BIRZEIT UNIVERSITY

Groundwater Flow Model of the South Eastern Sub-Aquifer (Bethlehem Area) /West Bank

By

Nazira Abu Zaid
(1025317)

The thesis was defended successfully on (17th of September 2005) and was approved by all members of the Supervision Committee.

Supervision Committee:	**Signature**
Dr. Marwan Ghanem (Chairman)	……………………………….
Dr. Ziad Mimi (Member)	……………………………….
Dr. Wasim Al Ali (Member)	………………………………..
Dr. Amer Marei (Member)	………………………………..

BIRZEIT UNIVERSITY

Groundwater Flow Model of the South Eastern Sub-Aquifer (Bethlehem Area) /West Bank

By

Nazira Abu Zaid
(1025317)

Supervisor

Dr. Marwan Ghanem

A thesis submitted in partial fulfillment of requirements for the Masters Degree in Water Engineering from the faculty of Graduate Studies at Birzeit University-Palestine

September, 2005

Abstract

This study concerns with building a model for the South Eastern Sub-Aquifer (SESA) to understand the physical characteristics of the Upper and Lower Aquifers and to studying the interaction between them.

This sub-aquifer locates within the Eastern Basin of the West Bank in Palestine. The total area is 584.6 Km^2. It includes the Palestinian areas of Bethlehem and parts of Jerusalem and Hebron mountains area. The boundaries of this area stretch from the axes of the Hebron and Ramallah anticlines in the west, open area which is characterized as specified head in the eastern boundary, and the southern and northern is characterized as equipotential lines on the water level lines.

SESA consists of two systems whose recharge was estimated. These are the Upper Aquifer System consists of Upper Cenomanian and the Turonian Formations in terms of geologic age. The other is the Lower Aquifer System consists of Albian and Lower Cenomanian formations. The recharge of the Upper and Lower Aquifers were 23.5 and 3.3 Mcm/yr, respectively.

For achieving the objectives of the study, a conceptual model for ten years (1990-1999) has been constructed by using a GIS system. Then, a MODFLOW that runs under GMS processor was used as the modeling method for the SESA. The study area domain composed of 85 rows and 104 columns.

The best-solution was attained with horizontal hydraulic conductivity values of 0.5 to 260 m/yr and 2-515 m/yr for Upper and Lower aquifer, respectively.

The result of studying that there was contact between the two aquifers that. The values of inflows and outflows were estimated in different zones of the SESA. The effective vertical hydraulic conductivity between the sub aquifers (Yatta Formation) varies between $3.65*10^{-6}$ to 1.46 m/yr.

The water budget was taken into consideration as approach for sustainable management. The results show that the Upper aquifer is sustainable because of the estimated recharge (23.5 Mcm/yr) more than the used water (3.5 Mcm/yr). But, the estimated recharge in Lower aquifer (3.3 Mcm/yr) is less than the used water (8.8 Mcm/yr). So, there should be further study to put a strategy to prevent any damage for Lower aquifer. And this required supported transient model to predict the future situation.

Finally, the results show that there are high discharges in the south eastern part of the study area because of presence of faults and fractures in that part.

بسم الله الرحمن الرحيم

قل ان صلاتي و نسكي و محياي و مماتي لله رب"

"العالمين

صدق الله العظيم

(سورة الأنعام-اية 162)

Acknowledgment

I wish to express my deep and sincere thanks and gratitude to Dr. Marwan Ghanem for his valuable help, encouragement, supervision, and guidance through the course of this thesis while serving as my advisor. I also wish to record my appreciation of the continuous assistance, guidance, and help rendered by Eng. Muath Abu Sadah.

My thanks extend to the Palestinian Institutions and their staff for their cooperation and provision of the necessary data to carry out this thesis in particular: The Palestinian Water Authority PWA, The Palestinian Hydrology Group PHG, and Applied Research Institute of Jerusalem ARIJ.

Thanks to Eng. Raslan Yasien, Theib Abdel-Ghafour and everyone who helped either through scripts given or suggestions, and ideas provided. for his advice given during the study.

My deep gratitude and appreciation to my family, my parents, my sisters, my brothers, and Naji, whose support was the trigger that kept me going and overcoming difficulties till the completion of the study

Table of Contents

List of Figures

List of Tables

List of Symbols

Abbreviation	In Words
SESA	The South Eastern Sub-Aquifer
E-W	East to West

W	West
NW	North Western
E	East
NE	North Eastern
SE	South Eastern
Mcm/yr	Million Cubic Meter Per Year
PWA	Palestinian Water Authority
PHG	Palestinian Hydrology Group
GMS	Groundwater Modeling System
ARIJ	Applied Research Institute of Jerusalem

Chapter One

Introduction

1.1 Background

Water resources have played an important role in shaping geopolitical boundaries of Palestine since the twentieth century.

Groundwater resources are considered as the vital water source for Palestinian people. The groundwater in Palestine flows in three main directions, to the east, to the northeast, and to the west, thus forming three main groundwater basins (Eastern, Northeastern, and Western Basins). The three basins, which collectively rainwater from the mountain Aquifer, are separated by groundwater divides. Some Palestinian and Israeli hydro-geologists are sub-dividing the Eastern Basin into three sub-basins which are; the Eastern Aquifer Sub-Basin, (Figures 1, 2), the Jordan Valley Floor Aquifer Sub-Basin, and the Dead Sea Aquifer Sub-Basin (Sabbah, 2004). In this study, part of the Eastern Basin is investigated.

The Eastern Basin is the major groundwater sources for Palestinians because they have no access to the Western Basin. Moreover, Palestinians must obtain permits from the Israeli Government to drill any new well or to rehabilitate any existing ones. For each permit granted by Israel to drill a new well, the Israeli Government limits the pumping quota (Sabbah, 2004).

The Eastern Basin extent is defined by structural and hydraulic boundaries: the Dead Sea and the Jordan River to the east, the Western and the Northeastern Basins to the west and north (Figure 2). The Eastern Basin study area includes a total area of approximately 2900 Km^2 (CDM/Morganti, 1997).

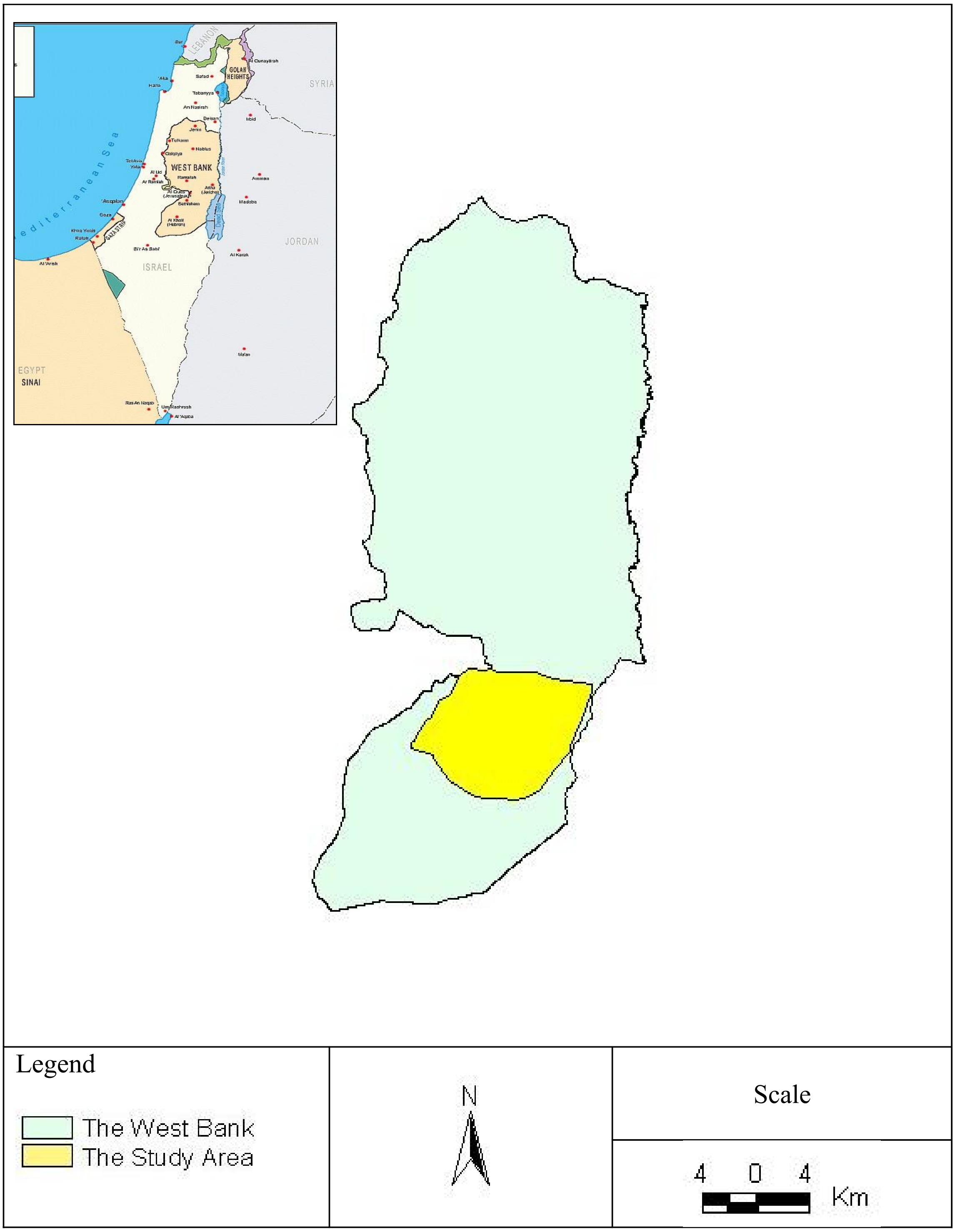


Figure 1: Location map of the study area, In the top frame: the location within the Eastern Mediterranean Region (adopted from PWA Data Bank)

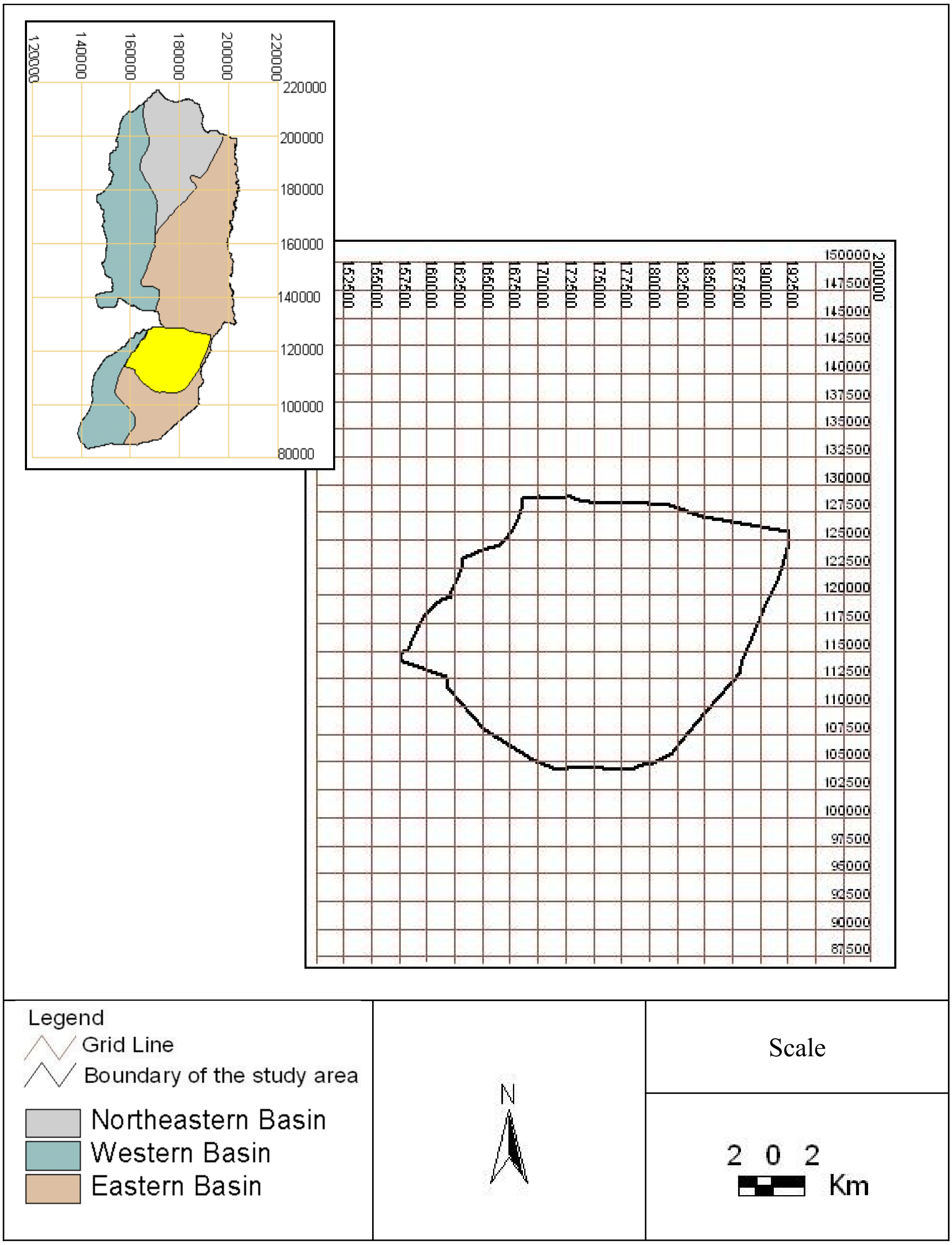


Figure 2: Location of the study area within the Eastern Basin and within the Palestinian Grid (adopted from PWA Data Bank)

1.2 Problem Definition and Major Concern

The growing water demand in the West Bank has increased groundwater abstraction, which in turn led to over utilization of the available groundwater of the Eastern Basin. So many wells were drilled in it. Recently, a few Israelis and Palestinians production wells have been added specially within the south eastern sub-aquifer (SESA: the study area). This caused an increase in the abstraction which lead to dropping in water levels.

In addition, the new wells were in production, there was a strong probability that interface between so many wells, in such a relatively small well field, could result in a massive combined draw down in the Herodian field (Aliewi and Jarrar, 2000). This field is located within the study area. The hydrologist regarded this exploitation as unsustainable (Scarpa, 2004). Moreover, without any management, this leads to damage the aquifers.

The number of groundwater management studies by Palestinian researchers and hydrologists has been limited. None of these Palestinian water management studies dealt with the water budget of Sub-basin.

This study will determine the physical characteristics of the aquifers of SESA by using GMS software MODFLOW Code as a tool to deal with the whole sub-basin in order to quantify aquifer inflows and discharges as well as to understand the groundwater regime and manage the groundwater resources for SESA.

The study will emphasize on the development of the conceptual geologic and hydrogeologic model of the study area, and outlines the methodology that will be used to construct the 3-dimensional numerical groundwater flow model.

1.3 Objectives

The objectives of this study were to investigate the hydrological and hydraulic characteristics of SESA area and to evaluate their potentialities. A hydrological study was conducted to determine the volume of recharge and groundwater balance in the study area. The main objectives of this study area can be summarized as follows:

1. Studying the physical characteristics of the SESA.
2. Studying the interaction between the Upper and Lower Aquifers for SESA.

1.4 Methodology

The main tasks that were undertaken for developing this thesis of the SESA are as follows:

1. Data survey: different institutions were visited to gather data about the area such as springs, wells, their locations …etc. Moreover, many journals, books, literature essays plus different web sites were used.
2. Field visits: some field visits were conducts in order to be in a full picture about wadis of this sub-aquifer.
3. Water balance study for the above area in 10-year (1990-1999).
   - Tabulating the gathered data of well abstractions, springs discharges, rainfall stations, …etc.
   - Preparing a geological and average annual rainfall maps.
   - Creating a topographic map with 50 m contouring line.
   - Estimating the volume of recharge using the TAHA's Equations:
   - Creating the top and bottom elevation maps for both Upper and Lower aquifers for SESA. The regional cross sections for the Eastern Basin, and geophysics prepared for Mountain Aquifer were used in this research to extract the aquifer geometry.

- Setting up a numerical groundwater flow model for SESA. GMS software, MODFLOW Code will be used as a tool for understanding the water budget for SESA. The model will be calibrated for steady state conditions in an attempt to test the best conceptual model and boundary conditions, sources and sinks, groundwater flow direction, head gradient distribution, the overall flow budget, and the optimal values of hydraulic conductivity and recharge that can minimize the difference between the observed and computed heads.
- Analyzing the water budget.

4. Writing the results, discussion, and recommendations.

1.5 Literature Review

Moorehead at al (2001) submitted a report entitled “Water For Palestine”. Showed that the USAID completed study for a re-assessment of Stage 1 that included analysis on the condition of the aquifer. It found, while the water extracted was of high quality, the current and future planned exploitation exceeded the replenishment capacity of the aquifer.

Guttmann and Zukerman (1995) did a groundwater modeling study on the Eastern Aquifer Basin which would serve as a tool to examine different operational regimes.

They used the finite-difference MODFLOW model. The area of the model was divided into cells, 58 rows by 36 columns. The size of the smallest cell was 0.5 Km and the biggest one was 2 Km. The model area was 2340.75 Km^2 with total active cells of 1387 cells. Steady state and transient calibration was done for the model.

Transmissivity values ranged from 5 to 5000 m^2/d and storativity values ranges between 10^{-2}-10^{-5}.

The model study concluded that it is the utilization of fresh water may be expands by reducing the flow of springs (outlets of the model area). They concluded when reducing the size of the outflows or the transmissivity in the region caused the calculated water tables to rise tens of meters above the measured levels.

J. Guttmann (1997) submitted a report entitled “Hydrogeology of the Eastern Aquifer in the Judea Hills and Jordan Valley”. The report included a comprehensive study of the geology, hydrology, and groundwater conditions of the Eastern Aquifer. He did a flow model, set up and calibrated for the basin area. In setting up the model, structural elements, low transmissivity zones, etc., were taken into account.

For water balance for a steady state, natural replenishment to the extent of 118.61 Mcm/yr was obtained for the basin. Dynamic calibration was done in 1998 aimed at examining the effect of the parameters incorporated in the model on the quality of the dynamic calibration.

ANTEA (1998) completed an elaboration study of the Eastern Aquifer System. The report included a comprehensive study of the geology, climatology, and groundwater conditions of the Eastern Aquifer.

CDM (1998) completed a model for Eastern Aquifer Basin to estimate a range of limits for the sustainable yield of groundwater sources.

The finite element code DYNFLOW was used to model the groundwater system. This code was developed by CDM. DYNFLOW simulates 3-dimensional groundwater flow and uses a triangular element in plane view.

The model area was about 3000 Km^2 with total 3350 elements. Steady state and transient calibration was done for the model.

The calculated Hydraulic conductivity values ranged from 0.04 to 15 m/d and storativity values ranges between 10^{-7}-10^{-5}.

CH2MHILL (2001) completed a groundwater modeling study on the Eastern Aquifer Basin which would serve as a tool to define the sustainability of the Eastern Aquifer and provide a regional management tool. The model was used in predictive scenarios to evaluate the behavior o the groundwater system under different management alternatives.

A MODFLOW flow model that runs under GMS processor was used as the modeling engine for the Mountain Aquifer. MODFLOW is a three dimensional, cell-centered, finite difference, saturated flow model developed by the United States Geological Survey (Mc Donald and Harbaugh, 1988. The model domain was divided into 50rows and 83 columns. The intersection of rows and columns create the cells (rectangular shape).The cell sizes were assumed to vary from 0.25 Km to 2.5 Km in both directions (x-y). The calibration options within the GMS include steady state and transient calibration.

Transmissivity values ranged from 5 to 1500 m^2/d. The best results were obtained by using vertical conductance values in a range of 0.1 per day.

Based on several model scenarios, the total estimated sustainable yield of the Mountain Aquifer is approximately 50 Mcm/yr, if no new wells are constructed. This may increase to a maximum 70 Mcm/yr by adding new well field in diverse areas. The sustainable yield of the Mountain Aquifer.

Ben-Itzhak (2003) submitted a groundwater model entitled "Groundwater Flow Modeling in the Eastern Judea Group Aquifer". The objective of this research was to do a steady state model for Judea Group Aquifer to understand the Flow regime.

The version used in this research was GMS 3.1, which supportsMODFLOW96 developed by McDonald and Harbaugh in 1996.

The study area domain composed 79 rows and 47 columns. The total active cells was 15714 cells.

The best-fit solution was attained with horizontal hydraulic conductivity values of 500-550 m/yr and 40-260 m/yr in the upper and lower aquifers, respectively.

The study concluded that the sub-basins are nit completely separated, which means the structural partiers do not block the eastward flow everywhere throughout the area and overflow from one sub-basin to the other occurs at some locations.

Scarpa (2004) submitted a research entitled "Water Resources and the Sustainability of Towns and Villages in Bethlehem and Hebron Governorates". The purpose of the research was three-fold: to explain hydro- geological context of the water resources available in the study area, to identify and analyze the political and socio-economic processes that determine water management and use in the conflict situation and to analyze water management options within the political constrains of an occupied people.

The research showed that the management of water quality through conservation measures and the appropriate use of treated wastewater are important priorities.

Sabbah (2004) submitted a research as requirements for the degree of Doctor of Philosophy entitled “Development a GIS Hydrological Modeling Approach for Sustainable Water Resources Management In the West Bank-Palestine”. This research deals with setting up a GIS and hydrological modeling based approach sustainable water resources management in the West Bank of Palestine. This water sustainability approach took into consideration the water balance, the social, the economic, the demographic, the environmental, and the institutional components in order to enhance and promote the sustainable development in Palestine, both on the short and long runs.

1.6 Structure of the Thesis

The subject matter of the thesis is presented in five chapters. The first chapter entitled “Introduction” outlines background, problem, objectives, methodology, literature review, structure of thesis, and obstacles. The second chapter entitled “Conceptual Model” describes the study area, geology, structure, hydrology, surface catchment, hydraulic stresses, flow system. The third chapter entitled “Conceptual Approach” describes introduction about GMS, theoretical modeling background, numerical model, model approach, selection of simulation period, boundary determination, geometry of SESA, Discretization, model coverages, model layers, interpolation, 3D representation. The fourth chapter entitled “Model Results” explains model results, Presentation of Computed Water Levels in the Observation Wells, Presentation of Computed Discharges in the Springs, Error Summary, Sustainable Management, The interaction between the aquifers. The fifth chapter entitled "Conclusion and Recommendation" displays the conclusion and recommendation.

1.7 Obstacles of the Thesis

There are no enough available data about the wells and springs in PWA of the study area because these data are controlled by Israeli government.

Rainfall data was not suitable to built rainfall map for SESA, because of few rainfall stations within the study area. In addition these stations had lots of missing data during the simulation period (1990-1999). So, this study depends on average annual rainfall map adopted from PWA.

Preparing the structural, topographical, elevation contour lines for Upper and Lower Aquifer maps was difficult and took a lot of times because of unavailability of these maps in Data Bank at PWA.

Moreover, studying the approaches of GIS and GMS (MODEFLOW code) took enough times to construct the model.

