication (MOPIC) prepared a general study for the vulnerable areas of the West Bank in 1997. The study only considered the recharging areas and outcropping formations to determine the vulnerability. The regions are categorized into highly sensitive, moderately sensitive, sensitive, and non-sensitive areas (HWE, 2009).

- CDM in 2003 adopted the DRASTIC method for the West Bank groundwater vulnerability assessment. They made the study but didn’t construct the vulnerability map. Additionally, the DRASTIC method is not suitable for karst aquifers (HWE, 2009).

- United Nations Environment Program (UNEP) (2002) conducted a hydrological vulnerability assessment of groundwater to pollution in the West Bank. The created map shows areas of low, medium and high vulnerability to pollution due to human activities. The results indicate that more than two thirds of the West Bank is of high vulnerability, see figure (7). However the UNEP report does not provide any information regarding the method used for the development of the vulnerability map.

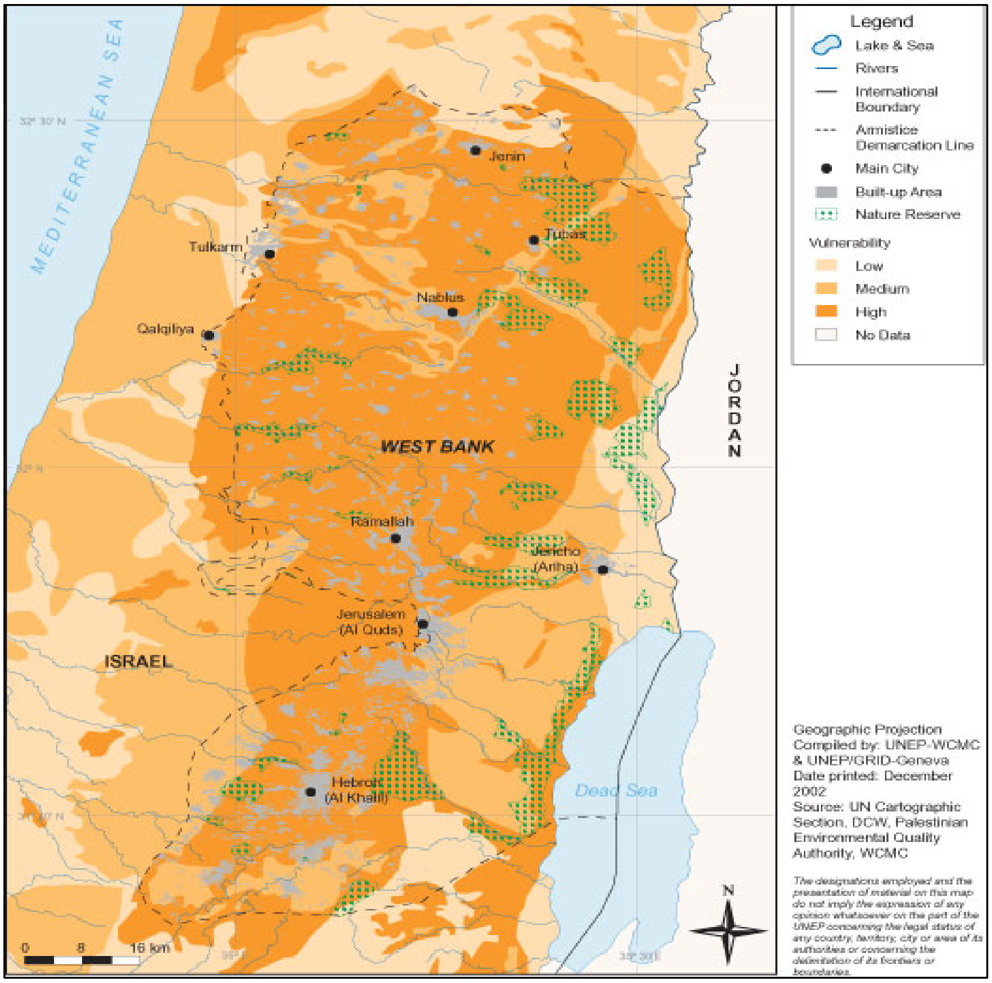


Figure (7): Hydrogeological vulnerability of groundwater to pollution in the West Bank (www.grid.unep.ch/product/map/index.php).

- Qamhieh (2006) evaluated the vulnerability of groundwater in the West Bank using the combination of DRASTIC model and GIS. The results show that 90% of the study area is at low risk to contamination, while 10% is at moderate risk, see figure (8).

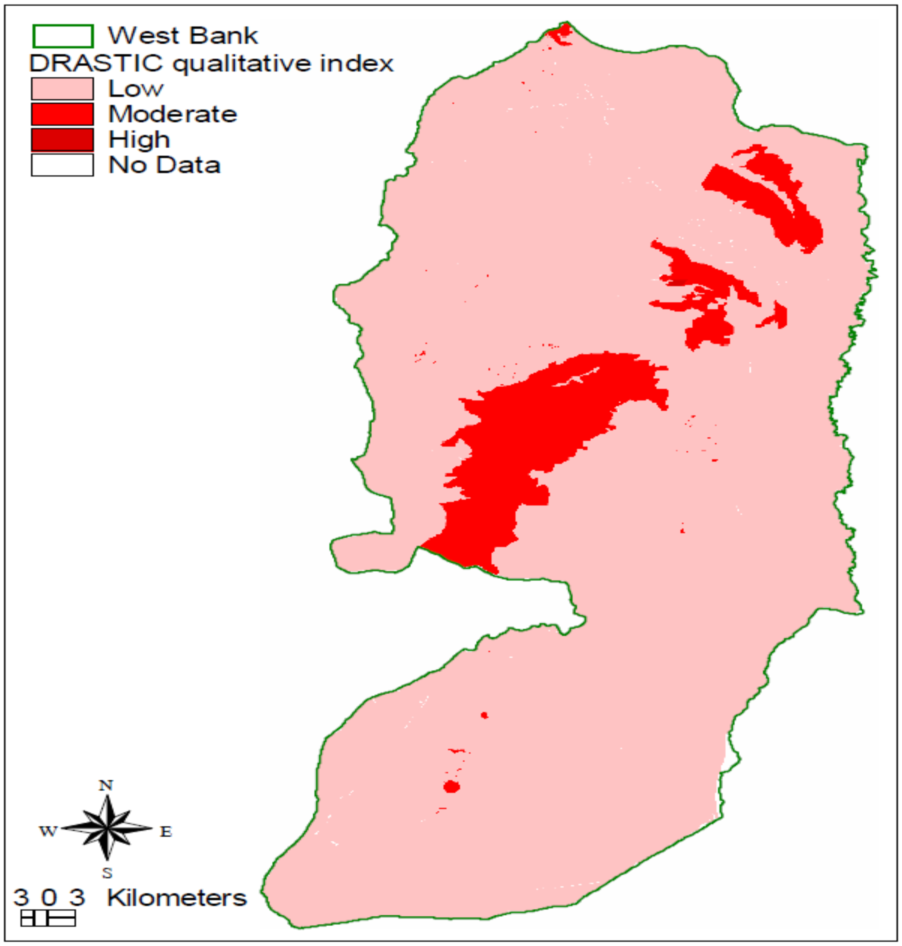


Figure (8): Groundwater vulnerability map of the West Bank (Qamhieh, 2006).

- The House of Water and Environment (HWE) (2009) developed a groundwater vulnerability map for Ramallah district using the PI method with the aid of GIS. The resulted map is shown in figure (9).

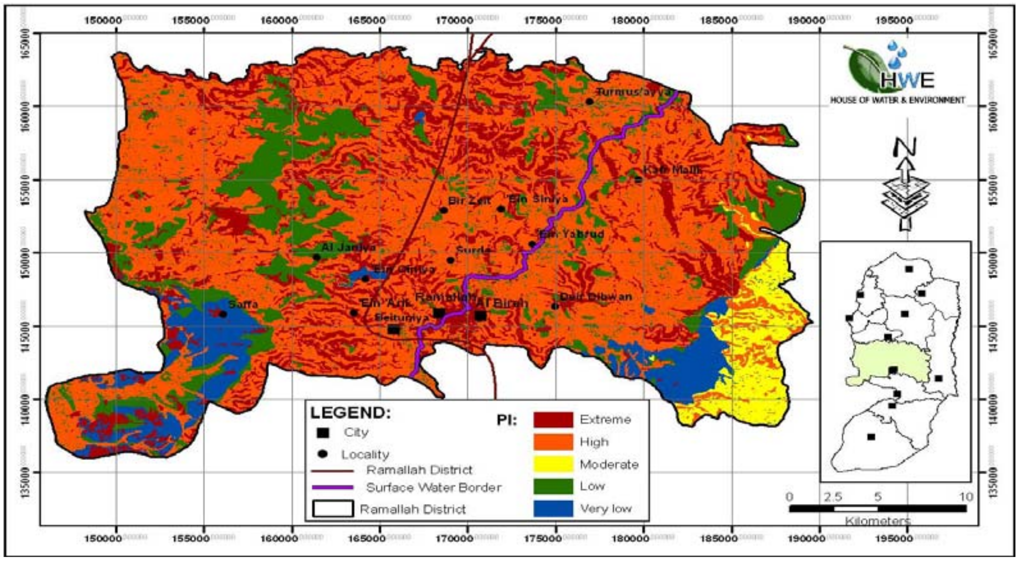


Figure (9): Vulnerability map according to the PI method (HWE, 2009).

- Mahamid and Thawaba (2007) also applied the same method for the same district. The vulnerability map is represented in figure (10).

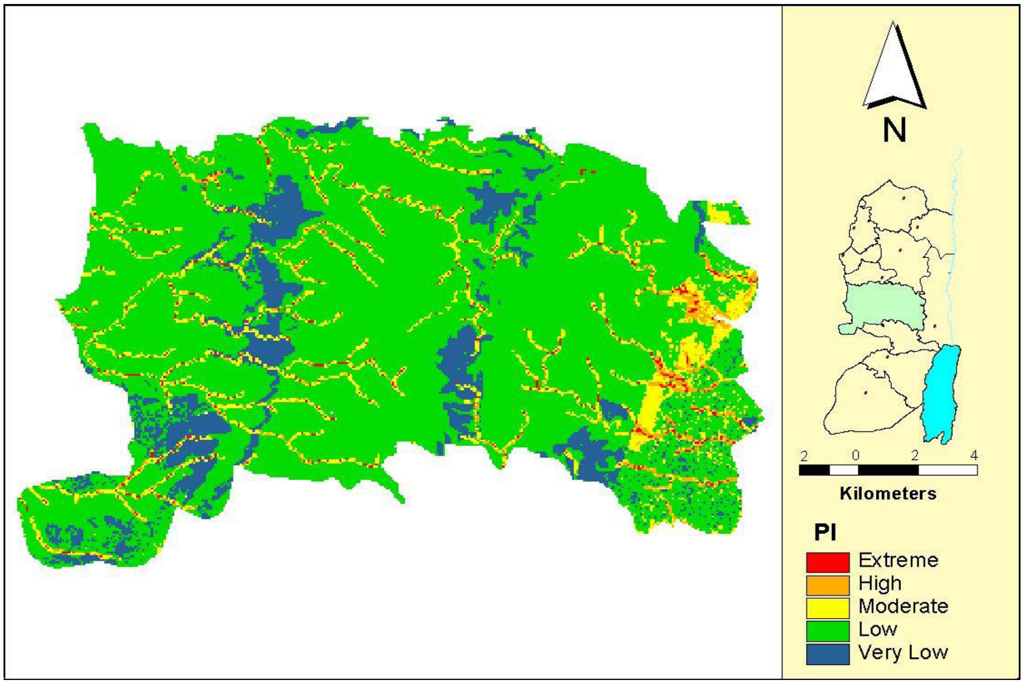


Figure (10): Vulnerability map for Ramallah district (Mahamid and Thawaba, 2007).

- The House of Water and Environment (HWE) in collaboration with The Friends of the Earth Middle East (FOEME) (2008) created a vulnerability map for Tulkarm governorate using the PI method, see figure (11).

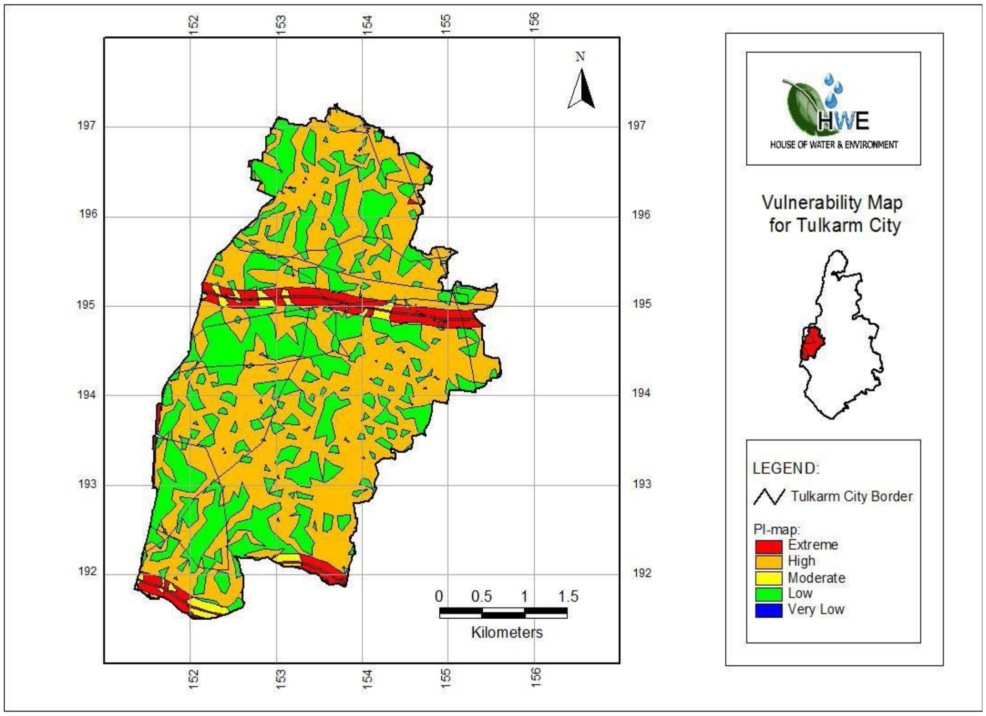


Figure (11): Vulnerability map for Tulkarm district (HWE and FOEME, 2008).

CHAPTER THREE

DESCRIPTION OF THE STUDY AREA

3.1 Introduction

The landmass that was considered in this research is the West Bank, Palestine. Its general and physical characteristics i.e. location, demography, topography, climate, soil, land use and hydrogeology are illustrated in this chapter.

3.2 Location

The West Bank is a physical part of Palestine. The Jordan River is its eastern border, while the Historical Palestine surrounds it from the west, north and south (ARIJ, 2007). It consists of eleven districts: Bethlehem, Hebron, Jenin, Jericho, Jerusalem, Nablus, Qalqiliya, Ramallah, Salfit, Tubas and Tulkarm, see figure (12).

3.3 Topography

The West Bank covers an area of about 5,820 km^2 (ARIJ, 1997). The geomorphology of the West Bank contains a series of mountains, extending from the north (Nablus) to the south (Hebron), and the Jordan Valley. The mountains, which play a significant role in collecting the rainfall and feeding the underground aquifers, have elevations ranging between 700 and 1,000 meters above sea level (SUSMAQ, 2002). The highest point in the area is 1,022 meters above sea level at Tal Asur (UNEP, 2003), whereas the lowest elevation is 349 meters below sea level at the Dead Sea (SUSMAQ, 2002), see figure (13).

Figure (12): The regional location of the West Bank along with the main governorates.

