An-Najah National University
Faculty of Graduate Studies

GIS-BASED MODELING OF GROUNDWATER RECHARGE FOR THE WEST BANK

By

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Dedicated to

My parents

In the loving memory of my brother Mo’tasem, I would like to dedicate this humble work to his soul. Mo’tasem had the rare gift of highly sensitive social perceptions. He strove for perfection in education as evidenced by the remarkable achievements throughout his studentship life.

Acknowledgments

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الإقـــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

GIS-BASED MODELING
OF GROUNDW ATER RECHARGE FOR THE WEST BANK

اقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وان هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أية درجة علميـــة أو بحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

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.

Student's name: **اسم الطالب:**

Signature: **التوقيع:**

Date: **التاريخ:**

List of abbreviations

CRD	Cumulative Rainfall Departure
ES	Soil Surface
ET0	Reference Crop Potential Evapotranspiration
ETC	Potential Transpiration of the crop
FRACSTOR	An Empirical Factor used to define the proportion of the increase in moisture
In	Infiltration
K'S	Evaporation Stress Coefficient
KC	Crop Coefficient
KE	Evaporation Coefficient
Ks	Soil Stress Coefficient
PMO	Palestinian Meteorological Office
NSSS	Near Surface Soil Storage
P	A factor between 0.2 and 0.7
PE	Potential Evaporation
PWA	Palestinian Water Authority
RAW	Readily Available Water
RCH	Recharge
REW	Readily Evaporable Water

SMD	Soil Moisture Deficit
SUSMAQ	Sustainable Management of the West Bank and Gaza Aquifers
SWB	Soil Water Balance
TAW	Total Available Water
TEW	Total Evaporable Water
WESI	Water and Environmental Studies Institute
WTF	Water Table Fluctuation
ZE	Depth of the surface soil layer subject to drying by evaporation
Zr	Root Depth
θ_{FC}	Field Capacity
θ_{WP}	Wilting Point

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GIS-BASED MODELING OF GROUNDWATER RECHARGE FOR THE WEST BANK

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Abstract

Groundwater is the major source of water for the Palestinians. Efficient management of this resource requires a good understanding of its status. This understanding necessitates a characterization of the utilizable quantities and the corresponding qualities. This thesis focuses on the quantification of groundwater recharge for the entire West Bank and for each aquifer using the Soil Moisture Deficit (SMD) method. The SMD method is the most applicable method for recharge estimation under arid and semi-arid conditions. ModelBuilder of GIS was utilized to facilitate the recharge quantification and to efficiently account for the spatiality inherent in recharge. Results confirm that the highest recharge occurs in the North-West of the West Bank and the lowest in the South-East. The long term average recharge for the entire West Bank was calculated based on the available historical records that start from 1975 to 1997. The results of the recharge for the entire West Bank equals 610 mcm. And the total annual recharge for the entire West Bank is 852 mcm for the year 2004. Overall, the recommendations call for an immediate intervention to study scenario analysis such as climatic change and its impact

is required to predict the recharge behavior in the future to get effective groundwater modeling and management.

CHAPTER ONE

INTRODUCTION

1.1General Background

Groundwater is an important source for water supply due to its wide existence and good quality. The quality of groundwater is usually good, and it does normally require much treatment compared to surface water to make it safe for drinking. The soil and rocks through which the groundwater flows helps to remove pollutants (UK Groundwater Forum, 2004). It is a natural resource that plays a vital role in the society, economy and ecology development. However, with population increase and the urbanization coupled with agricultural and industrial growth, the over exploitation of groundwater has resulted in many serious problems such as severe decline of water table, land subsidence, and seawater intrusion (Shu Long-cang et al., 2003).

Groundwater makes up nearly 70% of all the world's freshwater where only 0.2% is found in lakes, streams or rivers and 30% is bound up in snow and ice on mountains and in the polar regions. Since rivers and lakes tend to be supported by groundwater, it is not an exaggeration to say that almost all the water we use for agriculture, industry and domestic purposes is either groundwater or was originated from groundwater at some stage in the water cycle (UK Groundwater Forum, 2004).

Groundwater recharge is that amount of surface water which reaches the aquifer either by direct contact in the riparian zone or by downward percolation through the overlying zone of unsaturation. It is, thus, the quantity which may in the long term, be available for abstraction and which is of a prime importance in the assessment of the potential of groundwater resources.

Practically, recharge cannot be measured directly and so methods of estimation must be devised (Rushton and Ward, 1979).

An adequate representation of the recharge component is essential for any groundwater model. Recharge is viewed as a function of effective rainfall (precipitation minus evaporation) which is distributed according to land-use categories and soil types (Rushton and Ward, 1979).

Quantification of the rate of natural groundwater recharge is a basic pre-requisite for efficient groundwater management. It is particularly important in regions with large demands for groundwater supplies, where such resources are the key to economic development (Kumar, 2003).

With increasing demand on water supplies, it is important to consider avenues for enhancing groundwater recharge. With drought threatening water supply levels, available water quantity becomes a concern. Generally, land development continues to increase and this in turn leads to a decrease in the area of pervious ground surface that is available for natural recharge (Artificial Recharge of Groundwater, 1997).

Water demand in the West Bank is expected to increase substantially in the future by more than 50% until year 2020(Froukh, 2003). According to the 1993 Oslo Accords, the Palestinians may obtain additional volumes of water from the Eastern Basin to satisfy part of the increasing demand. In light of this, the Eastern Basin is expected to encounter sever drawdown which may lead to the depletion in water storage and the deterioration in the water quality due to the increase in salinity. Therefore, it is highly recommended to implement a long-term management plan for water extraction and to carry out a regular monitoring program on both water elevations and water quality in order to sustain this resource (Froukh, 2003).

In Palestine, as in many other countries, water is the most precious natural resource and its relative scarcity (due to the limited accessibility and availability) is a major constraint on economic development. Groundwater is the major source of fresh water, and is thus of primary importance to the Palestinians.

Water scarcity is one of the real challenges facing the Middle East and its sustainable development. Palestine is one of the most vulnerable areas to water related problems in terms of water quantity and quality because of the shortage in water and the restricted access to water resources(Salim and Wildi, 2003). Therefore, it is important to assess and estimate the water quantity available for recharge. Since recharge is the main component of aquifer replenishment and since the capacity of the aquifer yield depends mainly on the amount of recharge, it is of great importance to assess and quantify groundwater recharge using modeling tools (Salim and Wildi, 2003).

Recharge estimation can be based on a wide variety of methods such as Soil Moisture Deficit method (SMD), Wetting Threshold method (WT), the Cumulative Rainfall Departure (CRD) method, isotope techniques and solute profile techniques (Kumar, 2003; SUSMAQ, 2005; Baalousha, 2005).

Models, after proper simplification, can simulate not only the spatial distribution of groundwater recharge but also the temporal variability in the recharge magnitudes. Groundwater recharge is highly spatial depending on a multitude of factors that concurrently work together including (but not limited to) the rainfall amount, soil type, depth to water table, hydraulic conductivity of the unsaturated zone and the land use (Froukh, 2003).

This very feature of spatiality compels the use of a tool that from the one hand can account for the spatiality in recharge while on the other hand is efficient to use and utilize. Geographic Information Systems (GIS) acquire such characteristics. The literature is packed with studies that utilize GIS in this application (Froukh, 2003)..

Based on the above discussion, this research utilizes GIS in computing and mapping the spatial and temporal distribution of groundwater recharge using ModelBuilder of ArcGIS 9.2.

This research describes the development and implementation of a distributed recharge model for the aquifers of the West Bank. An analysis of recharge, i.e. the quantity of water that percolates from the land surface through the unsaturated zone to the aquifer, is essential input for the simulation of flow in the aquifers. Recharge is a complex process, but quantification is critical in order to understand the total water availability from the West Bank aquifers (SUSMAQ, 2005).

The outcome of this work is expected to be of great importance to the water resources managers who will be able to balance aquifer pumping rates with recharge quantities under different climate change scenarios. This indeed is the very essence and premise of safe-yield based strategies.

This research focuses on recharge estimation for the West Bank aquifers using the SMD method. The SMD method is the most applicable method for recharge estimation under arid and semi-arid conditions.

1.2 The Study Area

The area under consideration in this research is the West Bank. In chapter 3, the general characteristics and features pertinent to the West Bank are illustrated. These characteristics include the districts, population, geography, topography, ecology, climate and the water resources.

1.3 Research Objectives

The following are the research objectives:

1. To develop a generic model for the estimation of groundwater recharge using GIS ModelBuilder; and
2. To use the developed model for the estimation of the spatial and temporal recharge distribution for the West Bank.

1.4 Research Motivations

The following are the research motivations:

1. Groundwater is an important resource for the Palestinians and thus a reliable quantification of recharge is vital;
2. Site-specific characterization is needed to identify areas of high potential of groundwater recharge and hence every care should be considered when developing land use categories and related practices. The developed model can assist in this; and

3. No professional research was cited out to evaluate groundwater recharge in the West Bank but rather regression equations.

1.5 Who Will Benefit From This Work?

The outcome of this research will be of great importance to the following:

1. Water resources managers; recharge estimation for the West Bank is important in order to have a good understanding of the water budget for the entire West Bank.
2. Decision makers; groundwater is almost the sole water resource for the Palestinians and thus the assessment of the quantity is vital and provide an assessment analyses that can be utilized by decision makers for designing any proposed management options;
3. The education sector; and
4. Research institutes. There is a dire need to develop an Environmental Information System and a Groundwater Information System such that available data pertaining to the West Bank aquifers can be easily accessed and conveniently processed. Such proposed system would facilitate the accessibility to the data, enhance research, and will enable data sharing among the interested parties at the national level.

1.6 What's the new in this research?

The importance of this research are: this method is new for the recharge estimation for the whole of the West Bank. Besides this model is new and advanced based on GIS ModelBuilder.

SMD method was used for quantification the recharge for the entire West Bank. The new advantages in using this method:

1. In this research, the SMD method was used for the whole West Bank, while it is used in previous studies for parts of the West Bank.
2. ModelBuilder of GIS was utilized to facilitate the recharge quantification and to efficiently account for the spatiality inherent in recharge.
3. A generic model for the estimation of groundwater recharge using GIS ModelBuilder. Besides it is the first time that ModelBuilder was used for quantification recharge in the West Bank.
4. Recharge results are presented in temporal and spatial scales for the whole West Bank.

1.7 Methodology

The overall research methodology is divided into three components: data collection, data analysis, and output analysis.

The first stage includes data collection mainly from the Palestine Water Authority (PWA) and the Water and Environmental Studies Institute (WESI) at An-Najah National University. In addition, literature review was carried out in order to select the method for groundwater recharge, and to understand the processes that influence groundwater recharge. The second stage includes data processing and developing the groundwater recharge model based on SMD method. The second stage depends mainly on GIS capabilities. Model Builder (as supported by GIS) was utilized in the development of the SMD-based model. The third stage entails analysis of model output.

1.8 Research Problems

The following are the relevant problems:

1. No earnest and serious research was carried out to evaluate the groundwater recharge in West Bank,
2. There is no agreement on the amount of groundwater recharge for the West Bank; and
3. No studies or research that give a specific amount for groundwater recharge for the whole West Bank.

1.9 Research Questions

The key purpose of this research is to address the following questions:

1. What is the total recharge in the West Bank?
2. Which areas in the West Bank have high potential of groundwater recharge?

1.10 Research Outputs

The following are the research outputs:

1. A mathematical GIS-based model for the quantification of groundwater recharge both, spatially and temporarily; and

2. Maps for the spatial and temporal distribution of the groundwater recharge to the aquifers of the West Bank.

1.11 Thesis Outline

The thesis consists of eight chapters. Chapter 2 contains literature review. Chapter 3 describes the study area and its characteristics. Chapter 4 presents the research methodology. Chapter 5 illustrates the **SMD** method. An overview of the development of the groundwater recharge model is discussed in Chapter 6. Chapter 7 demonstrates the results and the corresponding maps. Finally, conclusions and recommendations are provided in chapter 8.

CHAPTER TWO

LITRETURE REVIEW

2.1 Introduction

There are many studies and that have been carried out to estimate groundwater recharge locally and worldwide.

Quantifying the spatial and temporal distribution of natural groundwater recharge is usually a prerequisite for effective groundwater modeling and management. As groundwater flow models become increasingly utilized for management decisions, there is an increased need for simple and practical methods to delineate recharge zones and quantify recharge rates. Existing models for estimating recharge distributions are data intensive, require extensive parameterization, and take a significant investment of time in order to establish (Dripps and Bradbury, 2007). Estimation of groundwater recharge from rainfall is not an easy task since it depends on many uncertain parameters (Baalousha, 2005).

In the following, different case studies are presented.

2.2 Worldwide Studies for Groundwater Estimation

Hartono (2005) estimated the groundwater recharge for Chicot aquifer (State of Louisiana, USA) using a GIS-based net water balance technique that incorporates rainfall, soil properties, runoff, soil moisture, storage, and evapotranspiration to estimate recharge rates across the aquifer. Results show how seasonal- and long-term variations in agricultural demand and rainfall can significantly impact the recharge. The pumping and recharge rates were incorporated into a regional groundwater model of the Chicot aquifer to simulate the groundwater flow over an 11 year period (Hartono, 2005)

Dripps and Bradbury (2007) estimated the spatial and temporal distribution of groundwater recharge in the temperate humid areas (two case studies in USA) using simple daily soil–water balance (SWB) model. The Wisconsin Geological and Natural History Survey has developed a simple daily soil–water balance (SWB) model that uses readily available soil, land cover, topographic, and climatic data in conjunction with GIS to estimate the temporal and spatial distribution of groundwater recharge at the watershed level for temperate humid areas. To demonstrate the methodology and the applicability and performance of the model, two case studies in USA were presented: one for the forested Trout Lake watershed of north central Wisconsin and the other for the urban-agricultural Pheasant Branch Creek watershed of south central Wisconsin. Overall, the SWB model performs well and presents modelers and planners with a practical tool for providing recharge estimates for modeling and water resource planning purposes in humid areas (Dripps and Bradbury, 2007).

Rushton et al. (2005) have estimated the groundwater recharge using the SMD method. Estimation of recharge in a variety of climatic conditions is possible using a daily soil moisture balance based on a single soil store. Both transpiration from crops and evaporation from bare soil are included in the conceptual and computational models. The actual evapotranspiration is less than the potential value when the soil is under stress. The stress factor is estimated in terms of the readily and total available water, parameters which depend on soil properties and the effective depth of the roots. Runoff was estimated as a function of the daily rainfall intensity and the current soil moisture deficit. A new concept, near surface soil storage, was introduced to account for continuing evapotranspiration on days following heavy rainfall even though a large soil moisture deficit exists. Algorithms for the computational model were provided. The data required for the soil moisture balance calculations are widely available or they can be deduced from published data. This methodology for recharge estimation using a soil moisture balance was applied to two contrasting case studies. The first case study refers to a rainfed crop in semi-arid northeast Nigeria, where recharge occurs during the period of main crop growth. For the second case study, a location in England was selected where the long-term average rainfall and potential evapotranspiration were of similar magnitudes. For each case study, detailed information was presented about the selection of soil, crop and other parameters. Uncertainties and variations in parameter values were explored using sensitivity analyses. These two case studies indicate that the improved single-store soil moisture balance model is a reliable approach for potential recharge estimation in a wide variety of climatic conditions (Rushton, Eilers and Carter, 2005).

Rushton et al. (1979) estimated the groundwater recharge for a chalk aquifer in North Lincolnshire using the SMD method. Methods of estimating groundwater recharge in temperate climates were reviewed and it was suggested that the conventional method of Penman and Grindley tends to underestimate the recharge. An alternative recharge mechanisms was proposed which allows recharge to occur even when a soil moisture deficit exists. Recharge cannot be measured directly and so methods of estimation must be devised. The implications of this approach are examined by considering a chalk aquifer in North Lincolnshire (K.R.Rushton and Catherine Ward, 1979).

The authors suggest that future research should focus on recharge mechanism itself, to determine whether the proposed models are on the right lines, rather than on the classical model for recharge estimation with its inherent weaknesses.

Moona et al. (2003) have estimated the groundwater recharge for Korea using water table fluctuation. Using water-table monitoring data from the National Groundwater Monitoring Network in Korea, groundwater hydrographs were classified into five typical groups. Then, to estimate groundwater recharge, a modified water-table fluctuation (WTF) method was developed from the relation between the cumulative WTF and corresponding precipitation records. Applying this method to different types of hydrographs, the spatial variability of recharge in river basins was evaluated. Each estimated recharge can be considered the maximum value, and therefore, could be used as a cut-off guideline (an upper limit) for groundwater development in river basins (Moona, Woo, and Lee, 2003).

2.3 Local Studies of Groundwater Estimation

Recharge estimation is a very important element in water resources studies in Palestine. Of particular interest are the modelling studies of the sustainable yield of Palestinian aquifers. Previous studies have concentrated on developing analytical recharge models for the aquifers but were based on annual averaging of the rainfall data. This has proved to be inadequate for developing flow and pollution models when the interest is to look at the changes in the aquifer on shorter periods , i.e. , on monthly to semi-annual bases.

Baalousha (2005) estimated the groundwater recharge for Gaza coastal aquifer using cumulative rainfall departure (CRD) method. In Gaza costal aquifers, where rainfall is the main source of groundwater recharge. The area is located in the semi-arid zone and there is no source of recharge other than rainfall. Estimation of groundwater recharge from rainfall is a difficult task since it depends on many uncertain parameters. The CRD method, which depends on the water balance principle, was used in this study to estimate the net groundwater recharge from rainfall. This method does not require much data as in the case with other classical recharge estimation methods. The CRD method was carried out using optimization approach to minimize the root mean square error (RMSE) between the measured and the simulated groundwater head. The results of this method were compared with the results of other recharge estimation methods from literature. It was found that the results of the CRD method were very close to the results of the other methods, but with less data requirements and greater ease of application. Based on the CRD method, the annual amount of groundwater recharge from rainfall in the Gaza strip is about 43 million m^3 (Baalousha, 2005).

Melloul and Bachmat (1975) have estimated the groundwater recharge for the Gaza Strip using recharge coefficients. They subdivided the area into three sub-zones and computed the coefficients for each sub-zone based on the soil type and the average rainfall. The coefficients were estimated based on regression analysis between groundwater recharge and soil type. According to their study, Melloul and Bachmat found that the annual groundwater recharge for Gaza Strip equaled to 41 million m^3 (Melloul, Bachmat, 1975)

Another study was carried out in the area by IWACO and Water Resources

Action Program (WRAP) in 1995 to estimate the net groundwater recharge based on chloride mass balance. The chloride mass balance method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. This study was applied to the northern part of the Gaza Strip, where the top soil is composed mainly of sand dunes. In other words, that particular area has a high infiltration rate. Results of this study have showed that the amount of groundwater recharge is about 46 million m^3 per year (IWACO, WRAP, 1995).

British Geological Survey (2005) has estimated the groundwater recharge for the West Bank aquifers using the SMD method.

This report based on using object-oriented techniques. The model has been applied to two areas, the Wadi Natuf catchment, and the main outcrops of the aquifers underlying the West Bank.

To aid in the quantification of recharge, a distributed recharge model was developed using object-oriented techniques. This recharge model has been adapted from an existing code to include the recharge mechanisms observed in the West Bank. The model has been applied to two areas, the Wadi Natuf catchment, as a pilot application, and the main outcrops of the aquifers underlying the West Bank. The work on the Wadi Natuf catchment was facilitated by various field visit reports undertaken by the "Sustainable Management of the West Bank and Gaza Aquifers" (**SUSMAQ**) team (e.g. Messerschmid, 2003). This model was based on ArcGIS and the method was used soil moisture deficit and wetting threshold (British Geological Survey, 2005).

Abu Saada et al (2005) estimated the monthly groundwater recharge in Wadi Natuf, Palestine. The aim of there work was to develop models for monthly recharge distribution based on annual recharge rates that should be used to model the flow system in Wadi Natuf Catchment. The approach developed in their study is reliant on two consistent observations: first any rainfall event on the ground surface does not mean that the aquifer response (e.g. recharge as a change in aquifer storage) is immediate. It is observed that only a small portion of that rainfall event will reach the water table in that month of the event and this will increase gradually till three or four months when the maximum of this event is reflected in the water level rise of the aquifer. After that, the contribution of this event to aquifer recharge reduces gradually till the end of a period of a bout another 3 months from the peak. Second it was clearly observed that the month of April exhibits the peak of rise in aquifer's water levels which indicates the delay and the accumulation in the rainfall events over the rainy season. The results of their study were new analytical equations for monthly estimations of recharge in Wadi Natuf catchment (Abu Saada et al., 2005) as in the following:

Recharge equation	**Rainfall (mm/year)**	
$R = 0.8(P-360)$	$P > 650$ mm	(1)
$R = 0.534(P-216)$	$650 > P > 300$ mm	(2)
$R = 0.15(P)$	$P < 300$ mm	(3)

where

R: Recharge from rainfall (mm/year)

P: Annual rainfall (mm/year)

The aim of this study is develop analytical estimation equation for the monthly distribution of annual recharge rates with applications in Wadi Natuf catchment (Abu Saada et al., 2005).

2.4 Why SMD Method ?

The SMD method is the most applicable method for recharge estimation under arid and semi-arid conditions.

The advantages of the SMD method over other alternatives are:

1. Its ability to model recharge over time, using datasets of rainfall and other meteorological variables in which we can have some confidence;
2. The very fact that it is a modelling based approach - lending itself to investigation of "What-if" scenarios (e.g. changes in rainfall, land use, soil properties);
3. Its ability to give recharge estimates from limited and readily available data;
4. The fact that there is no need to measure soil/formation properties below the root zone depth (making it a low-cost approach).

CHAPTER THREE

DESCRIPTION OF THE STUDY AREA

The area under consideration in this thesis is the West Bank. In this chapter, general characteristics and features of the West Bank pertinent to the work are illustrated. These characteristics include the districts, population, geography, topography, ecology, climate and the water resources.

