An-Najah National University

Faculty of Graduate Studies

Optimal Management of Groundwater Pumping
The Case of the Eocene Aquifer, Palestine

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I dedicate my thesis to my parents

My brothers and sisters

With all respect

Rana

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Abstract

The Eocene aquifer is an important source of water supply to local communities in Jenin district and parts of Nablus district. The aquifer is heavily utilized for agricultural activities in specific. It is believed that there is a potential for additional utilization of the aquifer through pumping. In order to verify this, a simulation/optimization model was developed in this study using the U. S. Geological Survery's MODFLOW and GWM. The groundwater model was constructed and calibrated under steady-state conditions. Based on the calibrated steady-state groundwater flow model, the annual discharge from the Eocene aquifer outside the West Bank is about 55 million cubic meters. This simulation model was then utilized in the development of the GWM model (optimization) to find out the optimal pumping rates that the aquifer can sustain without depleting the aquifer. The outcome from the GWM model shows that 23 mcm can be safely pumped out from the Eocene aquifer through the existing wells. This is achieved under the assumption that the Israeli wells tapping the aquifer pumps 11.7 mcm and that the drop in the saturated thickness does not

exceed 50%. Results are manifested and analyzed and the conculsions and recommendation are provided.

Chapter One
Introduction

1. 1 Importance of Groundwater

Water is essential for life. Groundwater—that part of all water that lies underneath land surface—constitutes more than ninety five percent of the global, unfrozen freshwater reserves. Given its vast reserves and broad geographical distribution, its general good quality and its resilience to seasonal fluctuations and contamination, groundwater holds the promise to ensure current and future world communities' safe water supply. Groundwater is predominantly a renewable resource which, when managed properly, ensures a long-term supply that can help meet the increasing demands and mitigate the impacts of anticipated climate change.

Groundwater has provided great benefits for many societies in recent decades through its direct use as a drinking water source, for irrigated agriculture and industrial development and indirectly through ecosystem and stream flow maintenance. The development of groundwater often provides an affordable and rapid way to alleviate poverty and ensure food security. Further, by understanding the complementary nature of ground and surface waters, thoroughly integrated water resources management strategies can serve to foster their efficient use and enhance the longevity of supply.

It is of great importance to manage efficiently the groundwater resources. Poor management and over exploitation can lead to adverse ramifications such as the intrusion of saline water in coastal aquifers and the depletion of groundwater resources. That is, when water is pumped out from an aquifer, the pumping rate should not be higher than the aquifer replenishment otherwise, water table may decline drastically. Apparently, efficient management of groundwater resources takes into account the prevention of the depletion of such resources while maintaining the maximum possible pumping rates.

In order to arrive at sound management decisions of groundwater resources (the quantity aspect), it is quite vital to understand the hydrogeology of the aquifer of interest. Such understanding and appreciation is attained through the development of a groundwater flow model that simulates the aquifer behavior under different pumping strategies as driven by the possible prevailing scenarios pertaining to natural (climate change) or man made effects.

However, simulation (modeling) though provides the potentiometric head distribution especially at control locations as a function of pumping rates from the different existing wells; it is indeed impossible to obtain an optimal pumping strategy out of that. It is the optimization when coupled with simulation can provide such an optimal strategy.

Simulation/optimization models for setting optimal pumping stratieges are powerful and can lead to reliable estimates of the potential safe yield of an aquifer under consideration.

Recently, many studies were developed to arrive at determining the optimal utilization of West Bank aquifer. Nevertheless, these studies did focus on utilizing groundwater flow models, explicitly.

This research focuses on the development of an optimal pumping strategy for the Eocene aquifer. This aquifer is an important source of water supply for local communities in Jenin district and parts of Nablus district. The aquifer is heavily utilized for agricultural activities. Yet there is a potential for further development of the aquifer based on the fact that the recharge largely exceeds the groundwater pumping where this surplus in water is ultimately flows northward beyond the Green Line.

Modeling the groundwater flow in the Eocene aquifer will provide basic information for the water resources manager to understand the behavior of the aquifer and thus support the decision making process regarding the future development of this aquifer especially for the agricultural sector.

Once the model is developed and calibrated, it becomes ready to simulate future management scenarios. These scenarios dictate the optimum pumping rates that would be considered for the Eocene aquifer to maintain water level at reasonable limits. However, in order to efficiently utilize the simulation model in developing the optimal pumping strategies; an optimization model that utilizes the developed simulation model was used.

As such, the Ground-Water Management (GWM) software of the United States Geological Survey (USGS) was utilized in this work to determine the optimal pumping strategies for the Eocene aquifer. The GWM utilizes MODFLOW to simulate the water table elevation for the decision variables (pumping rates).

To the best of my knowledge, this is the first time a simulation/ optimization model will be utilized in the management of groundwater resources in the West Bank.

1.2 Groundwater Resources in The West Bank

In Palestine, the large variations in rainfall and limited surface water resources have led to a heavy reliance on groundwater as the sole reliable source for various uses. The contribution of surface water to the overall water use in the West Bank is limited and marginal (Fadia Daibes-Murad, 2004). In the West Bank, there are three groundwater basins (see Figure 1.1) and these are (Abu Zahra, 2000):

Figure 1.1: The Groundwater Basins of the West Bank (UNEP, 2002)

1. The Western Basin: it is supplied and recharged from the West Bank mountains and extends beyond the western boundaries of the West Bank.

2. The Northeastern Basin: it covers Nablus and Jenin Governorates and drains into the Eocene and Cenomanian-Turonian aquifers.

3. The Eastern Basin: it is located entirely within the West Bank and the springs emerging out of it represent around 90% of spring discharge in this area.

The piezometry and geological structure indicate a defined groundwater divide between the Western aquifer and the Eastern aquifer basins, and between the Western and Northeastern aquifer basins (BGS, 2005).

Of the three basins, the Western basin is the most productive, flowing toward the Mediterranean with an annual replenishment capacity of approximately 362 million cubic meters (mcm), followed by the Eastern basin, with a capacity of 170 mcm and finally, the Northeastern basin at 145 mcm (PHG, 2004).

1.3 The Eocene Aquifer

The Eocene aquifer is one of several groundwater aquifers that provide water to local communities in the northern parts of West Bank with a total area of 526 Km^2. Part of this aquifer extends outside the West Bank (about 65 Km^2) where most of the productive Israeli wells are located.

The Eocene aquifer is located within the Northeastern basin and referred to as the Jenin sub-series (see Figure 1.2). The communities that are utilizing the Eocene aquifer depend mainly on its water to secure domestic and irrigation demands. The pumped water from this aquifer comes through variable types of renewable water-bearing carbonate rocks of limestone and chalky limestone with a variable thickness range from 300-500 m. Rainfall recharges this aquifer by considerable quantities of fresh water. Additional details about the Eocene aquifer are provided in the next chapter.

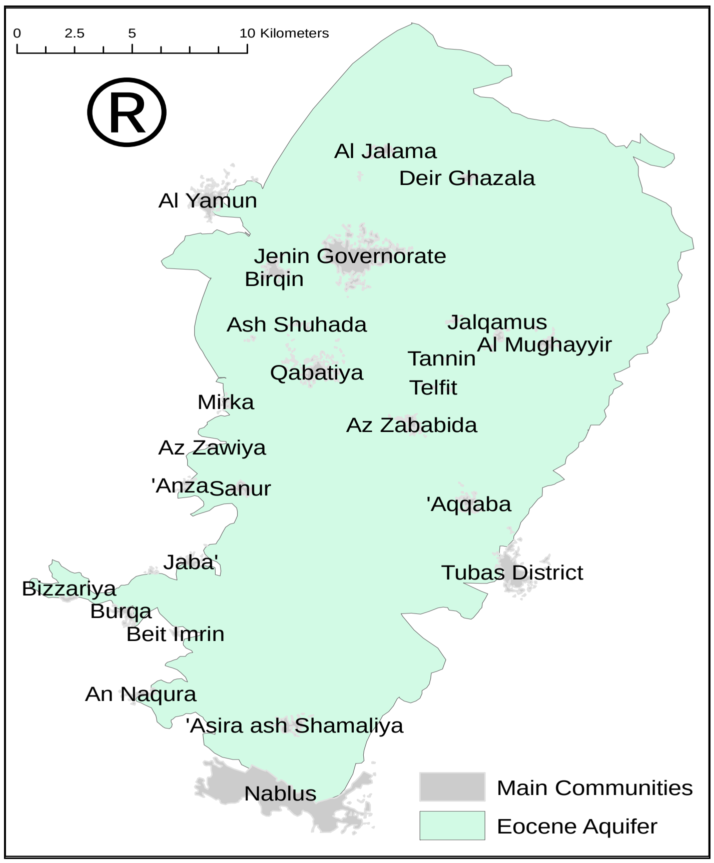


Figure 1.2: The Outline of the Eocene Aquifer Along with the Main Communities

1.4 Research Problem Identification

The following are research problems that apply well to the Eocene aquifer:

1. The sustainable yield of the Eocene aquifer is not fully known under various scenarios;

2. No previous attempts were made to utilize simulation/optimization techniques for the determination of the sustainable yield of the Eocene aquifer; and

3. Since the recharge from rainfall is the main replenishment to the aquifer, it is quite essential to figure out the impact of climate change scenarios on the spatial sustainable pumping rates from the Eocene aquifer.

1.5 Research Objectives

Based on the preceding discussion, the following are the broad objectives of this research:

1. To develop a management tool for the designation of the spatial distribution of the optimal (sustainable) pumping rates for the Eocene aquifer. This tool will be made available to the decision makers in the Palestinian water sector; and

2. To use the developed management tool in determining the optimal pumping rates under different scenarios

1.6 Research Motivation

1. The assessment of the potential yield of the Eocene aquifer is not previously determined in a scientific manner and systematic way;

2. Finding out the optimal pumping rates using the simulation/optimization code is an important contribution the field of management of the Palestinian groundwater resources; and

3. Since this is the first time to implement a simulation/optimization code to a groundwater management case in the West Bank, this would pave the road for other researchers to utilize similar techniques for other aquifer systems in the West Bank.

1.7 Research Overall Methodology

The cornerstone of the methodology is the development and utilization of the groundwater flow simulation model (MODFLOW) for the Eocene aquifer along with the optimization software (GWM). The methodology is comprised of the following: (i) Data collection; (ii) Data analysis; (iii) Development of the groundwater flow model; (iv) Optimization; (v) Scenario determination and processing; and (vi) Determination of the optimal pumping rates. The sixth chapter furnishes a great deal of details regarding the methodology and its implementation.

1.8 Thesis Outline

The thesis consists mainly of nine chapters. Chapter 2 describes the study area of the Eocene aquifer and its characteristics. Literature review is given in chapter 3. Chapters 4 and 5 provide a general background about groundwater flow modeling and the simulation/optimization tool (namely MODFLOW coupled with GWM). Chapter 6 clarifies the research methodology. An overview of the development of the groundwater flow model for the Eocene aquifer is discussed in chapter 7. Chapter 8 demonstrates the use of the GWM for the Eocene aquifer under different scenarios. Finally, conclusions and recommendations are provided in chapter 9.

Chapter Two
The Eocene Aquifer

2.1 Introduction

Palestinian entitlements for water include the groundwater of the West Bank and Gaza aquifers and their rightful shares in the waters of the Jordan River as a riparian country. However, at present, Israel utilizes at least 85% of the water from the Palestinian groundwater aquifers and Palestinians are denied access to the water of the Jordan River. This policy led to a severe water crisis in the Palestinian territory in general and the Gaza Strip in particular.

The West Bank uplands enclose the regional recharge area for the extended Lower and Upper Cretaceous carbonate limestone aquifers. Prior to well development and under natural conditions these aquifers discharged through springs (SUSMAQ, 2001).

Groundwater resources in the West Bank are derived from three aquifer basins through wells and natural springs. These aquifer basins are: the Eastern, Western, and Northeastern aquifer basin as shown in Figure 1.1 (SUSMAQ, 2001).

Northeastern basin encompasses Nablus and Jenin and drains into the Eocene aquifer and the Cenomanian-Turonian aquifer.

2.2 Northeastern West Bank Aquifers

The groundwater basin that lies between the cities of Nablus and Jenin drains north-eastwards into the Jalil. It is contained within a shallow syncline of Eocene strata floored by Upper Cretaceous rocks and partly covered by Quaternary sediments. About one third of the total area of the northern West Bank is of the Eocene, mainly nummulitic limestone group, referred to as the Jenin Subseries (Rofe and Raffety, 1965). This forms a triangular exposure, with Nablus in the south at the apex and Jenin in the north, in the middle of the base of this triangle. The Jenin Subseries is about 500 m thick and includes the following five faces (Aliewi et al., 1995):

1. chalk with minor chert;
2. chalk with minor interbedded nummulitic limestone;
3. limestone with minor interbedded chalk;
4. bedded massive nummulitic limestone;
5. reef limestone.

Karstic secondary porosity, the widening of joints, fractures and bedding planes by solution erosion, have made this basin an important aquifer. This Eocene basin is contained within the synclinal structure formed by the Upper Cretaceous strata which crop out to the east and west. The syncline plunges north-eastwards.

The area that includes Nablus, Jenin, Qabatiya, and Birqin is included in the Northeastern basin as shown in Figure 2.1. Rofe and Raffety (1965) define two aquifer systems, the shallow Eocene system and the deep Cenomanian-Turonian system. The Eocene system depends directly on the renewable recharge from precipitation, receiving an average annual rainfall of about 500 mm (Marei and Haddad, 1996). The water that enters this aquifer moves to the north-east (Rofe and Raffety, 1965). Many springs emerge from this aquifer and wells have been drilled for agricultural and domestic purposes.

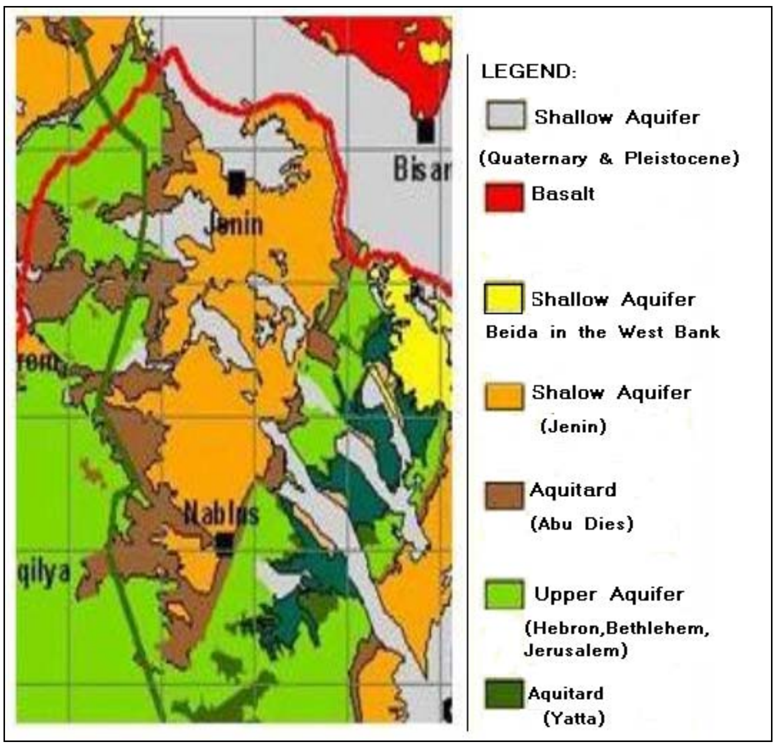


Figure 2.1: Geological Map of the Northeastern Basin Boundary

2.3 Geographical Location of the Study Area

This research studies the groundwater flow system of the Eocene (Jenin sub-series) aquifer which is part of the Northeastern aquifer basin. This represents the Nablus-Jenin syncline.

The Eocene aquifer is located in the north-eastern part of the West Bank. It is located to the north-eastern of the groundwater divide, which runs through the Jenin and Nablus district and part of it located at Tubas and outside the West Bank as shown in Figure 2.2.

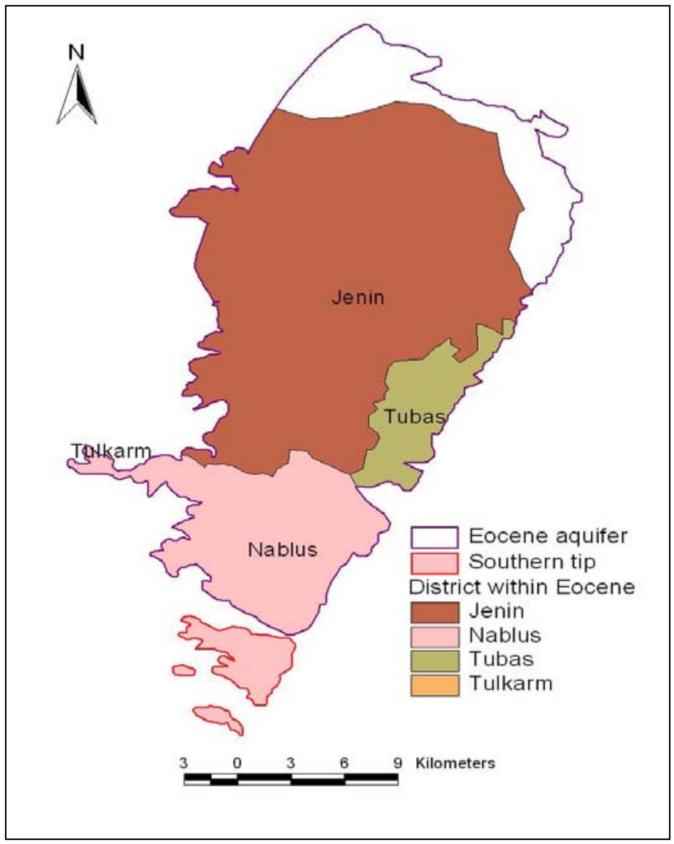


Figure 2.2: Eocene Aquifer Location

2.4 Southern Tip

The southern tip of the Eocene aquifer located at mountain Gerzim is not modeled in this study. This tip is a separate formation because of the physical separation caused by Senonian outcrops which isolate the southern tip from the Eocene aquifer. In addition, the literature and lithological features in the area do not clearly indicate a hydraulic connection between the two parts.

2.5 Study Area Geology

The stratigraphy and structural geology of the study area is very complex.

The Primary hydrostratigraphic features (from youngest to oldest) of the study area include:

- The Neogene Aquifer (Beida Formation) is composed of well-cemented conglomerates;
- The Eocene aquifer (Jenin Subseries Formations) is composed of limestones and nummulitic limestones;
- The Senonian Abu Dis Formation is composed of massive chalk, hard and bedded in its lower part and fragmented, soft and unbeded in its upper part;
- The Turonian and Upper Cenomanian (Jerusalem, Bethlehem and Hebron) Formations are composed of marls, marly limestones, limestones, dolomitic limestones and dolomites;
- The Lower Cenomanian (Yatta, Upper and Lower Beit Kahil) Formations are composed of marls, marly limestones, limestones, dolomitic lime stones and dolomites;
- The Qatana, Ein Qinya and Tammun/Albian Formations are composed of altering marls, marly limestones, shale and clay; and
- The Neocomian/Lower Cretaceous (Upper and Lower Ramali) Formation is composed of sandstone, interbedded with marl (CH2MHILL, 2002).

2.6 Cross-Sections of the Eocene Aquifer

Geologic cross-sections are the cornerstone to the conceptualization of the hydostratigraphy of any aquifer. They are used to evaluate the three-dimensional characteristics of folding, faulting and thickening of hydrostratigraphic units. Geologic cross-sections are essential to building a representative groundwater model because they allow the evaluation of the ways that subsurface geometry of hydrostratigraphic units affects groundwater flow. Once these features are conceptualized using cross-sections, they can be accurately represented mathematically in the groundwater model (MEG, 1999). The cross-section that describes the study area is shown in Figure 2.3 as obtained from BGS (2005).

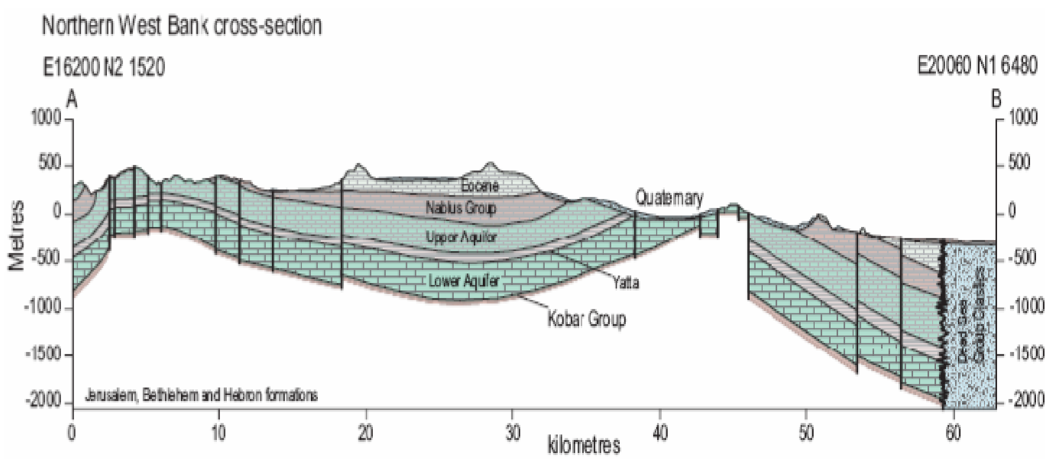


Figure 2.3: Northeastern Cross-section (BGS, 2005)

2.7 Structural Geology (Folding and Faulting)

2.7.1 Folding

The main foldings in this study area are the Nablus-Beit Qad syncline, the western water divide of the Northeastern aquifer lies the Anabta anticline, and at the eastern water divide lies Fari'a anticline (SUSMAQ, 2004).

The syncline is symmetrical with a gently dipping west limb and a steep east limb. The highest land occurs on the axial part of the major Nablus-Beit Qad syncline. The axis generally trends north-northeast to south-southwest. But near Jamma'in it tends sharply westwards.

This is a shallow north-south symmetrical structure, which bends westwards at its southern end towards Qalqilia where it dies out. There are two folds, one in the southwest, the Ein Qiniya anticline, and one in the northeast, the fari'a anticline, and between these is a minor impersistent syncline southwest of Qabalan (SUSMAQ, 2004).

The surface water divide follows the Ein Samiya Syncline in the south and the Nablus-Beit Qad Syncline in the north near Awarta (SUSMAQ, 2004).

2.7.2 Faulting

The main faulting in this study area are Fari'a and Gilboa' fault. Faulting in the Fari'a area follows the general axis northwest southeast. Faulting has resulted in the formation of several garben structures in the area. The effect of faulting on the Eocene limestones of the western West Bank is less visible than on the dolomitic limestones of the Turonian-Upper Cenomanian. In the northwest-southeast block, faults occur primarily in the east. Some penetrate through the Eocene, as shown in Figure 2.4 (SUSMAQ, 2004).

The Gilboa' Fault is a major fault and is defined as the boundary of the northeastern part of the Eocene aquifer. (It does not include the part after the fault, where the fault separates the two parts with minor connection and water flow).

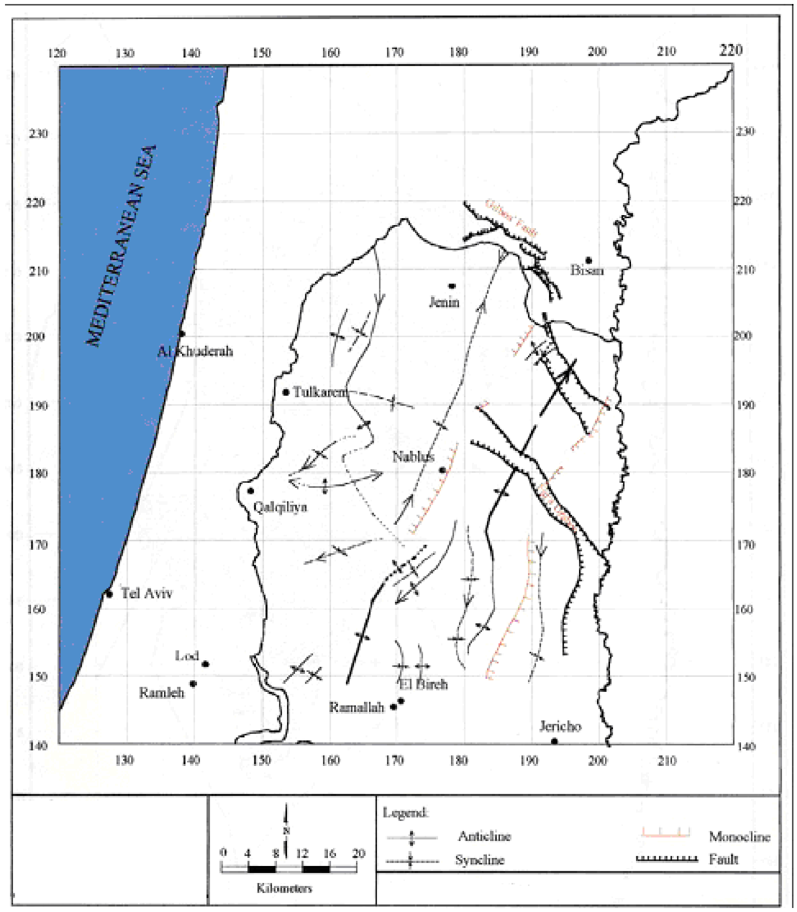


Figure 2.4: General Tectonic Sketch-Map of the Northern West Bank (SUSMAQ, 2001)

2.8 Topography

The central and northeastern parts of the Northeastern basin have a relatively flat to hilly topography that rises about 300 to 600 meters above sea level (masl). The area is characterized by closed and semi-closed depressions such as Marj Sanur and the Arrabeh Plain as well as the flat area north of Jenin City. The western slopes of the Anabta Anticline in the Northeastern basin have elevations ranging from 300 to 600 masl as shown in Figure 2.5 (CH2MHILL, 2002).

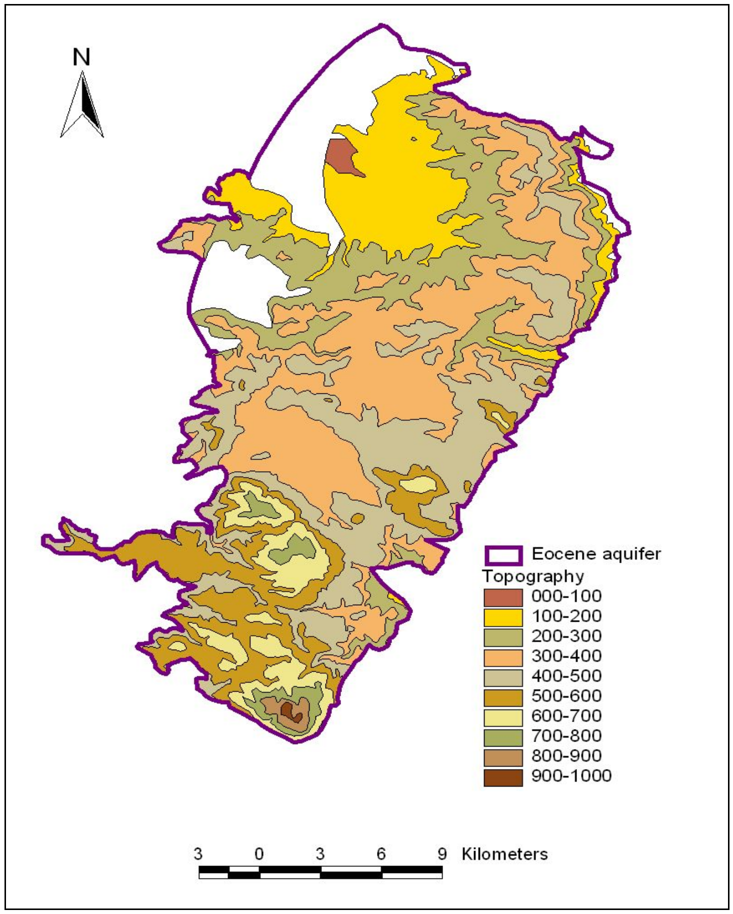


Figure 2.5: Topography of the Eocene Aquifer

The topography of the Jenin district can be divided into three areas; the eastern slopes, the mountain crests and the western slopes. The eastern slopes are located between the Jordan Valley and central highland. They are characterized by steep slopes, which contribute to forming young wadies. The mountain crests from the watershed line separates the eastern and western slopes. Altitude ranges on average between 500 and 650 masl. The western slopes, characterized by gentle slopes, have elevation ranges between 100 and 400 masl (ARIJ, 1996).

Nablus lies in a synclinal area extending west to east with an altitude varying from 440 masl in the bottom of valley to about 900 masl in the hills of north Ebal (Tubeileh, 2003).

2.9 Climate

The West Bank has a Mediterranean climate. There are two clearly defined climatic seasons; a wet winter and a dry summer. The rainy season extends from October to May. The highest annual rainfall in the west of Jenin area is about 600 mm. Average annual rainfall decreases sharply from 650 mm at Nablus to 150 mm to the east of the study area at the Jordan Valley. The lowest temperature occurs in January and February and the maximum rainfall occurs in January.

There are nine rainfall stations in the study area. The quantities of rainfall from these stations range between 642 mm in Tallozah station and 400 mm in Bait Dajan station (see Figure 2.6).

In winter, the minimum temperature is around 7 ºC and the maximum is 15 ºC. Temperatures below the freezing point are rare. In summer, the average maximum temperature is 33 ºC and the average minimum is 20 ºC.