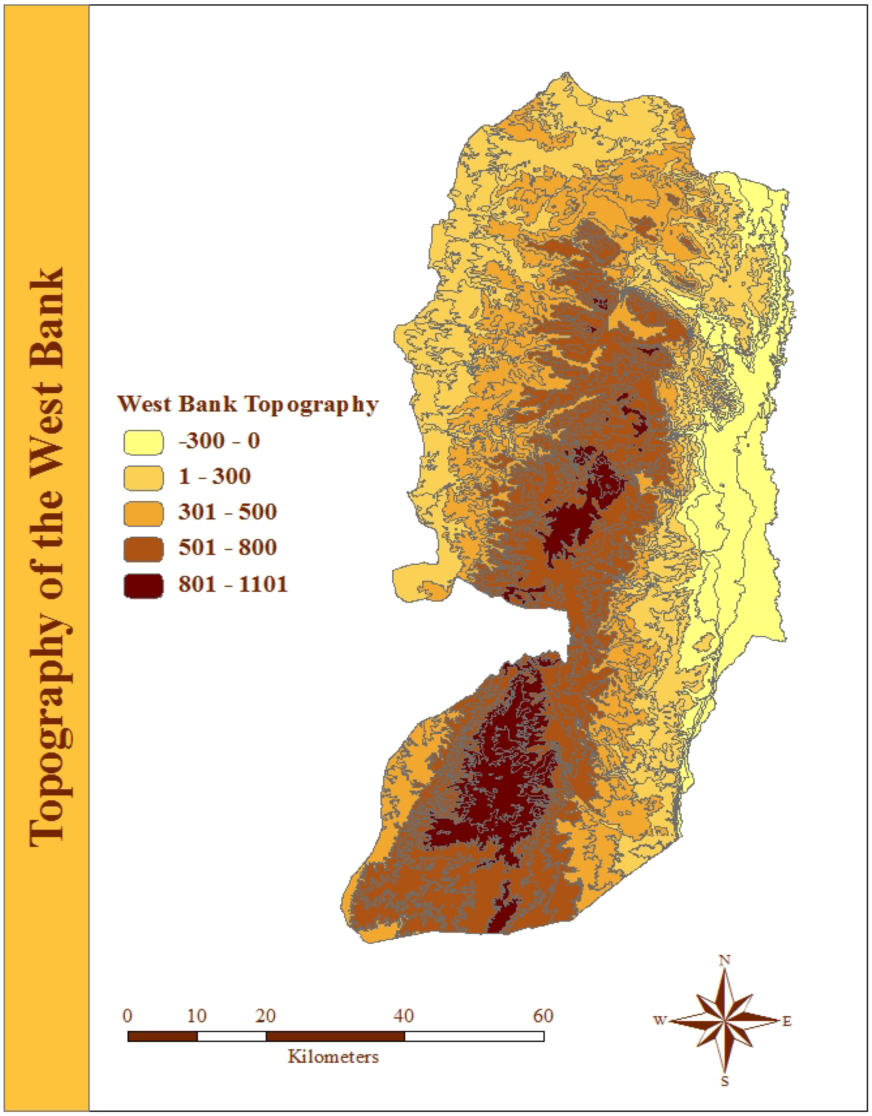


Figure (13): Topography of the West Bank.

3.4 Demography

The total number of population in the West Bank is about 2.4 millions, with 50.8% males and 49.2% females and a population density of 416 capita/km^2 (www.pcbs.gov.ps/pcbs/Portals/_PCBS/Downloads/book1624/book1624_0301.pdf). The percentage of refugees to the total population is 42.6%

(www.pcbs.gov.ps/pcbs/Portals/_PCBS/Downloads/book1624/book1624_0301.pdf). The growth rate is about 2.6% per annum.

3.5 Climate

The West Bank area is affected by the Mediterranean climate, which has a hot, dry, long summer and a cool, rainy, short winter. There are four main climatic regions in the West Bank i.e. the Jordan Valley, the Eastern Slopes, the Western Slopes and the Central Highlands (ARIJ, 2007).

The mean temperature ranges from 30ºC to 22ºC in summer and from 13ºC to 7ºC in winter at Jericho and Hebron, respectively (UNEP, 2003). The main component of precipitation in the West Bank is rainfall, which has more than 80 stations distributed geographically from north to south (HWE, 2009). The rainfall is seasonal and orographic (Jayyousi and Srouji, 2009). Commonly, the rainy season extends from the middle of October to the end of April (ARIJ, 2007). The annual precipitation decreases from north to south and from high to low altitude, taking an average value of 450-500 mm, see figure (14). The relative humidity has an average value of 52% at Jericho (UNEP, 2003). As a result of high temperature, intensive sunshine and low humidity, the evaporation rate will rise in summer. On the other hand, it will fall in winter when the solar radiation is low (ARIJ, 2007).

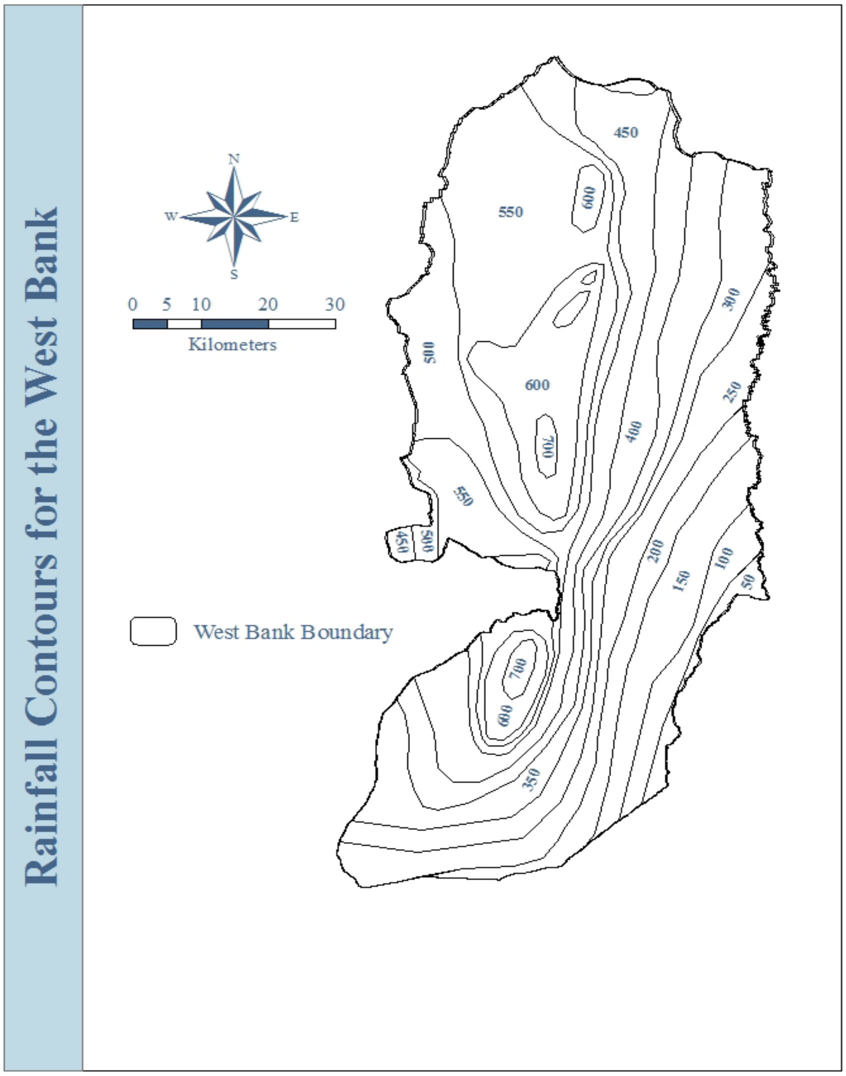


Figure (14): Rainfall contours of the West Bank.

3.6 Land Use

There are different land use activities within the West Bank's borders. They include: Palestinian built up areas, Israeli settlements, arable lands, forests and cultivated areas, see figure (15).

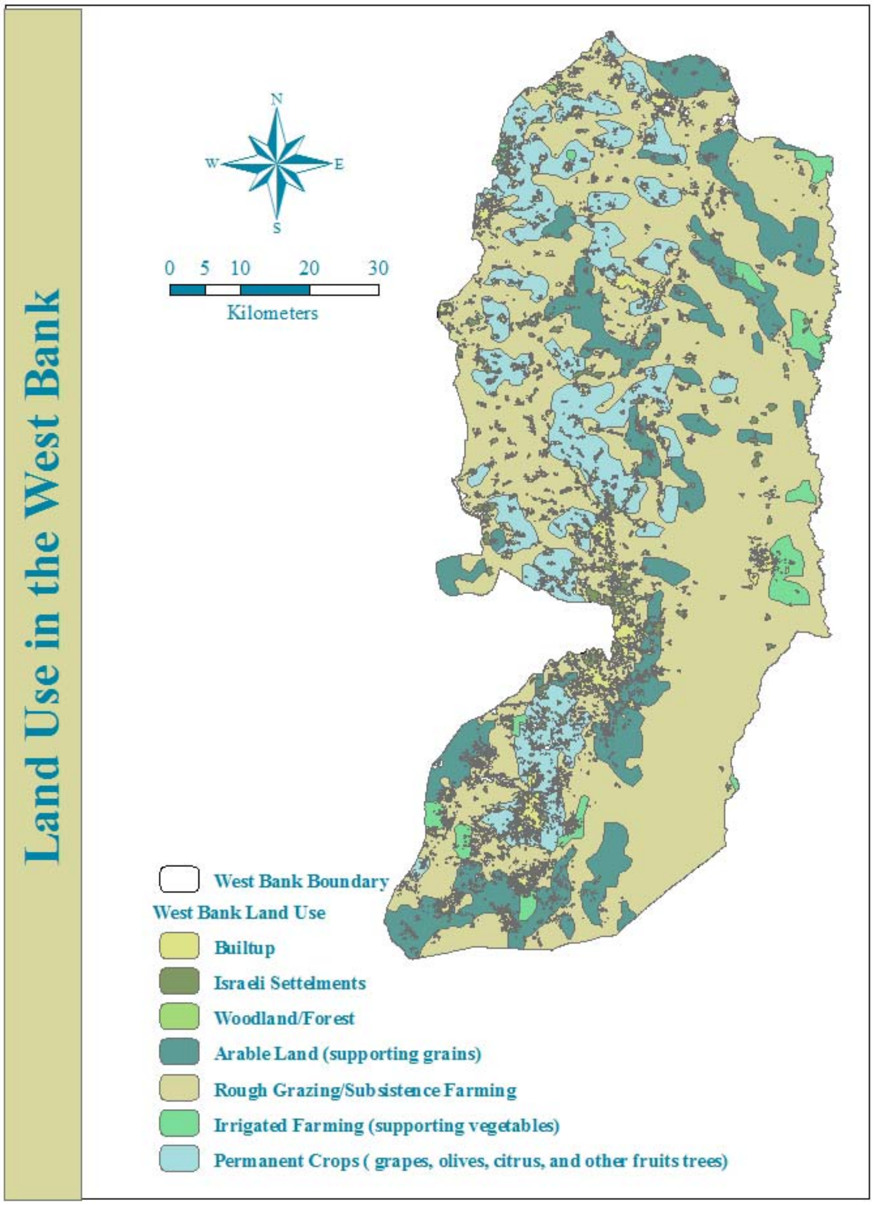


Figure (15): Land use in the West Bank.

The figure shows that 62% of the West Bank’s area is covered by rough grazing farming, 14.4% by permanent crops, 14.4% by arable lands, 5% by the Palestinian built up areas, 2.6% by irrigated farming, 1.42% by the Israeli settlements and 0.18% by forests.

3.7 Soil

The most dominant soil clusters in the West Bank are Terra Rossa and Brown Rendzinas in the central highlands and Brown Rendzinas and Pale Rendzinas in the northern and southern ridges of Hebron, Tubas and Qalqiliya mountains and in the eastern slopes region (ARIJ, 2007). Figure (16) presents the distribution of soil types over the West Bank.

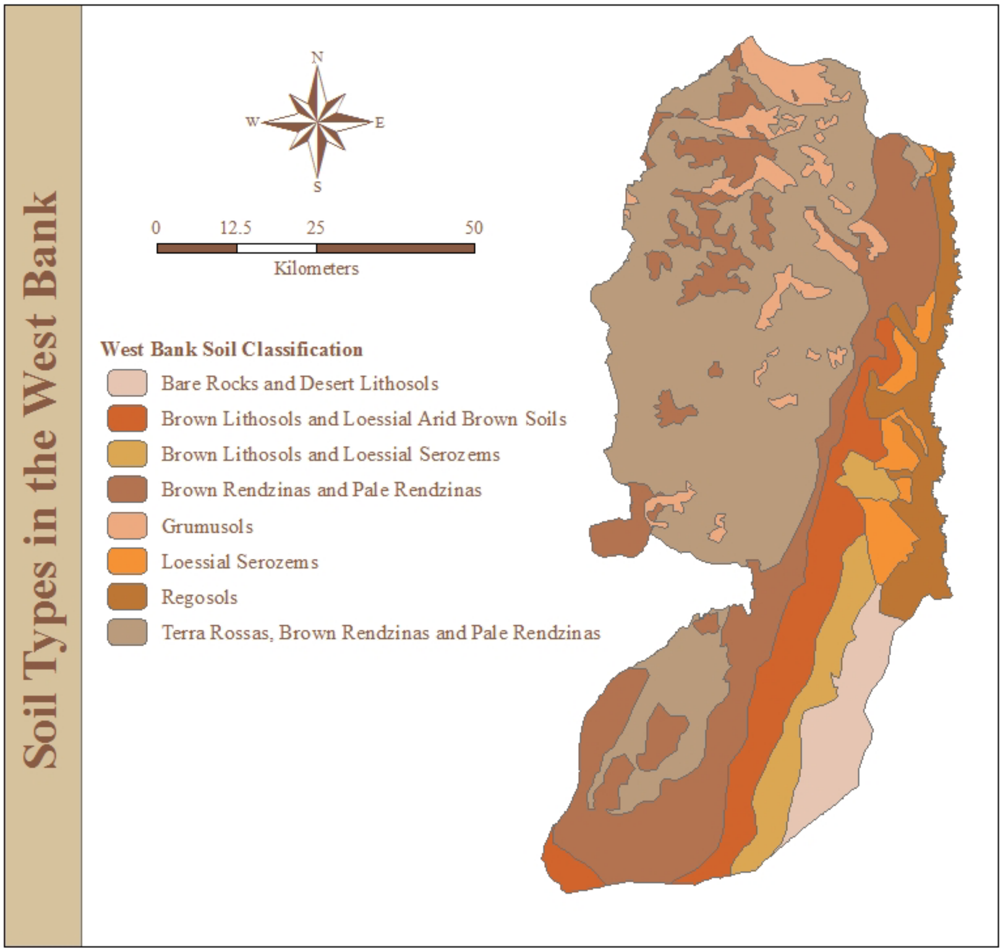


Figure (16): Soil associations in the West Bank

The soil associations found in the area are described as follows:

1. *Terra Rossa, Brown Rendzinas and Pale Rendzinas*

This soil type covers 41.41% of the West Bank's area. It's parent materials are dolomite and hard limestone. The soil depth ranges from 0.5 to 2 meters depending on the topography (HWE, 2009). The main soil texture is clay to clay loam.

2. *Brown Rendzinas and Pale Rendzinas*

It occupies 24.72% of the study area. Soil depths vary from 0.5 to 2 meters. Parent materials are hard to soft chalk (EQA, 2006). It has a clay loam texture.

3. *Brown Lithosols and Loessial Arid Brown Soils*

It covers 9.26% of the total area and has a loamy texture. The parent materials are mainly chalk, marl, limestone and conglomerates (HWE, 2009).

4. *Regosols*

It takes 6.22% of the West Bank's area with a clay loam texture. The parent materials for this soil type are sand, clay, loess and lisan marl (EQA, 2006).

5. *Grumusols*

Grumusols occupies 5.27% of the total area. Clayey texture is dominant in this soil type. Parent materials are alluvial and/or Aeolian deposits (EQA, 2006).

6. *Brown Lithosols and Loessial Serozems*

This soil type covers 5.21% of the West Bank with a sandy loam texture.

7. *Loessial Serozems*

Loessial Serozems takes 3.04% of the West Bank’s area. Parent materials are loessial and highly calcareous sediments (EQA, 2006). It has a sandy loam texture.

8. *Bare Rocks and Desert Lithosols*

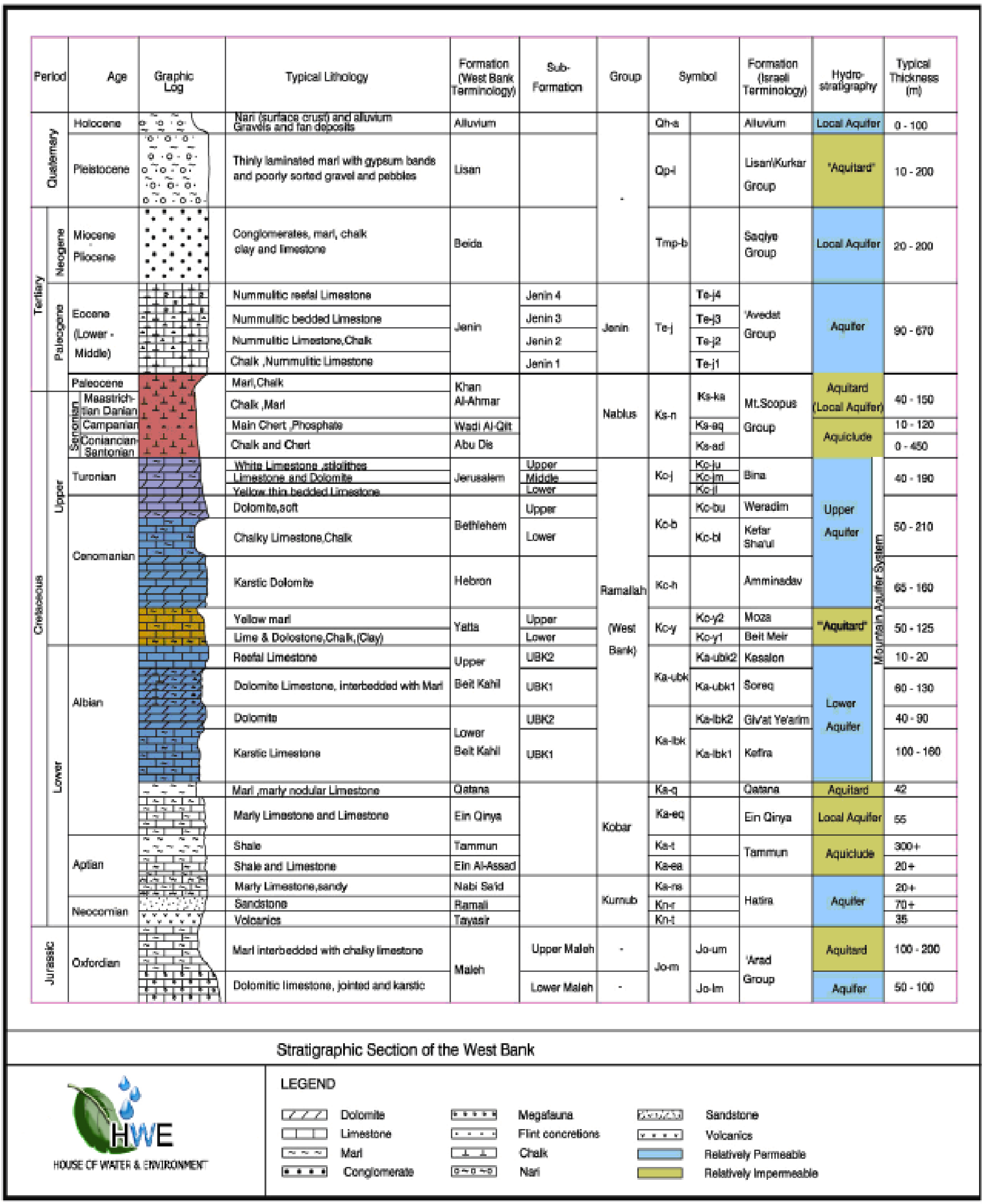
They are found in the south eastern part of the West Bank and covers 4.87% of the area.