3.1 Geography and Topography

The West Bank has a total area of approximately 5,800 km^2, a 130 km length from north to south and between 40 and 65 km in width from east to west (Abdul-Jaber et al., 1999). The West Bank is mostly composed of limestone hills that are between 700 and 900 m in high. The lowest elevation in the West Bank is the Dead Sea at approximately 400 m below the sea level and the highest is the Tall Asur at 1,022 m above sea level (UNEP, 2003). Fertile soils are found in the plains. Soil cover is generally thin and rainfall is erratic. The West Bank formations are comprised of limestone, dolomite, chalk, marl, chert, shale, and clays (PWA, 2001b) as shown in Figure 1.

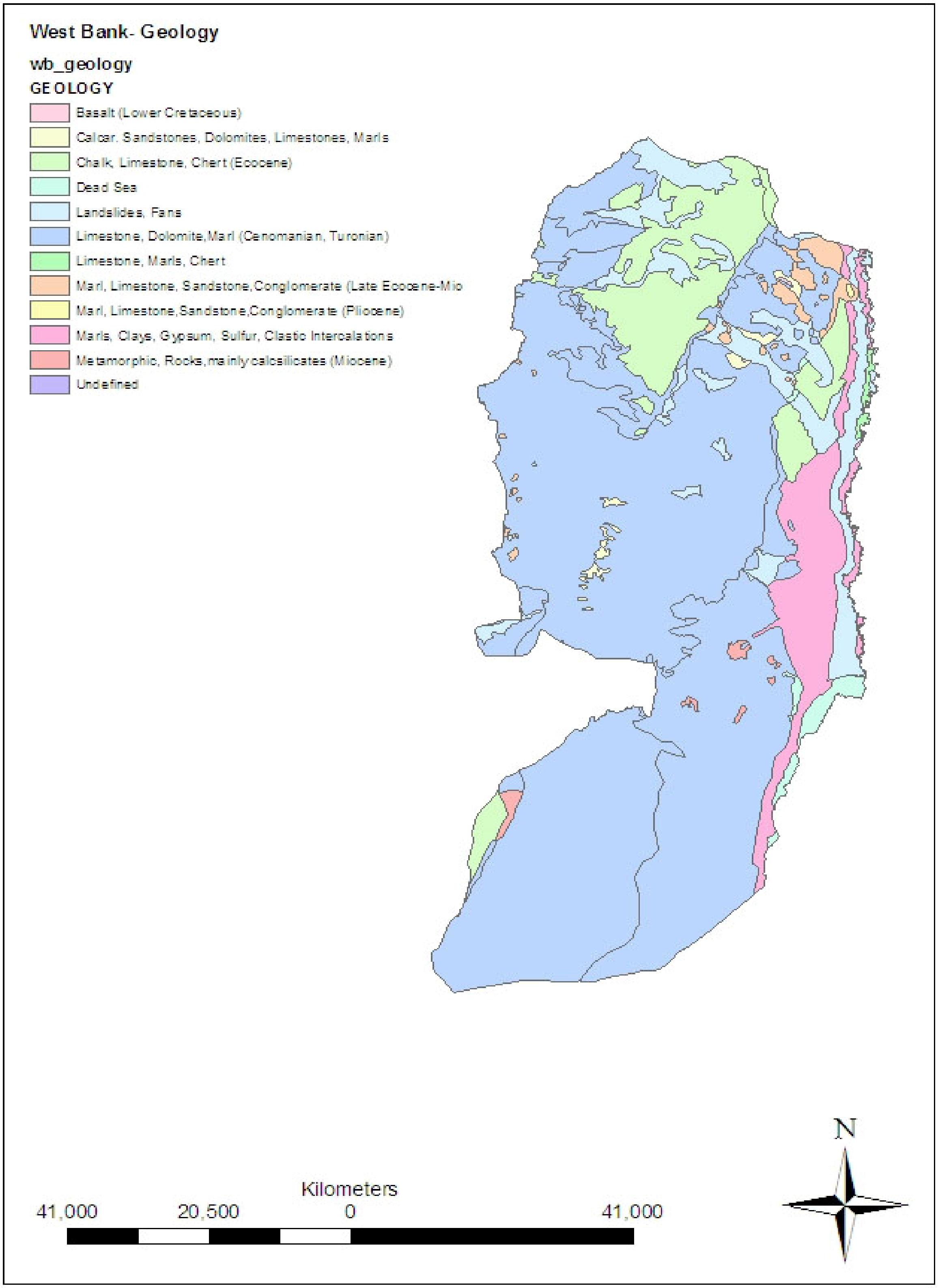


Figure 1:The West Bank geology map

The Figure 2 below show the West Bank topography.

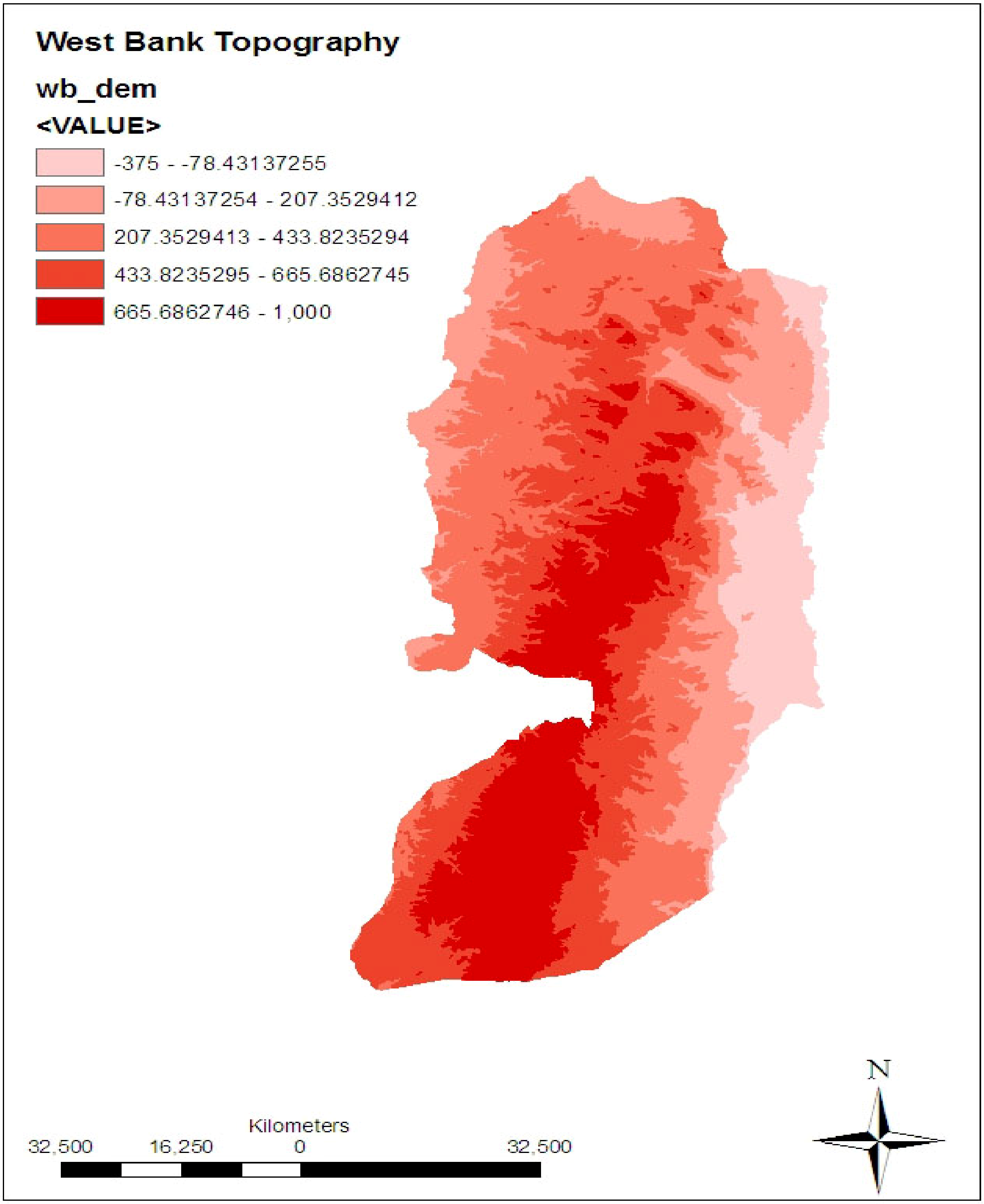


Figure 2:The West Bank topography map

The soil type for the West Bank as depicted in the Figure 3

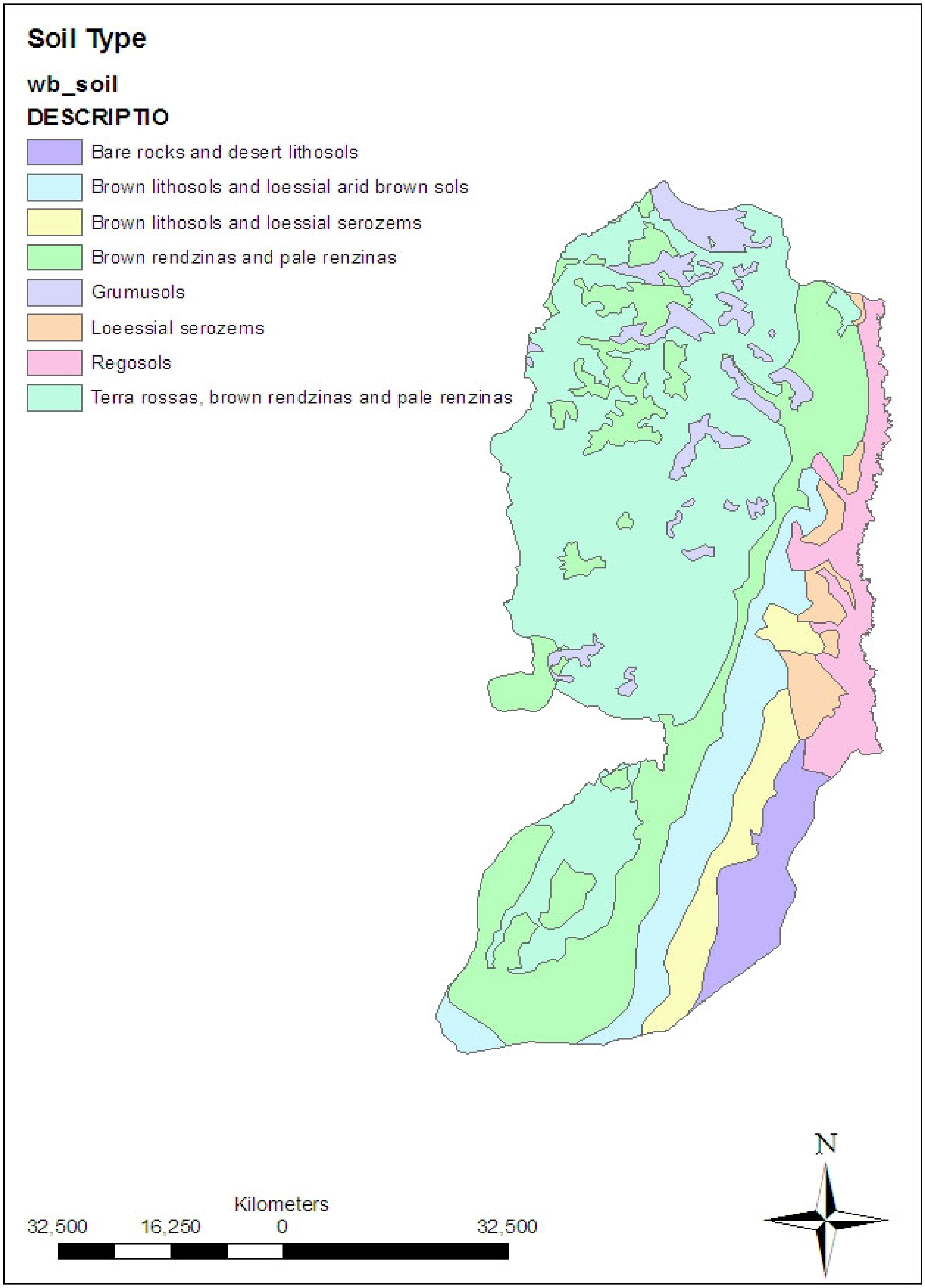


Figure 3:The West Bank soil type map

3.2 Districts

The West Bank is divided into eleven districts and these are: Bethlehem, Hebron, Jenin, Jericho, Jerusalem, Nablus, Qalqilya, Ramallah and Al-Bireh, Salfit, Tubas, and Tulkarm (see Figure 4 and Table 1). The districts are sub-divided into 89 municipalities. Local councils have been formed to manage all infrastructure and basic services.

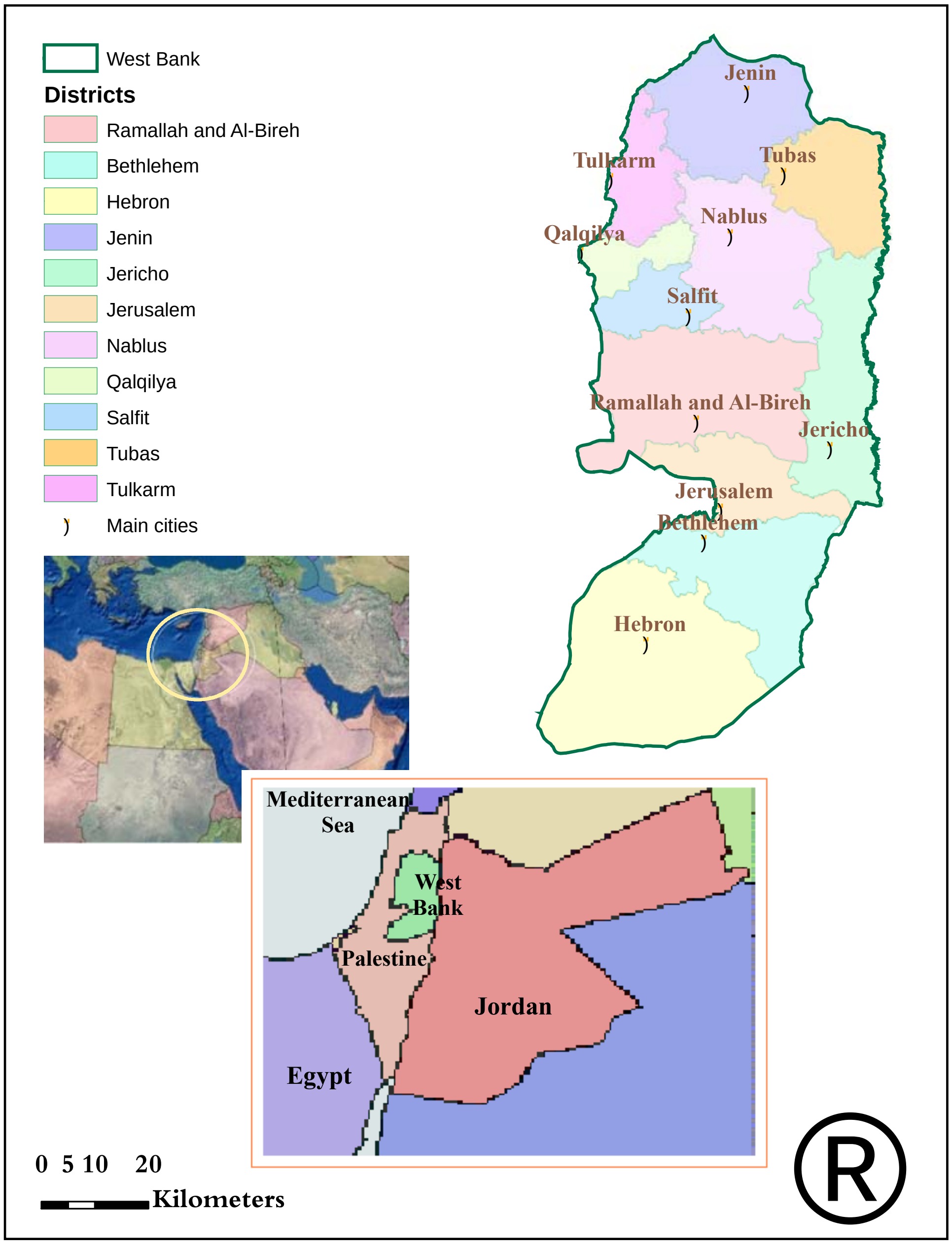


Figure 4: The regional setting of the West Bank, the districts, and the main cities.

Table 1: Total area for each district in the West Bank

Districts	Area (km^2)	% of the total area of the West Bank
Jerusalem	345	5.70
Jenin	583	9.70
Tubas	402	6.70
Tulkarem	246	4.10
Qalqilia	166	2.80
Salfit	204	3.40
Nablus	605	10.00
Ramallah and Al-Bireh	855	14.20
Bethlehem	659	10.90
Jericho and Al-Aghwar	593	9.90
Hebron	997	16.60
Total	**5,655**	**94.00**

3.3 Population

Approximately 2.5 million Palestinians live in the West Bank (PCBS, 1997). Almost 40 percent of the Palestinians are refugees since 1948. Around 65% of the population live in urban areas (UNFPA, 2001). Annual population growth is estimated at 2.8 % (UNDP, 2002).

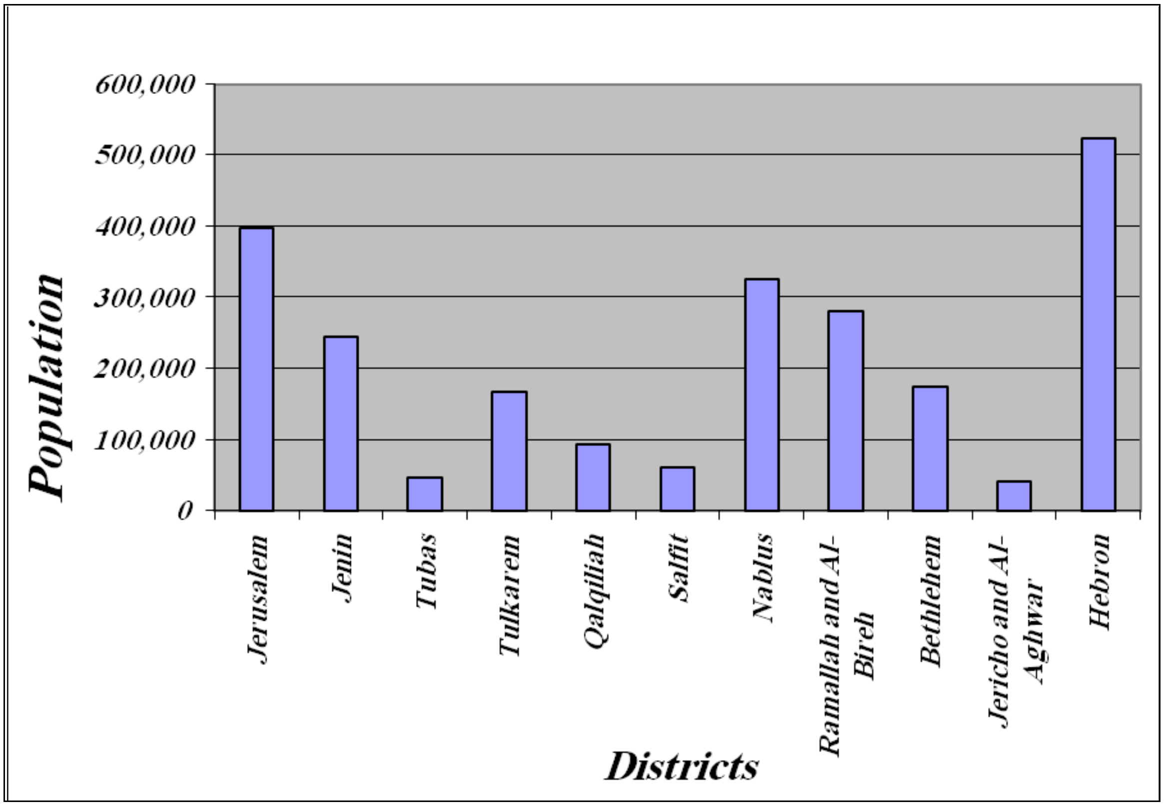


Figure 5:The population distribution of the West Bank (2005)

3.4 Ecology

Palestine can be divided into five main ecological sub-regions and these are: the Mediterranean shoreline coastal plain; the upper coastal plain; the central highlands; the semi-arid eastern slope steppes; and the arid semi-tropical Jordan Valley. 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 by Sudanian vegetations (UNEP, 2003).

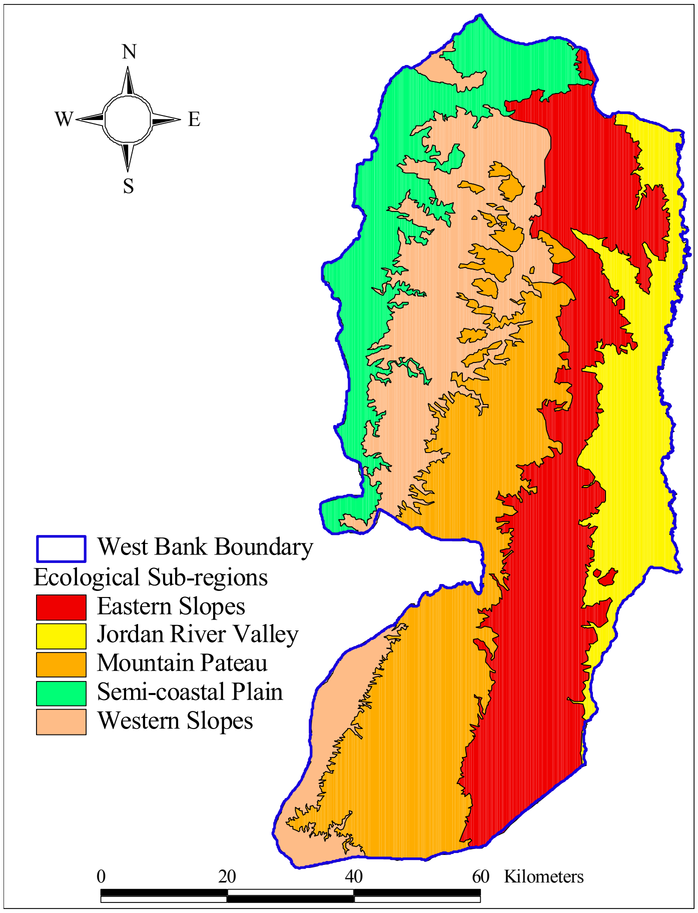


Figure 6: The main ecological sub-regions for the West Bank

3.5 Climate

The climate in the Mediterranean region has four months of hot dry summer and a short mild winter with rain from November to March. The climate in the West Bank can be characterized as hot and dry during the summer and cool and wet in winter (UNEP, 2003). The climate becomes more arid to the east and south. The central highlands, trending roughly north-south, are part of the South Syrian Arc fold system. These mountains act as a climatic barrier, responsible for the rain-shadow desert to the east down to the Dead Sea (Abdul-Jaber et al., 1999).

