An-Najah National University
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Groundwater Flow Modeling - Case Study of the Eocene Aquifer in the West Bank, Palestine

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Hamees Mohammad Sameh Tubeileh

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Abstract

The Eocene aquifer is one of the major groundwater basins in Palestine. It is located at the northeastern part of the West Bank covering areas in both Jenin and Nablus districts. The aquifer is considered one of the main sources for fresh water for the majority of the population in the northern West Bank.

Many models have been formulated to develop the groundwater resources within the Eocene aquifer. In this thesis a simulation for the groundwater flow is developed.

MODFLOW, as a strong available groundwater modeling tool, has been used to model the Eocene aquifer. The groundwater budget, flow computation and flow pathlines were estimated and calibrated. Groundwater balance has been also evaluated.

The modeling indicated that the model runs only for certain initial hydraulic groundwater levels of more than 340m. The recharge and hydraulic conductivity were found to be the most sensitive model parameters. The hydraulic conductivity has resulted double of the original

value in some areas. This is due to neglecting the faults and fractures effect. The recharge coefficients resulted in high inflow values. Groundwater balance indicated that the water budget of the Eocene aquifer totals about 72MCM/yr.

The simulation showed that the groundwater level increases gradually by increasing the recharge rate. The change of groundwater level is nearly linear. Due to the variation in the aquifer geometry, the groundwater levels were mild at the beginning and became steeper as the recharge ratio increase.

The groundwater levels showed higher sensitivity to hydraulic conductivity as its value increases from moderate to high or from moderate to low values.

There has been a reasonable matching between the observed and calibrated groundwater level and spring flows. The direction of the flow within the aquifer is from the south to north and northeast. The Far' a spring system located in the south of the aquifer, seems to be the major sink point within the aquifer since it attracts most of the particle tracking lines in the model. This is due to its high discharge rates.

Based on the results of this study it is recommended that groundwater wells located or proposed at or near the anticlinorium should be designed and operated carefully. The gradients and the modeling results indicate that a substantial quantity of groundwater flow across the eastern and the northeastern boundaries, materialized as lateral subsurface outflow. It is recommended that this good quality water could be tapped and exploited. Field investigations are recommended to verify the geological conditions. It is recommended to monitor the existing wells and springs permanently and to construct a reasonable additional monitoring network. this package can be applied to model groundwater transport model for the Eocene aquifer. A finer grid is important in order to control the variation in hydraulic properties. In this study the effects of the fractures (due to the faults) are neglected. So it is recommended to assess carefully the effect of the faults on the actual hydraulic conductivity.

1. Introduction

1.1 General

In the Palestinian territories, water is the most precious natural resource and its relative scarcity is of major constraint on economic development. Groundwater is the major source of fresh water, and is thus of primary importance to the Palestinians.

The system of aquifers in the West Bank is divided into three main groundwater drainage basins; these are the western, the north-eastern (Eocene) and the eastern basins.

The water of the Eocene aquifer is partly utilized by the Palestinians. People who are utilizing the Eocene aquifer, mainly depend on its groundwater to secure domestic and irrigation needs.

The Eocene aquifer area is a vital region and become a highly populated area, with a combined total population of about half a million. This reflects the importance of groundwater management within this aquifer and emphasizes the need for groundwater assessment and control.

1.2 Study Area

The Eocene Aquifer is located in the northeastern part of the West Bank. It is located to the northeastern of the groundwater divide, which runs through the Jenin district and part of the Nablus district. The outcrop area of the Eocene aquifer is about 520 km^2 .

The Eocene aquifer is composed mainly of limestone and chalk, which form the groundwater water-bearing formations (aquifers), separated by relatively impermeable beds of chalk, clay, and marl (aquitards). The groundwater potential of the northeastern aquifer system was estimated to be around 140MCM/yr (PHG, 1996).

1.3 Problem Identification

Water demand and consumption are increasing rapidly. Supply systems have nothing to do with modeling the flow system of the Eocene. This is due to the increase in the population growth, rising of living standard, and the development in irrigation.

The study area is a vital region with respect to the developments and activities related to the water sector in Palestine.

Because the Eocene aquifer is very important to the agricultural sector in Palestine, it is very important to model its flow system so that its sustainable yield can be estimated.

Modeling the flow in the Eocene aquifer, will provide basic information for the managers to understand the flow within the aquifer and thus support the decision-making process about future development of this aquifer especially for the agricultural sector.

The modeling has three main steps; the first step is the conceptual model. The second step is the translation of the conceptual model into a numerical model, which can be solved. The third step is the calibration of the model and estimating the sensitive parameters that affect the results of the model.

1.4 Objectives

The most important objectives of this research are:

1) Evaluate the sustainable yield of the Eocene aquifer.
2) Evaluate the flow system of the Eocene aquifer.
3) Evaluate the steady state flow case in the Eocene aquifer.

1.5 Methodology

It is assumed that modeling the flow in the Eocene aquifer will be used to satisfy the above objectives. The flowchart of the methodology is presented in Figure 1.1 and is summarized as follows:

- Collect and review available studies on the groundwater of the West Bank in general and of the Eocene aquifer in particular. These include geological, topographical, hydrogeological, meteorological and modeling studies.
- Collect data about the study area from the local establishments.
- Based on the literature review for the groundwater modeling studies, a suitable computer code to model the Eocene flow system will be recommended.
- The collected data will be analyzed, and the conceptual model will be formulated by identification of the model boundary, hydrological data, and the water budget components of the area.
- Preparation of the input data from hydrogeological and topographical data and maps, in addition to the historical meteorological records.
- Set-up the model using the suitable data.
- Calibration and validation of the groundwater flow model.
- Assessing the groundwater balance for the Eocene aquifer.

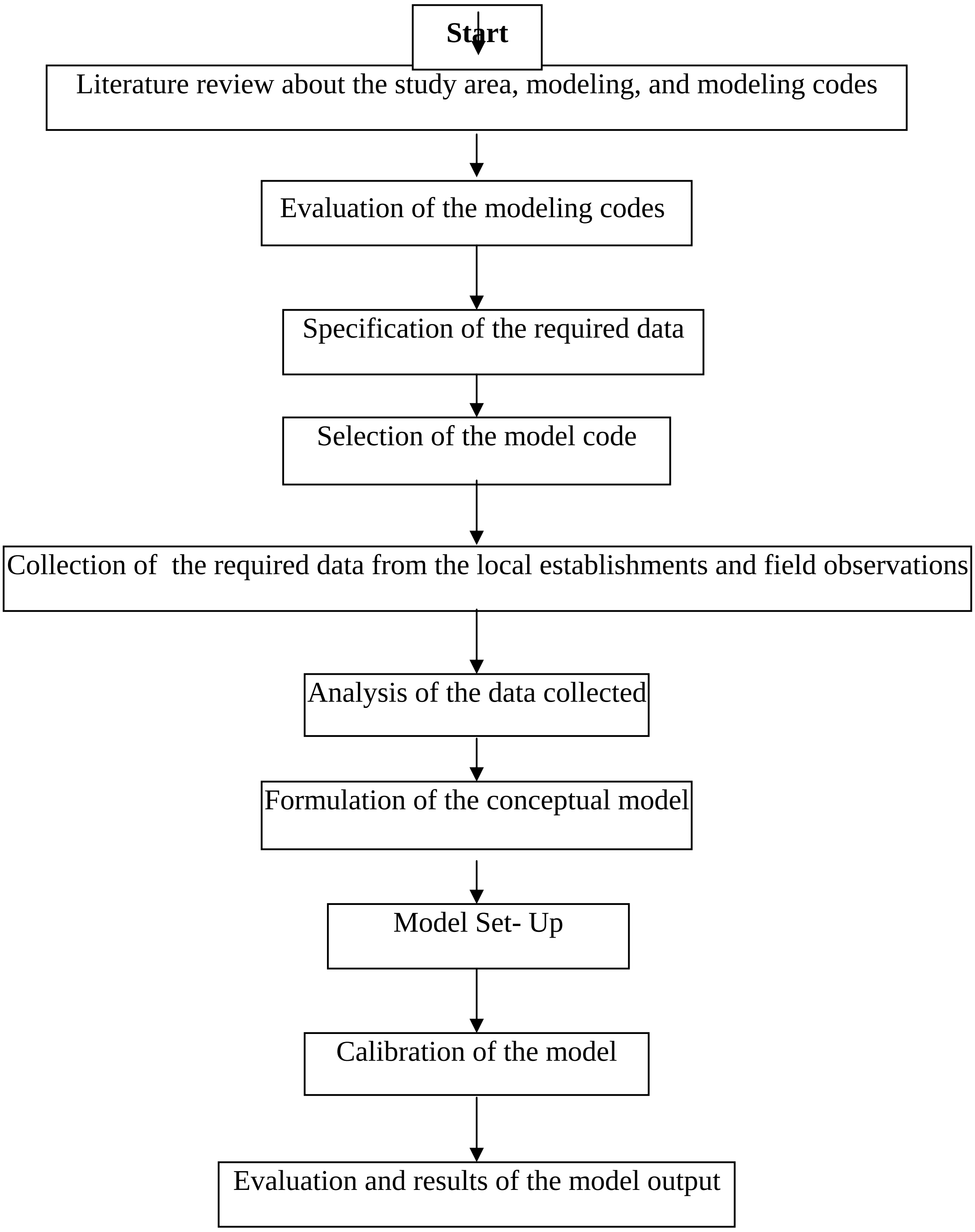

Figure 1.1: Methodology Chart for the Groundwater Modeling of the Study Area.

1.6 Model Set-Up

Generally, the data required to set-up the simulation model depends upon the selected code, the study approach, and the objectives proposed. For this study and to define the aquifer system and assess its groundwater quantity, data collected are as follows:

1.6.1 Physical data

The physical data collected includes but not limited to:

- Geological maps and cross-sections indicating the horizontal and vertical extent of the system.
- Topographical and hydrological maps showing the surface water bodies, springs, and divides.

1.6.2 Hydrogeological data

The hydrogeological data are essential for the formation of the flow equation. These include:

- Groundwater level data.
- Aquifer boundaries.

- Pumping test data.

1.6.3 Water budget data

In order to determine the water balance of the aquifer, the following data are used:

- Hydrological and meteorological data.
- Spring data.
- Pumped abstractions.

1.6.4 Structural data

The structure of the aquifer affects the determination of the hydraulic conductivity. The following data are needed:

- Data on fault systems such as fractures and fissures.
- Data on anticlines, synclines, and monoclines.

1.7 Thesis Outline

This thesis consists mainly of 7 chapters. Chapter 2 clarifies the modeling process and the selection of suitable simulation code. Further, an overview of the study area, the hydrological and structural situation, in addition to the meteorological conditions are presented in Chapter 3. An overview of the groundwater flow model and set-up of the model are discussed in Chapter 4. Calibration and representation of the most sensitive factors that affect the model are represented in Chapter 5. In Chapter 6, the flow path in the aquifer is shown. Also groundwater balance is estimated in this Chapter. Finally Chapter 7 tackles the most important conclusions and recommendations for the modeling. It elaborates the groundwater development and control of the Eocene Aquifer in particular and the Palestinian groundwater resources in general.

2. Groundwater Modeling Process

2.1 General

A groundwater model is an approximate representation of physical situation using computer software or code. Groundwater model could be represented by a set of boundary conditions, initial conditions, hydrological stresses, and aquifer characteristics (Bear, 1979).

Modeling is important to express and clarify actual physical situation and its processes. In addition, it can be used to understand and analyze the complex phenomena of groundwater systems. Models can also be used as tools for the assessment of groundwater characteristics and the interpretation of the associated parameters and their spatial distribution. Finally, modeling can help in synthesizing and organizing the field data.

2.2 Groundwater Modeling

There are two approaches for modeling; the deterministic and the stochastic approach. The selection of approach mainly depends on the complexity of the study area and the availability of suitable data.

2.2.1 Deterministic Approach

The deterministic approach means the complete and accurate presentation of the actual physical situation with its details. In other words, it specifically locates known features and assigns appropriate properties. However, it will be very complex and sophisticated to the degree of impossibility in terms of the amount of data required to specify the actual complex 3-dimensional heterogeneity, especially in the case of highly heterogeneous environments (Marry et al, 1992).

The deterministic models are widely used to describe the behavior of the hydraulic heads in time and space (Cacas, 1990).

2.2.2 Stochastic Approach

The stochastic approach mainly depends on the hypothesis that natural parameters in reality are not completely, randomly, and spatially distributed, but have a kind of trend and uniformity to some degree. The shape, size, orientation and location of fractures in an impermeable matrix are almost random variables. A stochastic approach generates all the fractures randomly using statistical distributions of geometric parameters from field data. Usually, most of the fractures observed in a single outcrop are approximately parallel to some extent (Chiles et al, 1992).

The process and its model are considered as stochastic (probabilistic) if the chance of the occurrence is taken into consideration and the concept of probability is introduced in formulating the model. A stochastic approach treats the groundwater flow in a probabilistic framework (Cacas, 1990).

2.3 Modeling of Porous Media

2.3.1 Fractured Versus Porous Media Flows

Generally, a fractured part of the rock has a high transmissivity and low storativity due to the existence of open conduits. On the other hand, the rock matrix has low transmissivity and high storativity because of relatively large amount of pores with high hydraulic resistivity. Since flow mechanism and quantity depend mainly upon the media hydraulic characteristics of the rock, this concept could be used as a basic concept to clarify the fracture and rock matrix media flow (Long et al, 1982).