3.8 Hydrogeology

This section provides a general description of the geology and hydrogeology of the West Bank.

3.8.1 Geology

The geological surface of the area consists of well-fractured and karstified carbonate rocks i.e. limestone, dolomite and chalk (Strum et al., 1996). These rocks extend from the Lower Cretaceous to Quaternary ages (EQA, 2006). Generally, most of the geological formations are non-covered and have outcrops at the surface. The lithological units, arranged from older to youngest and their features are presented in figure (17). Figure (18) shows the geological map of the West Bank.



Period	Age	Graphic Log	Typical Lithology	Formation (West Bank Terminology)	Sub-Formation	Group	Symbol		Formation (Israeli Terminology)	Hydro-stratigraphy	Typical Thickness (m)
Quaternary	Holocene		Nari (surface crust) and alluvium Gravels and fan deposits	Alluvium		-	Qh-a		Alluvium	Local Aquifer	0 - 100
	Pleistocene		Thinly laminated marl with gypsum bands and poorly sorted gravel and pebbles	Lisan			Qp-l		Lisan\Kurkar Group	"Aquitard"	10 - 200
Tertiary Neogene	Miocene Pliocene		Conglomerates, marl, chalk clay and limestone	Beida			Tmp-b		Saqiye Group	Local Aquifer	20 - 200
Paleogene	Eocene (Lower - Middle)		Nummulitic reefal Limestone	Jenin	Jenin 4	Jenin	Te-j	Te-j4	'Avedat Group	Aquifer	90 - 670
			Nummulitic bedded Limestone		Jenin 3			Te-j3			
			Nummulitic Limestone,Chalk		Jenin 2			Te-j2			
			Chalk ,Nummulitic Limestone		Jenin 1			Te-j1			
	Paleocene		Marl,Chalk	Khan Al-Ahmar		Nablus	Ks-n	Ks-ka	Mt.Scopus Group	Aquitard (Local Aquifer)	40 - 150
Cretaceous Upper Senonian	Maastrichtian Danian		Chalk ,Marl								
	Campanian		Main Chert ,Phosphate	Wadi Al-Qilt				Ks-aq		Aquiclude	10 - 120
	Coniancian-Santonian		Chalk and Chert	Abu Dis				Ks-ad			0 - 450
	Turonian		White Limestone ,stiolithes	Jerusalem	Upper	Ramallah (West Bank)	Ko-j	Ko-ju	Bina	Upper Aquifer Mountain Aquifer System	40 - 190
			Limestone and Dolomite		Middle			Ko-jm			
			Yellow thin bedded Limestone		Lower			Ko-jl			
	Cenomanian		Dolomite,soft	Bethlehem	Upper		Ko-b	Ko-bu	Weradim		50 - 210
			Chalky Limestone,Chalk		Lower			Ko-bl	Kefar Sha'ul		
			Karstic Dolomite	Hebron			Ko-h		Amminadav		65 - 160
			Yellow marl	Yatta	Upper		Ko-y	Ko-y2	Moza	"Aquitard"	50 - 125
			Lime & Dolostone,Chalk,(Clay)		Lower			Ko-y1	Beit Meir		
Lower	Albian		Reefal Limestone	Upper Beit Kahil	UBK2		Ka-ubk	Ka-ubk2	Kesalon	Lower Aquifer	10 - 20
			Dolomite Limestone, interbedded with Marl		UBK1			Ka-ubk1	Soreq		60 - 130
			Dolomite	Lower Beit Kahil	UBK2		Ka-lbk	Ka-lbk2	Giv'at Ye'arim		40 - 90
			Karstic Limestone		UBK1			Ka-lbk1	Kefira		100 - 160
			Marl ,marly nodular Limestone	Qatana		Kobar	Ka-q		Qatana	Aquitard	42
			Marly Limestone and Limestone	Ein Qinya			Ka-eq		Ein Qinya	Local Aquifer	55
	Aptian		Shale	Tammun			Ka-t		Tammun	Aquiclude	300+
			Shale and Limestone	Ein Al-Assad			Ka-ea				20+
			Marly Limestone,sandy	Nabi Sa'id		Kurnub	Ka-ns		Hatira	Aquifer	20+
	Neocomian		Sandstone	Ramali			Kn-r				70+
			Volcanics	Tayasir			Kn-t				35
Jurassic	Oxfordian		Marl interbedded with chalky limestone	Maleh	Upper Maleh	-	Jo-m	Jo-um	'Arad Group	Aquitard	100 - 200
			Dolomitic limestone, jointed and karstic		Lower Maleh	-		Jo-lm		Aquifer	50 - 100

Stratigraphic Section of the West Bank

HWE
HOUSE OF WATER & ENVIRONMENT

LEGEND

- Dolomite
- Limestone
- Marl
- Conglomerate
- Megafauna
- Flint concretions
- Chalk
- Nari
- Sandstone
- Volcanics
- 🟦 Relatively Permeable
- 🟨 Relatively Impermeable

Figure (17): Stratigraphical Section of the West Bank (HWE, 2009).

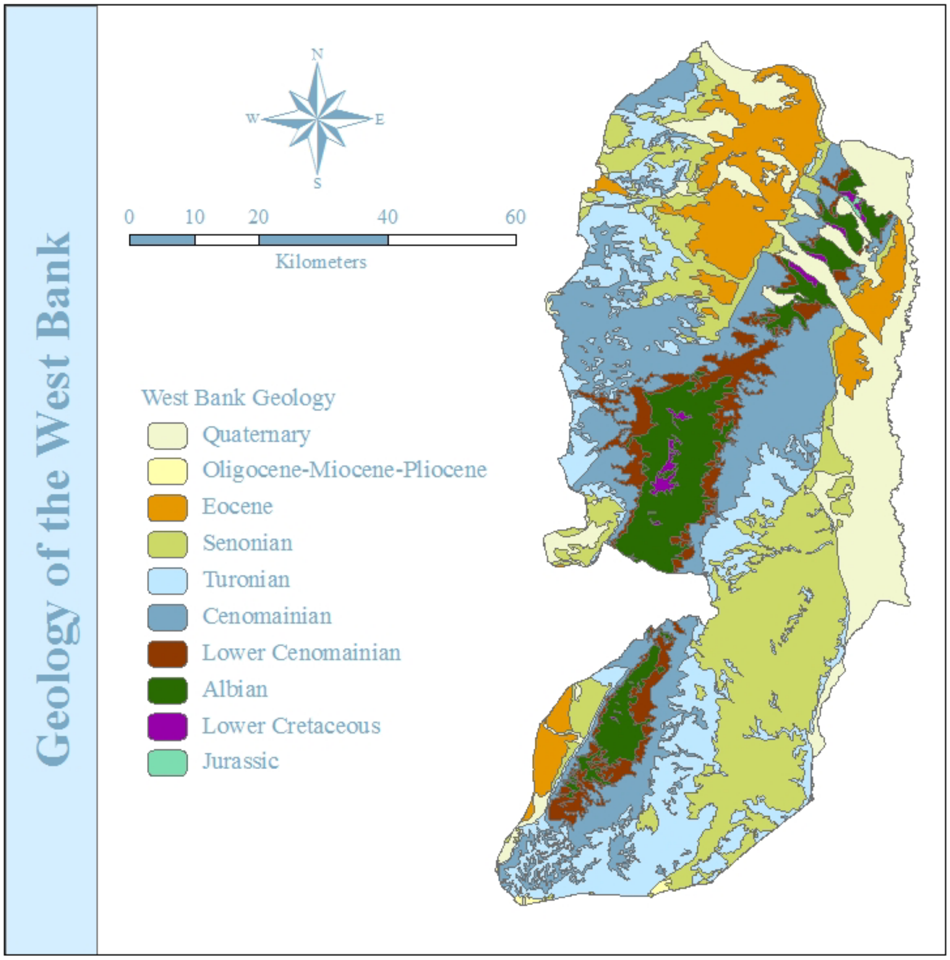


Figure (18): The outcropping geology of the West Bank (HWE, GIS Unit).

3.8.2 Water Resources

Groundwater is the main water resource in the West Bank. Most of this water occurs in fissures, joints, and karstic features of the carbonate Ajlun Group of Late Cretaceous period (Froukh, 2002).

The most important West Bank's aquifers are found in the Cenomanian-Turonian formation of the Upper Cretaceous period and in the Beit Kahil formations of the Lower Cretaceous period. These formations consist mainly of limestone, dolomite, marl and chalk (Sturm et al., 1996). The aquifer system of the West Bank is known to be heterogeneous (Tahal, 1996). The water is found at depths ranging from hundreds of meters to many meters (Ghanem, 2005).

Following the topography of the underlying structures, water will flow from the so called groundwater divide to different directions. This water divide lies on the mountain ridge, on a north-south line east of the cities of Nablus, Ramallah, Jerusalem and Hebron. Water which infiltrates west of this line feeds the Western Aquifer Basin (Yarqon-Tanninim Aquifer). To the east of this line, water recharges the Eastern Aquifer Basin. Another division of the recharge basins exists north of Nablus. From this line, water will flow to the north-east direction to feed North-Eastern Aquifer Basin (Nablus-Gilboa Aquifer) (Sturm et al., 1996), see figure (19).

Below is a brief description of the main basins and sub-basins (www.mena.gov.ps/part3/water.htm):

1. *Western Aquifer Basin*

It is the most important basin of the West Bank having a surface area of 11,398 km^2 and an average thickness of 600-900 m (Aliewi, 2007). It contains two sub-basins, Nahr El-Auja, El-Tamaseeh and Hebron Beer Shaba that drain the Cenomanian aquifers with a total discharge of 380-400 MCM/yr. This basin has a storage capacity of 360 MCM/yr. It is considered a shared basin between Palestine and Historic Palestine.

2. North-Eastern Aquifer Basin

It has a surface area of 1,067 km^2 (Aliewi, 2007). It consists of Nablus-Jenin basin, that drains the Eocene aquifer and the overlying Samarian basin, that drains the Eocene and Neogene aquifers. Its storage capacity is 140 MCM/yr.

3. Eastern Aquifer Basin

The surface area of this basin is about 3,079 km^2 (Aliewi, 2007). It includes the eastern flank of the West Bank. Its total storage capacity is 100-150 MCM/yr.

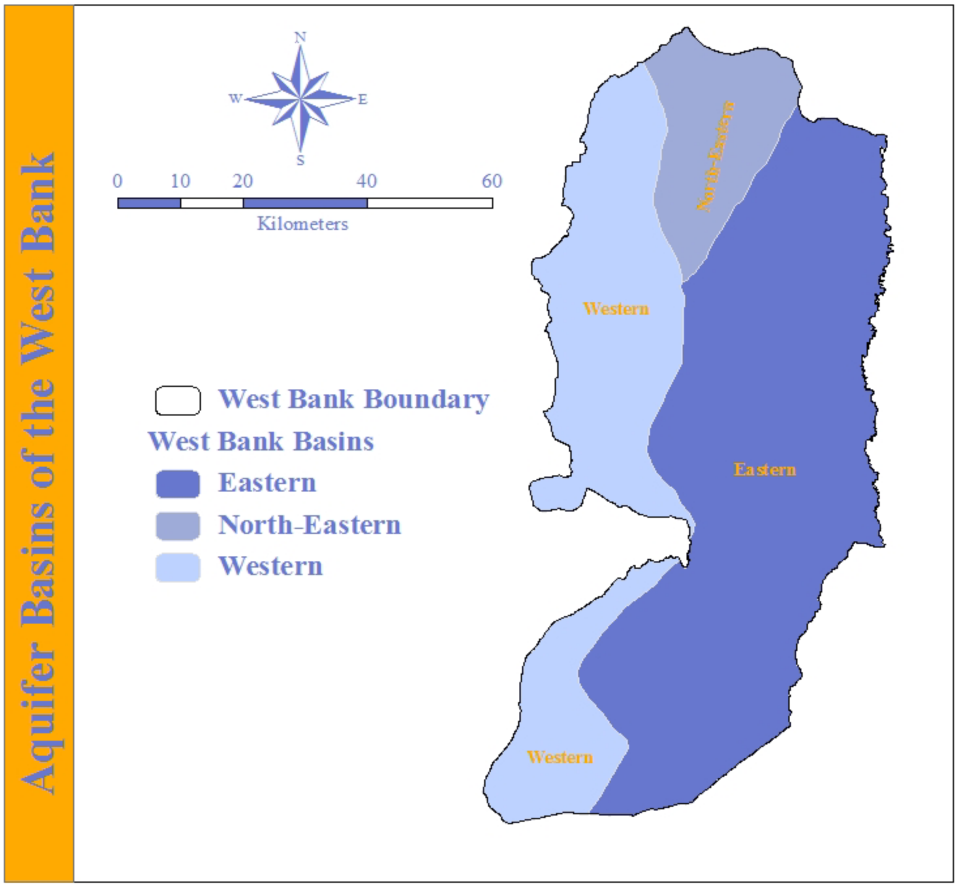


Figure (19): Aquifer basins of the West Bank.

3.8.3 Groundwater Pollution in the West Bank

Despite of its good quality, groundwater can be easily contaminated in some zones, depending on soil type, geological formation and land use. The dominant geological unit in the area is limestone. It has low efficiency in attenuating pollutants, so they will penetrate easily, making aquifers vulnerable to contamination (UNEP, 2003).

Groundwater salinity is high in some places. It is particularly caused by natural factors, and expected to increase due to over-abstraction of fresh water (UNEP, 2003). The Palestinian standard for Chloride in drinking water is (250-600 mg/l), while the observed values range from less than 25 to 1000 mg/l. In locations close to cities, like Jerusalem, Nablus and Jenin, Cl has values between 50 and 100 mg/l. Chloride concentration takes an increasing trend when moving from the recharge areas in the eastern highlands to Jordan Valley in the east and from the south of Nablus to Al-Jalameh in the north. The highest Chloride values are found in Pleistocene aquifer _that extends along the Jordan Valley_ and close to Jordan River in Jericho District (www.hwe.org.ps/Water Sector/data files/Part 203-Water Quality.pdf).

Agricultural practices i.e. the use of pesticides, fertilizers and herbicides, industrial activities and improper disposal of solid wastes and wastewater are the main causatives of groundwater pollution in the West Bank (UNEP, 2003).

The existence of Nitrate in groundwater is an indicator of pollution from fertilizers and/or wastewater (ARIJ, 1997). Nitrate levels in up to one-third of the sampled wells in the Jordan Valley in the West Bank were above the MCL i.e. 50 mg/l (Marei and Haddad, 1998). Generally, all districts except Ramallah and Al-Bireh, have NO_3 values that severely exceed the MCL. The mean annual Nitrate concentrations take the values of 29.8, 35.4 and 45.0 mg/l for the Eastern, North-Eastern and Western groundwater basins, respectively. The groundwater under the brown-red degrading sandy soils have a high mean NO_3 levels that jump above the MCL followed by Vertisols soils and Rendzinas soils of valleys (Anayah and Almasri, 2009).

Microbiological groundwater quality is of major concern in the West Bank, as there are frequent outbreaks of diarrhea among the Palestinian population (UNEP, 2003). Many natural springs are polluted by fecal coliforms, since most of them are located downstream from some sources of pollution, usually unsanitary cesspits of uphill villages (Tagar and Emmanuelle, 2008).

CHAPTER FOUR

THE PI METHOD

4.1 The PI Method

The PI method is a GIS-based approach, which was adopted in the framework of the European COST Action 620 program for mapping the intrinsic groundwater vulnerability (Goldscheider et al., 2000). It can be applied to all types of aquifers, but provides special considerations for karst ones (Kouli et al., 2007). It is based on the origin-pathway-target model. The ground surface is taken to be the origin of the assumed contamination, the water table in the uppermost aquifer is the target and the pathway includes all layers in between (Kouli et al., 2007).