The mean summer temperatures range from 30 °C at Jericho to 22 °C at Hebron which is 850 meters above sea level. The mean ranges in winter are from 13°C at Jericho to 7°C at Hebron. The annual average relative humidity is about 52% at Jericho (UNEP, 2003). Evaporation is high in summer when there is always a water deficit. Annual rainfall on the Central Highlands averages 700 mm and becomes less than 100 mm, at the Dead Sea. However, great variations in rainfall amount and distribution exist as shown in Figure 7. It is common for only half the average to fall in any one year (Abdul-Jaber et al., 1999).

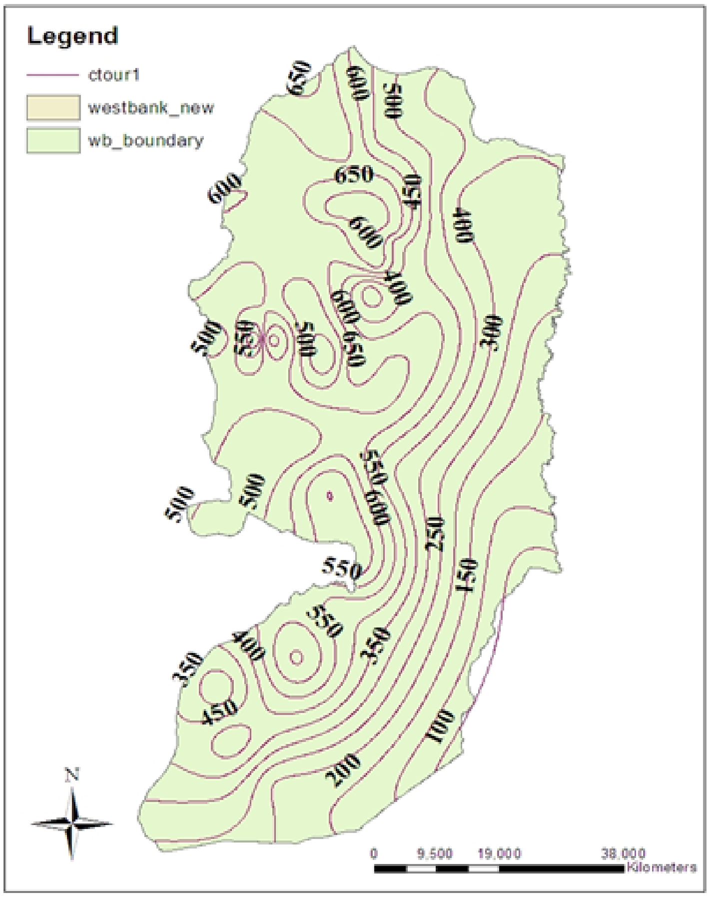


Figure 7: The rainfall contour map in the West Bank

The West Bank is composed of four main climatic regions: hyper-arid; arid, semi-arid, and sub-humid. Figure 8 shows the main climatic regions of aridity in the West Bank.

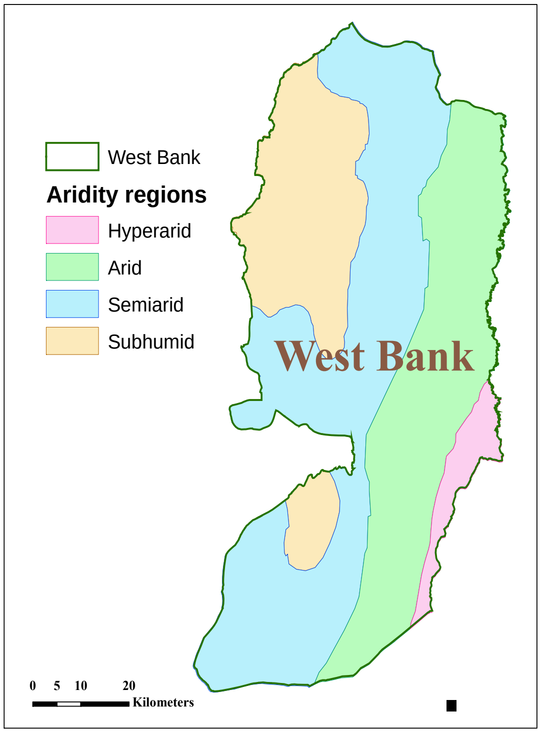


Figure 8: The main climatic regions of aridity in the West Bank

3.6 Water Resources

The principal water resources available to Palestinians include groundwater, springs, and harvested rainwater (UNEP, 2003). There is little surface water and thus groundwater is the principal source of water in the West Bank. Surface water (in wintertime) drains either westwards to the Mediterranean or eastwards to the Jordan River and Dead Sea. The lower Jordan River flows southwards at the eastern edge of the West Bank from Lake Tiberias to the Dead Sea (Abdul-Jaber et al., 1999).

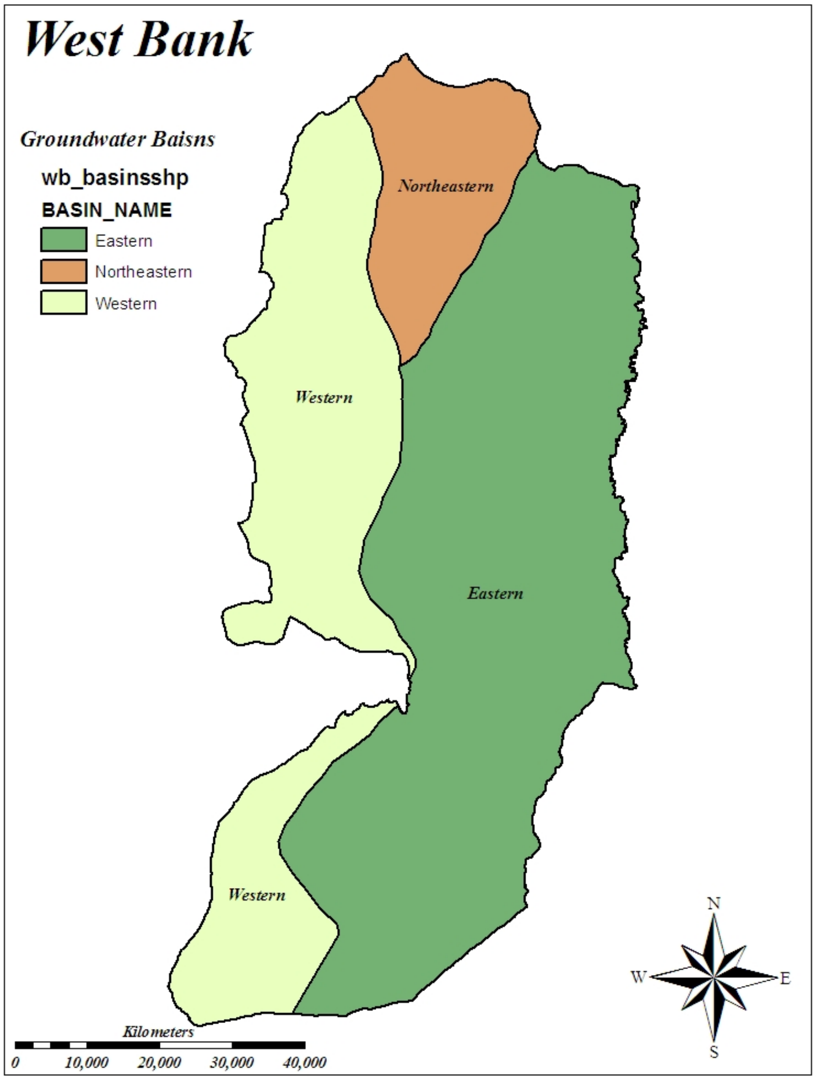


Figure 9 : Northeastern, Western, and Eastern Aquifer Basins of the West Bank.

The West Bank lies over the Mountain aquifer. The Mountain aquifer is divided into the eastern aquifer, the northeastern aquifer, and the western aquifer as depicted in Figure 9. The eastern aquifer flows east towards the Jordan River. The western aquifer flows westerly towards the Mediterranean Sea (Scarpa, 1994; Abed and Wishahi, 1999; PWA, 2001b; Almasri, 2005).

None of these aquifers is completely encompassed within the West Bank political boundaries; however, the recharge areas of these basins fall within the West Bank boundaries (Froukh, 2003).

The aquifer systems rely on recharge from rainfall to a great deal of extent. In the last five years, rainfall dropped significantly by 20 to 30 %. As a result, a drastic drop in the water table elevation was noticed in many wells across the West Bank. It was noticed that around 5 to 10 m drop in the water table elevation in these wells was due to recent drought as a result, the average recharge volume from rainfall had also dropped by 10 to 20 % (Froukh, 2003).

On the other hand, it was also noticed that in the hydrologic year 1991/1992 where rainfall exceeded the average by far, the water table elevations went up. This spike in the water table at different wells is the outcome of the increase in recharge as a result to the increase in rainfall.

The quantity of cross boundary fluxes between the groundwater aquifer basins and the inter-aquifer flow within the basins are not well understood, making it difficult to accurately quantify the total groundwater storage and yield in each aquifer system (PWA, 2001b). This uncertainty is reflected by the wide ranges given for each basin, as shown in Table 2.

Table 2: Reported annual recharge rates of the groundwater basins in the West Bank (PWA, 2001b)

Aquifer basin	**Annual recharge rate (mcm)**
Eastern	100 - 172
North eastern	130 - 200
Western	335 - 380
Total	**565 - 752**

Regionally, the Jordan River is about 260 km long and drains a total area of 18,300 km^2 (UNEP, 2003). The river is composed of four tributaries: Banias, Hasbani, Dan, and Yarmouk. Banias, Hasbani, and Dan meet in the north of Palestine to form the Upper Jordan River that flows into Lake Tiberias.

However, Yarmouk River flows in a southwesterly direction into the Lower Jordan River forming the border between Jordan and Syria and Jordan and Palestine. Yarmouk River has a higher flow during winter which dilutes the increasing salinity of the Jordan River (Lonergan and Brooks, 1994).

CHAPTER FOUR

METHODOLOGY

METHODOLOGY

The overall research methodology is divided into the following three stages as depicted in Figure 10:

1. Literature review and data collection;
2. Model development; and
3. Analysis of model output.

Management of groundwater resources requires a method to accurately calculate recharge rates at local and regional scales. Many methods are available to calculate recharge, yet many require a great deal of information that is not available in general.

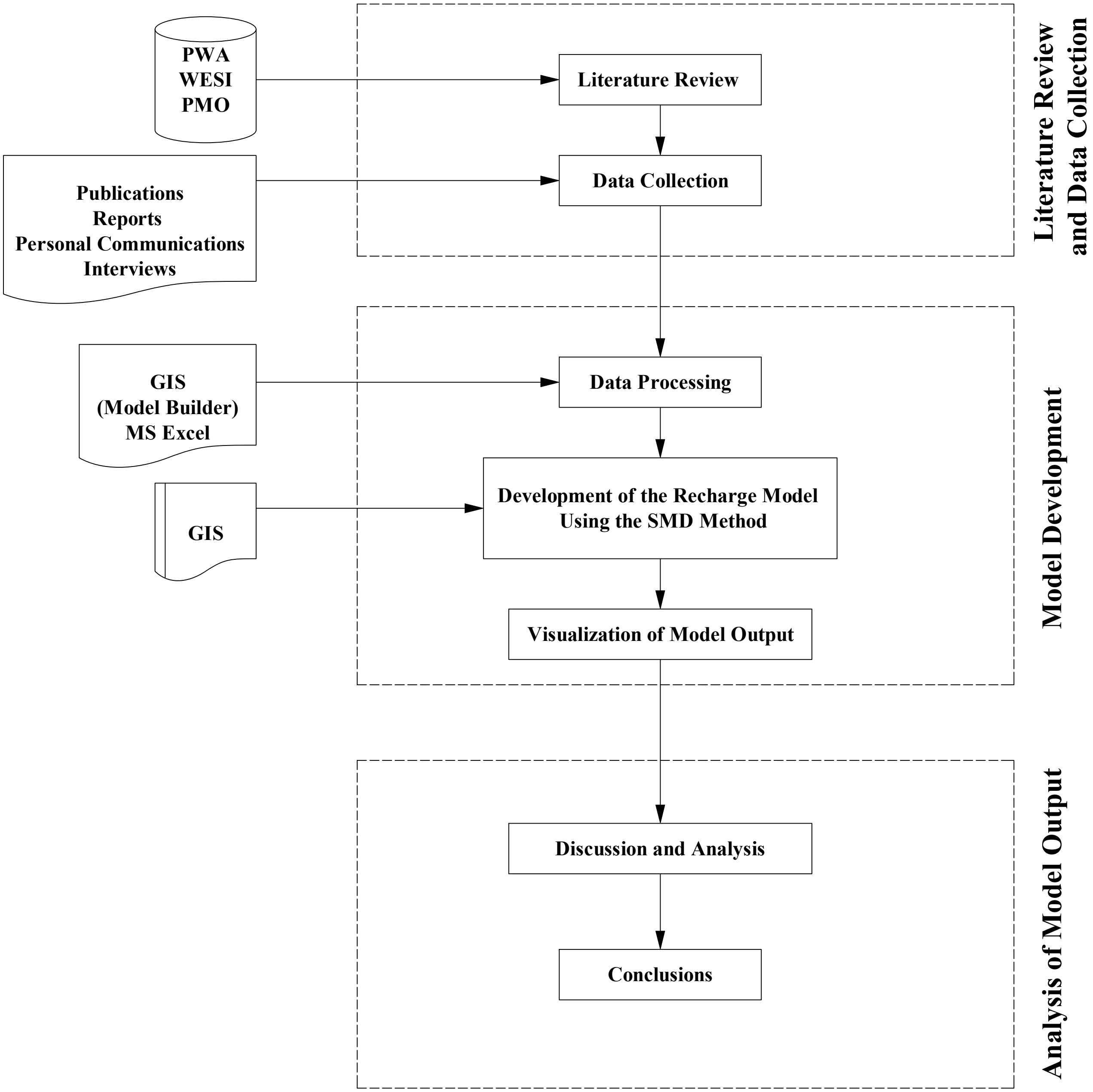


Figure 10: Depiction of the overall research methodology

Literature review was carried out in order to select the method for recharge estimation and to comprehend the processes of groundwater recharge. Based on the literature review, the SMD method was chosen to estimate the groundwater recharge for the West Bank.

Many of the reviewed studies were conducted worldwide. Additional reviewed studies were developed for the estimation of recharge in Palestine. These studies were helpful in providing a general blueprint of how to estimate recharge, conduct calculations, and widen the disciplines of the study and analysis. A variety of local and international publications and reports were considered. In addition to past studies, interviews and personal communications were employed in data collection and acquisition. As a result of the profound readings carried out at early stages of this work, it was obvious that there is a dire need for a study that utilizes GIS capabilities (especially ModelBuilder of GIS) for groundwater recharge estimation for the West Bank aquifers and for the visualization of the outcomes.

GIS technology enables the ease of data processing, visualization, sorting, assessment, computation and map preparation when compared with other technologies.

Thereafter and after selecting the appropriate method for recharge estimation, data collection was carried out. Data was obtained from the Palestinian Water Authority (PWA), Palestinian Meteorological Office (PMO), and the Water and Environmental Studies Institute (WESI) at An-Najah National University.

The second stage in the methodology includes data processing and the development of the groundwater recharge model using the SMD method. Model Builder (as supported by GIS) was utilized in the development of the SMD-based model.

The SMD method though conceptually simple, encompasses many parameters and requires different factors. In order to develop the recharge model efficiently, all the data should be available in a processable format. So, much of the effort at this stage was directed toward streamlining the available data, digitizing, and checking the data compatibility.

Ultimately and since the intent is to compute the spatial distribution of recharge, the spatial analyst of ArcGIS was utilized. The spatial analyst necessitates that the data be in a raster format. Proper raster cell size was chosen taking into consideration a compromise between execution time and resolution level.

Note: The cell size was used in this model (6 km× 6 km).

In the second stage that includes data processing and model development, model builder of ArcGIS was utilized. Model Builder is a practical way for automating the calculations and for implementing the SMD method.

In the third stage, the developed model was utilized to study the spatial distribution of groundwater.

Based on the outcome of this research, the conclusions are made and the recommendations for future work are highlighted.

CHAPTER FIVE

THE SMD METHOD

5.1 Introduction

Groundwater resource studies require estimates of the quantity of water moving downwards from the soil zone which represent the potential recharge. Any methodology selected for the estimation of potential recharge must be applicable in a wide variety of climatic and hydrological situations. The important physical processes must be represented adequately. Unnecessary complexities should be avoided with parameter values based on readily available field information. Estimates are usually required for several decades. There are several detailed reviews of methods for estimating recharge (Lerner et al., 1990; Simmers, 1997; Scanlon and Cook, 2002).

Identification of the net groundwater recharge is essential for groundwater modeling and water resources management. The calculation of the net groundwater recharge is a big challenge for the hydrologist since there is no specific method to find out the net recharge reliably. There are so many methods for quantification of groundwater recharge from rainfall. Each method has its limitations in terms of applicability, accuracy and complexity (Husam Baalousha, 2005). Although many empirical formulas were developed to find out the net groundwater recharge, none of them have been shown to be efficient and accurate (Husam Baalousha, 2005).

One of these methods is the SMD method. The basis of the SMD method for estimating recharge is that the soil becomes free draining when the moisture content of the soil reaches a limiting value called the field capacity. Excess water then drains through the soil to become recharge (K.R. Rushton, V.H.M. Eilers, R.C. Carter, 2005).

To determine when the soil reaches this critical condition, it is necessary to simulate soil moisture conditions throughout the year. This involves the representation of the relevant properties of the soil and the capacity of crops to collect moisture from the soil and transpire water to the atmosphere. If no crops are growing or there is only partial crop cover, bare soil evaporation must be considered. Bare soil evaporation is important both in semi-arid locations to represent soil moisture conditions at the end of the dry season and in temperate climates where recharge occurs in winter when evaporation is usually the major loss from the soil (K.R. Rushton, V.H.M. Eilers, R.C. Carter, 2005). Transpiration and evaporation often occur at less than their potential rate due to crop stress arising from limited soil moisture availability (K.R. Rushton, V.H.M. Eilers, R.C. Carter, 2005). Crop stress is included using the concepts of total available water and readily available water and thus reduced evaporation depends on this concept. The input to the soil moisture balance is infiltration which equals the daily precipitation less than any interception or runoff. Runoff can be represented as a function of daily rainfall intensity and the current soil moisture deficit.

5.2 Soil moisture deficit method for recharge estimation

This part describes the methodology of the improved SMD method for estimating recharge.

Inputs and outputs for the soil moisture method are shown schematically in Figure 11. Apparently the amount of water that leaves the soil zone becomes recharge.

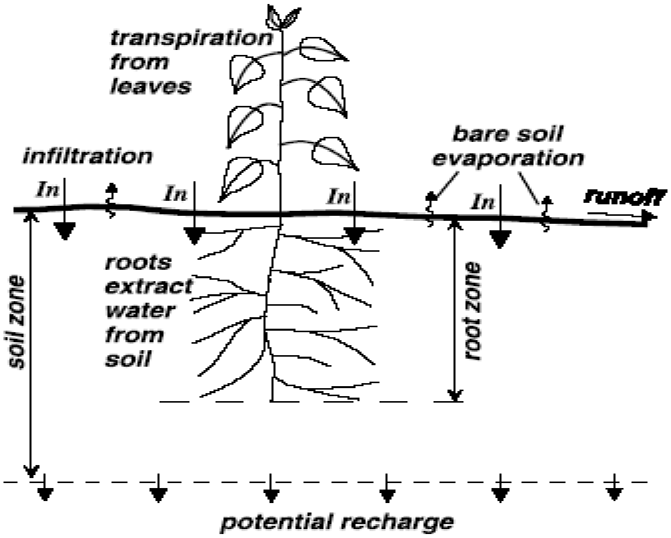


Figure 11: Conceptual depiction of the components of the SMD method (Rushton et al., 2005)

5.3 Total soil moisture and soil moisture deficit

The concept of the total moisture stored in the soil is illustrated by the soil moisture distribution on a representative section as shown in Figure 12. This soil moisture distribution is related to the permanent wilting point (θ_{WP}) which is the soil moisture content below which plant roots cannot extract moisture and field capacity (θ_{FC}) which is defined as the amount of water that a well-drained soil can hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased. (Rushton et al., 2005)

In the left-hand diagram of Figure 12, the moisture content at the soil surface is just above the moisture content at wilting point while at a depth of 2 m the moisture content approaches field capacity. For soil moisture balance calculations, the sum to a depth of 2 m of the moisture contents above the wilting point, which is shaded on the left-hand graph of Figure 12, can be represented as shown on the right-hand diagram of Figure 12. This diagram does not imply that there is a sudden change in moisture content at a depth of 0.79 m but rather it is a convenient way of representing the total moisture stored in the soil zone. (Rushton et al., 2005)

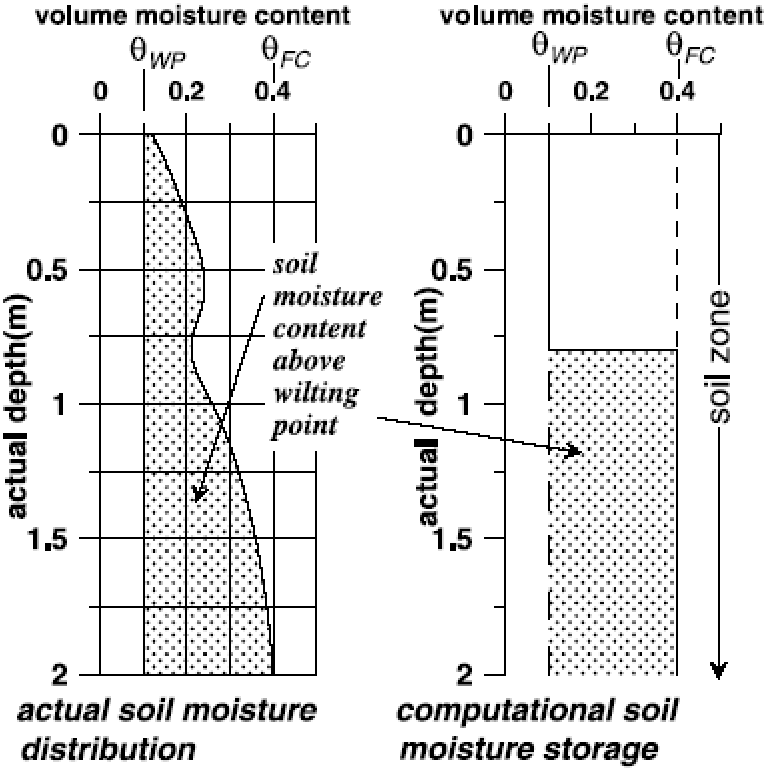


Figure 12: Representation of the actual soil moisture distribution and the corresponding computational soil moisture storage. (Rushton et al., 2005)

As mentioned earlier, the SMD is defined as the depth of water required to bring the soil up to field capacity. This concept of a soil moisture deficit is useful for carrying out calculations; however it makes no assumptions about the variation of moisture content with depth.