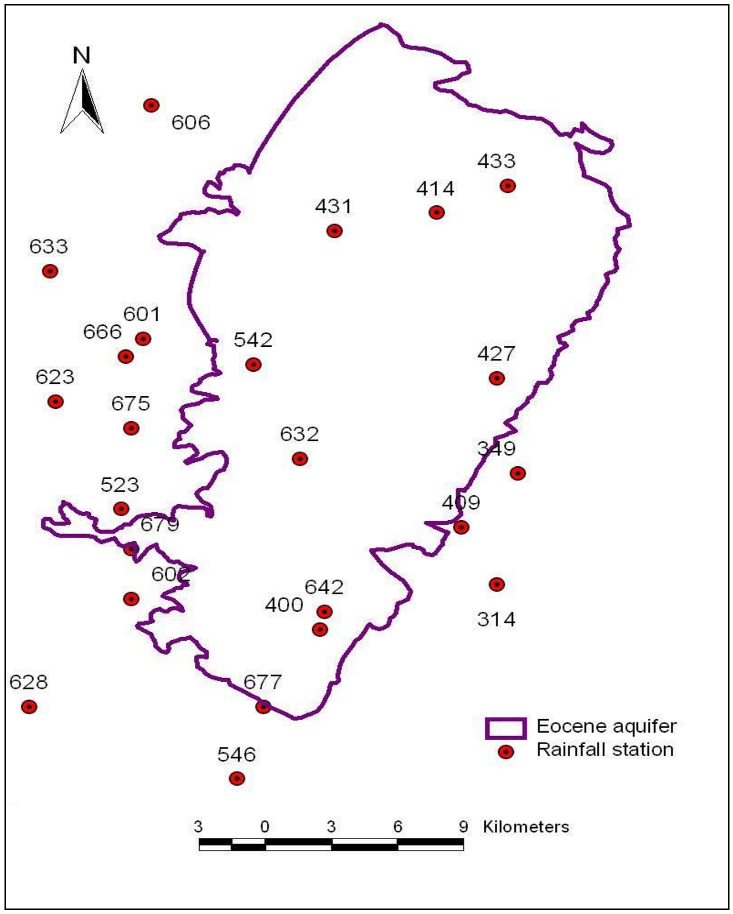


Figure 2.6: The Distribution of Rainfall Stations in Eocene Aquifer Along with the Average Annual Rates of Rainfall

Rainfall intensity varies according to topography and storm event. The number of rainy days range from 25 days to 60 days. Evaporation is particularly high in summer and low in winter (MEG, 1999). Towards the west, the rate of evaporation decreases. The evaporation range from 1850 mm to 2100 mm (see Figure 2.7) .The average annual relative humidity is around 62% with peak values in winter up to 84%. It drops to 40% on average during May. In summer, the average annual humidity is 56%.

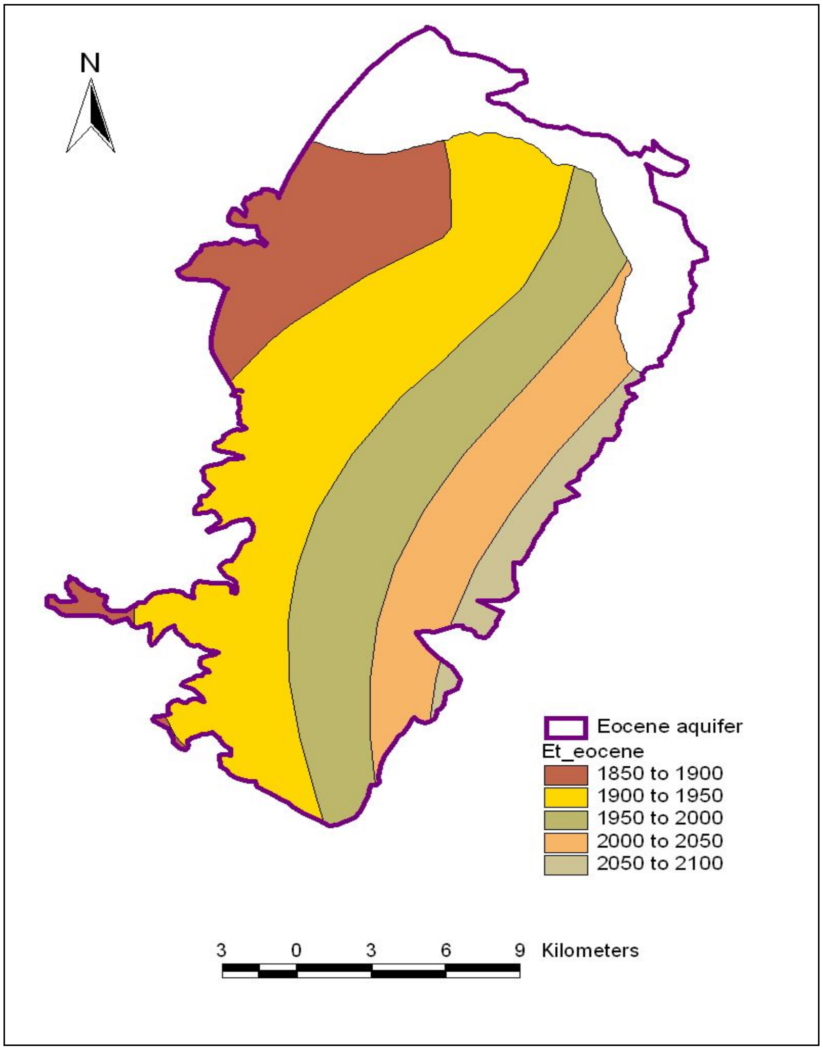


Figure 2.7: Evaporation Rates of the Eocene Aquifer. (Note that for Areas Outside the West Bank no Data is Available)

2.10 Land Use

The land use patterns within the study area have been shaped up by topographical and climatic conditions as well as by political factors. Such factors affect the distribution of the cultivated areas, urban Areas, road construction and other land uses. The land use can be classified into the following categories:

- Built-up areas: due to the restrictions imposed by the Israelis on granting building permits to the Palestinians, the Palestinians built-up areas are very limited;
- Israeli Settlements: the settlements are distributed over the study area and there is a gradual progressive expansion in the Israeli settlements;
- Closed military and bases: the Israeli army occupies Palestinian land by claiming that these areas are important both as security zones and for military purposes;
- Natural reserves: the Israeli authorities declare a piece of land as a natural reserve;
- Forests: there are many forests in the study area and most of these forests are located on fertile soil types;
- Cultivated areas: the total cultivated area varies from one year to another depending on the annual amount of rainfall. About 7.88% of the cultivated areas are irrigated from rainfall and about 92.12% of are irrigated by another sources of water (see Figure 2.8);
- Industrial area: there are few industrial zones in the study area;
- Dumping sites: there are many dumping sites in the study area;
- Quarries: there are five quarries in Jenin district;
- Roads: there are 77 km of main roads and 382 km of secondary roads in Jenin district;

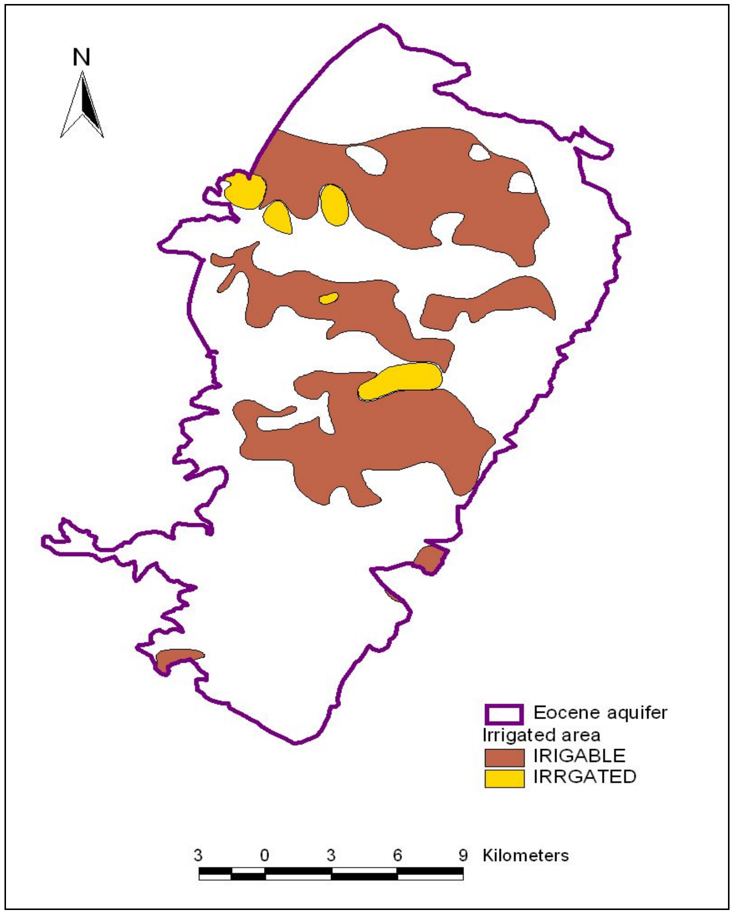


Figure 2.8: Cultivation Area in the Eocene Aquifer

2.11 Soil Types

The study area is well-known for its fertile agricultural land, which can be divided into three major soil associations as shown in Figure 2.9:

1. Terra Rossa, Brown Rendzinas and Pale Rendzinas: This type of soil association occupies of about 63.10% of the study area;
2. Brown Rendzinas and Pale Rendzinas: this type of soil association occupies of about 9.17% of the study area;

3. Grumusols: The topography of this soil is almost flat and is originally formed from fine textured alluvial or aeolian sediments and it occupies about 27.73 % of the study area.

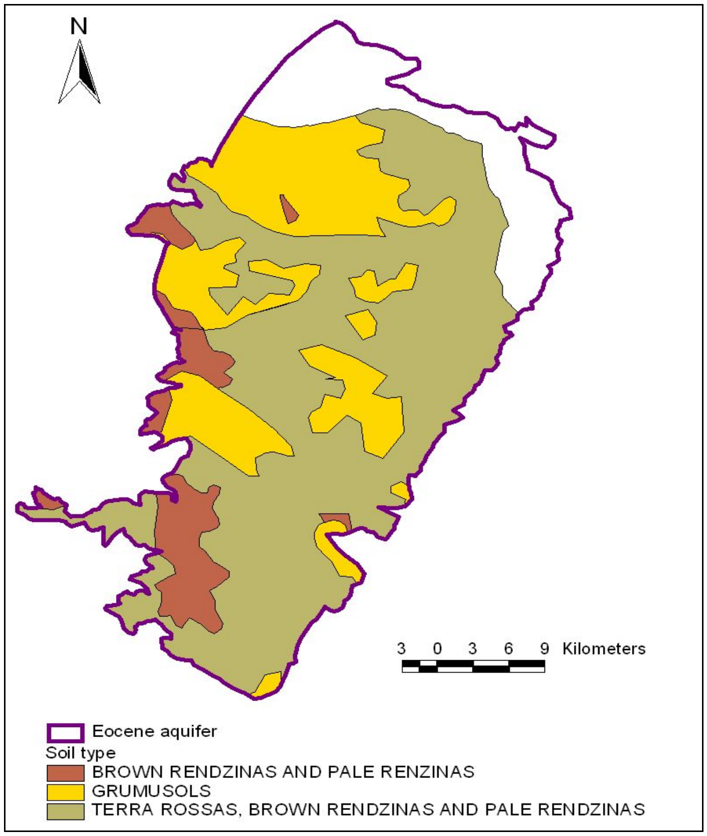


Figure 2.9: Soil Association at the Eocene Aquifer (Note that Outside the West Bank no Data is Available)

2.12 Communities Living within the Outline of the Eocene Aquifer

Three Palestinian districts are located within this aquifer and these are: Nablus, Jenin and Tubas .There are 27 grouped communities within the study area as shown in Figure 2.10.

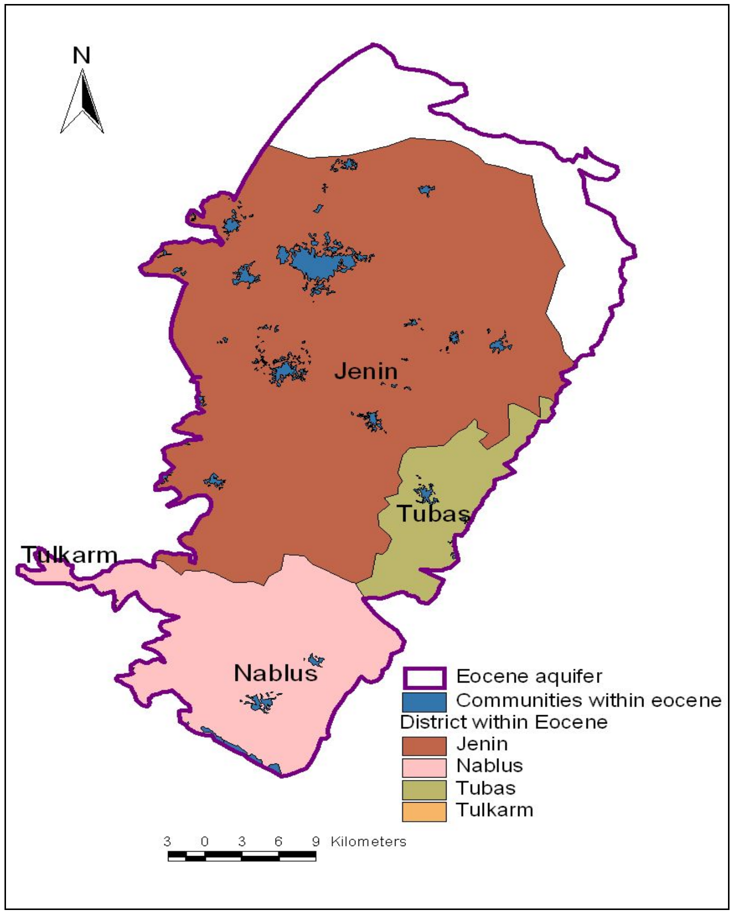


Figure 2.10: Communities Living within Eocene Aquifer (Note that Outside the West Bank no Data is Available)

Chapter Three
Literature Review

3.1 Introduction

In recent years, groundwater simulation models have been linked to optimization tools to address important groundwater management problems. The combined simulation and optimization model accounts for the complex behavior of the groundwater system and identifies the best management strategy considering specific constraints. This chapter summarizes the relevant recent studies about simulation/optimization models and the previous studies regarding the Eocene aquifer and Northeastern Basin.

3.2 Application of Groundwater Simulation/Optimization Models

Chau (1992) uses the simulation/optimization approach to design relief well system for the Cochran Valley aquifer in Alberta, Canada, which has been subject to excessive pressure since the filling of a reservoir that is hydraulically connected to the aquifer. A two dimensional groundwater flow model is used to simulate changes in groundwater heads with changes in reservoir level. The management model seeks to determine the locations and discharge schedules of relief wells such that the managed hydraulic heads are less than or equal to the grouped surface elevation and the total water losses from the ground water system are minimized. The general conclusion is that existing relief wells are inadequate, but it would be possible to relieve aquifer pressure with new wells. Further, it is shown that simple functions can be used to relate necessary well discharge to reservoir stage. In this way the relief wells can be operated in real time in response to changes in reservoir levels.

Nishikawa (1998) developed a simulation/optimization model for the optimal management of the city of Santa Barbara's (California, US) water resources during drought. The model, which links groundwater simulation with linear programming, has a planning horizon of 5 years. The numerical simulation model used in this study is MODFLOW. The objective is to minimize the cost of water supply subject to water demand constraints, hydraulic head constraints to control seawater intrusion, and water capacity constraints. The decision variables are monthly water deliveries from surface water and groundwater pumping rates. The state variables are heads at specified control locations. The response coefficient method was used to estimate the head from a particular pumping pattern. By use of response coefficients, it is implicitly assumed that the groundwater system responds linearly to pumping and recharge stresses. LINDO (Scharge 1991) was used to solve the optimization problem.

The study of Belaineh et al (1999) aimed to enhance conjunctive water use by simulation/optimization models that would especially benefit irrigated agriculture in areas where there is significant interflow between surface and groundwater resources. The new models better reflect stream/aquifer (S/A) systems interflow response to reservoir releases, stream-flow diversions, and groundwater pumping. These models describe aquifer recharge due to percolating irrigation water and conveyance losses. The simulation/optimization model computes optimal groundwater pumping, reservoir release, stream diversion, and the resulting system responses, including aquifer hydraulic head, stream reach outflow, and end-of-time reservoir storage. For the tested system, improving S/A interflow representation alone permitted 13% more water use. Downstream flow was also better managed since unnecessary flow leaving the model area was reduced by 52%.

Finney et al. (1992) develop an optimization model for control of saltwater intrusion in the Jakarta Basin, Indonesia. The goal is is to identify the pumping and recharge policy that minimizes the squared volume of saltwater intrusion. They show that increased water demands will lead to a significant degradation in the basin. They then demonstrate that, in comparison to historical policies, an optimized policy that redistributes pumping and introduces artificial recharge can significantly reduce the salt-water volume.

Danskin and Frackleton (1992) use a simulation/optimization model to address the problem of high groundwater levels in the San Bernardino Valley, California. In this case, a decrease in agricultural groundwater usage along with above average recharge has caused groundwater heads to rebound, causing a variety of groundwater related problems. Linear programming is coupled with a transient, multi-layer groundwater flow model to determine the most efficient pumping policy to reduce hydraulic heads in the effected areas. To account for the nonlinearities associated with the evapotranspiration function, an iterative solution method is used. Danskin and Frackleton solve twenty-six alternative model formulations, evaluating the effects of variations in the hydraulic head targets, maximum time to meet draw down targets, amount of recharge, and number and locations of managed wells. The Primary conclusion was that the head constraints could not be met in a twelve-month period using the existing facilities. Only with a combination of existing and new wells could the drawdown targets be met under all studied conditions.

Gharbi et al. (1994) adapted an embedding optimization modeling approach to aid groundwater quantity and quality management of the complex nonlinear multilayer of Salt Lake valley aquifers, Utah, US. Implicit block-centered finite difference approximations of the two-dimensional advection-dispersion transport equation are embedded directly as constraints in the model. The embedding technique can be applied successfully to optimize long term, reconnaissance scale planning of large-scale nonlinear groundwater problems. The use of both linear and nonlinear formulations in a cyclical manner reduces execution time and improves confidence in the optimal solution. The methodology is demonstrated for Salt Lake valley where groundwater quantity and quality management are needed, the proportion of pumping cells and cells needing head constraints is large, and many flows are described by discrete nonlinear or piecewise linear functions. Having both nonlinear and linear forms of the same problem is a key element of the process. The nonlinear form can be essential for developing an initial feasible or optimal solution. The linear form frequently solves and converges much more rapidly in subsequent optimizations. The simulation abilities of this embedding approach are useful for coarse management of groundwater flow and dispersed groundwater contamination. It is assumed that each cell might have many wells and that treating a cell's pumping as if it were uniformly distributed across the cell is appropriate. This approach is not substitute for the detailed transient management capabilities of the response matrix approach. The approach should be useful for integrated management of groundwater supply and non-point source pollution. The objective function emphasizes both maximizing groundwater pumping and achieving target groundwater qualities. The use of weights in the objective function makes it easy to determine trade-offs between management goals.

Alley et al (1999) emphasized in their study the issue of sustainability of groundwater resources on many interrelated facts and concepts. They extensively discussed the idea of that volumes of water pumped from a groundwater system must come from somewhere and must cause a change in the groundwater system. Possible sources of water for pumpage are: (1) more water entering the groundwater system (increased recharge), (2) less water leaving the system (decreased discharge), and (3) removal of water that was stored in the system. One of the critical linkages is between groundwater and surface water. Pumping water from aquifers that are hydraulically connected with surface water bodies can have a significant effect on those bodies by reducing groundwater discharge to surface water and possibly causing outflow from those bodies into the groundwater system .Thus, an evaluation of groundwater management strategies need to involve consideration of surface water resources among other considerations.

3.3 Studies on the Eocene Aquifer and Northeastern Basin

There are many previous studies on the Northeastern basin that have covered its geology, hydrology and structural system. Picard (1929) was the first to investigate the geology of the northern area of the West Bank, relating spring flow to faults and geologic structure. Blake and Goldschmidt (1947) also conducted some of the earliest comprehensive work on geologic and groundwater in the northeastern area. This work was a compilation of data collected during 20 years of work in the region (CH2MHILL, 2002).

In the early 1960s, the Hashemite Kingdom of the Jordan Central Water Authority commissioned the British consulting firm "Rofe and Raffety" to perform detailed hydrogeologic studies in the West Bank. These detailed studies define the basic geologic framework upon which many subsequent studies have been based. Rosenthal (1965) surveyed groundwater resources of the Besan area and studied the flow regime of the Eocene aquifers in the Northeastern Basin (CH2MHILL, 2002).

The University of Newcastle and the Palestinian Hydrology Group in 1995 developed a MODFLOW-based model for the flow system of the upper unconfined Eocene aquifer. The study highlights the importance of the renewable yield of the Eocene aquifer and provides a water balance (SUSMAQ, 2001).

CH2MHILL (2002) constructed a groundwater flow model for the shallow aquifer which includes the Eocene formations and alluvium deposits for the Northeastern Basin and the eastern tip of the Eastern basin. The model was calibrated under both steady state and transient conditions. Based on the model calibration results, the total long-term average recharge from rainfall is about 165 mcm/yr and about 82 mcm/yr of this recharge is being abstracted by wells, while the remainder flows to the Gilboa'a area to the north or the Jordan valley to the east (SUSMAQ, 2004).

Tubeileh (2003) developed a groundwater flow model for the Eocene aquifer. She used visual MODFLOW to construct the contour map of the potentiometric heads of the aquifer and found that the groundwater budget for the Eocene aquifer is about 72 mcm and the recharge and hydraulic conductivity were the most influential sensitive model parameters.

A detailed study on the hydrology and flow modeling for the Eocene aquifer of the North-Eastern Basin was prepared by SUSMAQ team in 2004. This study was part of the regional SUSMAQ project that aims at assessing the sustainable yield of the West Bank and Gaza aquifers. The modeling study focuses on the geology and hydrology of the Eocene aquifer of Northeastern aquifer basin, its inflows (recharge) and outflows (spring and well abstractions). The conceptual and steady-state models are followed by the transient model, using Groundwater Modeling System (GMS) software modeling code. According to the steady state conditions of the period 1985-1990, the calibrated model showed that around 63 mcm/year were entering the Eocene aquifer system as net recharge, while the same amount was leaving the system through several outlets. The model showed high sensitivity to recharge variation, since the aquifer is a renewable one. During the transient–state period 1991-2000, the simulated recharge ranged from 65 mcm/year to 142 mcm/year. The model showed that there were high uncertainty regarding the missing data of discharge and pumping rate of the Israeli springs and wells in the northern side of the model boundary.

As can be seen from the above literature review regarding the Eocene aquifer, no attempt was made previously to develop a simulation/optimization model for the optimal management of the Eocene aquifer.

Chapter Four
Groundwater Modeling: General Background

4.1 Introduction

The consideration of groundwater in development and planning of water resource has been frequently neglected because many believed that groundwater could not be adequately evaluated in terms of availability, quality, cost of development, or effect of development on the surface-water supply. The development of predictive groundwater models now provides adequate tools to evaluate management actions. Highly sophisticated mathematical models can be used in planning the development of groundwater and the conjunctive use of groundwater and surface water. About 250 different models have been used to evaluate groundwater problems (Moore, et al., 1979).

Groundwater hydrologists are responsible for formulating a representative conceptual model, selecting parameter values to describe spatial variability within the groundwater flow system, as well as spatial and temporal trends in hydrologic stresses and past and future trends in water levels.

The best tool available to help groundwater hydrologist meet challenge of prediction is usually a groundwater model (Anderson, et al., 1992). With these models, one can easily predict the response of an aquifer in terms of poteniometric head due to the different acting stresses such as pumping and recharge. In fact this is the essence of groundwater management, where pumping rates are altered until meeting a specific head value as shown in Figure 4.1.

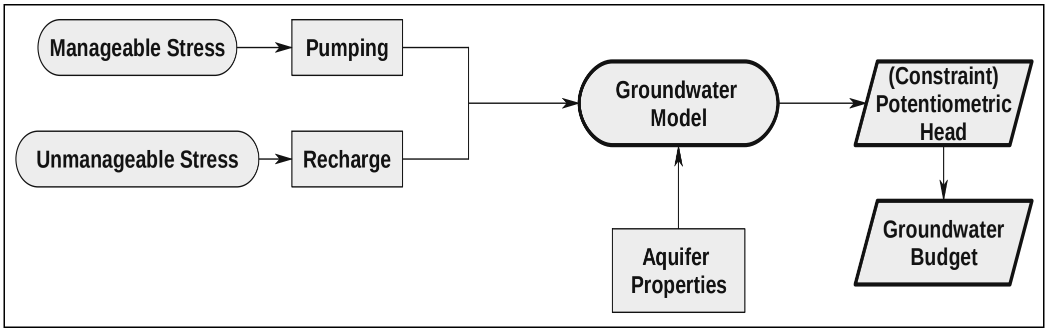


Figure 4.1: Simple Representation of a Groundwater Flow Model

4.2 What is a Groundwater Model?

First of all, a model is a tool that represents an approximation of a field situation. Models are the best available alternative for analyzing complex resource problems (Anderson, et al., 1992).

A groundwater model is a mathematical model that provides a relationship between aquifer response and external stresses.

Because a model is a simplified version of a real-world system, no model is unique to a given groundwater system. The first step in the modeling process is the construction of a conceptual model consisting of a set of assumptions that verbally describe the aquifer properties, the flow processes that take place in it, the mechanisms that govern them, and the hydrogeology of the aquifer. This is a vision by the modeler for constructing a model as intended to provide information for a specific problem (Bear et al., 1992).

It should be kept in mind that applications of groundwater models do require extensive field information for input data and for calibration (Anderson et al., 1992). However, this depends largely on the purpose and application type of the model.

4.3 Types of Modeling Applications

There are general types of modeling applications and these are (Anderson et al., 1992):

- Predictive: models are used to predict the future and thus requires calibration;
- Interpretive: models are used as a framework for studying system dynamics and/or organizing field data and thus do not necessarily require calibration;
- Generic: models are used to analyze flow in hypothetical hydrologic systems to help for example setting up regulatory guidelines for a specific region. These models do not necessarily require calibration.

4.4 Modeling Protocol

The process of model development encompasses the entire modeling protocol described below (see

Figure **4.2**) (Anderson et al., 1992):

1. Establish the purpose of the model;
2. Develop a conceptual model of the system;
3. Select the governing equations and a computer code;
4. Model design;
5. Calibration;
6. Sensitivity analysis;

7. Model verification;

8. Prediction;

9. Presentation of modeling design and results;

10. Postaudit; and

11. Model redesign (if needed).

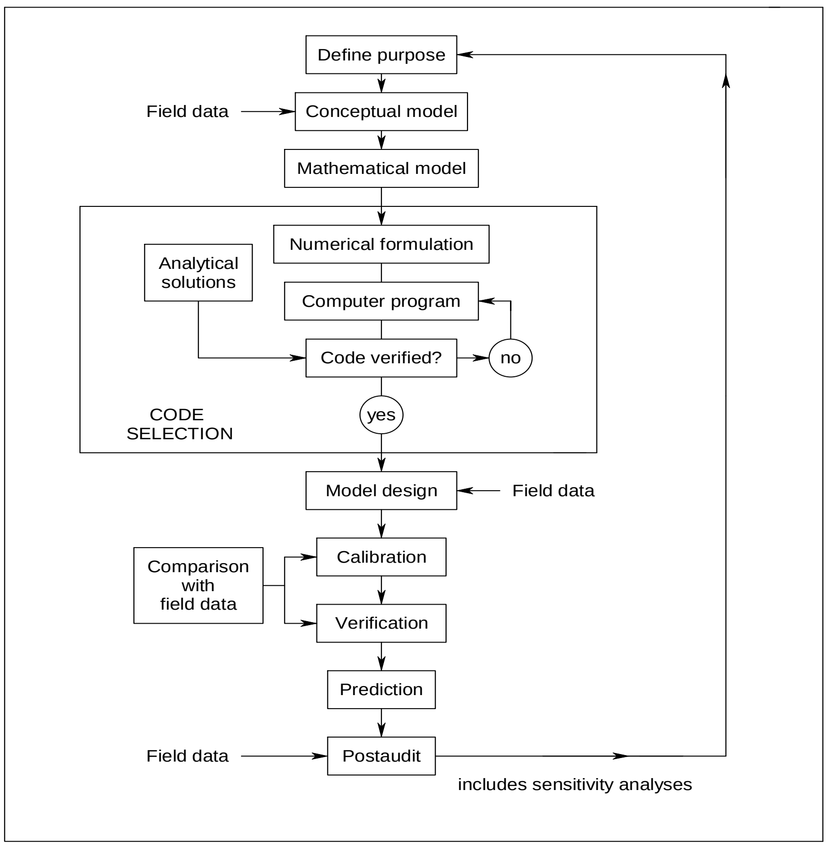


Figure 4.2: General Steps in Modeling Protocol

4.5 Modeling as a Management Tool

In groundwater systems, management decisions may be related to rates and location of pumping and artificial recharge, changes in water quality, location and rates of pumping in pump and treat operations, etc (Bear et al., 1992).

An essential part of a good decision-making process is that the response of a system to the implementation of contemplated decisions must be known before they are implemented (Bear et al., 1992).

This fact is quite important since these models will provide the necessary information that a water resources manager would need to assess the efficiency of a specific management decision. Based on this information, the best management strategy can be chosen out of a set of strategies.

4.6 Data Requirements for Groundwater Models

The data requirements for groundwater models depend upon many factors such as the hydrologic complexity of the area, types of water problems, and size of area. Some studies require sophisticated large-scale model analysis while others require only a descriptive evaluation of existing hydrologic data (Bear et al., 1992).

The types of field information needed to build a model can be classified into two categories and these are: (i) field data to define the physical framework; and (ii) field data to describe the hydrologic stresses on the system (Bear et al., 1992).

4.7 Simplicity and Complexity of Groundwater Models

It should be distinguished between physical and mathematical models. In mathematical models, the aquifer system and its behavior are represented in the form of mathematical expressions, e.g., partial differential equations or linear algebraic equations (Bear, 1979). In addition, time is discretized.

The physical model is regarded as a simulator; the flow regime in the aquifer is simulated in the model.

It is obvious that an aquifer can be modeled in a great number of ways depending on the assumptions that are made in order to simplify the real physical system. The choice of the most appropriate conceptual model for a given aquifer system and for a given management problem is dictated not only by the features of the aquifer itself (e.g., its geological properties), but also by the following criteria:

I) It should be sufficiently simple so as to be amenable to mathematical treatment;

II) It should not be too simple so as to exclude those features which are of interest to the investigation on hand;

III) Information should be available for calibrating the model; and

IV) The model should be the most economic in terms of running time one for solving the problem on hand.

For instance, it is wasteful to select a very sophisticated model which may give very accurate results and whose construction and solution are costly and time consuming when satisfactory results for a problem on hand can be obtained by a simpler model. For such a simple model, the operation of which is much cheaper.

Similarly, it is useless to choose a model which yields very detailed results when these cannot be verified by observing the behavior of the real system in the present and future.