Chapter Two

Conceptual Model

2.1 Introduction

The aim of the conceptual model is to define the requirements for a numerical model that is under steady state conditions. The groundwater system is defined by its hydrologic framework, aquifer, hydraulic parameters, inflows, discharges and boundary conditions.

2.2 The Study Area

The study area is situated in the south eastern part of the West Bank, and lies within the Eastern Basin, which is located east of the Mediterranean Sea, east of Hebron-Rammallah anticlinorium, (Figures 1 & 2). The length of the study area is 24.5km from south to north and 34.8 km from west to east. It has an area 584.6 km^2.

It lies within the following coordinates:

Latitude (Y0, Y1) 104,315-128,820m north (N), (Palestinian national grid).

Longitude (X0, X1) 157,735-192,564m east (E), (Palestinian national grid) (Figure 2).

It includes the Palestinian areas of Bethlehem and parts of Jerusalem and Hebron mountains area.

This area stretches the general surface water divide which passes along the axis of the Hebron and Ramallah anticlines in the west and to the longitudinal open boundary near the Jordan Valley and the Dead Sea in the East. The Northern and southern edges were determined as no flow boundary from the water contour maps for both Upper and Lower Aquifers.

The study area ranges in elevation from about 1000 m above sea level (asl) in the mountain areas in the west to 375 m below sea level in the Jordan Rift Valley in the East; which is the major structure in the area, over a distance of approximately 15Km. The prepared topographic map of the study area is shown in (Figure 3).

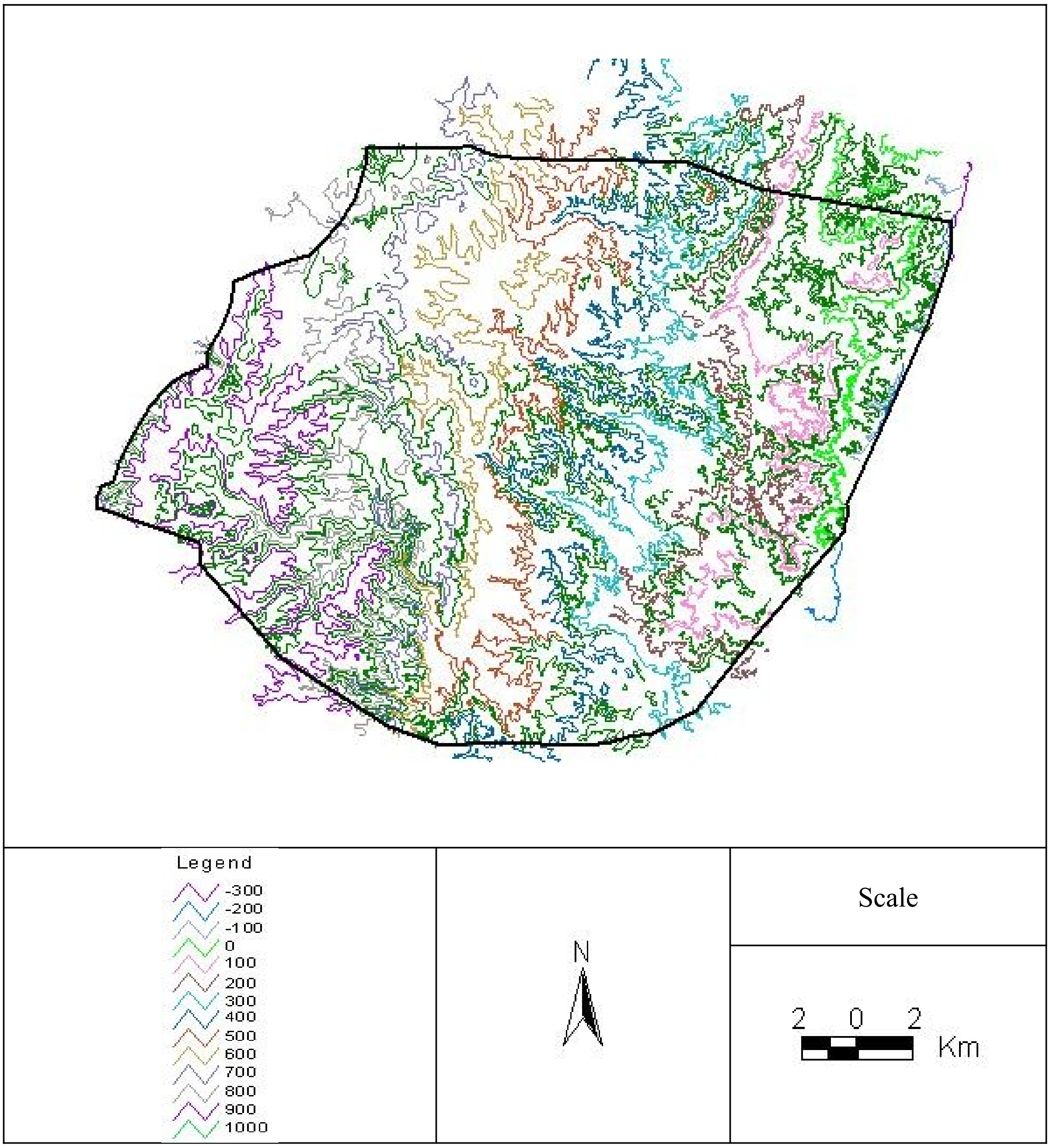


Figure 3: Topographic map of the study area

2.3 Geology

In general, the West Bank is divided into two main topographic units: a hilly region in the western and Jordan Rift valley in the eastern parts (Ghanem, 1999). The study area is also divided into three physiographic regions from west to east: the mountain regions, the hills of the eastern slopes, and the Jordan Rift. The study area is located within the mountain regions.

2.3.1 Stratigraphy

The general description of the stratigraphic features of the various geological formations of the Eastern Basin are shown in (Table 1). The stratigraphical units are based on geological time sequence and physical properties, such as lithology (stage classification).

The stratigraphic profile exposed in the research area and vicinity has been studied according to (Guttman and Zukerman (1995), Guttman (1998), CH_2MHILL (2001), Ben-Itzhak (2003), and Sabbah (2004)) as follows:

- Senonian Formation

"The Senonian sediments (Abu Dis formation) are composed of massive chalk, hard and bedded in its lower part and fragmented, soft and un-bedded in its upper part. Its thickness ranging from 200 to 450m (CH_2MHILL, 2001) .This formation is considered as aquiclud.

- Turonian Formation

It is the youngest formation of the Mountain Aquifer System. The Turonian rocks of the Jerusalem formation underlie the Abu Dis formation. Its thickness ranges between 70 to 130 m and consists of alternating well-bedded limestone, chalky limestone and some marl. Hyrogeologically, this formation can be considered as good aquifer(CH_2MHILL, 2001).

- Upper Cenomanian Formation

The Upper Cenomanian rocks of the Bethlehem and Hebron formations underlie the Jerusalem formation. The Bethlehem formation consists of dolomite, limestone, marly chalk, and chalky limestone. The thickness of this formation is between 30 and 115m.

The Hebron formation represents the bottom of the Upper Aquifer. It consists mainly of limestone, which is dolomitic and calcitic. The Hebron formation has a thickness of 105 to 260 m and its rocks are characterized by karsitification and strong jointing that make it an excellent aquifer (CH_2MHILL, 2001).

The Hebron, Bethlehem, and Jerusalem Formations are usually considered, from hydrogeological point of view, as a single system of aquifers bounded below Yatta Aquitard and Cenomanian-Turonian Aquifer. This aquifer represents the upper aquifer of the study area (Rofe and Raffety, 1967).

- Lower Cenomanian Formation

The Lower Cenomanian rocks of three formations: Yatta, Upper Beit Kahil, and Lower Beit Kahil. The Yatta formation consists of chalky limestone, dolomite, chert, marl and calcareous karstic limestone. The thickness of this formation ranges between 70 and 155 m. This formation is considered hydro-stratigraphically as an aquitard that separates the underlying Albian Aquifer from overly Cenomanian-Turonian Aquifer.

The Upper Beit Kahil formation consists of limestone and dolomite with marl and some chert. The thickness of this formation ranges between 160 and 190 m.

The Lower Beit Kahil formation consists of alternating of limestone and dolomite with some limited quartzite. The thickness of this formation ranges between 110 and 210 m (CH_2MHILL, 2001).

- Albian Formation

The Albian rocks are composed of alternating marls, marly limestones, shale, and clay (Qatana, Ein Qinya, and Tammun formations). The upper 40 to 50m consist of the impervious bituminous dark green to gray marls and clay of the Qatana formation. The middle 70 to 100m consists of the marls and marly limestone of the Ein Qinya formation. The lower 50 to 90m consists of the clay and marl of the Tammum formations.

A 300m thick sequence of shale and clay interlaid with marl and thin beds of limestone underlies the lower Beit Kahil and acts as an aquitard separating the Lower Aquifer from the Ramli Aquifer (CH_2MHILL, 2001). This layer is considered as the base layer in the model.

To the east of the Lower Cretaceous layers and to the east of the Hebron anticlineaxis, the layers of the Mountain Aquifer System, which make up the regional aquifer in the area are exposed (Guttmann and Zukerman, 1995).

2.3.2 Structure

In the Eastern Basin, the anticlines and synclines are asymmetric, where the east flank of the anticlines is the flank with the sharp tendencies. In the synclines, the western flank is one with the sharper tendencies.

The area is characterized by intensive faults systems in a general east to west (E-W) direction as shown in (Figure 4). The dominant structures in the area are of two types: folds and fractures, with each of the structure types related to a different stress field (Eyal and Reches, 1983 in Ben-Itzhak, 2003). The folds are the product of the Syrian Arc stress field, with dominating maximum horizontal compression trending west (W) to north western (NW), while most of the fractures are related to the dead Sea stress field, with dominating horizontal extension trending east (E) to north eastern (NE) (Ben-Itzhak, 2003).

- Folds

The folds are characterized by a series of asymmetric anticlines and synclines with axes plunging on average to the NE. The two main structures of this type are Hebron and Ramallah anticlinoriums. The Hebron anticlinal axis extends from Hebron-Halhul area to Jerusalem and plunges to the NE. The distance between Ramallah anticline southern tip in the west and Hebron anticline northern tip in the east is 15 Km. Both are composed of a series of smaller anticlines, in which the southeastern flanks are more steeply inclined than the northwestern flanks. The larger among those anticlines are: Bani-Naim, Mar-Saba, Maon and Hatzron, and respectively between them are the synclines: Beit Sahour (Herodion), Han-El- Ahmar, Jericho and Um-Darag (NE) (Roth, 1969; Fink, 1973 in Ben-Itzhak, 2003).

- Fractures

The main fracture structure in the area is the western dislocation/translation of the Graben of the Dead Sea and the Jordan Valley. This translation stretches along the western shore of the Dead Sea to the city of Jericho and directed north-south (Guttmann and Zukerman, 1995).

The Dead Sea basin is the largest fracture-related structure in the area. It was formed as a “pull-apart” within the Dead Sea Rift System (Garfunkel and Ben-Avraham, 1996). It is bounded to its north and south by two major strike-slip faults (Jericho and Arava faults) and along its margins is a belt of sub-parallel normal faults. The western of these faults are the dominant morphological feature in the study area, creating a steep cliff, against the Dead Sea Shore (Ben-Itzhak, 2003).

Table (1): Generalized stratigraphic section of the West Bank

System	Stage	Typical Lithology	Formation WB Terminology	Hydro-stratigraphy		Thickness (m)
Neogene	Holocene	Nari (surface crust) and alluvium Gravels and fan deposits	Recent	Valley Aquifer		0-100
	Pleistocene	Thinly laminated marl with gypsum bans and poorly sorted gravel and pebbles	Lisan	Aquitard		Unknown
	Pliocene and Miocene	Conglomerates	Beida	Beida Aquifer		200
Palaeogene	Paleocene-M.Eocene	Reef limestone Nummulitic limestone (Bedded massive) Limestone with chalk Chalk with nummulitic limestone	Jenin Subseries	Jenin Aquifer		300-600
Cretaceous	Senonian	Chalk and chert, undifferentiated, with baselt conglomerate in parts	Abu Dis	Aquitard		200-450
	Turonian	Limestone and dolomite, karstic	Jerusalem	Upper Aquifer	Mountain Aquifer System	40-120
		Limestone, dolomite and marly limestone, karstic				5-30
	Upper Cenomanian	Limestone, marly limestone, chalky limestone and dolomitic limestone	Bethlehem			30-115
		Karstic limestone and dolomite	Hebron			105-260
	Lower Cenomanian	Marl, clay and marly limestone	Yatta	Aquitard		50-150
		Limestone, chalky limestone and dolomite				
		Limestone interbedded with marl	Upper Beit Kahil	Lower Aquifer		10-40
		Dolomite interbedded with marl				50-150
		Limestone, dolomitic	Lower Beit Kahil			10-50
		Limestone, dolomitic and marly limestone				100-160
	Albian	Marl and clay	Qatana	Aquitard		40-60
		Marls and marly limestone	Ein Qinya			70-100
		Clay and marl	Tammun			50-90
	Neocomian	Sandstone	Ramali	Ramali Aquifer		50-250
Jurassic	Callovian Bajocian	Marls interbedded with chalky limestone	Upper Malih	Aquitard		100-200
		Dolomitic limestone, jointed and karstic	Lower Malih	Lower Malih Aquifer		50-100

(Modified after Rofe and Raffety)

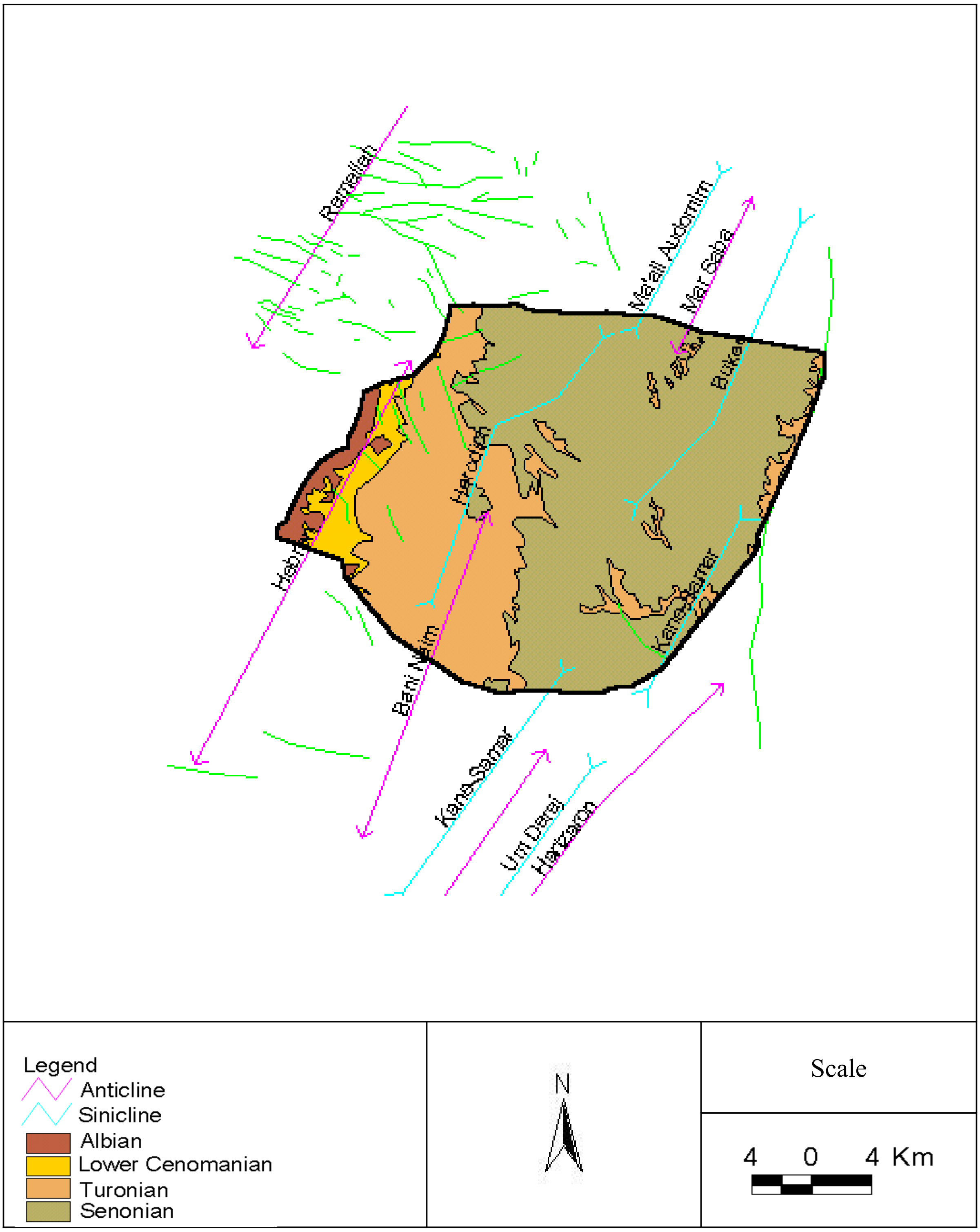


Figure 4: Structural and geological map of the study area

(Geological map adopted from PWA Data Bank)

2.4 Hydrology

2.4.1 Rainfall

The West Bank has a mediterranean type climate. The wet season stretches from October to May and has usually less than 50 wet days (Rofe and Raffety, 1963). Rainfall is the source of the groundwater recourses in the West Bank. Part of this rainfall infiltrates to the subsurface and recharges aquifers.

The area is characterized by sharp fluctuations in precipitation. On the high mountains in the west, the average rainfall ranges from 500 to 700 mm/yr. Towards the east and southeast there is a sharp drop in precipitation over a relatively short distance. The steep gradient of the Jordan Valley produces an effect which reduces the quantity of the rainfall, so the average rainfall ranges from 100 to 150mm/yr. Rainfall decreases to less than 100mm/yr on the Dead Sea shores (CDM/Morganti, 1997), (Figure 5).

There are three rain gauge stations in SESA, distributed in different schools and monitored by the school employee. The rainfall stations with the necessary information concerning location specified by X, Y, and Z coordinates, the name, and place of installation are listed in (Table 2).

An annual rainfall map which available for longer period (30 yr) in the West Bank and adopted from PWA was used in this research because there were no completion data of rainfall records. In addition, the rainfall stations located in a small geographical area in the western part of the study area are not enough to build a rainfall map.

2.4.2 Evapotranspiration

The annual evapotranspiration potential in the West Bank exceeds the mean annual rainfall, ranging from 2,300 mm at the Dead Sea to about 1,900 mm in the Mountain Aquifer (Metrological Service in Palestine). Surface runoff and groundwater recharge therefore depend on factors such as rainfall intensity, duration, and surface characteristics of catchment areas.

2.4.3 Temperature

In the West Bank, the average temperature in summer times varies between 20 – 23ºC, with a maximum of 43 ºC (Metrological Service in Palestine). The average temperature in winter is 10 – 11 ºC, recharging a minimum of about -3 ºC. Wind direction is predominantly from the west and northwest (CDM/Morganti, 1997).

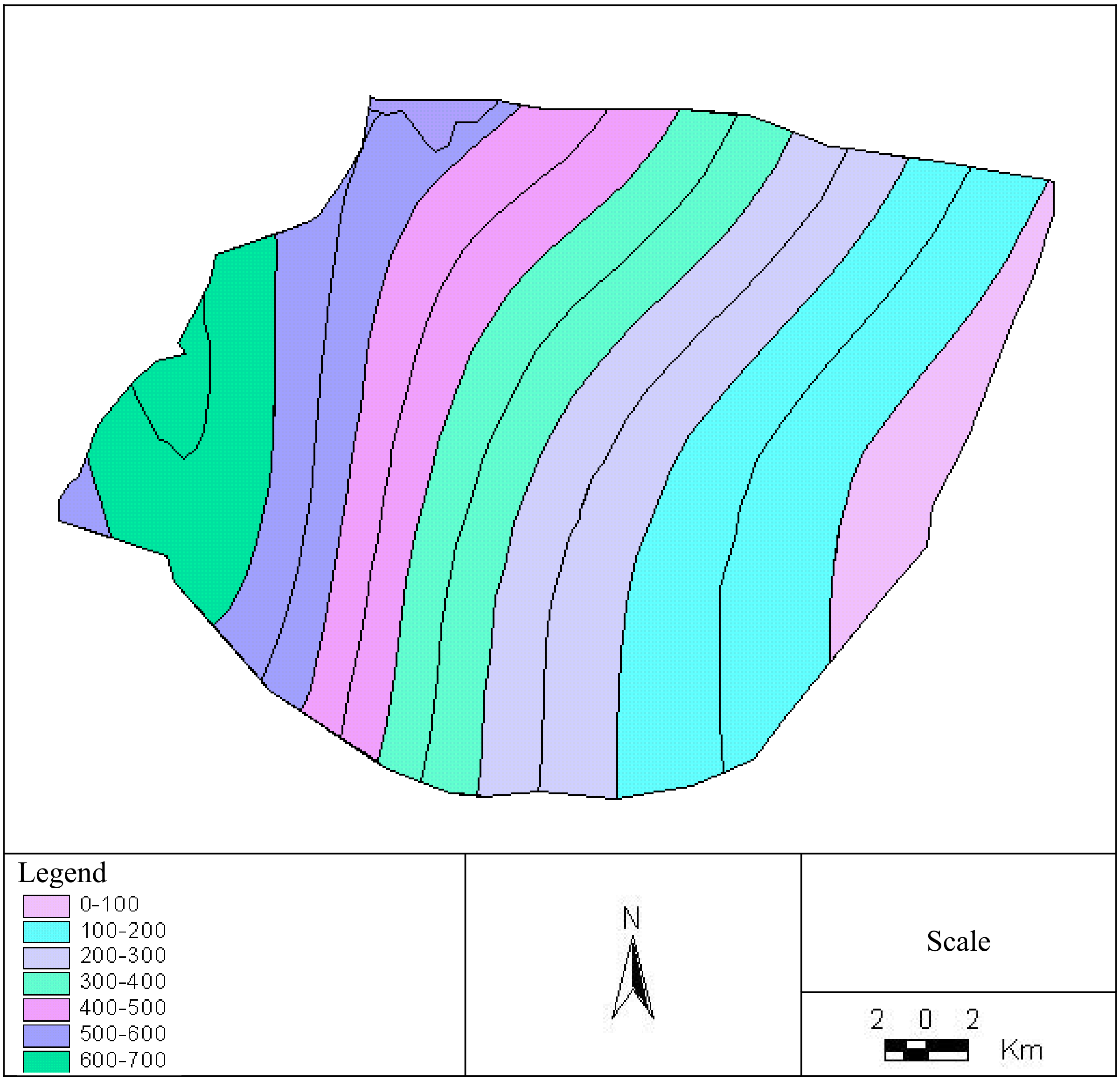


Figure 6: Average rainfall map of the study area (1970-2000)

(Adopted from PWA Data Bank)

Table 2: Summary data for rain stations in the study area

Name	X Km	Y Km	90 mm	91 mm	92 mm	93 mm	94 mm	95 mm	96 mm	97 mm	98 mm	99 mm	Ave mm
Bethlehem Primary School	169.8	123.7	490	845	565	450	560	No data	503	178	No data	442	504
Beit Jala Primary School	168.0	125.0	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	825
Al’Arrub Station	162.7	115.7	486	1178	761	No data	644	644	606	261	No data	558	642

(Adopted from PWA Data Bank)

2.5 Surface Catchment

The study area faces Nar, Daraja, and parts of Hasasa, Ghar, Qumran, and Mukallak sub-catchments according to surface drainage classification catchments, the descriptive properties of these catchment areas that define its geology, hydrology, and hydrogeology are considered as prerequisites before embarking on the recharge study (Figure 6).