The main differences stem from pathway geometry. Usually, flow in small fractures is covered by the same flow equations as porous media. The major geometric difference between porous and fractured materials is the connectivity. Usually, fractures provide high conductivity conduits within the rock matrix. In fracture networks, connections exist only along the fracture pathways from continuous networks and flow lines follow these pathways completely. In porous media, all points have connections to all other points and flow lines will have a special behavior that depends mainly upon the particle size and distribution (Long et al, 1982).

2.3.1.1 Discrete Fractured Flow Systems

A discrete fracture model assumes that water moves only through the fracture network. It is usually applied to fractured media with low primary (rock matrix) permeability. The discrete approach considers each fracture individually. For example, an isolated fracture, which does not intersect any other fracture effectively, contributes almost nothing to the permeability of the total rock mass. Therefore, measurements of fracture length, orientation, width, aperture, wall roughness, and overall connectivity between fractures should be carried out carefully (Bradbury et al, 1994).

2.3.1.2 Dual Porosity Flow Systems

The approach signifies the rock masses where the fractures and the porous blocks (rock matrix) are the most obvious components of the main rock. This concept considers the rock matrix as a porous medium and the fractures as flow conduits. Flow in this case will be mainly from the rock matrix towards the fractures and then to the emerging point (well or spring) (Long et al, 1982).

The dual porosity approach signifies the rock masses where the porous blocks are obvious components of the main rock beside the fractures. It assumes that the fractured medium at some working scale and the properties of individual fractures are not as important as the general properties of large regions or volumes of fractured material. The dual porosity approach could simulate the flow in the rock matrix separately from the fracture conduits (Long et al, 1982).

2.4 Modeling Codes

For groundwater modeling a suitable simulation modeling code has to be chosen carefully in order to represent the physical situation properly. To achieve this purpose, some criteria must be considered, such as geological, hydrogeological and structural conditions of the formations prevailing in the study area. On the other hand, the objectives of the study should also be taken into consideration (Yasin, 1999).

The most related groundwater modeling computer codes that have been considered in the code study is listed as follows:

1- GGWP: It is a 2-D steady state or transient finite element simulation model for vertical or axisymmetric and quasi three-dimensional flow and transport of reactive solute in anisotropic, heterogeneous, multi-layered aquifer systems (USGS, 1999).
2- SDF: This 2-D (Stochastic Discrete Fractured) flow model is coupled with a particle tracking code to explore the validity of porous media approximations for simulating groundwater flow in fractured-rock aquifers (USGS, 1999).
3- FRAC3DVS; This code handles porous and/or discretely fractured porous media, steady state and transient variably saturated groundwater flow, and advective, and dispersive solute transport in porous or discretely fractured porous media, it is 3-D finite element model (USGS, 2000).
4- SWIFT: A three-dimensional model, which simulates the flow and transport of fluid, heat (energy), brine, and radionuclide chains in porous fractured geologic media. Its reliability is low (USGS, 1999).
5- TwoDAN: Two-dimensional groundwater flow model in the horizontal and vertical plane. It uses analytical solution for head and discharge (USGS, 1999).

6- TRAFRAP-WT: This code stands for TRAnsport in FRActure Porous media with Water Table boundary conditions. It is a 2-D finite element research code designed to simulate flow and transport in fractured and granular aquifers. It can handle discrete-fracture or dual porosity approaches or both of them (USGS, 1999).

7- FRACMAN: It is an MS-DOS PC software package used to model the geometry of discrete features such as faults, fractures, paleochannels, karsts, and stratigraphic contacts. Its features include data analysis, geometric modeling, finite element mesh, and exploration simulation (USGS, 1999).

8- PMWIN (MODFLOW & MT3D): This 3-D, finite difference model can be applied for porous and homogenous aquifers. It is less applicable for karst modeling because the fracture system can not be considered in an accurate way (USGS, 1998).

9- BIOF&3D: It provides a 1-D, 2-D or 3-D water flow and multi-species dissolved phase transport solution in the unsaturated zone. It also has uncoupled 2-D or 3-D flow and multi-component aqueous phase transport in groundwater aquifers (USGS, 1999).

10- MAFIC: It is a finite element flow model designed to simulate transient flow and transport through the 2-D and 3-D rock matrix with a discrete fractured network. Solute transport is simulated in the fractures only (USGS, 1999).

11- MOC: Two-dimensional, and finite difference groundwater model for both flow and transport cases. It is applicable to 1-D or 2-D problems involving steady-state or transient flow. It can be used for heterogeneous and anisotropic. It is one of the most used models for solute-transport problems (USGS, 2000).

12- SHARP: A quasi-three-dimensional, numerical finite difference model to simulate freshwater and saltwater flow separated by a sharp interface in layered coastal aquifer systems (USGS, 2000).

Table 2.1 presents the summary of the above modeling codes, including advantages, disadvantages. Most of the information about these codes are taken from USGS (1999,2000). Further important comments have been chosen, they are to help select the suitable code for this study.

Code	**Advantages**	**Disadvantages**	**Comments**
1- GGWP	Quasi-3D modeling flow and transport	Designed mainly for porous media	Not suitable for fractured environments
2- SDF	It handles the flow in fractured aquifers by porous media approximation	It has some conditions to apply	1- 2D flow discrete model 2- It is composed of four separate packages which makes it more complex
3- FRAC3DVS	3D flow and transport model. It handles porous/ discretely fractured porous media.	It uses a dual system approach, which needs a lot of data about fractures.	It is a very general and comprehensive model. Not enough experience available.
4- SWIFT/486	1- It is a 3D flow and transport model in transient mode 2- Dual porosity, and discrete fractured can be considered.	Fully transient and comprehensive	2D steady state simulations, less specific.
5- TWODAN	Lack of fixed grid, simple input, accuracy, speed, and direct graphic output.	It is a 2D flow model. It uses analytic element method.	It is not an efficient way to model 3d and fractured environments.
6- TRAFRAP-WT	It handles various element geometry and shapes	1- It is 2-D flow model 2- Runs under MS-DOS mode 3- Needs data on chain reaction	2D models are not suitable for the modeling of two layered aquifer systems
7- FRACMAN	It can model discrete fractures.	It is an MS-DOS package. No warranty about the accuracy and functionality.	It needs a lot of data about the fracture characteristics. The author does not confirm the results. So it is less suitable.
8- MODFLOW	3D flow and transport modeling. It has the parameter estimation program.	It is designed for porous media, which is less suitable for fractured media	It can calculate the water budget, which is one of our objectives.

			It also can be used for porous media approximation.
9- BIOF & T3D		Used for transport modeling	1-Not suitable for fractured rock environments 2- Used for unsaturated zone
10- MAFIC	2D&3D transient flow model. It can simulate the flow in fractures and rock matrix.	It simulates solute transport in fractures only.	The author does not confirm its results. It is complicated and difficult to handle
11-MOC	1D & 2D flow and transport model. It can be used for steady state and transient flow.	It is an MS-DOS package. The model couples the ground-water equations with the solute transport flow.	It is complicated and difficult to handle
12- SHARP	3D quasi-modeling, used to simulate fresh and salt water in coastal aquifers	It is designed for porous media and coastal aquifers only.	Can not be used for fractured environment and it is designed only for coastal aquifers.

Table 2.1: Summary of the Modeling Codes.

2.5 Approach and Code Selection

Basically, there are many modeling codes that are used to describe and simulate a specific physical situation. Each code has its own approach. The approach depends mainly upon the conditions of physical situation in addition to the objectives of modeling process.

2.5.1 Approach Selection

Because complete deterministic modeling is complex and the Eocene aquifer is characterized as a porous media, dual porosity flow approach is proposed.

Flow through porous media domain is three-dimensional. According to this approach, it is assumed that the flow in the aquifer is everywhere essentially horizontal (aquifer-type flow) or that it may be approximate as such, neglecting vertical flow components (Bear, 1979). In this approach, the base (rock matrix) hydraulic conductivity is considered as the value of the aquifer system and the effects of the fractures (due to the faults) are neglected

2.5.2 Code Selection

To select a suitable code to the case study model, a study is made on the merits of the modeling codes including availability, their characteristics, in addition to the data required to setup the simulation model. On the other hand, a geological and structural study is used to help in obtaining a better selection. Then according to those criteria mentioned above, the most suitable code can be selected to approach the required objectives of the research.

Appendix A has been prepared to assist in the model selection process. The Appendix shows a comparison between different codes. Also Table 2.1 helps in selecting the suitable model code.

Comparing the general features of the modeling codes (Section 2.5) and the advantages and disadvantages of the model with the characteristics of the Eocene area, the proper model is selected. This procedure is used here to select the model code for the Eocene aquifer under study. The most suitable code for the study area is PMWIN (MODFLOW).

MODFLOW is a three-dimensional finite difference flow model and has powerful capability for the simulation of regional groundwater flow. It simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined.

It can calculate the water budget for the study area, which is one of the research objectives. It can also be used for porous area approximation as the case here. It is available, widely used and easy to handle.

3. Description to the Study Area

3.1 Introduction

The aquifer under study in this research thesis is the Eocene aquifer. The Eocene Aquifer is located in the north eastern part of the West Bank in Palestine and overlaps both Nablus and Jenin districts (see Figure 3.1). It is considered one of the main water supply sources for these areas. Development projects are still going on to exploit this groundwater basin. Consequently, miss-management and improper control of the groundwater development projects could deplete this water resource.

3.2 Climate of the Study Area

Palestine’s position on the southeastern edge of the Mediterranean makes it fall in the transitional zone between two major climate zones; the Mediterranean and the arid Tropical zone. Rainfall is limited to the winter and spring months (October to May) and summer is completely dry. The climate of the area is of an eastern Mediterranean type, moderate and rainy winter, while summer is hot and dry.

Figure 3.1: Location and Boundary of the Eocene Aquifer in the West Bank

Table 3.1 shows the variation of average climate parameters from data collected over 42 years from Beit Qad weather station, which is located on the outcrops of the Eocene Aquifer (ARIJ, 1996).

Month	Max. Temp. (°C)	Min. Temp. (°C)	R.H. %	Wind speed (km/hour)	Sunshine (hours/day)	Solar Radiation ($MJ/day/m^2$)
January	17.4	6.8	80	7.5	5.4	10.1
February	18.2	7.1	84	7.9	5.6	12.4
March	21.6	8.6	76	7.9	6.8	16.5
April	28.3	11.2	67	7.9	7.8	20.3
May	31.0	14.0	39	9.0	9.7	24.3
June	32.9	17.3	63	9.4	11.3	26.9
July	33.6	19.6	63	9.7	11.1	26.4
August	34.2	21.1	65	8.6	10	23.7
September	33.2	19.8	64	7.2	9.1	20.4
October	30.6	16.1	65	5.4	8.1	16.2
November	25.0	11.8	66	6.1	6.8	12
December	18.8	8.7	74	7.5	5.4	9.6

Table 3.1: Variation of Average Climate Parameters for 42 Years (ARIJ, 1996)

3.2.1 Rainfall

The rainy season starts in the middle of October and continues to the end of April. Approximately 3.2% of the annual rainfall falls in October, while almost 80% falls during November through February. As indicated in Table 3.2, rainfall usually decreases in March. The highest rainfall in the west of the Jenin area is about 600mm per year. Average rainfall decreases sharply from 550mm at Nablus to 150mm to the east of the study area at the Jordan Valley. Table 3.2 gives the average monthly rainfall of different stations in the Northern West Bank. According to the table, the average annual rainfall in Qabatya (which is part of the study area) is about 569mm.

Month	Burqa Station	Meithaloun Station	Nablus Station	Qabatya Station	Talluza Station	Toubas Station	Tulkarem Station	Total
Jan.	167	149	155	134	158	104	160	147
Feb.	125	122	135	109	119	87	107	115
March	91	87	90	85	105	56	79	85
April	32	27	34	26	26	16	26	27
May	6	6	5	4	4	1	4	1
June	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0
Aug.	0	0	0	0	0	0	0	0
Sep.	0	0	2	0	0	0	2	1
Oct.	21	18	17	18	16	11	23	18
Nov.	77	72	60	60	73	53	77	68
Dec.	153	139	158	133	138	81	156	137
Average	672	620	656	569	639	409	634	**602**
*All the rainfall values are in (mm)								

Table 3.2: Average Monthly Rainfall for Different Stations (Husary et al, 1995)

3.2.2 Temperature

Referring to Table 3.1, in winter the minimum temperature is around 7^{o}C and the maximum is 15^{o}C. Approximately the average daily temperature is 10^{o}C. Temperatures below the freezing point are rare. In summer, the average maximum temperature is 33^{o}C and the average minimum temperature is 20^{o}C.

3.2.3 Humidity

As indicated in Table 3.1, the average annual relative humidity is around 62% with a peak values in winter up to 84%. It drops to 40% on average during May; the Khamaseen period. In summer, the average annual humidity is 56%.

3.2.4 Evapotranspiration

Rofe and Raffety (1965) estimated the annual values for potential evaporation E_p for 1962/63 at 1250mm in the southern part of the high lands in the vicinity of Nablus and Qaryut rising to 1950mm at Far'a in the Jordan Valley. The water deficit, that is the difference between potential evapotransporation and rainfall is estimated at 900mm in the study area. Table 3.3 shows the average monthly evaporation (E_{pan}) measured at Tulkarem weather station. Tulkarem is located at south western edge of the study area. This station gives an indication and reflects approximately the evapotransporation value in the adjacent area (Eocene area). The effect of the evapotransporation is included in the recharge coefficient factor in modeling the Eocene aquifer case.