The PI method takes two main factors into account; the protective cover (P) and the infiltration conditions (I). Both factors are mapped separately and then combined to obtain the groundwater vulnerability map (Margane, 2003), as shown in figure (20).

The P factor indicates the effectiveness of the protective cover, which includes all layers located between the ground surface and the groundwater table; the topsoil, the subsoil, the non-karst rocks and the unsaturated karst rocks (Vlaicu and Munteanu, 2008). Protectiveness is evaluated on the base of the effective field capacity (eFC) of the topsoil, the grain size distribution of the subsoil, the lithology, fissuring and karstification of non-karst and karst rocks, the thickness of all strata above the groundwater surface, the mean annual recharge and artesian pressure in the aquifer (Kouli et al., 2007). The P factor ranges between 1 and 5 (Hölting et al., 1995), with the lowest degree of protection for P=1 and very thick and protective overlying layers for P=5 (Kouli et al., 2007).

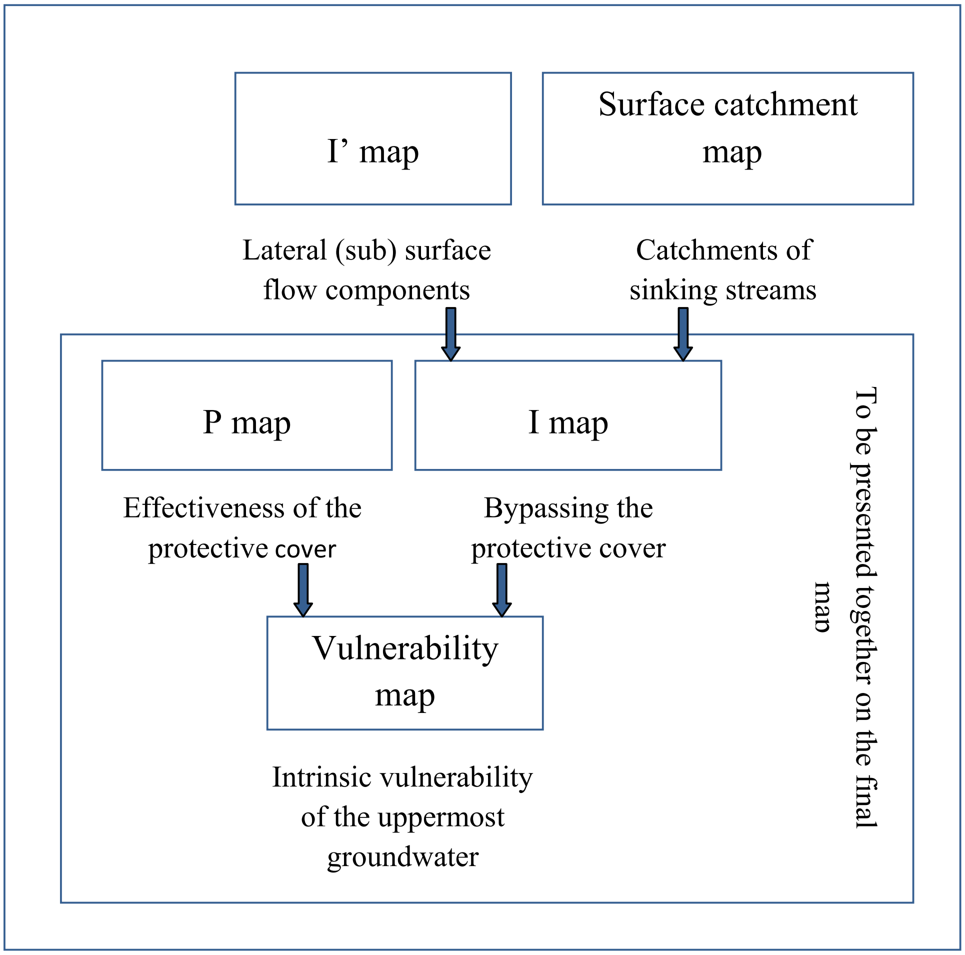


Figure (20): Flow chart for the PI method (Margane, 2003).

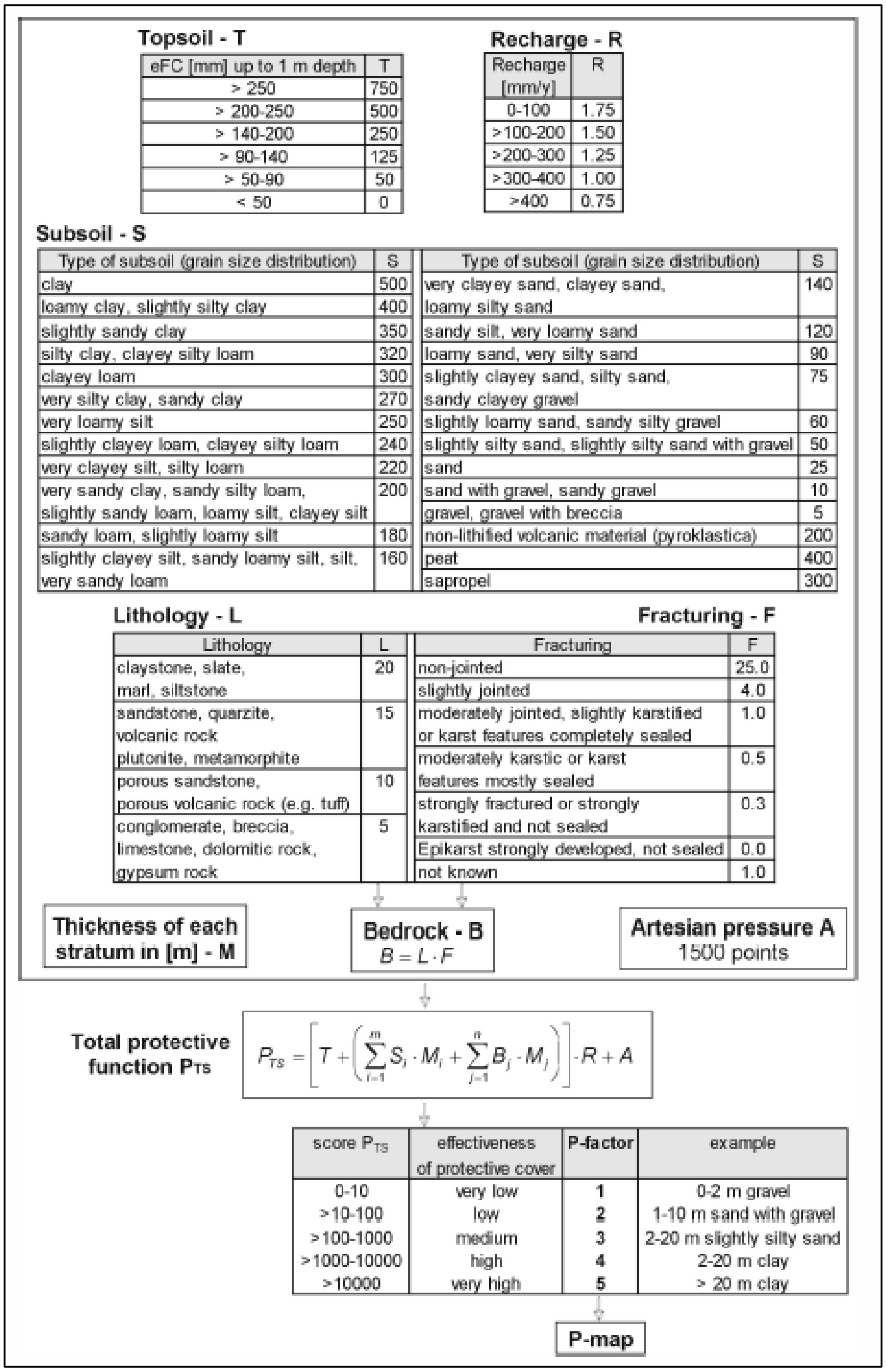
I is a critical factor to be applied in karst areas to describe the infiltration conditions, particularly the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow in the catchment's swallow holes and sinking streams. The factor ranges from 0 to 1. It is 1 if the infiltration occurs diffusely, i.e. on flat, highly permeable and free draining surfaces. In contrast, the protective cover is bypassed completely by swallow holes, through which surface water may directly pass into karst aquifers; where the I factor is 0 in this case. All other areas takes intermediate values (0.2, 0.4, 0.6 and 0.8), depending on the soil properties that control predominant flow processes, the land use, slope gradient, and the position of a given point in or outside the catchment of a sinking stream (Kouli et al., 2007).

The final protection factor Π is the product of P and I (Margane, 2003). It is subdivided into five classes. If Π=1, then there is a low degree of protection and a high vulnerability to contamination. On the other side, if Π=5, then the degree of protection is high and the vulnerability is very low (Vrba and Zaporozec, 1994).

The adopted way for the P factor calculation is shown in figure (21). By multiplying the lithology factor (L) and the factor for degree of karstification and fracturing (F), the bedrock score (B) is obtained. The subsoil and bedrock scores are multiplied by the respective thickness (M) in meters. The total protective function (P_{TS}) is subdivided into five classes, that present the final P factors in the PI method. To be suitable for the West Bank conditions, a simple modification was made in the P factor determination process (HWE, 2009), see table (2).

Table (2): the P factor modification, which is made to suit the West Bank conditions (HWE, 2009).

P_{TS}	Effectiveness of the protective cover	P factor	Example
0-10	Very low	1	0-2 m gravel
>10-100	Low	2	1-10 m sand with gravel
>100-1,500	Medium	3	2-20 m slightly silty sand
>1,500-10,000	High	4	2-20 m clay
>10,000	Very high	5	>20 m clay



Topsoil - T

eFC [mm] up to 1 m depth	T
> 250	750
> 200-250	500
> 140-200	250
> 90-140	125
> 50-90	50
< 50	0

Recharge - R

Recharge [mm/y]	R
0-100	1.75
>100-200	1.50
>200-300	1.25
>300-400	1.00
>400	0.75

Subsoil - S

Type of subsoil (grain size distribution)	S
clay	500
loamy clay, slightly silty clay	400
slightly sandy clay	350
silty clay, clayey silty loam	320
clayey loam	300
very silty clay, sandy clay	270
very loamy silt	250
slightly clayey loam, clayey silty loam	240
very clayey silt, silty loam	220
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200
sandy loam, slightly loamy silt	180
slightly clayey silt, sandy loamy silt, silt, very sandy loam	160

Type of subsoil (grain size distribution)	S
very clayey sand, clayey sand, loamy silty sand	140
sandy silt, very loamy sand	120
loamy sand, very silty sand	90
slightly clayey sand, silty sand, sandy clayey gravel	75
slightly loamy sand, sandy silty gravel	60
slightly silty sand, slightly silty sand with gravel	50
sand	25
sand with gravel, sandy gravel	10
gravel, gravel with breccia	5
non-lithified volcanic material (pyroklastica)	200
peat	400
sapropel	300

Lithology - L

Lithology	L
claystone, slate, marl, siltstone	20
sandstone, quarzite, volcanic rock plutonite, metamorphite	15
porous sandstone, porous volcanic rock (e.g. tuff)	10
conglomerate, breccia, limestone, dolomitic rock, gypsum rock	5

Fracturing - F

Fracturing	F
non-jointed	25.0
slightly jointed	4.0
moderately jointed, slightly karstified or karst features completely sealed	1.0
moderately karstic or karst features mostly sealed	0.5
strongly fractured or strongly karstified and not sealed	0.3
Epikarst strongly developed, not sealed	0.0
not known	1.0

Thickness of each stratum in [m] - M

Bedrock - B

$B = L \cdot F$

Artesian pressure A

1500 points

Total protective function P_{TS}

$$P_{TS} = \left[T + \left(\sum_{i=1}^{m} S_i \cdot M_i + \sum_{j=1}^{n} B_j \cdot M_j \right) \right] \cdot R + A$$

score P_{TS}	effectiveness of protective cover	P-factor	example
0-10	very low	1	0-2 m gravel
>10-100	low	2	1-10 m sand with gravel
>100-1000	medium	3	2-20 m slightly silty sand
>1000-10000	high	4	2-20 m clay
>10000	very high	5	> 20 m clay

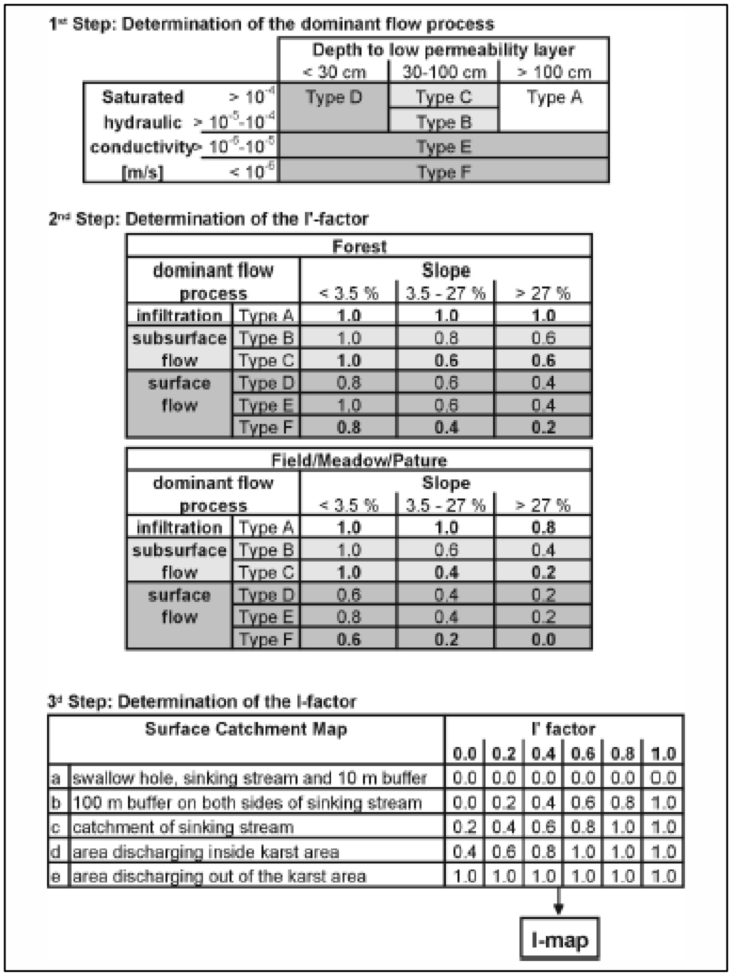
P-map

Figure (21): The sequence of the P factor calculation (Margane, 2003).

The I factor (I map) is obtained by intersecting the (I' map) with the (surface catchment map), see figure (22).

The permeability of the top soil and the presence of permeable layers are the main foundations for the dominant flow process. Subsurface flow takes place in highly permeable soils with low permeable layers, while infiltration predominates if these layers are absent. The dominant flow process was determined by intersecting the ‘topsoil permeability’ and ‘depth to low permeable layers’. Flow process is a function of the saturated hydraulic conductivity (m/s) and the depths to low permeability layers (HWE, 2009). Dominant flow processes also depend on the land use factor and the slope of the land surface. Forests and gentle slopes favor infiltration, while agricultural areas and steep slopes favor lateral flow (HWE, 2009). The (I’ map) is determined by combining the ‘dominant flow process’, ‘land use’ and ‘slope’ (HWE, 2009).

The surface catchment map is based on a digital map that shows the catchment areas of sinking streams disappearing into swallow holes and buffering zones of 10 and 100 meters on both sides of the streams (HWE, 2009).



1st Step: Determination of the dominant flow process

Saturated hydraulic conductivity [m/s]	Depth to low permeability layer < 30 cm	30-100 cm	> 100 cm
> 10^{-4}	Type D	Type C	Type A
> 10^{-5}-10^{-4}		Type B	
> 10^{-6}-10^{-5}	Type E		
< 10^{-6}	Type F		

2nd Step: Determination of the I'-factor

Forest				
dominant flow process		Slope < 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**1.0**
subsurface flow	Type B	1.0	0.8	0.6
	Type C	**1.0**	**0.6**	**0.6**
surface flow	Type D	0.8	0.6	0.4
	Type E	1.0	0.6	0.4
	Type F	**0.8**	**0.4**	**0.2**

Field/Meadow/Pature				
dominant flow process		Slope < 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**0.8**
subsurface flow	Type B	1.0	0.6	0.4
	Type C	**1.0**	**0.4**	**0.2**
surface flow	Type D	0.6	0.4	0.2
	Type E	0.8	0.4	0.2
	Type F	**0.6**	**0.2**	**0.0**

3d Step: Determination of the I-factor

Surface Catchment Map		I' factor **0.0**	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
a	swallow hole, sinking stream and 10 m buffer	0.0	0.0	0.0	0.0	0.0	0.0
b	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
c	catchment of sinking stream	0.2	0.4	0.6	0.8	1.0	1.0
d	area discharging inside karst area	0.4	0.6	0.8	1.0	1.0	1.0
e	area discharging out of the karst area	1.0	1.0	1.0	1.0	1.0	1.0

Figure (22): I factor calculations (Margane, 2003).

The final ∏ map represents the intrinsic vulnerability and the natural protection of the uppermost aquifer. The protection factor, which is the result of P and I multiplication is spatially distributed on the map. Five vulnerability classes are symbolized with colors ranging from red for high vulnerability to blue for low vulnerability (HWE, 2009), see table (3).