4.8 Boundary Conditions of Groundwater Models

This section provides a brief introduction on the types of the boundary as it is explained by (SUSMAQ, 2001). It is important to realize that the correct determination of boundary conditions of the modeled aquifer system plays a major role in the determination of its flow patterns.

In general, there are four types of hydrogeological boundaries:

1. Specified head boundaries ;
2. Specified flow boundaries ;
3. No-flow boundaries ; and
4. Head-dependent flow boundaries.

4.8.1 Specified head boundaries

These are the boundaries where the head is known. This helps numerically because the governing equations of groundwater flow are written in terms of differences in heads (derivatives). Therefore, known head values will guarantee a unique solution to the partial differential equations of the flow system.

Examples of these boundaries are seas, lakes, reservoirs, rivers and sometimes spring.

4.8.2 Specified Flow Boundaries

Specified flow boundaries can be surface water bodies, spring flows and underflows. One example of underflow is the case when there is a hydraulic connection between aquifer basins and water moving underground from one basin to another. This is also true for water that seeps to or from aquifer bedrock underlying the modeled system.

In regional modeling terms, it is sometimes more accurate to model rivers as a specified flow condition rather than as a specified head boundary. Also, it is recommended to investigate whether it is more accurate to simulate injection or pumping wells at the specified flow boundaries such that the total injection or withdrawal equals the specified flow.

4.8.3 No-flow Boundaries

In general, a no-flow boundary may represent impermeable bedrock, an impermeable fault zone, a groundwater divide or a streamline. In terms of modeling, no-flow boundaries are modeled by assigning zero values to the hydraulic conductivities.

4.8.4 Head-Dependent Boundaries

Head-dependent boundaries can be in leaks from or to a river, lake or reservoir. Drains (springs) can be simulated to flow using this type of boundary.

4.9 Contents of a Conceptual Model

The assumptions that constitute conceptual models should relate to such items as:

- The geometry of the boundaries of the investigated aquifer domain;
- The kind of solid matrix comprising the aquifer (with reference to its homogeneity, isotropy, etc.);

- The mode of the flow in the aquifer (e.g., one-dimensional, two-dimensional horizontal, or three-dimensional);

- The properties of the water (with reference to its homogeneity, compressibility, effect of dissolved solids and/or temperature on density and viscosity, etc);

- The relevant state variables and the area, or volume, over which the averages of such variables are taken;

- Sources and sinks of water and of relevant contaminants within the domain and on its boundaries (with reference to their approximation as point sinks and sources, or distributed sources);

- Initial conditions within the considered domain; and

- The conditions on the boundaries of the considered domain that express the interactions with its surrounding environment.

Selecting the appropriate conceptual model for a given problem is one of the most important steps in the modeling process. Oversimplification may lead to a model that does not provide the required information, while under a complicated conceptual model the data required for model calibration and parameter estimation may not be available (Bear et al., 1992).

The selection of an appropriate conceptual model and the degree of simplification in any particular case depends mainly on:

- The objectives of the management problem (or the purpose and type of model application);

- The available resources; and
- The available field data.

It is important to emphasize that the availability of field data required for model calibration and parameter estimation dictates the type of conceptual model to be selected and the degree of approximation involved. The next step in the modeling process is to express the conceptual model in the form of a mathematical model (Bear et al., 1992).

4.10 Contents of a Mathematical Model

The mathematical model contains the same information as the conceptual one but expressed as a set of equations which are amenable to analytical and numerical solutions (Bear et al., 1992). Mathematical models may be deterministic, probabilistic, or some combination of the two. The procedure for developing a deterministic mathematical model of any physical system can be generalized as shown in Figure 4.3.

The mathematical model for groundwater flow consists of a partial differential equation together with appropriate boundary and initial conditions that express conservation of mass and that describe continuous variables (for example, hydraulic head) over the region of interest. In addition, it entails various phenomenological laws describing the rate processes active in the aquifer. An example is Darcy's law for flow through porous media (James W. Mercer, et al., 1980).

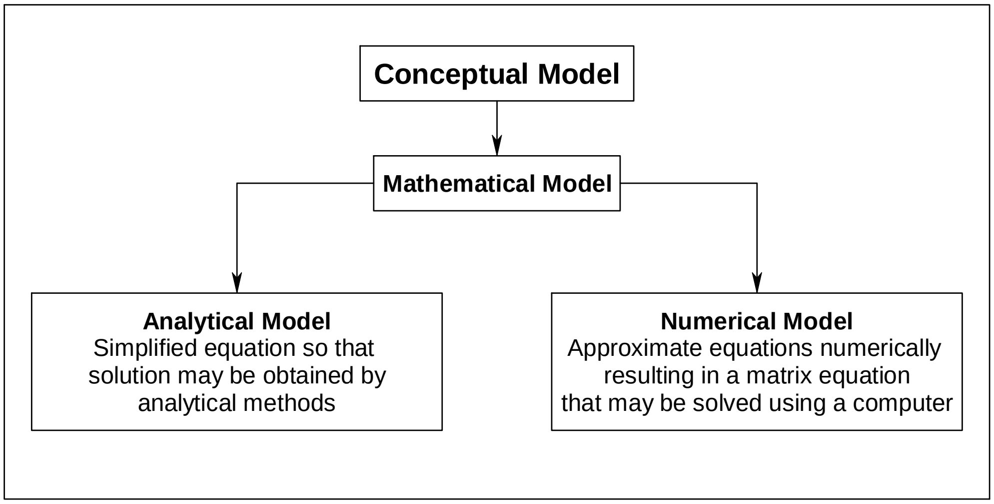


Figure 4.3: Logic Diagram for Developing a Mathematical Model

Once the mathematical model is formulated, the next step is to obtain a solution using one of two general approaches. The groundwater flow can be simplified further, for example, assuming radial flow and infinite aquifer extent, to form an equation that is amenable to analytical solution. The equations and solutions are referred to as analytical models (Mercer et al., 1980).

Alternatively, for problems where the simplified analytical models no longer describe the physics of the situation the partial differential equations can be approximated numerically for example with finite difference techniques or with the finite-element method. In so doing, one replaces continuous variables with discrete variables that are defined at grid blocks (or nodes). Thus, the continuous differential equation, defining hydraulic head everywhere in an aquifer, is replaced by a finite number of algebraic equations that defines hydraulic head at specific points. This system of algebraic equations is generally solved using matrix techniques. This approach constitutes a numerical model, and generally, a computer program is written to solve the equations on a digital computer (Mercer et al., 1980).

4.11 Deterministic Models

Deterministic models are models that define cause and effect relationships based on an understanding of the physical system. The first step is to understand the physical behavior of the system to develop the conceptual model. Cause-effect relationships are determined and a conceptual model of how the system operates is formulated. For groundwater flow, these relationships are generally well known, and are expressed using concepts such as hydraulic gradient to indicate flow direction. Deterministic models are widely used to describe the behavior of the hydraulic heads in time and space (Yasin, 1999).

A deterministic model uniquely defines its output for specified input and initial and boundary conditions. That means, the same input gives the same output. The input of the deterministic model may be either deterministic or stochastic. In other words, a deterministic model is a model where two equal sets of data input always yield the same output if run through the model under identical conditions (Yasin, 1999).

4.12 Stochastic Models

The stochastic model mainly depends on the hypothesis that natural parameters in reality are not completely randomly spatially distributed, but have a kind of trend and uniformity to some degree. A stochastic model generates all fractures randomly using statistical distributions of geometric parameters from field data (Yasin, 1999).

The process and its model are considered as a stochastic (probabilistic) if the chance of occurrence is taken into consideration and the concept of probability is introduced in formulating the model (Yasin, 1999).

The stochastic model is often used because the complexity of reality does not allow a complete description of the actual physical field (Yasin, 1999).

In summery, a system is considered as stochastic if its behavior is governed by laws of probability. That is to say, there is a certain element of chance with obtaining an output for a specified input (Yasin, 1999).

4.13 Analytical Models

Analytical models offer an inexpensive way to evaluate the physical characteristics of a groundwater system. Such models enable investigators to conduct a rapid preliminary analysis of groundwater. A number of simplifying assumptions regarding the groundwater system are necessary to obtain an analytical solution.

Although these assumptions do not necessarily dictate that analytical models cannot be used in real-life situations, they do require sound professional judgment and experience in their application to field situations. Nevertheless, it is also true that in many field situations few data are available; hence, complex numerical models are often of limited use. When sufficient data have been collected, however, numerical models may be used for predictive evaluation and decision assessment. Analytical models should be viewed as a useful complement to numerical models (Bear et al., 1992).

4.14 Numerical Models

Once the conceptual model is translated into a mathematical model in the form of governing equations, with associated boundary and initial conditions , a solution can be obtained by transforming it into a numerical model and writing a computer program (code) for solving it using a computer (Bear et al., 1992).

Numerical solution normally involves approximating continuous (defined at every point) partial differential equations with a set of discrete equations in time and space. Thus, the region and time period of interest are divided in some fashion resulting in an equation or set of equations for each sub-region and time step. These discrete equations are combined to form a system of algebraic equations that must be solved for each time step (Faust et al., 1980). Finite-difference and finite-element methods are the major numerical techniques used in groundwater applications.

To use models, the hydrologist must assess the merits of alternative numerical methods, evaluate available data, estimate data where missing or absent, and interpret computed results (Mercer et al., 1980).

The hydrologist must first decide whether a numerical model is necessary for project objectives. If needed, he is then faced with the decision of which numerical method is best for his problem. Once a particular method or computer program is selected, he must assess the reliability of data that are needed to run the program and the quality of the data that will be used to verify computed results. Because available data are never as comprehensive as desired, he will probably have to fill in data gaps with estimated, interpolated, or extrapolated values. Although running the computer program is fairly straightforward, interpreting or analyzing the output can be very difficult (Mercer et al., 1980).

The computed results may not compare well with observed data. It is then necessary to adjust and refine input data and rerun the computer program until some satisfactory agreement is obtained. This refinement procedure is known as model calibration. A calibrated model may be used for future forecasting, but care must be taken to avoid unwarranted predictions.

The above discussion suggests that a successful model application requires a combination of experience with (i) hydrologic principles, (ii) numerical methods, (iii) the aquifer to be modeled, and (iv) model use.

4.15 Modeling Codes

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

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

1. SDF: It is 2-D (Stochastic Discrete Fractured) flow model is coupled with a particle tracking code to explore the validity of porous media approximations for simulating groundwater flow in fractured-rock aquifers.

2. FRAC3DVS: This code handles porous and/or discretely fractured porous media, steady state and transient variably saturated groundwater flow, and dispersive solute transport in porous or discretely fractured porous media, it is 3-D finite element model.

3. SWIFT: A three-dimensional model, which simulates the flow and transport of fluid, heat (energy), brine, and radionuclide chains in porous fractured geologic media. Its reliability is low.

4. TwoDAN: Two-dimensional groundwater flow model in the horizontal and vertical plane. It uses analytical solution for head and discharge.

5. TRAFRAP-WT: TRAFRAP-WT (TRAnsport in FRActured Porous media with Water Table boundary conditions) is a two-dimensional finite element code designed to simulate ground-water flow and solute transport in fractured or granular aquifers, and is capable of treating both (leaky) confined and water table systems. Fractured porous media are represented by either the discrete-fracture or dual porosity approaches, or a combination of both. The model solves either for flow or transport. Solving for flow provides a steady-state velocity field which can be used in a successive the transport simulation. The flow and transport equations are solved using improved finite element algorithms with special features designed to handle aquifer-aquitard systems and options to account for water table boundary conditions and fracture skin effects. (USGS, 1999).

6. FracMan: It is the premier software for analysis and modeling of heterogeneous and fractured rock masses. Its features include data

analysis, geometric modeling, finite element mesh, and exploration simulation.

7. MODFLOW: MODFLOW is the name that has been given the USGS Modular Three-Dimensional Ground-Water Flow Model. Because of its ability to simulate a wide variety of systems, its extensive publicly available documentation, and its rigorous USGS peer review, MODFLOW has become the worldwide standard ground-water flow model. MODFLOW is used to simulate systems for water supply, containment remediation and mine dewatering. When properly applied, MODFLOW is the recognized standard model used by courts, regulatory agencies, universities, consultants and industry.

8. MAFIC: It is a finite element flow designed to simulate flow and transport through the 2-D and 3-D rock matrix with a discrete fractured network.

9. MOC: MOC simulates solute transport in flowing ground water. MOC is both general and flexible in that it can be applied to a wide range of problem types. It is applicable for one- or two-dimensional problems involving steady-state or transient flow. MOC is based on a rectangular, block-centered, finite-difference grid. It allows the specification of injection or withdrawal wells and of spatially-varying diffuse recharge or discharge, saturated thickness, transmissivity, boundary conditions and initial heads and concentrations.

From the above-mentioned modeling code, MODFLOW was found to be the most suitable model to represent the Eocene aquifer and used to construct the simulation model and then it is followed by the development of an optimization framework for the Eocene aquifer using GWM software which depending on MODFLOW. More information about MODFLOW and GWM will be in the next chapter.

4.16 Model Calibration

The selected model must be well defined. The definition should be based on the detailed geometry of the aquifer, information about its physical parameters, boundaries, inputs, and outputs, etc. All of this information is derived from geological studies and from observations in the real aquifer system. Whenever information is not available, it must be assumed on the basis of experience (or even guessed) and then verified during the calibration process (Bear, 1979).

The calibration, or identification, of a model is the processes in which the various model parameters (and that may also include its geometry, inputs, etc...) are determined (Bear, 1979) such that the model output matches closely the actual observed values. Generally, the hydraulic conductivity is changed and updated during the calibration process until the potentiometric head at certain locations matches closely the measured values.

4.17 Model Misuse

The most crucial step in groundwater modeling is the development of the conceptual model. If the conceptual model is wrong (i.e., does not represent the relevant flow processes) the transpired model would be faulty (Bear et al., 1992).

One must assess the complexities of the problem, the amount of data that is available, and the objectives of the analysis, and then determine the best approach for the particular situation. Because groundwater models deal with the subsurface, there are always unknown factors that could affect results (Mercer et al., 1980).

Perhaps the Worst possible misuse of a model is blind faith in model results. Calculations that contradict normal hydrologic intuition almost always are the result of some data entry mistakes, a bug in the computer program, or misapplication of the model to a problem for which it was not designed. Proper application of a groundwater model requires an understanding of the specific aquifer. Without this conceptual understanding, the whole exercise may become meaningless (Mercer et al., 1980).

Chapter Five
MODFLOW and GWM Codes: General Overview

5.1 Introduction

For a successful groundwater modeling, a suitable simulation modeling code has to be chosen in order to represent the physical situation properly. Because of the complex nature of groundwater systems and the large number of engineering, legal, and economic factors that often affect groundwater development and management, the process of selecting a best operating procedure or policy for a groundwater system can be extremely difficult. To address this difficulty, groundwater simulation models have been linked to optimization modeling techniques to determine best (or optimal) management strategies from many possible strategies. Optimization models explicitly account for water resource management objectives and constraints and have been referred to as management models (Ahlfeld and Mulligan, 2000).

The use of combined simulation/optimization models greatly enhances the utility of simulation models alone by directly incorporating management goals and constraints into the modeling process. In the simulation/optimization approach, the modeler specifies the desired attributes of the hydrologic and water-resource management systems (such as minimum stream flow requirements or maximum allowed groundwater-level declines) and the model determines, from a set of several possible strategies, a single management strategy that best meets the desired attributes. In some cases, however, the model may determine that none of the possible strategies are able to meet the specific set of management goals and constraints. Such outcomes, while often not desirable, can be useful for identifying the hydrologic, hydrogeologic, and management variables that limit water-resource development and management.

The main objective of this chapter is to touch base the simulation and optimization software that will be used to figure out the optimal pumping strategy for the Eocene aquifer. MODFLOW and GWM are chosen to carry out the research work.

GWM is a new process for the USGS MODFLOW-2000 modular groundwater model (Harbaugh and others, 2000). The response-matrix approach, which has been used widely in groundwater management modeling, is used to transform a groundwater management problem into an optimization formulation that can be solved by GWM. GWM uses the simplex and branch and bound optimization algorithms to solve the resulting formulations where these algorithms have been coded internally in GWM in the FORTRAN-90 computer language. Currently, MODFLOW-2000 is the most recent version of the MODFLOW code, which was originally developed in the 1980s.

5.2 MODFLOW

MODFLOW is a modular three-dimensional finite-difference groundwater model and is an easy-to-use modeling environment for practical applications related to groundwater.

MODFLOW is groundwater model that was first published in 1984. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model, which is called MODFLOW-2000 in order to distinguish it from earlier versions.

MODFLOW-2000 simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a source of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for groundwater flow problems.

In addition to simulating groundwater flow, the scope of MODFLOW-2000 has been expanded to incorporate related capabilities such as solute transport and parameter estimation.

The groundwater flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. In plan view, the blocks are made from a grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is written for each block called a cell. Several solvers are provided for solving the resulting matrix problem where the user can choose the best solver for the particular problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid. Primary output of MODFLOW is head, which can be written to the listing file or into a separate file under specified format. Other output includes the complete listing of all input data, drawdown, and budget data. Budget data are printed as a summary in the listing file and detailed budget data for all model cells can be written into a separate file.

The user views the program according to its capability to simulate different kinds of groundwater flow problems. To facilitate this perspective, the program is divided into pieces called packages. Each hydrologic capability, such as leakage to rivers, recharge, and evapotranspiration that is included within the groundwater flow equation is a separate package. Further, because there are many methods for solving the simultaneous equations resulting from the finite-difference method, each solution method is a package.

5.3 GWM—A Groundwater Management Software

GWM is a Groundwater Management software for the U.S. Geological Survey modular three-dimensional groundwater model MODFLOW-2000. GWM uses a Response-Matrix Approach to solve several types of linear, nonlinear, and mixed-binary linear groundwater management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints. Three types of decision variables are supported by GWM: (i) flow-rate decision variables, which are withdrawal or injection rates at well sites; (ii) external decision variables, which are sources or sinks of water that are external to the flow model and do not directly affect the state variables of the simulated groundwater system (heads, stream flows, and so forth); and (iii) binary variables, which have values of 0 or 1 and are used to define the status of flow-rate or external decision variables.

A single objective function is supported by GWM, which can be specified to either minimize or maximize the weighted sum of the three types of decision variables. Four types of constraints can be specified in a GWM formulation: (i) upper and lower bounds on the flow-rate and external decision variables; (ii) linear summations of the three types of decision variables; (iii) hydraulic-head based constraints, including drawdown, head differences, and head gradients; and (iv) stream flow and stream flow-depletion constraints.

The Response Matrix Solution (RMS) Package of GWM uses the Groundwater Flow Process of MODFLOW to calculate the change in head at each constraint location that results from a perturbation of a flow-rate variable; these changes are used to calculate the response coefficients. These response coefficients are quite vital in figuring out the changes in the state variables to the changes in the decision variables without running the simulation model. This indeed saves a great deal of time.

The GWM Process runs with the MODFLOW-2000 Global and Groundwater Flow Processes. The GWM Process is written with a modular structure so that new objective functions, constraint types, and solution algorithms can be added whenever needed.

The input data for MODFLOW are generated by GWM and saved to a set of files. These files are read by MODFLOW when it is launched from GWM menu. The output from MODFLOW is then imported to GWM for post-processing.

5.4 Formulation of Groundwater Management Problems with GWM

This section describes the components available in the GWM software for formulating groundwater management problems. A groundwater management formulation consists of three components: (i) decision variables, (ii) an objective function, and (iii) a set of constraints. Together, these three components define a mathematical model of the management decision-making (or design) process (Ahlfeld and Mulligan, 2000; Hillier and Lieberman, 2001).

The decision variables of the management problems are the quantifiable controls (or decisions) that are to be determined by the model, such as the withdrawal rates at a set of managed wells. The values determined by GWM for these control variables define the solution of the problem. The objective function of the problem, which is stated in terms of one or more of the decision variables, is a measure of the performance of the design process. The objective function is used to identify the best solution among many possible solutions. This function may be maximized or minimized, depending upon the GWM application. The third component of the management problem is a set of constraints that impose restrictions on the values that can be taken by the decision variables. The solution of a well-defined groundwater management formulation consists of values for the decision variables that optimize the objective function while satisfying all constraints on decision-variable values (Ahlfeld and Mulligan, 2000).

5.4.1 Decision Variables

GWM supports three types of decision variables: flow-rate decision variables, external decision variables, and binary variables.

The primary type of decision variables is a withdrawal (discharge) or injection (recharge) flow rate at a managed well site.

The second type of decision variables that can be specified in GWM is a source or sink of water that does not have a direct effect on the state variables of the groundwater flow system.

The third type of decision variables supported by GWM is a binary variable, which is defined to indicate the status of associated sets of flow-rate and external decision variables. One or more flow-rate or external decision variables, or combinations of flow-rate and external decision variables, can be associated with a single binary variable.

5.4.2 Objective Function

GWM supports a single objective function, which is to minimize or maximize the weighted sum of the three types of decision variables:

$$\sum_{n=1}^{N} \beta_n Qw_n T_{Qw_n} + \sum_{m=1}^{M} \gamma_m Ex_m T_{Ex_m} + \sum_{l=1}^{L} K_l I_l , \quad (1)$$

where

β_n is the cost or benefit per unit volume of water withdrawn or injected at well site n;

γ_m is the cost or benefit per unit volume of water imported or exported at external site m;

K_l is the unit cost or benefit associated with the binary variable I_l;

T_{Qw_n} is the total duration of flow at well site n;

T_{Ex_m} is the total duration of flow at external site m; and

N,M,L are the total number of flow-rate, external, and binary decision variables, respectively.

T_{Qw_n} and T_{Ex_m} are calculated by GWM by summing the duration of all stress periods during which the *n*th or *m*th decision variable is active. Again, note that GWM does not require that stress periods specified in a MODFLOW simulation be of equal length. The coefficients β_n, γ_m, and K_l are called the objective-function coefficients.

5.4.3 Constraints

GWM supports four general types of management-model constraints. These constraints can be divided broadly into two types: those for which response coefficients need not be generated (constraints on the decision variables themselves and linear-summation constraints), and those for which response coefficients between the decision variables and groundwater flow system state variables must be generated (the hydraulic-head and stream flow constraints).

5.5 Calculation of the Response Coefficients

The partial derivatives that define the response coefficients are not calculated directly; instead, they are approximated by a first-order, finite-difference perturbation method. The derivative of head with respect to each flow-rate decision variable is approximated by the following forward-difference equation:

$$\frac{\partial h_{i,j,k,t}}{\partial Qw_n} \approx \frac{\Delta h_{i,j,k,t}}{\Delta Qw_n} = \frac{h_{i,j,k,t}(Qw_{\Delta n}) - h^0_{i,j,k,t}(Qw^0)}{Qw_{\Delta n}}, \quad (2)$$

where $Qw_{\Delta n}$ is the perturbation value for the nth flow-rate decision variable and $h_{i,j,k,t}(Qw_{\Delta n})$ is the head at constraint location i,j,k and stress period computed by using a vector of withdrawal and injection stress rates $Qw_{\Delta n}$ that differs from the original vector of stress rates Qw^0 only in the nth element, which is changed by an amount $Qw_{\Delta n}$.

To calculate each response coefficient defined by equation (2), the Ground Water Flow (GWF) Process of MODFLOW is run a total of N+1 time. In the first run, which is called the base-condition run, the head is calculated at each constraint location and stress period for the set of base-condition withdrawal and injection rates [that is, each $h^0_{i,j,k,t}(Qw^0)$]. In each of the remaining N runs, the head for each constraint location is calculated on the basis of the change (perturbation) in the withdrawal or injection rate for the nth flow-rate decision variable. For each of these runs, the withdrawal or injection rate at each of the remaining N-1 well sites is kept at the base-condition value. The N runs and consequent computations of the response coefficients result in a matrix of response coefficients that is used to solve the optimization problem.

Chapter Six
Methodology

6.1 Introduction

In this study, a steady-state groundwater flow model for the Eocene aquifer was developed in order to be used and utilized with GWM. The overall methodology utilized in this research is summarized in the following sections and depicted in Figure 6.1. As can be seen from the figure, the methodology is comprised from three major steps and these are the characterization of the study area, modeling, and decision-making.

6.2 Characterization of the Study Area

The characterization step includes the selection of the study area, collection of relevant data, and data analysis.

6.2.1 Selection of the Study Area

Since the Eocene aquifer is an important source of water in Jenin District for providing water for agricultural and domestic purposes, it was chosen for this research. In addition, no previous attempts were made to utilize simulation/optimization tools to determine the potential yield of the aquifer.

6.2.2 Collection of Relevant Data

Relevant data to the Eocene aquifer from main previous studies were collected and the relevant databases of the Palestinian Water Authority (PWA) and British Geological Survey (BGS) were obtained. These data were used in the preparation of the conceptual model for the study area such as aquifer spatial extent, well and spring coordinates, land use practices, time series of withdrawal rates and potentiometric heads, topography, climate data, recharge, geological formations and soil types. GIS technology was used in data preparation, collection, model processing, visualization, and analysis.

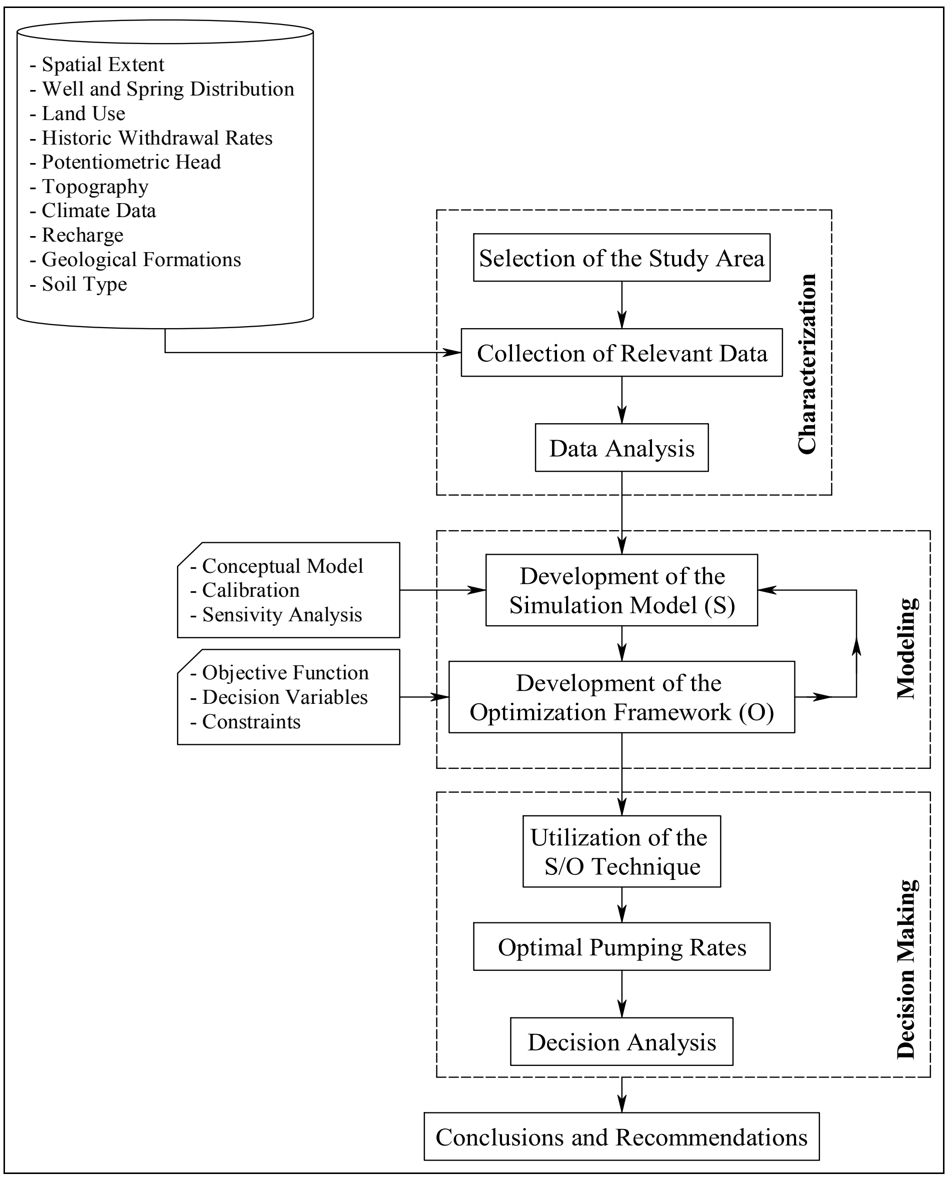


Figure 6.1: Flowchart of the Methodology for the Optimal Management of the Eocene Aquifer

6.2.3 Data Analysis

The collected data was analyzed using GIS, programming, and Microsoft Excel.

6.3 Modeling

The development of the simulation model (using MODFLOW) and the optimization framework (using GWM) followed the characterization step. In this step, codes were selected and used for model development.

6.3.1 Development of the Groundwater flow Model (The Simulation Model)

The simulation model was formulated after the development of the conceptual model and after carrying out calibration and sensitivity analysis. MODFLOW was selected to develop the mathematical model and to solve it numerically. The outcomes from the model are the groundwater heads, the water budget, and flow directions.

Thereafter, model calibration took place through the refining of the aquifer properties such as hydraulic conductivity to achieve a desired degree of matching between model simulation heads and observed ones.

The last stage in this step is the sensitivity analysis. The sensitivity of the simulated heads at different locations for various input parameters is tested to evaluate the uncertainty of model output. If the model is particularly sensitive to a parameter, which has a high uncertainty, there will be a need for future efforts in data collection.

6.3.2 Development of the Optimization Framework

After the development of MODFLOW, the optimization code, which contains the objective function, decision variables and constraints, was developed. As mentioned earlier, the GWM software was selected and adopted in this work to find out the optimal pumping strategies for the Eocene aquifer under different scenarios.

6.4 Decision Making

The final step in the methodology is the utilization of the simulation/ optimization model to find out the optimal pumping strategy. The optimal pumping strategy developed out of this work is according to the current level of stresses (practices and corresponding water consumptions). However, different scenarios were considered and the corresponding optimal pumping strategies were determined.

6.4.1 Utilization of the Simulation/Optimization Technique

The simulation/optimization technique (GWM software) was used to evaluate possible future management scenarios to find out the optimum pumping rates and water table elevation at each control locations. The scenarios, in part, pertain to changes in recharge and changes in head constraints (allowable limits).