Month	Evaporation (mm)
January	55
February	59
March	55
April	87
May	97
June	111
July	125
August	119
September	118
October	79
November	70
December	73

Table 3.3: Average Monthly Evaporation (Tulkarem Station, 1996)

3.3 Topography

The topography of the Jenin district can be divided into three areas; the eastern slopes, the mountain crests and the western slopes. The eastern slopes are located between the Jordan Valley and central highland. They are characterized by steep slopes, which contribute to forming young wadis. The mountain crests form the watershed line and separate the eastern and western slopes. Altitude ranges on average between 500 and

650 meters above sea level. The western slopes, characterized by gentle slopes, have elevation ranges between 100 and 400 meters above sea level (ARIJ, 1996).

Nablus lies in a synclinal area extending west to east with an altitude varying from 440m above sea level in the bottom of the valley to about 900m in the hills of north Ebal and south Gerizim (ARIJ, 1996).

3.4 Hydrogeology

3.4.1 Geology

3.4.1.1 Rock Formations

The study area is controlled geologically by Anabta anticline in the west and two major anticlines flank are called Nablus-Jenin synclines.

As indicated in Figure 3.2, the geological column of the area shows the following geological units arranged from oldest to youngest (PWA, 1997):

1. Limestone, dolomite, and marl (Cenomanian to Turonian).
2. Chalk and chert of Senonian age.
3. Chalk, limestone and chert of Eocene age.
4. Alluvium of Pleistocene to Recent age.

The detailed geological studies for the study area show the following geological formations (ARIJ, 1996):

1- Cretaceous Rocks

Cretaceous rocks can be divided into the following formations:

a) Lower Beit Kahil Formation. This formation refers to the lower part of the lower Cenomanian. The lower part of the of the sequence consists of thick and massive limestone, then passes through sandy marl shales, and becomes finer upwards merging into sandy ferruginous limestone at the top. This formation is considered a good aquifer.

b) Upper Beit Kahil Formation. This is regarded as the upper part of lower Cenomanian. This formation is composed mainly of limestone, marl, dolomite and dolomitic limestone. It is a moderate to good aquifer.

c) Yatta Formation. This is related to the lower part of the middle Cenomanian. Generally, the formation consists of chalky limestone, marl and calcareous karstic limestone. Hydrogeologically, it is regarded a poor aquiclude.

d) Hebron Formation. This formation refers to the upper part of the middle Cenomanian. The lithological composition consists of limestone, dolomite and chalky limestone. Joints are well developed within this formation.

e) Jerusalem Formation. It consists of massive, bedded limestone, dolomite and chalky limestone. Generally, the formation forms a good aquifer.

Figure 3.2: Geological Column of the West Bank (PWA, 1997)

f) Bethlehem Formation. This forms the upper Cenomanian. This formation consists of dolomite, limestone and chalky marl. A number of shelly beds are included within the chalky and dolomitic faces. It forms a very good aquifer.

2- Rocks of Cretaceous to Tertiary Transition Chalk

This formation consists mainly of chalk of Senonian to Paleocene age. The chalk is usually dark colored due to the presence of bituminous materials and has a variable thickness due to the earth's movements during its composition. It also includes conglomerated, thin-bedded limestone. The chalk faces make the formation a good aquiclude.

3- Tertiary Rocks

These rocks are represented by two lithological units:

a) Jenin Subseries. This consists mainly of chalk of Eocene age. In this formation five facies of limestone and chalk are described: chalk with minor chert, chert with inter-bedded limestone, limestone with minor chalk, massive limestone and reef limestone. Generally, it forms a good aquifer expect in the chalk zones, where it forms an aquiclude. Variable thickness reaches about 700 meters in some places of the Jenin district.

b) Bayda Formation. This ranges in age from the Miocene to the Pliocene. Conglomerate forms the main composition of this formation, with some marl and limestone. There is unconformity between the conglomerate and the Cretaceous rocks.

4- Quaternary Rocks

This consists of unconsolidated, laminated marl with some siliceous sand known as alluvium rocks. It has a red color and fine texture which is due to its derivation from limestone.

5. Igneous Rocks

These are widespread east of Beit Qad. These rocks are dark, green, fine-grained, basic or sub-basic, and have a strong jointing.

3.4.1.2 Structure and Tectonics

1. Folding

Nablus-Beit Qad Syncline

The syncline is symmetrical with a gently dipping west limb and a steep east limb. The highest land occurs on the axial part of the major Nablus-Beit Qad syncline.

The axis generally trends north and northeast to south and southwest (NNE-SSW). But near Jamm'in it trends sharply westwards. Northeast of this aquifer, groundwater movement is likely to be into the main syncline while the southwest minor warps will tend to direct water westwards (Figure 3.3)

Anabta Anticline

This is a shallow north-south symmetrical structure which bends westwards at its southern end towards Qalqiliya.

Figure 3.3: Folding and Faulting Structures in the Study Area.

There are two folds, one in the southwest, the Ein Qiniya anticline, and one in the northeast, the Fari'a anticline. Between these is a minor impersistent syncline southwest of Qabalan (Figure 3.3)

2. Faulting

Faulting in the area follows the general axes northwest southeast (NW-SE). Faulting has resulted in the formation of several garben structures in the area. The effect of faulting on the Eocene limestone of the western West Bank is less visible.

3.4.2 Hydrology

3.4.2.1 Water Resources

The main resources of water in the study area, are the followings:

a) Wells

Groundwater wells in the Eocene are owned by the municipalities and the farmers. Most of wells are drilled as holes or shafts. Water wells are used mainly to face the demand of domestic, municipal, industrial and irrigation requirements. (For more details see Section 4.6.2)

The annual abstraction from the Jenin aquifer (Eocene) for domestic and industrial use is about 1 MCM ($m^3 \times 10^6$) and for agriculture 9.4 MCM (GTZ, 1996).

b) Springs

Springs are important as most of the villages depend upon them. They provide water for domestic and animal use and for irrigation of small fields and for cropping in summer. The springs flowing from the Jenin (Eocene) aquifer can be grouped as (Rofe and Raffety, 1965):

1) Nablus group

The average annual yield of this group is 2.4MCM (Nuseibeh and Nasser, 1995). This group consists of tens of small springs used for domestic water supply to the city of Nablus located at the base of the northward dipping Jenin limestone on the southern side of the Nablus valley.

2) Sabastiya group

Numerous small springs and seepages emerge against the dip, at the contact between the Jenin limestone and the chalk. The infiltration area and storage are very limited and few have perennial flow. The average annual yield is 0.166 MCM (Nusiebeh and Nasser, 1995).

3) Fari'a group

The outlet of these springs is outside the study area. The group contains two springs, the Ein el Fari'a and the smaller Ein Duleib. Both springs are located at the eastern margin of the Jenin limestone outcrop on the eastern flank of the Nablus-Beit Qad syncline. The northwest-southeast (NW-SE) faulting, forming the northern margin of the Fari'a Garben, permits southeasterly groundwater movement from this syncline to the springs. There may also be a supplement from aquifers, such as the Ajlun at a deeper level in the syncline, moving up the fault system. The springs emerge from the chalk which has a thick alluvial cover. The average annual yield is 7.64 MCM (Nuseibeh & Nasser, 1995), which discharges outside the study area.

4) Beidan group

The Jenin limestone south and west of the springs form the aquifer. The underlying chalk acts as a retaining aquiclude and the water emerges immediately below the contact. The average annual yield is 3.4 MCM, which discharges outside the study area (Nuseibeh and Nasser, 1995).

5) Jenin group

These springs are associated with the east-west faulting which provides a route to the surface from the storage of the Nablus-Beit Qad syncline. The influence of the alluvium, through which the water emerges, is clear from the chemical composition. Considerable sub-surface transmission of groundwater from the limestone to the alluvium also takes place. Few springs have a perennial flow due to extraction outside the green line.

3.4.2.2 Aquifer System in the Northeaster Part of the West Bank

An aquifer is a geologic formation, or a group of formations, which holds water and also allows water to flow through it under ordinary field conditions. Gravity causes rain to seep down into the soil until it reaches the water table. Below this level, groundwater fills the tiny spaces that lie within the soil and rock layer. The water in an aquifer can be tapped for use. The main aquifers in the northeastern part of the West Bank are:

1) Upper Cenomanian-Turonian Aquifer System: This system is composed of carbonate rocks (dolomite and limestone) with thickness ranging from 185 to 475m. This system is separated from the Eocene aquifer system by a variable poor aquiclude formation of chalk and chert of the senonian geologic age of the Upper Cretaceous. The system is composed of (from the oldest to the youngest) Hebron, Bethlehem and Jerusalem formations.

(2) Eocene Aquifer System: This aquifer system overlies the Upper Cenomanian-Turonian aquifer system, with a transition zone of chalk of variable thickness ranging from 0 to 480m lies in between. This system is represented by the Jenin sub-series of the Tertiary age and exposed in 80% of the Jenin area. It constitutes a fully utilized shallow aquifer which is

lithologically composed of reef limestone, numulitic, and limestone with chalk and chalk with numulitic limestone. In this system, limestone rocks form an aquifer while chalk rocks form an aquiclude.

3.4.2.3 Groundwater Levels and its Movement in the Eocene Aquifer

The water table contours of the Eocene aquifer have been mapped from spring levels and from the elevation of static water in wells (see Figure 3.4). This map shows that flow within the aquifer is from the south to northeast. At the northern flank of the Gerzim mountain near Nablus city and in Burin springs the level is 600m above sea level. In the vicinity of Jalboun, the gradient steps reflect changes in permeability of the aquifer system. In the north at Jenin area, the gradient is very small, which reflects a thickening of the saturated section rather than changes in permeability. (PHG, 1996).

The two large spring groups of Beidan and Fari'a, occur as a direct result of faulting at right angle to the axis of a syncline, permitting the water to leak laterally.

Figure 3.4: Observed Groundwater Levels in the Study Area (PWA, 1997).

Only small quantities of water escape laterally from the margins of the structure through faulting. The water passes northwards across the green line to emerge naturally, or be extracted artificially in the Beisan plain.

From the very sparse data available the quantity of groundwater moving northwards is estimated to be 30 MCM per year (PWA, 1997).

The northwest-southeast (NW-SE) graben which truncates the northern end of the syncline forms a base level to which the groundwater moves. The large quantity which crosses the green line feeds the springs and boreholes of the Afula-Beisan plain. There is no known emergence above the chalk, indicating that the Jenin limestone groundwater migrates down to the Ajlun at the northern end of the syncline, probably via the east-west faulting.

3.4.2.5 Groundwater Recharge from Rainfall

The quantity of recharge depends on many factors especially climate which includes rainfall, temperature, relative humidity, and wind, soil type (infiltration capacity), land use and topography.

The Eocene aquifer recharged through infiltration of rainfall and wadi runoff. Eocene rocks outcrop across most of the central parts of Jenin District. (PWA, Task 46, 1996).

4- Groundwater Flow Model

4.1 Background

Based on the outline in Chapter 2, and the description of the environment in the study area, MODFLOW has been considered in this study to approach its objectives. It has further been selected due to its ease of handling, accessibility as it is friendly in data input and requires less data.

Usually, the hydrological model transfers data from the study area into the simulation model. After calibration, the model can be used for prediction. Then, these results could be used for the purpose of planning, design and management. Therefore, a model is a handy tool to synthesize data and output results for analysis and then transfer these to the policy and decision-makers.

4.2 Conceptual Model

The conceptual model is a kind of verbal set of descriptions, governing relationships, equations, or natural laws that describe reality. A conceptual model for hydrologists is a schematic representation of the groundwater system. It mainly consists of a typical cross section for the study area. It is used for the purpose of simplification of the field problem and organizes the associated data so that the system can be analyzed more readily.

In modeling, simplification is necessary because complete reconstruction of the field is not feasible. The conceptual model is defined by the main hydrostratigraphic units and their boundaries. In this study, the domeninant direction of water movement is represented as a two-dimensional nearly horizontal flow to the north and northeast. Vertical flow to the lower aquifer is neglected, since the separating layer (aquiclude) is of chalk which is almost impervious and passing no water to the lower aquifer. The model consists of one hydrogeological layer (see section 4.5.2). This layer represents chalk, limestone and chert of the Tertiary rock formation. Its thickness is taken in the range of 50m to 450m as shown in Figure 4.1.

Figure 4.1: Conceptual Model of the Eocene Aquifer.

4.3 Model Geometry

The model geometry defines the size and shape of the model domain. The model geometry is also associated with the model boundaries both external and internal. The boundary conditions are mathematical statements specifying heads or fluxes across the boundaries of the whole model domain. All the external boundaries of the study area are no-flow boundaries.

4.4 Model Governing Equation

Mainly, the governing equation is used to describe the physical behavior of groundwater flow in the subsurface formations. The governing equation is derived mathematically combining a water balance equation with Darcy's law. As a result, a matrix of equations could be formed to describe the flow through the individual model cells.

MODFLOW utilizes a numerical solution for the equation governing groundwater flow through porous media. The general form of the governing equation is expressed as:

$$\frac{\delta}{\delta x}\left[Kxx\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta y}\left[Kyy\frac{\delta h}{\delta y}\right]+\frac{\delta}{\delta z}\left[Kzz\frac{\delta h}{\delta z}\right]-W = Ss\frac{\delta h}{\delta t}$$

Whereby:

K_{xx}: value of hydraulic conductivity along the x-coordinate axis (m/d);

K_{yy}: value of hydraulic conductivity along the y-coordinate axis (m/d);

K_{zz}: value of hydraulic conductivity along the z-coordinate axis (m/d);

h: potentiometric hydraulic head (m);

W: volumetric flux per unit volume and represents sources and/or sinks of water (d^{-1})

s_s: specific storage of the porous material (d^{-1}) and;

t: time unit (d).