The catchments over the recharge and discharge areas of the SESA are shown in (Figure 6). It can be noted that wadis are almost uniformly distributed over the recharge areas. This leads to the assumption that the recharge volume from the wadis can be considered as a percentage from rainfall and this total recharge volume can be divided according to the area of each recharge/rainfall zone.

Outcropping surface areas of the Upper and Lower Aquifers, Senonian and Yatta Formations were calculated as shown in (Table 3), (Figure 4).

Table 3: Outcrop area of aquifers and aquitards

Aquifer	Outcrops in Km^2	Aquitard	Outcrops in Km^2
Upper Aquifer	183	Senonian	360
Lower Aquifer	15	Yatta	26

The Upper Aquifer represents 31.5% of the total surface area, Lower Aquifer represents 2.5% of total area, while Senonian and Lower Cenomanian Formations represents 66% of the total area, (Table 3). These two formations do not infiltrate the rainfall.

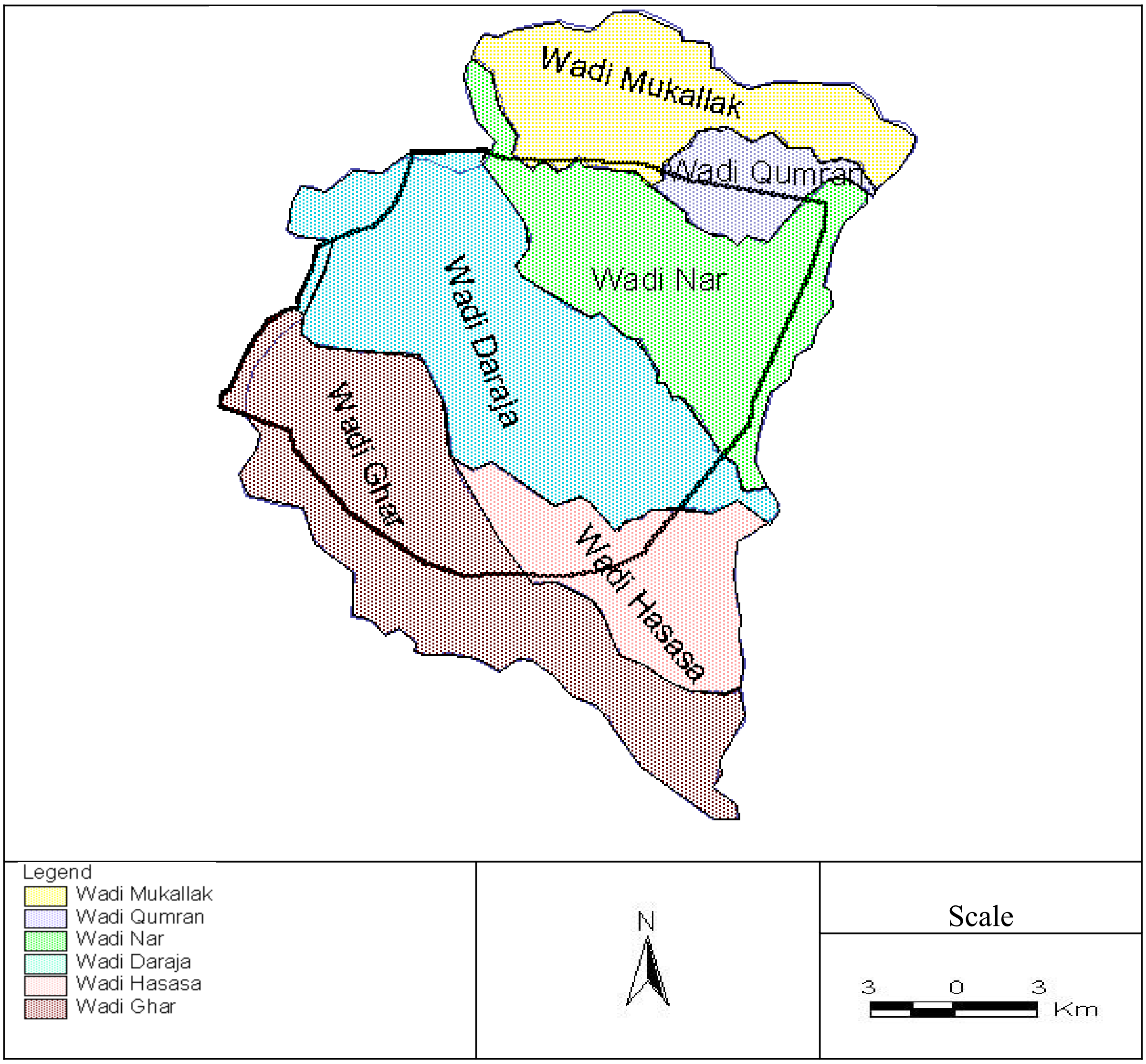


Figure 6: Catchments area which locate within the study area

2.6 Hydraulic Stresses

Hydraulic stresses, which are applied in this model, include recharge from rainfall and discharge from springs and pumping wells.

2.6.1 Recharge

The two major fresh aquifers in the Eastern Basin are Upper and Lower Cenomanian Aquifers. These are separated by the "Middle Aquitard" Yatta formation.

Areas of limestone outcrops along the Hebron anticline (the boundary between the Western and Eastern Aquifer Systems in the Hebron-Bethlehem area) are the main recharge locations for the Upper and Lower Cenomanian Aquifers. Accurate estimates of recharge quantities are not available because of few studies in this field. Recharge from rainfall in semi-arid regions is expected to have the range from less than 5 to 20 percent of rainfall (CDM/Morganti, 1997). In this study, the recharge is ranging from 15 to 39 percent of rainfall according to the estimation for SESA by TAHAL's equations (eq. (1), (2), & (3)) (Figure 13).

Recharge estimation is a prerequisite for the determination of sustainable yield of the various Palestinian aquifer basins. Palestine Recharge is low and variable in magnitude over place and time (Asbah S., 2004). Recharge estimations are considerably affected by the climatic properties of the area; rainfall, runoff, and evaporation quantities (Guttmann, 1995). The variation phenomena of rainfall quantities in Palestine over the years produce varying recharge value. Study of recharge on annual averaging of rainfall data on semi annual basis and especially in Eastern Basin was done by TAHALs in 1995. They considered that the amount of recharge to the aquifer is a function of the amount of rainfall. The recharge equations which were obtained and used for calibrating the steady state model were divided into three equations as follows:

Recharge equation for rainfall greater than 650 mm

$R = 0.8 * (Pi – 360)$……………………….…………………………………....eq (1)

Recharge equation for rainfall in the rage 300-360 mm

$R = 0.534 * (Pi – 216)$……………………………..…………………………eq (2)

Recharge equation for rainfall less than 300 mm

$R = 0.15 * Pi$…………………………………………………...…….……..eq (3)

Where,
R = recharge from rainfall in mm, Pi = rainfall in the cell, in mm. Equations (1), (2) and (3) are established by TAHALs and adopted from Guttmann and Zukerman report (1995).

The long term average rainfall, which adopted from PWA, was used to refine the outcrop polygons into smaller sub-polygons. Each sub-polygon has a unique value of rainfall which then substitute in one of the suitable of previous equations to get value represents the recharge.

The recharge volume for both Upper and Lower Aquifers were estimated for SESA and tabulated, (Table 4). Then, recharge values were inserted in steady state model as input data.

Table 4: Conceptual Recharge

Aquifer	Inflow (Recharge) in Mcm/yr
Upper Aquifer	23.5
Lower Aquifer	3.3
Total	26.8

The estimated recharge volume of Upper Aquifer was approximately 23.5 Mcm/yr, while the recharge volume from Lower Aquifer was about 3.3 Mcm/yr. The total recharge volume was 26.8 Mcm/yr.

2.6.2 Well abstraction

The Upper Cenomanian Aquifer is an important regional source of drinking water in the study area. There are Israelis and Palestinian wells in the study area. It was very difficult to get the completion data of the wells which control by Israelis. So, the data was adopted from the PWA, (Table 5), (Figure 7).

Most of the abstraction wells are located a long north- south line to the west of the study area in a small geographical area (Figure 8). Six wells tap the upper aquifer and nine wells tap the lower aquifer. Five of these wells were drilled in the study area after 1999, which tap the upper and lower aquifers.

Two production wells in the Herodian well field currently abstract high-quality water from Upper Aquifer for domestic use: Beit Fajjar 1A and Herodian 5.

For the period 1990-1999, the total average abstraction from the study area was 12.3MCM of which 3.52 MCM/yr (28.5% of total wells abstraction) and 8.8 MCM/yr (71.5% of total wells abstraction) are extracted from the Upper and Lower Aquifers, respectively.

Wells are simulated as extraction nodes where discharge is assigned a negative sign.

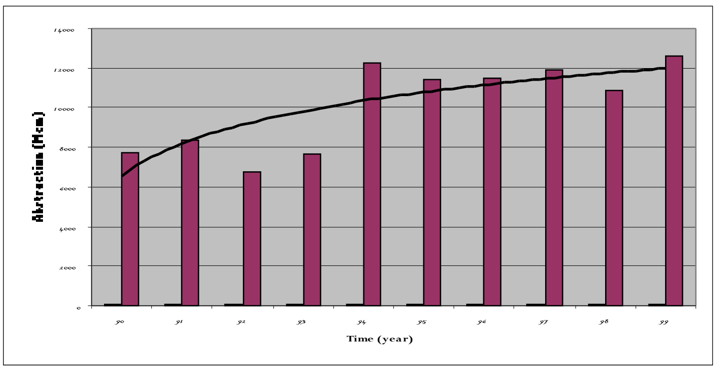


Figure 7: Well abstraction of the study area (1990-1999)

Table 5

Table of Wells from Excel Sheet

2.6.3 Spring discharge

Several springs from Eastern Aquifer System provides relatively small quantities of water in the study area. Water from these springs are mostly used for agricultural use.

There are seven springs in the study area shown in (Table 6).Most of these springs are located at the west southern of the study area, (Figure 8). The springs totally discharge 426135.8 m^3/yr (0.43 MCM/yr) during the study period (1990-1999). Most of the springs discharge from the upper aquifer and the Turonian aquifer (Guttmann, 1997). Most of the springs, except for the Dead Sea springs, drain upper natural replenishment zones of varying sizes, depending on the discharge (Guttmann, 1998).

Barradah spring which discharges from Lower Cenomanian and Deer Al Bus spring discharges from Upper Cenomanian both dried since 1999. In the recent years, there are draw down in water level in the aquifers which influenced by the increased of wells abstraction and less in precipitation. Most of the springs in the Eastern Basin (with the exception of the Jericho springs) are influenced to a great degree by changes in precipitation (Guttman, 1998).

The largest spring in Bethlehem District is the Irtas spring with an average annual discharge rate that ranges from 0.03 to 0.75 MCM/year (CDM/Morganti, 1997). This spring is emerging from Upper Cenomanian Aquifer with maximum long term average discharge of 0.33 MCM/year.

Springs are simulated as discharge nodes where discharge is assigned a negative sign.

Table 6

Table of Springs from Excel Sheet

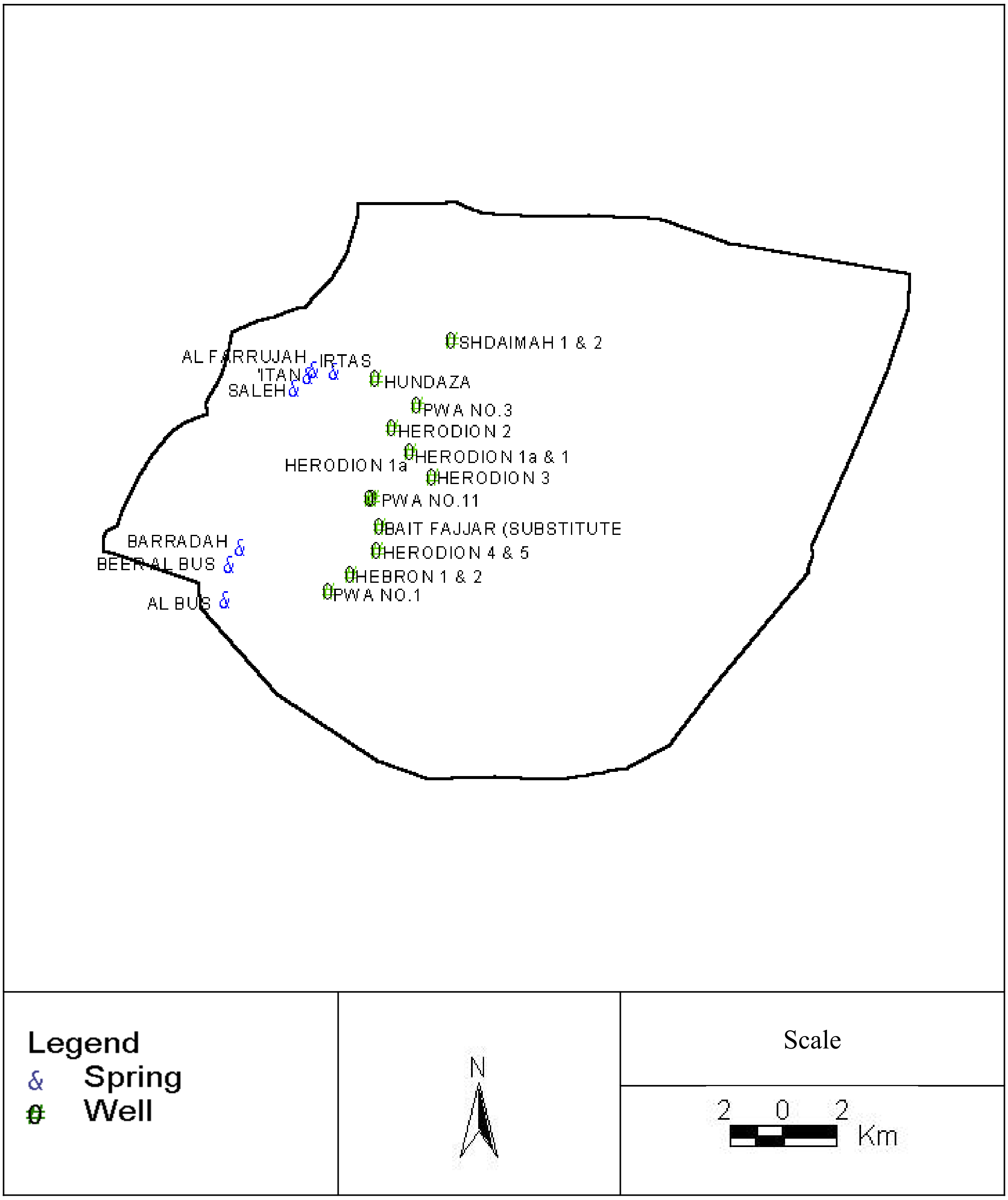


Figure 8: Distribution of wells and springs in the study area

Chapter Three

Conceptual Approach

3.1 Introduction

GMS (Groundwater Modeling System) is one of the most popular and sophisticated groundwater modeling environments available today. It is a comprehensive system, which provides tools for every phase of groundwater simulation including site characterization, model development, post processing, calibration, and visualization. GMS supports different database types and functions including: TINs, grids, meshes, borehole data, 2D and 3D. MODFLOW is one of the various codes supported by the interface (GMS web site). The version used in this study is GMS 3.1, which supports MODFLOW96 of the U.S. Geological Survey, by McDonald and Harbaugh, 1996).

MODFLOW is the most widely-used 3D groundwater flow model in the world. MODFLOW can represent the effects of wells, drains, and recharge on flow systems with heterogeneous aquifer properties and complex boundary conditions to simulate groundwater flow. Using GMS, the user can select a single cell or a series of cells and then define the hydrogeologic characteristics and/or boundary conditions using interactive dialog boxes. In addition, a spread sheet dialog can be displayed allowing the user to edit the values for each individual hydrogeologic characteristic for the entire model. Input data may be imported or interpolated from a sparse set of scattered data points. All popular packages are supported including the Horizontal Flow Barrier package and the Stream/Aquifer Interaction package. GMS reads and writes native MODFLOW files. The MODFLOW model is also included.

3.2 Theoretical Modeling Background

3.2.1 Darcy's Law

The steady state flow of fluid through a porous medium governed by physical processes which are expressed mathematically by two fundamental equations.

- Darcy's Law, which expresses the relationship between the motive force applied to the fluid and the resulting discharge of fluid through the pipe or the system.
- $q = -K\nabla h$

Where

q is Darcy's velocity or volumetric flow rate per unit surface area (L/T^2); K is the hydraulic conductivity which is dependent on both medium and fluid properties (L/T); ∇h is the change of hydraulic head with the distance in the direction of flow (L).

- The continuity equation, which expresses the conservation of fluid mass within the system

The three dimensional equations of groundwater flow are developed under the assumptions that the groundwater density is homogeneous, and that the coordinate axes are aligned with the principal directions of hydraulic conductivity (Riley, 2000):

$$\frac{\delta \rho n}{\delta t} = -\rho\left(\frac{\delta q_x}{\delta_x} + \frac{\delta q_y}{\delta_y} + \frac{\delta q_z}{\delta_z}\right) \text{ ....eq}$$

(1)

Assuming in addition that the coordinates axes are aligned with the principal directions of hydraulic conductivity, Darcy's law is:

$$q_x = -K_x\frac{\delta h}{\delta x},\ q_y = -K_y\frac{\delta h}{\delta y},\ \text{and}\ q_z = -K_z\frac{\delta h}{\delta z} \text{ .... eq}$$

(2)

Substituting the values of specific discharge from Darcy's law into eq (2) gives

$$\frac{\delta(\rho n)}{\delta t} = \frac{\delta}{\delta x}\ \rho K_x \frac{\delta h}{\delta x} + \frac{\delta}{\delta y}\ \rho K_y \frac{\delta h}{\delta y} + \frac{\delta}{\delta z}\ \rho K_z \frac{\delta h}{\delta z} \quad \text{.................................. eq (3)}$$

This equation describes flow through an anisotropic saturated porous medium. For a system in steady state, there is no change in head with time. Under such conditions, time is not one of the independent variables so the left-hand side of eq (3) is zero.

$$0 = \frac{\delta}{\delta x}\ \rho K_x \frac{\delta h}{\delta x} + \frac{\delta}{\delta y}\ \rho K_y \frac{\delta h}{\delta y} + \frac{\delta}{\delta z}\ \rho K_z \frac{\delta h}{\delta z} \quad \text{.. eq (4)}$$

For an incompressible fluid in a homogeneous isotropic medium eq (4) becomes Laplace's equation:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0 \quad \text{.. eq (5)}$$

3.2.2 Boundary Conditions

In order to solve the groundwater flow equations one should be able to specify the boundary conditions. There are several basic types of boundary conditions:

1. If the head is known at the boundary of the flow region, this is known as a Dirchlet condition. Specified head for which h(x,y,z)=const or $h(x,y,z,t)=f_1$.

2. If the flux across a boundary to the flow region is known, this is a Neumann condition specified flux, for which the flux normal to the boundary Qn is a Known function f_2, ($Q_n=f_2$), or for an isotropic medium $\frac{\delta h}{\delta n}=f_3$, where $\frac{\delta h}{\delta n}$ is the head gradient in the outward direction normal to the boundary and f_3 is a known function).

3. In some cases, the boundary conditions will be mixed with some portions having known head and some portions having known flux, this type is known as Cauchy type which is a combination of the former two is expressed as $\frac{\delta h}{\delta n}$ $+\beta h = f_4;\ \beta \geq 0$.
4. A phretic surface boundary condition. The shape and location of the free surface are unknown and their determination is part of the required solution. The pressure on all points of this surface is equal zero (BenItzhak, 2003).

3.3 Numerical Model

Development of the groundwater flow equation in finite-difference form follows from the application of the continuity equation: the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Under the assumption that the density of groundwater is constant, the continuity equation expressing the balance of flow for a cell is

$\sum Q_i = SS\,\Delta h\ \Delta V$ ……………………………………………………………eq (6)

Where, Qi is a flow rate into the cell (L^3t^{-1}); SS has been introduced as the notation for specific storage in the finite-difference formulation, it is the volume of water which can be injected per unit volume of aquifer material per unit change in head (L^{-1}); ΔV is the volume of the cell (L^3); and Δh is the change in head over a time interval of length Δt.

The term on the right hand side is equivalent to the volume of water taken into storage over a time interval Δt given a change in the head Δh.

Inflow and storage gain in terms are stated in equation (6). Outflow and loss are represented by defining outflow as negative inflow and loss as negative gain (McDonald and Harbaugh, 1988).

A cell i,j,k and six adjacent aquifer cells i-1,j,k; i+1,j,k; i,j-1,k; i,j+1,k; i,j,k-1; and i,j,k+1 are depicted in (figure11). To simplify the following development, flows are considered positive if they are entering cell i,j,k; and negative sign usually incorporated in Darcy's law has been dropped from all terms. Following these conventions, flow into cell i,j,k in the row direction from cell i,j-1,k (Figure 11), is given by Darcy's law as

$$q_{i,j-1/2,k} = \quad KR_{i,j-1/2,K} \Delta C_I \ \Delta V_K \frac{h_{i,j\ \ 1,k} \quad h_{i,j,k}}{\Delta r_{j\ \ 1/2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq$$

(7)

Where, $h_{i,j,k}$ is the head at node i,j,k, and $h_{i-1,j,k}$ that at node i-1,j,k; $q_{i,j-1/2,k}$ is the volumetric fluid discharge through the face between cells i,j,k and i-1,j,k (L^3t^{-1}); $KR_{i,j-1/2,k}$ is the hydraulic conductivity along the row between nodes i,j,k and i-1,j,k (Lt^{-1}); $\Delta C_I \ \Delta V_K$ is the area of the cell faces normal to the row direction; and Δr j-1/2 is the distance between nodes i,j,k and i-1,j,k (L). The discussion is phrased in terms of flow into the central cell (McDonald and Harbaugh, 1988).

A similar expression can be written for the other five neighboring cells of cell i,j,k and with the addition of sources and sinks ($W_{i,j,k}$), should all be balanced with the change of the water mass in this cell with time. In a steady state simulation, the change with time equals zero. When the simulation, the change with time equals zero.