Table (3): Legend for the ∏, P and I maps (HWE, 2009).

Color	**∏ map**		**P map**		**I map**	
	GW vulnerability	***∏ factor***	***Protection cover***	***P factor***	***Bypassing degree***	***I factor***
Red	Extreme	0-1	Very low	1	Very high	0-0.2
Orange	High	>1-2	Low	2	High	0.4
Yellow	Moderate	>2-3	Moderate	3	Moderate	0.6
Green	Low	>3-4	High	4	Low	0.8
Blue	Very low	>4-5	Very high	5	Very low	1

CHAPTER FIVE

DEVELOPMENT OF THE GROUNDWATER VULNERABILITY MAP FOR THE WEST BANK

5.1 Development of the Groundwater Vulnerability Map for the West Bank

The PI method will be applied to develop the vulnerability map for the West Bank.

The two factors contained in this method; the protective cover (P factor) and the infiltration (I factor) are mapped separately as individual maps and then integrated to achieve the groundwater vulnerability map.

A code system for the vulnerability controlling parameters, listed under each factor, is developed with the aid of MS Excel and GIS. The West Bank area (5,820 km^2) is converted to a grid of cells which have the same dimensions (0.5km×0.5km). Each cell will carry a specific weighting and rating depending on the data of each parameter. The P value for a cell is multiplied by the I value for the same cell to construct the PI map.

5.2 Determining the P Factor for the West Bank

The P factor gives an indication for the effectiveness of the protective cover as a function of thickness and hydraulic characteristics of the layers between the ground surface and the groundwater surface.

The P map represents the spatial distribution of the P factor and is prepared after applying the mathematical equation (1) shown below.

$$P_{TS} = \left[T + S.M + \left(\sum_{i=1}^{n} B_i \times M_i\right)\right] \times R + A \qquad (1)$$

Where:

P_{TS}: Total protective function

T: Field capacity of the topsoil

S: Grain size distribution for subsoil

M: Thickness of each stratum (m)

B: Bedrock

R: Recharge

A: Artesian pressure

5.2.1 Field Capacity of the Topsoil

It gives an idea about the maximum amount of water that can be held by the topsoil as a function of the topsoil type and the effective field capacity (eFC), see table (4).

Due to lack of information about some soil properties in the study area such as the effective field capacity, some assumptions are made to determine the T values.

Table (4): Effective field capacity for each topsoil type and its corresponding T value

Topsoil type	Measured/Estimated eFC (mm) up to 1m depth	T
Bare Rocks and Desert Lithosols	NA	125
Brown Lithosols & Loessial Arid Brown Soils	140-200	250
Brown Lithosols and Loessial Serozems	90-140	125
Brown Rendzinas & Pale Rendzinas	334	750
Grumusols	460	750
Loessial Serozems	140-200	250
Regosols	NA	125
Terra Rossas, Brown Rendzinas & Pale Rendzinas	446	750

Using GIS, the top soil map was converted to a grid map in which each cell has its own T value, see figure (23).

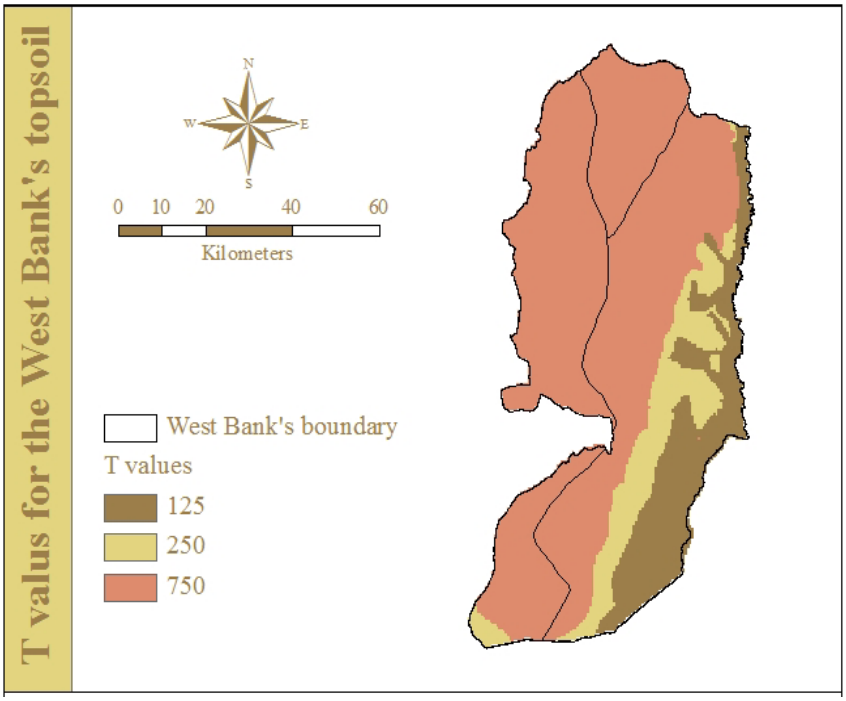


Figure (23): T values for the West Bank

5.2.2 Grain Size Distribution for the Subsoil

The subsoil includes all the layers under the topsoil. It can be classified into gravel, sand, silt and clay.

On the basis of subsoil type, the corresponding S values are determined, see table (5). The M value for each subsoil type is assumed to be 1m. The S value for each cell is then multiplied by its corresponding M value. The S*M grid map is shown in figure (24).

Table (5): Subsoil types and their corresponding S values.

Soil type	Subsoil type	S	M (m)	S×M
Bare Rocks and Desert Lithosols	NA	10	1	10
Brown Lithosols & Loessial Arid Brown Soils	Loamy	250	1	250
Brown Lithosols and Loessial Serozems	Sandy Loam	180	1	180
Brown Rendzinas & Pale Rendzinas	Clay Loam	300	1	300
Grumusols	Clay	500	1	500
Loessial Serozems	Clay	500	1	500
Regosols	Clay Loam	300	1	300
Terra Rossas, Brown Rendzinas & Pale Rendzinas	Clay	500	1	500

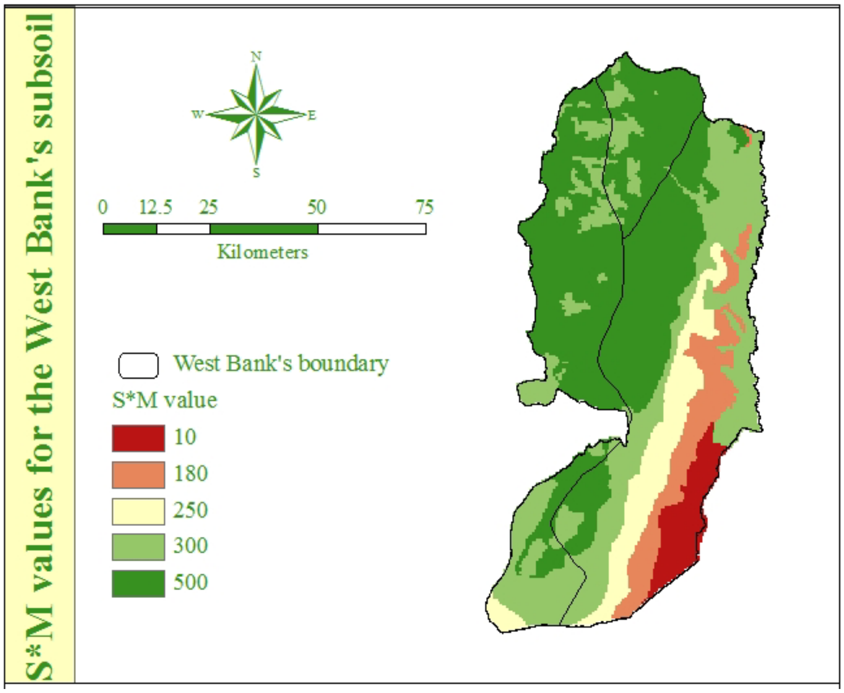


Figure (24): S*M values for the West Bank

5.2.3 Lithology and Fracturing for the Geological Formations

Lithology i.e. (L) is a branch of geology that gives the characteristics of rocks in terms of their structure, color, mineral composition, grain size and arrangements. On the other hand, fracturing (F) describes any local discontinuity in a geological formation, in the shape of faults and joints that divides the rock into two or more pieces. Fractures are commonly caused by stresses exceeding the strength of rocks.

From the geological maps of the West Bank, the outcropping formations, lithology and fracturing for the unsaturated geological formations can be obtained, see table (6).

It should be noticed that the higher the L and F values, the lower the transmissivity and the lower the porosity values of the rocks.

The bedrock value (B) can then be calculated by multiplying the lithology and fracturing factors. The thickness for each geological stratum (M) in meters is estimated using the stratigraphical section of the West Bank and then multiplied by B. The B*M grid map is presented in figure (25).

Table (6): Lithology and fracturing values for the unsaturated layers

Formation	L	F	B= L×F	M (m)	B×M
Quaternary	5	4	20	50	1000
Oligocene_Miocene_Pliocene	5	20	100	200	20,000
Eocene	5	0.5	2.5	150	375
Senonian	20	25	500	200	100,000
Turonian	5	0.5	2.5	130	325
Cenomanian	5	0.3	1.5	250	375
Lower Cenomanian	5	0.4	2	400	800
Albian	5	0.3	1.5	200	300
Lower Cretaceous	20	25	500	250	125,000
Jurassic	5	0.5	2.5	130	325

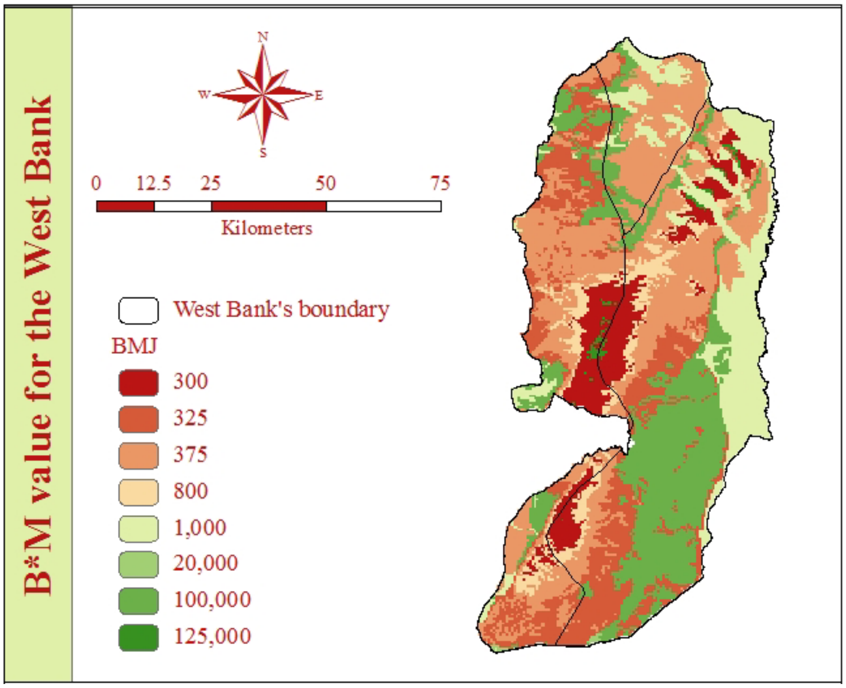


Figure (25): B*M value for the West Bank

5.2.4 Groundwater Recharge and the R Value

Recharge is the amount of water that percolates from the ground surface to an aquifer. Rainfall-recharge equations, which are used in SUSMAQ project in the West Bank, are adopted to determine the recharge values depending on the outcropping formations of the study area. These equations are:

$$R = 0.6\,(P-285) \quad \text{if } P > 700 \text{ mm}$$

$$R = 0.46\,(P-159) \quad \text{if } 700 \text{ mm} > P > 456 \text{ mm}$$

$$R = 0.3\,(P) \quad \text{if } 456 \text{ mm} > P$$

Where:

P: annual rainfall in mm

R: annual recharge from rainfall in mm

The mean annual rainfall classes and their corresponding recharge and R values for the West Bank are listed in table (7). Figure (26) represents the R value grid map. R values are obtained based on figure (21).

Table (7): Groundwater recharge for different mean annual rainfall and their corresponding R values.

Mean annual rainfall (mm)	**Recharge (mm/yr)**	**R values**
0-100	0-30	1.75
100-150	30-45	1.75
150-200	45-60	1.75
200-250	60-75	1.75
250-300	75-90	1.75
300-350	90-105	1.75
350-400	105-120	1.50
400-450	120-135	1.50
450-500	135-157	1.50
500-550	157-180	1.50
550-600	180-200	1.50
600-700	200-250	1.25
700-1,000	250-429	1.00

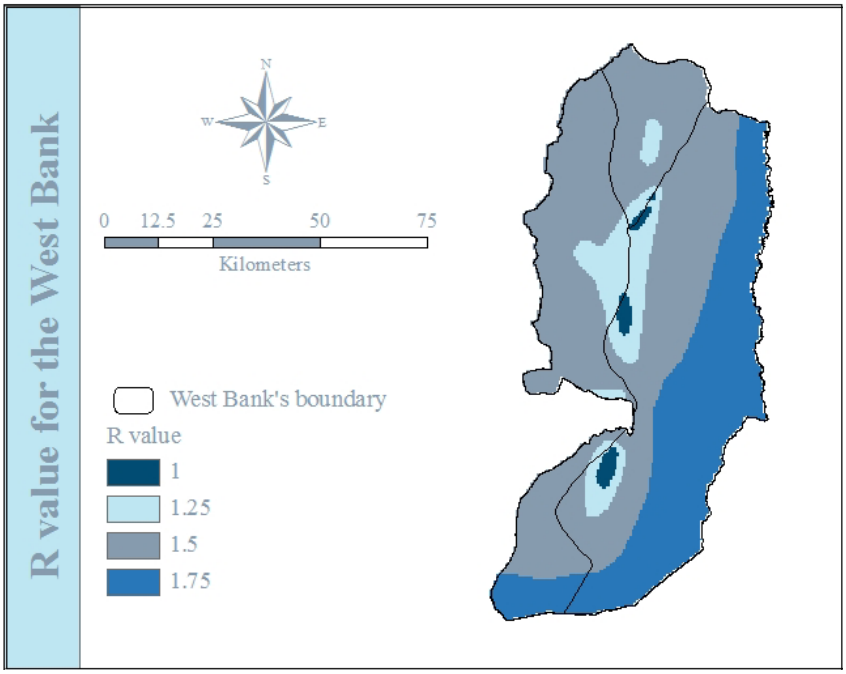


Figure (26): R values for the West Bank

5.2.5 Artesian Pressure

It is the pressure exerted by the vertical water column extending up to the surface of the water table. Taking the outcropping formations as a foundation, the aquifer type is determined, table (8). If the aquifer is confined, A=1500 otherwise A=0, see figure (27).

Table (8): Aquifer types in the West Bank

Formation	Aquifer type	A
Quaternary	Unconfined	0
Oligocene_Miocene_Pliocene	Confined	1500
Eocene	Unconfined	0
Senonian	Confined	1500
Turonian	Confined	1500
Cenomanian	Unconfined	0
Lower Cenomanian	Confined	1500
Albian	Unconfined	0
Lower Cretaceous	Unconfined	0
Jurassic	Confined	1500

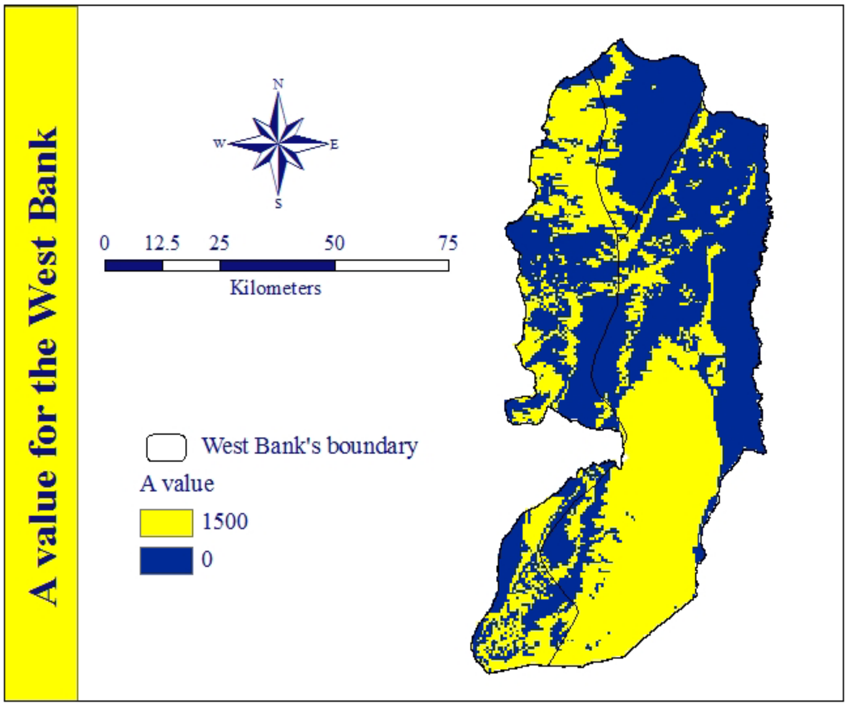


Figure (27): Artesian pressure grid map for the West Bank

5.2.6 Total Protective Function

The P_{TS} value for each cell is calculated using equation (1) and the grid maps are presented in figures (23) through (27).