This equation describes the groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principle axes of hydraulic conductivity are aligned with the coordinate directions. For steady state conditions and long-term water balance calculations, the storage term can be neglected.

4.5 Set-up of the Model

4.5.1 Grid Types and Mesh Size

The grid in MODFLOW consists of two parallel lines that are orthogonal. Cells are formed by the intersection of these lines. A node is located at the center of each cell. It is assumed that hydrologic and hydraulic properties are uniform all over the extent of the cell area. A cell's node represents the cell. This system is called a "block-centered grid". There are also mesh-centered grids whereby the nodes are located at the intersections of the cells. Boundaries of the problem domain should be assigned regarding the grid type used for modeling, i.e. for both mesh and block centered grids.

In MODFLOW modeling, the grid size is slightly larger than the actual model area. For the Eocene Aquifer, the grid is taken as a size of 30 columns and 50 rows. The cells follow a 1km by 1km mesh size. The actual model area of the Eocene aquifer in the Jenin area is 26km by 41km relating to maximum distances east west and north south respectively. Active cells (see section 4.5.3 and Figure 4.2) cover the modeled area of the formation while inactive cells occupy the rest of the grid area.

4.5.2 Layer Type and Model Layers

In general, layers are the nucleus of the simulation model. The representation of the conceptual model is helpful to describe how many layers have to be represented in the simulation model in addition to their hydrological conditions (confined, unconfined, or semi-confined). The Eocene aquifer is modeled as one layer and unconfined aquifer.

4.5.3 The Eocene Aquifer Boundary Conditions

The representation of the boundaries by MODFLOW has been carried out by assigning to the boundary cells special cell indicator according to the physical behavior of the area.

To describe no-flux boundaries in MODFLOW, the boundary between inactive and active cells can be used. Inactive cells are those for which no flow into or out of the cell occurs during the entire simulation. Hydraulic heads and flows from or into the cell are not calculated. On the other hand, active or variable head cells are assigned to the locations of interest inside the studied domain. The hydraulic heads for active cells are calculated by the model and are free to vary during the simulation process. Moreover, constant head cells, which are special active cells (inside the domain of the problem), could be used to describe a model boundary with known heads such as aquifer contacts with surface water bodies such as lakes, river…etc. Such boundaries are not included in the model for the Eocene aquifer.

4.5.4 Top and Bottom of the layer

Generally, the top and bottom of the layers define the main hydrogeological formations for the simulation model. In MODFLOW, the top and bottom of the layers are required to calculate the transitivity, vertical leakance, and storage coefficient and to carry out the particle tracking.

The elevations for the top and bottom of the layers have been obtained utilizing the topographical map and geological cross sections. The top elevation of the Tertiary formation (Jenin Subseries, which mainly forms the Eocene aquifer) ranges between 450m and 75m above the sea level. The bottom elevation of the layer ranges between 300m and 50m above the sea level. Figures 4.3 and 4.4 present the top and bottom elevations of the Eocene layer.

4.5.5 Horizontal Hydraulic Conductivity

From the well pumping test done by the Palestinian Water Authority in the study area, the horizontal hydraulic conductivity is presented as constant on average value equal to 2.5m/day. It is important to know that the effect of the faults on the hydraulic conductivity was neglected.

4.5.6 Vertical Hydraulic Conductivity

For the model involving more than one layer, MODFLOW requires the input of the vertical transmission or leakance term, known as vertical leakance.

MODFLOW uses the vertical hydraulic conductivities and thicknesses of layers to calculate the vertical leakance. In this study, there is one layer, so there is no need to input the vertical hydraulic conductivity.

4.5.7 Storage Coefficient and Specific Yield

Generally, the specific yield is related to unconfined aquifers and it is usually used to describe the storage properties of the phreatic aquifers. Specific yield is defined as the quality of water that a unit volume of unconfined aquifer gives up by gravity, while the remaining quantity of water is called specific retention. The storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit volume of aquifer per unit change in head. The storage coefficient is related to the confined aquifers.

The Eocene aquifer model for this study is a steady-state model. Therefore, precise values for the specific yield and storage coefficient are less important.

4.6.8 Initial Conditions and Observed Groundwater Levels

Initial conditions

The initial condition is the groundwater level distribution within the model area at some initial time. It is used to solve steady state flow problems. The level values can be used as starting values for the numerical calculations of the equation solvers. The levels for each active cell should be higher than the elevation of the cell bottom.

Observed groundwater levels

Based on the available well records, it was noticed that most of water tables fluctuate around an average value. Furthermore, some of the well water tables fluctuate over a considerable magnitude. This fluctuation of the water table could be caused by the effect of high rates of abstraction during the dry period, which recover during the wet period. Another possibility for the water table fluctuation could be the effect of consecutive years of dry periods followed by a recovery in years of high rainfall. Considerable amount of recharge then refresh the aquifer and raise the water table to its original level.

As stated by a consultant at the PWA, monitoring wells are absent all over the aquifer. Water level data have been measured inside production wells by the PWA. Pumping and insufficient recovery at these production wells surely affected the accuracy of water level measurements. Usually, these measurements were taken only 1 day or 2 days after stopping the pumping.

Furthermore, the recorded data of the water levels inside the wells are not the same with respect to period and length. For example, most of the available water levels have time series of more than 20 years. Moreover, the distribution of groundwater wells is irregular, which means that the representation of water levels all over the study area will carry some uncertainty.

For the model calibration process, it is convenient to take the initial groundwater levels the same as the observed levels. In view of the relative scarcity of data, the groundwater level maps prepared by the Palestinian Water Authority have also been considered to generate the observed water level maps. Nevertheless, in the model the initial water levels were not related to observed values, but by trial and error, which have been taken 340m above the sea level.

4.6 Hydrological Stresses

4.6.1 Rainfall Recharge

The primary source of groundwater recharge in the Eocene aquifer is considered to be rainfall. Recharge values are taken as percentages of rainfall as considered in Ba'ba' study (1996). The area in Ba'ba's study covered the northern and central parts of the West Bank, which was divided into four zones. For groundwater recharge considerations in the four zones, the exposures of the Jenin limestones, the chalks, the Ajlun limestones and superficial deposits was measured seperately in the study (Ba'ba', 1996). The percentage (recharge coefficient) varies according to the distribution of rainfall intensity, topography, and soil characteristics comprising the outcropped zone in addition to the land cover.

The Recharge package of MODFLOW (RCH1) is designed to simulate distributed recharge to the groundwater flow system. According to the variability of rainfall, topography and soil characteristics, different values of recharge coefficients for each of the different sub-regions have been considered. These sub-regions are the area between different rainfall isohyets.

The eastern part of the district has a relatively low percentage of recharge according to the relatively low percentage of rainfall. On the other hand, at the western side of the aquifer, the recharge coefficients are relatively high due to the high yearly rainfall. For implementation into the Eocene aquifer model, the recharge coefficients of Ba'ba' (see Table 4.1) have been taken.

After the computations of the recharges, the values have been applied for the various sub-regions of the model. The representation of the recharge shown in Figure 4.5 shows that values range between 2.877×10^{-5} to 8.192×10^{-4} m/day.

Rainfall Range (mm/yr)	Recharge coefficient (%)
150-200	6
200-250	15
250-300	22
300-350	26
350-400	30
400-450	34
450-500	37
500-550	40
550-600	43
600-650	46
650-700	48

Table 4.1: Recharge Coefficient for Different Values of Rainfall (Ba'ba', 1996)

4.6.2 Well Abstraction

A pumping well is a point sink or source represented in a model by a node at the cell center. The pumping rate for an abstraction well should be designed in units of water volume per unit of time.

In MODFLOW, the Well package is used mainly to simulate the outflow through pumping wells and inflow through recharge wells. Abstraction wells have to be assigned negatively, which recharge values have to be assigned positively. Usually, either recharge or discharge wells, are identified by specifying their location and flow rate.

The package considers a full penetration of the well for the layer and the well usually represents a single layer. In case the well is penetrating more than one layer, then the flow rate should be distributed over all these layers.

In the Eocene aquifer, the groundwater wells located in the study area are many. There are 67 wells with available data about location and abstraction rate as indicated in Table 4.2 and Figure 4.6.

Well No.	Well Identification	Locality	Cell Coordinate (X,Y)	Abstraction Rate (m^3/d)
1	17-21/012	Kafr Dan	17,11	362
2	17-21/013	Kafr Dan	17,12	82
3	17-21/014	Kafr Dan	18,11	57
4	17-21/015	Al- Jalameh	20,10	587
5	17-21/017	Al- Jalameh	20,9	44
6	17-21/022	Al- Jalameh	21,10	72
7	17-21/025	Al- Jalameh	21,9	110
8	17-21/028	Tinnik	13,7	33.5
9	17-21/034	Kafr Dan	16,11	737
10	18-18/001	Ras Al- Far'a	21,32	975
11	18-18/004	Ras Al- Far'a	22,32	215.5
12	18-18/016	Ras Al- Far'a	23,31	723
13	18-18/017	Ras Al- Far'a	23,31	463

Table 4.2: Wells and Abstractions of the Eocene Aquifer (Palestinian Water Authority, 1997).

Well No.	Well Identification	Locality	Cell Coordinate (X,Y)	Abstraction Rate (m^3/d)
14	18-18/025A	Ras Al- Far'a	24,30	679

15	18-18/032	Ras Al- Far’a	24,30	525
16	18-18/033	Ras Al- Far’a	25,29	214
17	18-20/007	Az- Zababida	21,21	11.5
18	18-21/003	Deir Ghazala	24,11	763
19	17-19/001	Sanur	16,23	601
20	17-19/002	Sanur	17,23	147
21	17-20/003J	Jenin	20,13	92
22	17-20/004J	Jenin	20,14	2
23	17-20/005J	Jenin	21,13	17.5
24	17-20/006J	Jenin	21,14	311
25	17-20/007Q	Qabatiya	17,15	107.5
26	17-20/009J	Jenin	20,12	165
27	17-20/009Q	Qabatiya	16,18	104
28	17-20/012J	Birqin	19,13	201
29	17-20/013Q	Qabatiya	16,17	74.4
30	17-20/014A	Arraba	14,19	32.5
31	17-20/014Q	Qabatiya	17,17	16
32	17-20/015Q	Qabatiya	17,18	35
33	17-20/018A	Arraba	14,15	155
34	17-20/018Q	Qabatiya	15,15	112
35	17-20/019A	Arraba	15,15	58
36	17-20/019J	Jenin	21,12	36
37	17-20/020J	Jenin	20,16	111
38	17-20/020Q	Qabatiya	17,16	36
39	17-20/022Q	Qabatiya	18,20	137
40	17-20/023Q	Qabatiya	17,16	44
41	17-20/024	Al- Jalameh	22,9	683
42	17-20/024A	Qabatiya	15,20	158
43	17-20/024J	Jenin	20,17	55
44	17-20/026Q	Qabatiya	18,15	135
45	17-20/028Q	Qabatiya	18,16	323
46	17-20/030Q	Qabatiya	18,17	296
47	17-20/031Q	Qabatiya	18,15	79
48	17-30/032	Al-Jalameh	22,10	507
49	17-20/033J	Jenin	21,15	471
50	17-20/035A	Birqin	16,15	59
51	17-20/035Q	Qabatiya	19,15	207
52	17-20/036A	Birqin	14,16	61
53	17-20/036Q	Qabatiya	20,19	275
54	17-20/037J	Birqin	14,16	12
55	17-20/040A	Mirka	15,21	156
56	17-20/041Q	Qabatiya	17,19	135
57	17-20/042Q	Qabatiya	19,20	394

Table 4.2: Wells and Abstractions of the Eocene Aquifer (Palestinian Water Authority, 1997) Cont.

Well No.	Well Identification	Locality	Cell Coordinate (X,Y)	Abstraction Rate (m^3/d)
58	17-20/043Q	Qabatiya	19,20	76
59	17-20/044Q	Qabatiya	19,19	84.5
60	17-20/046	Kafr Dan	17,10	424
61	17-20/046Q	Qabatiya	19,18	171
62	17-20050J	Jenin	20,15	179
63	17-20/050Q	Qabatiya	21,20	1244
64	17-20/052A	Birqin	15,16	197.5
65	17-21/002	Rummana	13,6	6
66	17-21/009	Kafr Dan	18,12	171
67	17-21/010	Kafr Dan	16,10	516

Table 4.2: Wells and Abstractions of the Eocene Aquifer (Palestinian Water Authority, 1997) Cont.

4.6.3 Spring Discharges

Usually, springs form when the water table intersects the land surface. Drain nodes in MODFLOW usually simulate springs or seeps. The drain package can simulate the flow from a spring by representing the point of emergence of the spring (the land surface) as the drain elevation. The drain nodes (cells) will be activated only in the case the water table rises up to the level of the drain. Springs can also be represented as a constant head cells due to the permanent discharge around the year from the same elevation. Moreover, springs could be represented as wells for the purpose of simulation during the calibration process. Practically, the best representation of the springs depends upon the simulation model performance and the geometrical settings of the model.

For the Eocene aquifer model, the springs have been represented by drain Package. During model calibration, the positive outflow at each spring is verified.

Table 4.3 shows the most important spring systems within the study area. Also Figure 4.7 presents the location of springs in the model cells.