5.4 Rainfall, runoff and infiltration

The main source of water for a soil moisture balance is rainfall or irrigation. However, the actual infiltration to the soil zone may be reduced due to interception or runoff. The magnitude of infiltration can be estimated using an infiltration coefficient but, due to both the effect of farming practices which modify the soil properties and the drainage of fields, it is preferable to use a method that represents the observed runoff from the study area. However, runoff can be estimated using coefficients for the fraction of rainfall that becomes runoff. These coefficients are selected to reflect field observations. (Rushton et al., 2005)

5.5 Potential evapotranspiration, reduced transpiration and evaporation

The reference crop potential evapotranspiration ET_0 can be estimated using the FAO version of the Penman–Monteith equation (Allen et al., 1998). Different crops require different amounts of water depending on factors such as the date of sowing, the growth of the crop and the date of harvest.

The potential transpiration of the crop ET_C is related to the reference evapotranspiration of grass ET_0 as in the following equation:

$$ET_C = K_C \times ET_O \qquad (4)$$

where K_C is the crop coefficient (Allen et al., 1998). During the development stage of the crop and the mid stage when the crop matures, the transpiration is higher than that for grass and hence $K_C > 1.0$. During the late stages, when the crop is ripening, little water is required so that the evapotranspiration is less than that for grass and hence $K_C<1.0$. The crop coefficient, which changes with the different growth stages, is an aggregate of the physical and physiological differences between crops. Quantitative information about crop growth and crop coefficients can be found in Allen et al. (1998). Evaporation from bare soil occurs from harvest until the crop completely covers the ground surface.

The potential evaporation from a soil surface ES can be calculated from the reference crop evapotranspiration as in the following equation:

$$ES = K_E \times ET_O \qquad (5)$$

where K_E is the evaporation coefficient which is set at 1.10 for temperate climates and 1.05 for semi-arid climates. Values of ET_C and ES deduced from Equations (4) and (5) assume that there is sufficient water in the soil for transpiration and evaporation to occur at the potential rate. However, when soil water is limited, transpiration and evaporation may occur at less than the potential rate. Reduced rates of transpiration and evaporation depend on properties of the soil and the crop.

An important parameter in determining whether roots can transpire at the potential rate is the total available water (*TAW*): TAW is the product of the root depth,(Zr) and the difference between the moisture contents at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}) (Hulme et al., 2003).

A second important parameter, the readily available water (*RAW*). RAW is required to represent the conditions before the wilting point is reached when the plant can no longer transpire at the potential rate. The limiting soil moisture deficit when the plant transpires at the potential rate is *RAW* which depends on the nature of the plant and is typically 40% to 60% of the *TAW*. (Hulme et al., 2003).

There are two specific soil moisture deficits that are defined; the soil moisture deficit at which evaporation ceases and is defined as TEW which is the corresponding value beyond which evaporation occurs at a reduced rate (REW). (Rushton, 2003)

Reduced evaporation is considered first. Hillel (1998) describes three stages in the evaporation process which are illustrated in Figure 13. The stages can be identified in terms of the total evaporable water (TEW) and the readily evaporable water (REW). Diagrams (i) and (ii) refer to Stage I when there is no restriction on the ability of the soil to transmit water to the soil surface since the soil moisture deficit is less than the REW. Diagram (iii) refers to Stage II when the quantity of water delivered to the evaporation zone is limited; the SMD is greater than REW but less than TEW. Diagram (iv) represents Stage III when no evaporation occurs because the soil moisture deficit is greater than TEW. These processes are quantified using the lower diagram of Figure 13 in terms of an evaporation stress coefficient K'**S**,

$$\text{Actual Evaporation} = \text{K's} \times \text{Potential Evaporation} \qquad (6)$$

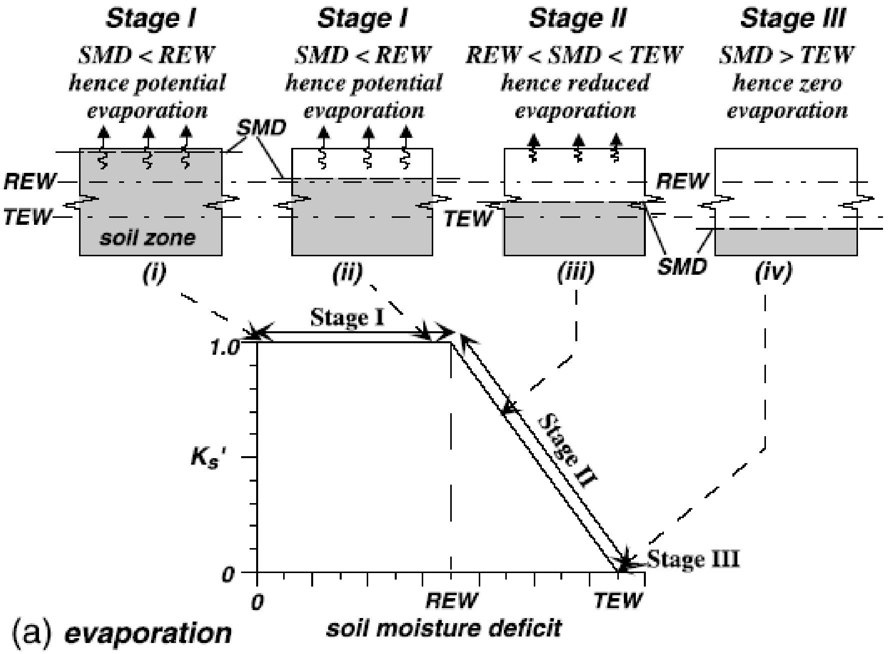


Figure 13: Reduced evaporation due to limited moisture availability resulting from increasing soil moisture deficits. (Rushton et al., 2005)

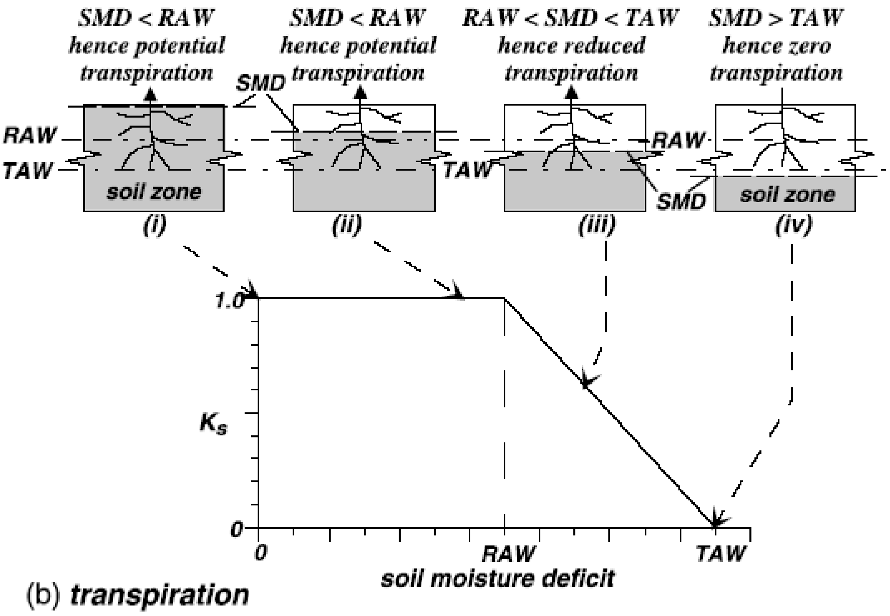


Figure 14: Reduced transpiration due to limited moisture availability resulting from increasing soil moisture deficits. (Rushton et al., 2005)

The stress coefficient K's equals 1.0 when SMD ≤ REW but falls to zero when SMD ≥ TEW. TEW is estimated from the following equation:

$$TEW = 1000\left(\theta_{FC} - 0.5\theta_{WP}\right)\times Z_E \quad \text{(mm)} \qquad (7)$$

where Z_E is the depth of the surface soil layer subject to drying by evaporation. It lies within the range (0.10 – 0.25) m. The coefficient 0.5 is introduced before (θ_{WP}) since evaporation can dry the soil to mid-way between the wilting point and oven dry. Reduced transpiration depends on the soil–plant–atmosphere continuum for the movement of water from the soil, through the plant, to the leaves and out to the atmosphere (see Figure 11).

As soil wetness decreases, the actual transpiration begins to fall below the potential rate because the soil cannot supply water fast enough and/or because the roots can no longer extract water fast enough to meet the meteorological demand. Plants with growing roots try to reach into moist regions of the soil rather than depend entirely on the conduction of water over considerable distances in the soil against a steadily increasing hydraulic resistance. As reported by Hillel (1998), many field experiments have been carried out and numerical models devised to represent crops under stress. The ability of roots to seek out moist soil, and the capacity of the root system to adapt quickly to varying soil moisture profiles, presents difficulties in multi-store models where the distribution of evapotranspiration with depth needs to be predetermined.

For a single-store soil moisture balance calculation, the effect of limited soil moisture on transpiration is represented approximately as shown in Figure 14.Note that this approach is similar to that for evaporation, Figure 13, so that it is possible to simulate evaporation and transpiration occurring at the same time. A soil stress coefficient K**s** is introduced so that actual transpiration (AE) can be computed from the following equation:

$$AE = K_S \times K_C \times ET_o \qquad (8)$$

where K**s**

$$K_S = \left(\frac{TAW - SMD}{TAW - RAW}\right), \text{ for } TAW < SMD < RAW \qquad (9)$$

When assessing the ability of the roots to draw water from the soil, information is required about the depth of the roots. A number of maximum root depths for different crops are listed in Allen et al. (1998).

Different soils have different moisture holding properties. Soil water availability is concerned with the capacity of a soil to retain water which can be extracted by the roots of plants. The limiting soil moisture conditions are the total available water TAW which is defined as:

$$TAW = 1000(\theta_{FC} - \theta WP) \times Z_r \quad \text{(mm)} \qquad (10)$$

where Z**r** is the rooting depth (m) which changes with time. RAW = pTAW in which **p** is a factor between 0.2 and 0.7 as in Allen et al. (1998).

On days when the soil is under stress and rainfall occurs which is less than PE, the rainfall is transpired plus a further component which equals the remaining evapotranspiration demand multiplied by the current soil stress coefficient K**s**.

5.6 Modifications for near surface soil storage

When the soil moisture deficit is less than the readily available water (or readily evaporable water), the distribution of moisture in the soil profile is unimportant since the actual evapotranspiration equals the potential value. Furthermore, when the soil moisture deficit is greater than the readily available (or evaporable) water, allowance is made for the reduced soil moisture by introducing stress and evaporation coefficients Ks and K's as illustrated in Figure 12. There is, however, one situation when the distribution of soil moisture with depth is important; this occurs when the SMD is greater than RAW or REW and there is significant rainfall. The conventional single store approach assumes that evapotranspiration occurs at the potential rate on the day of rainfall with all the excess water allocated to reduce the SMD. On the following day, if no rainfall occurs, transpiration only occurs through the deeper roots at a reduced rate. In a similar manner, with bare soil when SMD > TEW, none of the rainfall is available for evaporation on the following days according to the conventional soil moisture balance. (Rushton et al., 2005)

This response of the single store soil moisture balance model is contrary to what is observed in the field. When a significant soil moisture deficit exists and there is substantial rainfall, moisture is retained near the soil surface. This is most noticeable when the soil has an appreciable clay content; the soil remains moist near the ground surface and crops continue to revive for several days after significant rainfall. This field response is represented by the introduction of near surface soil storage (NSSS) (Rushton et al., 2005).

A conceptual diagram of the procedures is included in Figure 15. The soil moisture distribution at the start of a day is indicated by the chain-dotted line in Figure 15(a). Following infiltration (due to rainfall or irrigation) and allowing for evapotranspiration, the increase in soil moisture is indicated by the shaded area. This increase in soil moisture is transferred to the computational model of Figure 15(b). A proportion of the increase in the soil moisture is retained near to the soil surface for transpiration or evaporation on the following day; this is indicated by the pentagon labelled Component 1. The remainder of the water reduces the soil moisture deficit, Component 2. An empirical factor (FRACSTOR) is used to define the proportion of the increase in moisture content which becomes near surface soil storage, SURFSTOR.

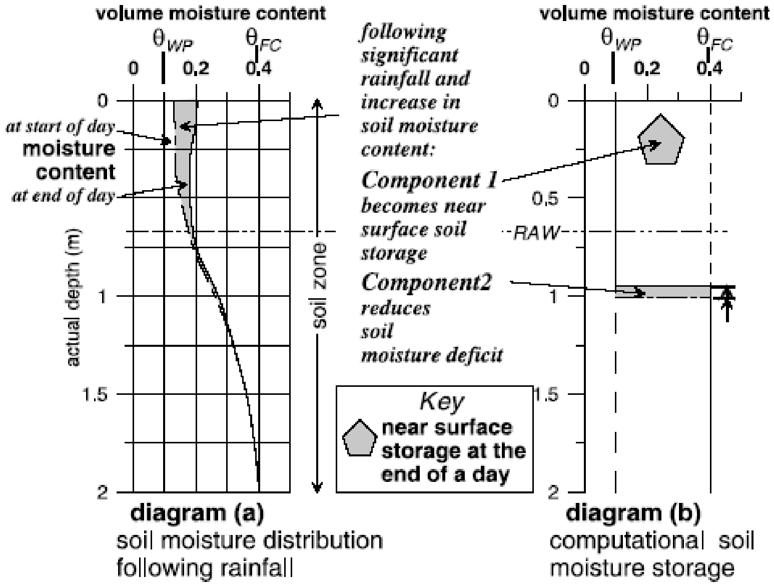


Figure 15: Near surface soil storage (NSSS): (a) change in soil moisture content due to significant rainfall, (b) diagram of computational technique with some of the excess water held as NSSS and the remainder reducing the soil moisture deficit (Rushton et al., 2005).

A pragmatic approach is used in estimating the value of (FRACSTOR) from field observations. If the soil surface remains wet after heavy rainfall, so that it is not possible to work the soil for several days, then (FRACSTOR) is likely to be in the range (0.6–0.8) while if the soil dries quickly then FRACSTOR will be less than 0.3. Appropriate preliminary values of the empirical constant

FRACSTOR are 0.0 for a coarse sandy soil, 0.4 for a sandy loam and 0.75 for a clay loam.

5.7 Occurrence of recharge

In the soil moisture deficit approach, recharge is assumed to occur on days when the calculation leads to a negative soil moisture deficit. As the soil moisture deficit becomes zero the soil reaches field capacity and becomes free draining. Consequently, recharge equals the quantity of water in excess of that required to bring the soil to field capacity.

Based on the algorithms presented in this chapter, a flowchart was prepared as shown in Figure 16:

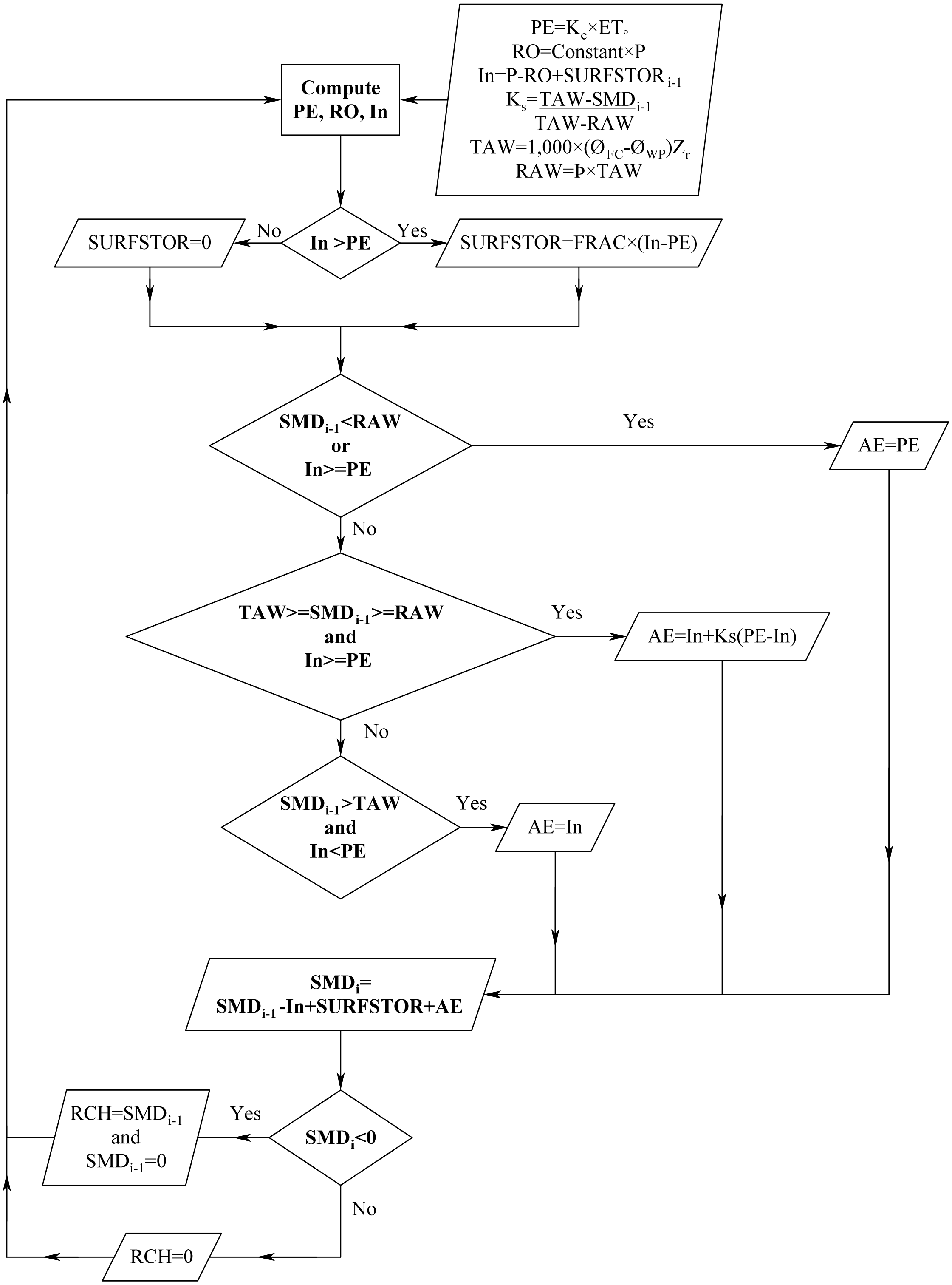


Figure 16: Depiction of the SMD method.

CHAPTER SIX

MODEL DEVELOPMENT

6.1General Background

Groundwater is a precious resource of limited extent. In order to ensure a sustainable use of groundwater, proper evaluation of recharge is required. In general, groundwater model needs a large volume of multidisciplinary data from various sources. GIS can provide the appropriate platform for efficient processing and analysis of diverse data sets for decision making in groundwater management and planning. In this work, an integrated GIS-based methodology is developed and tested for the quantification of groundwater recharge.

GIS is one of the most important tools for integrating and analyzing spatial information from different sources or disciplines. It helps to integrate, analyze and represent spatial information and database of any source, which could be easily used for planning of resource development, environmental protection and scientific researches and investigations (Maruo, 2003).

In this work, all the needed data were prepared as GIS layers and were integrated through GIS tools for analysis.

GIS technology has been around since early 1960's. However and after all of this time, most people still use GIS merely for map preparation and visualization purposes. GIS capabilities enable us to discover the embedded patterns and to figure out the spatial relationships in the geographic data across data of different types. The outcome of GIS analysis helps to focus our efforts and actions and choose the overall best option or plan (Parrish et al., 2005).