Cell i, j-i, k Cell i, j, k

`

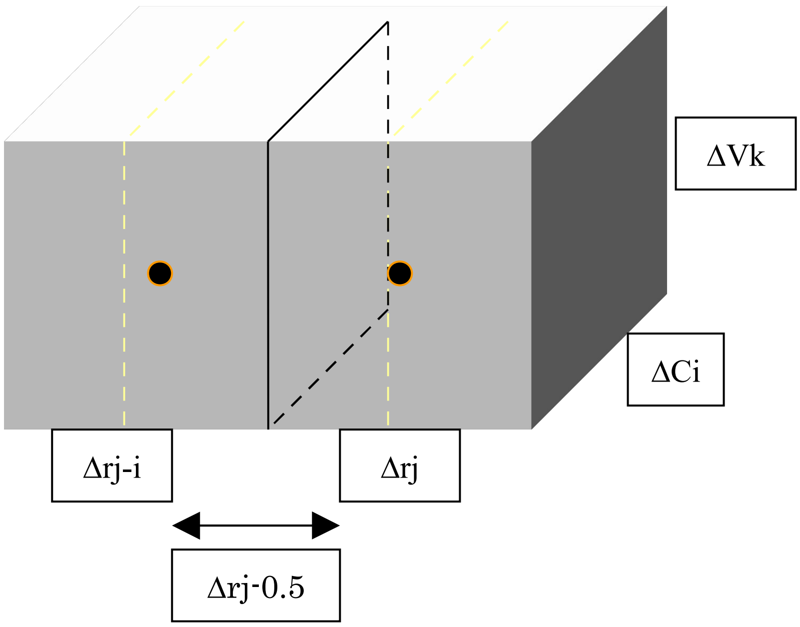


Figure 9: Flow into cell i,j,k from cell i,j-1,k, (from McDonald and Harbaugh, 1988)

3.4 Model Approach

The conceptual model deals mainly with the layers representing the aquifer geology, the lateral extent of the region to be modeled, the boundary conditions, the sources and sinks, the head and flow observations, etc (Sabbah, 2004)

3.4.1 Selection of Simulation Period

It is very important to analyze the groundwater system of the study area in order to enhance the understanding of the water budget. The period 1990 to 1999 was chosen for the stressed steady state analysis because this period comes between an extremely rainy year 1991/1990 and a period of draught years from 1996 and towards.

Moreover, there are enough data to build the steady state model during the section period (1990-1999).

3.4.2 Boundary Determination

The horizontal boundaries of the study area for Upper and Lower Aquifers are shown in (Figure 10). The horizontal boundaries (western, northern and southern boundaries) of the study area are all of the no-flow boundary type which the specified flux equals zero.

3.4.2.1 The Western Boundary

The western boundary is a no-flow boundary corresponding to surface water divide which is the highest crest of the fold structure in the Jerusalem-Hebron mountain series.

3.4.2.2 The Northern and Southern Boundaries

The northern and southern boundaries defined as no-flow boundary. Adjacent flow lines will be parallel to the no-flow boundary, and equipotential lines will intersect water table lines at right angles (Todd D., 1993).

Water level lines of the Lower Aquifer of the eastern basin were taken from Guttman and Zukerman Model (1995) then the equipotential lines were drawn to determine the southern and northern boundaries of the study area, appendix (Figure A3). In the same way, the northern and southern boundaries of Upper Aquifer of the study area were determined after the figure of water levels of the upper eastern basin was taken from Palestinian Water Authority (PWA), appendix (Figure A4). But, small part at the southeastern part in the study area could not to be determined as no-flow boundary because this part does not intersect the water level at right angles. So, this small part is considered as flow boundary.

Two boundaries of the Upper and Lower Aquifers were determined because of the difference of water levels between the two aquifers, (Figure 10).

3.4.2.3 The Eastern Boundary

Determining an appropriate eastern boundary condition of this study area was difficult because of absent of a known discharge in the study area such as a main spring with known elevation to use it as outflows from study area plus to help in regulate the contour lines in calibration process. Unfortunately, Dead Sea Springs are located at great distance from the interest site.

So, the regional model of the eastern Basin was deeply studied and water level lines were adopted again from PWA (2000) and Guttmann and Zukerman (1995) for the Upper and Lower Aquifers, respectively Appendix (Figures A3 & A4). Then the local scale model of the study area is constructed which occupies a small area within the regional model. The smallest value of water level lines for both Upper and Lower Aquifers within the model area is applied as the specified head. So, this eastern boundary is represented the main discharge areas. Discharge occurs along the eastern boundary.

3.4.3 Geometry of SESA

Getting the accurate geometry of the study area represented by the top and bottom of the model layers was the most difficult and challenging effort required to complete the model set up. With presence well logs, boreholes, cross sections, geological and structural maps, regional, and geophysics maps for the Mountain Aquifer were used to extract the geometry of the study area. These maps were geo-referenced, digitized, and then converted to draw its lines by using AutoCAD software. Then, these maps were converted from AutoCAD dxf. Format to GIS to converted theses lines into xyz data points. After getting the elevations of the tops and bottoms of the Upper and Lower aquifers, and the Yatta formations, placing were made for the topographic map to get the Abu Dis Layer which placing on the top of the Upper aquifer and determine the correct top elevations of the Upper, Yatta Formation, and Lower outcropping. Finally, the base layer with thickness 200 m which is considered as aquitard.

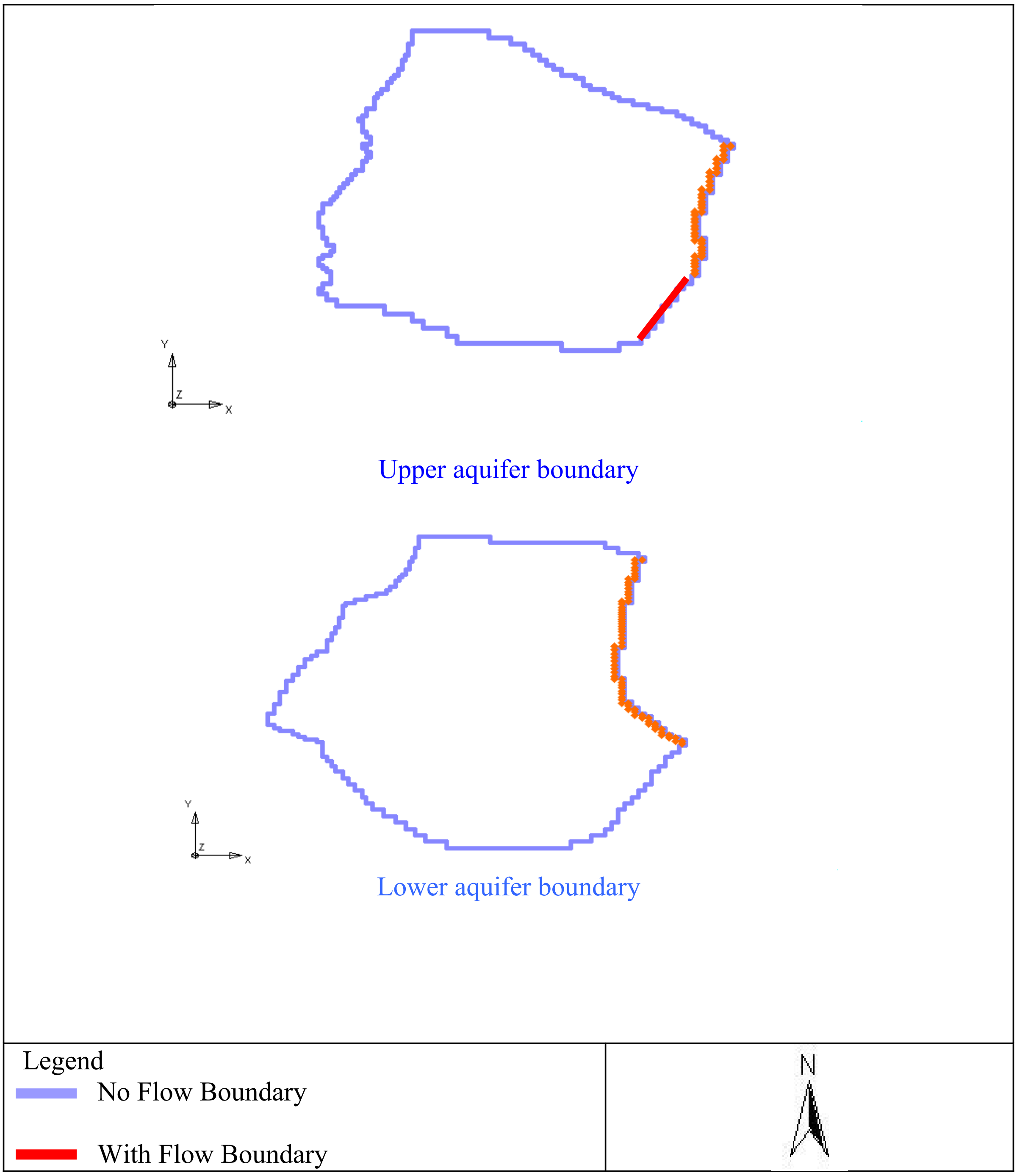


Figure 10: Proposed boundary of Upper and Lower aquifers of the study area

3.4.4 Discretization

A base map was drawn representing SESA, its boundaries, positions of the wells and springs. The external geometry of the system is defined by the configuration of its natural boundaries. The geometry is lying within Xmin=157,000m, Xmax= 193,000m, Ymin= 104,000m, and Ymax= 129,000m of Palestinian Grid.

GMS is used to build the conceptual model. A grid is constructed to fit this conceptual model. Once the conceptual model has been defined, GMS will construct a grid, automatically refined around the wells with the cells outside the model boundary already inactivated. The defined modeling data is then superimposed onto the grid with the appropriate parameters. The constructed finite difference grid in the model area is composed of 85 rows and 104 columns. The rows and columns dimensions vary from 250 to 500 m in the layer itself, (Figures 11). The width of the smallest rows was 250 m and width of the smallest columns was 250m. The biggest size of the cell was 500*500 m^2.

3.4.5 Model Coverages

This model consists of six coverages as follows:

- Sources and Sinks

The first coverage represents Sources and Sinks. This coverage is defined as MODF/MT3D local sources/sinks type. In this coverage, the type of the boundary (no-flow boundary, specified head, general head, variable head…etc.), wells abstractions (total was 12.5 Mcm/yr, the amount includes: 3.3 Mcm/yr from the Upper Aquifer and 8.8 from the Lower Aquifer), springs discharges (total average discharge was 0.43 Mcm/yr) is defined from which layer is assigned. All units in m^3 per day.

Distribution of Sources and Sinks which are located within the SESA are shown in (figure 12).

- Hydraulic Conductivity

The second, third , and fourth coverages (represents upper aquifer, aquitard, and lower aquifer, respectively) are defined as MODF/MT 3D/MOD P layer attributes type by using True Layer (Explicit definition) method. This method can be used for both steady state and transient model. The unit of this coverage is m per day. Each coverage of upper, lower aquifers, and Yatta formation was divided for number of zones for each coverage separately. Each cell in these zones was given values for horizontal and vertical hydraulic conductivities. These values were changed in calibration process. Each cell

An anisotropy ratio of 10 was used between horizontal and vertical conductivities.

- Recharge Coverage

The fifth coverage represents Recharge. This coverage is defined as MODF/MT 3D areal attributes type. The unit of this coverage is m per day. The groundwater recharge coverage of SESA was created based on the estimated recharge from the rainfall using TAHALs equations because of the simulation of aquifer properties in the study area.

The recharge area coverage with the distribution of recharge zones which are used in this model are shown in (Figure 13). The outcropping areas for Upper and Lower Aquifers of the study area were drawn as zones. Each zone is given the estimated recharge according to TAHA'Ls equations. The recharge from Abu Dis and Yatta Formations is considered zero.

- Observation coverage

Finally, the last coverage represents the observation coverage. This coverage, is defined as observation types, which include 24 scattered observation wells covers the whole model area, 10 in the Upper Aquifer, while 14 in the Lower Aquifer. These points defined by x, y coordinates (according borehole coordinates and water level measurements), confidence interval, confidence percentage, and which specified layer are assigned to.

These coverages are summarized as follows:

1. Sources/Sinks Coverage
2. Hydraulic (horizontal and vertical) conductivities for Upper Aquifer
3. Hydraulic (horizontal and vertical) conductivities for Yatta Formation
4. Hydraulic (horizontal and vertical) conductivities for Lower Aquifer
5. Recharge Coverage
6. Observation Coverage

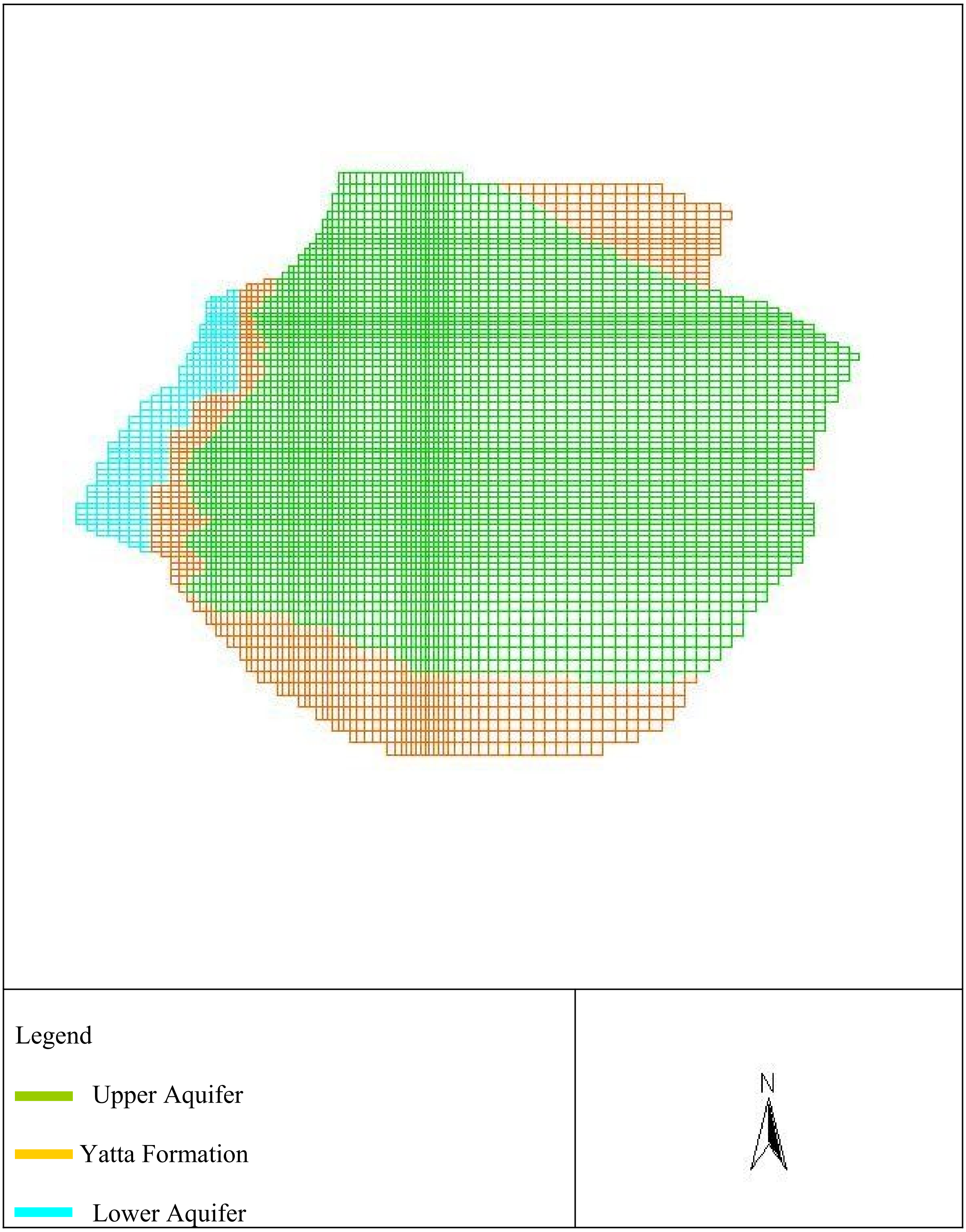


Figure 11: Distribution cells of Upper, Lower Aquifers, and Yatta Formation

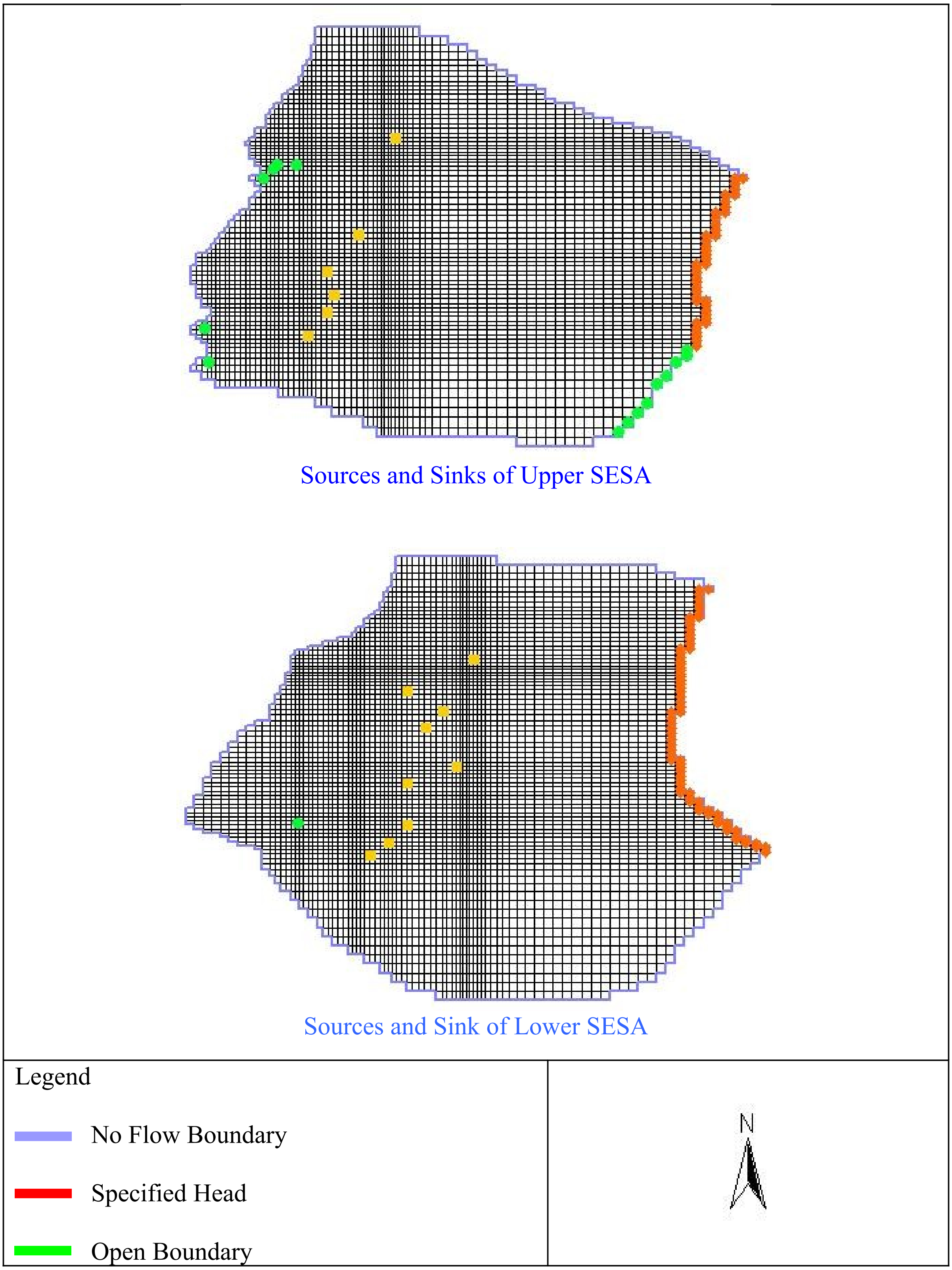


Figure 12: Sources and Sinks of the Upper and Lower SESA

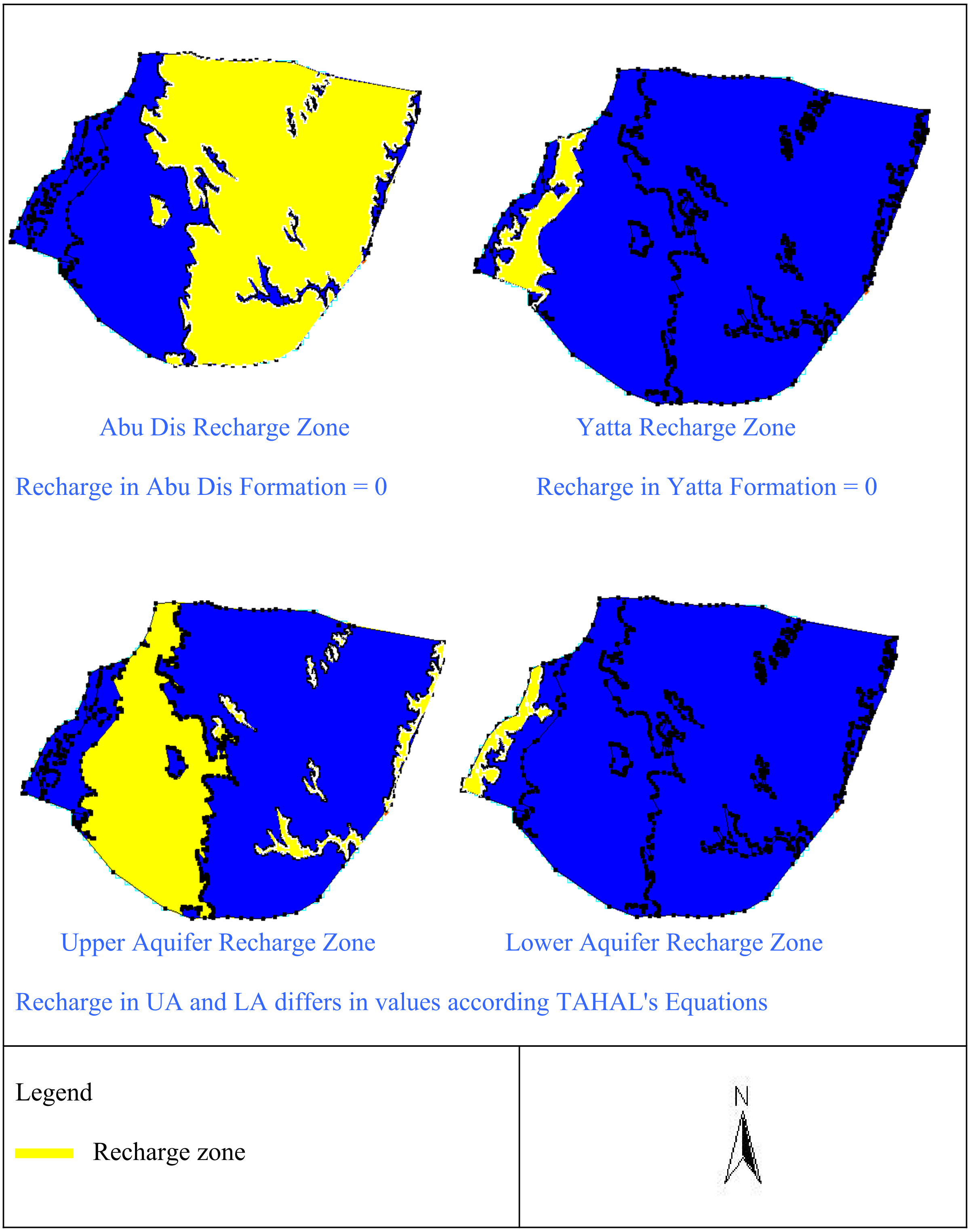


Figure 13: Recharge coverage of Abu Dis and Yatta Formations, and the Upper and Lower aquifers of the study area

3.4.6 Model Layers

The conceptual approach for the study area consists of five layers. The top layer represents the topography. AutoCAD was used to create topographic map for the study area. Topographical lines were drawn every 50m contouring line. The elevation of the study area was ranges from 1000 m asl in the mountains of the study area to less than 415 m bsl in the Jordan Valley (in the eastern boundary). Topographic contour lines were used to determine the top elevation of the outcroppings, (Figure 3). Then, the top and bottom elevations of beneath layers were drawn in AutoCAD by using the cross sections, outcropping maps, well logs, the created topographic map, and geophysics maps. After preparing these layers by using AutoCAD software in .dwg format these converted to GIS as lines by using .dxf format. These lines are processed by using GIS. Then, they converted to GMS as scattered points. Each Layer is imported to layer in GMS and modeled as a hydraulic layer. First layer is defined as the Abu Dis and above formations, the Upper Aquifers, Yatta, Lower Aquifer, and base Layer as the beneath layers, respectively.