Spring No.	Spring Name	Cell Coordinate X,Y	Elevation (m) ASL*	Historical Discharge (m^3/d)
1	Fari'a	21,28	160	20403
2	Duleib	21,29	155	2606
3	Sedreh	19,31	240	698
4	Jiser	18,35	200	442
5	Tabban	19,32	160	3902
6	Subyan	19,33	130	538
7	Balata	15,38	510	442
8	Dafna	14,38	560	442
9	Ras El-Ein	12,36	570	538
10	El- Asal	13,37	575	538
11	Qaryoun	14,37	550	1682
12	Shreish	13,36	510	538
13	Beit El Ma	15,37	458	1682
14	Zawata	14,36	520	376
17	Harun	11,33	420	376
18	Burqa	6,30	460	193
*ASL: means Above Sea Level				

Table 4.3: Springs Discharge of the Eocene Aquifer (Palestinian Water Authority, 1997).

4.7 Model Run and Results

The first stage in the model after the set-up is to run the model. The main objective in the run is to find results nearly coincide with the actual or real case. Many iterations are done to achieve this objective. This is done by changing the sensitive parameters which affect the result of the model (see Chapter 5), until the suitable results are determined and performed. Three main packages are important in the run stage; flow simulation package, results extract package, and finally water budget package

In order to determine the groundwater levels and water budget, flow simulation package must be run. At the results extract package, all the results of the model run are found, for example, water level, draw down and water flow in each cell.

The water budget package is used to calculate the amount of water that enters or outs the Eocene aquifer. This stage can be help performing water balance for the aquifer as indicated in Chapter 6.

5- Sensitivity Analysis

The simplest form of sensitivity analysis is a visual graphical comparison of changes in parameter values versus the effect on the groundwater levels. To approach this objective, some spatially well-distributed cells over the area have been chosen and groundwater levels recorded for each trial or change of the calibrated parameter. Sensitivity analysis for this simulation model focused on recharge and hydraulic conductivity. They are found to be the most sensitive model parameters. It is further found that hydraulic conductivity is more sensitive than recharge.

As indicated by the graph for the recharge sensitivity analysis shown in Figure 5.1, the groundwater level increases gradually by increasing the recharge rate. The change of groundwater level is nearly linear (See Appendix B). This means that the recharge is relatively less sensitive for the more realistic high range of recharge percentages. For more selected cells the groundwater levels start mild and then become steeper for higher ratios. This could be caused by the complex aquifer geometry.

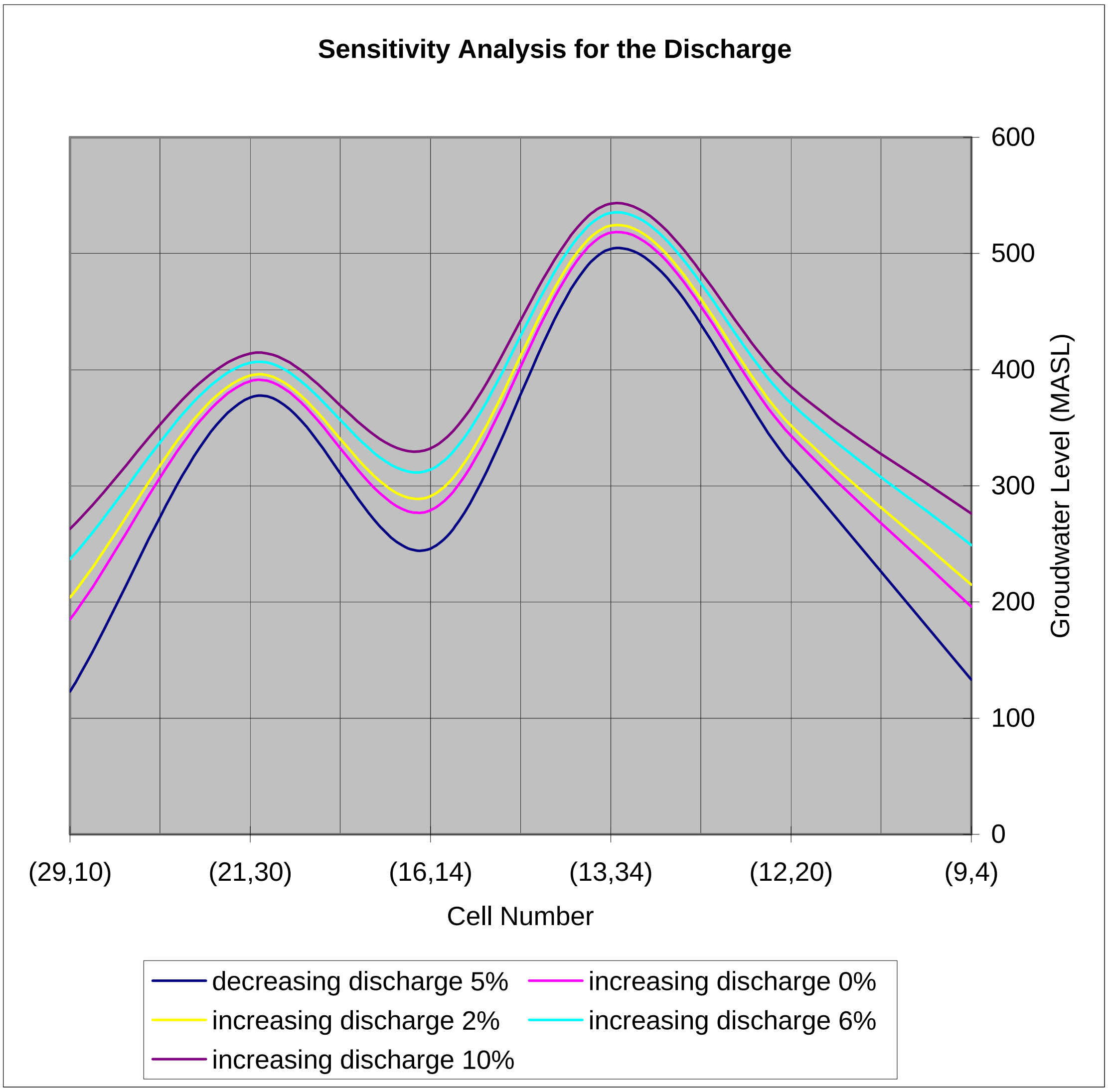

Figure 5.1: Sensitivity Analysis of the Discharge for the Eocene Aquifer.

On the other hand, the hydraulic conductivity has a large effect when its values are increased from moderate to high or from moderate to low values as shown in Figure 5.2.

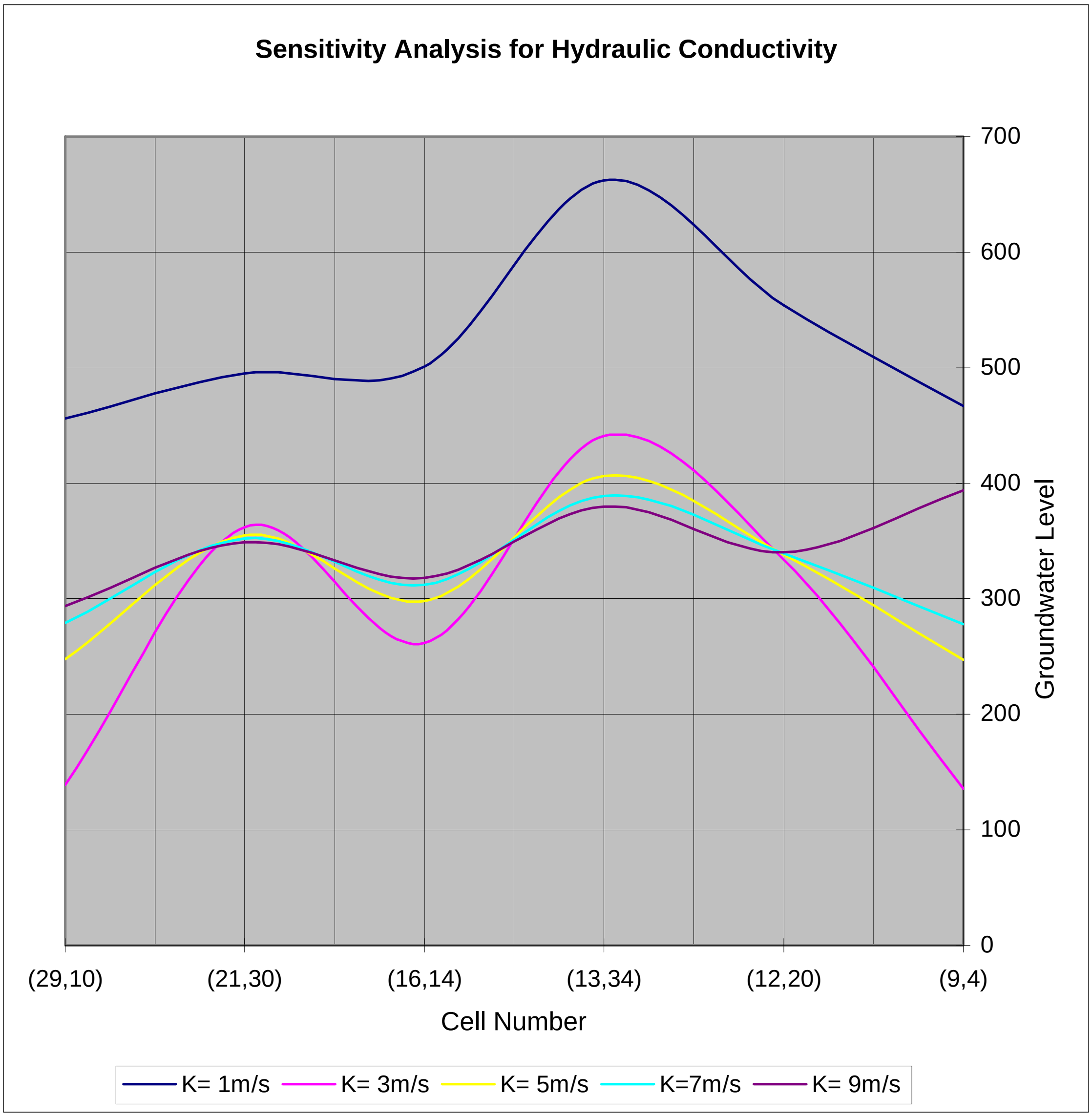

Figure 5.2: Sensitivity Analysis of the Hydraulic Conductivity for the Eocene Aquifer.

6- Model Calibration

During the calibration process, simulated values of the groundwater levels and spring flows are compared with the groundwater levels and spring flows that were collected by the PWA. After error analysis, the model input data (calibration parameters) are altered within a reasonable range until the simulated outputs and observed values fit within a chosen tolerance. If the results are acceptable, the model is considered calibrated. Basically, the calibration process could be carried out either by automated or trial and error calibration procedures. Model calibration for this study has been done by trial and error adjustment, considering both errors in groundwater levels and flows at springs in the area. The following sections present the results of the calibration.

6.1 Calibration for Groundwater Levels

Observed Groundwater Levels

The goal of the calibration process was to reconstruct the flow regime, which exists in the aquifer. Maps with observed groundwater levels of the aquifer basin were prepared in order to act as reference calibration maps for groundwater levels.

As indicated in section 4.6.8, the Palestinian Water Authority has data available on groundwater levels. An observed groundwater level map is made using the MODFLOW Field Interpolator sub-program. It is noticed that even for the same points of the Palestinian Water Authority groundwater contour map, the Field Generator produces a special pattern of the groundwater level distribution, which is slightly different, especially where well data points are absent.

Simulated groundwater levels

The calibration process has been done to compare the simulated and the observed groundwater levels. During the calibration process, the hydraulic conductivity is the main calibration parameter in addition to the spring recharge. There is also an adjustment for the water level elevations at the springs. The hydraulic conductivity is substantially increased during the calibration process, being the most uncertain parameter. Recharge is only slightly adjusted. Figure 6.1 shows the calibrated groundwater levels as resulted in the model. Also Table 6.1 represents the observed and simulated groundwater levels for certain wells in the model.

Cell Number	Observed GWL (MASL)	Calibrated GWL (MASL)	Difference (M)
(22,9)	116	118.4	2.4<5
(18,16)	223	219.3	4.7<5
(21,14)	186	188.9	2.9<5
(16,18)	257	260.4	3.4<5
(21,20)	248	251.8	3.8<5
(15,21)	280	275.2	4.8<5
(16,23)	296	298.5	2.5<5
Average Difference= 3.5m			

Table 6.1: The Calibrated and Observed Groundwater Levels for Specific Monitored Wells.

6.2 Calibration for Spring Flows

Simultaneously with the calibration based on groundwater levels, the calibration of spring flows is carried out. The calibration results are indicated in figure 6.2.

This figure shows a reasonable match between the observed and the computed spring flows. Reasons for spring flow discrepancies are similar as for the discrepancies between the observed and the calculated groundwater levels in addition to the uncertain elevations of the springs.