After modifying P_{TS} values to suit the West Bank's conditions, table (2), the P factor is determined and presented in the P grid map, figure (28).

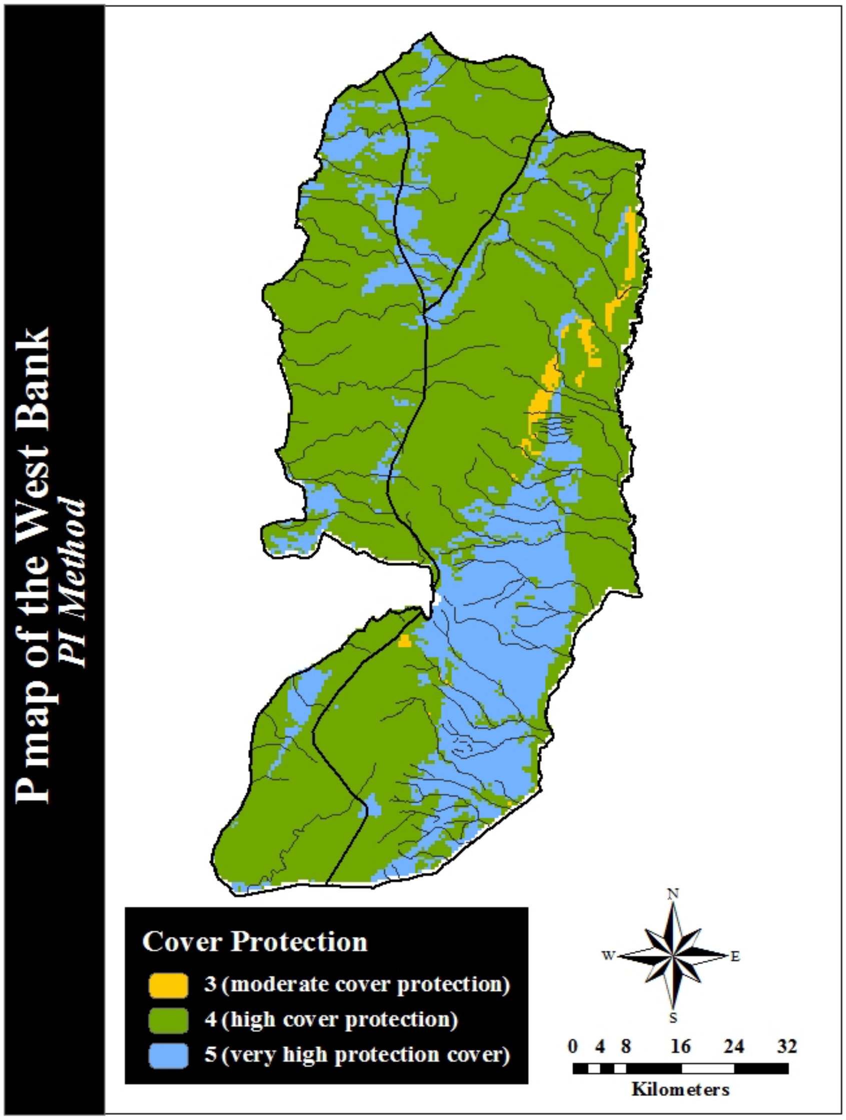


Figure (28): The P factor map for the West Bank

From the previous map and referring to the legend illustrated in table (3), it is found that about 1.3% of the total area has a moderate cover protection, 74.4% has a high protection cover and 24.3% has a very high protection cover.

5.3 Determining the I Factor for the West Bank

The I factor, which gives an indication about the degree to which the protective cover is laterally bypassed within the catchment of a sinking stream, is derived by intersecting land use, slope, and dominant flow process evaluated under the surface catchment map. After achieving the I factor, the I grid map is prepared.

5.3.1 Determination of the Dominant Flow Processes

The soil map used to determine the T value is also used here to determine the dominant flow which is evaluated on the basis of the permeability of the topsoil and the presence of low permeable layers. Infiltration takes place if low permeable layers are absent, while the subsurface flow is dominant in high permeable soils with low permeable layers. The dominant flow process for each soil type is estimated and presented in table (9) and figure (29).

Table (9): Dominant flow for different soil types in the West Bank

Soil type	Dominant Flow	Flow type
Bare Rocks and Desert Lithosols	Saturated Surface Flow	D
Brown Lithosols & Loessial Arid Brown Soils	Saturated Surface Flow	D
Brown Lithosols and Loessial Serozems	Saturated Surface Flow	D
Brown Rendzinas & Pale Rendzinas	Infiltration and Subsequent Percolation	F
Grumusols	Hortonian Surface Flow	F
Loessial Serozems	Saturated Surface Flow	D
Regosols	Hortonian Surface Flow	F
Terra Rossas, Brown Rendzinas & Pale Rendzinas	Hortonian Surface Flow	F

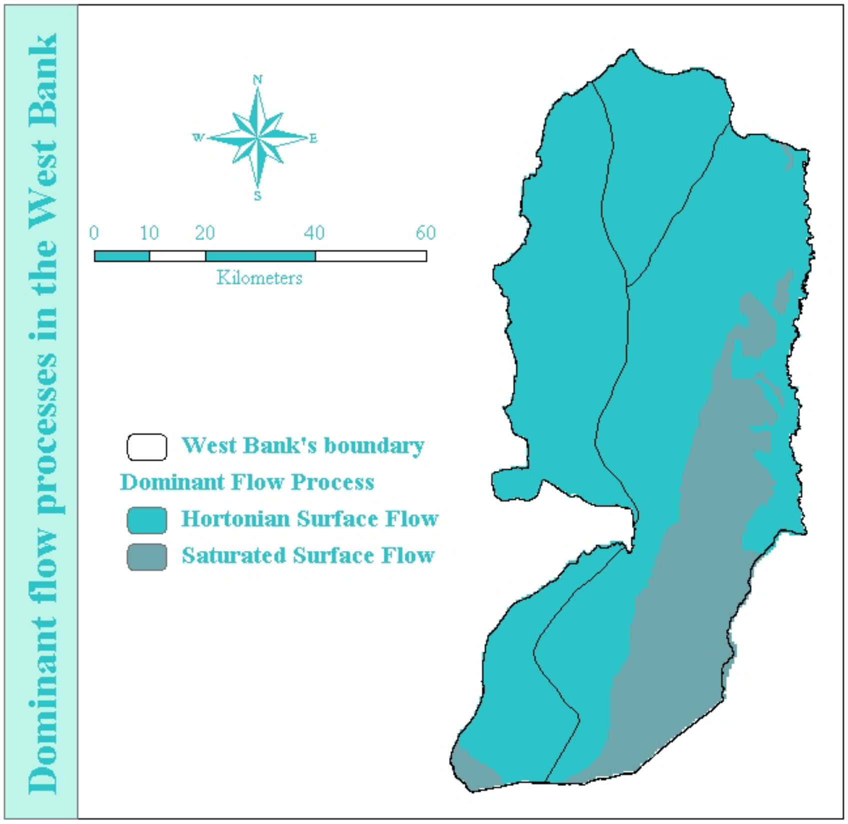


Figure (29): Dominant flow processes in the West Bank

5.3.2 Slope

A slope grid map is created on the basis of the West Bank's contour map and then classified into three classes as suggested by the COST Action 620, see figure (30).

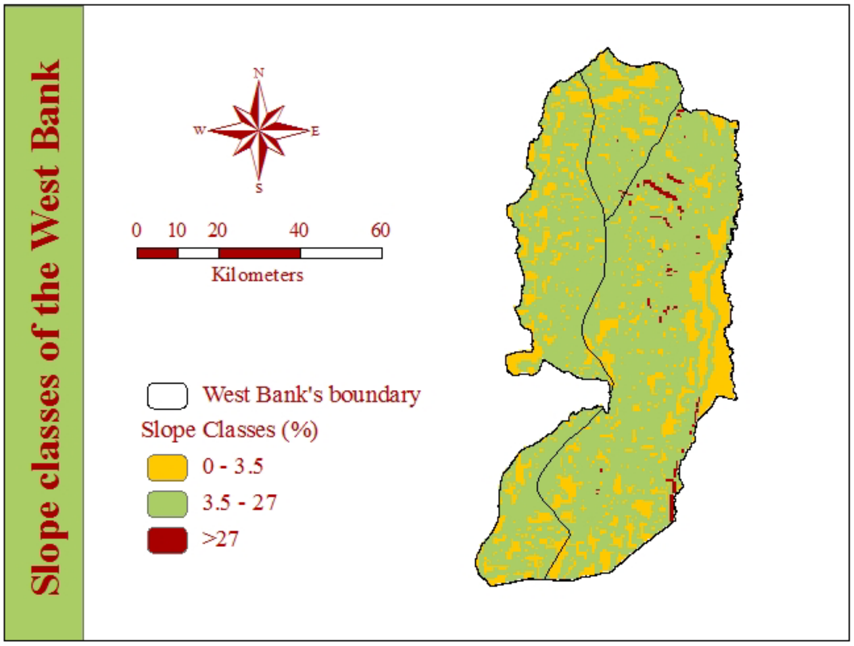


Figure (30): Slope classes of the West Bank

5.3.3 Vegetation

Following the procedure of COST Action 620, the West Bank's land use map is reclassified into two land use types; Forests and Field/Meadow/Pasture, see figure (31).

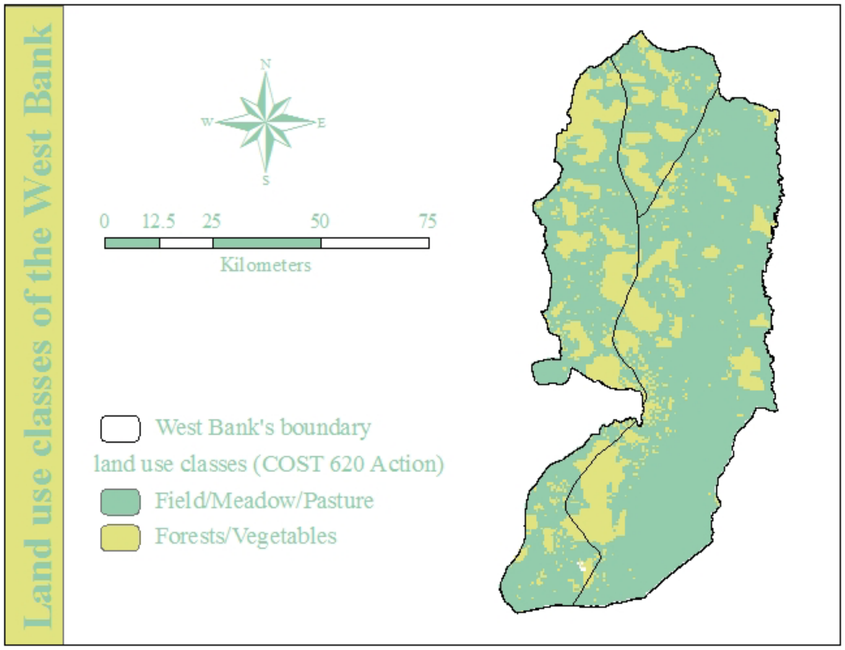


Figure (31): West Bank's land use map according to COST Action 620

5.3.4 The I’ Factor

It expresses the direct infiltration in relation to surface and lateral subsurface flow. The controlling factors are soil properties, slope and vegetation, tables (10) and (11). Infiltration takes place in areas of gentle slopes and forests, while lateral flow is dominant in steep slopes and agricultural areas. The spatial distribution of the I’ factor is shown on the I’ map, see figure (32).

Table (10): I’ factor for forests

Dominant Flow Type	slope		
	0-3.5%	**3.5-27%**	**> 27%**
A	1.0	1.0	1.0
D	0.8	0.6	0.4
F	0.8	0.4	0.2

Table (11): I’ factor for field/meadow/pasture conditions

Dominant Flow Type	slope		
	0-3.5%	**3.5-27%**	**> 27%**
A	1.0	1.0	1.0
D	0.6	0.4	0.2
F	0.6	0.2	0.0

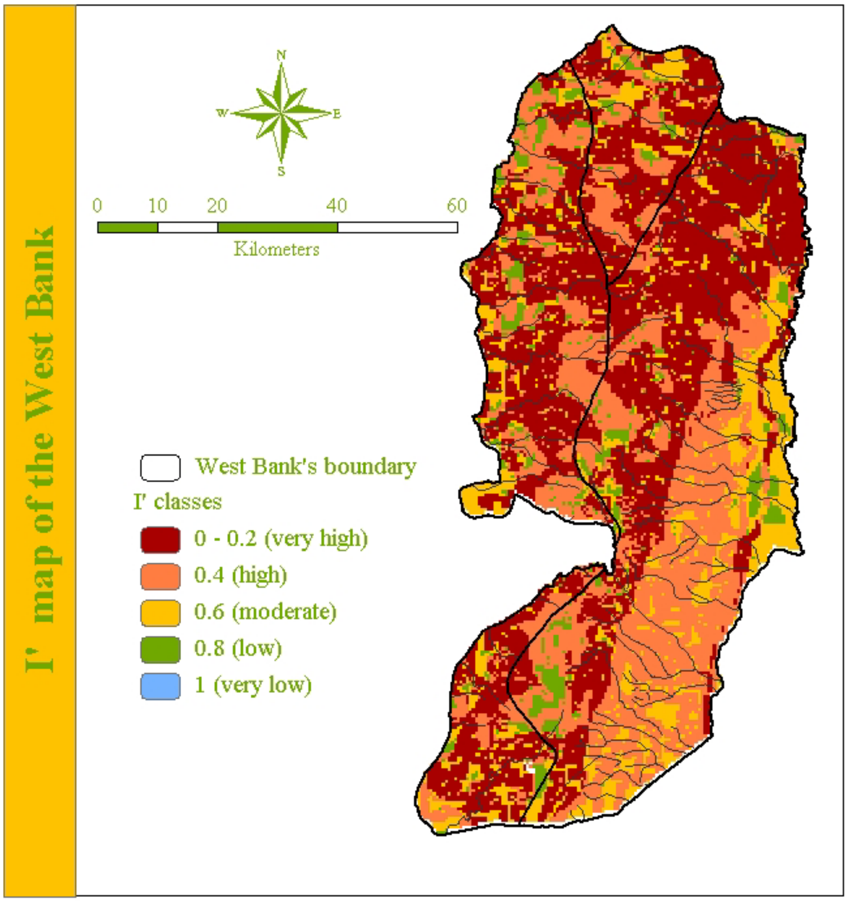


Figure (32): I' map for the West Bank

5.3.5 Surface Catchment Map

The surface catchment areas of sinking streams disappearing into swallow holes and the 10 m and 100 m buffering on both sides of the sinking streams are presented in the surface catchment map, see figure (33).

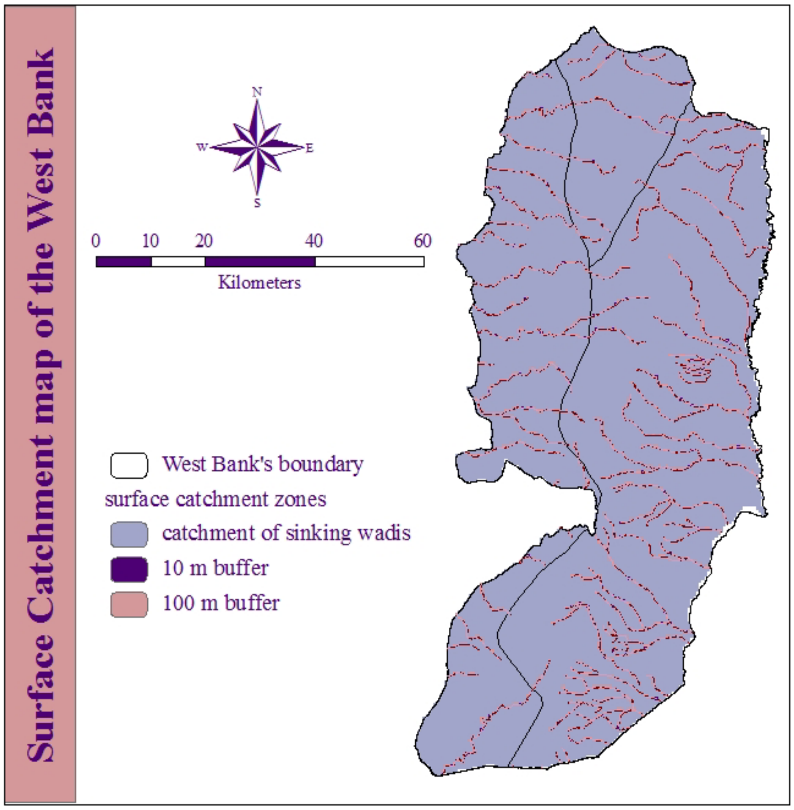


Figure (33): Surface catchment map for the West Bank

By intersecting the I’ map with the surface catchment map, the I map, which gives an indication about the degree to which the protective cover is laterally bypassed, can be obtained. Table (12) describes the determination of the I factor which is spatially presented in figure (34).