6.4.2 Determination of Optimal Pumping Rates

The final output from the implementation of the methodology is the optimal pumping strategies for different scenarios that connote different stresses.

6.4.3 Decision Analysis

After the designation of the optimal pumping strategies for the different scenarios were determined, the results were studied and analyzed. GIS was used to visualize the results and the main deductions were made accordingly.

6.5 Conclusions and Recommendations

Conclusions and recommendations were summarized.

Chapter Seven
Development of the Groundwater Flow Model

7.1 Introduction

Model development consists of converting the conceptual model of the aquifer system to a numerical model. This was done by using MODFLOW. MODFLOW performs the mathematical computation and simulation and generates the results in terms of groundwater heads and budget. Following numerical model development, calibration is the process of refining the model representation of the hydraulic properties and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater head and flow. The last stage for the completion of model development is the sensitivity analysis. At this stage, the sensitivity of various estimated parameters is tested to evaluate the degree to which the model results are dependent on uncertain data.

7.2 Model Discretization

In order to use MODFLOW, the model domain should be divided into a finite-difference grid. Uniform cell sizes of 100 m by 100 m were chosen. This discretization level allows a proper capturing of the different properties and insures a smooth simulated potentiometric head. As such, the model domain contains 386 rows and 288 columns with a total of 111,168 cells. This number of cells includes all the active and in-active cells. However, the number of active cells (cells within the model domain) is 52,495. Figure 7.1 depicts the grid of the Eocene aquifer.

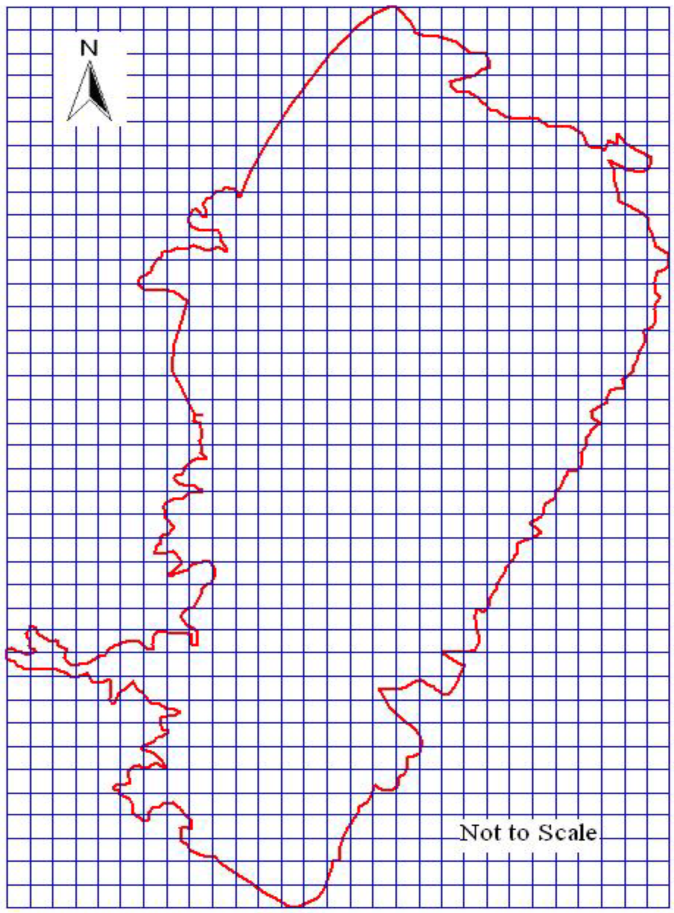


Figure 7.1: The Finite-Difference Grid of the Eocene Aquifer Model. Note that the Grid is not to Scale for Ease of Visualization

7.3 Model Stratigraphy

The representation of the conceptual model is helpful to describe how many layers ought to be represented in the simulation model in addition to their hydrological conditions (confined, unconfined, or semi-confined).

According to SUSMAQ study (2004), the outcropping formation of the study area is mainly characterized by the following: (i) low transmissivity layer (Abu Dis formation) and (ii) relatively low to moderate transmisivity layer (Eocene sub-series formation). Due to their natural composition, it is believed that the Eocene formation has the capability to act as an unconfined aquifer while the Abu Dis formation acts as an aquitard. Therefore, these indications support the decision that the model is composed of one layer representing the Eocene formation and simulated as an unconfined layer. However, the Senonian formation of Abu Dis is in certain places considered a poor to fair aquifer.

As such, the vertical descritization of the model would mainly consist of one layer, which represents the Eocene formation and the simulated system will be a single-layer two-dimensional groundwater flow.

7.4 The Boundary Conditions of the Study Area

The boundary conditions of the model domain depend on many considerations, such as domain extent, stratigraphy, water bodies and physical features within the study area. The Gilboa' fault system acts as the eventual natural discharge point for the entire model area. As such, it is modeled as a general-head boundary. The remaining boundaries are structurally separated from the adjacent formations and were modeled as no-flow boundaries. All springs within the entire area were modeled using the Drain Package of MODFLOW. In the eastern side of the model domain (near Wadi Faria) the Drain Package of MODFLOW was used at specific locations. So, the boundary conditions of the Eocene aquifer in this study are classified into two types: no-flow boundary due to the physical boundary of the impermeable Abu Dis rocks and the general-head boundary as illustrated in Figure 7.2 .

The representation of the boundaries by MODFLOW has been carried out by assigning specific indicators to the cells according to type of the boundary.

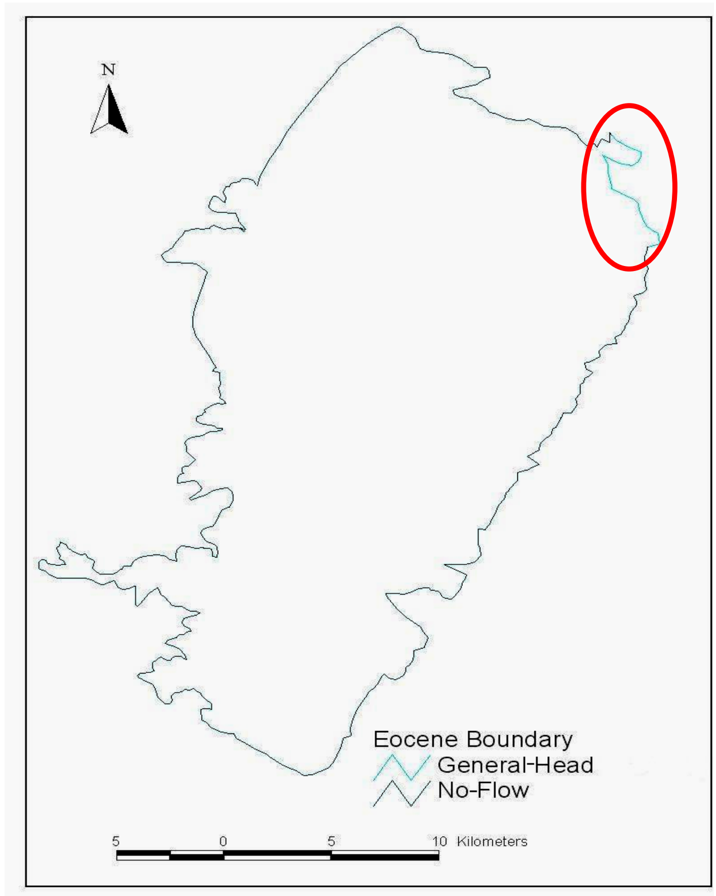


Figure 7.2: Boundary Conditions for the Eocene Aquifer

7.4.1 No-flow Boundary

The geological map (Figure 2.1) and the structural geology map (Figure 2.4) show that the study area is located between two major anticlines; Anabta anticline in the west and Fari'a anticline in the east.

All areas where Eocene is eroded and stands in lateral contact to the outcrops of the underlying Senonian formations are considered as a no-flow boundary. This is because the Senonian mainly consists of the thick layer of impermeable chalk of Abu Dis Aquiclude.

7.4.2 General-Head Boundary

The general-head boundary simulates the boundaries that allow groundwater to pass through it in both directions (to and from) the aquifer. The possible location for general-head boundary is the Gilboa' fault, where the groundwater flows through the fault laterally. On the one hand, the water level at the boundary is lower than the water level inside the model domain. On the other hand, a drop in water levels in the model area reverses the flow from outside towards inside. However, the established hydrological settings in this specific area suggest that the Eocene flow system always discharges through springs (SUSMAQ, 2004).

7.5 Groundwater Recharge

Groundwater recharge is the replenishment of an aquifer with water. For the Eocene aquifer, the sources of the recharge are rainfall and return flow. The Recharge Package of MODFLOW was used to simulate the spatial distribution of the recharge to the Eocene aquifer.

7.5.1 Recharge from Rainfall

Direct recharge from rainfall is considered by far the principle source of recharge in the Eocene aquifer (SUSMAQ, 2004). Review of the previous studies and literature indicates varying estimates of recharge from rainfall. Therefore, accurate estimate for this parameter is bristled with difficulties and is subject to a wide range of variabilities and uncertainties.

Most of the recharge estimates made for the West Bank are based on catchment scale water balances or empirical relationships between rainfall and recharge. Guttman (1998) revised these equations for use in estimating recharge for the Eastern basin. The equations were adapted by Guttman (1998) with different coefficients according to the amount of rainfall. The modified equations are (CH2MHILL, 2002):

For rainfall < 300 mm/yr,

$$\text{Recharge} = 0.15 \times (\text{rainfall}) \quad (3)$$

For rainfall ≥ 300 and ≤ 650 mm/yr,

$$\text{Recharge} = 0.534 \times (\text{rainfall} - 216) \quad (4)$$

For rainfall > 650 mm/yr,

$$\text{Recharge} = 0.8 \times (\text{rainfall} - 360) \quad (5)$$

In this study, the modified empirical equations by Guttman (1998) were used to estimate recharge for the Eocene aquifer. To find out the recharge at each cell of the model domain, a rainfall grid of the same model cell size was created by interpolating the point locations of rainfall stations and corresponding annual rainfall values. Figure 2.6 shows the spatial distribution of the rainfall stations in the model domain for the use in interpolation. Thereafter, the above equations were used at each cell to compute the recharge from rainfall. GIS spatial analyst was utilized in this computation process. Figure 7.3 depicts the spatial distribution of the annual recharge from rainfall for the Eocene aquifer. The average annual recharge from rainfall is about 78 mcm.

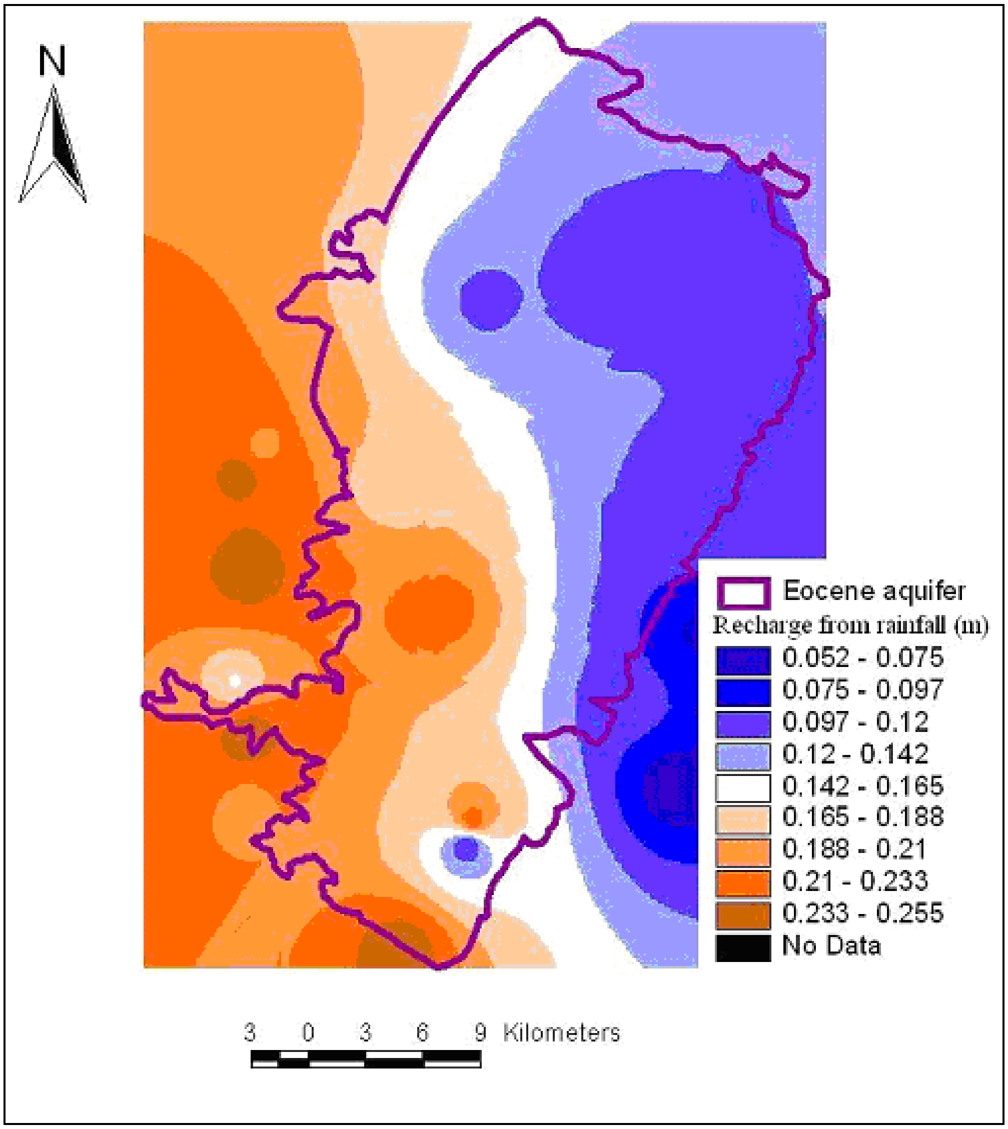


Figure 7.3: The Spatial Distribution of Annual Recharge from Rainfall for the Eocene Aquifer in meters

7.5.2 Recharge from Return Flow

Two types of return flow were considered in the estimation of total groundwater recharge and these are:

- Return flow from irrigation; and
- Return flow from leakage of water supply networks.

Within the study area, the majority of the irrigated areas are located in the northeastern part near Jalameh Village. The total irrigated area is 13,630 dunums (see Figure 2.8) as computed using GIS. Each dunum receives approximately 628 m^3 of water (SUSMAQ, 2004). The total annual volume of water used in irrigation is about 8.6 mcm. The return flow is estimated to be around 20% from irrigation water volume (CH2MHILL, 2001). This yields an annual return flow from irrigation of 1.7 mcm.

The annual total quantity of water supplied to Nablus and Jenin communities within the study area is 11 mcm as obtained from the database of PWA. The assumed annual losses are about 34% or 3.73 mcm. This lost quantity is assumed to percolate down to recharge the aquifer.

7.6 Abstraction Wells

Groundwater wells in the Eocene aquifer are owned by the municipalities or privately by farmers. The wells are used mainly to provide water for domestic and agricultural uses.

A pumping well is a point sink represented in the model by a node at the cell center. In MODFLOW, the Well Package is used mainly to simulate the outflow through pumping wells and inflow through recharge wells. Wells are identified in MODFLOW by specifying their locations (i.e. layer, row, and column) and the corresponding pumping rates.

There are 67 wells located within the Eocene aquifer boundary. Figure 7.4 and Table 1 (see Appendix) show the spatial distribution of the wells within the Eocene aquifer that have available data regarding the abstraction rate and well usage. The number of wells tapping the same aquifer outside the political boundary of the West Bank is uncertain. Most speculations report nine wells. The locations of the Israeli wells and their total abstraction were taken from PWA through personal communication. The total abstraction rate was evenly distributed over all the Israeli wells. The annual long-term average abstraction from the Eocene aquifer is about 18.2 mcm of which 11.7 mcm are attributed to the Israeli wells. The average annual abstraction rates for the Palestinian wells were calculated for each well from year 1977 to 2003 using MS Excel.

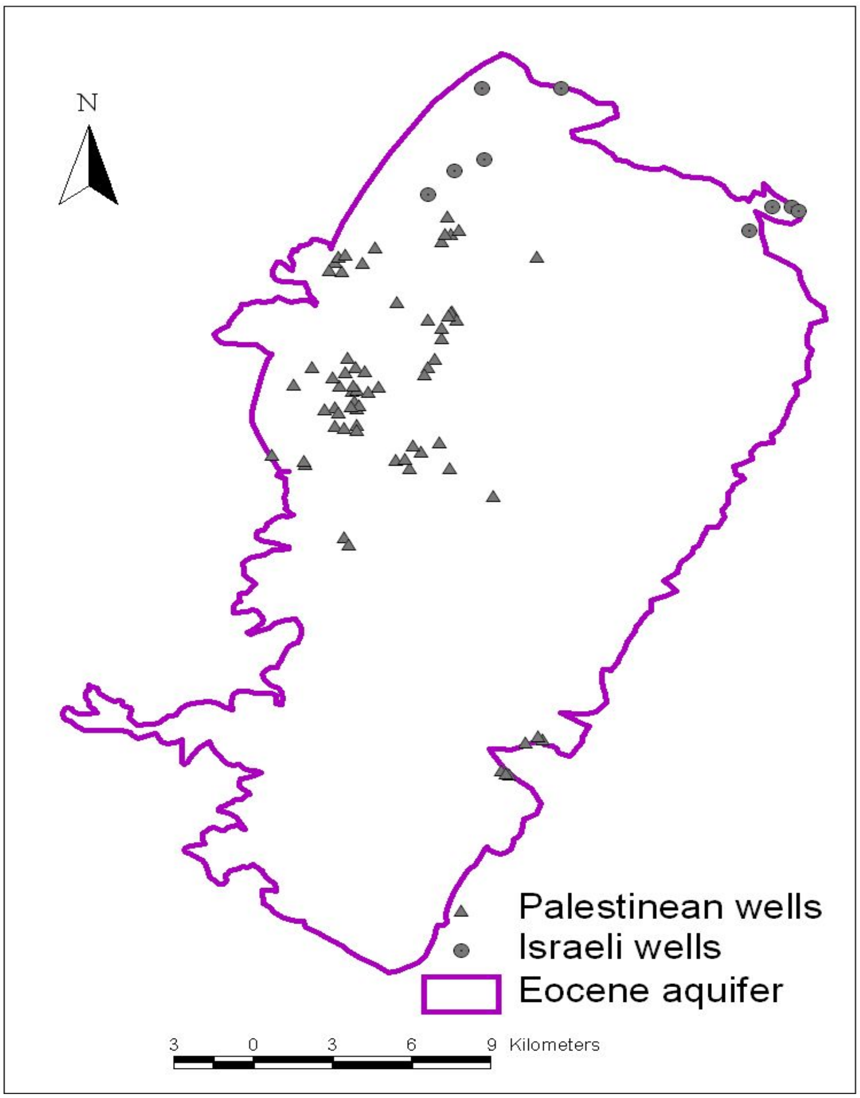


Figure 7.4: Wells Location in the Eocene Aquifer

7.7 Springs

Drain packages of MODFLOW is usually used to simulate springs. The Drain Package simulates the flow from a spring by representing the point of emergence of the spring (the land surface) as the drain elevation. The drain cells function only in the event that the water table rises above the level of the drain. The spatial location of the Palestinian springs in the Eocene aquifer is shown in Figure 7.5 and Table 2 in the appendix.

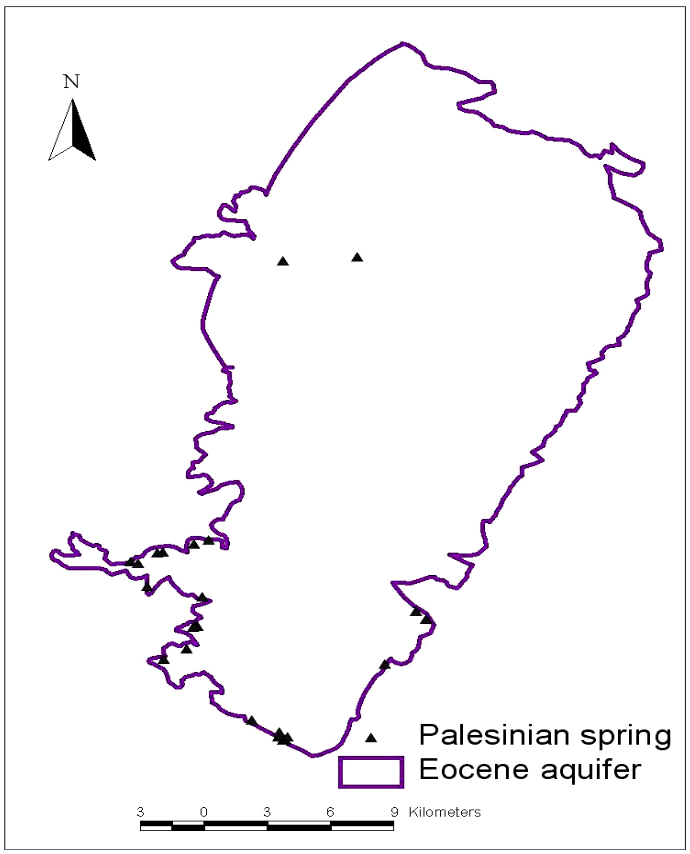


Figure 7.5 The Spatial Distribution of the Palestinian Springs of the Eocene Aquifer

The Palestinian springs in the Eocene aquifer are used for domestic and agricultural purposes. The annual average discharge of these springs is estimated at 10.4 mcm. The data for the locations and discharges for

Israeli springs are not available. It was assumed that the amount of water that discharges from Israeli springs were added to the amount of water that leaves the Eocene aquifer from the general head boundary. The average annual discharge from the general-head boundary is about 55 mcm and its value was taken from water budget as obtained from the list file generated by MODFLOW.

The average discharge values for Palestinian springs were calculated for each spring based on data from the year of 1977 to 2003 using MS Excel. The discharge values for Israeli springs were taken from the SUSMAQ study (2004). These discharge values were used in calculating the conductance value for each spring. The conductance values were then used in the development of the Drain Package input file.

7.8 Top and Bottom of the Eocene Aquifer (Aquifer Geometry)

Generally, the top and bottom of the layers define the main hydrological formations for the simulated model. The elevations for the top and bottom of the Eocene aquifer layer were obtained utilizing the topographical map, Eocene base map and cross-sections. Figure 7.6 and Figure 7.7 present the top and bottom elevations of the Eocene aquifer layer.

The top elevation for the Eocene aquifer range from 50 m to 950 m, while the bottom range from -200 m (below mean sea level) to 600 m.

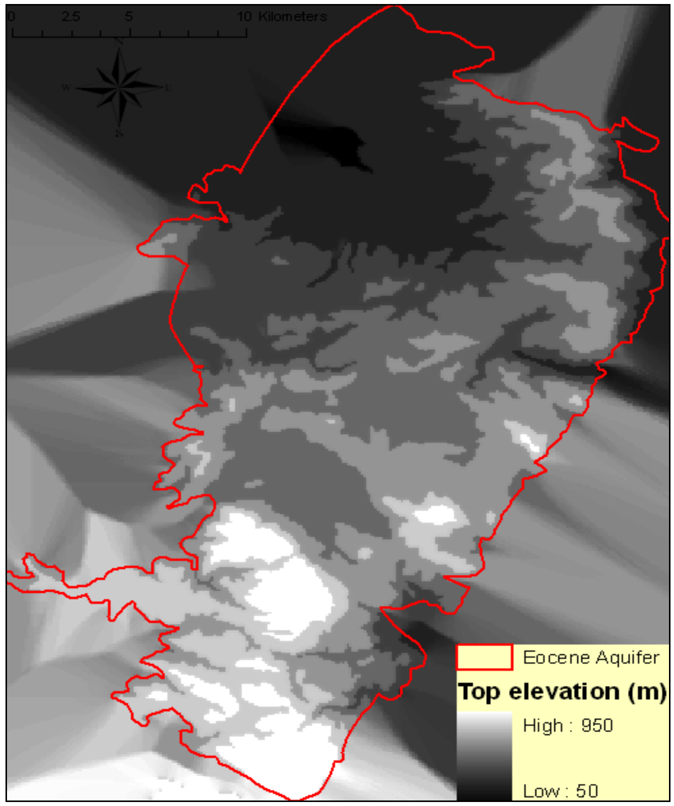


Figure 7.6: Top Elevation for the Eocene Aquifer

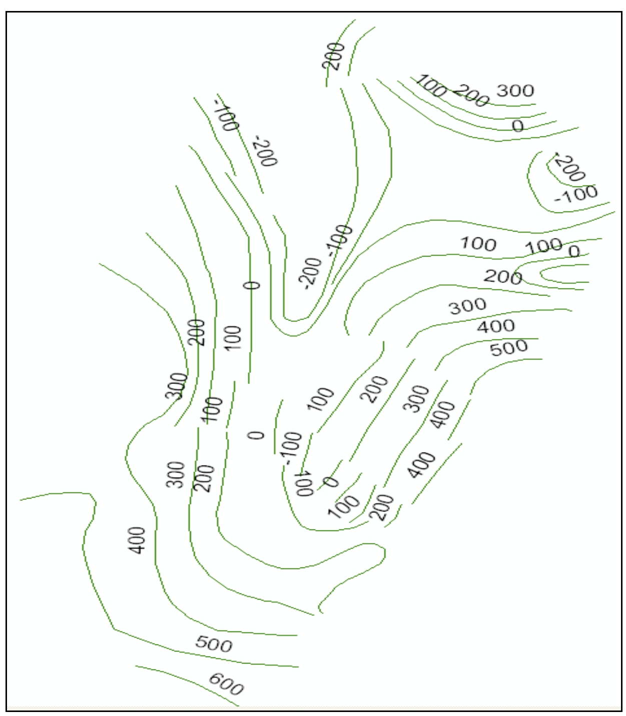


Figure 7.7: Contour Map for the base of the Eocene Aquifer

7.9 Groundwater Elevation

Groundwater elevation is an important parameter for monitoring the groundwater system. For example, if groundwater levels decline with time, this is an indication of an imbalance between recharge and discharge.

Based on the available well records, it was noticed that in general water table fluctuates around an average value. The distribution of groundwater wells is irregular in the study area. This means that the representation of water levels all over the study area will carry some uncertainty in the calibration stage. The time series of the fluctuation in the groundwater elevations for selected wells within the Eocene aquifer are shown in Figure 7.8. Water table elevations for specific wells for the year 2003 are shown in Figure 7.9 and these wells were used in model calibration.

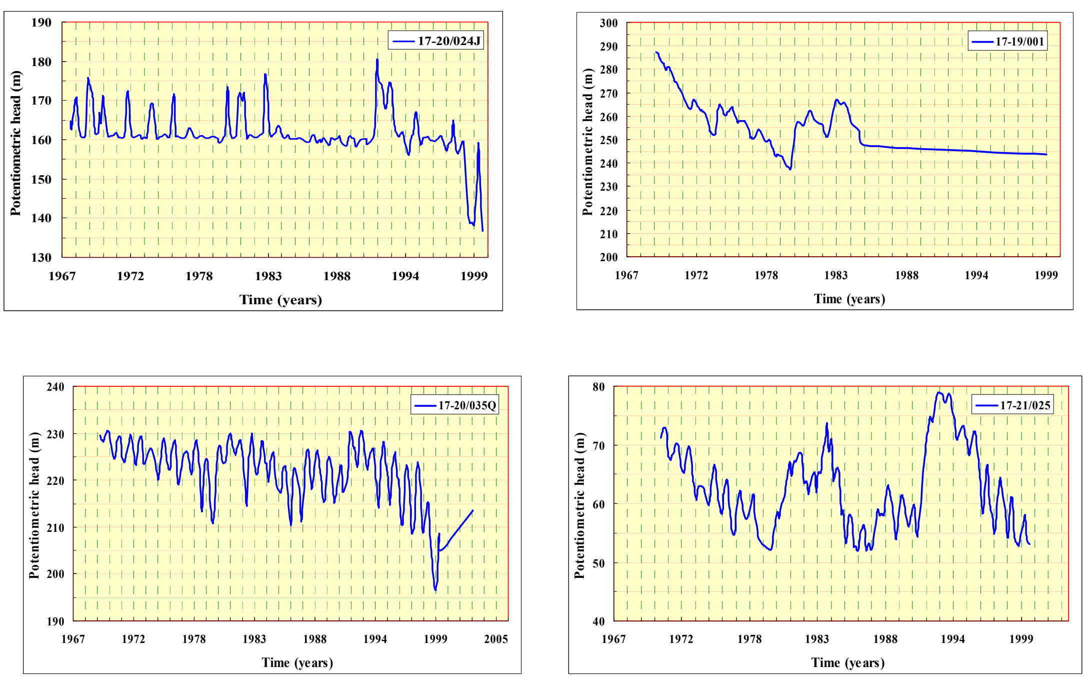


Figure 7.8: Time Series of Water Table Elevations for Selected Wells in the Eocene Aquifer

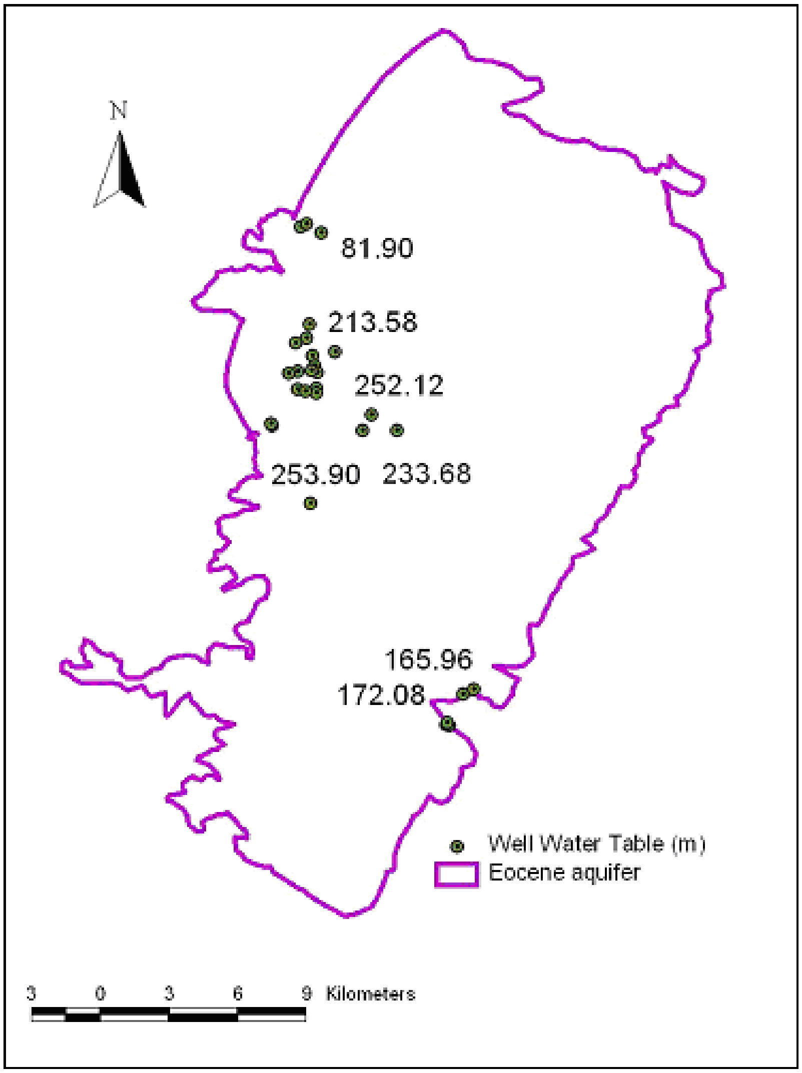


Figure 7.9: Water Table Elevations for Selected Wells in the Eocene Aquifer for Year 2003

7.10 Compilation of Data for Model Formulation

After collecting all the needed data in developing the conceptual model, these data were used in formulating the numerical model using MODFLOW. In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid. MODFLOW has a modular structure where it is divided into pieces called packages. The packages which were utilized in developing MODFLOW are summarized in Table 7.1.