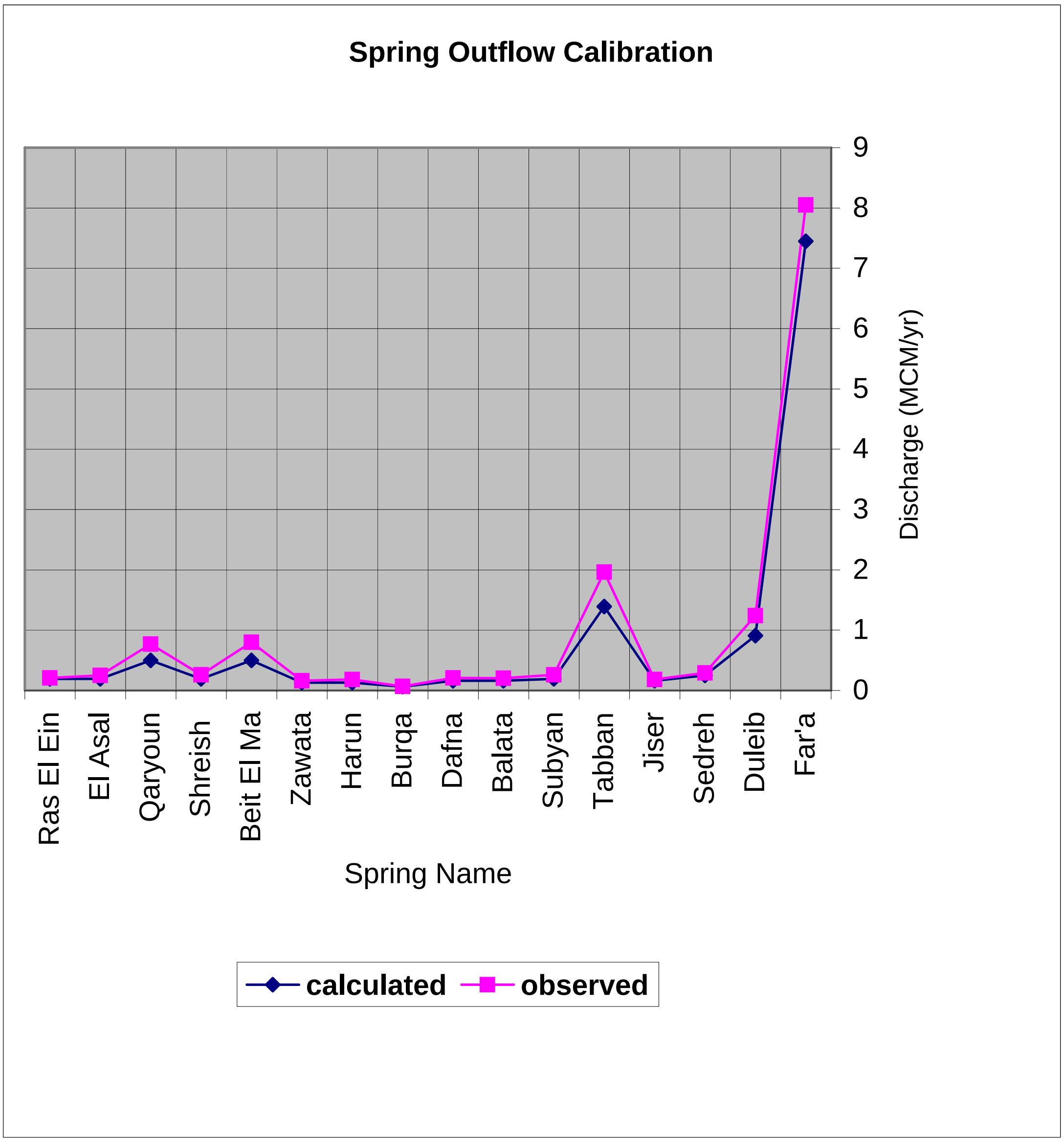

Figure 6.2: Calibrated Versus Observed Spring Discharge in (MCM/yr).

7- Particle Tracking and Groundwater Balance

7.1 Particle Tracking

MODFLOW has an option to carryout particle tracking using the sub-program PMPATH. The particle tracking results indicate that the main groundwater flow is from the south to the northeast (see figure 7.1 shown below). The pathway geometry is highly affected by sinks such as abstraction wells and springs.

The Far'a spring system seems to be the major sink point within the aquifer since it attracts most of the particle tracking lines according to its high discharge flow rate.

According to the particle simulation result, the protection zones for the wells and springs could be schematized and then groundwater quality could be better controlled.

7.2 Groundwater Balance

To determine Groundwater availability for the Eocene Aquifer, the water balance can be formulated. This balance describes the inflow and outflows of the groundwater into and out of the aquifer area.

The groundwater balance can be set up when the groundwater recharge and discharge mechanisms of the groundwater aquifer are known. Although more balance components are identified in Chapter 3, precipitation can be considered as the main component of recharge. On the other hand, discharge components can be divided into groundwater abstraction from wells and outflow through springs. The amount of groundwater that could be abstracted from the aquifer can be clarified from the components of the long-term groundwater balance.

The balance equation for a groundwater aquifer can be formulated in the following mode:

Inflow – Outflow = Rate of change of storage

For long-term calculations, assuming that the change of storage within the aquifer over a very large time is negligible, the steady state balance equation could be presented in the following form:

Inflow – Outflow = 0

Whereby:

Inflow: total groundwater inflow (m^3/yr);

Outflow: total groundwater outflow (m^3/yr)

Flow term	In (m^3/d)	Out (m^3/d)	In (MCM/yr)	Out (MCM/yr)
Springs	**0.0**	**1.037E+05**	**0.0**	**37.37**
Wells	**0.0**	**1.29E+04**	**0.0**	**4.74**
Sub-Surface Outflow	**0.0**	**8.22E+04**	**0.0**	**30.1**
Recharge from Precipitation	**1.988E+05**	**0.0**	**72.27**	**0.0**
SUM	**1.988E+05**	**1.988E+05**	**72.27**	**72.21**
Discrepancy (%)= 0%				

Table 7.1: Water Budget of the Model Domain of the Eocene Aquifer.

```
-------------------------------------------------------
         PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
-------------------------------------------------------
  FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
                         THE UNIT OF THE FLOWS IS [L^3/T]
                       TIME STEP    1 OF STRESS PERIOD    1

  -----------------------------------------------------
                         WATER BUDGET OF THE WHOLE MODEL DOMAIN:
```

```
         FLOW TERM           IN             OUT          IN-OUT
           STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
     CONSTANT HEAD  0.0000000E+00  0.0000000E+00  0.0000000E+00
             WELLS  0.0000000E+00  9.5095602E+04 -9.5095602E+04
            DRAINS  0.0000000E+00  1.0375926E+05 -1.0375926E+05
          RECHARGE  1.9885442E+05  0.0000000E+00  1.9885442E+05
                ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
     RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
    STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   NTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
------------------------------------------------------------
               SUM  1.9885442E+05  1.9885486E+05 -4.3750000E-01
                                       DISCREPANCY [%]  0.00


The value of the element (i,j) of the following flow matrix gives the flow
         rate from the i-th zone into the j-th zone. Where i is the column
                                         index and j is the row index.

                                                          FLOW MATRIX:

                                                                     1
                                                     .................
                                                     0  1   0.0000
```

Figure 7.3: Output From the Water Budget Calculator (Model Results)

8. Conclusions and Recommendations

8.1 Conclusions

In this study, the groundwater data of the Eocene aquifer in the northern part of the West Bank are analyzed. MODFLOW model is used in the analysis. The following are the conclusions that have been derived and are related to groundwater modeling:

1- The hydrogeology of the Eocene aquifer is complex, therefore it should be handled carefully when modeling the aquifer to get accurate results.

2- The uphill anticlines in the western and southern sides of the aquifer are the recharge areas, where the groundwater levels are relatively deep. Therefore it is not recommended to construct groundwater production wells in that area.

3- Wadi courses in the area proved high hydraulic conductivity, which indicating the presence of faults.

4- The modeling of springs near the boundaries has to be carried out carefully. These springs have caused errors as constant head cells. The problem was solved by presenting them as drains, using the drain package of the model.

5- The model runs only for certain initial hydraulic groundwater levels of more than 340m.

6- To model the Eocene aquifer, the hydraulic conductivity had to be increased to about twice of its initial values. This could be the result of the effects of faults, which was neglected in the model. The initial value of the hydraulic conductivity was estimated considering the hydrogeological formation and the results of pumping tests.

7- The recharge coefficients used in the model, result in high inflow values. These coefficients have been calibrated to obtain more realistic values.

8- The General Head Boundary package of MODFLOW should be present in order to cover the subsurface outflow and then to improve groundwater levels at the northeastern part of the aquifer.

9- The sustainable yield of the Eocene aquifer as resulted in the model was about 72MCM/yr.

8.2 Recommendations

Based on the data analysis and the results of the modeling of the Eocene aquifer, the following recommendations are formulated:

1- The model results supported the recommendation that groundwater wells located or proposed at or near the anticlinorium should be designed and operated carefully. This is due to the sensitivity of anticlinorium areas for groundwater level variations, both seasonal and long term.

2- The gradients and the modeling results indicate that a substantial quantity of groundwater flow across the eastern and the northeastern boundaries, materialized as lateral subsurface outflow. It is recommended that these good quality water could be tapped and exploited.

3- The hydrogeological properties of the aquifer were estimated based on the available geological cross-sections proved to be not accurate. Therefore, field investigations are recommended to verify these geological conditions.

4- It is recommended to monitor the existing wells and springs permanently and to construct a reasonable additional monitoring network.

5- Applying the Particle Tracking package has clearly showed the groundwater flow paths. Therefore this package can be applied to model groundwater transport model for the Eocene aquifer. This would be useful in modeling and controlling the groundwater quality.

6- To overcome model run, it is recommended to insert the hydrological stresses gradually.

7- A finer grid is important in order to control the variation in hydraulic properties. Such a refined model could be a good tool for groundwater planning of the Eocene aquifer and the other Palestinian aquifers.

8- In dual porosity flow approach, it is assumed that the flow in the aquifer is everywhere essentially horizontal, neglecting vertical flow components. The effects of the fractures (due to the faults) are also neglected. So it is recommended to assess carefully the effect of the faults on the actual hydraulic conductivity.

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10. Appendices

- Appendix A: Groundwater Models.
- Appendix B: Sensitivity Analysis for Both Recharge and Hydraulic Conductivity for the Eocene Aquifer.

Appendix A: Groundwater Models

1) GGWP Code

Description

GGCP (Golder Groundwater Computer Package) is an integrated suite of computer programs for steady state or transient finite-element simulation of two-dimensional, vertical or axisymmetric and aquasi-three-dimentional flow and transport of reactive solutes in anisotropy, heterogeneous, multi-layer aquifer systems. Auxiliary computer programs are included for semi-automatic mesh generation, input preparation, and presentation of model results (contour and vector plots). Confined, leaky-confined and unconfined flow problems are simulated with the programs AFPM (Aquifer Flow in Porous Media) and FPM (Flow in Porous Media. They can handle a moving phreatic surface, evaporation, and interaction with surface flows. The transport program (SOLTR) includes convection, dispersion, dilution, sorption, and radioactive decay.

2) SDF (Stochastic Discrete Fracture) flow model

Two Dimensional Stochastic Discrete flow model (SDF). Coupled with a particle-tracking code to explore the validity of the porous media approximation for simulating groundwater flow in fractured-rock aquifers. Applying it to porous media it becomes more significant especially for a large domain of the problem.

SDF is a computer model composed of 4 models, which are NETWRK, NETFLO, NETRANS and APEGEN

- The model simulates fractures as openings between smooth parallel plates.
- Major assumptions incorporated into the model include:-
  a) steady state laminar flow
  b) 2-D flow of an incompressible viscous fluid
  c) impermeable rock matrix

A) NETWRK

NETWRK defines all elements or line segments that lie between two consecutive effective fracture intersections and records the node numbers corresponding to the ends of these elements for future identification. The Output from the program NETWRK include summary information on the line patterns generated on the fracture aperture, lengths, orientations, total and effective porosity of the network. Thus, when used alone, NETWRK provides information on the physical, internal characteristics of the created fracture system, i.e., degree of fracture interconnection, effective porosity, and total porosity. NETWRK produces input files for other programs, such as NETFLO (or WELFLO), which simulates fluid flow conditions through the network.

B) NETFLO

The program NETFLO simulates fluid flow in discrete fracture networks with specified boundary condition and hydraulic heads using a theory of two-dimensional flow through a fractured rock system with an impermeable rock matrix. The boundary conditions may be one of the following types: Constant head, Linear or log decreasing head or No-flow.

C) PARTRACK

It is accessory program to track advective particle movement through the fracture network (system). Particle movement is simulated based on volumetric intersection. It can also simulate both forward and reverse particle tracking through time.

Comments

The SDF code is a 2-D stochastic discrete flow model. Transport is a separate package and simulates the transport as particles flowing in the fracture system. The whole model composed of 4 models or more. It can handle only the systems with limitations such as laminar flow, incompressible viscous fluid. In addition, it assumes an impermeable rock matrix, and flow in the discrete fractures. This code seems less suitable, since the modeling of discrete fractures is complex and data are not available.

3) FRAC3DVS Code

FRAC3DVS is 3 Dimensional, finite element model for simulating steady state or transient, variably saturated groundwater flow and advective-dispersive solute transport in porous or discretely fractured porous media. The code was developed at the Waterloo Center for Groundwater Research (WCGR Laval University for a purpose of research problem domain).

Input Features

FRAC3DVS can be used either an 8-node block or 6-node prism finite element or 7-point finite element discretisation of the porous medium and rectangular or triangular plane elements to represent fractures if present.

Block elements can be subdivided into tetrahedral so those grids grids composed of non-orthogonal block elements can be accommodated.

Transport processes include advective, hydrodynamic dispersion, sorption according to a linear Freundlich isotherm, and multi-species transport of either straight or branching decay chains.

Solution Technique

FRAC3DVS uses numerical approach, which can be a control-volume finite element, Galerkin finite element or finite difference method. A highly efficient conjugate –gradient-like solver based on CGSTAB acceleration is used (USGS, 1999)

The flow solution has the following features: an exact treatment of the saturation term by using a mixed, mass conservation formulation, full Newton-Raphson iteration for robustness in handling non-linearities in Ritchard’s equation describing variably-saturated flow, proper treatment of flow boundary conditions along well screens and drainage tiles in heterogeneous media through a non-iterative scheme with uses 1 D line elements to discretise the wells and tiles. An efficient, adaptive timestepping procedure adjusts time-step size based on the system response and user defined criteria.