6.1.1 Why GIS in This Work?

Determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the time variability of precipitation in arid and semi-arid climates and the spatial variability in soil characteristics; topography, vegetation and land cover (Anderson and Woessner, 1992). Moreover, recharge amounts are normally small in comparison with the resolution of the investigation methods. The greater the aridity of the climate, the smaller and more variable is the recharge flux (Maruo, 2003). Management of groundwater resources requires a method to calculate accurate recharge rates at local and regional scales using readily available information. Many methods are available to calculate recharge yet most are unable to satisfy all these conditions.

GIS technology enables the ease of data processing, visualization, sorting, assessment, computations, and map preparation when compared with traditional technologies. GIS assists in measurement, management, multi-dimensional monitoring and analysis, modeling operations, output visualization and data processing. In addition, GIS capabilities in developing models that consider the spatiality in properties are very advanced. For instance, Model Builder has a lot of advantages that automate repetitive tasks, explore data iteratively, has a visual approach and enables considering more processes and data.

6.1.2 What is GIS-based modelling?

A model is any device that represents an approximation of a real situation (Anderson and Woessner, 1992). Models are used in many ways, ranging from water applications to scientists developing complex models to monitor global warming. Within the GIS context, a model can simplify complex data and emphasize relationships and patterns in the data, making it easier for the decision maker to understand the problem and develop an appropriate solution (Parrish, 2005). In addition, GIS modeling capabilities facilitate an efficient environment for handling spatial data.

The advent of GIS has allowed for the expansion of modeling. Spatial models use GIS to combine digital maps in an ordered process to assist decision making. As with any thing else, as you gain more experience, you can increase the sophistication of your modeling techniques (Parrish, 2005).

6.1.3 ModelBuilder

GIS technology has not only made it possible to process, analyze, and combine spatial data, but it has also made it easy to organize and integrate spatial processes into larger systems that model the real world. However, the more complex a spatial model becomes, the more difficult it is to keep track of the various data sets, processing procedures, parameters, and assumptions that you have used (ESRI Educational Services, 2000).

ModelBuilder is a new technology from ESRI that helps you create and manage spatial models that are automated and self documenting. A spatial model in ModelBuilder is easy to build, run, save, modify, and share with others (ESRI Educational Services, 2000).

ModelBuilder is a tool that helps you create spatial models for geographic areas. A model is a set of spatial processes that converts input data into an output map using specific functions that simulates specific phenomena. Large models can be built by connecting several processes together. In ModelBuilder, a spatial model is represented as a diagram that looks like a flowchart (ESRI Educational Services, 2000).

It has nodes that represent each component of a spatial process. Rectangles represent the input data, ovals represent functions that process the input data, and rounded rectangles represent the output data that is created when the model is executed. The nodes are connected by arrows that show the sequence of processing in the model (ESRI Educational Services, 2000).

The model is much more than a static diagram; it stores all the information necessary to run the processes and create the output data in ArcView GIS. You can also create documentation that is saved as part of the model. This enables you to reuse the model and share it with others. You can apply the same model to different geographic areas by changing the input data. You can easily modify the model to explore "what if" scenarios and obtain different solutions (ESRI Educational Services, 2000).

ModelBuilder has the tools you need to create, modify, and run a model. ModelBuilder uses ArcView GIS to process the input and create the output data (ESRI Educational Services, 2000).

Some features of ModelBuilder include:

- A model window where you build and save your models.
- Wizards that automate the creation of new spatial processes or the editing of existing processes.

- Property sheets that let you quickly modify the properties of input data, processes, or output data.

- Drag-and-drop tools that let you build and connect processes manually.

- Layout tools that help you arrange your model neatly.

6.1.4 What is a Spatial Model?

In general terms, a model is a representation of reality. The purpose of a model is to help you understand, describe, or predict how things work in the real world. By representing only those factors that are important to your study, a model creates a simplified, manageable view of the real world (ESRI Educational Services, 2000).

Spatial models can do the following:

- Rate geographic areas according to a set of criteria.

Perhaps the most common type of spatial model evaluates site suitability. To choose the most suitable land for a park, you must decide how many factors you will consider and which are most important. You might decide that land cost is the most important factor, or proximity to residential neighborhoods, or aesthetic considerations such as the view (ESRI Educational Services, 2000).

- Make predictions about what occurs or will occur in geographic areas.

To predict areas where soil erosion may be a problem, you need to know where loose soils occur in combination with steep slopes, the absence of vegetation, and high rainfall. Overlaying, or superimposing, layers (such as themes) of geographic data that occupy the same space to study the relationships between them lets you isolate areas of high erosion potential (ESRI Educational Services, 2000).

- Solve problems, find patterns, and enlarge your understanding of systems.

  To determine whether water contamination might be the cause of disease in a plant species, a model identifies a pattern of diseased plants occurring in proximity to water contamination (ESRI Educational Services, 2000).

6.1.5 Why to use spatial models?

Building a model helps you manage and automate your workflow. Managing process and the supporting data can be difficult without the aid of the model. A sophisticated model contains a number of interrelated processes. At any time you may add new processes, delete existing processes, or change the relationships between the processes. You can change variables, for example, replace old datasets with newer ones. You can also consider alternative scenarios in which input factors are prioritized differently. Building a model helps you manage this complexity.

6.1.6 How is a Spatial Model Represented in ModelBuilder?

In ModelBuilder, a spatial model is composed of one or more processes. A process includes input data, a spatial function that operates on the input data, and output data. Processes can be connected so that the output of one process becomes the input to another process (ESRI Educational Services, 2000).

The model does not actually contain spatial data; it has placeholders, called nodes, which represent the data that is processed and created when the model is run. The actual data is managed and displayed in ArcView GIS. ModelBuilder gives processing instructions to ArcView GIS when you run the model (ESRI Educational Services, 2000).

Figure 17 illustrates a model that has three processes. The rectangular nodes represent project (input) data. The oval nodes represent spatial functions that will process the data. The rounded rectangular nodes represent derived data (output data) created by the function. Connector lines connect the nodes and show the flow of processing through the model. Notice that the data derived from one process can become the input to another process (ESRI Educational Services, 2000).

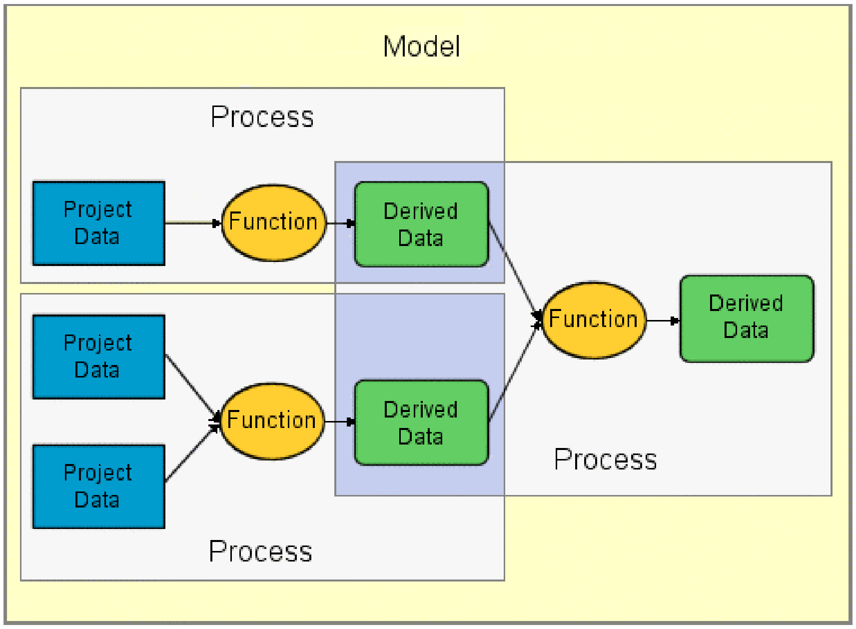


Figure 17: Depiction of modeling processes using Model Builder. (ESRI Educational Services, 2000).

6.1.7 What ModelBuilder Does?

ModelBuilder helps you build, manage, and automate spatial models. Without ModelBuilder, the management of models and of the data supporting them can be difficult. A sophisticated model contains a number of interrelated processes. At any time, you may add new processes, delete existing processes, or change the relationships among processes. In addition, you may replace old data sets with newer ones, change assumptions or model parameters, and consider alternative scenarios in which input factors are prioritized differently (ESRI Educational Services, 2000). ModelBuilder helps you manage the complexity of a model in the following ways:

- It makes processes and the relationships among processes explicit. ModelBuilder diagrams processes and the relationships among processes in a flowchart that is dynamically updated whenever a change is made.
- It lets you set the properties of the input data, the functions, and the output data, and it records this information in the model. This makes the model output reproducible.
- It stores documentation inside the model. You can document sources of input data and assumptions you made in the model.
- It stores and manages the model files and the output data on disk.
- It lets you edit the structure of the model by adding and deleting process or by changing the relationships among the processes.

- It lets you edit the properties of processes to experiment with alternative outcomes.
- When using ModelBuilder, you can create, visualize, document, run, modify, and share models.

ModelBuilder provides both beginning and advanced users with a set of easy-to-use tools for building various types of spatial models within ArcView Spatial Analyst (ESRI Educational Services, 2000).

ModelBuilder is a comprehensive geographic decision support tool that makes the solving of complicated problem simple. ModelBuilder will help you easily manage your project analysis requirements, from simple geographic analysis to complex spatial modeling (ESRI Educational Services, 2000).

6.2 Model Iteration

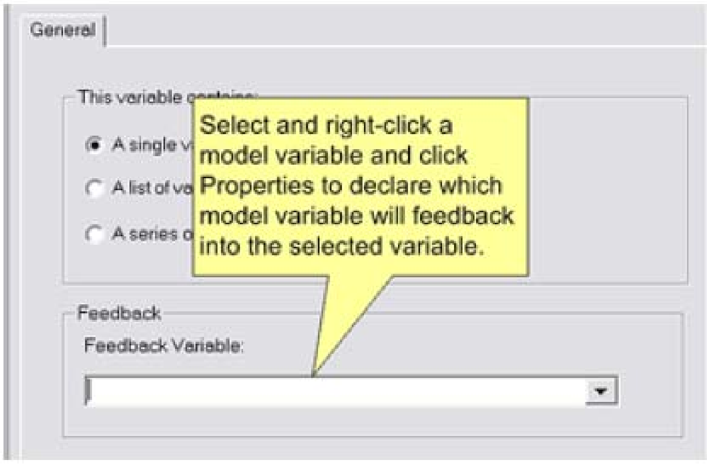
Iteration means to repeat a process and is sometimes referred to as looping. Iteration is a key concept in most programming languages. With iteration, you execute a process over and over using different data in each iteration.

In ModelBuilder, you can use iteration to cause the entire model to iterate, or just iterate an individual process.

Also, you can use several methods to cause a process or model to iterate. These methods are described in the following subsections.

6.2.1 Feedback

Feedback is where the output of a process is made the input to an earlier process. You can declare a variable as feedback by opening the properties of the input variable and selecting the output variable that will feed back as the input, as shown below in Figure 18. You can also use the Connect tool and connect an output variable to feed back to an input variable.



Select and right-click a model variable and click Properties to declare which model variable will feedback into the selected variable.

Figure 18: Depiction of the feedback window

6.2.2 Iteration variables

ModelBuilder provides two variables that contain the current iteration number and the current list index; %i% and %n% where %i% is the current position, or index, in a list variable. The first position is zero and %n% is the current model iteration. The first iteration is zero.

6.2.3 Iteration using feedback

You can use the output of a process as an input to a previous process. This is known as feedback, since you feed the output back to the input.

The model will produce one output dataset for each iteration, so it is important to have a unique output name for each iteration.

6.3 Development of the recharge model

As mentioned earlier, Model Builder of ArcMap (Arc Toolbox) was used in developing the recharge model. There are seven phases to develop the recharge model as depicted in Figure 19

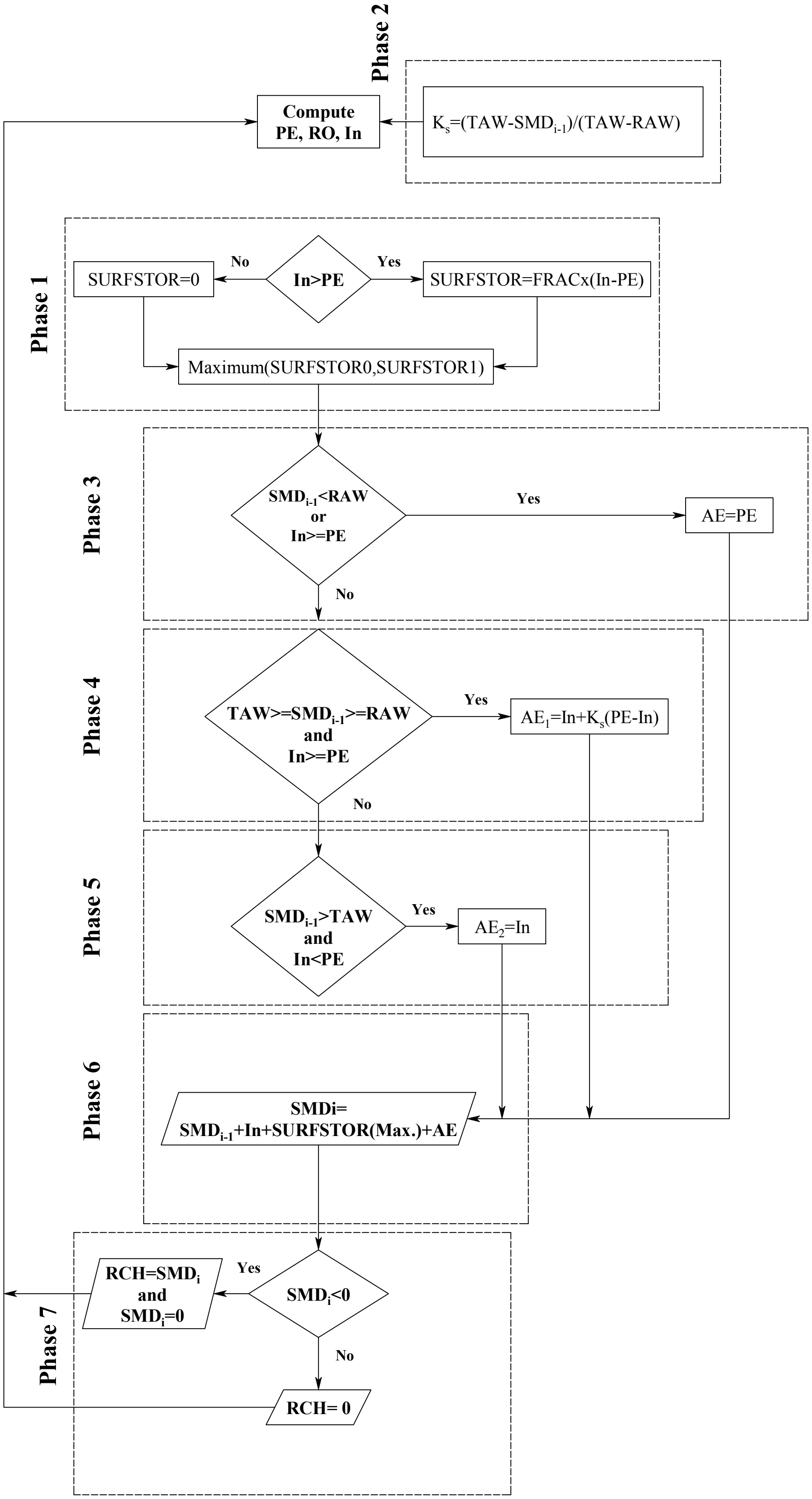


Figure 19: Depiction of the seven phases of recharge model.

The following are the steps followed in developing the recharge model:

1. New model was created in Arc Toolbox. Right-click the model and click Edit. Model builder will open, and you will be able to view and work with the existing model as depicted in Figure 20.

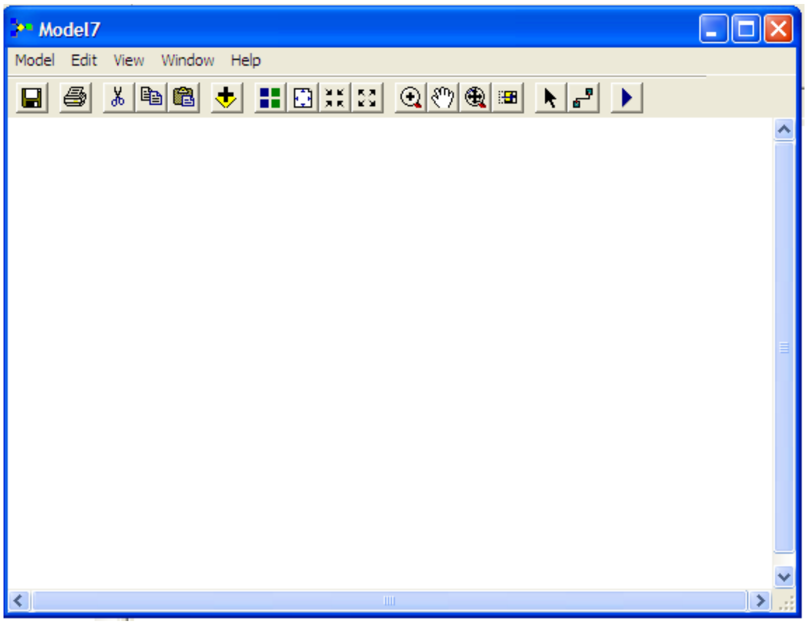


Figure 20: The main window of the Model Builder

2. The following layers were added: “SMD”, “PE”, “In”, “TAW” and “RAW” as shown in Figure 21. Symbols are as described earlier in the list of abbreviations.

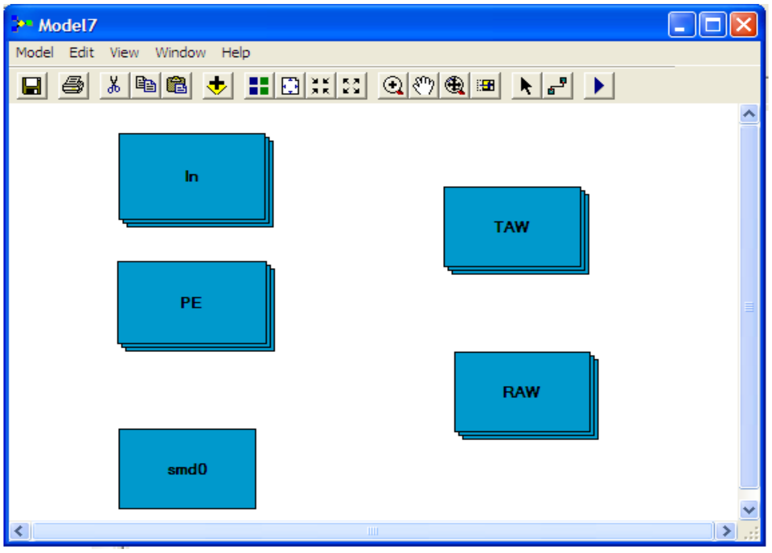


Figure 21: Depiction of the five layers (SMD, PE, TAW, RAW, In) added to the Model Builder.

3. The tool “Single Map Algebra” was added and connected to the layers, “In” and “PE”. Apply this tool “Single Output Map Algebra” when “In” > “PE” and when “In < PE”, “Single Output Map Algebra (2)”. The output layers are: “surfstor0 “and “surfstor 1” as shown in Figure 22.

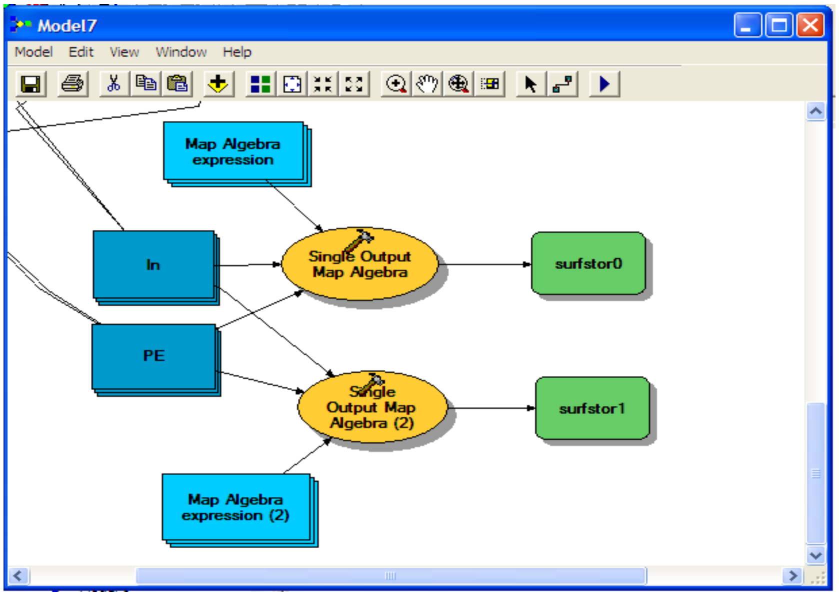


Figure 22: Depiction of the “Single Output Map Algebra(1)” and “Single Output Map Algebra(2)” and the output.

The step 3 was developed as depicted in phase 1 in Figure 19

The “Single Output Map Algebra” Tool has many Advantages and duties as explained in the following:

- Map Algebra expressions that generate a raster as output are supported.
- Inputs with different spatial references can be used with “Single Output Map Algebra” (SOMA). The datasets will be projected on the fly to complete the analysis (ArcGIS 9.2 Desktop Help, 2007).
- If the dataset is identified in the input raster or feature data list, it is not necessary to specify the path in the Map Algebra expression.
- The results from “Single Output Map Algebra” are added to the table of contents for the active ArcMap session (ArcGIS 9.2 Desktop Help, 2007).

4. The “Single Output Map Algebra” tool was added and connected to the “surfstor0” and “surfstor1” layers to produce and obtain the maximum values from the two layers as shown in Figure 23.