Table 7.1: Summary of Packages Used in the Development of MODFLOW for the Eocene Aquifer

Package Name	Key Data
Name (NAM)	Input and output packages used in model simulation
Basic (BAS6)	Model boundary and initial head
Layer-Property Flow (LPF)	Hydraulic conductivity Values
Well (WEL)	Well locations and pumping rates
Recharge (RCH)	Recharge distribution
Preconditioned Conjugate Gradient (PCG)	Method for solving the groundwater flow equation along with all the settings
Multiplier Array (MULT)	Defines multiplier arrays for selected parameters
Discretization File (DIS)	Provides the number of rows, columns, and layers
Drain (DRN)	Spring locations, elevations and conductance values
General Head Boundary (GHB)	Boundary locations and corresponding elevations

7.11 Model Calibration

As mentioned earlier, calibration is the process of adjusting model input parameters (aquifer hydraulic parameters, recharge coefficient, and boundary conditions) until the model output (groundwater elevations and water budgets) approximates the real observations. The model was calibrated under steady-state conditions. During the calibration process, the goal is to reproduce groundwater elevations and spring flows on a long-term average basis.

The average values of well abstractions and spring flows are based on the available data. The recent groundwater elevations were used for the steady-state calibration. For the purpose of the steady-state calibration, a set of observation wells were selected to represent the target elevations.

The traditional method of calibration is based on a trail-and-error process where the simulated heads at the designated points and the water budget were compared to the observed ones. This method was carried out sequentially by adjusting the model parameters until the computed values approximate the observed values.

To facilitate model calibration, the model domain was divided into zones as shown in Figure 7.10. This made it easier to alter the hydraulic conductivity values at selected locations and to observe the corresponding effect on the values of the water table and the water budget after running the model.

After different changes in input parameters using trail-and-error process, the distribution of the calibrated hydraulic conductivity values (HK) for the Eocene aquifer is shown in Figure 7.11. The hydraulic conductivity values of the Eocene aquifer range from 0.013 to 5.94 m/day.

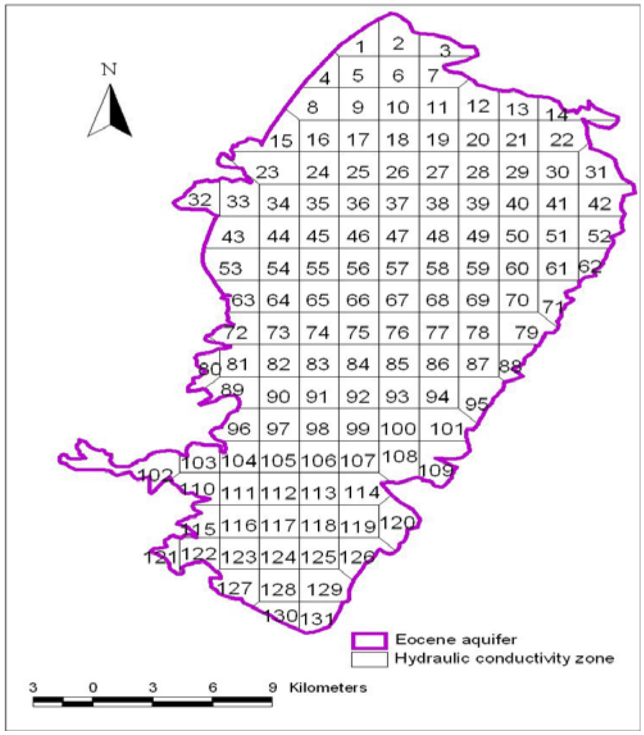


Figure 7.10: Hydraulic Conductivity Zones Utilized in Calibration. Numbers Indicate Zone ID

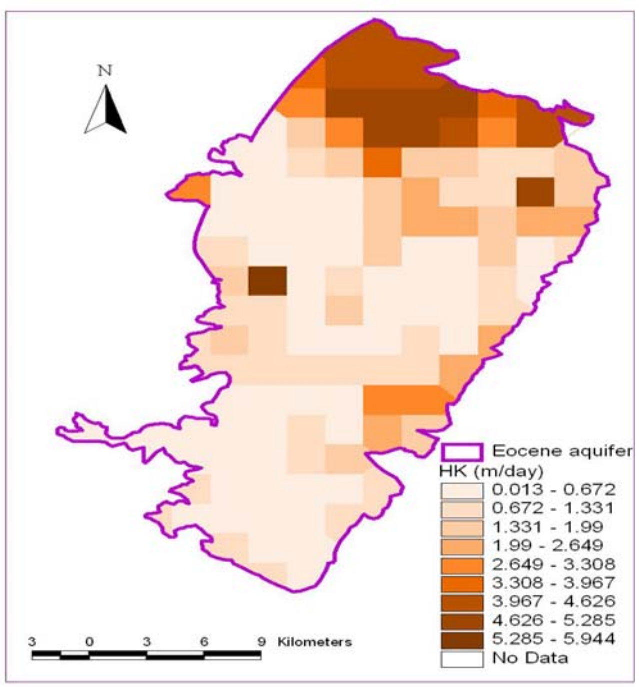


Figure 7.11: The Spatial Distribution of the Simulated Hydraulic Conductivity Values

The transmissivity, T, of an aquifer is a measure of how much water can be transmitted horizontally. Transmissivity is directly proportional to the aquifer thickness. For a confined aquifer, this remains constant, as the saturated thickness remains constant. The aquifer thickness of an unconfined aquifer is from the base of the aquifer (or the top of the aquitard) to the water table. The water table can fluctuate, which changes the transmissivity of the unconfined aquifer.

The transmissivity values for the Eocene aquifer were calculated after achieving the simulated value of the hydraulic conductivity and the result ranged from 3.7 m^2/day to 4350 m^2/day as shown at Figure 7.11.

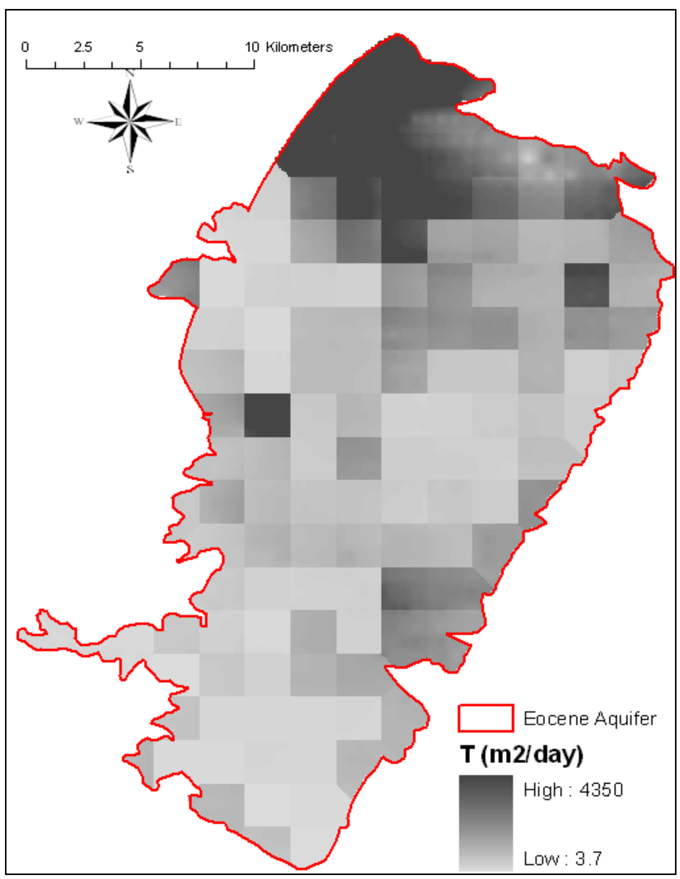


Figure 7.12: The Spatial Distribution of the Simulated Transmissivity Values

The calibrated distribution of water table elevation as simulated by MODFLOW is shown in Figure 7.13. The scatter plots of the simulated and observed heads at the calibration locations are depicted in Figure 7.14 and show a good match.

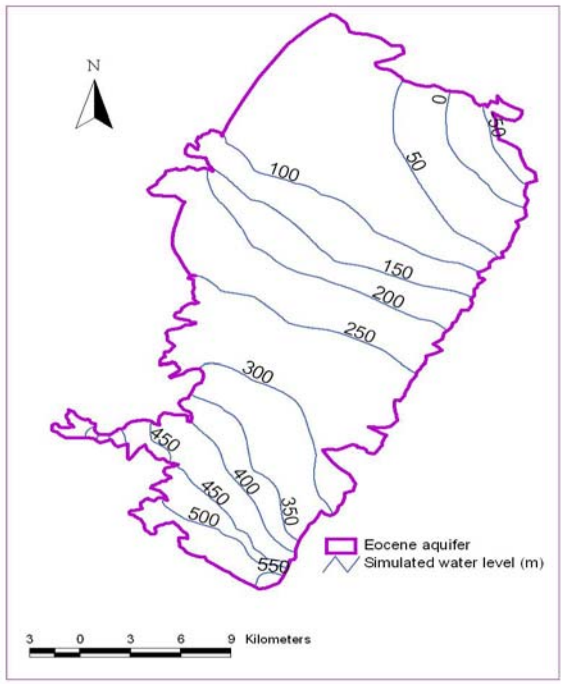


Figure 7.13: The Contours of the Simulated Water Table Elevations of the Eocene Aquifer

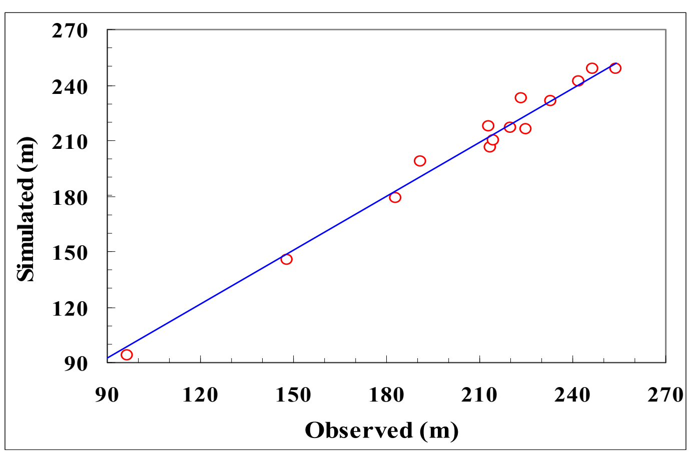


Figure 7.14: Simulated Versus Observed Water Table Elevations of the Eocene Model at the Calibration Locations

Table 7.2 summarizes the simulated water budget for the Eocene aquifer. Under the steady-state conditions, the average inflow to the system is approximately 83 mcm. About 55 mcm leaves the model domain as a lateral outflow. Differences between the inflow and outflow are due to the numerical approximation by MODFLOW.

Table 7.2: Annual Steady-State Water Budget for the Eocene Aquifer

Inflow/Outflow Component	Inflow (m^3/yr)	Outflow (m^3/yr)
Wells	0	18,209,232
Springs	0	10,407,288
Head-Dependant Boundary	0	55,005,472
Recharge	83,621,968	0
Total	**83,621,968**	**83,621,992**

7.12 Sensitivity Analysis

The purpose of the sensitivity analysis is to quantify the uncertainty in the calibrated model output as caused by the uncertainty in the aquifer input parameters. A sensitivity analysis is an essential step in model development. The parameters tested in the sensitivity analysis are the hydraulic conductivity, groundwater recharge, and well abstraction rates. The sensitivity tests were conducted by varying the above-mentioned parameters by ± 10% to ± 50% from the calibrated values.

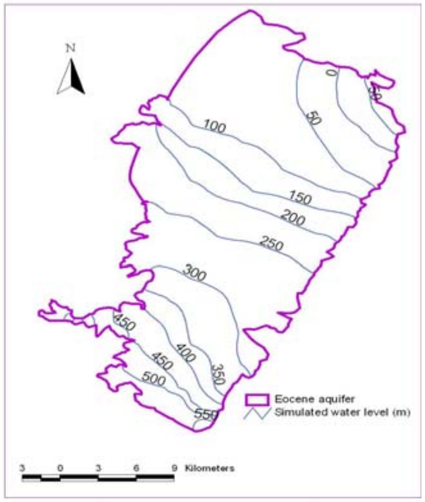
The sensitivity analysis results are presented as contours of water table elevations. In addition, the contours of water table deviations were computed for each perturbation to make it easy to observe the sensitivity as compared to the base conditions. Water table deviation is the difference between the water table elevation that results from the perturbation of a specific parameter and that of the base conditions. Deviation in water table elevation for specific row and column and sensitivity in spring yield and general-head boundary outflow were also considered in the presentation of the sensitivity analysis results.

As for perturbations in hydraulic conductivity and groundwater recharge, they were made by changing the multiplication factor in the Multiplier Array Package. Perturbations in well abstraction rates were made by changing the multiplication factor for well abstraction in Well Package.

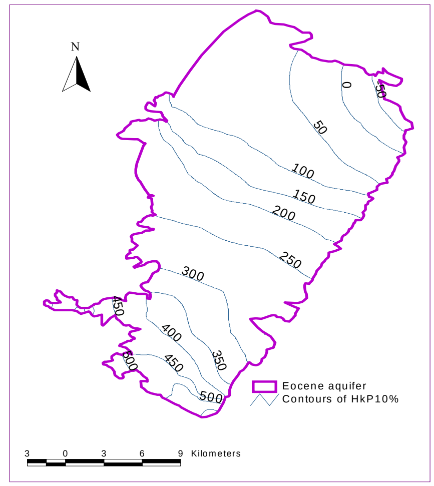
7.12.1 Model Sensitivity to Hydraulic Conductivity

Model output was found to be very sensitive to changes in hydraulic conductivity. An increase in the hydraulic conductivity causes a lowering in the simulated heads and vice versa. Water table contours and deviations that correspond to the different perturbations are shown in Figure 7.15, Figure 7.16, Figure 7.17 and Figure 7.18.

Figure 7.19 shows the variation in water table elevation for selected rows across all columns due to perturbations in hydraulic conductivity. As can be inferred, increasing the hydraulic conductivity cause a decrease in the spring yield and thus an increase in lateral outflow as depicted in Figure 7.20.



Base Conditions



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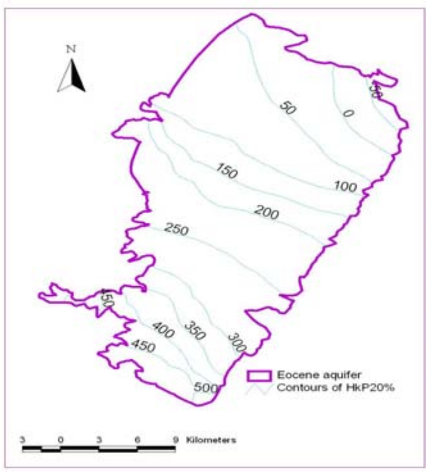

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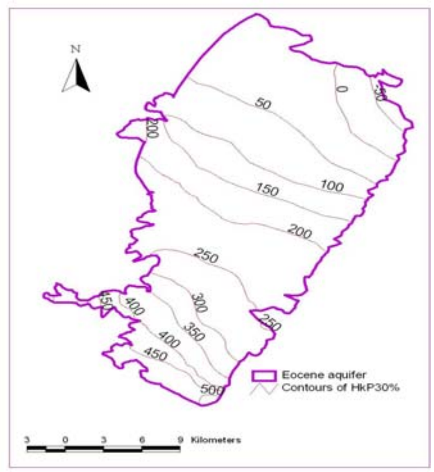

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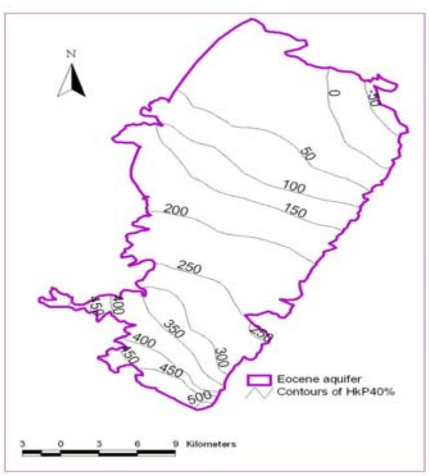

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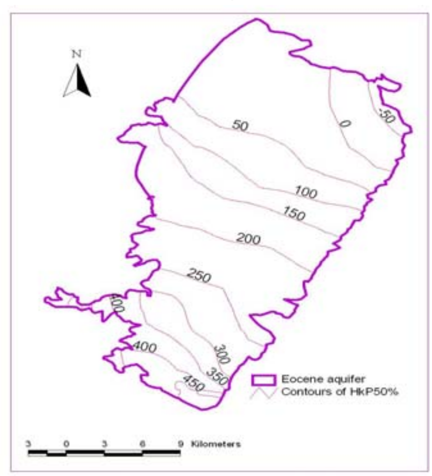

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Figure 7.15: The Contours of Water Table Elevation for Different Increase Percentages in the Hydraulic Conductivity Values

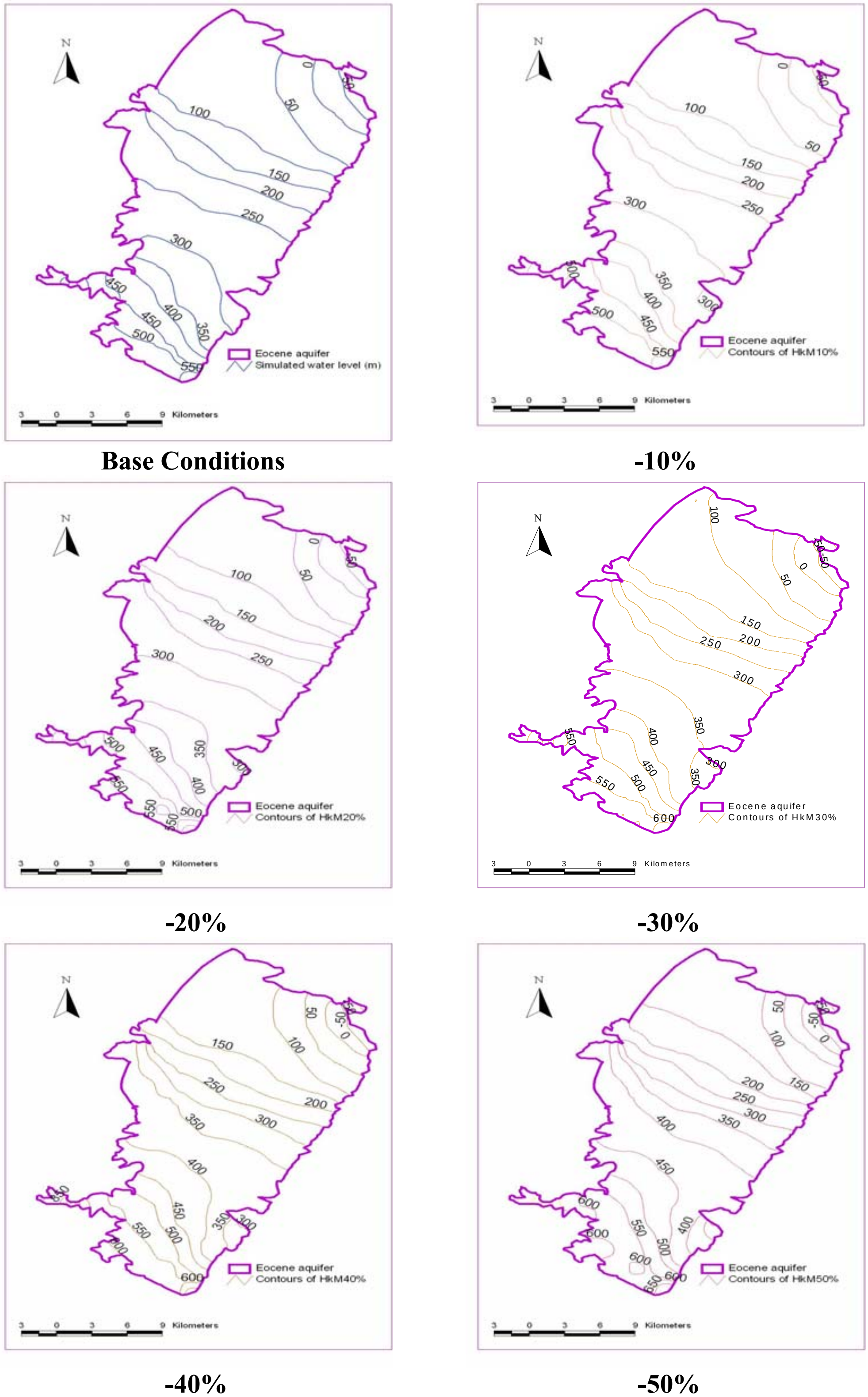
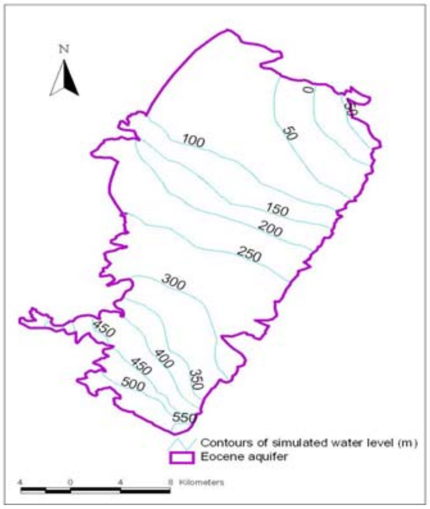


Figure 7.16: The Contours of Water Table Elevation for Different Decrease Percentages in the Hydraulic Conductivity Values



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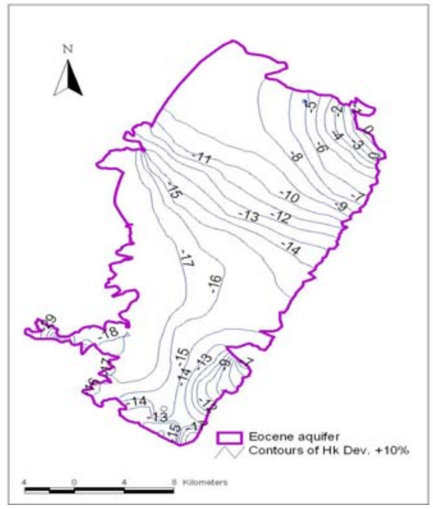

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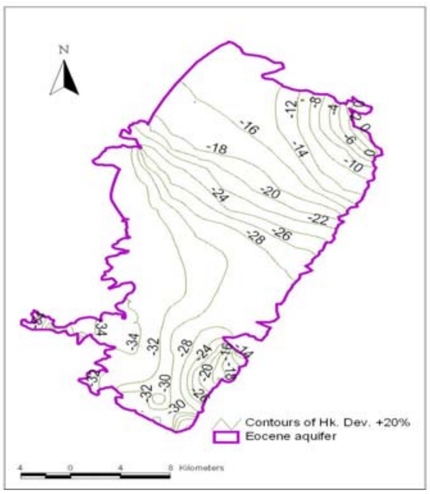

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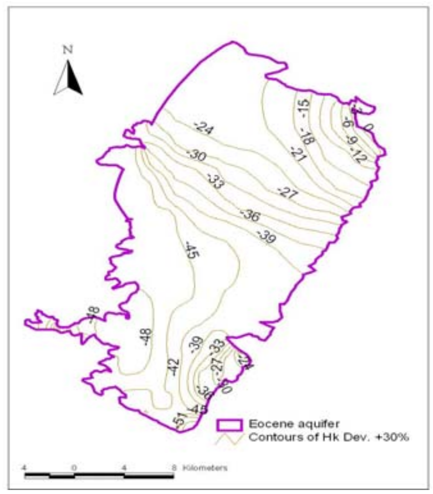

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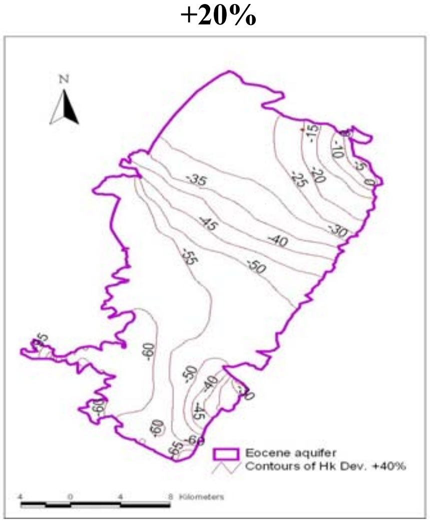

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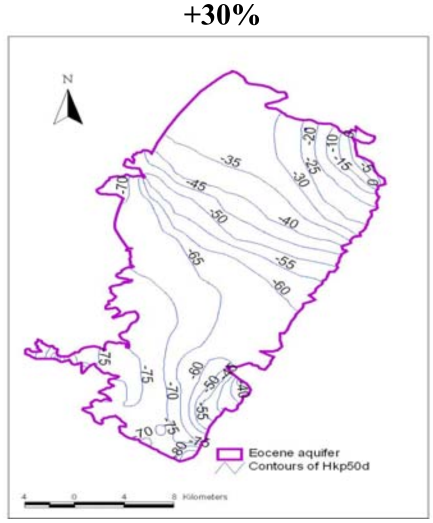

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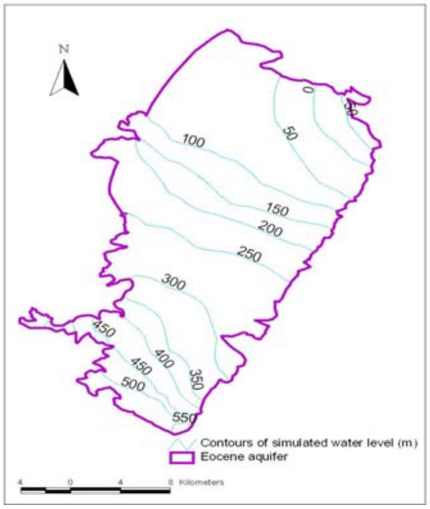
Figure 7.17: The Contours of Water Table Deviation for Different Increase Percentages in the Hydraulic Conductivity Values



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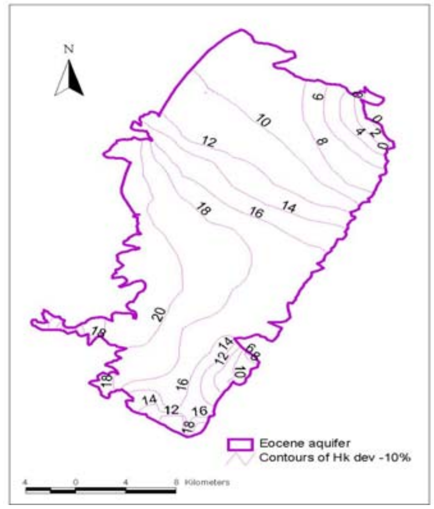

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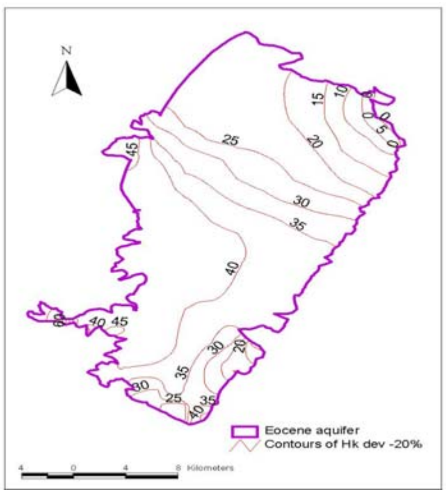

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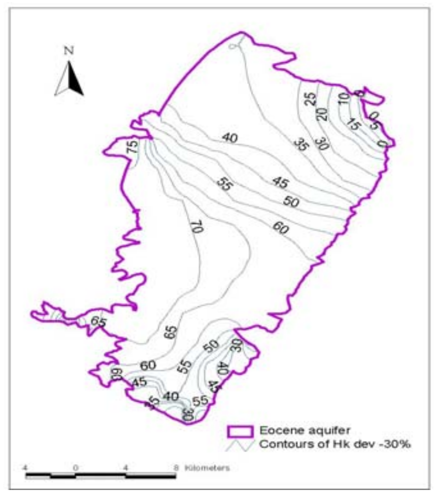

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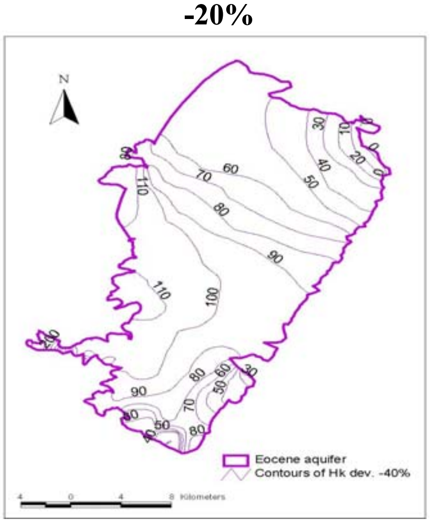