Output Features

A separate post-processor (F3DPLOT) for PC-based systems is provided. F3DPLOT uses an interactive, menu driven graphical interface to generate 2-D slices through the 3-D domain, which show hydraulic head, saturation or concentration output from FRAC3DVS. Flow velocity vectors can also be shown if desired. F3DPLOT is restricted to orthogonal rectangular domains composed of block elements. F3DPLOT also has the ability to generate TECPLOT compatible output files in 2-D or 3-D, and also supports the generation of output in postscript, HPHL or raster graphics format.

Comments

FRAC3DVS is a very comprehensive model that can also tackle transport. It has been designed for fractured media following a dual system approach. Graphics are not fully attractive and the model itself is not much used yet.

Less suitable in view of many data needed and lack of experience with the model. Moreover, Auxiliary programs are needed to get the output.

4) SWIFT/486 Code

Description

SWIFT/486 is a fully transient, three-dimensional model, which simulates the flow and transport of fluid, heat (energy), brine, and radionuclide chains in porous and fractured geologic media. Fluid density, fluid viscosity, and porosity couples the primary equations for fluid, heat, and brine. Steady state options are available for the fluid and brine equations, and both Cartesian and cylindrical coordinate systems may be used; however, the latter is restricted to two-dimensional, r-z simulations. Both dual-porosity and discrete fractured conceptualization may be considered for the fractured system. Migration within the rock matrix is characterized as a one-dimensional process. SWIFT/486 includes a runtime monitor for on-screen display, restart, post processing (via SURFER) and particle tracking (STLINE, included).

Comments

SWIFT/486 is a very comprehensive and complex model that can be used for all sorts of applications; in addition, the model is less suitable for the specific application of groundwater flow in fissured rock formations.

5) TWODAN Code

Description

TWODAN models two-dimensional groundwater flow in the horizontal or vertical plane. It is based on the “Analytic Element Method” described by Strack (1989). The principle advantages of this method over conventional numerical methods are its lack of fixed grid, simple input, accuracy, speed, and direct graphic output. It has diverse technical capability for analytic software in this price range, with layered aquifers, heterogeneities, resistant boundaries, impermeable boundaries, transient wells, steady wells, line sinks, variable recharge/leakage, and many other features. TWODAN’s interface consists of intuitive menus, data entry forms, and graphic input and editing of spatial data using standard DXF file base-maps. Because of this flexibility, TWODAN is an efficient tool for modeling regional flow, capture zones for wellhead protection, or remedial design alternatives.

Comments

This code is a 2-D flow simulation model. It is not designed specifically for fractured aquifer systems. Since analytical element modeling is completely different modeling technique (from numerical modeling) it is less suitable for the purpose of modeling the Eocene aquifer.

6) TRAFRAP-WT Code

TRAFRAP-WT (TRAnsport in FRActured Porous Media with Water Table boundary conditions) is a 2-dimensional finite element research code designed to simulate groundwater flow and solute transport in fractured and granular aquifers, and is capable of treating both (leaky-) confined and water table systems. Fractured porous media are presented by either the discrete-fractured or dual porosity approaches or a combination of both.

The model solves for either flow or transport. Solving for flow provides a steady state velocity field, which can be used in a successive flow simulation. The flow and transport equations are solved using finite element algorithms with special features designed to handle aquifer-aquitard systems and options to account for water table boundary conditions and fracture skin effects.

The code takes into account:

1) Fluid interactions between the fractures and porous matrix blocks
2) Advective-dispersive transport in the fractures and diffusion in the porous matrix blocks and fracture skin
3) Chain reactions of radionuclide components.

In addition, for the fractured system the model distinguishes between cases in which the matrix blocks have low permeability and those in which the matrix blocks have substantial permeability. The model can handle various model geometry and element shapes (rectangular, triangular, and linear).

TRAFRAP-WT runs in batch mode under MS-DOS. Example data sets are provided, which can be copied and edited with a text editor for individual problems. Results are saved in binary file to reuse in later runs, and in text files. The non-proprietaries TRAFRAP-WT package includes source code, executable image, and example data sets. The documentation contains installation procedures, theory, user's manual, and example problems.

Comments

This is a 2-D code. It needs data of chain reactions of radiunoclide components. It runs under MS-DOS. It is not widely used and there are not enough experiences to handle. Therefore, this code is less suitable for the modeling of the Eocene aquifer.

7) FRACMAN Code

Description

It is an MS-DOS PC software package used to model the geometry of discrete features, fractures, paleochannels, karst and stratigraphic contacts. FracMan is designed to provide the geologists and engineers with an easy to use tool for modeling fractured rock masses, for rock mechanics and hydrologic applications in hazardous and unclear waste management, underground construction, mining and petroleum and reservoir engineering. It provides an integrated environment for the entire process and modeling.

FracMan provides:

- Data analysis features to allow transformation of raw data into the format needed for discrete fracture modeling.
- Stochastic simulation of fracture patterns to facilitate three-dimensional visualization.

- Exploration simulation, to improve the designated interpretation of site characterization programs for collection of fracture data.
- Finite element meshes generation and output post-processing, to facilitate flow transport modeling in networks of fractures.
- Macro support, to facilitate Monte Carlo stochastic simulation.

FracMan's data analysis capabilities include new techniques for analyzing fracture orientation, size, intensity, and transmissivity. These techniques provide the data needed for fracture geometric modeling from data, which are frequently collected as part of comprehensive site investigations, but are rarely used in hydrologic or mechanical modeling.

Comments

The accuracy of the results, functionality, or application of FRACMAN is not confirmed by the author. It is complicated and difficult to handle. It is mainly designed to be helpful in groundwater exploration simulations. But for the efficiency for flow simulation is not indicated or confirmed. The authors make no warranty of the accuracy, functionality, or application of this software. As a result of complexity, FRACMAN is considered to be less suitable for applying the objectives of this research.

8) PMWIN (MODFLOW & MT3D) Code

Processing Modflow for Windows (PMWIN) is a simulation system for modeling of groundwater flow and transport process with the modular three-dimensional finite-difference groundwater model MODFLOW.

The particle tracking model PMPATH for Windows or the MODPATH for solute transport model MT3D could be used to simulate 3D solute transport.

MODFLOW application describes and predicts the behavior of groundwater systems for flow and solute transport.

Features in PMWIN are

- PMWIN is capable of handling a very large problem domain. There is almost no limit to model size (80 layers, 2000×2000 cells per layer)
- It provides comprehensive support to the parameter estimation program, PEST
- It provides a powerful results extractor. Which allows the used to extract simulation results into a spreadsheet. And then to view the

results or to save them in ASCII or SURFER compatible data files

- It can display temporal development curves for simulation results
- The water budget calculator can calculate the budget of user-specified zones and the exchange of flows between zones.
- It can create contour maps or solid fill plots or input data or simulation results.

MODFLOW is the USGS “A Modular three-dimensional groundwater flow model”. Groundwater flow within the aquifer is simulated using a block centred finite-difference approach.

Layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow associated with external stresses, such as wells, Arial recharge, evapo-traspiration, drains and streams, can be simulated.

MODFLOW is the most widely used groundwater flow model in the world. It has been subjected to the justly famous USGS review system. The source code is available to every one so the mathematical basis has been critically reviewed by hundreds of users. MODFLOW is accepted as a standard by those involved with regulatory decisions. Its widespread use also means that there is available experience and thus help can be obtained when applied.

Comments

It is designed mainly for porous medium modeling. According to a comparative study made to evaluate MODFLOW and SDF, the MODFLOW can represent the fractured environment. It was noticed that the error value becomes smaller for large scales of the problem domain.

The field generator option may be used in PMWIN to represent permeability stochastically, especially in fractured zone. Also the permeability can be presented deterministically. This code is thus selected for modeling the porous soil in the Eocene aquifer.

9) BIOF&T3D Code

Description

Transient 1-D or 2-D Cartesian (x,z) or 2-D Radial (r,z) or 3-D water flow and multi-species dissolved phase transport solution in the unsaturated zone uncoupled with 2-D or 3-D flow and multi-component aqueous phase transport in groundwater aquifer. This feature enables computationally efficient simulations with a model that gives due regard to the dimensionality of the problem and hydro-geologically defensible.

10) MAFIC Code

MAFIC is a finite element flow model designed to simulate transient and solute transport through two-dimensional and three-dimensional rock matrix with a discrete fracture network. Solute transport is simulated in fractures only. Flow in the rock matrix is simulated using either a fully discritised multi-dimensional Galerkin finite element approach, or a generic matrix block scheme. Solute transport is simulated using a convective particle tracking approach. Solute dispersion is simulated stochastically.

MAFIC uses triangular elements to discretise fracture surfaces and tetrahedral, spherical or rectangular elements to describe the rock matrix. Input files may be specified by the user or created by fracture network simulation programs such as FRACMAN. MAFIC models fracture flow through a network of interconnecting plates and matrix flow through a three dimensional volume. It is capable of handling very general fracture network geometries. MAFIC provides a number of special features including:

- Choosing of linear or quadratic elements using the same input data.
- Simulation of matrix flow using either a fully discretised finite element procedure, or a generic matrix block scheme which can accommodate a variety of fracture geometries.
- Specification of nodal groups with identical time-varying head or flux boundary conditions.
- Capacity of multiple simulations with different fracture network geometries but identical problem parameters and boundary conditions to accommodate stochastically generated fracture networks
- Solute transport modeling with either steady state or transient flow conditions and stochastic emulation of convective dispersion.
- Input file must exist and output file must be created.

Comments

MAFIC is a 2-D flow model; it simulates the solute transport in fractures only. The author does not confirm the results of MAFIC. Finally, it is complicated and difficult to handle. Therefore, this code is considered to be less suitable.

Table A1 shows the summary of the available modeling codes, their advantages and disadvantages.

Code	Advantages	Disadvantages	Comments
1- GGWP	Quasi-3D modeling flow and transport	Designed mainly for porous media	Not suitable for fractured environments
2- SDF	It handles the flow in fractured aquifers by porous media approximation	It has some conditions to apply	1- 2D flow discrete model 2- It is composed of four separate packages which makes it more complex
3- FRAC3DVS	3D flow and transport model. It handles porous/ discretely fractured porous media.	It uses a dual system approach, which needs a lot of data about fractures.	It is a very general and comprehensive model. Not enough experience available.
4- SWIFT/486	1- It is a 3D flow and transport model in transient mode 2- Dual porosity, and discrete fractured can be considered.	Fully transient and comprehensive	2D steady state simulations, less specific.
5- TWODAN	Lack of fixed grid, simple input, accuracy, speed, and direct graphic output.	It is a 2D flow model. It uses analytic element method.	It is not an efficient way to model 3d and fractured environments.
6- TRAFRAP-WT	It handles various element geometry and shapes	1- It is 2-D flow model 2- Runs under MS-DOS mode 3- Needs data on chain reaction	2D models are not suitable for the modeling of two layered aquifer systems
7- FRACMAN	It can model discrete fractures.	It is an MS-DOS package. No warranty about the accuracy and functionality.	It needs a lot of data about the fracture characteristics. The author does not confirm the results. So it is less suitable.
8- MODFLOW	3D flow and transport modeling. It has the parameter estimation program.	It is designed for porous media, which is less suitable for fractured media	It can calculate the water budget which is one of our objectives. It also can be used for porous media approximation.
9- BIOF & T3D		Used for transport modeling	1-Not suitable for fractured rock environments 2- Used for

			unsaturated zone
10- MAFIC	2D&3D transient flow model. It can simulate the flow in fractures and rock matrix.	It simulates solute transport in fractures only.	The author does not confirm its results. It is complicated and difficult to handle
11-MOC	2D & 3D flow and transport model. It can be used for steady state and transient flow.	It is an MS-DOS package. The model couples the ground-water equations with the solute transport flow.	It is complicated and difficult to handle
12- SHARP	3D quasi-modeling, used to simulate fresh and salt water in coastal aquifers	Designed for porous media.	Can not be used for fractured environment.

Table A1: Summary of the Available Groundwater Models (USGS, 1999 and 2000)

Appendix B: Sensitivity Analysis for Both Recharge and Hydraulic Conductivity for the Eocene Aquifer.