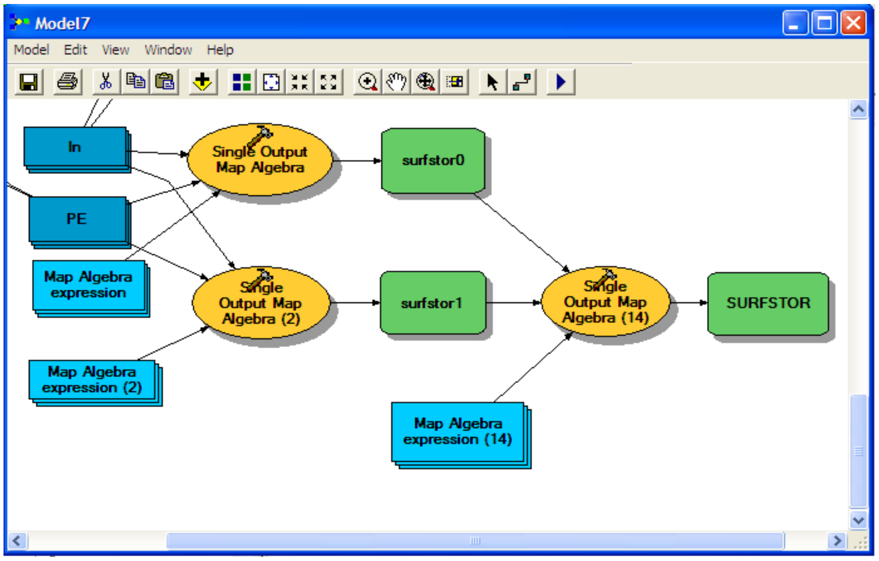


Figure 23: Depiction of the "Single Output Map Algebra(14)" and the "SURFSTOR" Maximum output.

The step 4 was developed as depicted in phase 1 in Figure 19

5. The "Single Output Map Algebra" tool was added and connected to the "TAW", "smd0" and "RAW" layers. The output layers are "numerator" and "denominator" as shown in Figure 24.

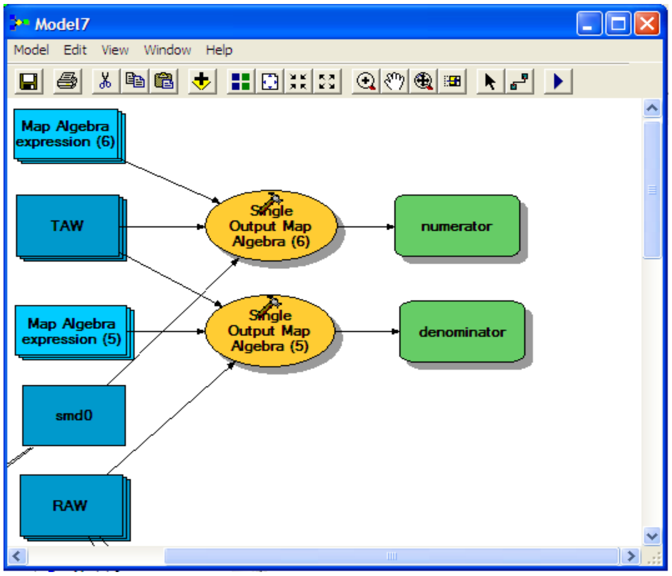


Figure 24: Depiction of the "Single Output Map Algebra (5)" and "Single Output Map Algebra (6)" and output.

6.The “Divide” tool was added and connected to the layers “numerator” and “denominator” and the output layer “ks%n%”as shown in Figure 25.

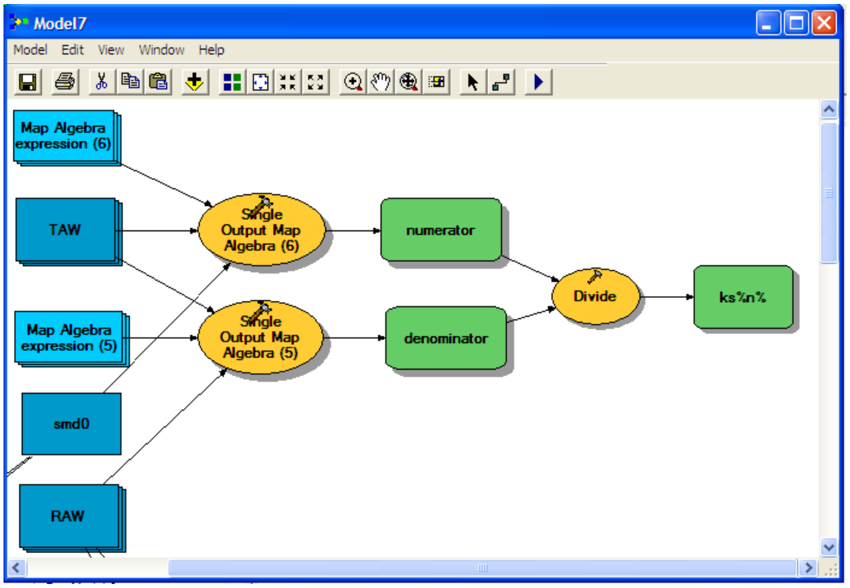


Figure 25: Depiction of the “Divide” tool and output.

The step 5 and step 6 were developed as depicted in phase 2 in Figure 19

7. The “Single Output Map Algebra” was added and connected to the layers “SMD”, “RAW”, “In” and “PE”. When condition “SMD < RAW” or “In ≥ PE” is true then the output layer is “AE = PE” as indicated by “Single Output Map Algebra (3)”

When this condition is false then the output layer will be “SMD” as indicated by “Single Output Map Algebra (4)” and as shown in Figure 26:

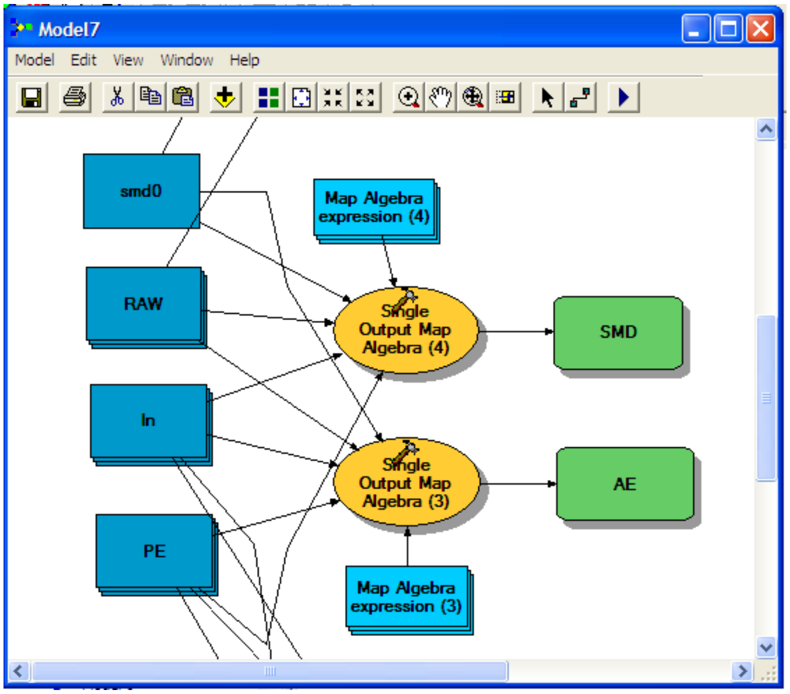


Figure 26: Depiction of the “Single Output Map Algebra (3)” and (4) and output.

The step 7 was developed as depicted in phase 3 in Figure 19

8. The “Single Output Map Algebra” was added and connected to the layers “SMD”, “RAW”, “In”, “TAW” and “PE”. When the condition “TAW ≥ SMD ≥ RAW and In ≥ PE” is true then the output layer is “AE 1 = In + Ks (PE – In)” as indicated by “Single Output Map Algebra (7)”

When this condition is false, then the output layer is “SMD” as indicated by “Single Output Map Algebra (8)” and shown in Figure 27.

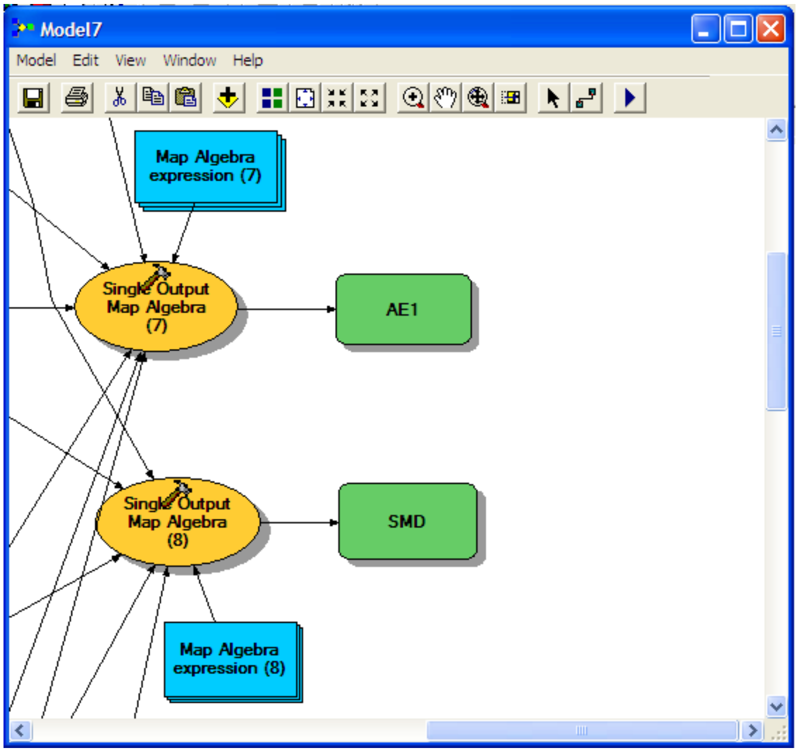


Figure 27: Depiction of the “Single Output Map Algebra (7)” and (8) and output.

The step 8 was developed as depicted in phase 4 in Figure 19

9. The “Single Output Map Algebra” was added and connected to the layers “SMD”, “In”, “TAW” and “PE”. When condition “SMD ≥ TAW” and “In < PE”, is true then the output layer is “AE 2 = In” as indicated by “Single Output Map Algebra (9)” and as shown in Figure 28.

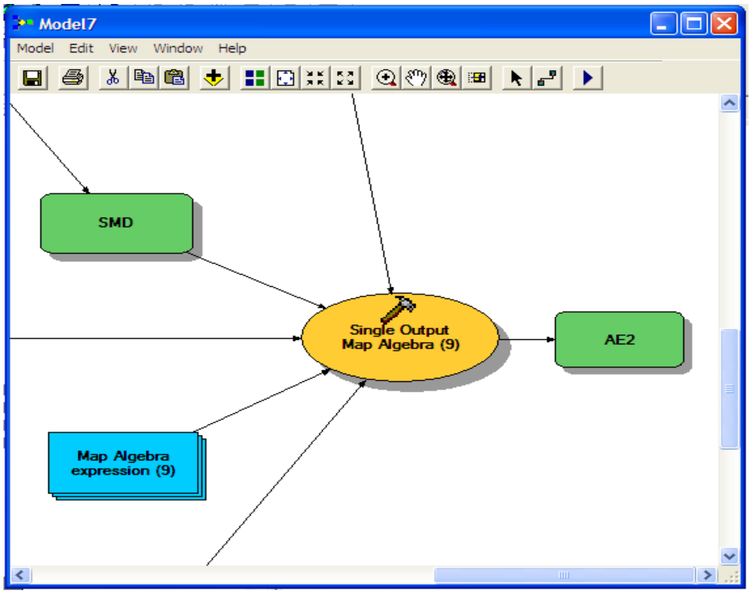


Figure 28: Depiction of the "Single Output Map Algebra (9)" and output.

The step 9 was developed as depicted in phase 5 in Figure 19

10. The "Weighted Sum" was added and connected to the layers "In", "AE", "SMD", and "SURFSTOR". It sums up the layer that satisfies this equation. The output layer is "SMDi%n%" as illustrated in the following equation and shown in Figure 29.

$$SMD_i = SMD_{i-1} - In + SURFSTOR + AE \qquad (11)$$

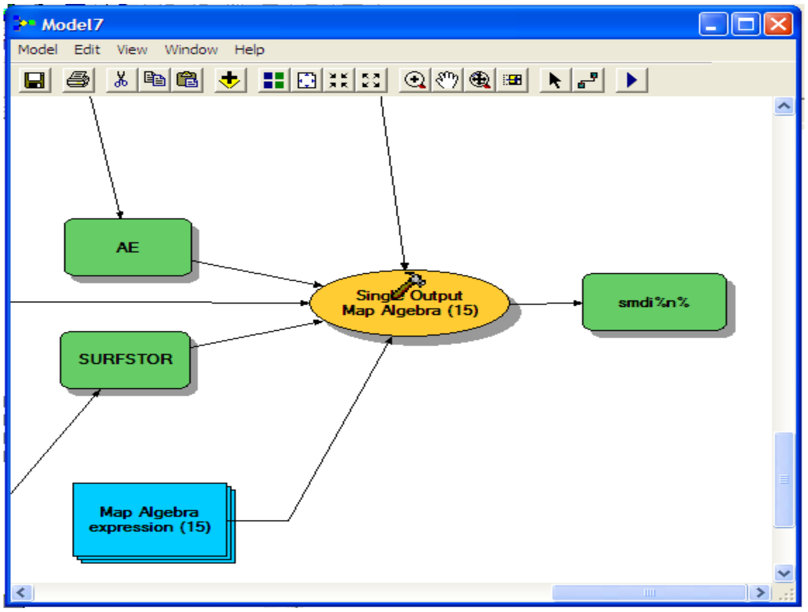


Figure 29: Depiction of the tool “Weighted Sum 15” and its output.

The step 10 was developed as depicted in phase 6 in Figure 19

The “Weighted Sum” Tool has many advantages and duties. The Weighted Sum tool provides the ability to weight and combine multiple inputs to create an integrated analysis. It is similar to the Weighted Overlay tool in that multiple raster inputs, representing multiple factors, can be easily combined incorporating weights or relative importance.

One major difference between the weighted overlay tool and the Weighted Sum tool is the Weighted Sum tool allows for floating point values whereas the Weighted Overlay tool only accepts integer rasters as inputs.

A useful way to add several rasters together is to input multiple rasters and set all weights equal to 1 (ArcGIS 9.2 Desktop Help, 2007).

11. The tool “Single Output Map Algebra 11” was added and connected to the computed three layers “SMDi”. Thereafter, the condition, “SMDi < 0” was

examined. When this condition is true, then output layers are “recharge0”. When this condition is false, then output layers are “recharge” as shown in Figure 30.

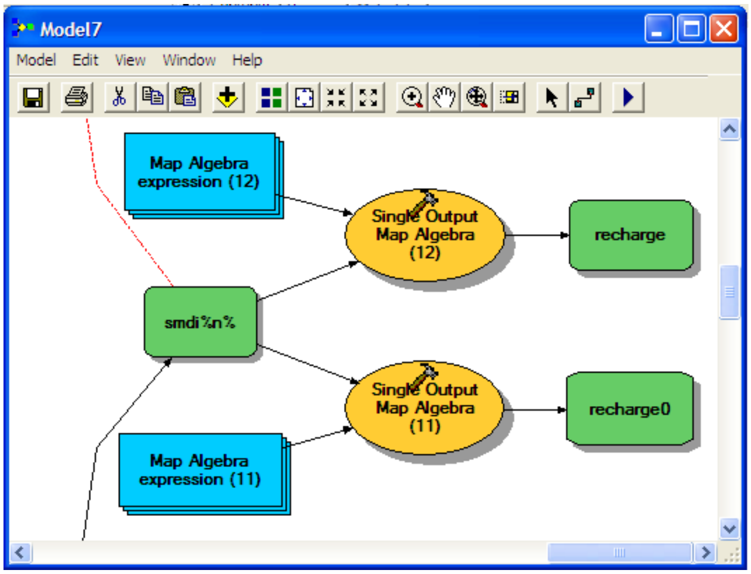


Figure 30: Depiction of the “Single Output Map Algebra (11)” tools and the corresponding output.

The step 11 was developed as depicted in phase 7 in Figure 19

12. The “Weighted Sum (2)” was added and connected to the layers “recharge” and “recharge0”. It sums up the layers, and the corresponding output layer is “Net Recharge%n%” as shown in Figure 31.

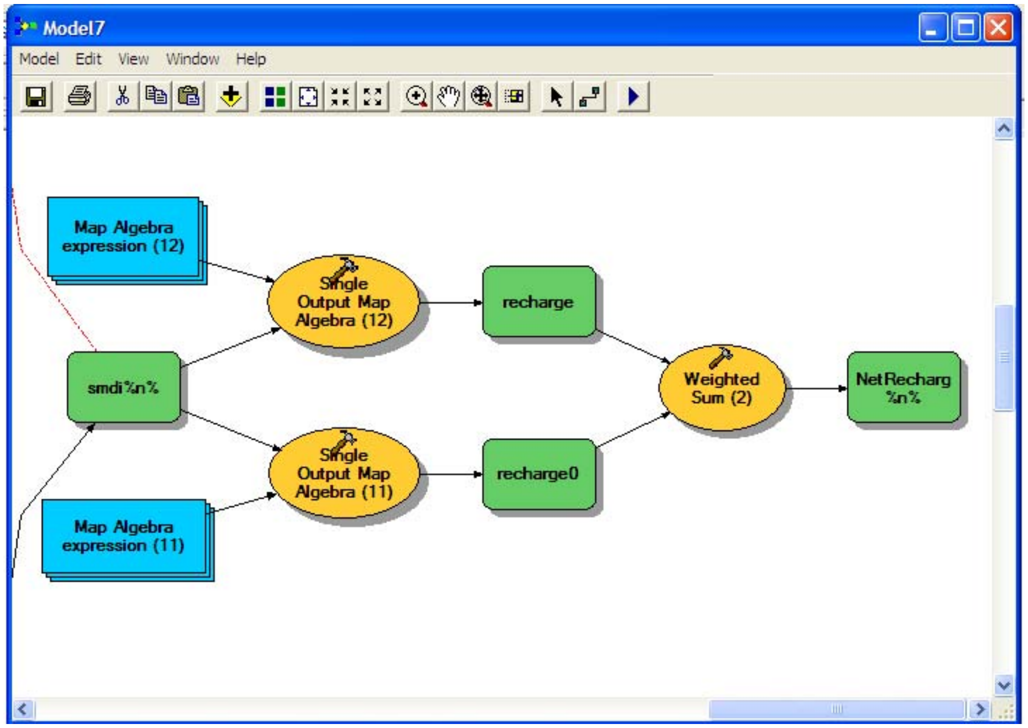


Figure 31: Depiction of the “Weighted Sum (4)” tool and the output.

13. After carrying out all the preceding steps, the overall model becomes as depicted in Figure 32:

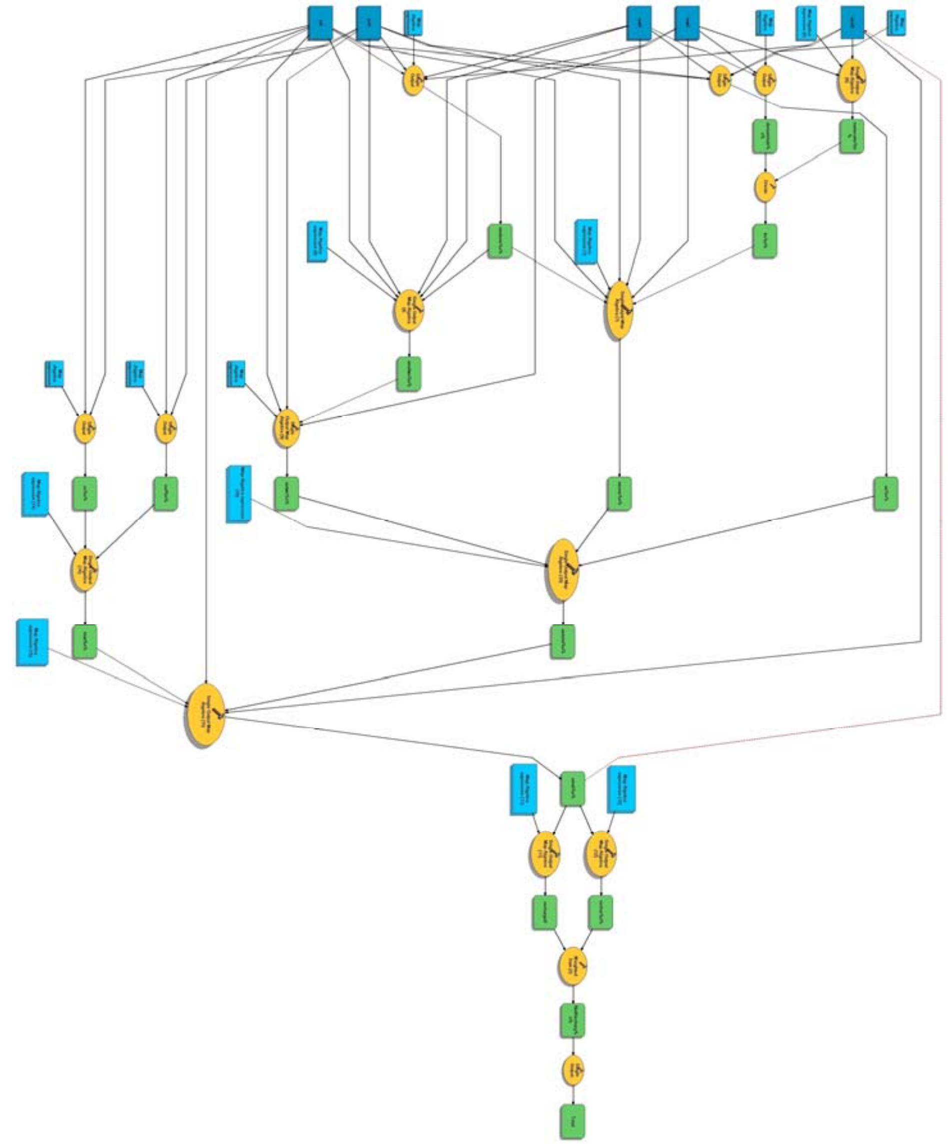


Figure 32: Depiction of the setup of the recharge model.