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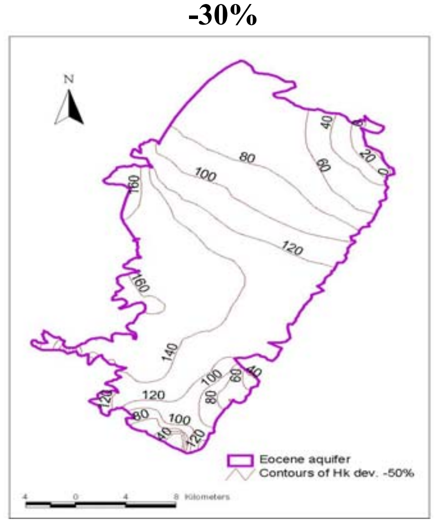

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Figure 7.18: The Contours of Water Table Deviation for Different Decrease Percentages in the Hydraulic Conductivity Values

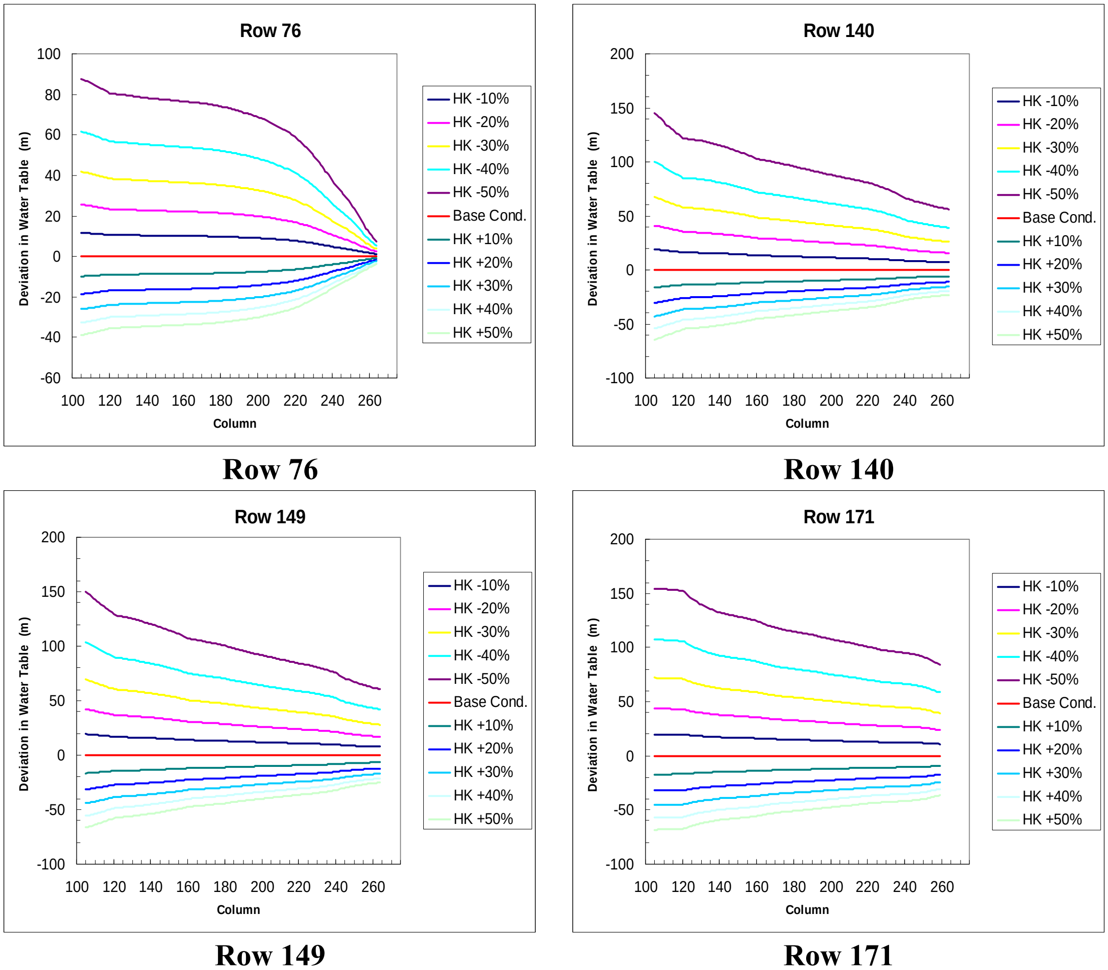


Figure 7.19: Deviation in Water Table Elevation for Specific Row and Columns to Perturbations in the Hydraulic Conductivity

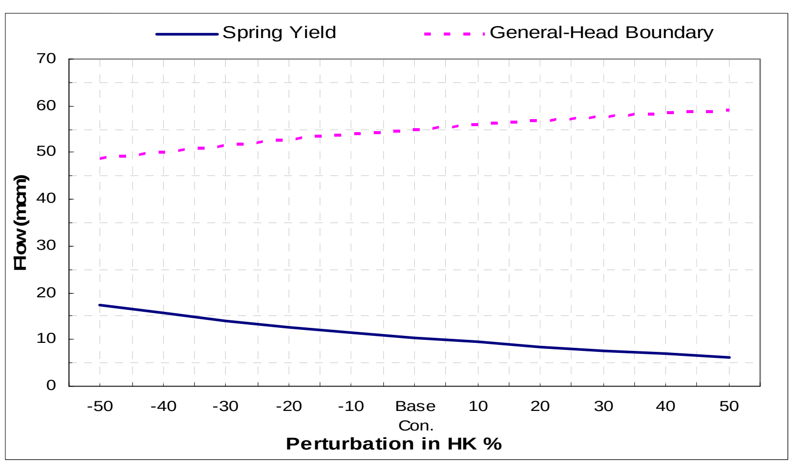


Figure 7.20: Sensitivity in Spring Yield and General-Head Boundary Outflow to Perturbations in the Hydraulic Conductivity

7.12.2 Groundwater Recharge

The model shows a high sensitivity to changes in groundwater recharge. As expected, an increase in the recharge causes an increase in the simulated heads and vice versa. The results in terms of water table contour lines and deviations for perturbation in groundwater recharge are shown in Figure 7.21 , Figure 7.22, Figure 7.23 and Figure 7.24. Figure 7.25 shows the variation in water table elevation for selected rows across columns due to the changes in groundwater recharge. Results also show that an increase in the recharge causes an increase in spring yield and lateral outflow as shown in Figure 7.26.

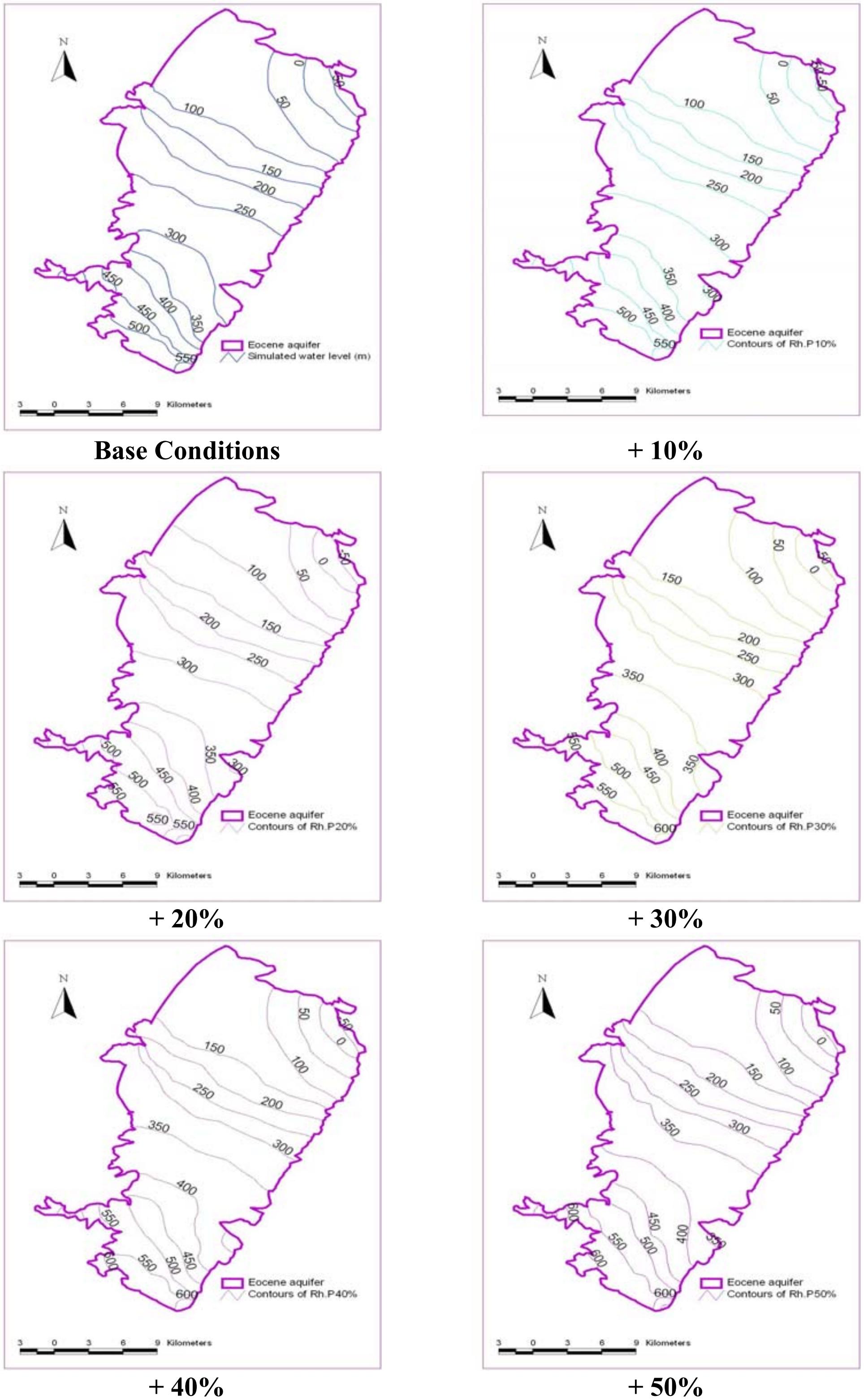


Figure 7.21: The Contours of Water Table Elevation for Different Increase Percentages in Groundwater Recharge

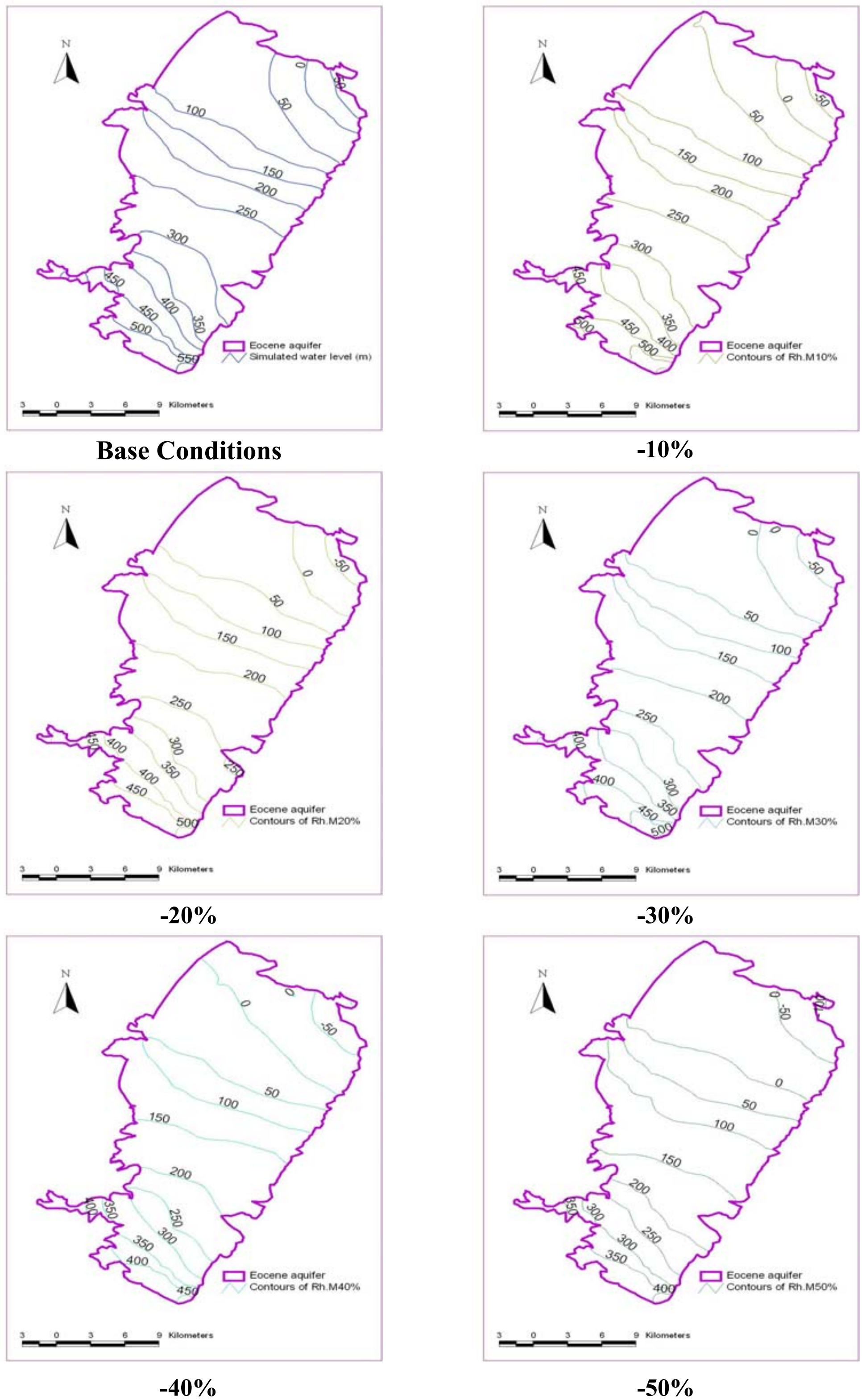
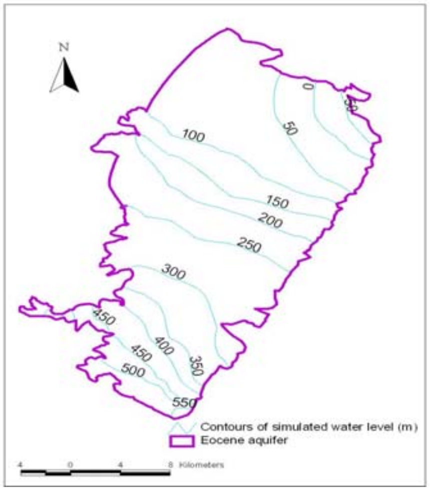


Figure 7.22: The Contours of Water Table Elevation for Different Decrease Percentages in Groundwater Recharge



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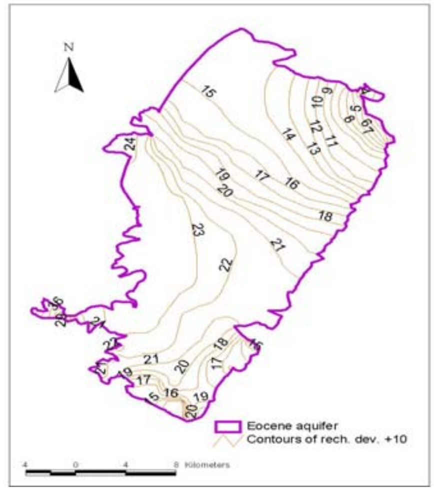

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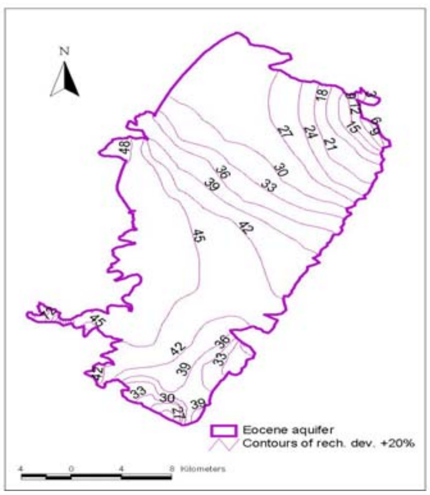

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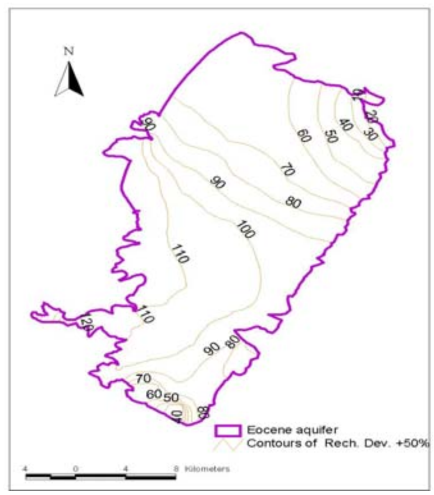

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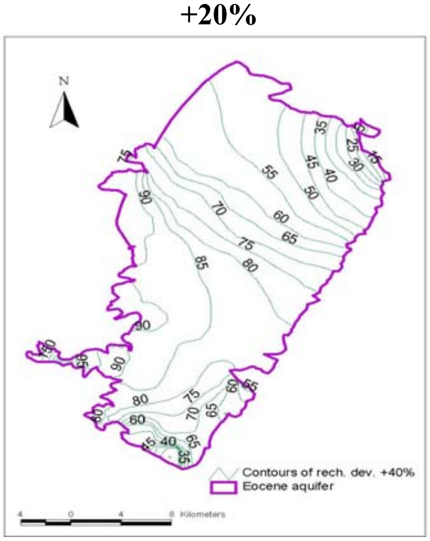

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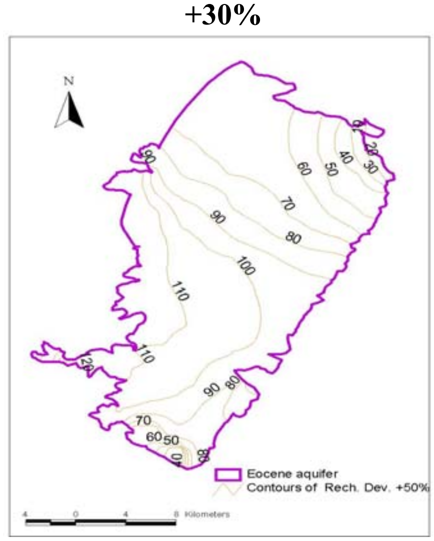

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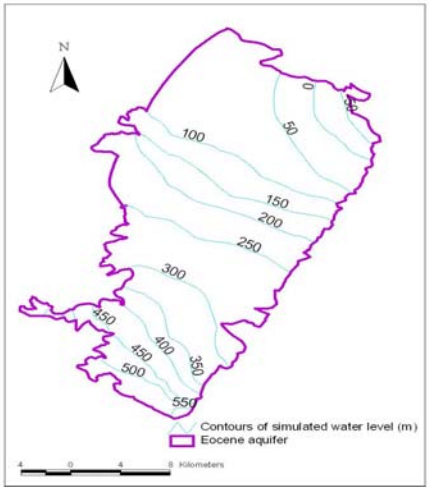
Figure 7.23: The Contours of Water Table Deviation for Different Increase Percentages in the Recharge Values



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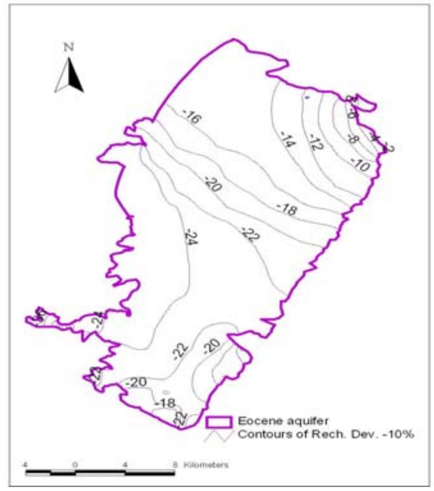

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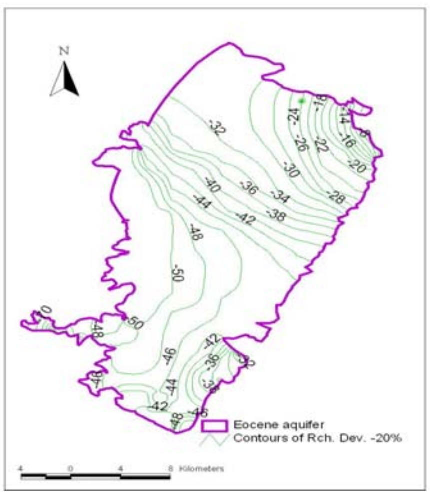

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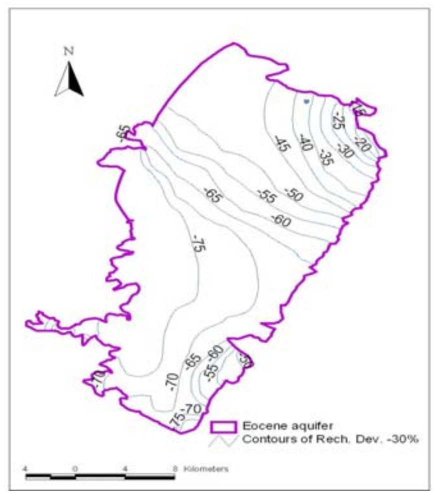

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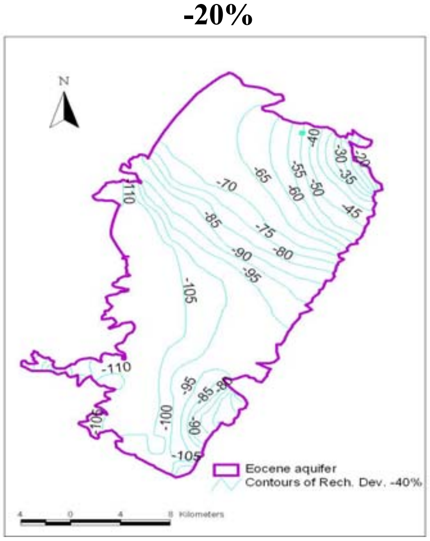

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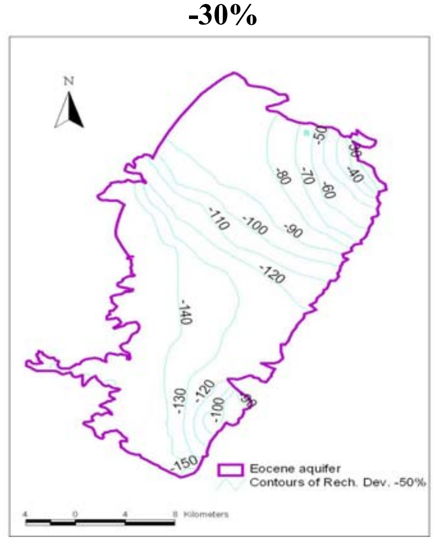

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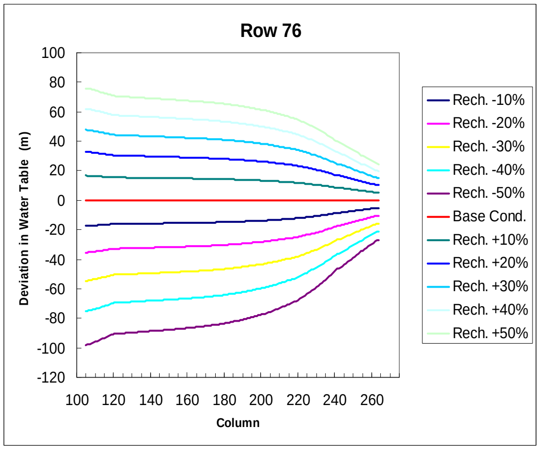
Figure 7.24: The Contours of Water Table Deviation for Different Decrease Percentages in the Recharge Values



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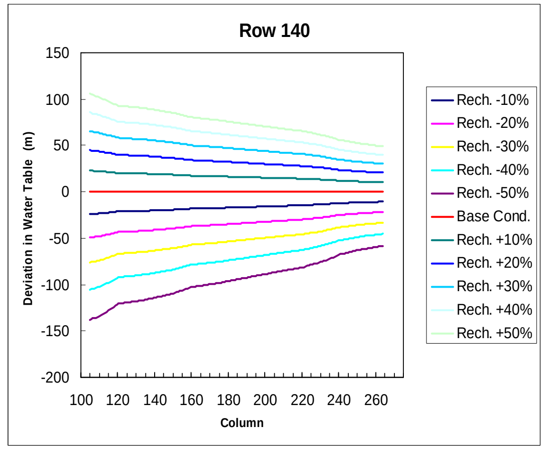

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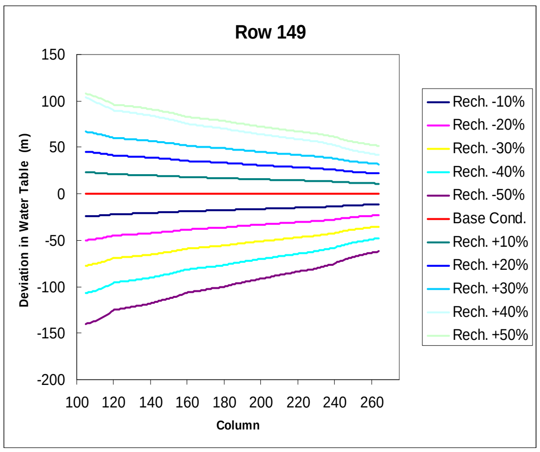

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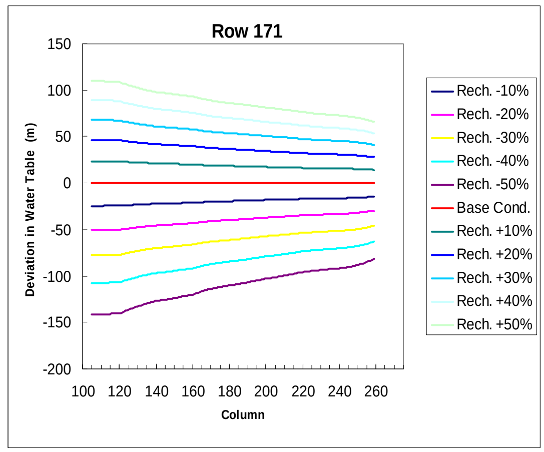

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Figure 7.25: Deviation in Water Table Elevation for Specific Row and Column to Perturbations in the Groundwater Recharge

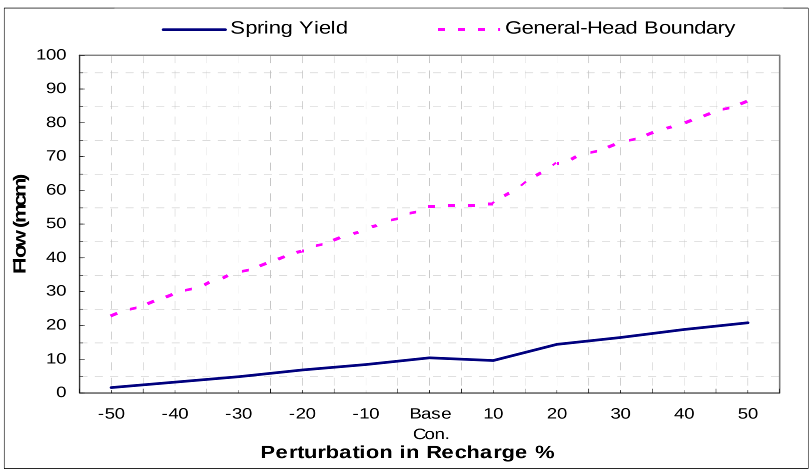


Figure 7.26: Sensitivity of Spring Yield and General-Head Boundary Outflow to Perturbations in the Groundwater Recharge

7.12.3 Well Abstraction

The model showed a moderate sensitivity to changes in pumping rates. As expected, an increase in the well abstraction causes a decline in the simulated heads as shown in Figure 7.27, Figure 7.28, Figure 7.29 and Figure 7.30. Figure 7.31 shows the variation in water table elevation for a specific row across all columns due to the changes in pumping rates. In addition, increasing the pumping rates causes a decrease in the spring yield and lateral outflow as shown in Figure 7.32.