So, the relevant formations can be summarized from top to down as follows:

Layer 1: Senonian represents Abu Dis formation

Layer 2: Upper Aquifer represents Jerusalem, Bethlehem, and Hebron formations of mainly dolomite.

Layer 3: Middle Aquitard represents Yatta formations dominated by marl, or sometimes chalk.

Layer 4: Lower Aquifer represents Upper and Lower Beit Kahil formations dominated by limestone.

Layer 5: Base layer which considered as aquitard

Layer 1 and 5 were removed to ease the run Modeflow during the calibration process.

3.4.7 Interpolation

After imported the prepared data from the structural GIS layers using the GMS Scatter Point Module, the top and bottom elevation of the grid cells are interpolated. The GMS 2D Scatter Point Module is used to interpolate from groups of 2D scattered data to other objects grids. The Inverse Distance Weighted (IDW) interpolation schemes are used in this model. This type of interpolation Includes constant, gradient plane, and quadratic nodal functions.

3.4.8 3D Representation

3D representation is completed by using all collected data about topography and elevations of the geometry of the three layers modeled in this study. Data from topographical maps were used to form the top elevations of the outcroppings. The top and bottom elevations were assigned to each layer in the model as points, then the GMS used these data to build geometry for the study area by interpolating each layer surface in the model using the inverse distance weighted method. The 3D representation of the study area is shown in (Figure 14 & 15).

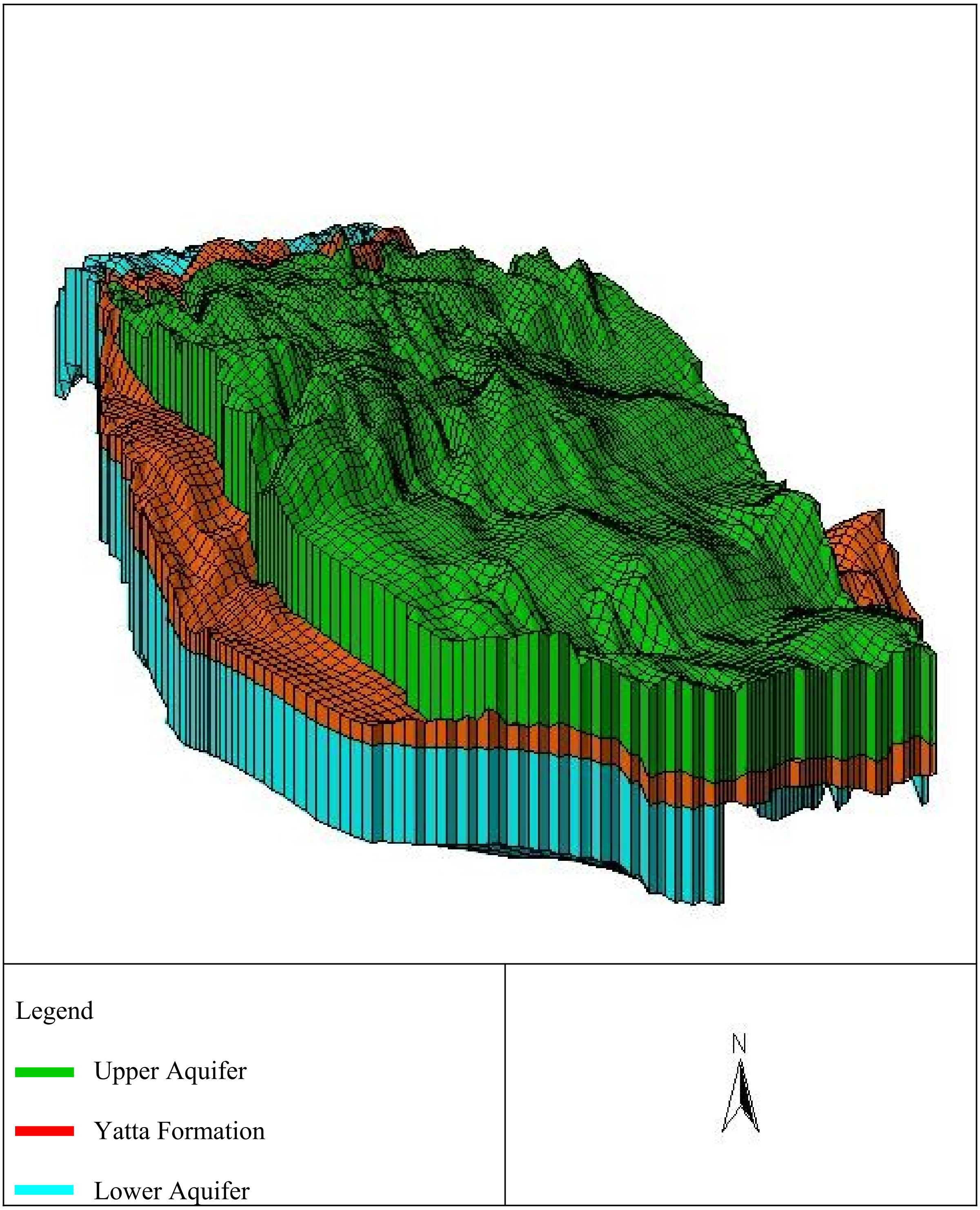


Figure 14: A 3D representation of the simulation’s best-fit solutions

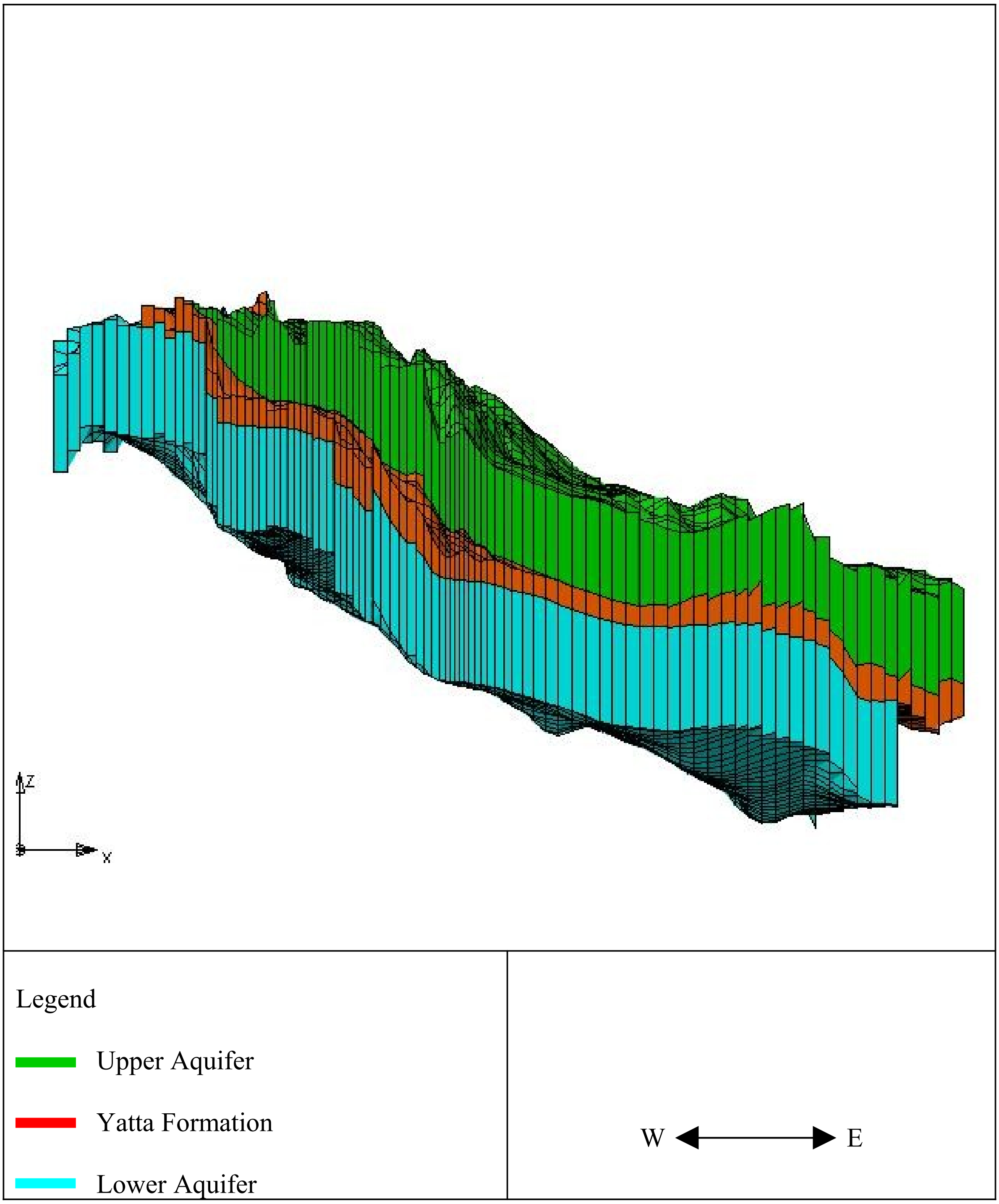


Figure 15: A 3D representation cross section of the simulation's best-fit solutions

Chapter Four

Model Results

4.1 Introduction

An important part of any groundwater model is the model calibration process. In order for a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate observed aquifer behavior. Calibration is a process wherein certain parameters of the model such as recharge and hydraulic conductivity are altered in a systematic fashion and the model is repeatedly run until the computed solution matches field-observed values within an acceptable level of accuracy. GMS software was used to calibrate the model which contains a suite of tools.

4.2 Model Results

Steady state was used to calibrate the model. Steady state calibration aimed at simulates the natural conditions.

4.2.2 Presentation of Computed Water Levels in the Observation Wells

By using 10 and 14 observation wells for Upper and Lower Aquifers respectively, the calibration was done for heads and drain across the eastern boundary by comparison with the conceptual water balance.

The observation wells show that the residuals between calculated and observed heads are all green bars within the defined tolerance of ±9 m and the calibration target, (Table 7). The center of the target corresponds to the observed value. The top of the target corresponds to the observed value plus the interval and the bottom corresponds to the observed value minus the interval. The colored bar represents the error. If the bar lies entirely within the target, the color bar is drawn in green. If the bar is outside the target but the error is less than 100%, the bar is drawn in yellow. If the error is greater than 100%, the bar is drawn in red see an illustrated (Figure 16).

Table 7: Calibration of water level for target (observation) wells

Aquifer	Well name	Depth of well in m	Average water level in m	Simulated water level in m	Residual
Upper	Herodion 1a	350	342.9	339	3.9
Upper	Shdema 2	440	199.7	203	-3.3
Upper	T16*	-	-225	-216	-9
Upper	T17*	-	-225	-220	-5
Upper	T18*	-	160	162	-2
Upper	T19*	-	160	159	1
Upper	T20*	-	750	749	1
Upper	T22*	-	500	503	-3
Upper	T23*	-	500	505	-5
Upper	T24*	-	500	503	-3
Lower	Herodion 2	770	353	348	5
Lower	Herodion 4	691	372	366	6
Lower	Shdema 1	910	223	217	6
Lower	T1*	-	400	404	-4
Lower	T2*	-	400	397	3
Lower	T3*	-	400	408	-8
Lower	T6*	-	350	358	-8
Lower	T7*	-	350	359	-9
Lower	T8*	-	-250	-255	5
Lower	T9*	-	-250	-255	5
Lower	T10*	-	-250	-258	8
Lower	T11*	-	-50	-46	-4
Lower	T12*	-	-50	-56	6
Lower	T13*	-	-50	-55	5

*: supposed observation well

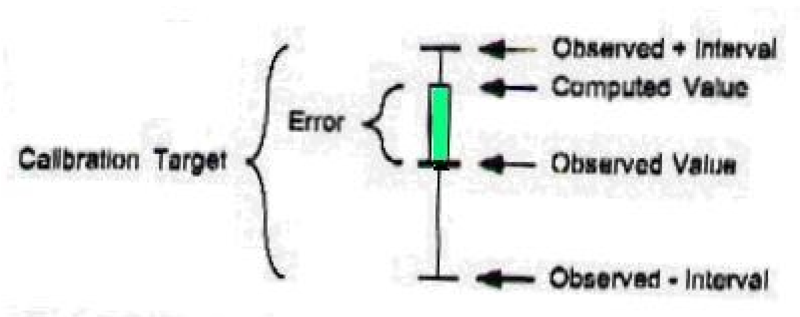


Figure 16: Calibration target

Distribution of these observation wells are shown in figures 22, and 23.

4.2.1 Presentation of Computed Discharges in the Springs

By using 6 consists from Upper Aquifer and one from Lower Aquifer. The calibration was done for drain by comparison with the conceptual water balance. These springs locate at the western part of the study area.

The observation springs show that the residuals between calculated and observed heads are all green bars within the defined tolerance of ±2.7 m^3 per day (Table 8).

Table 8: Calibration of discharges for springs which located within model area

Aquifer	Name	Observed discharge m^3 /d	Simulated discharge m^3 /d	Residual
Upper	Irtas	903.82	903.705	0.115
Upper	Al Farrouja	1.8219	1.817	0.0049
Upper	Itan	88.316	85.602	-2.714
Upper	Saleh	99.13	98.959	0.171
Upper	Deer Al Bus	41.916	41.805	0.111
Upper	Al Bus	30.491	31.314	-0.823
Lower	Barradah	0	0	0
Total	All springs	1165.495*	1163.202*	2.293

4.2.3 Model Results of Hydraulic Conductivities

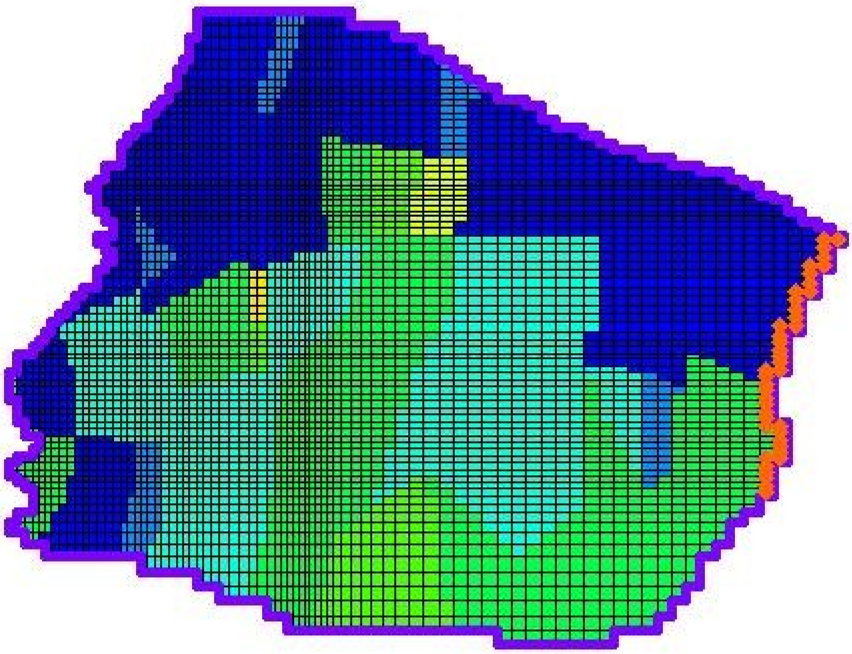
The estimated recharge was considered to be fixed and to be not changed from the input during the calibration process.

The parameters that were changed in the calibration process are the horizontal and vertical conductivities of the layer. The calculated horizontal hydraulic conductivity (Kh) of the Upper Aquifer is approximately 0.001 – 0.7 m/d (0.5 – 260 m/yr), while calculated Kh of the Lower Aquifer is 0.006 – 1.4 m/d (2 – 515) m/yr.

Calculated Kh of Upper Aquifer increases eastwards in the southeastern part of SESA. Lower Aquifer has high value in the west and east parts of the SESA, while in the middle part of it have low value. An anisotropy ratio of 10 was used between horizontal and vertical conductivities. This assumption was used for both aquifers and Yatta Formation.

The distribution of estimated horizontal and vertical hydraulic conductivities of the upper aquifer are shown in (Figures 17 and 18), respectively. And for lower aquifer are shown in (Figures 19 and 20), respectively.

The third layer, aquitard layer which lies between the upper and lower aquifers was given a different values of vertical hydraulic conductivity ranges between $1*10^{-8}$ - $4*10^{-4}$ m/d ($3.65*10^{-6}$ to 1.46 m/yr) as shown in (Figure21).



		Units in

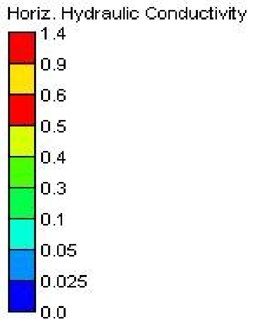
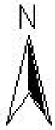
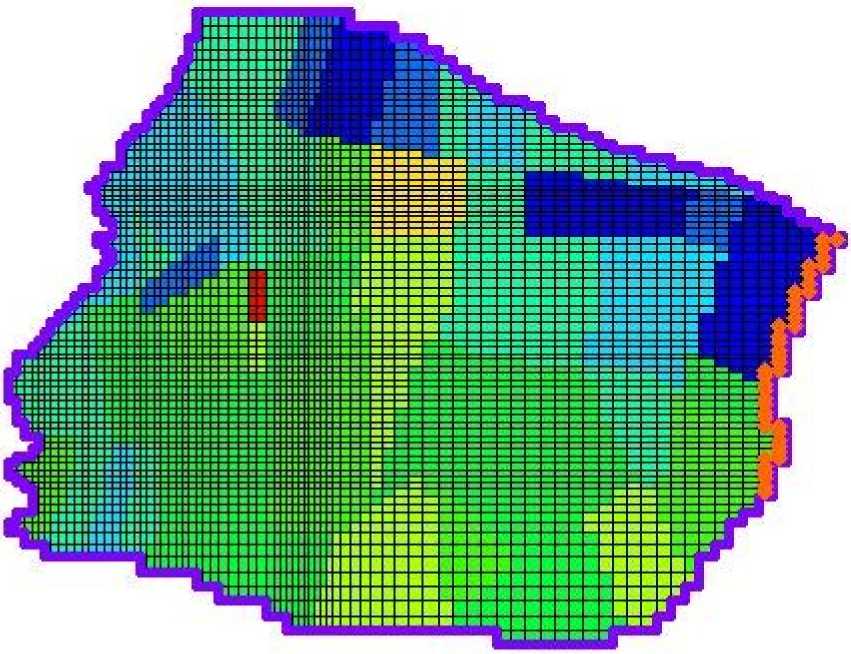
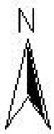
		m/d

Figure 17: Calibrated horizontal conductivity for Upper Aquifer



		Units in m/d

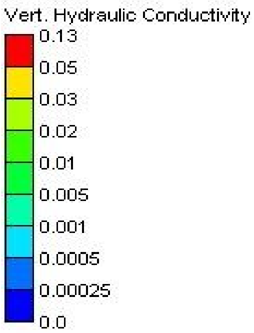
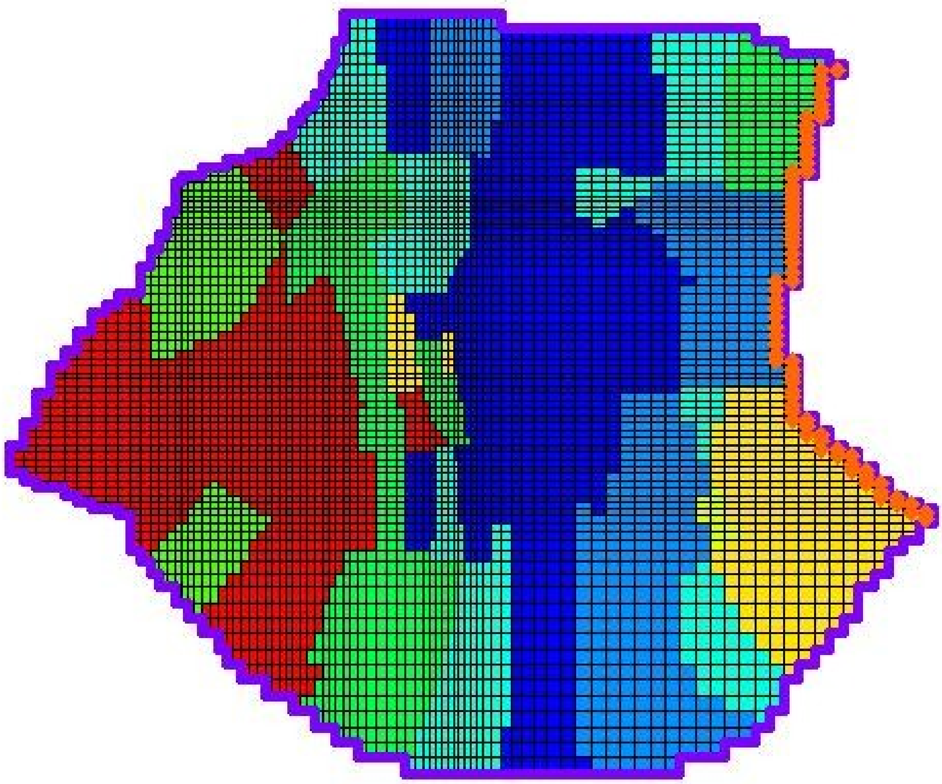
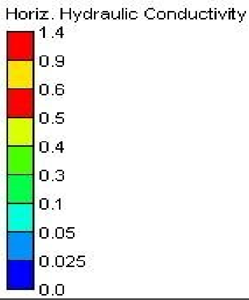
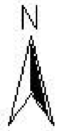