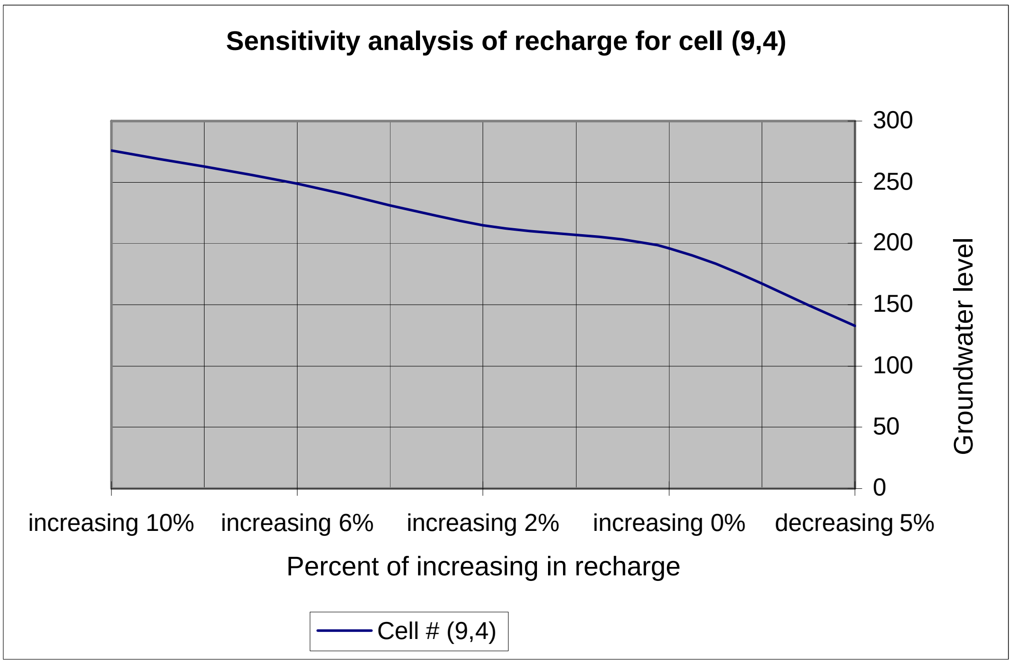

Figure B1: Sensitivity Analysis of Recharge for Cell # (9,4) in the Model.

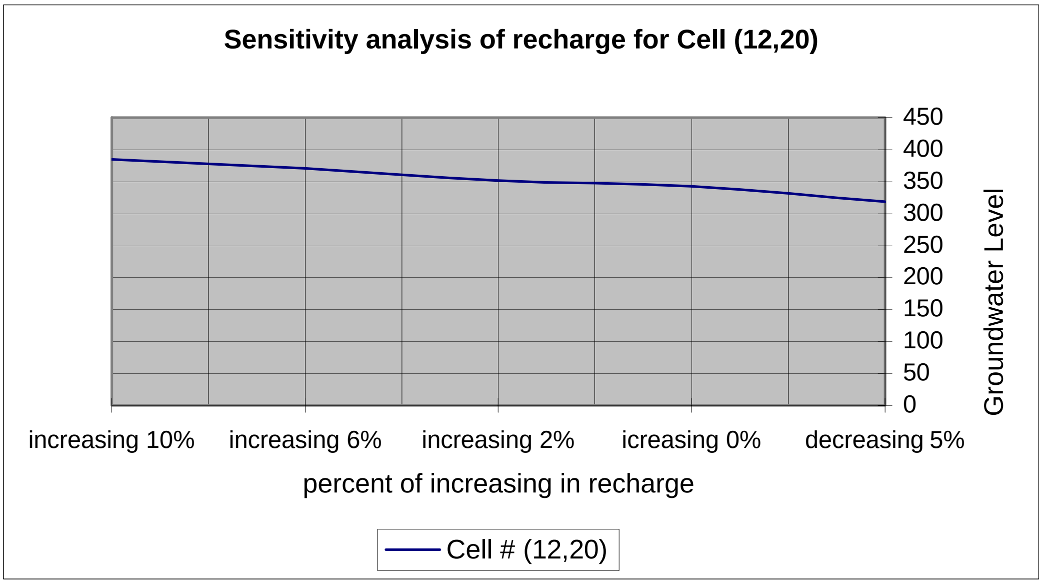

Figure B2: Sensitivity Analysis of Recharge for Cell # (12,20) in the Model.

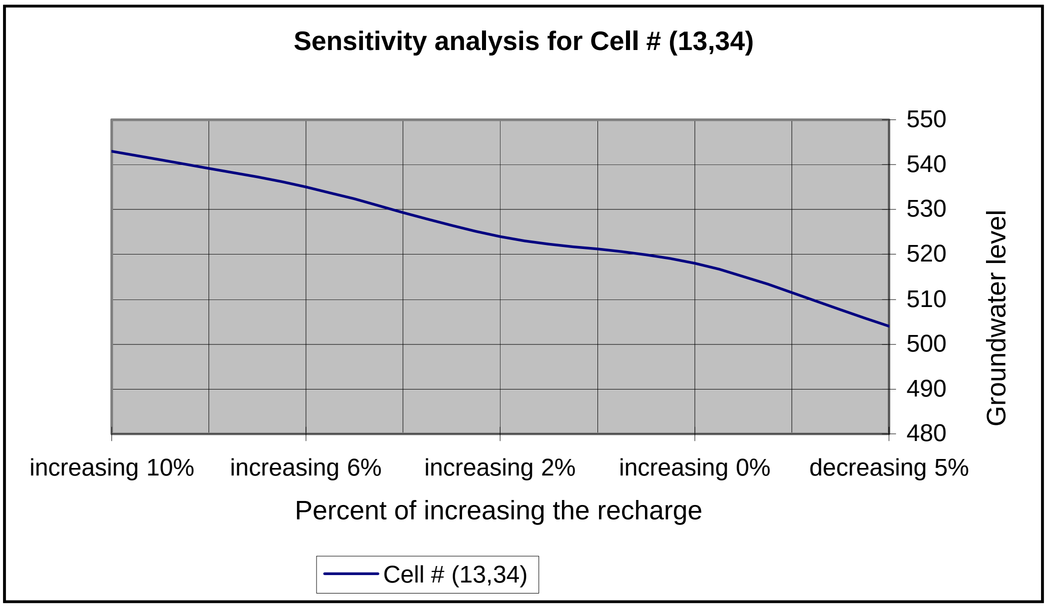

Figure B3: Sensitivity Analysis of Recharge for Cell # (13,34) in the Model.

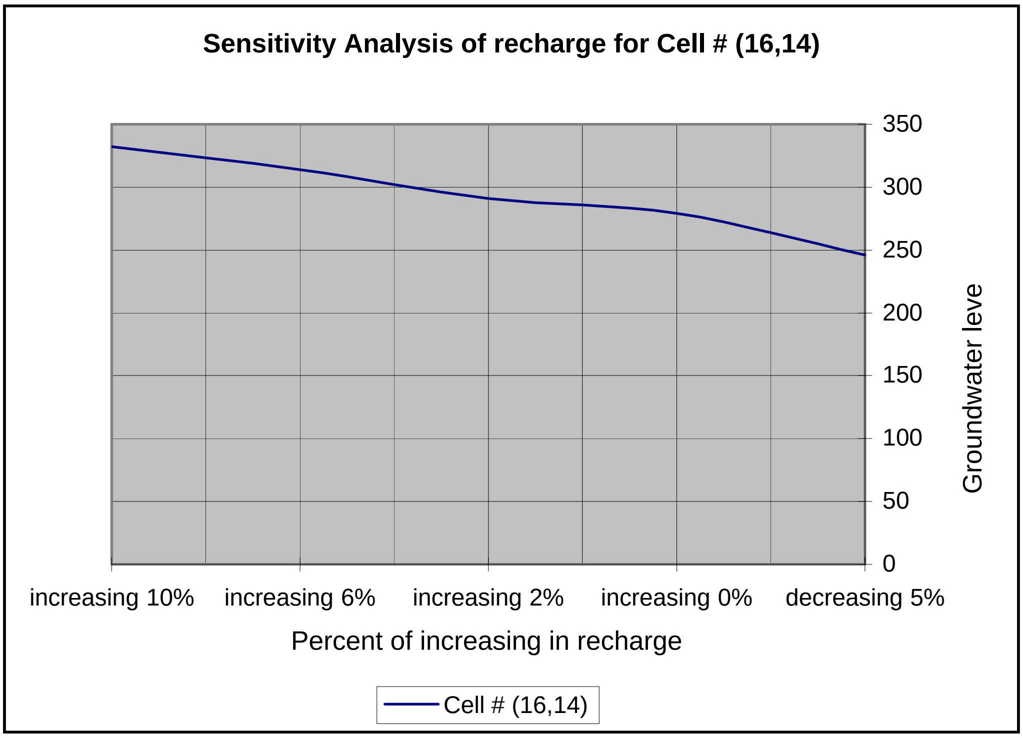

Figure B4: Sensitivity Analysis of Recharge for Cell # (16,14) in the Model.

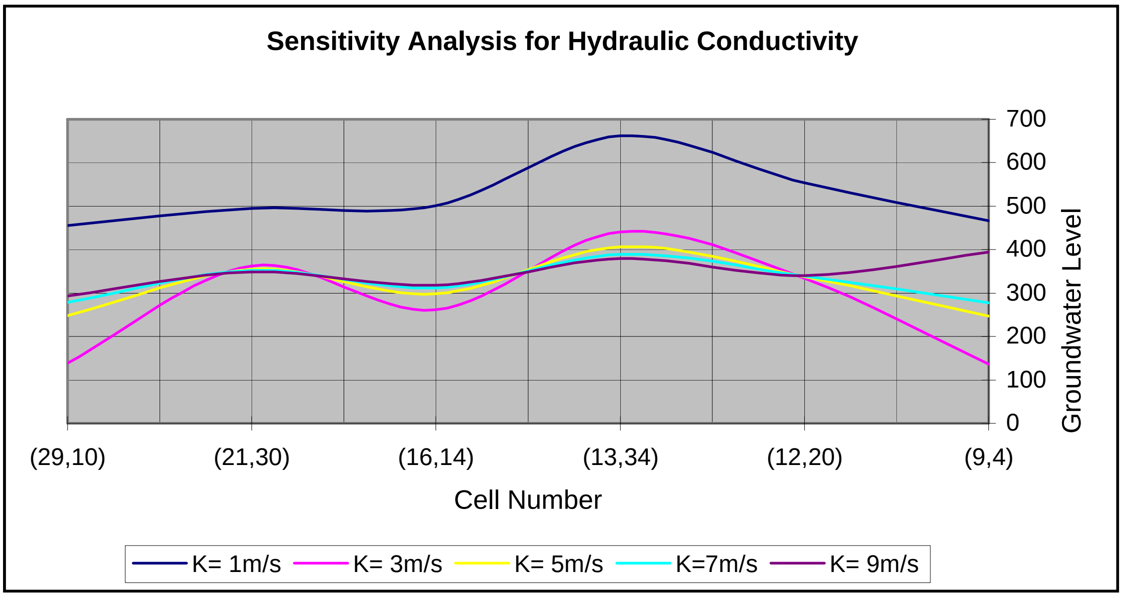

Figure B5: Sensitivity Analysis for Hydraulic Conductivity for the Eocene Aquifer.

جامعة النجاح الوطنية
كلية الدراسات العليا

نموذج لحركة المياه الجوفية في منطقة الحوض الأيوسيني في الضفة الغربية، فلسطين

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قدمت هذه الأطروحة إستكمالاً لمتطلبات درجة الماجستير في هندسة المياه والبيئة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين

2003

الملخص

يعتبر الحوض الأيوسيني (جزء من الحوض الشمالي الشرقي) من أهم الأحواض الجوفية في فلسطين. يقع الحوض في الجزء الشمالي الشرقي للضفة الغربية على طول منطقتي جنين ونابلس. يعتبر من مصادر المياه الجوفية العذبة التي تزود السكان في المناطق الشمالية في الضفة الغربية.

تم عمل عدة خطط ونماذج لتطوير مصادر المياه الجوفية ضمن هذا الحوض. لذلك كانت فكرة عمل نموذج كحاجة ملحة للاستفادة من هذه المصادر.

ركزت هذه الرسالة وهذا البحث على عمل نموذج لمنطقة الحوض الأيوسيني. تم جمع معلومات حول الوضع الجيولوجي والهيدروجيولوجي في المنطقة ومن ثم تم تحليل هذه المعلومات. وباستخدام برنامج MODFLOW تم تقييم كل من كمية المياه التي يعطيها الحوض سنوياً، وكمية المياه الداخلة والخارجة من الحوض، واتجاه حركة المياه الجوفية، وعمل ميزانية للمياه الجوفية في الحوض.

تم معايرة كل من مستوى المياه الجوفية وتدفق الينابيع باستخدام طريقة المحاولة والخطأ. كما تم دراسة العوامل الحساسة والتي تؤثر على النموذج أكثر من غيرها، وكانت العوامل الحساسة في هذه الدراسة هي كمية التغذية من مياه الأمطار ومعامل النفاذية . حيث تبين أنهما أكثر تأثيراً على النموذج للحوض الأيوسيني.

أشارت النتائج أن النموذج لا يعمل إلا على مستوى هيدروليكي ابتدائي للمياه الجوفية لا يقل عن 340م فوق سطح البحر. القيم الابتدائية للنفاذية زادت إلى ضعفين عن القيم الأولية في بعض المناطق وهذا قد يعود إلى تأثير الفوالق والإنكسارات في الصخور الموجودة في منطقة الدراسة. أما معاملات التغذية من مياه الأمطار، فقد أعطت كميات كبيرة من التدفق الداخلي للنموذج (الحوض) .

وأظهرت النتائج أن كمية المياه التي يمكن أن يغذي بها الحوض حوالي 62 مليون متر مكعب سنوياً.

أخيراً، تبين من النتائج أن نبع الفارعة الموجود في المنطقة الجنوبية الشرقية، هو بمثابة حفرة بالوعية في الحوض وذلك بسبب ارتفاع كمية التدفق المستهلك منه.

بالاعتماد على النتائج السابقة يوصى بتصميم وتشغيل الآبار بدقة في المنطقة، كما أن المياه الخارجة من الحوض بسبب طبيعة الأرض يمكن الاستفادة منها. كما يوصى بعمل زيارات حقلية لتمثيل الحالة كما الجيولوجية كما هي في الواقع. في هذه الدراسة لم يتم اخذ تأثير الفوالق على الدراسة، لذلك يوصى بعمل بحث لدراسة هذا التأثير.