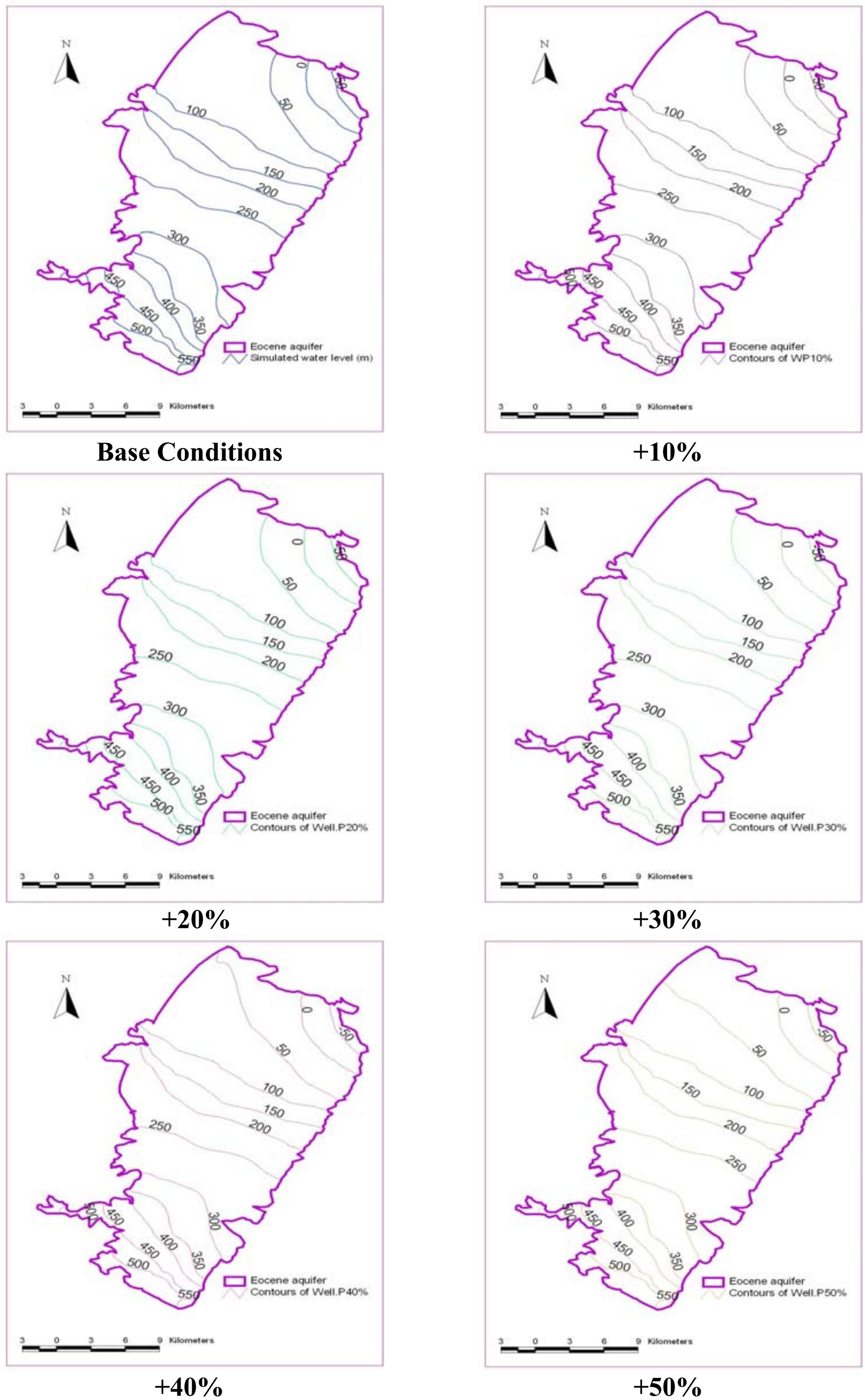
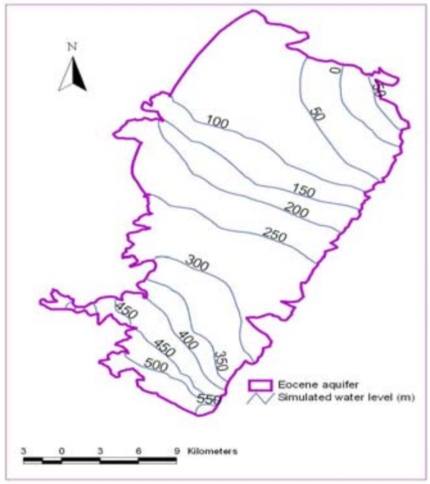
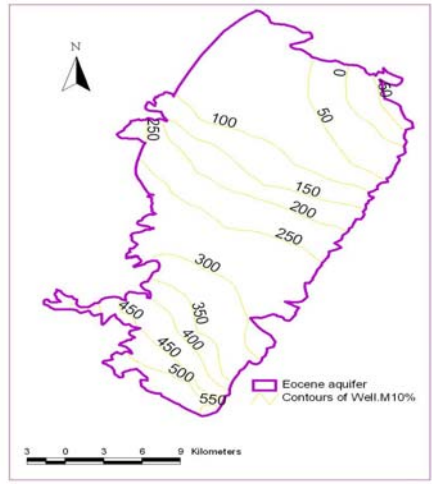


Figure 7.27: The Contours of Water Table Elevation for Different Increase Percentages in Pumping Rates



Base Conditions



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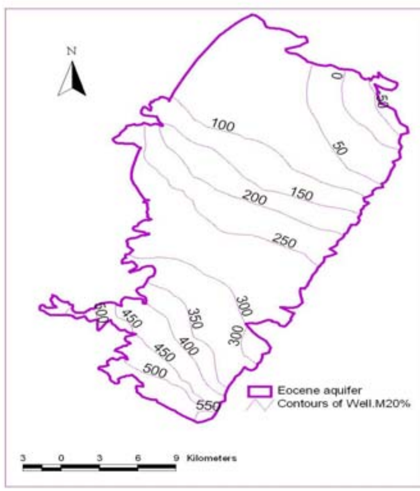

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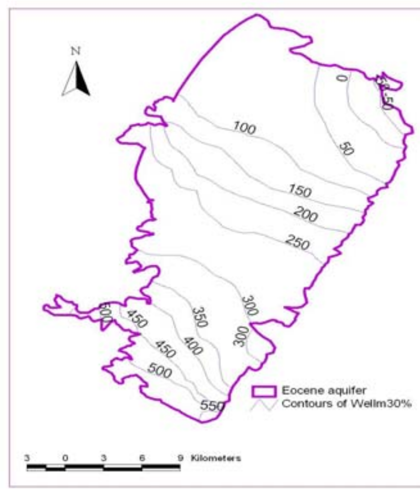

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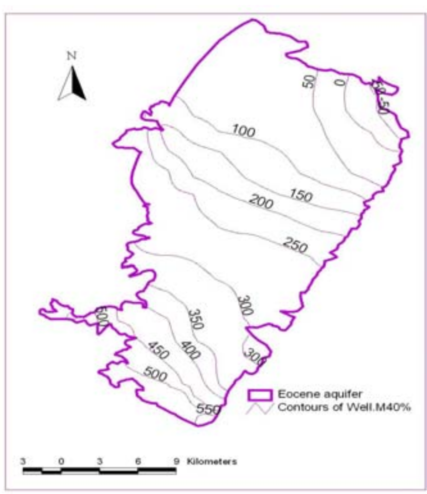

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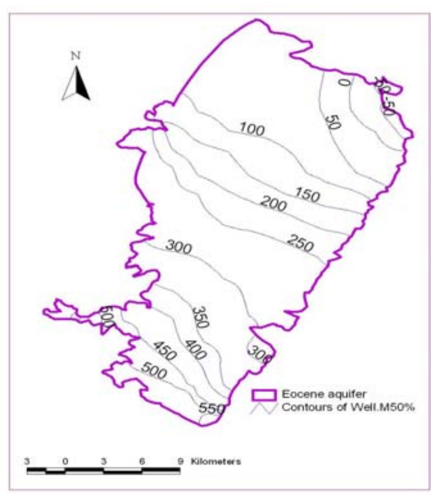

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Figure 7.28: The Contours of Water Table Elevation for Different Decrease Percentages in Pumping Rates

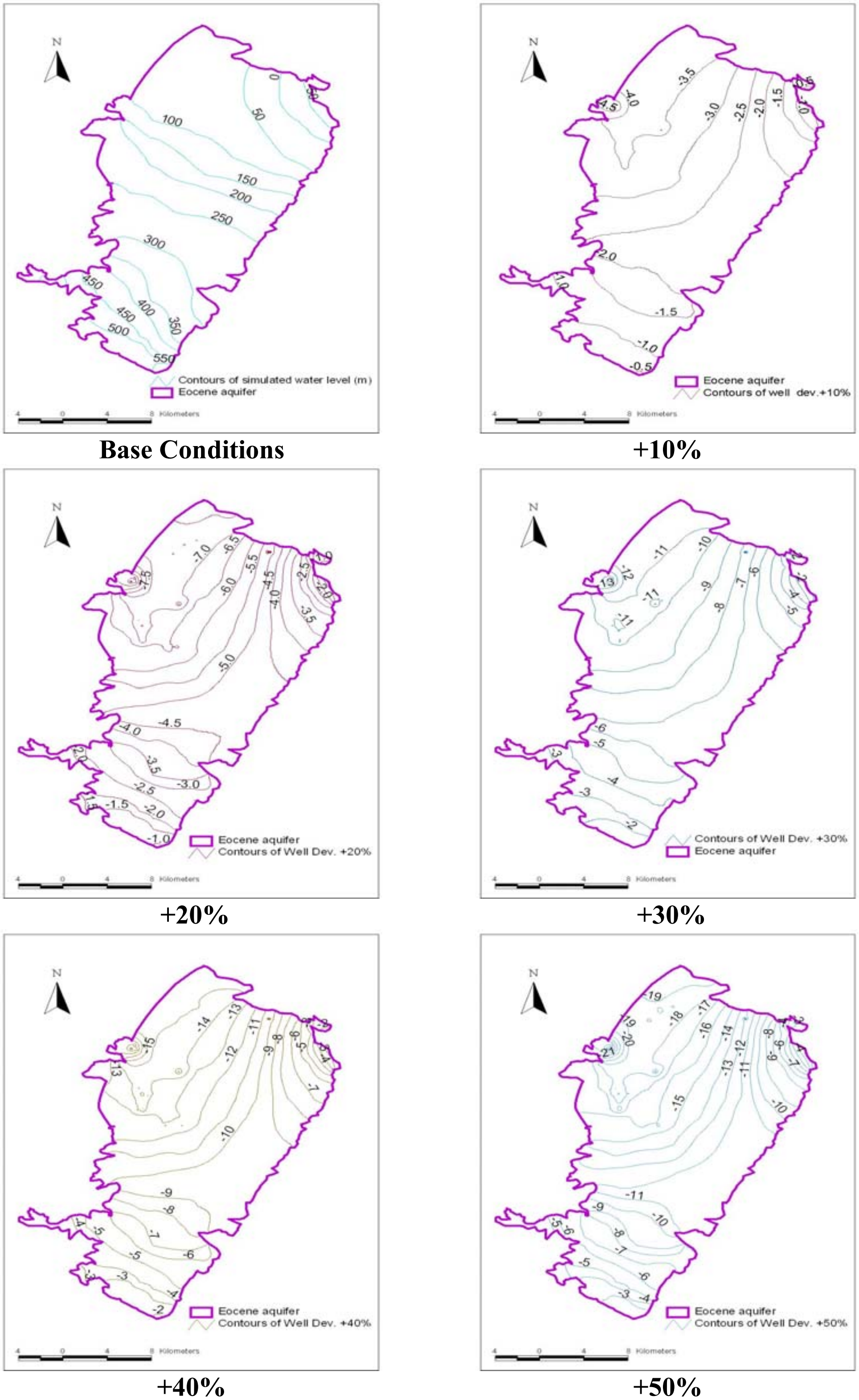


Figure 7.29: The Contours of Water Table Deviation for Different Increase Percentages in Pumping Rates

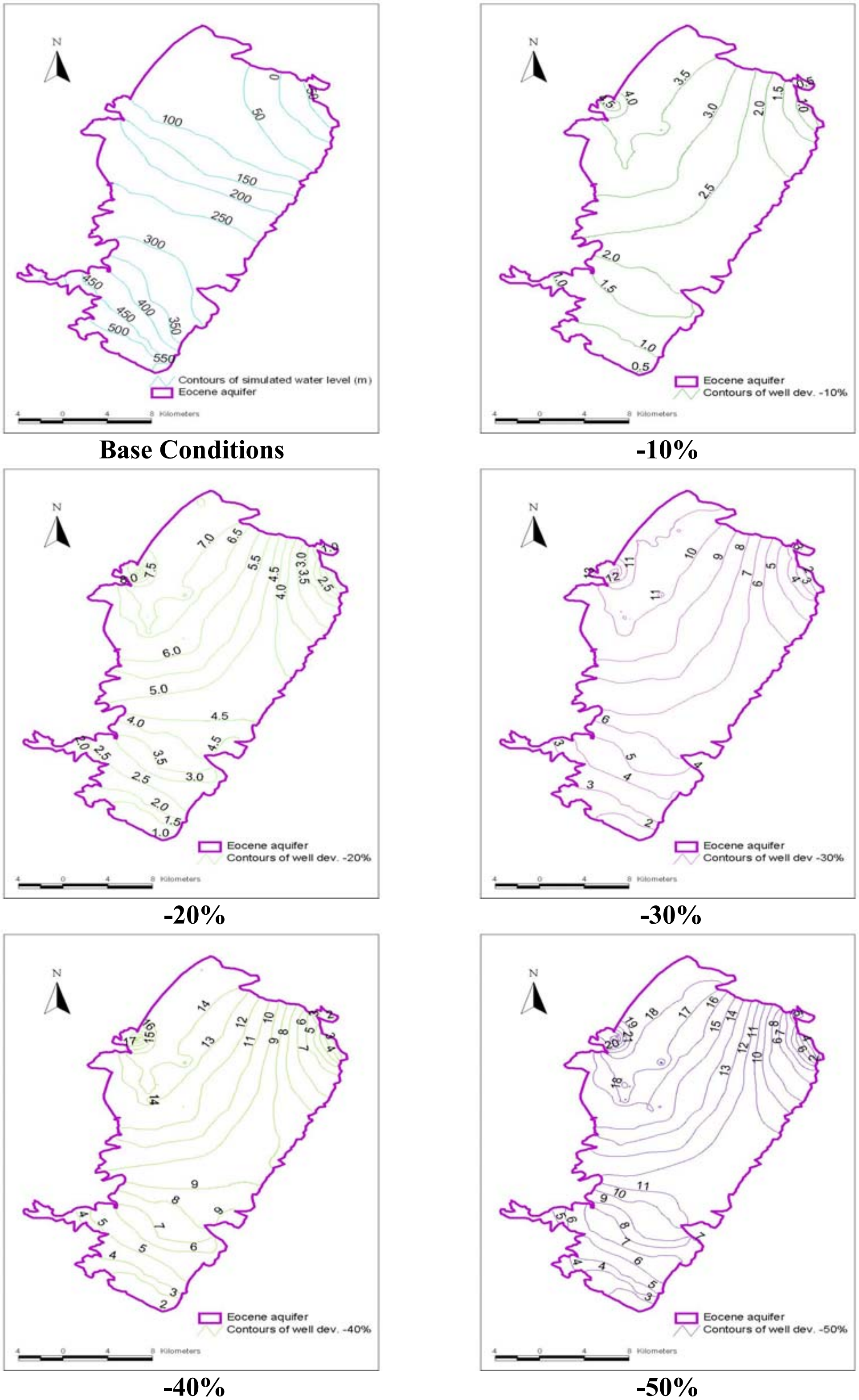
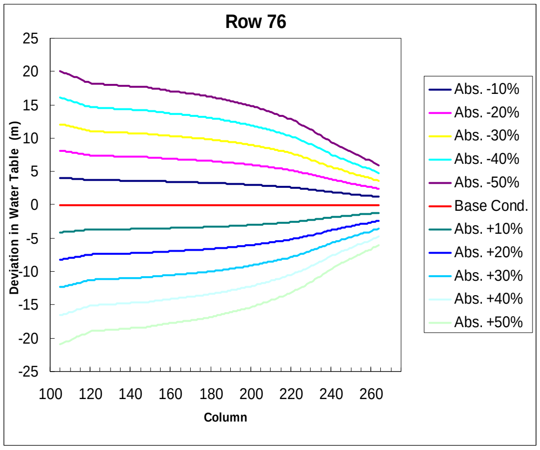


Figure 7.30: The Contours of Water Table Deviation for Different Decrease Percentages in Pumping Rates



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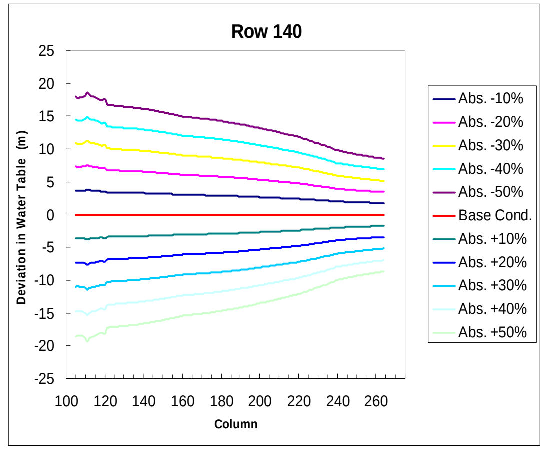

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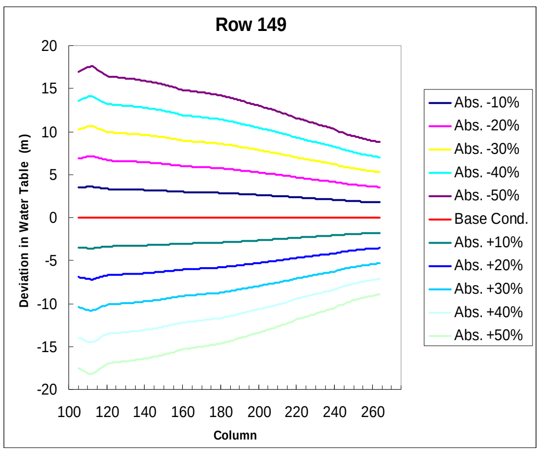

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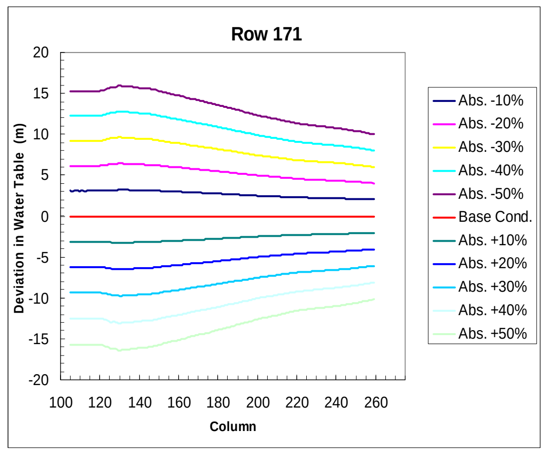

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Figure 7.31: Deviation in Water Table Elevation for a Specific Row Due to Perturbations in Pumping Rates

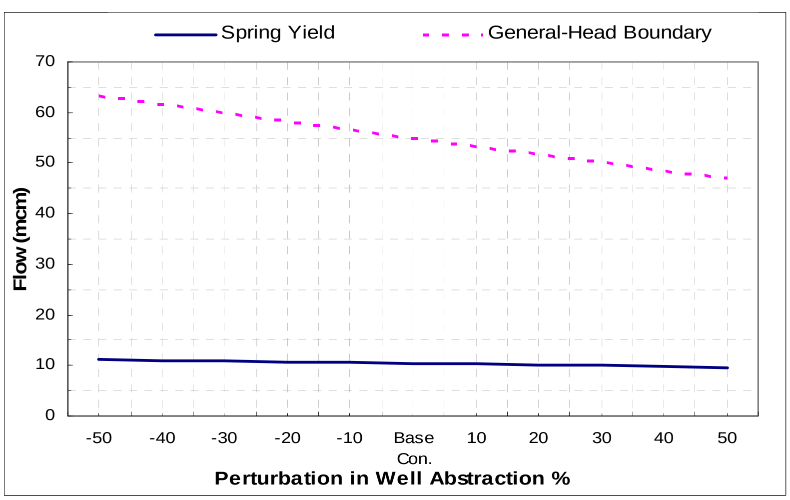


Figure 7.32: Sensitivity in Spring Yield and General-Head Boundary Outflow Due to Perturbations in Pumping Rates

7.12.4 Overall Results of Sensitivity Analysis

After completing the perturbations for the selected parameters in the sensitivity analysis, the model was found to be very sensitive to changes in recharge rate and hydraulic conductivity and less sensitive to well pumping. Figure 7.33 shows the mean deviation of the head for different perturbation percentages of the different considered parameters. Also, Figure 7.34 and Figure 7.35 show the positive and negative mean deviations for different perturbation percentages in hydraulic conductivity values.

The model shows that the annual spring yield is very sensitive to changes in recharge rate and hydraulic conductivity and less sensitive to changes in well pumping. Figure 7.36 shows the annual spring yield for different perturbation percentages of the different parameters.

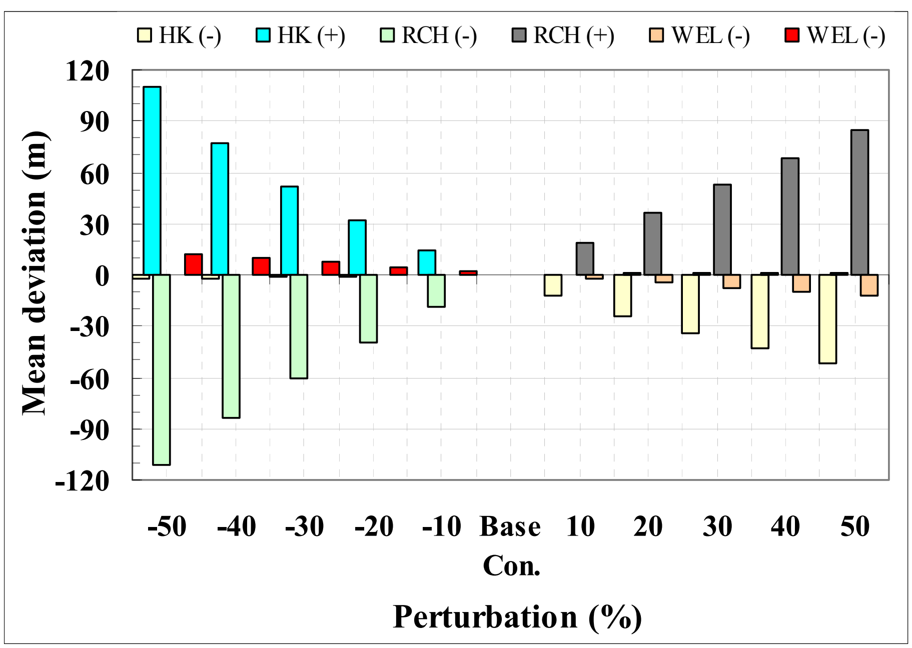


Figure 7.33: Mean Deviation in Water Table Elevation for Different Perturbation Percentages

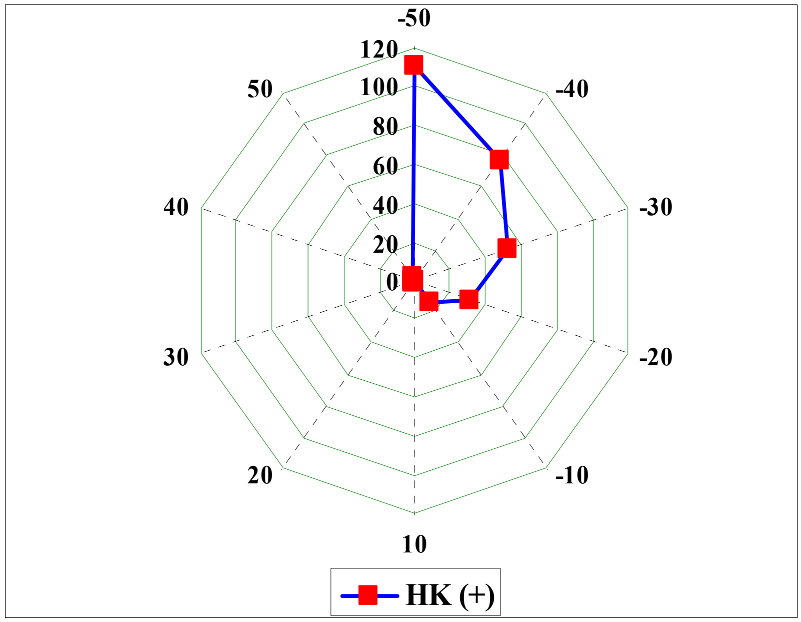


Figure 7.34: Positive Mean Deviation in Water Table Elevation for Different Perturbation Percentages in Hydraulic Conductivity

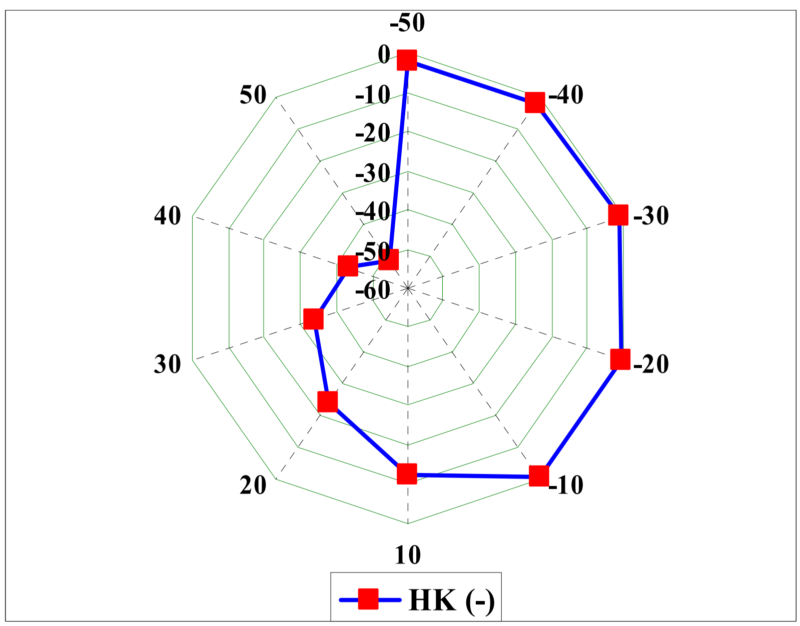


Figure 7.35: Negative Mean Deviation in Water Table Elevation for Different Perturbation Percentages in Hydraulic Conductivity

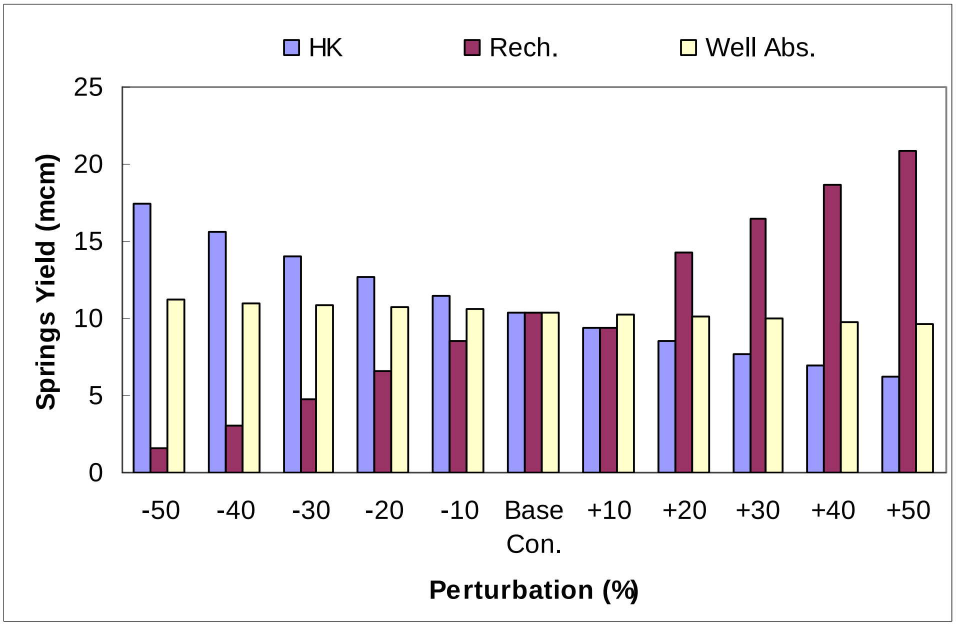


Figure 7.36: Annual Spring Yield for Different Changes in the Hydraulic Conductivity, recharge and Well Abstraction

Chapter Eight
Optimal Management of the Eocene Aquifer

8.1 Introduction

The Eocene aquifer is an unconfined aquifer of regional importance. Because of the complex nature of groundwater systems, however, and the large number of many factors that often affect groundwater development and management, the aquifer optimal pumping rates are difficult to determine especially under several scenarios that entail extreme conditions.

It is believed that the Eocene aquifer can be further utilized. However, no previous attempt was made to utilize simulation/optimization models to find out the optimal pumping rates. The use of combined simulation/optimization models greatly enhances the utility of simulation models alone by directly incorporating management goals and constraints into the modeling process (Barlow, 2005).

So far, a finite-difference groundwater flow model was developed and calibrated for the Eocene aquifer using MODFLOW and the model becomes ready to be incorporated within the optimization model. In this chapter, the simulation/optimization model was developed using GWM software. Thereafter, the developed GWM model was used to estimate optimal withdrawal rates that could be sustained from the Eocene aquifer under management and policy constraints.

The aim of this chapter is to develop the GWM model for the Eocene aquifer to figure out the optimal sustainable pumping rates under different scenarios. Such scenarios resemble potential climate change, uncertainty of hydraulic conductivity, and different levels of management constraints.

8.2 Management of Groundwater Resources

Groundwater simulation models are now commonly used for analysis and decision making in a wide variety of groundwater related problems. The management problem can be viewed as determining the appropriate type, location, and settings for controls to produce desired system outputs (Ahlfeld et al., 2000).

Groundwater management practices include the engineering, economic, and political factors that affect the locations, rates, and timing of imposed hydrologic stresses to the groundwater system (groundwater withdrawals, artificial recharge, and so forth). This imposed hydrologic stresses then affect the responses, or outputs, of the groundwater system groundwater levels, discharge rates, and water quality conditions that in turn may affect stream flow rates, aquatic habitats, and other environmental conditions. Ultimately, legal and political forces may prompt renewed scientific investigation of the groundwater system for the purpose of improved management of the resource (Galloway et al., 2003).

8.3 The Simulation/Optimization framework

Because of the complex nature of groundwater systems and the large number of engineering, legal, and economic factors that often affect groundwater development and management, the process of selecting a best operating procedure or policy can be extremely difficult. To address this difficulty, groundwater simulation models have been linked with optimization techniques to determine best (or optimal) management strategies from among many possible strategies. Optimization techniques explicitly account for water-resource management objectives and constraints and have been referred to as management models (Ahlfeld and Mulligan, 2000).

Figure 8.1 depicts the simulation/optimization model for the optimal management of the Eocene aquifer. In the simulation/optimization model, the modeler specifies the desired attributes of the hydrologic and water resource management system (such as maximum allowed groundwater level declines) and the model determines from a set of several strategies a single management strategy that best meets the desired attributes.

In order to evaluate weather the increase in the current extraction rates are sustainable, a simulation/optimization model was developed and used to determine the optimum pumping rates from the current 67 Palestinian wells keeping the Israeli pumping rates unchanged.