Table (12): I factor determination

Surface Catchment Map		**I’-Factor**					
		0.0	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
a	10 m buffer on both sides of sinking stream	0.0	0.0	0.0	0.0	0.0	0.0
b	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
c	Catchment of sinking wadi	0.2	0.4	0.6	0.8	1.0	1.0

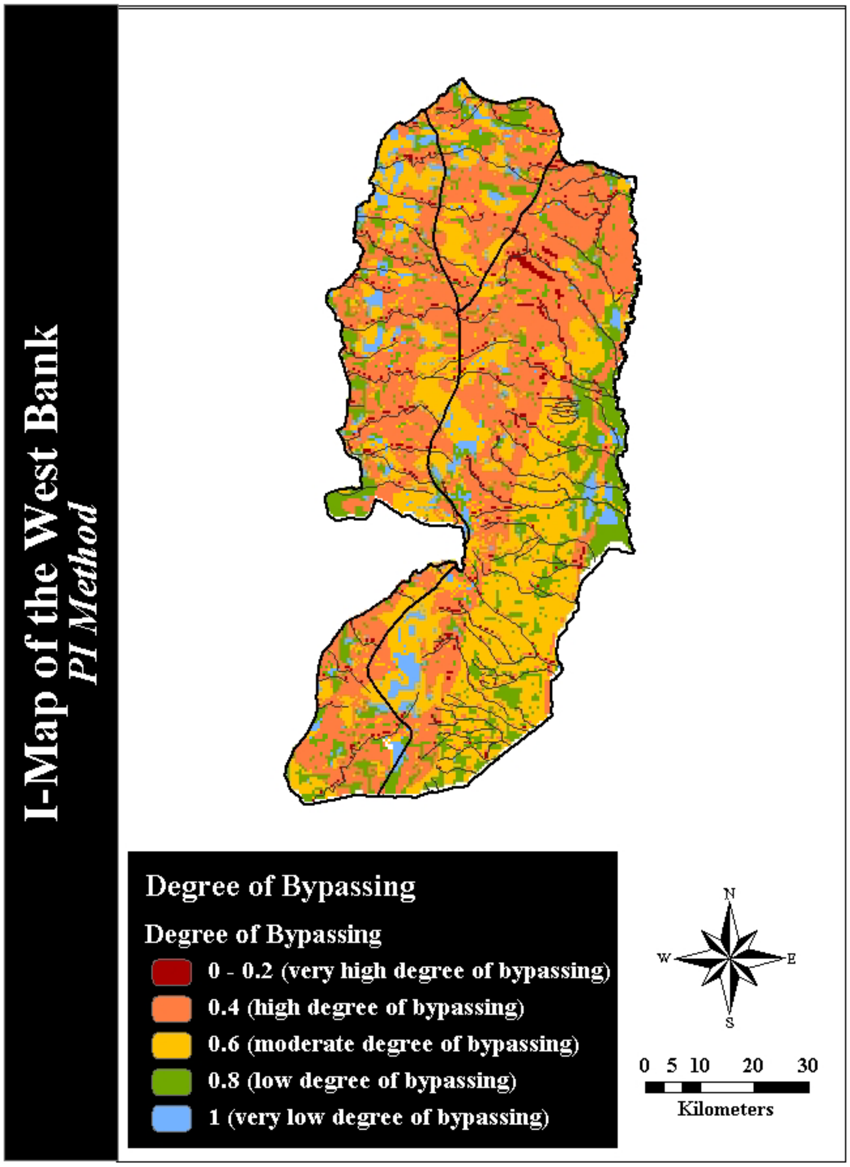


Figure (34): I factor map for the West Bank

From the previous map and referring to the legend illustrated in table (3), it can be seen that 45.8% of the area has a high to very high degree of bypassing, 32.9% has a moderate degree of bypassing and 21.3% has a low to very low degree of bypassing.

5.4 Compilation of the Groundwater Vulnerability Map

The vulnerability map, which reflects the intrinsic vulnerability and , in the contrast sense, the natural protection of the uppermost aquifer, shows the spatial distribution of the protection factor $\prod$, which is obtained by the multiplication of the P and I factors; $\prod = P \times I$. The $\prod$ values range between 0.0 and 5.0, with high values representing low vulnerability and high degree of natural protection.

The $\prod$ map for the West Bank is illustrated in figure (35), from which it can be seen that 47% of the study area has an extreme to high groundwater vulnerability, 32% has a moderate vulnerability and 21% has a low to very low vulnerability.

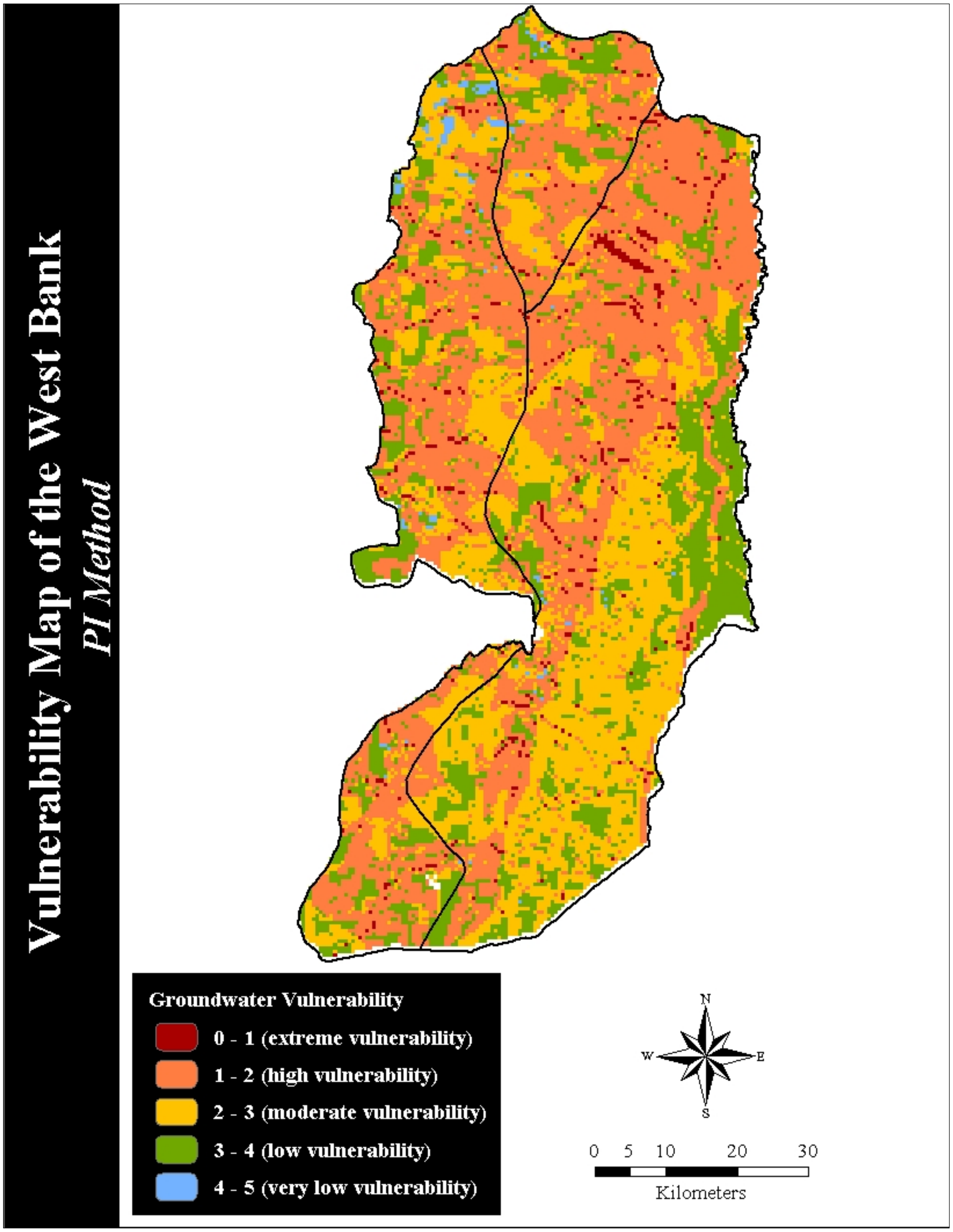


Figure (35): Groundwater vulnerability map for the West Bank according to the PI method

5.5 Discussion of the Results

Referring to figure (28) and the legend illustrated in table (3), it can be seen that the majority of the area of the West Bank, i.e. about 75%, is under a high degree of protection of groundwater against contamination.

The degree to which the protection cover is laterally bypassed by contaminants ranges from very high, especially near sinking streams, to very low.

The groundwater vulnerability map illustrated in figure (35), shows that about 47% of the study area (2610 km^2) has an extreme to high vulnerability to contamination, 32% (1777 km^2) has a moderate vulnerability and 21% (1166 km^2) has a low to very low vulnerability.

With respect to groundwater vulnerability, the high risk situation occurs close to swallow holes and sinking streams.

According to land use activities, it can be clearly seen that most areas under irrigated vegetables farming are of low vulnerability, while those under permanent cropping, i.e. grapes, olives, citrus and fruits, are of moderate to low vulnerability. Rough grazing lands have high vulnerability in the northern parts of the area and moderate to low vulnerability in the south-eastern parts, see table (13) and figures (36) through (40).

Table (13): Groundwater vulnerability according to land use activities (% area)

	Groundwater Vulnerability		
Land Use Activities	High	Moderate	Low
Arable Lands (Supporting Grains)	39	24	37
Irrigated Farming (Supporting Vegetables)	20	27	53
Permanent Crops (Olives, Grapes, Citrus and Other Fruits)	31	21	48
Rough Grazing	43	24	33

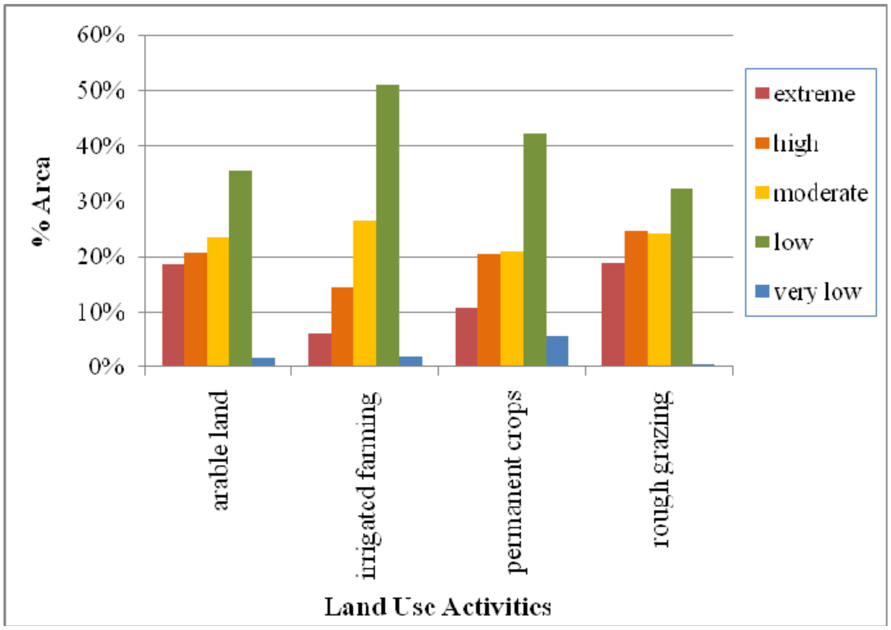


Figure (36): Groundwater vulnerability according to land use activities

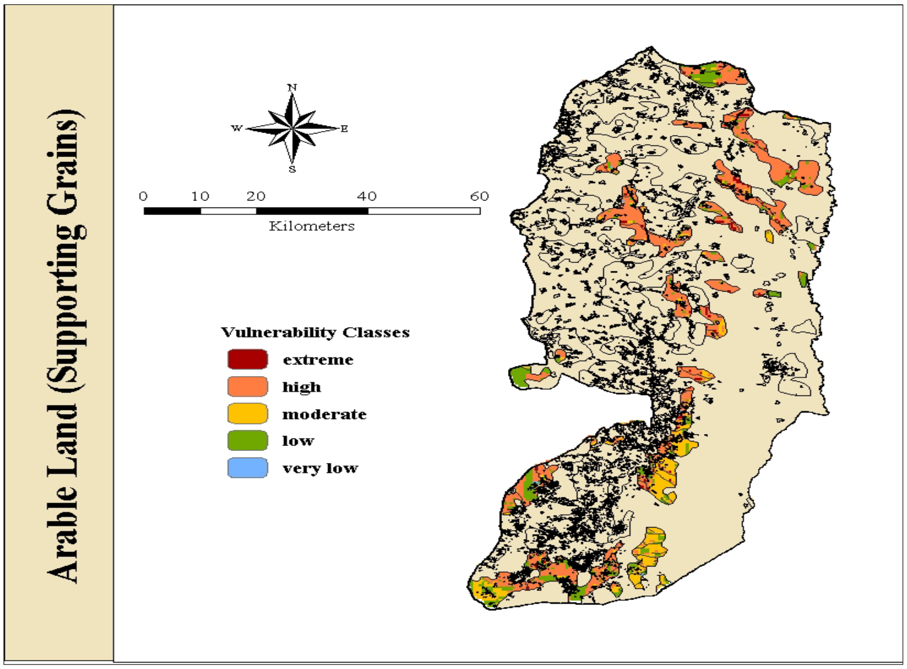


Figure (37): Groundwater vulnerability (Arable Lands)

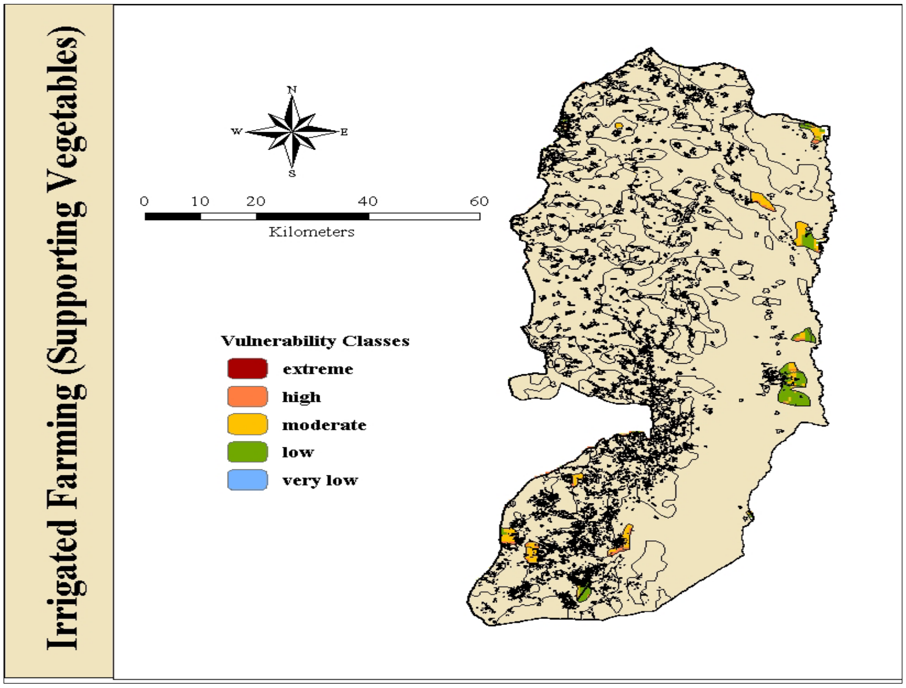


Figure (38): Groundwater vulnerability (Irrigated Farming)

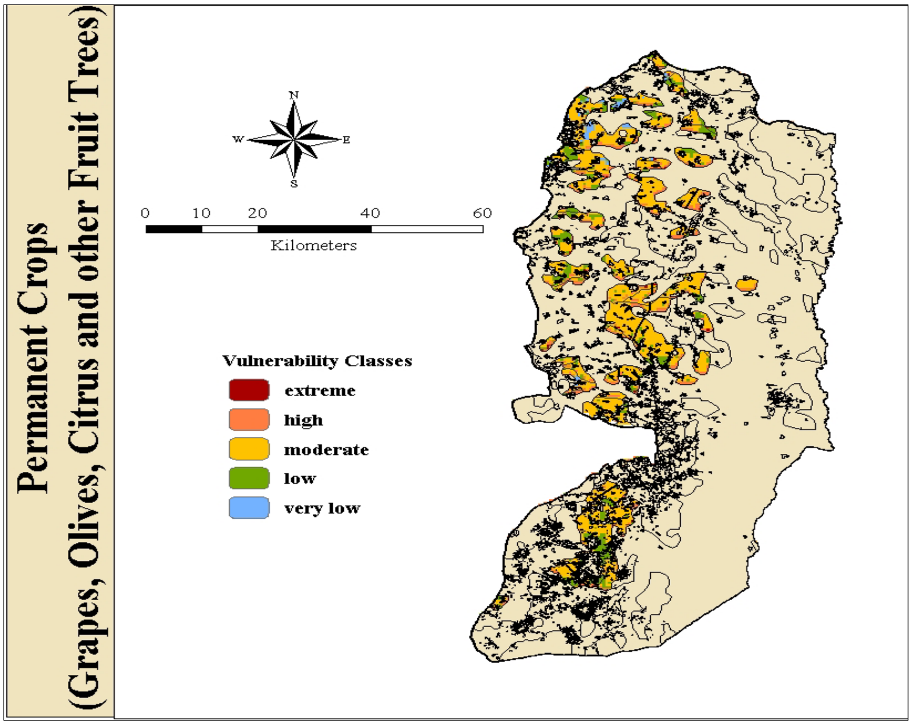


Figure (39): Groundwater vulnerability (Permanent Crops)