14. Before executing the model, the iteration value (number of runs) value

must be set as shown in Figure 33 and Figure 34.

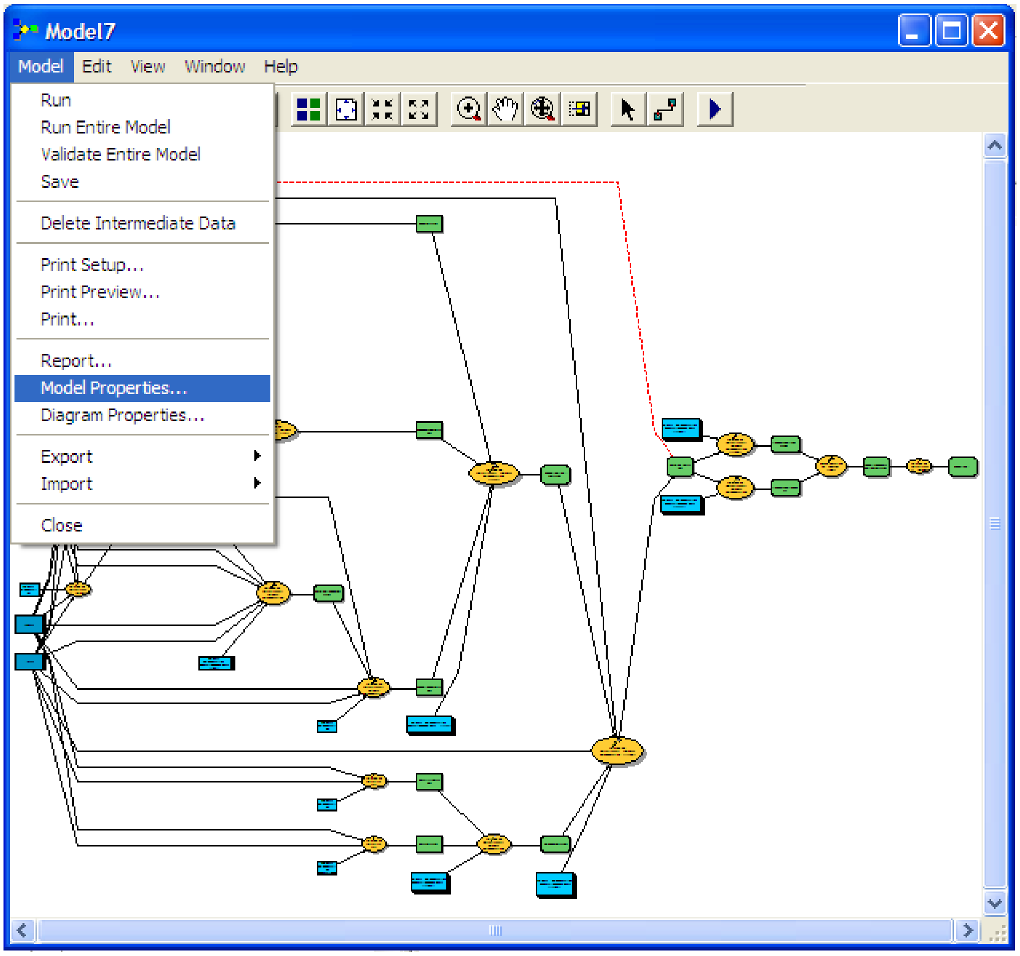
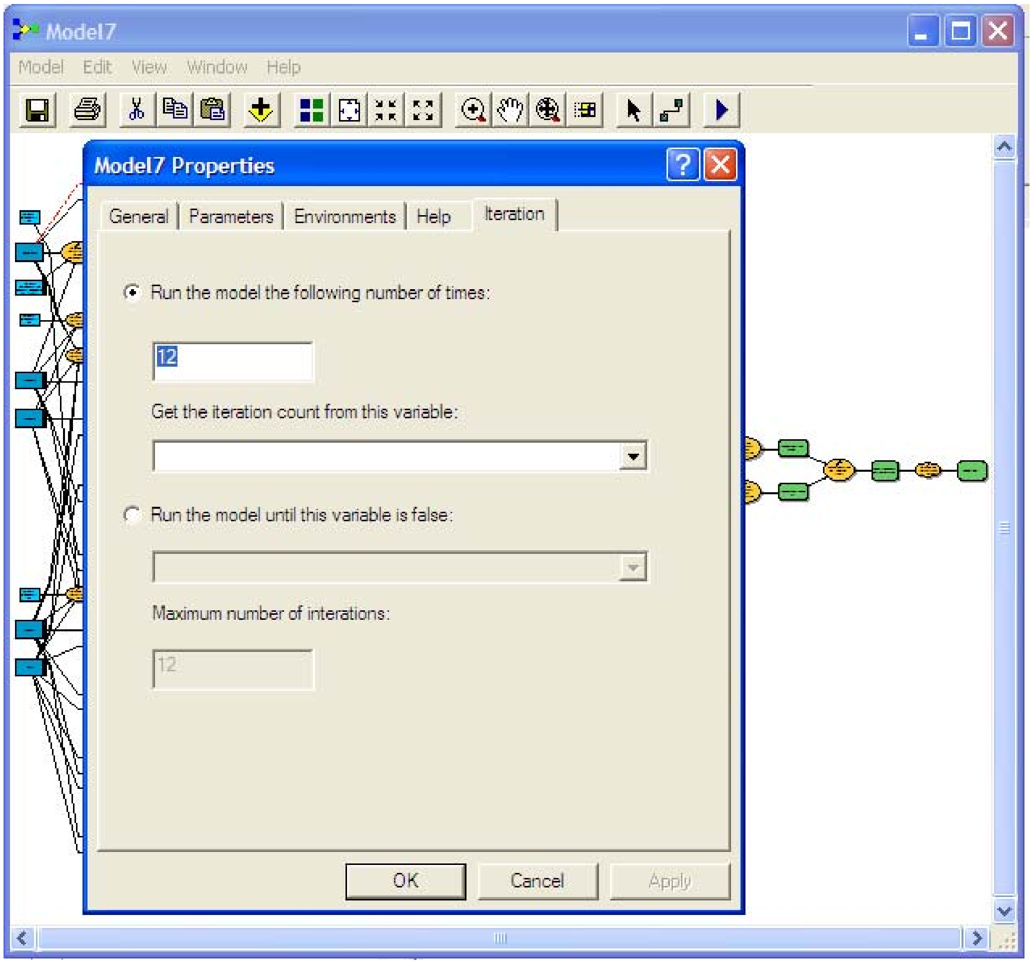


Figure 33: Depiction of the dropped menu of the model, to use “Model Properties”.



● Run the model the following number of times:

12

Get the iteration count from this variable:

○ Run the model until this variable is false:

Maximum number of interations:

12

Figure 34: Depiction of the window of the "Model Properties" .

15. Now the model is ready and can be executed.

6.4 ModelBuilder Problems

There are many problems we have encountered in developing the model. These problems were discovered during the model building.

1. The model is a new tool developed recently by ESRI and is still under development. As such, many GIS tools are still not fully supported within ModelBuilder;

2. The new version of ModelBuilder includes iteration, looping, and branching. The current ModelBuilder does not support all the tools available in ArcGIS Geoprocessing;

3. The ModelBuilder is still complicated and need a lot of development in terms of the programming environment;

4. The ModelBuilder works better and faster with dual motherboard; and

5. A great deal of simplification is required in the theoretical model in order to be able to model tools that are available within ArcGIS Model Builder**.**

Most of these problems were solved. While the solution of these problems take a long time.

CHAPTER SEVEN

RESULTS AND ANALYSIS

7.1 Introduction

The recharge model was developed and utilized to estimate the spatial distribution of recharge for the West Bank aquifers. Recharge estimation of the West Bank is important in order to have good insights of the water budget for the West Bank and to make balance between the total pumping and the aquifer recharge.

7.2 Temporal and Spatial Variation of Recharge

Recharge results are presented at the following temporal and spatial scales:

- Total annual recharge for the entire West Bank; and
- Temporal and spatial distribution of recharge for the West Bank.

The different results of recharge variation (spatially and temporally) are depicted in the following sections.

7.2.1 Spatial Distribution of Annual Groundwater Recharge

The spatial distribution of annual recharge for the entire West Bank for the year 2004 is depicted in Figure 35.

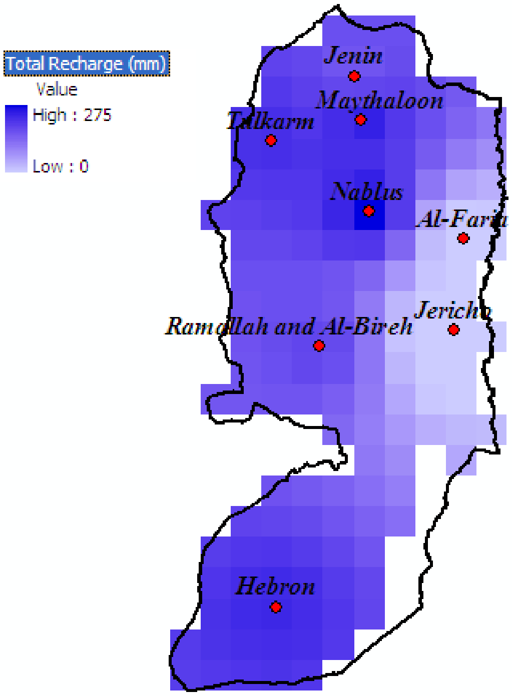


Figure 35: Depiction of the spatial distribution of annual recharge for the year 2004

As can be inferred from Figure 35, we can easily distinguish between areas of high and low recharge estimates. For instance, the eastern portions of the West Bank witness low recharge values due mainly to the low rainfall and high evaporation losses.

The total annual recharge for the entire West Bank was computed and equaled 852 mcm.

7.2.2 Temporal variation of recharge

The temporal variations of recharge from January to December are as depicted in the Figures below (Figure 36 to Figure 47):

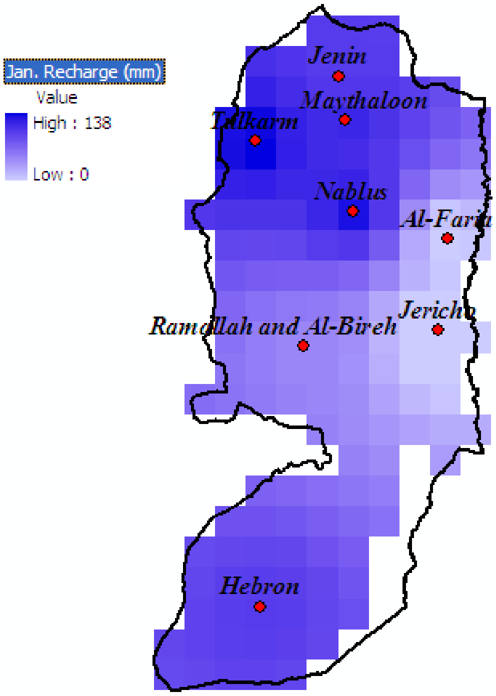


Figure 36: Depiction of the recharge for the month of January

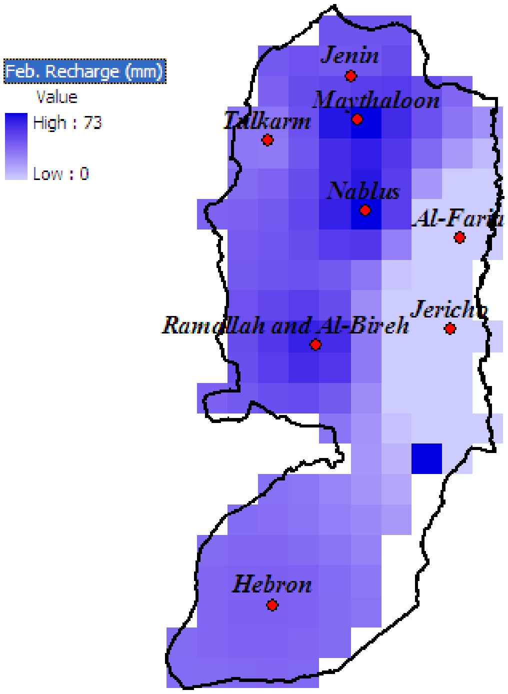


Figure 37: Depiction of the recharge for the month of February

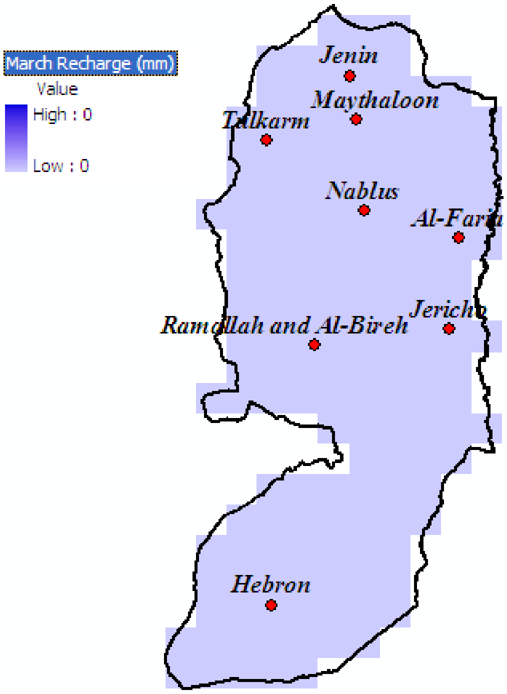


Figure 38: Depiction of the recharge for the month of March

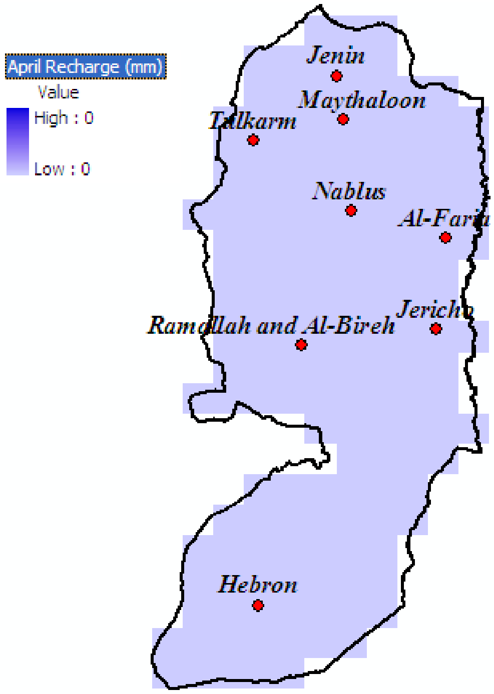


Figure 39: Depiction of the recharge for the month of April

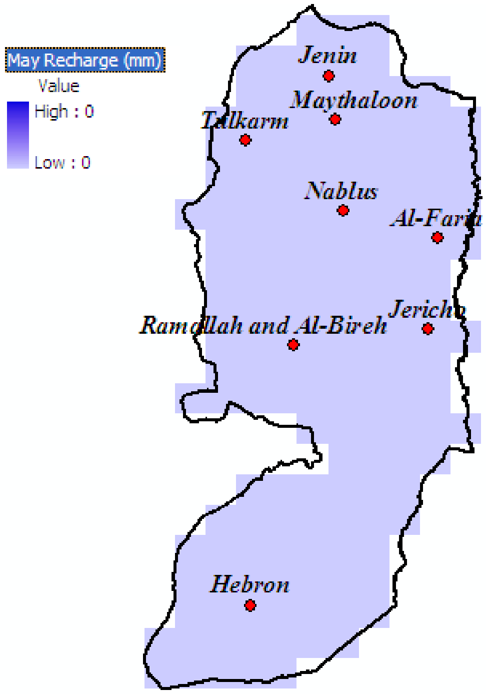


Figure 40: Depiction of the recharge for the month of May

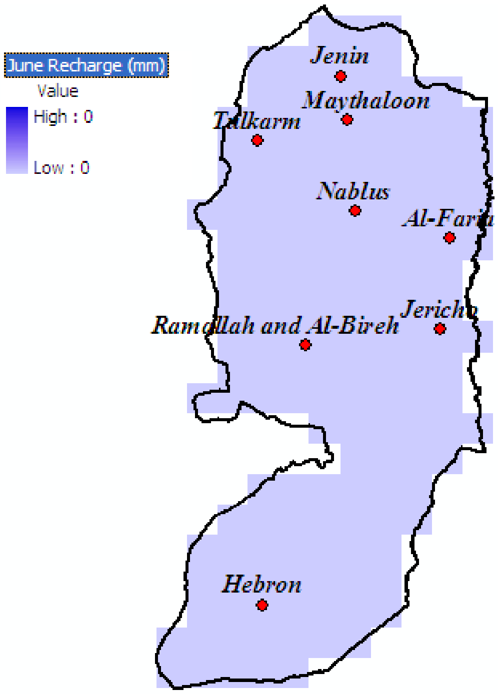


Figure 41:Depiction of the recharge for the month of June

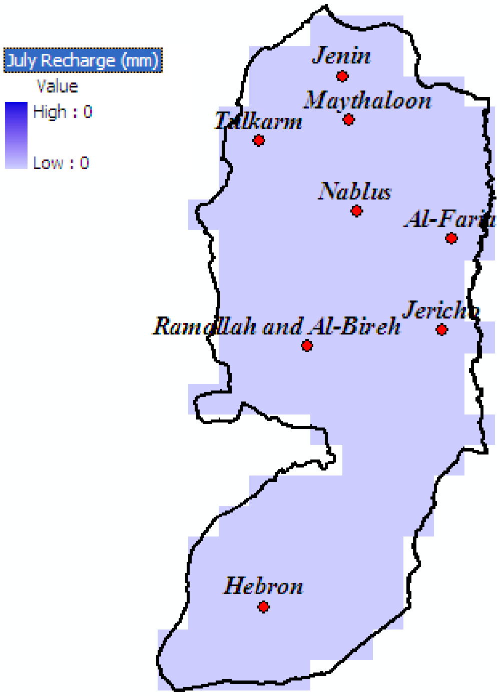


Figure 42: Depiction of the recharge for the month of July

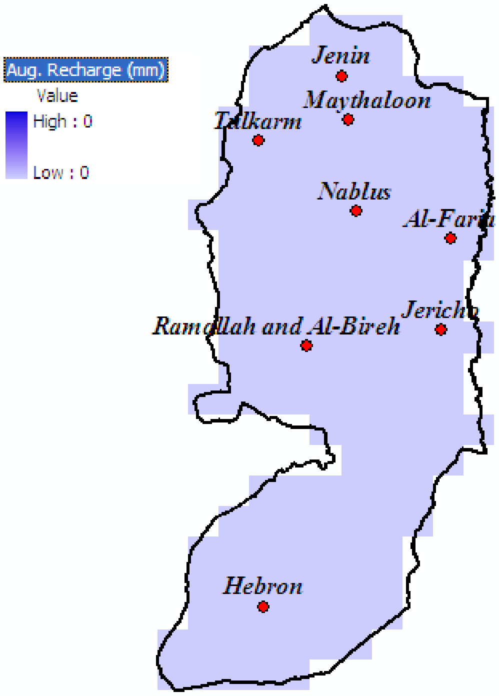


Figure 43:Depiction of the recharge for the month August

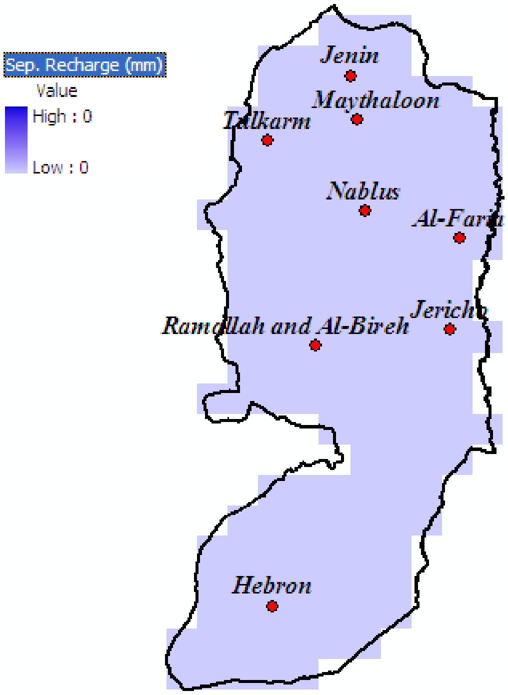


Figure 44: Depiction of the recharge for the month of September

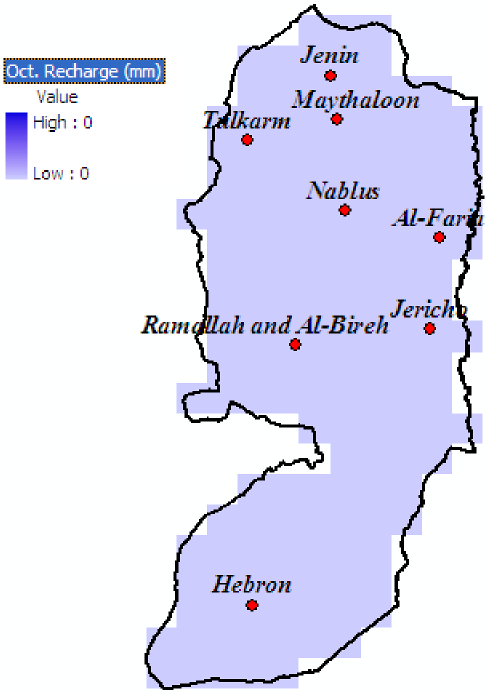


Figure 45: Depiction of the recharge for the month of October

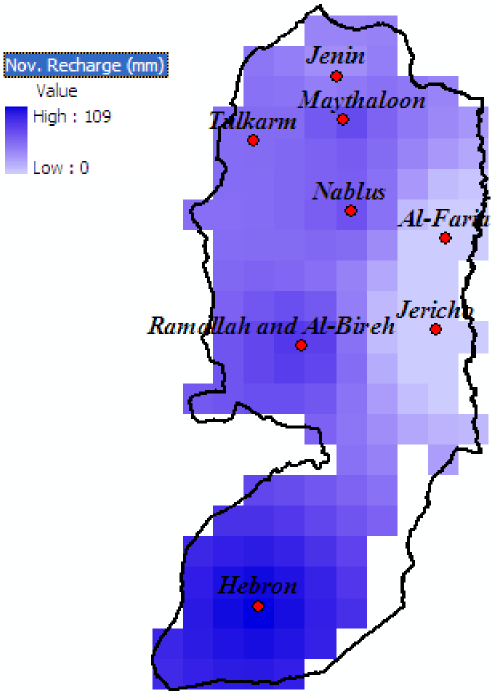


Figure 46: Depiction of the recharge for the month of November

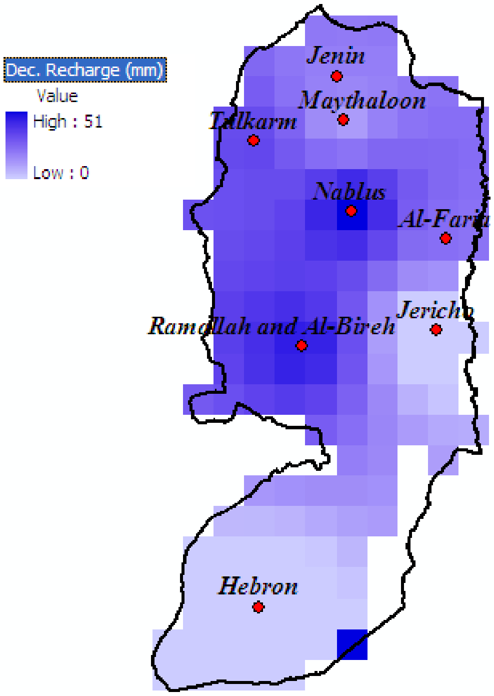


Figure 47: Depiction of the recharge for the month of December

The temporal variation of recharge from Junuary to December for year 2004 as depicted in Figure 48.