Figure 19: Calibrated vertical conductivity for Upper Aquifer



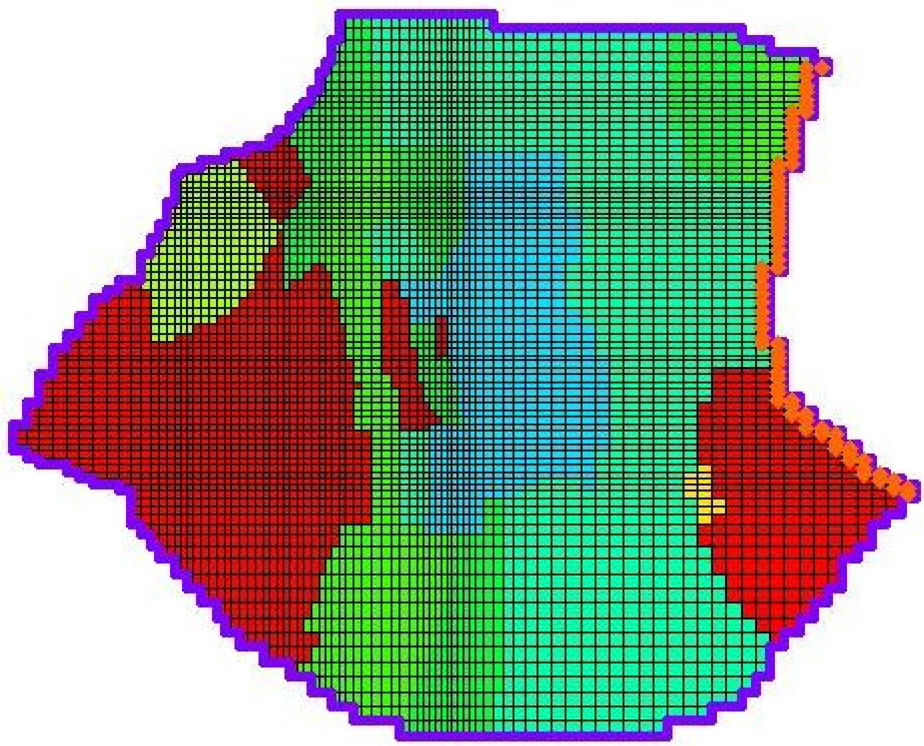
Units in

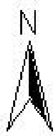




m/d

Figure 19: Calibrated horizontal conductivity for Lower Aquifer





Units in

m/d

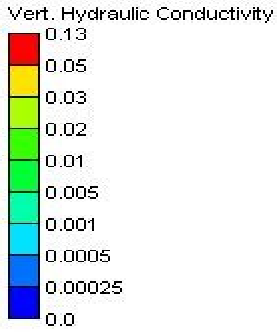
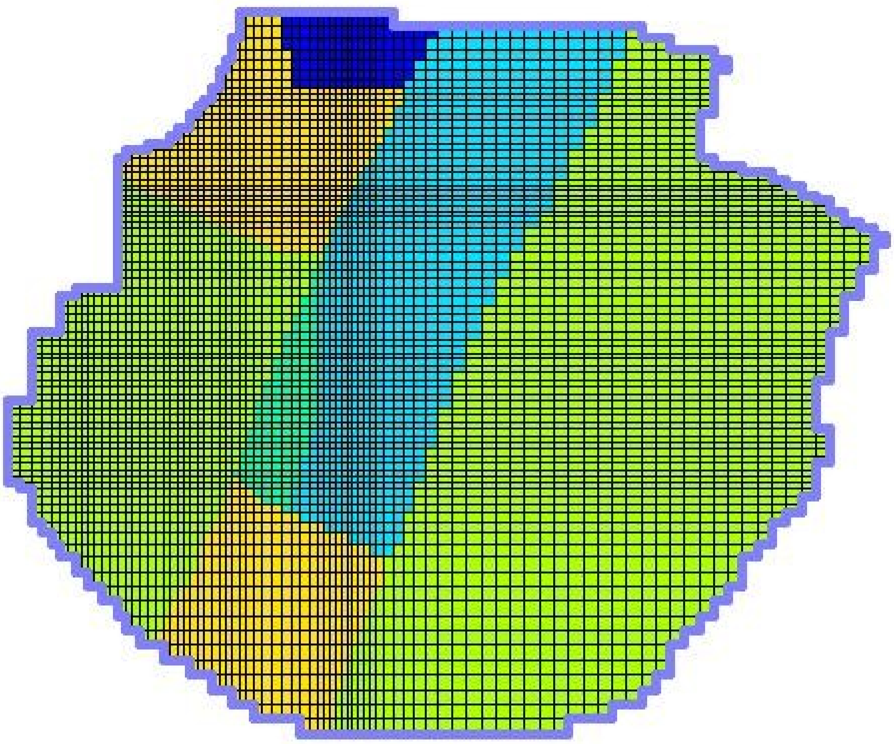
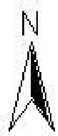


Figure 20: Calibrated vertical conductivity for Lower Aquifer





Units in

m/d

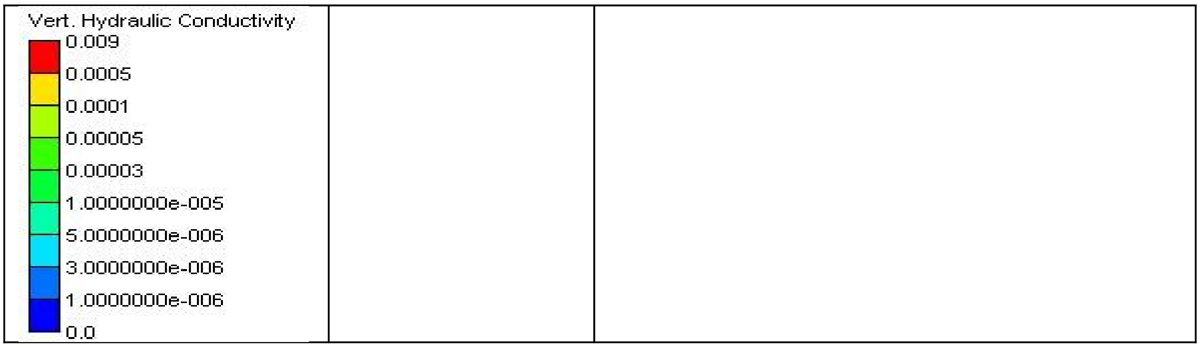


Figure 21: Calibrated vertical conductivity for Yatta Formation

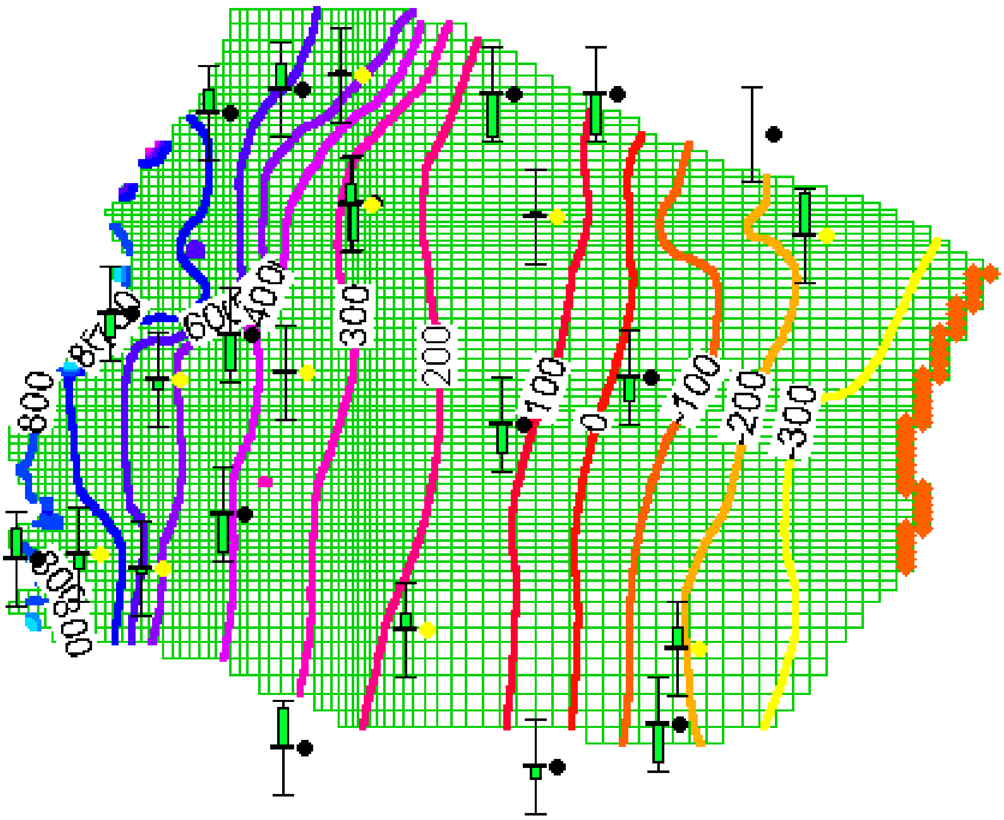
4.2.4 Model Results of Water Levels and Flow Pattern

Calculated water level in the recharge areas is generally high 750 m asl. And it ranges from 340-200 m at the middle SESA; about 339 m asl at Herodion 1a, and 203 at Shdema2 at the Upper SESA. While the calculated water level at the middle in the Lower SESA ranges between 370-200; about 348 m asl Herodion2, 366, and 217 m asl at Herodion 4, Shdema1, respectively, (Table 7). Calculated water table of the upper and lower aquifer are illustrated in (Figure 22 and 23) respectively. In addition, these figures show the locations of the target wells and calibration results for the simulation period 1990-1999 for the same calibrated k-values obtained in the calibration process of the simulation period. The spatial distribution of the target wells covers all model areas.

The flow lines originate mainly from the recharge zones in the western part of SESA. The general direction is west-east. It was observed that the water level have a response to the abstractions from the SESA, (Figure 24 and 25).

At south eastern part of the Upper Aquifer, the groundwater directions trend from west to south eastern (W-SE). While, the south eastern part of the Lower aquifer trends from west to north eastern (W-NE). While, the same part of the study area of the Lower Aquifer trends from west to north eastern (W-NE).

In the south eastern part of the study area, there is significantly high discharge from Upper and lower aquifers because of presence fractures in this part, (Figure 24 and 25). In these figures, vector length is proportional to flow velocity. The maximum lengths of these vectors were encountered in the south eastern part of the study area.



Legend		Note

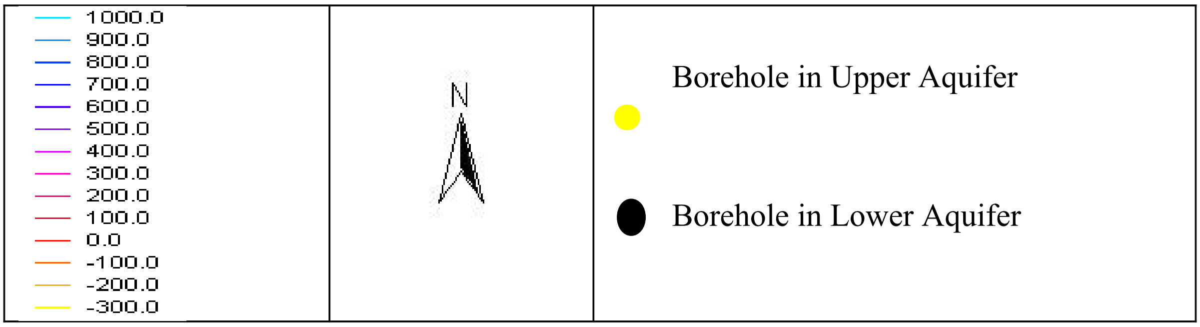
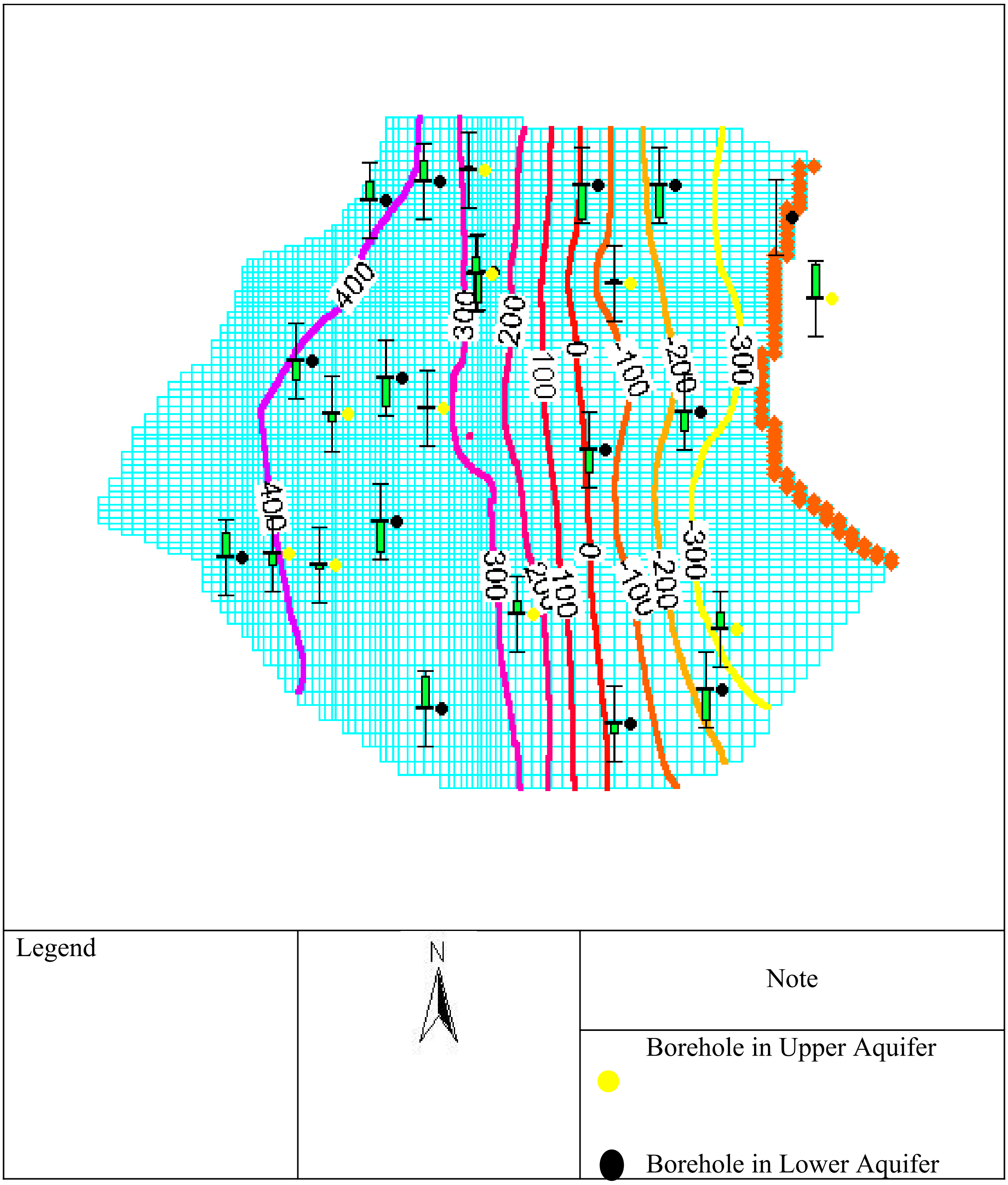
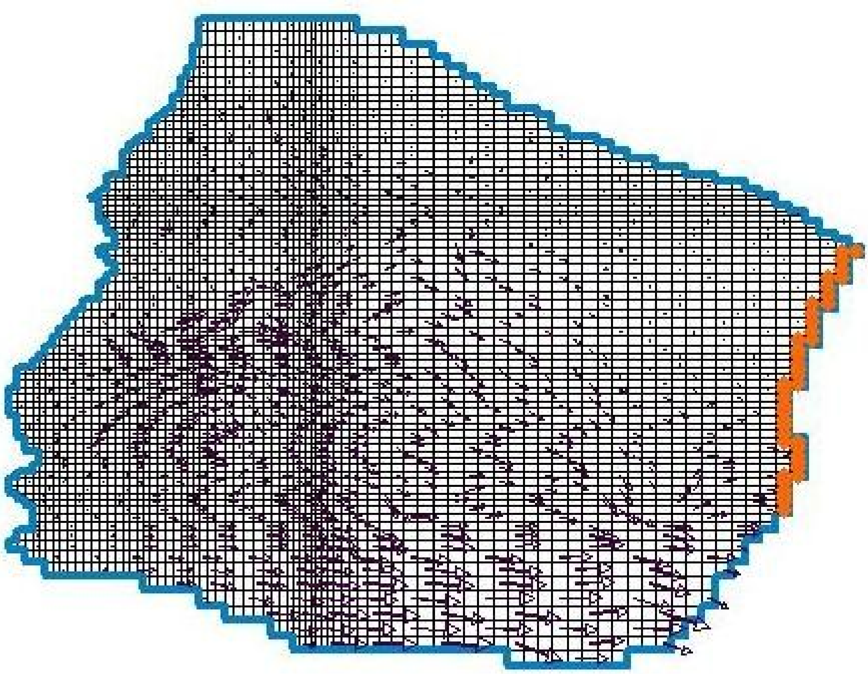


Figure 22: Calculated water level map of the Upper Aquifer



1000.0 900.0 800.0 700.0 600.0 500.0 400.0 300.0 200.0 100.0 0.0 -100.0 -200.0 -300.0		

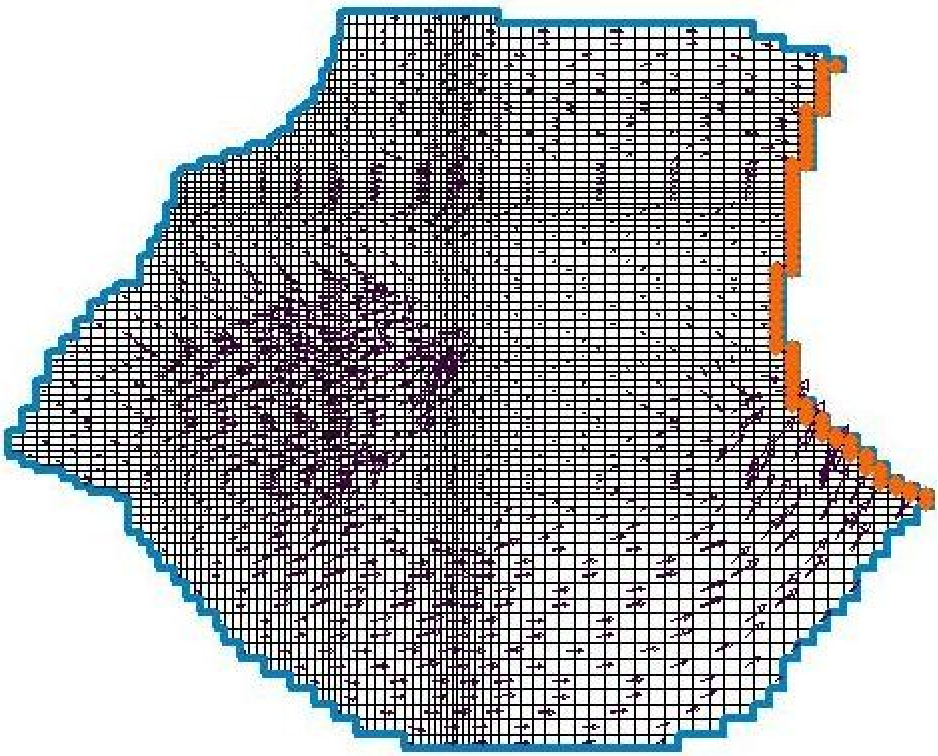
Figure 23: Calculated water table map of the Lower Aquifer



Legend		Note

Vector	N	Vector length is proportional to flow velocity

Figure 24: Calculated vectors in the Upper Aquifer



Legend Vector	N	Note Vector length is proportional to flow velocity

Figure 25: Calculated vectors in the Lower Aquifer

4.3 Error Summary

The computed error summary indicates that the difference between computed and observed heads ranges from 1 to 9. The error norms used to present the model results are:

- The Mean Residual (MR) which represents the sum of differences between the computed head and observed head divided by the number of observations. Equation (5.1) shows the mathematical expression formula of the Mean Residual.

- Mean Absolute Residual (MAR) which represents the absolute value of the sum of differences between the computed and observed heads divided by the number of observations. Equation (5.2) shows the mathematical expression formula of the Mean Absolute Residual.

- Root Mean Squared Residual (RMSR) which represents the square root of the sum of the squared differences between the computed and observed heads divided by the number of observations. Equation (5.3) shows the mathematical expression formula of Root Mean Squared Residual.

The error summary shows the following results:

The Mean Residual = $\frac{1}{n}\sum_{i=1}^{n}\left(h_c \quad h_o\right)_i$ .. …………….. …………………………eq(5.1)

Mean Absolute Residual = $\frac{1}{n}\sum_{i=1}^{n}\left|\left(h_c \quad h_o\right)\right|_i$ ………..………………….……… eq(5.2)

Root Mean Squared Residual = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_c \quad h_o\right)_i^2}$ ……..……………..…………eq(5.3)

Where, n: number of observations, hc: the computed head, and ho: the observed value.

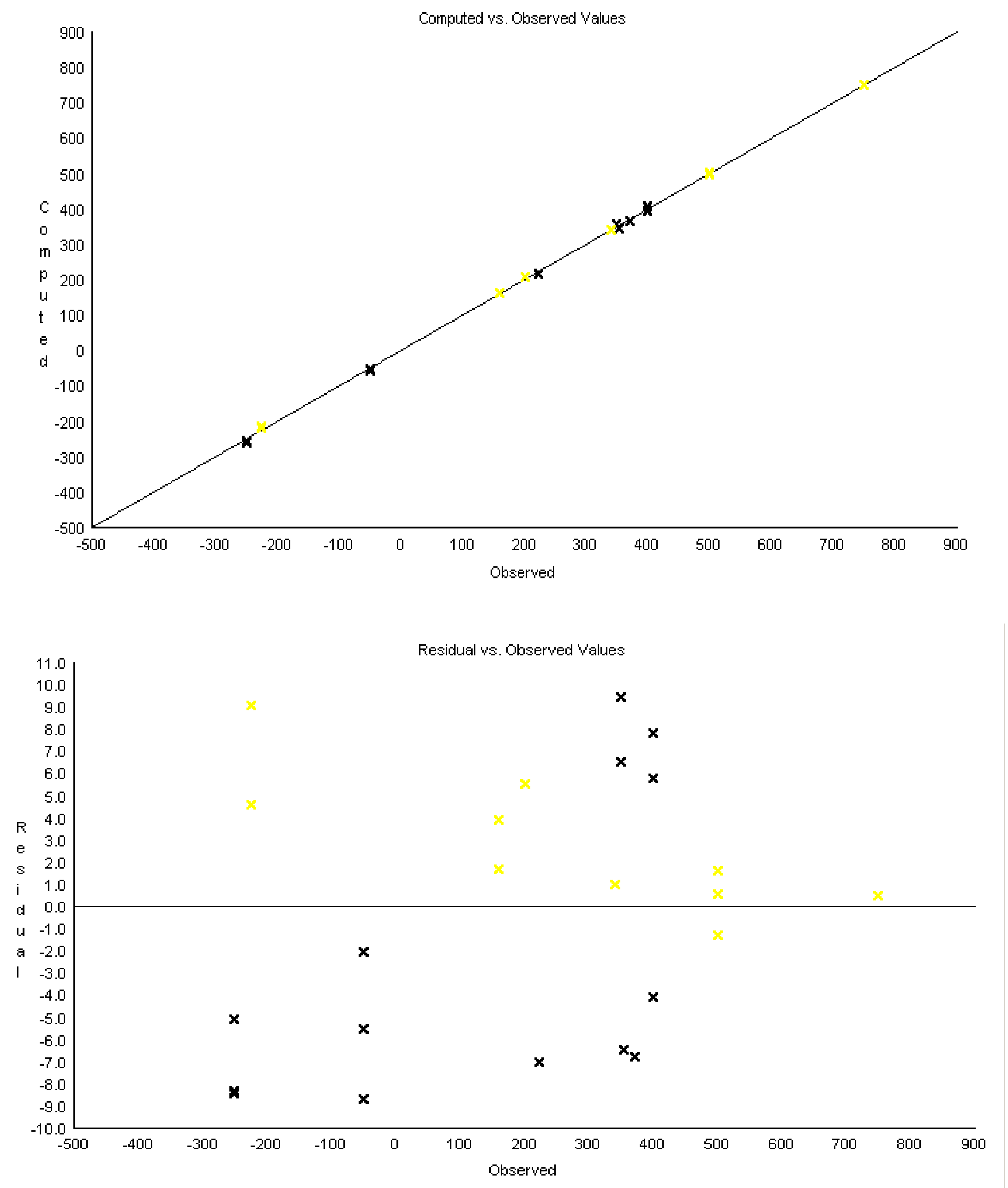
The norms of the study area's calibrated model are shown in Table 9.