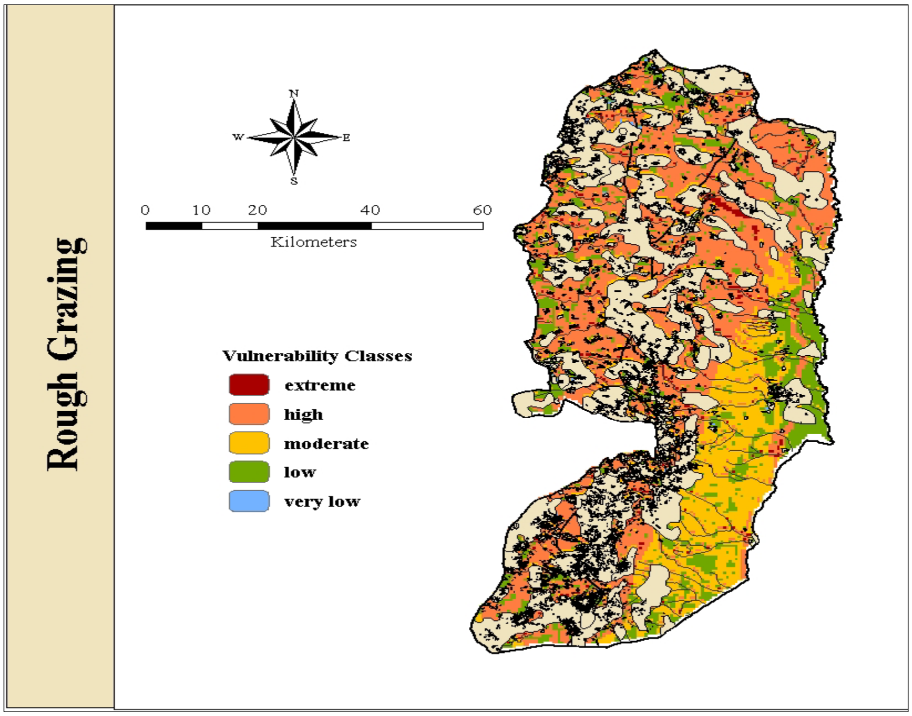


Figure (40): Groundwater vulnerability (Rough Grazing)

Groundwater vulnerability analysis was carried out for the aquifer basins, see table (14) and figures (41) and (42). The analysis shows that the Eastern groundwater basin has the highest vulnerability to contamination compared to the other two basins.

Table (14): Groundwater vulnerability according to aquifer basins (% area)

	Groundwater Vulnerability		
Aquifer Basins	High	Moderate	Low
Eastern	39	26	35
North-Eastern	33	28	39
Western	29	27	44

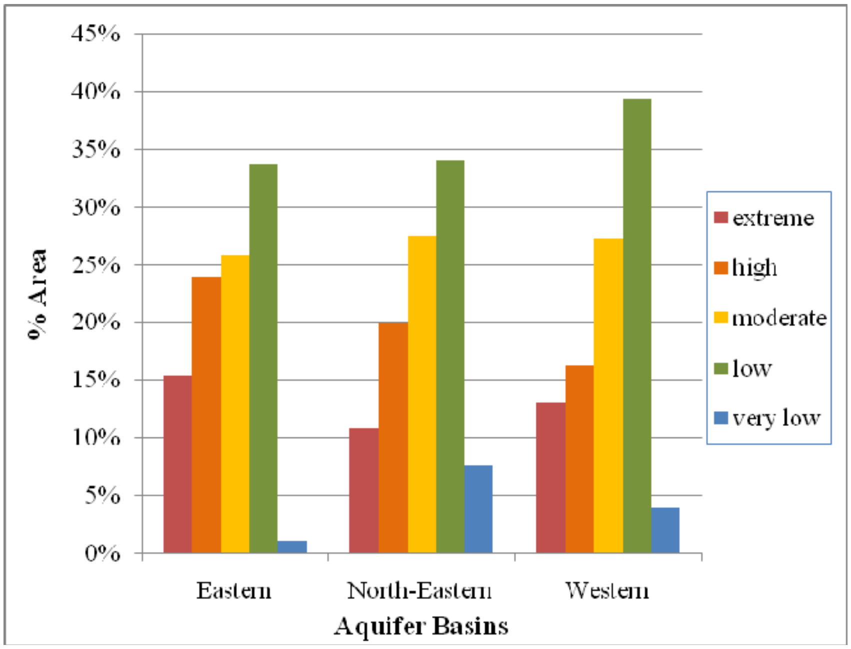


Figure (41): Groundwater vulnerability according to aquifer basins

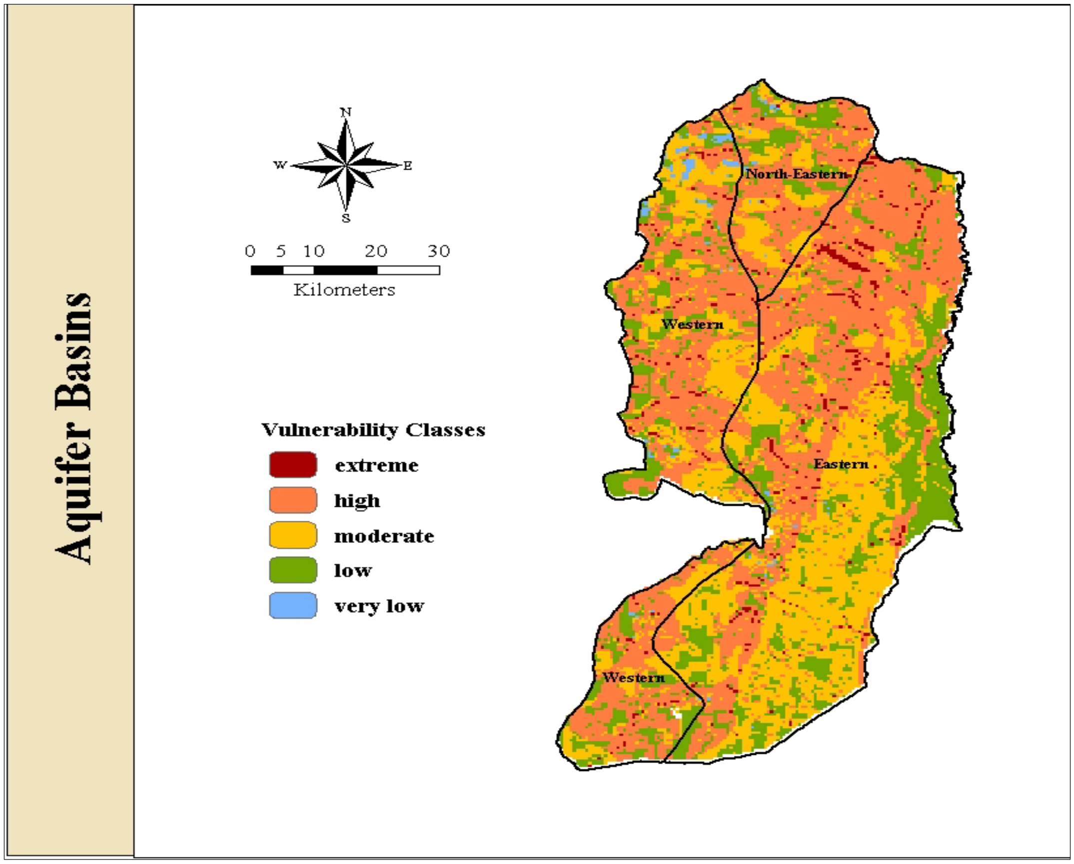


Figure (42): Groundwater vulnerability (Aquifer Basins)

Groundwater vulnerability based on the West Banks districts was carried out, see table (15) and figures (43) and (44). The highest groundwater vulnerability was observed in Tubas, Jerusalem, Nablus, Ramallah and Al-bireh and Bethlehem districts.

Table (15): Groundwater vulnerability according to West Banks districts (% area)

	Groundwater Vulnerability		
Districts	High	Moderate	Low
Jenin	31	28	41
Tubas	43	18	39
Tulkarm	29	23	48
Nablus	41	24	35
Qalqiliya	17	34	49
Salfit	38	19	43
Ramallah and Albireh	40	27	33
Jericho	31	36	33
Jerusalem	42	26	32
Bethlehem	39	24	37
Hebron	28	29	43

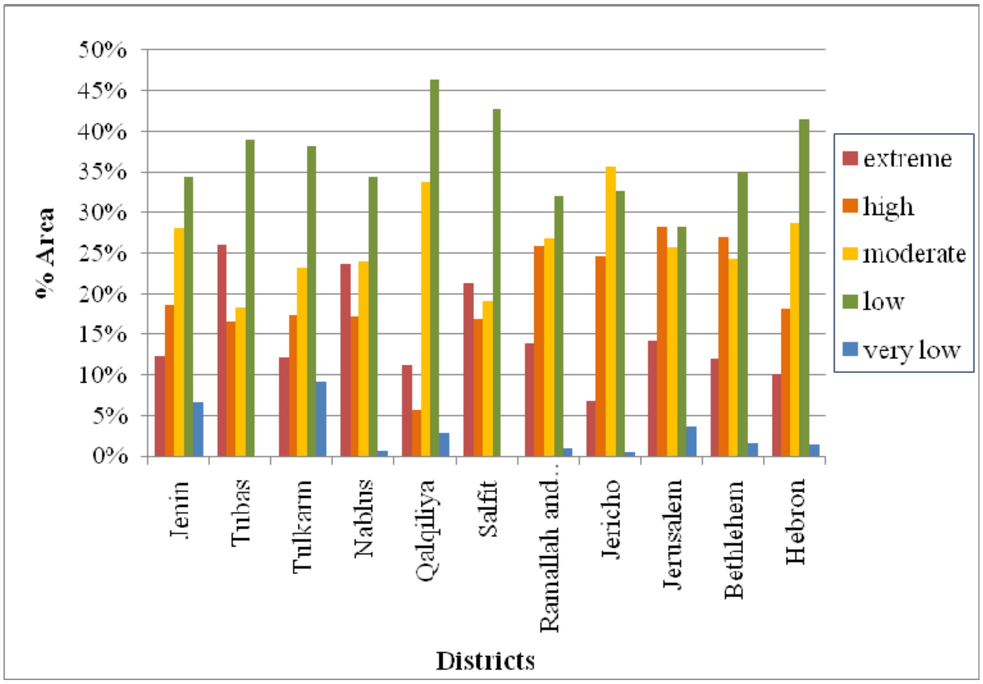


Figure (43): Groundwater vulnerability according to West Banks districts

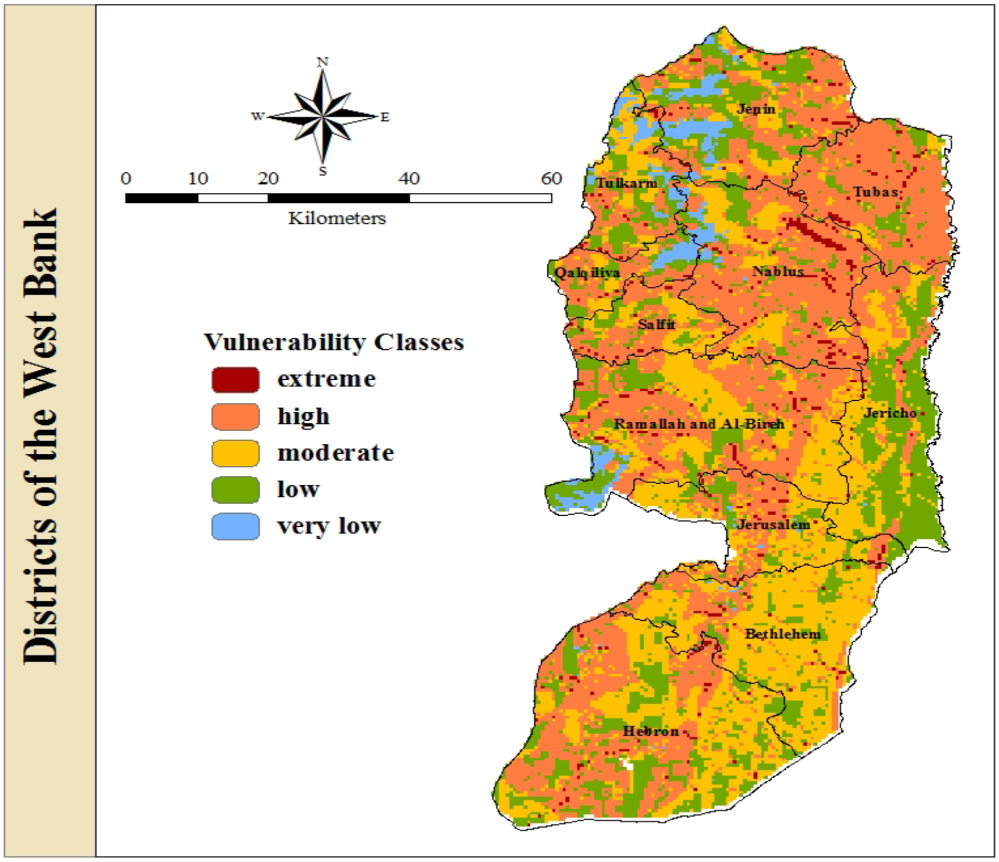


Figure (44): Groundwater vulnerability (West Banks districts)

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In light of the previous analyses and discussions, the following are the research main conclusions:

- GIS is an effective tool for analyzing the spatial variability of the key parameters affecting groundwater vulnerability. Additionally, it facilitates the analysis of the interrelated relationships between the different parameters.
- The PI method, which is used for assessing groundwater vulnerability to contamination, can be applied to all aquifer types, though provides special methodological tools for karst.
- Intrinsic vulnerability mapping is not a stand-alone element, but should be integrated into a comprehensive groundwater protection scheme.
- The derived vulnerability map can be used to find a balance between human activities and economic interests on one hand and groundwater protection on the other hand.
- The vulnerability maps neither replace detailed hydrogeological site assessment for specific issues, nor replace water quality monitoring on a regular basis.
- 21% and 47% of the West Bank is under low and high vulnerability of groundwater contamination, respectively. While 32% of the area is under moderate vulnerability.

6.2 Recommendations

The following recommendations can be drawn out of this research:

- Since the study focused on intrinsic groundwater vulnerability to contamination, specific vulnerability assessments are recommended for delineating areas with high potential for specific contamination.
- Palestinian authorities that deal with planning issues such as the Palestinian Water Authority, the Environmental Quality Authority and the Ministry of Planning, have to take the issue of groundwater protection into consideration when deciding about locations and conditions for the establishment of facilities and activities which are possibly hazardous to groundwater, such as waste disposal sites and sewage treatment plants and sewer mains. By locating such sites in areas where a contamination of the groundwater resources is likely not to occur, a deterioration of the groundwater resources can be actively avoided.

References

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جامعة النجاح الوطنية
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تقييم و وضع خرائط لحساسية المياه الجوفية للتلوث باستخدام طريقة ال (PI)، الضفة الغربية، فلسطين

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الملخص

تشكل المياه الجوفية و خاصة الأحواض الكارستية مصدراً مهماً للمياه العذبة بالنسبة للفلسطينيين. زاد الضغط الكمي و النوعي في العقود القليلة الماضية على المياه الجوفية نتيجة الاستغلال البشري مما شكل تهديدا حقيقياً لتلوث هذه المصادر. تعتبر الحماية و الإدارة المثلى لمصادر المياه الجوفية في الطبقات الصخرية المائية الكارستية أولوية في كل من البلدان الصناعية و النامية، حيث تبدأ من تقييم حساسية هذه المصادر للبيئة و الظروف المحيطة.

تسعى هذه الدراسة لإنتاج خريطة توضح قابلية المياه الجوفية في الضفة الغربية للتلوث، موضحة المناطق الأكثر عرضة للتلوث على أساس الظروف المائية و الجيولوجية. لتحقيق هذا الهدف فقد تم تبني طريقة ال(PI) بالاستعانة بنظام المعلومات الجغرافية (GIS). تمتاز الطريقة المستخدمة بأنها تأخذ بعين الاعتبار طبيعة طبقات المياه الجوفية الكارستية. تم تجميع البيانات الجيولوجية، والهيدرولوجية، والهيدروجيولوجية، و البيانات المناخية بالإضافة إلى استخدامات الأراضي بصيغة خرائط (GIS) لاستخدامها في إنشاء خريطة قابلية التلوث لمنطقة الدراسة.

تشير النتائج التي تم الحصول عليها من هذه الدراسة إلى أن حوالي 47% من مياه الضفة الغربية الجوفية لها قابلية عالية للتلوث، بينما 32% لها قابلية متوسطة، فيما تشكل المياه ذات القابلية الأضعف للتلوث ما نسبته 21% .