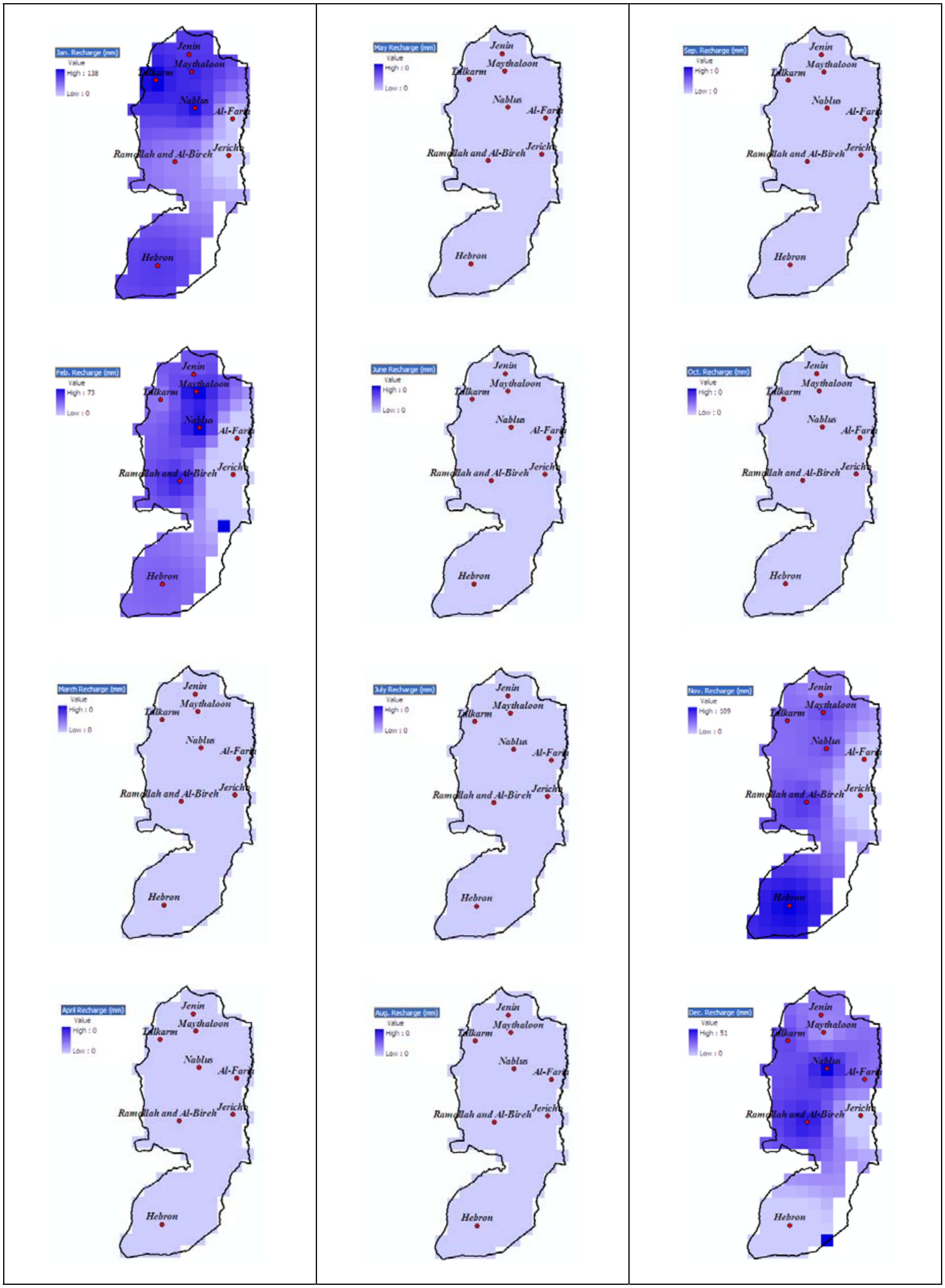


Figure 48: Depiction of the temporal variation of recharge from January to December for year 2004.

The highest recharge occurs in the months of January, February, November and December. The lowest recharge occurs in the months of March, April, May, June, July, August, September and October. This corresponds to the temporal variation of rainfall as depicted in Figure 49.

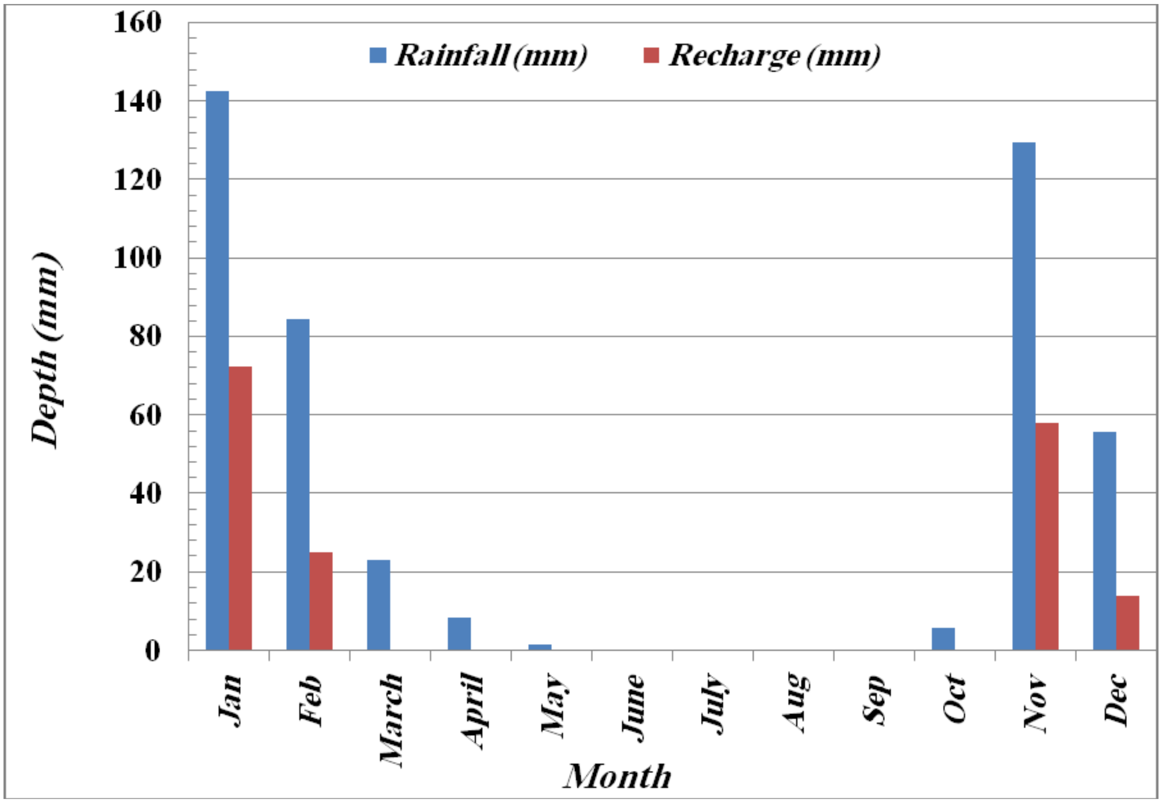


Figure 49: Depiction of the total monthly rainfall and the total monthly recharge for the year 2004 for the entire West Bank.

7.3 Recharge calculations based on the available analytical equations

According to Guttman and Zukerman (1995), the annual recharge equations for the entire West Bank are:

Recharge equation	**Rainfall (mm/year)**	
$R = 0.6(P-360)$	$P > 700$ mm	(12)
$R = 0.46(P-159)$	$700 > P > 456$ mm	(13)
$R = 0.15(P)$	$P < 456$ mm	(14)

where

R: Recharge from rainfall (mm/year)

P: Annual rainfall (mm/year)

Applying these analytical equations for the entire West Bank gives the results summarized in the Table 3.

Table 3: The recharge rate for the West Bank governorates based on the Guttman and Zukerman equations for the year 2004

West Bank Governorate	Annual Rainfall (mm)	Recharge (mm/yr)
Hebron	571.2	189.6
Nablus	638.5	220.6
Jericho	128.5	19.3
Jenin	424.8	63.7
Ramallah and Al-Berieh	524.3	168.0
Tulkarem	547.3	178.6
Maithaloon	521.3	166.7
Al-Far'a	234.3	35.1
Weighted Average	**450.8**	**126.4**

The tabulated results in the previous table were derived based on Guttman and Zukerman equations, which take percentages of the three ranges of rainfall, then apply one of these equations for each governorate that satisfies the rainfall range. The total recharge, as a depth, for the entire West Bank was computed using the Inverse Distance Weighted (**IDW**) method based on ArcGIS 9.2. After that the area for each polygon was determined, and then the total volume of recharge was computed and found to equal to 796 mcm. Recharge results presented in this section according to the (Guttmann and Zukerman equations) show that the highest recharge occurs in the North-West portion of the West Bank (such as Nablus) whereas the lowest is in the South-East portion (such as Jericho). This is in accordance with the spatial distribution of the rainfall as depicted in Figure 50.

Note: Inverse Distance Weighted (**IDW**) method based on eight governorates since this is the available rainfall records for the West Bank.

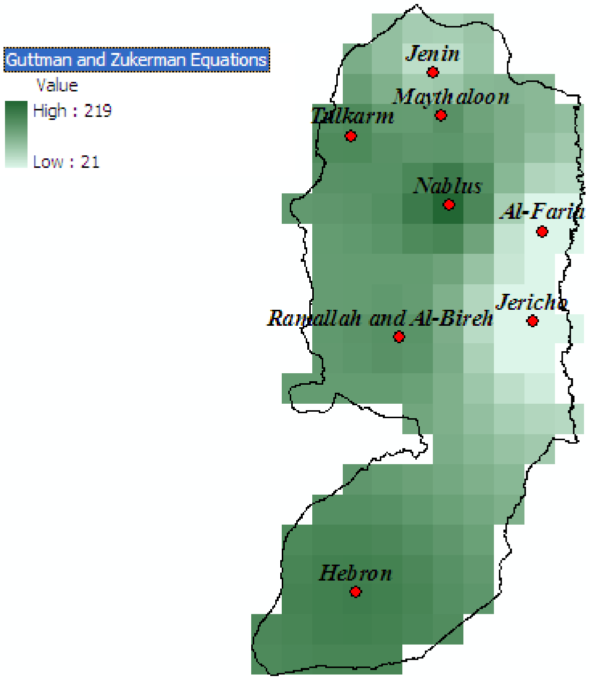


Figure 50: Depiction of the total annual recharge based on the Guttman and Zukerman equations for the year 2004.

The total annual recharge based on the SMD method and the total annual recharge based on the Guttman and Zukerman equations are as depicted in Figure 51.

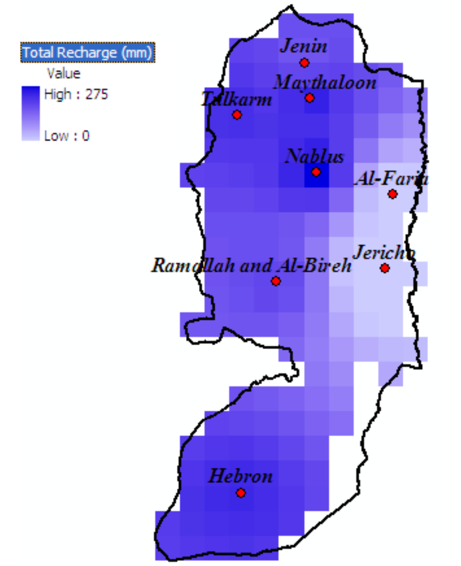
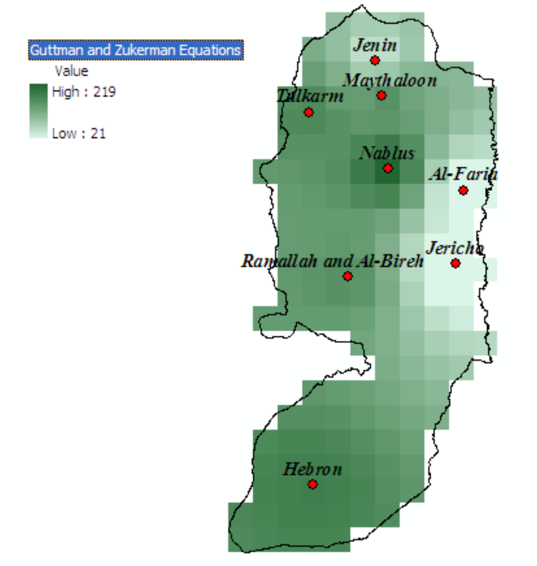
	
Total Recharge = 852 (mcm)	***Total Recharge = 796 (mcm)***

Figure 51: Depiction of the total annual recharge based on the SMD method and Guttman and Zukerman equations.

The value of groundwater recharge obtained by the SMD method is comparable to the results of the other method (Guttman and Zukerman equations) and seems very reasonable when applied to the groundwater model for the entire West Bank.

7.4 Spatial Distribution of Long Term Average Recharge Results

In this section, the long term average recharge for the entire West Bank was calculated based on the available historical records that start from 1975 to 1997. The results of the recharge for the entire West Bank equals 610 mcm.

The spatial distribution of the long term average recharge for the entire West Bank is shown in Figure 52

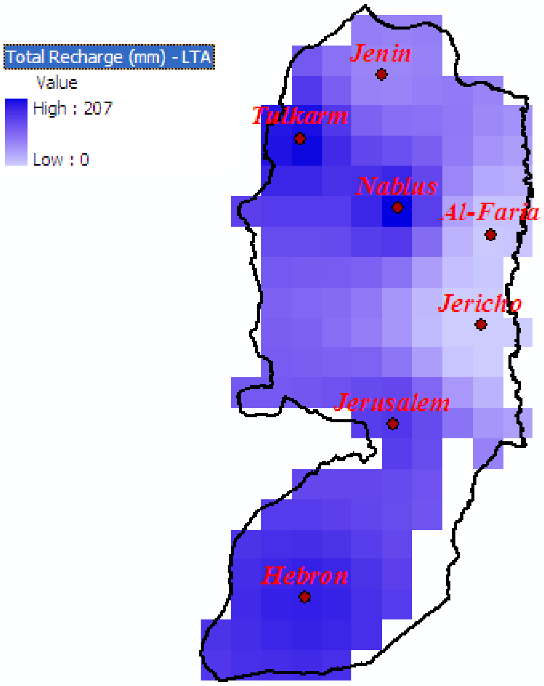


Figure 52 : Depiction of the Spatial Distribution of the long term average recharge for the entire West Bank based on the rainfall data from 1975 to 1997.

The Long Term Average recharge was calculated based on the available historical records that start from 1975 to 1997 based on the SMD method. The long term average recharge for the entire West Bank equals 610 mcm.

This number (610 mcm) is the average for 22 years, besides the 610 mcm represents the average of drought years and wet years.

This number 610 mcm is more representative and accurate than the recharge number for one year. This number derived from ModelBuilder.

The total annual recharge for the entire West Bank for the year 2004 based on Guttman and Zukerman equations:

The number 796 mcm was derived based on Guttman and Zukerman equations, which take percentages of the three ranges of rainfall, then apply one of these equations for each governorate that satisfies the rainfall range. The total volume of recharge was computed and found to equal to 796 mcm.

The total annual recharge for the entire West Bank for the year 2004 based on the SMD method is 852 mcm. This number derived from ModelBuilder.

It is important to compare the results for this model with previous studies and research, to verify that the results for this model were valid.

Note:

The year 2004 was chosen based on the following:

1. The data for year 2004 were complete and no missing data for all months for this year.

2. The data were available for the year 1999 until 2006. The data for these years were incomplete and have missing data except year 2004. For example some months for these years do not contain any data, which makes it difficult to use these data.

7.5 Discussion of the Results

- Recharge results presented in the previous sections show that the highest recharge occurs in the North-West portion of the West Bank whereas the lowest is in the South-East portion. This is in accordance with the spatial distribution of the rainfall and the potential evaporation (a general trend of greater aridity to the South-East) in the West Bank.

- Recharge predominantly occurs when the soil moisture content exceeds field capacity (during the winter months). During this period, rainfall significantly exceeds evaporation. While during the summer months, once a soil moisture deficit has developed, recharge does not take place.

- The highest recharge occurs in the months of January, February, November and December. The lowest recharge occurs in the months of March, April, May, June, July, August, September and October. This corresponds to the temporal variation of rainfall.

- The results for SMD method used in the present research and Guttman and Zukerman equations are in good agreement.

- The Long Term Average recharge was calculated based on the available historical records that start from 1975 to 1997 based on the SMD method. The long term average recharge for the entire West Bank equals 610 mcm.

- The results presented in this research indicated that the Palestinian water rights in the entire West Bank is 852 mcm. This finding is much higher than what is mentioned according to the Oslo II agreement (679 mcm).

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following are the research main conclusions:

1. Recharge estimation for the West Bank is important in order to have a good understanding of the water budget for the entire West Bank. This helps to achieve a balance between total pumping and recharge;
2. GIS is an effective tool for estimating the spatial variability of recharge. In addition, GIS facilitates the analysis of the interrelated relationships between the different explanatory parameters related to the calculation of recharge;
3. ModelBuilder of GIS was utilized to facilitate the recharge quantification and to efficiently account for the spatiality inherent in recharge;
4. The SMD method provides a robust way to estimate recharge;
5. The highest recharge occurs in the North-West of the West Bank and the lowest is in the South-East. This corresponds to the spatial distribution of rainfall;
6. The highest recharge occurs in the months of January, February, November and December. The lowest recharge occurs in the months of March, April, May, June, July, August, September and October;
7. The total annual recharge for the entire West Bank based on the SMD method is 852 mcm for the year 2004; and

8. The long term average recharge for the entire West Bank equals 610 mcm.

8.2 Recommendations

Many recommendations can be drawn out of this research. The recommendations listed herein address future studies that can consider the following issues:

1. Importance of improving the current version of this model by reducing the running time and by using daily data;

2. Scenario analysis (such as climate change and its impact) is required to predict the corresponding recharge behavior.

3. It is important to consider different methods in order to carry out a cross comparison analysis; and

4. It is important to establish vulnerability zones and to identify the areas of high potential of groundwater recharge. And hence every care should be considered when developing land use categories and related practices for these areas.

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قدمت هذه الأطروحة استكمالا لمتطلبات نيل درجة الماجستير في هندسة المياه والبيئة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.
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الملخص

تعتبر المياه الجوفية المصدر الرئيس للمياه بالنسبة للفلسطينيين. ولإدارة فاعلة لهذا المصدر، لا بد من فهم عميق لوضع المياه الجوفية يمكننا من تحديد كمية المياه ذات الجودة والقابلة للاستغلال. ركز البحث على تحديد كمية التغذية للمياه الجوفية في الضفة الغربية وكذلك كمية التغذية في كل حوض من أحواض الضفة الغربية. استخدمت تكنولوجيا أنظمة المعلومات الجغرافية (GIS) لتسهيل عملية حساب هذه الكميات وإبراز أهمية التوزيع المكاني للعناصر المختلفة المؤثرة في كمية المياه الجوفية. وكذلك تمت دراسة التغير الزمني وتأثيره على كمية التغذية للمياه الجوفية. أكدت نتائج هذا البحث أن الكميات تكون مرتفعة في الشمال الغربي, ومنخفضة في الجنوب الشرقي للضفة الغربية. وأكدت نتائج هذا البحث أن كمية التغذية للمياه الجوفية في الضفة الغربية (معدل البيانات من عام 1975 الى عام1997) تساوي 610 مليون مترمكعب.وكذلك أن كمية التغذية للمياه الجوفية في الضفة الغربية لعام 2004 تساوي 852 مليون مترمكعب. وبشكل عام، فقد جاءت توصيات هذا البحث لتؤكد أن وضع المياه الجوفية في أحواض الضفة الغربية بحاجة ماسة لدراسة التغيرات المناخية وأثرها على كمية التغذية وكذلك التنبوء بأثر هذه التغيرات على كمية التغذية لسنوات قادمة.