Table 9: The Calibration Error Norms

Error Type	Value in m
The Mean Residual	-0.23
Mean Absolute Residual	5.08
Root Mean Squared Residual	5.83

The mean residual between the computed head and the observed head was -0.23 m, the mean absolute residual was 5.08 m, and root mean squared residual of head was 5.83 m (Table 9).

The overall results of the error norms show that the computed head matches the observed head to an acceptable degree (Figure 26).



Legend	
Observation well in Upper Aquifer Observation well in Lower Aquifer	Units in meters

Figure 26: Water level calibration plots and statistics

4.4 Sustainable Management

Sustainable management aims at analyzing the current water budget to manage the future discharges of the groundwater wells from the study area. Aquifer sustainability will be evaluated by comparison the previous and current situation of wells abstraction, springs discharges, and future need.

The 10-year (1990-1999) water balance was estimated for the study area using GMS software, MODFLOW Code and what is really required is to classify the outcrops of the Upper and Lower aquifers in order to be used for management programs.

Since the recharge coverage was already derived from rainfall, the water balance was derived based on intersecting the estimated recharge coverage with both the groundwater aquifers (Upper and Lower aquifers) and the coverage of the outcropped geologic formations.

The total groundwater recharge for the study area is about 26.8 Mcm/yr., (Table 10). According to this the aquifers could be classified into two systems as follows:

- The Upper Aquifer System which consists of the Upper Cenomanian and the Turonian Formations in terms of geological age. This system is composed of limestone and dolomite carbonate rock formations which is mainly located in the western part of the study area. The total estimated groundwater recharge of this aquifer is about 23.5 Mcm/yr.

- The Lower Aquifer System which consists of two aquifers; Albian and Lower Cenomanian aquifers. The total estimated groundwater recharge of this aquifer is about 3.3 Mcm/yr.

Table 10: Natural recharge is considered the main input in the model area

Aquifer	Inflow (Recharge) in Mcm/yr
Upper Aquifer	23.5
Lower Aquifer	3.3
Total	26.8

The total outflows for the SESA is about 26.8 Mcm/yr., (Table 11) where:

- The total estimated outflows from Upper Aquifer are about 9.3 Mcm/yr: outflows from the eastern and southeastern boundary of the study area are 5.4 Mcm/yr, the abstraction from wells is 3.5 Mcm/yr, and the total springs discharges from Upper Aquifer about 0.4 Mcm/yr.
- The outflows from Lower aquifer are from open boundary at the eastern part of SESA and from well abstraction which are 8.7 and 8.8 Mcm/yr, respectively.

Table 11: Outflows through the eastern border, wells abstraction, discharges

Aquifer	Outflows in Mcm/yr			
	Open eastern boundary	Wells abstraction	Springs discharge	Total
Upper Aquifer	5.4	3.5	0.4	9.3
Lower Aquifer	8.7	8.8	0	17.5
Total	14.1	12.3	0.4	26.8

To achieve the groundwater resources sustainability, the total long term water use from any aquifer or groundwater basin should not exceed the natural long term groundwater recharge. This means, if the recharge 10 Mcm/yr and the discharges 5 Mcm/yr, the aquifers is considered sustainable. But, if the recharge 10 Mcm/yr and the discharges 12 Mcm/yr, the aquifers is considered un-sustainable.

According to this, the results of the estimated natural groundwater recharge with the total annual groundwater use, two results can be noted:

- **Upper Aquifer:** during the period (1990-1999), the total annual use was 3.5 Mcm/yr, while the total annual recharge was 23.5 Mcm/yr. As a result, the resultant quantity of water is positive, and it is estimated about 19.5 Mcm/yr. This means, the Upper Aquifer is sustainable.

- **Lower Aquifer**: during the same period (1990-1999), the total annual use was 8.8 Mcm/yr, while the total annual recharge was 3.3 Mcm/yr. As a result, the resultant quantity of water is negative, and it is estimated about 5.6 Mcm/yr. This means, the Lower Aquifer is un-sustainable.

Moreover, it should be checked the interaction between the aquifers to understand how the difference of water quantities were compensated.

4.5 The Interaction between the Aquifers

Areas of limestone outcrops along the Hebron anticline (the boundary between the Western and Eastern Aquifer Systems in the Hebron-Bethlehem area) are the main recharge locations for the Upper Aquifer. The Upper Aquifer has no inflow and outflows from the upper face which covers by Abu Dis Formation. The upper face, represents Abu Dis Formation, is considered an aquiclud. While, the inflows and outflows from lower face of the modeled Upper Aquifer is 0.96 and 11.4 Mcm/yr, respectively. The outflows from the Upper Aquifers (11.4 Mcm/yr) percolates to the Lower Aquifer among Yatta Formation, (Figure 27).

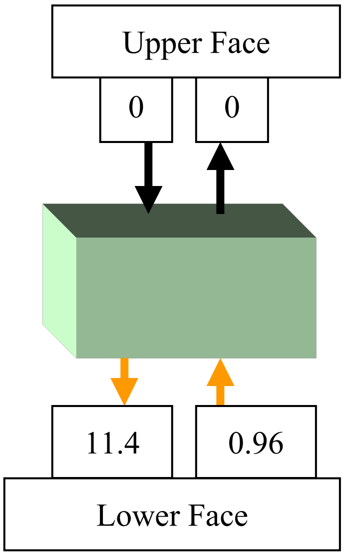


Figure 27: The inflows and out flows from the upper and lower faces of modeled area of the Upper Aquifer

In addition, the estimated inflows and outflows from the part of the Upper Aquifer of the study area which have no model in the Lower aquifer are 0.018 and 0.091 Mcm/yr, respectively. The Upper Aquifer has no inflow and outflows from the upper face of the study area which represents Abu Dis Formation which is considered an aquiclud, (Figure 28).

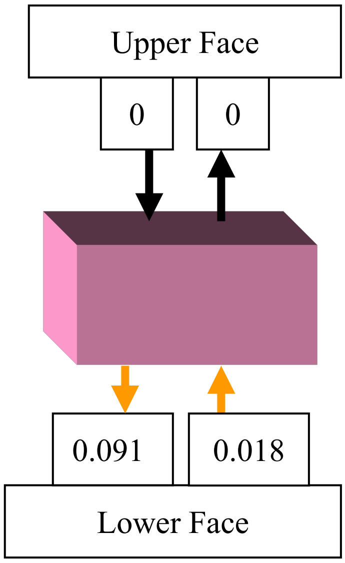


Figure 28: The inflows and outflows from the upper and lower faces of modeled area of the Upper Aquifer which recharges the uncovered model area of the Lower Aquifer

Moreover, the Lower Aquifer part which represents the whole modeled area of the Lower Aquifer of the study area, have inflows and outflows from the upper face of the study area. The inflows and outflows from lower face of the modeled Upper Aquifer are 15.2 and 0.83 Mcm/yr, respectively. The inflows from the Upper Aquifers (15.2 Mcm/yr) percolates to the Lower Aquifer among Yatta Formation. This value plus the value of recharge of the Lower aquifer will be compensated the difference between the water use and the groundwater resources, (Figure 29).

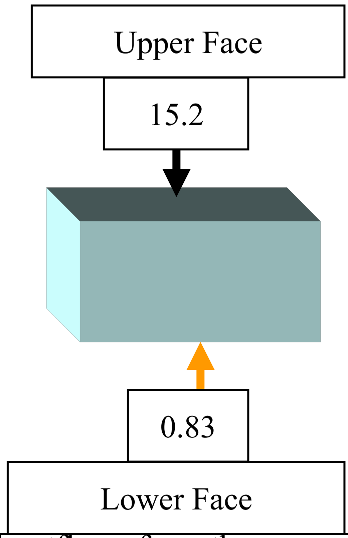


Figure 29: The inflows and outflows from the upper and lower faces of modeled area of the Lower Aquifer

Finally, the Lower Aquifer part which does not covered by Upper Aquifer model area, the estimated value of recharged water from Upper to Lower Aquifers is 3.52 Mcm/yr, while the outflows from this part is 0.011 Mcm/yr, (Figure 30).

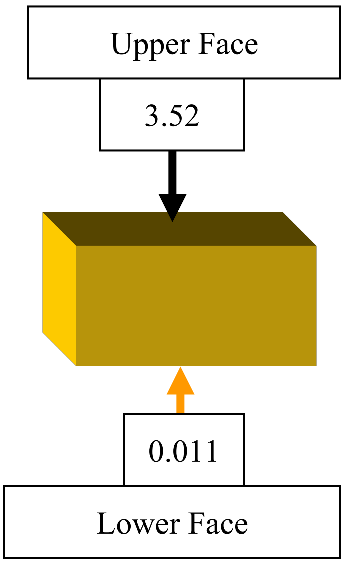


Figure 30: The inflows and outflows from the upper and lower faces of modeled area of the Lower Aquifer which recharges the uncovered model area of the Upper Aquifer

The results of the model represent that Yatta Formation acts as path for groundwater for the aquifers.

After understanding the interaction between the Upper and Lower aquifers, the volume of recharge of these aquifers, the water use leads to think of the following scenario as follows:

The scenarios assumed that existing wells will continue to pump at the current rate plus add wells within the location of the existing wells. This scenario required to study the water levels in the study area.

From the available data of the water level which adopted from Guttmann model, the figures showed that the aquifer water table at the study area continuous to drop by 1-3 m a year. The study area suffers from excessive drawdown because of high capacity extraction wells in a small geographic area. Moreover, this fact is confirmed by recent studies that the aquifer water table specially in Herodion well field which is located within the study area continuous to drop 2-3 m a year. As a result of dropping the water table, many of springs at the Upper Aquifer became dry at the last years (1998-1999).

As a result of this scenario, any addition wells drilled in the study area within the location of existing wells, will lead to continuous in dropping in water table in aquifers more and more. In situation of addition new wells, it should be known the exact water table by doing advanced model depending of this research. If the water table drops more than one third the water level, then the water resources in critical situation and the management not sustainable.

Chapter Five

Conclusion and Recommendation

5.1 Conclusion

A hydrogeological study was conducted covering the drainage sub- basins of Daraja, Nar, and parts of Hasasa, Ghar, Qumran, and Mukallak sub-catchments area of 584.6 km^2 which is part of the Eastern Basin 2,895.5 km^2. It includes the Palestinian areas of Bethlehem and parts of Jerusalem and Hebron mountains area. The area represents the south eastern sub-aquifer in the West Bank (SESA).

The boundaries of the model area were determined by water divide from the west, open boundary from the east, and the others were drawn as equipotential lines of the water levels and those assigned as no-flow boundaries.

After calibration process, the observation wells show that the residuals between calculated and observed heads within the defined tolerance of ±9 m. But the residuals between calculated and observed drains of the observation springs are ±2.7 m^3 per day.

The steady state model is done for period of ten years. In this research, ten years from 1990-1999 was chosen to complete the conceptual model.

By using the collection and preparation data such as stratigraphy, geophysics maps, cross sections, outcropping, average rainfall distribution, topographical lines ,the elevations of aquifers and aquitard, recharge estimation, determination of boundaries, stresses (wells and springs),…etc, the conceptual model was constructed for the study area.

The recharge volumes to upper and lower aquifers were estimated by doubting TAHAL's equations. These equations were obtained for the eastern aquifers. The volumes of direct recharge to upper and lower aquifers were 23.5 Mcm/yr, and 3.3

Mcm/yr, respectively. The rate of infiltration was found to be 39% of the rainfall when the precipitation over 650 mm, 29% when precipitation between 650-300 mm, and 15% when precipitation less than 300 mm, which varies between 675 and 75 mm per year in the western and eastern parts, respectively.

The recently discharge of the aquifers through wells and springs were calculated to be about 12.3 and 0.4 Mcm per year, respectively. The unused groundwater which was discharged through the eastern boundary was estimated to be about 14.1 Mcm/yr in the area, 5.4 and 8.7 Mcm/yr from Upper and Lower Aquifer, respectively.

This study classified the study area aquifers into two systems. These are:

- The Upper Aquifer consists of Turonian and Upper Cenomanian sub-aquifer. This system is composed of limestone and dolomite carbonate rock formations
- The Lower Aquifer System consists of Albian sub-aquifer.

The horizontal and vertical hydraulic conductivity for each layer were determined by calibration process. The Upper Aquifer has a horizontal hydraulic conductivity range of 0.5 to 260 m/yr, while the Lower Aquifer has a range from 2 to 515m/yr.

Turonian and Upper Cenomanian sub-aquifers show a wide range of hydraulic conductivity within the model area due to the fracturing caused by the complex structure in the area that were formed during the formation of the Jordan Rift Valley.

For the simulation period, for the Upper Aquifer water levels in the recharge areas at the western part of the model area, are generally high 750 m asl, while 400 in the Lower Aquifer.

Water level gradients in the basin are very steep while they are specially in abstraction‘s area.

The direction in which groundwater flows is a function of the potential field and the degree of anisotropy of the hydraulic conductivity and the orientation of the axes of permeability with respected to grad h.

The flow lines originate mainly from the recharge zones in the recharge zones in the western part of SESA. The general direction is west-east. It was observed that the water level have a response to the abstractions from the SESA. The groundwater direction at south eastern part of the Upper Aquifer trends W-SE. While, the south eastern part of the Lower aquifer trends W-NE.

The results of the model show that the water budget of the Upper Aquifer of SESA is sustainable but the water budget of Lower Aquifer un-sustainable because there is excessive water use from the aquifer. In addition, the results shows that Yatta Formation acts in the calibrated model as path that means the water comes from Upper Aquifer will recharge the Lower Aquifer especially in south western part of the study area because of the presence of faults and fractures.

5.2 Recommendation

- Steady state is the subject of this research which represents a group of possible solutions. To be more accurate, it is necessary to run a model as transient simulation. The transient model can put several scenarios to understand the sustainability of the Aquifer Systems. Periodic calibration and testing of the model will improve future predictions.
- It is recommended to re-calculate the water budget and to re-calibrate the model once aquifer parameter data are updated
- Monitoring programs should be done for SESA to predict draw downs in the aquifers to put a short and long sustainable management by the specialist.
- Data such as water level, their situations, rainfall, etc should be recorded as possible to give full picture about SESA, and then the model can be more reprehensive.

- Environmental aspect should be studied to know the influence of draw down upon the situation of SESA.

References

Aliewi, and Jarrar, (2000): Technical Assessment of the Potentiality of the Herodion Wellfield Against Additional Well Development Programs, Palestinian Authority, Ramallah.

ANTEA, Palestinian Hydrology Group and Palestinian Water Authority, (1998): Geological Sketch. In: Well Development Study of the Eastern Aquifer Basin, Northern Districts of Palestine. Vol.1: Interim Report. Conceptual Model.

Asbah, (2004): Monthly Recharge Estimation for the Auja-Tamseeh Catchment of the Western Basin Aquifers-System, Palestine. Birzeit University. Palestine.

Ben-Itzhak, (2003): Groundwater Flow Modeling in the Eastern Judea Group Aquifer, thesis for the Degree of Master, The Hebrew University of Jerusalem.

CDM/Morganti, (1997): Eastern Aquifer Monitoring Wells (Preliminary Design Standards and Technical Specification Report), Palestinian Water Authority and USAID. Deliverable number 20.03.

CDM/Morganti, (1997): Preliminary Conceptual Model and Initial Estimate of the Sustainable Yield of the Eastern Aquifer basin, Palestinian Water Authority and USAID. Deliverable number 18.01.

Eyal and Reches, (1983): Tectonic Analysis of the Dead Sea Rift Region since the Late-Cretaceous Based on Mesostructures. Tectonics, 2.

Fetter, (1993): Applied Hydrogeology. Third Edition, Macmillan College Publishing Company, New York, U.S.A.

Fleisher, Gelberman, and Wolff, (1993): A Geological-Geophysical Reassessment of the Judea Group (Yarkon-Taninim Aquifer). Institute of Petroleum Research and Geophysics.

Ghanem, (1999): Hydrogeology and Hydrochemistry of the Faria Drainage Basin/ West Bank. Technische Universitat Berakademie Fgreiberg Institut FurGeologie. Freiberg.

Garfunkel, and Ben-Avraham, (1996). The structure of the Dead Sea Basin. Tectonophysics, Tel Aviv.

Guttman, (1997): Study of the Sustainable Yield of the Eastern Aquifer Basin- Conceptual and Model. Water Resources Department, Tel Aviv.

Guttman, (1998). Hydrogeology of the Eastern Aquifer in the Judea Hills and Jordan Valley, TAHAL Consulting Engineers Ltd, Tel Aviv.

Guttman, and Zukerman, (1995): A Model of the Flow in the Eastern Basin of the Mountains of Judea and Samaria from the Far'ah Stream to the Judean Desert. TAHAL Consulting Engineers Ltd, Tel Aviv.

Harpaz, and Schwar, (1998). Operating a Limestone Aquifer as a Reservoir for a Water Supply System, TAHAL, Water Planning for Israel, Tel Aviv.

McDonald and Harbaugh, (1988): A Modular Three-Dimensional Finite-Difference Groundwater Flow Model. U.S Geological Survey. U.S.

McDonald and Harbaugh, (1996) A Modular Three-Dimensional Finite-Difference Groundwater Flow Model. U.S Geological Survey. U.S.

Moorehead at al (2002): Water For Palestine. A Critical Assessment Of The European Investment Bank's Lending Strategy By the Sanitation and Environment Program Of The Palestinian Hydrology Group.

CH2MHILL, (2001): Aquifer Modeling-Task 7, The Mountain Aquifer Model-Draft Report. .Palestinian Water Authority

CH2MHILL, (2001): Aquifer Modeling-Task 7, The Jericho Model-Final Report. Palestinian Water Authority

Rofe and Raffety, (1965): Jerusalem and District Water Supply. Geological and Hydrological Report. Ministry of Water and Irrigation, Central Water Authority, The Hashemite Kingdom of Jordan, London.

Sabbah, (2004): Developing A GIS And Hydrological Modeling Approach For Sustainable Water Management In The West Bank-Palestine. Brigham Young University.

Scarpa, (2004): Water Resources and the Sustainability of Towns and Villages in Bethlehem and Hebron Governorates. Thesis for the Degree of Ph.D.,. School of Oriental and African Studies, London University.

Schneider, (1924): Geologic and Hydrologic Factors Related to Artificial Recharge of the Carbonate Rock Aquifer System of Central Israel, Tel Aviv.

Tamimi, (1998): Recharge Flow and Discharge Mechanisms of the Eastern Aquifer Bordering the Jordan Valley. German Israeli Jordanian Palestinian Joint Research Program for the Sustainable Utilization of Aquifer Systems, Final Progress Report.

Teutsch, Sauter, and Liedl, (1997): Modeling of Groundwater Flow Between the Cretaceous Mountain Aquifer Systems and the Jordan-Dead Sea. Geologisches Institut. Lehrstuhi fur Angewandte Geologie. German Israeli Jordanian Palestinian Joint Research Program for the Sustainable Utilization of Aquifer Systems

Todd, (1993): Groundwater Hydrology. Second Edition. Consulting Engineers, Inc. John Wiley and Sons, New York, U.S.A.

نموذج انسياب المياه الجوفية للحوض الجنوبي الشرقي لمنطقة بيت لحم/ الضفة الغربية

اعداد

نظيره أبو زيد

(1025317)

مشرف الرسالة

د. مروان غانم

أيلول، 2005

BIRZEIT UNIVERSITY

نموذج انسياب المياه الجوفية للحوض الجنوبي الشرقي لمنطقة بيت لحم/ الضفة الغربية

اعداد

نظيره أبو زيد

لجنة الاشراف

د. مروان غانم (مشرف الرسالة)

د. زياد الميمي (عضو)

د. وسيم العلي (عضو)

د. عامر مرعي (عضو)

أيلول، 2005

ملخص

تهدف هذه الدراسة الى بناء نموذج جوفي (Model) للحوض الجنوبي الشرقي لمنطقة بيت-لحم لمعرفة الخصائص الفيزيائية و التعرف على طبيعة الاتصال بين الحوض الجوفي العلوي(Upper Aquifer) و الحوض الجوفي السفلي (Lower Aquifer).

تقع منطقة الدراسة ضمن منطقة الحوض الشرقي و تغطي مساحة 584.6 كم ^{2}. فالحدود الغربية لمنطقة الدراسة هو الخط الفاصل بين الحوض الشرقي و الحوض الغربي (water divide)، أما بالنسبة للحدود الشمالية و الجنوبية فحددت بشكل عمودي على خطوط المياه الجوفية لنموذج جوفي عام لمنطقة الحوض الشرقي. و تعتبر الحدود الغربية و الشمالية و الجنوبية حدود مانعة لمرور المياه (no-flow boundary)، أما بالنسبة للحدود الشرقية فهي حدود مفتوحة أمام سريان المياه (flow boundary).

تم عمل دراسة مسبقة للمنطقة (conceptual model) من ناحية طبوغرافية و جيولوجية و هيدرولوجية و هيدروجيولوجية، و تم تحصيل المعلومات الضرورية و جدولتها.

و من خلال هذه الدراسة تم حساب مساحة التكشفات للطبقات للاعتماد عليها في حساب حجم التغذية للحوض العلوي من منطقة الدراسة و الذي يضم طبقات نفاذة (القدس و بيت لحم و الخليل). كانت كمية التغذية حوالي 23.5 مليون متر مكعب لكل سنة (ممم/س) و 3.3 ممم/س للحوض السفلي و الذي يضم طبقات بيت كاحل العلوية و السفلية النفاذة. و اعتبرت التغذية للطبقتين غير النفاذتين (طبقة أبو ديس (aquiclud) و طبقة يطا (aquitard)) تساوي صفر و ذلك حسب الفرضيات لمعدلات تاهال (Tahal) التي تم الاعتماد عليها في حساب التغذية.

و لتحقيق أهداف الدراسة تم اعداد الخرائط الضرورية لبناء النموذج الجوفي ثم أدخلت على برنامج المياه الجوفية المتطورة (GMS: Groundwater Modeling System) لبناء نموذج جوفي لمنطقة الدراسة (Steady state model) لفترة الدراسة الواقعة بين 1990-1999. من خلال هذا البرنامج تم معالجة الخرائط و البيانات و عمل معالجة ضرورية (calibration process) للتوصل الى التوازن المائي للحوض (water budget).

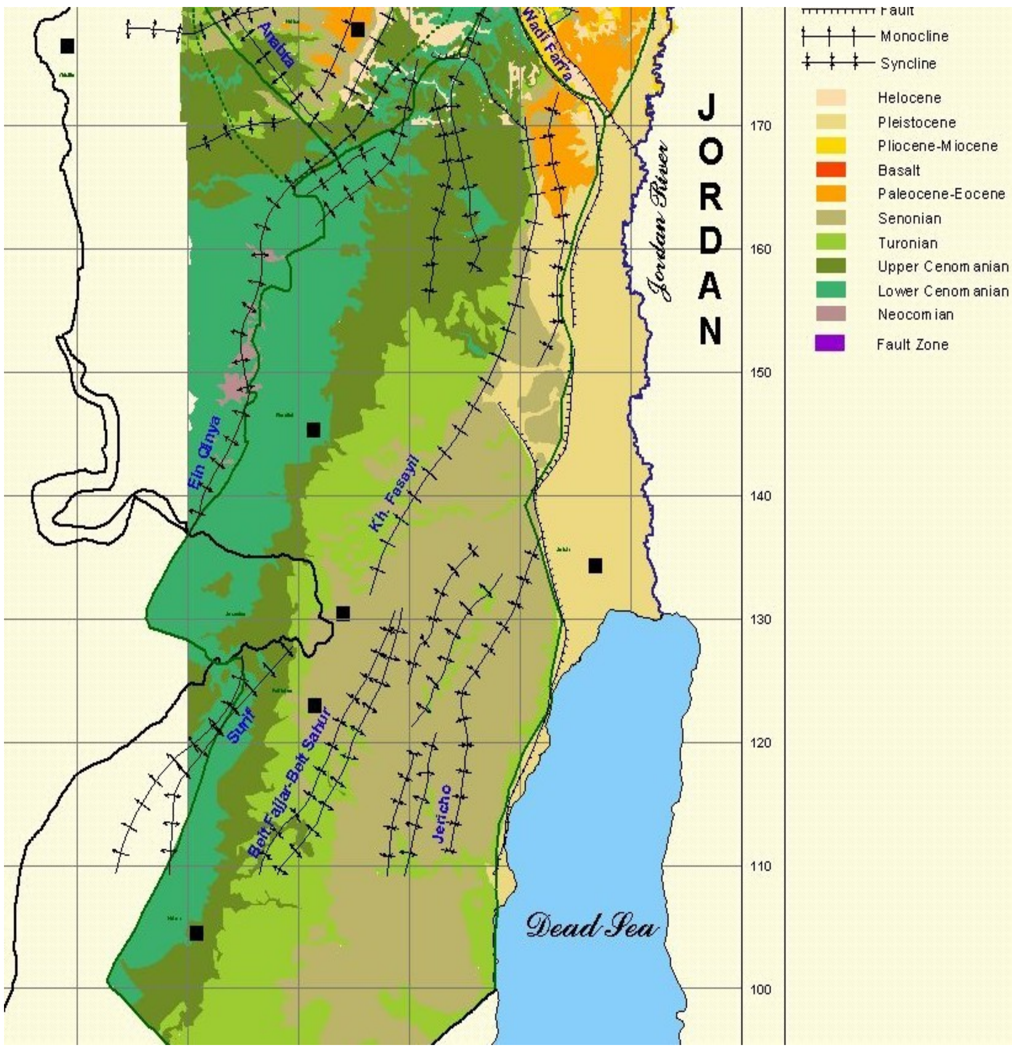
تشير النتائج للنموذج الجوفي أن النفاذية الأفقية للحوض العلوي تتراوح بين (0.5-260) م/سنة و للحوض السفلي بين (2-515) م/سنة. أما بالنسبة لطبقة يطا فكانت النفذية العمودية تتراوح بين 1×10^{-8} – 4×10^{-4} م/سنة.

كذلك بينت النتائج ان الحوض العلوي مستدام (sustainable) بشكل عام لأن كمية التغذية أعلى بكثير من كمية السحب من الابار الجوفية، بينما الحوض السفلي غير مستدام بسبب ارتفاع كمية السحب بحيث يتخطى كمية

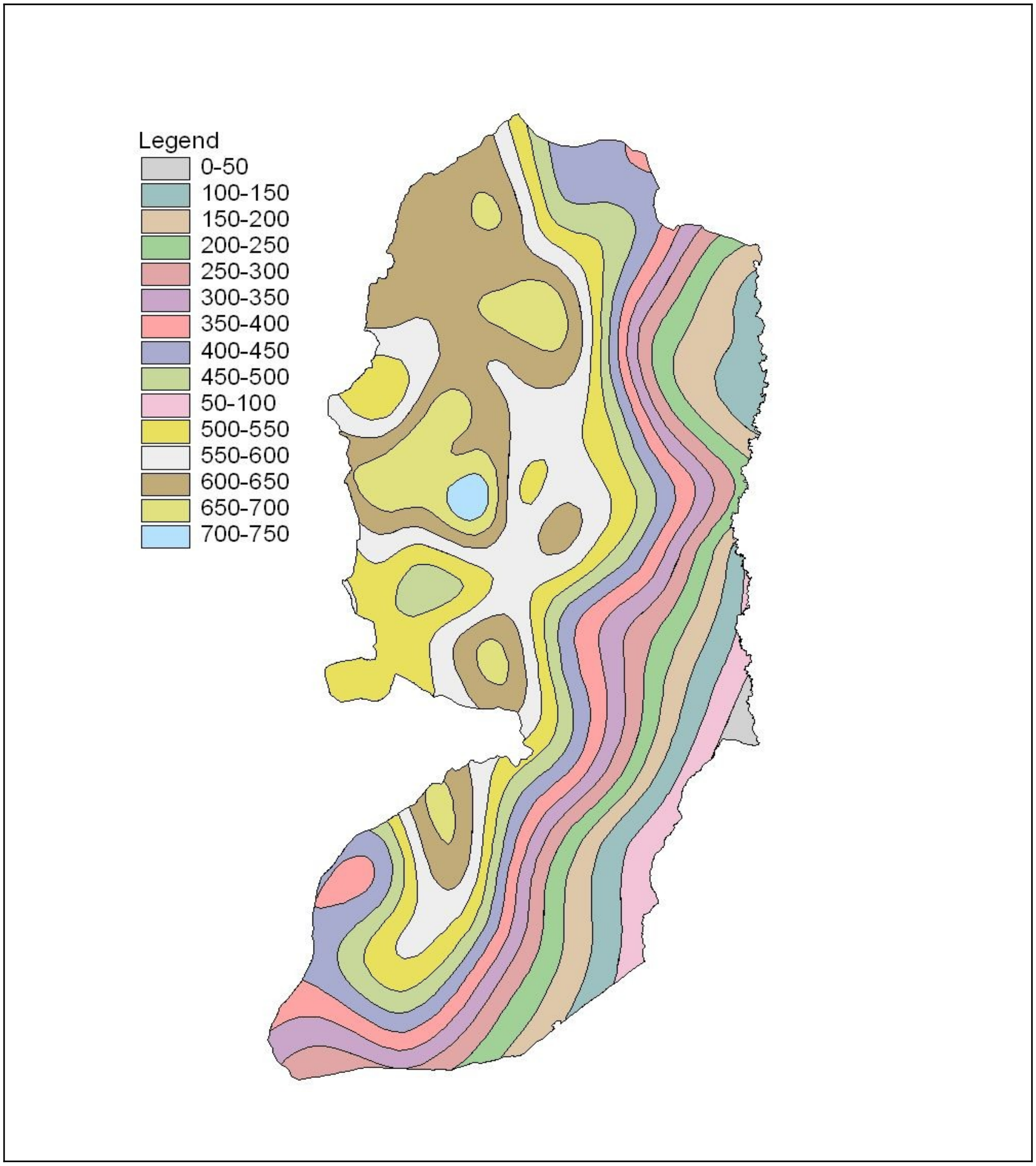
التغذية للحوض، و لكن ما يعوضه الى وجود اتصال بين الحوض العلوي و السفلي و يظهر هذا بصورة كبيرة في المنطقة الجنوبية الغربية من منطقة الدراسة.

كذلك أظهرت التوازن المائي للحوض الى وجود تدفق عالي في المنطقة الجنوبية الشرقية للحوض العلوي و السفلي على حد سواء. و يرجع وجود هذا التدفق العالي الى وجود شقوق كبيرة في ذلك الجزء من المنطقة.

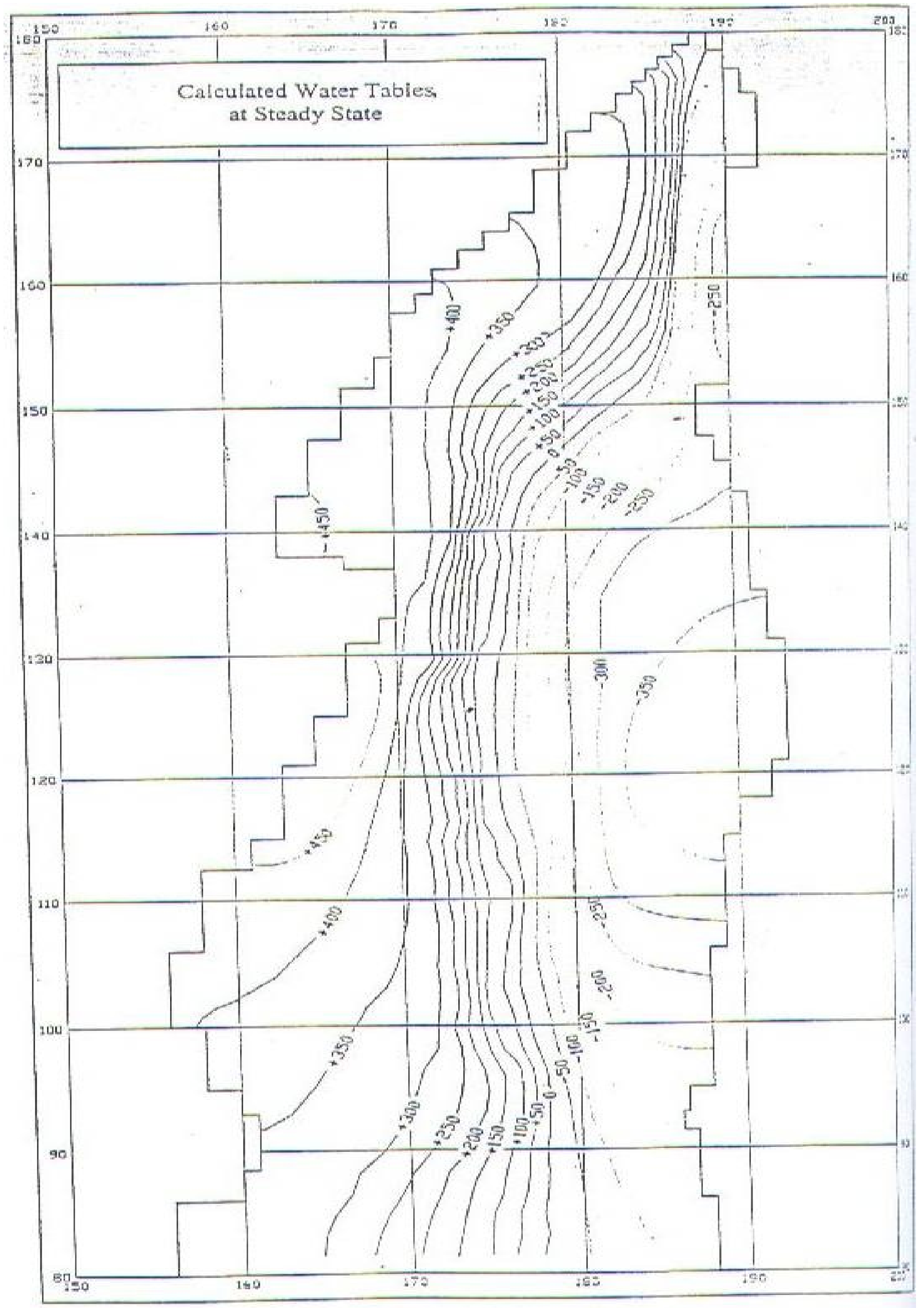
Appendix



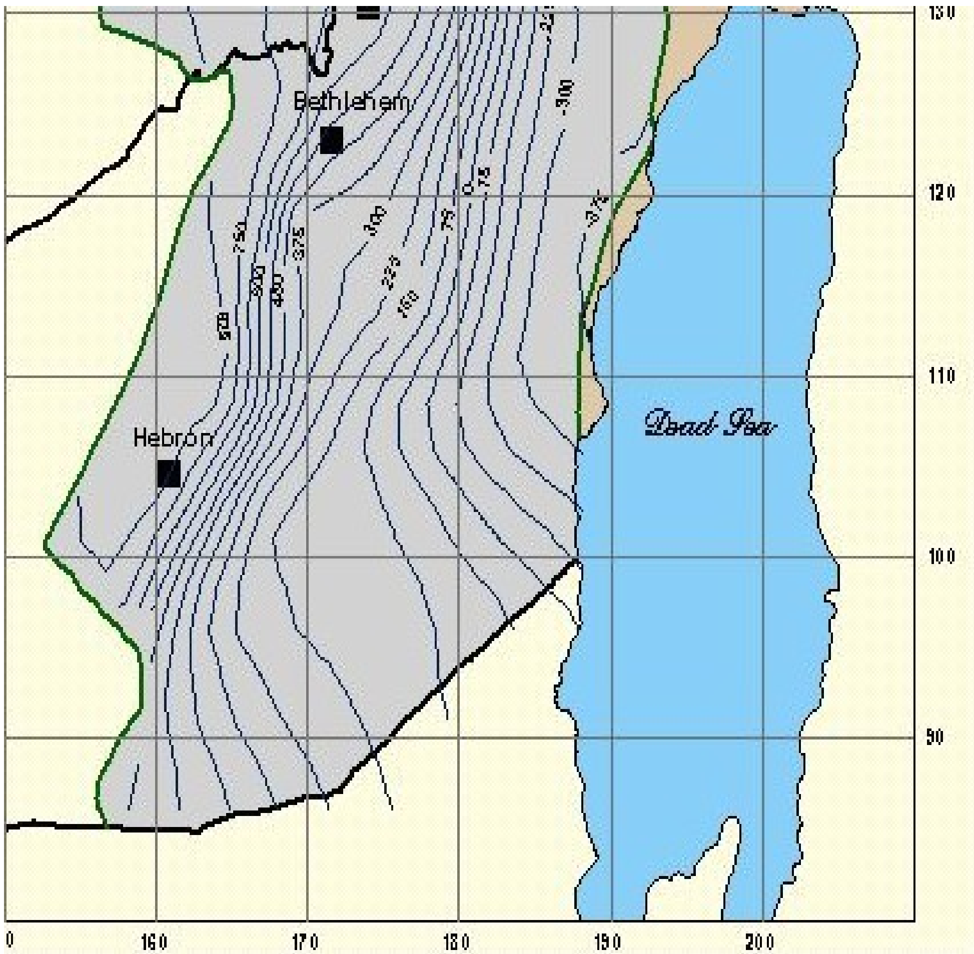
A1: Structural map of the West Bank
(Adopted from PWA Data Bank)



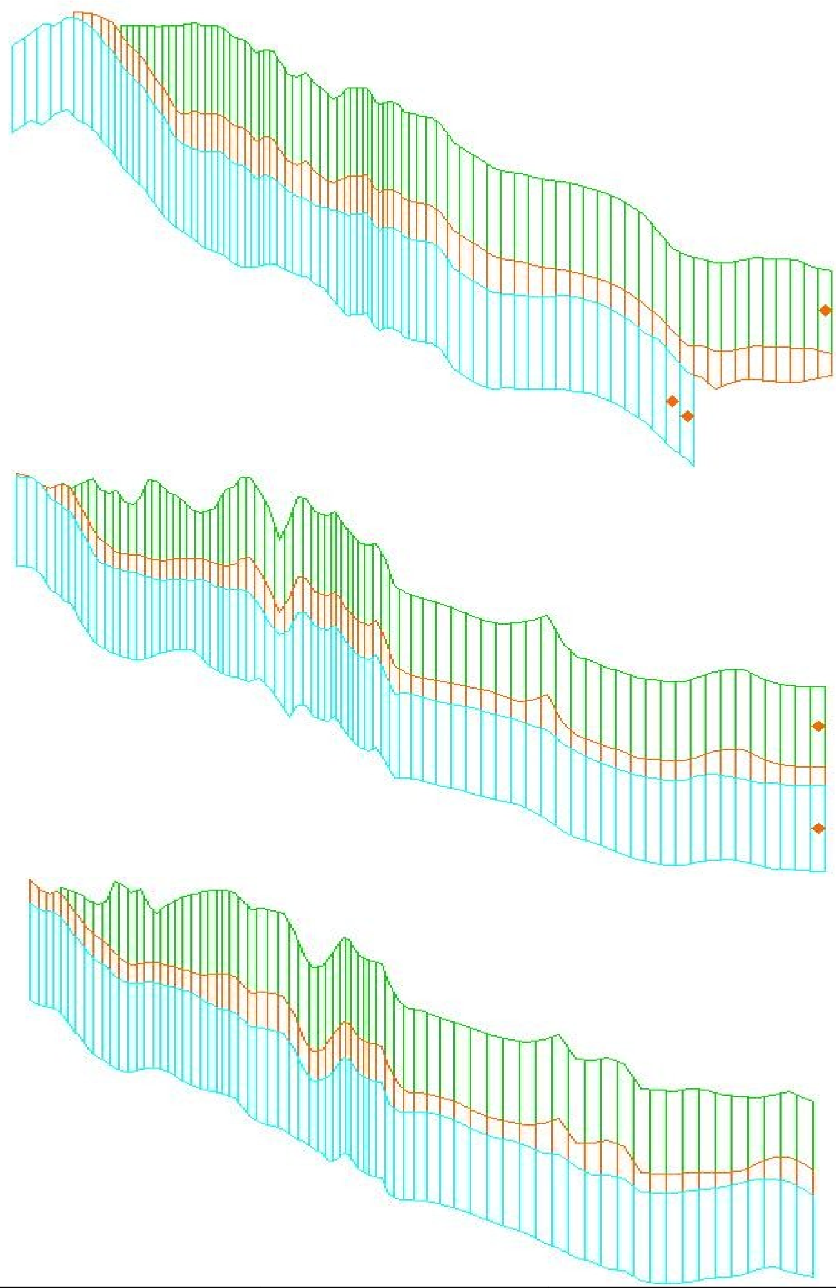
A2: Average Rainfall Map of the West Bank
(Adopted from PWA 1970-2000)



A3: Calculated Water Map for Lower Aquifer
(Adopted from Gutmann Report (1995)

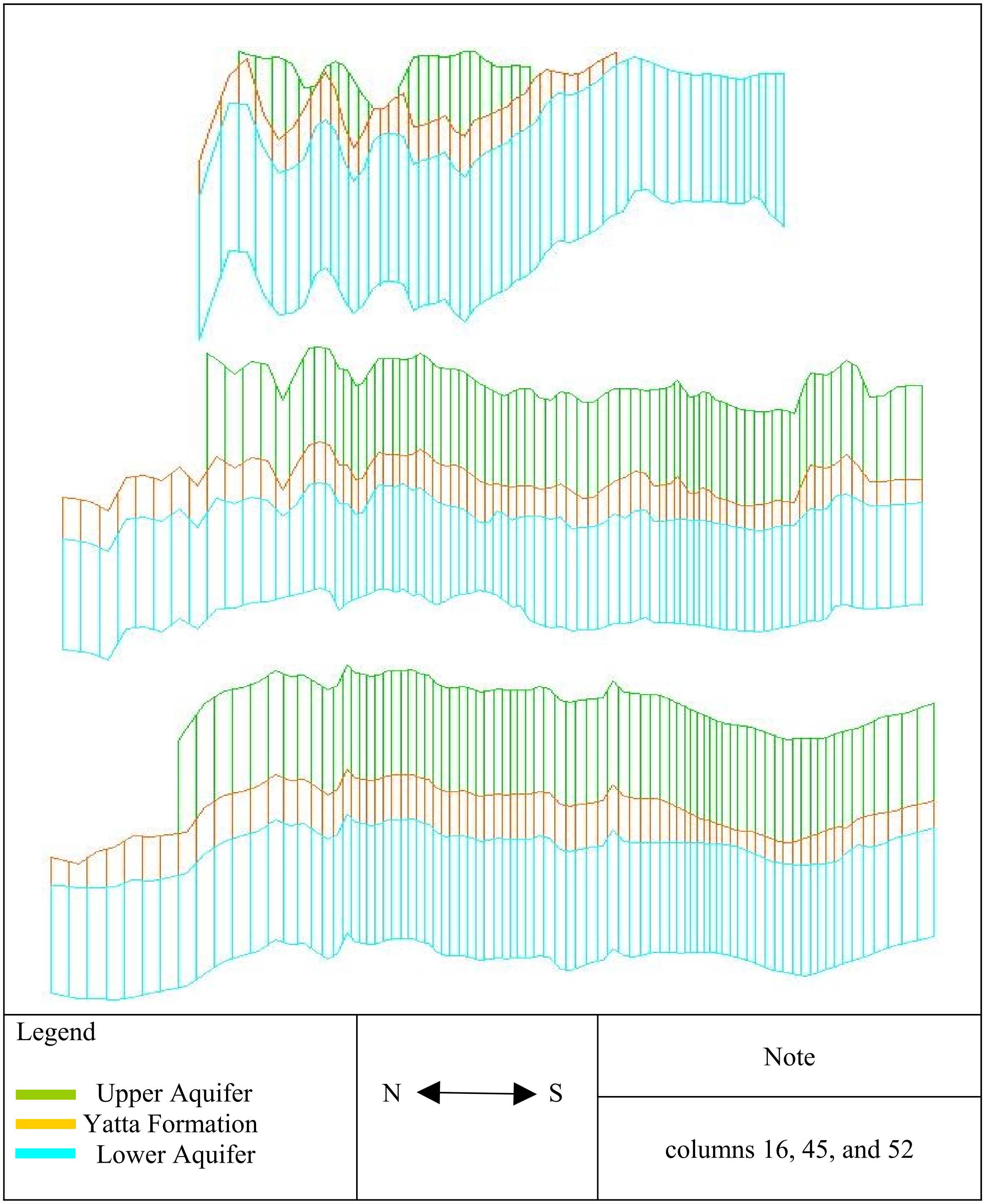


A4: Calculated Water Map for Upper Aquifer
(Adopted from PWA (2000))



Legend		Note
Upper Aquifer Yatta Formation Lower Aquifer	W ⟷ E	rows 44, 66, and 72

A5: West-East cross sections of the solution (Model Results)



A6: North-South cross sections of the solution (Model Results)