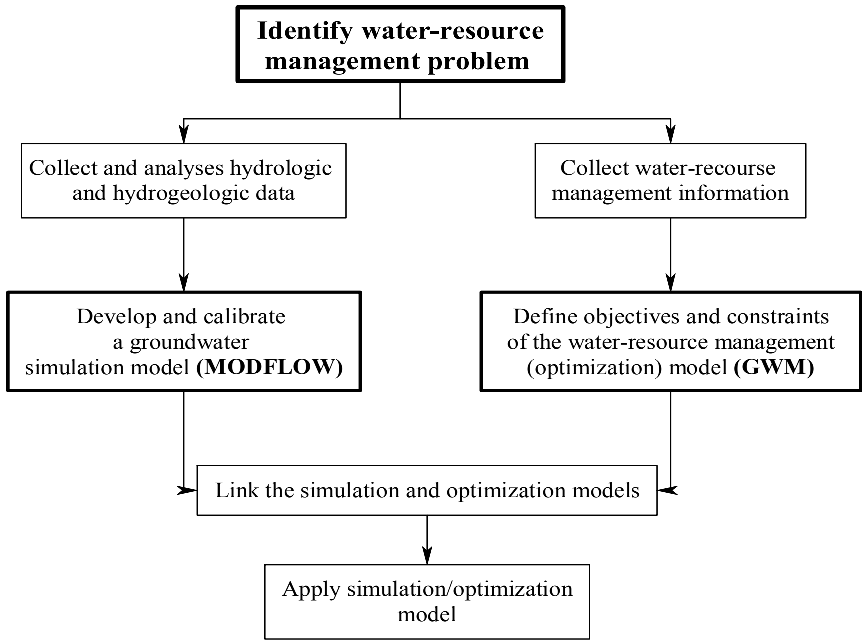


Figure 8.1: The Steps for the Development and Application of a Groundwater Simulation/Optimization Model for the Eocene Aquifer

In order to evaluate weather the increase in the current extraction rates are sustainable, a simulation/optimization model was developed and used to determine the optimum pumping rates from the current 67 Palestinian wells keeping the Israeli pumping rates unchanged.

The optimization model was formulated as a linear programming problem with the objective of the maximization of the water production from wells subject to the following constraints:

(I) Prevent the dewatering of model cells;

(II) Maintaining groundwater levels at or above specified level; and

(III) Amount of pumping rates are within specified limits.

In this simulation/optimization model, the decision variables are the withdrawal rates for the 67 Palestinian wells.

8.3.1 The Objective Function

The objective function is to maximize total pumping from the Eocene aquifer. The objective function can be expressed as in the following:

$$\max \sum_{i=1}^{67} w_i Q_i \qquad (6)$$

where $\sum_{i=1}^{67} w_i Q_i$ is the sum of the weighted annual groundwater pumping rates from all the Palestinian managed wells; Q_i is annual pumping rate from well i; and w_i is the weight associated with annual groundwater pumping rate Q_i.

8.3.2 Model Constraints

Model constraints are specified to limit the maximum amount of groundwater that can be withdrawn through the wells of the Eocene aquifer subject to the following constraints:

<u>Head constraints</u>

These can be expressed as follows:

i. $h_k \geq h_k^{DWT}$ (7)

where h_k is the head at the constraint location k and h_k^{DWT} is the limit placed at location k to prevent dewatering.

ii. $h_j \geq h_j^{\min}$ (8)

where h_j is the head at constraint location j and $h_j^{\min}$ is the limit placed to address management and policy considerations (see Figure 8.2).

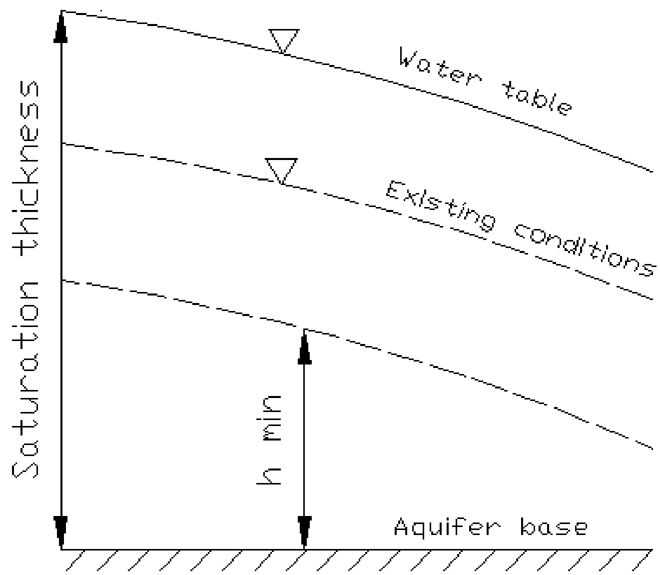


Figure 8.2: Head Constraint for the Eocene Aquifer Model

Head constraints were specified to prevent dewatering in all the pumping wells. MODFLOW may face difficulty with the drying and rewetting solution iterations. Such a problem can lead to convergence failure. To prevent this from occurring, limits on head at well cells were placed at 15% of the initial saturated thickness (Figure 8.3). These lower bounds are purely numerical and have no management meaning (David Ahlfeld, personal communication, 2007).

The second set of head constraints were set at 50% of the predevelopment saturated thickness of the Eocene aquifer. This is to prevent the head from dropping below the 50% of initial saturated thickness. This constraint was specified across the entire model domain with a total of 2178 control locations as shown in Figure 8.3. A uniform distribution of model cells was selected for the control locations at which the heads are maintained at or above the minimum specified head during the optimization process. It is worth mentioning that the specification of the head constraints at every model cell is numerically difficult and is unneeded since this implies a large number of linear programming iterations.

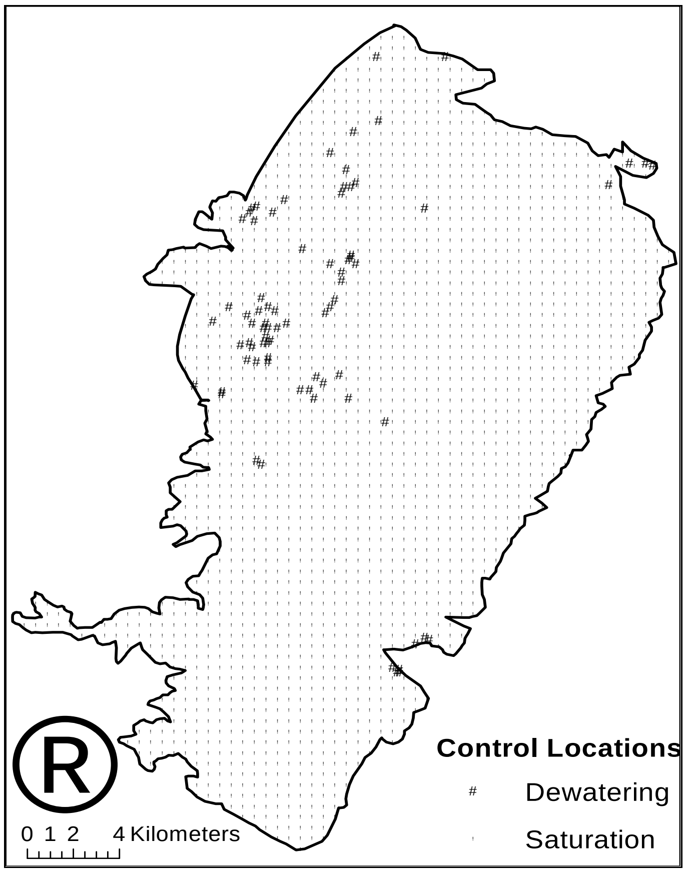


Figure 8.3: Control Point Locations for the Head Constraints for the Eocene Aquifer

Groundwater withdrawals constraints

Groundwater withdrawals constraints are for the decision variables and correspond to the spatial distribution of the managed wells. That is, they correspond to the current locations of the 67 Palestinian wells. Limits on groundwater pumping rates were specified for each well in the model such that:

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \qquad (9)$$

where Q_i is the optimal groundwater withdrawal for well i and $Q_i^{\min}$ and $Q_i^{\max}$ are the minimum and maximum pumping rates for well i; respectively. Lower bounds for the well pumping rates were set equal to the current pumping rates while the upper bounds were set equal to 150 m^3/hr.

8.4 Development of the GWM Model for the Eocene Aquifer

The simulation/optimization model was performed to assist in estimating the maximum amount of groundwater that can be safely withdrawn from the manageable wells within the Eocene aquifer without violating the head constraints.

As mentioned earlier in Chapter 6, GWM is the Groundwater Management software developed by the US Geological Survey for the modular three-dimensional groundwater model, MODFLOW-2000. GWM uses a Response-Matrix Approach to solve several types of linear, nonlinear, and mixed-binary linear groundwater management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints.

Before solving the optimization model using GWM, the groundwater flow model was developed and calibrated using MODFLOW. The global process controls the overall program operation and sets up data structures that can be used by all MODFLOW processes. GWM requires the specification of the certain files such as DECVAR, OBGFNC, VARCON, HEDCON, and SOLN files. The files that were utilized in developing the GWM are depicted in Figure 8.4 and illustrated below.

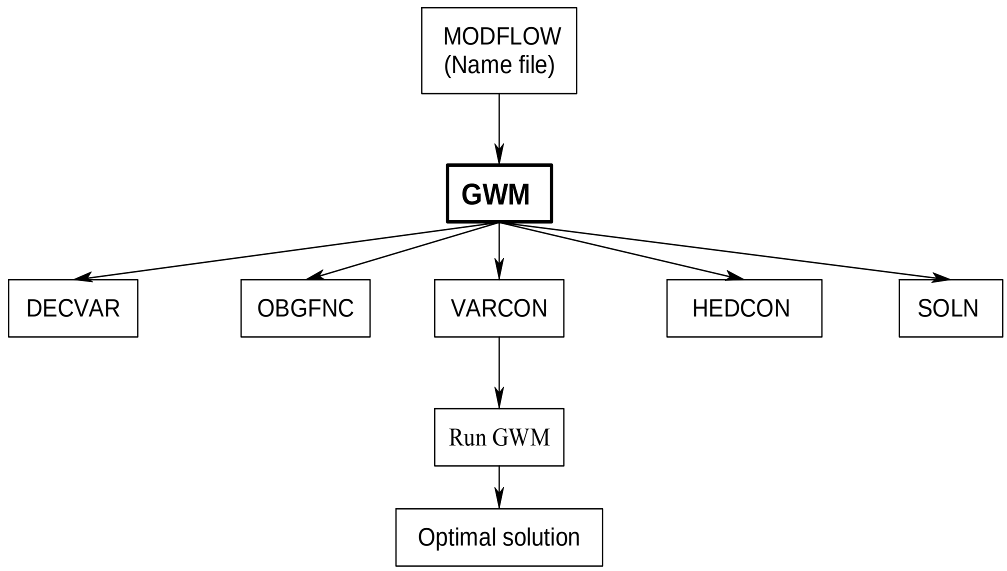


Figure 8.4: The Files Utilized in Developing the GWM for the Optimal Management of the Eocene Aquifer

The following files were used in the development of the GWM model:

DECVAR: Provides information on decision variables

OBGFNC: Provides information on objective function

VARCON: Provides information on the lower and upper bounds specified for the pumping rate (decision variables)

HEDCON: Provides information on head constraints

SOLN: Provides information on the solution and output-control parameters

The solution method for the groundwater management formulation considered herein for the Eocene aquifer is linear programming. A linear program is an optimization formulation in which the objective function and all constraints are linear with respect to the decision variables.

8.5 Management Scenarios

Optimal pumping strategies were obtained using GWM for the following four management scenarios:

1. Existing conditions (scenario 1).
2. Pumping priority is given to agricultural wells (scenario 2).
3. Pumping priority is given to domestic wells (scenario 3).
4. No Israeli wells under operation in the aquifer (scenario 4).

8.6 Result and Analysis

Optimal pumping rates for the Eocene aquifer were obtained from GWM. Table 8.1 summarizes for each scenario the optimal pumping rates, annual spring yield, and groundwater discharge from the general-head boundary. The optimal pumping rate from Palestinian wells is shown in Figure 8.5.

Table 8.1: Summary of Optimal Pumping Rates under the Different Management Scenarios along with Spring Yield and Outflow from the General Head Boundary

Scenario	Total Annual Optimal Pumping from Palestinian Wells (m^3)	Annual Spring Yield (m^3)	Outflow from General Head Boundary (m^3)	Increase in Total Pumping (m^3)
Base conditions	6,509,232	10,407,288	55,005,472	0
Scenario 1	29,516,227	4,975,609	37,546,577	23,006,995
Scenario 2	29,086,388	5,292,851	37,658,334	22,577,156
Scenario 3	28,044,200	5,740,438	38,247,909	21,534,968
Scenario 4	39,002,670	4,675,369	39,936,659	32,493,438

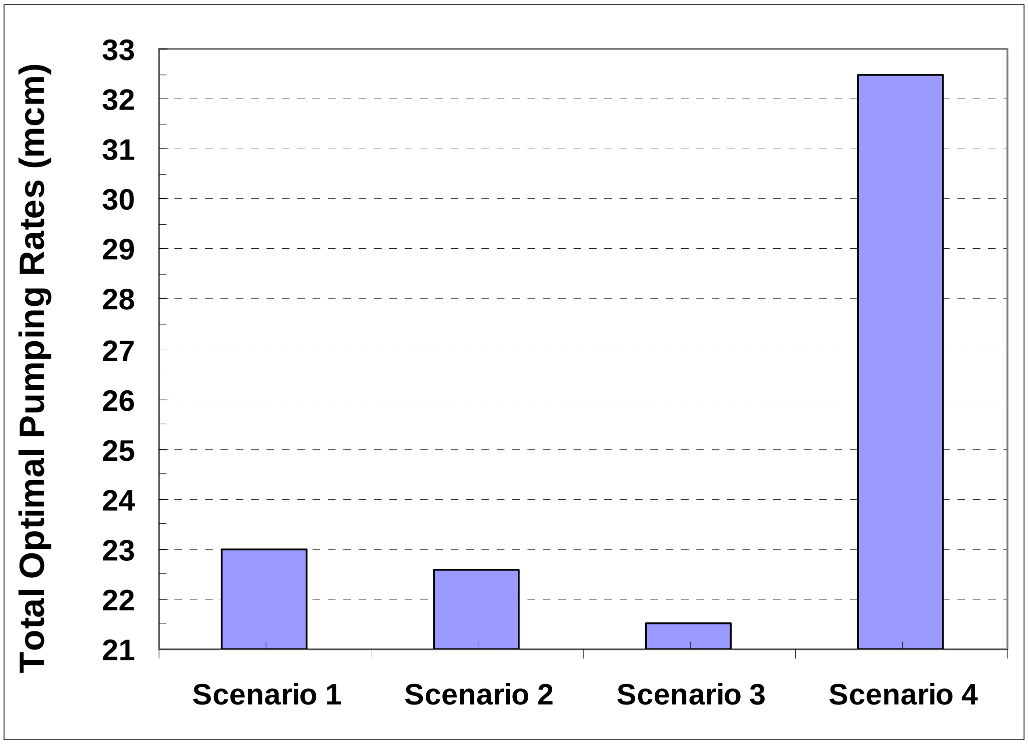
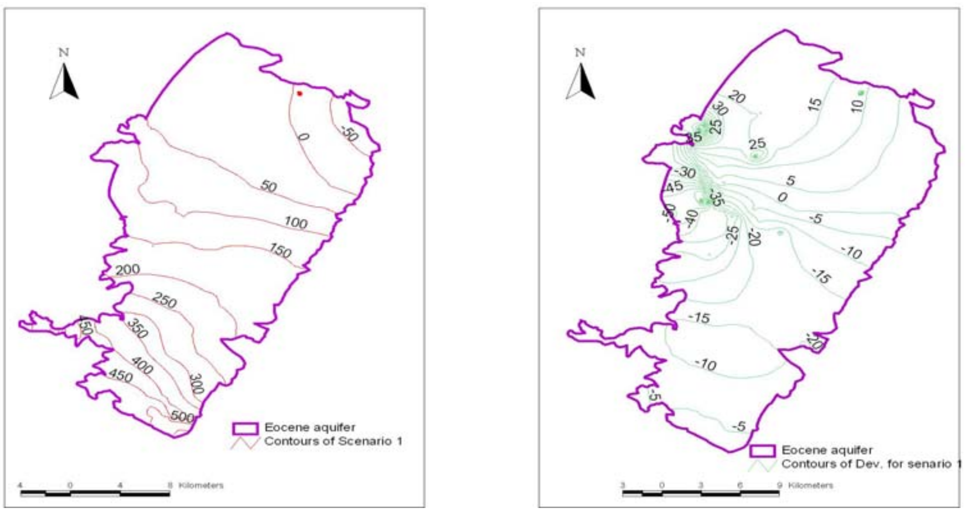


Figure 8.5: Increase in Total Pumping Rates as Compared with the Existing Conditions

The results from the first three scenarios show that the optimal pumping rates give approximately over four times much more water as compared to the existing conditions for Palestinian pumping wells. However, this increase in pumping rates leads to a decrease in total spring yield by almost 50%, whilst the outflow from the general head-boundary decreases by approximately 30%. The decreasing amount in spring yield is compensating by the amount of water recived from pumping wells. Scenario 4 gives about 32 mcm of optimal pumping rates that could be withdrawn from Palestinian wells in addition to the amounts being pumped corresponding to the base conditions.

In scenarios 1, 2 and 3 the pumping rates from the Israeli wells were kept unchanged. In scenario 4, the Israeli wells were shut off and only Palestinian wells were put into operation.

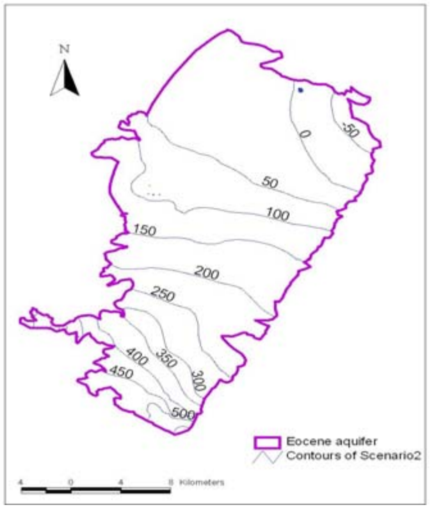
Scenario 1 gave an optimal total pumping rate of almost 30 mcm from Palestinian wells. The distribution of water table elevation and its deviation from base conditions that correspond to Scenario 1 are shown in Figure 8.6. The water table deviation has high values in the middle area of the Eocene aquifer were the wells are concentrated.



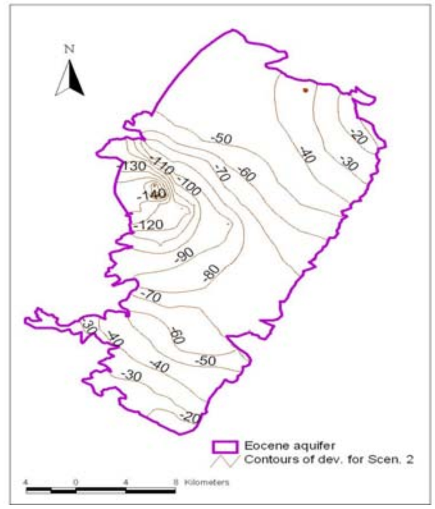
Water table elevation for scenario 1 **Water table deviation for scenario 1**

Figure 8.6: Contours of Water Table Elevation and its Deviation from the Simulated Model for Scenario 1

Scenario 2 was formulated considering a priority for agricultural wells. This was attained by assigning higher weights for the agricultural wells as shown in equation (6). The total optimal pumping rate exceeds 29 mcm and the water table elevation and its deviation from the simulated model are shown in Figure 8.7. The water table deviation has high values in the location of agricultural wells.



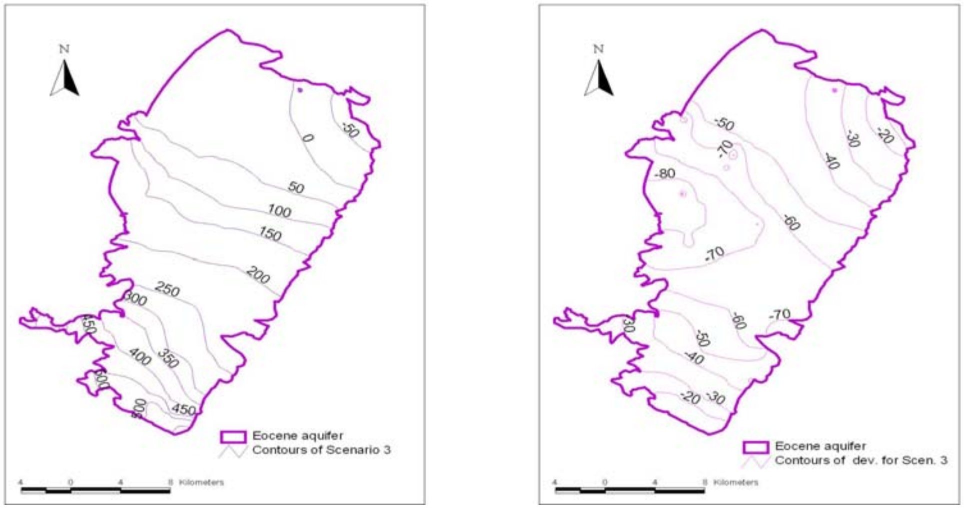
Water table elevation for scenario 2



Water table deviation for scenario 2

Figure 8.7: Contours of Water Table Elevation and its Deviation from the Simulated Model for Scenario 2

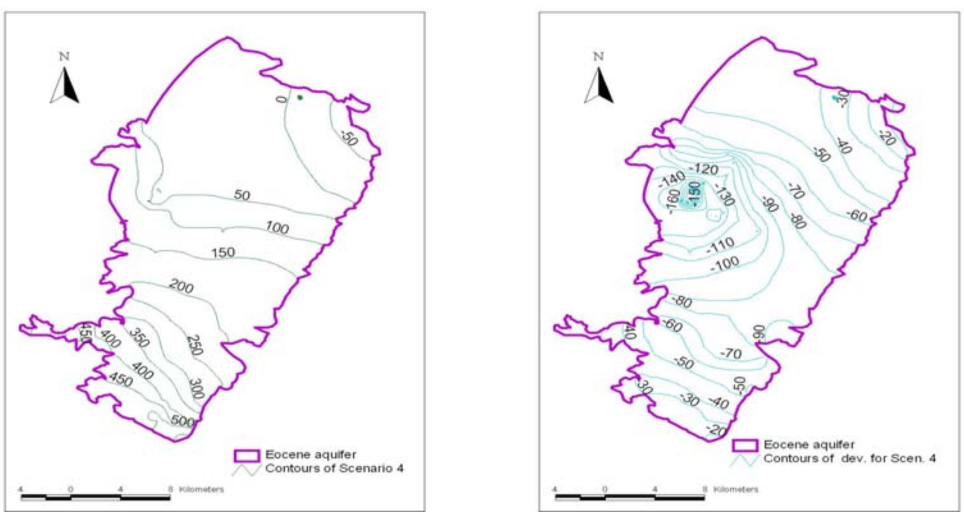
Scenario 3 was set up considering the priority to the domestic wells. This was attained by assigning higher weights for the domestic wells. The total optimal pumping rate is about 28 mcm and the water table elevation and its deviation from the simulated model are shown in Figure 8.8. The water table declines notably in the middle of the Eocene aquifer at the locations of the pumping wells. However, less deviation occurs under this scenario as compared to scenario 2 where only four wells are used for domestic purposes and six wells for both domestic and agriculture.



Water table elevation for scenario 3 **Water table deviation for scenario 3**

Figure 8.8: Water Table Elevation and its Deviation from the Simulated Model for Scenario 3

Scenario 4 assumes no Israeli wells. The total optimal pumping rate is almost 39 mcm and the water table elevation and its deviation from the simulated model is shown in Figure 8.9. In this scenario, the optimal pumping rates and water table deviation are the highest amongst all scenarios.



Water table elevation for scenario 4 **Water table deviation for scenario 4**

Figure 8.9: Water Table Elevation and its Deviation from the Simulated Model for Scenario 4

The optimal pumping rates that correspond to the four scenarios are shown in Figure 8.10. Apparently, the highest amounts of water that can be safely pumped out of the aquifer correspond to agricultural purposes. Scenarios 3 and 4 have identical optimal pumping rates for domestic wells.

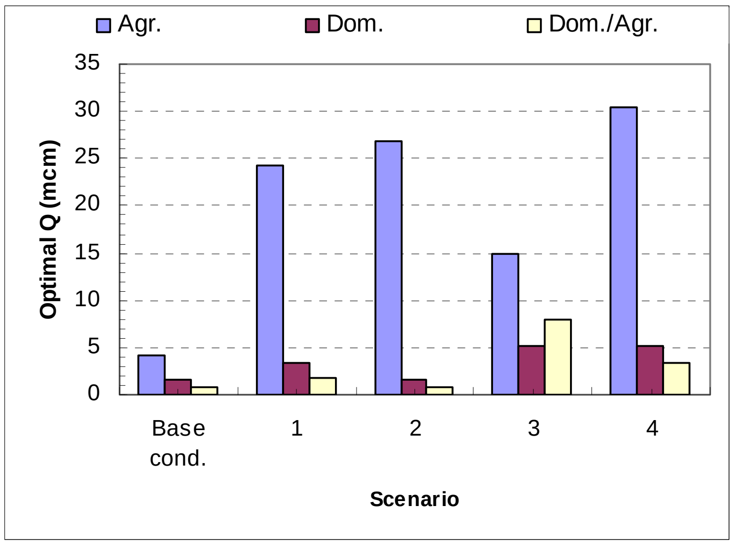


Figure 8.10: Optimal Pumping Rates for the Wells of the Eocene Aquifer as Classified According to Well Use under Different Management Scenarios

8.7 Sensitivity Analysis of the Optimal Pumping Strategy

The GWM model relies greatly on the simulation of the groundwater flow system. This in turn implies that changes in the current flow system would likely alter the optimal pumping strategy. This is of great importance when considering for instance the increase or decrease in the recharge due to changes in the rainfall. The same applies to hydraulic conductivity field that represents the ease of the movement of water through aquifer media.

Another situation to consider is the sensitivity of the optimal pumping strategy to the value of the right-hand side of the head constraints. In other words, a deviation from the 50% reduction in saturation thickness is ought to be considered. This in particular reflects the desire of the decision makers and water resources managers. It also reflects the status of the aquifer in terms of the exploitable water quantities.

In the following subsections, the sensitivity of the optimal pumping strategy to recharge, hydraulic conductivity and saturation head constraints is investigated. To assess the sensitivity of the optimal pumping rates to the designated parameters, changes in the values of these parameters were made, input files were updated accordingly, GWM was executed and results were extracted.

8.7.1 Sensitivity to Groundwater Recharge

In the Eocene aquifer, the groundwater recharge originates mainly from rainfall. Thus, an increase in rainfall is expected to increase the optimal pumping rates and vice versa. A range of recharge perturbation of ±5 to ±25% was considered and the corresponding optimal pumping rates were obtained. Results are summarized in Table 8.2 and depicted in Figure 8.11 as well. It is worth mentioning that an infeasible solution is encountered when the decrease in recharge is greater than 20%. This is due to the violation of the head constraints.

It is possible to overcome this infeasibility in solution by reducing pumping rate constraints (reduce Q_i^{min}) or by decreasing the minimum value of the head constraints. On the other hand, with increasing recharge the total optimal pumping rate also increases.

Table 8.2: Summary of Optimal Pumping Rates, Spring Yield, and Discharge from the General-Head Boundary Corresponding to Recharge Perturbations

Perturbation in Recharge	Annual Optimized Withdrawal from Palestinian Wells (mcm)	Annual Spring Yield (mcm)	Outflow from General Head Boundary (mcm)	Increase in Total Pumping (mcm)
+25 %	50,237,950	7,633,032	35,133,223	43,728,718
+20 %	46,424,943	6,988,594	35,398,960	39,915,711
+15 %	42,345,686	6,433,702	35,839,178	35,836,454
+10%	37,453,923	5,964,136	36,993,756	30,944,691
+5 %	33,542,335	5,414,189	37,267,641	27,033,103
Base conditions	6,509,232	10,407,288	55,005,472	0
-5 %	25,435,774	4,607,789	37,809,780	18,926,542
-10%	21,322,158	4,269,029	38,077,401	14,812,926
-15 %	17,164,018	3,962,325	38,357,001	10,654,786
-20 %	13,050,507	3,733,208	38,517,348	6,541,275
-25 %	----	----	---	---

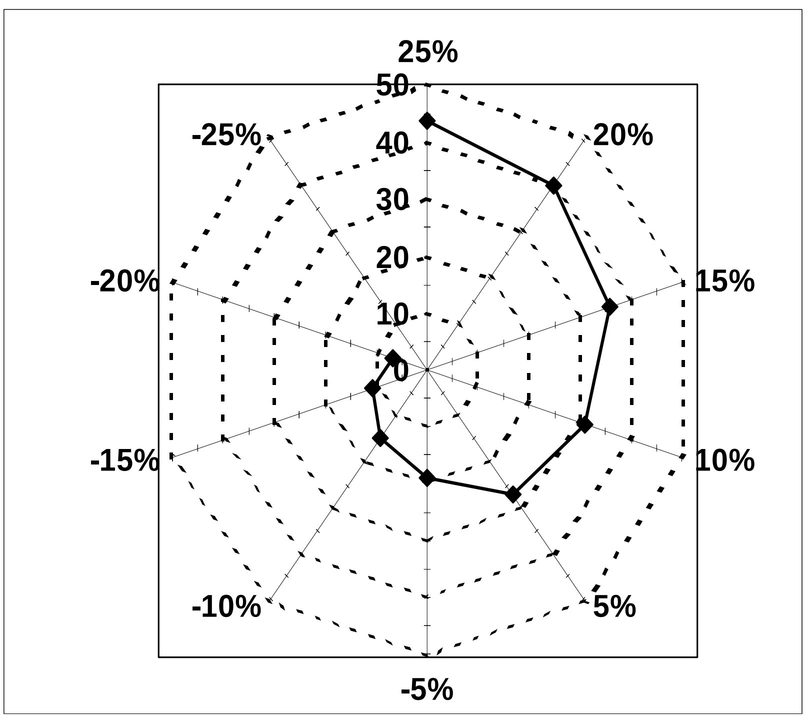


Figure 8.11: Variability of Optimal Pumping Rates for Different Perturbation Percentages in Recharge

8.7.2 Hydraulic Conductivity

In the previous chapter, the model showed high sensitivity to hydraulic conductivity. The impact of hydraulic conductivity on the optimal pumping strategy was assessed by changing the simulated hydraulic conductivity by ±10 and ±20%. Results of optimal pumping rates are summarized in Table 8.3 and depicted in Figure 8.12. Optimal pumping rates and spring yield decrease with increasing the hydraulic conductivity values, while outflow from general head boundary increases.

Table 8.3: Summary of Optimization Flow for Hydraulic Conductivity Perturbation

Hydraulic Conductivity Perturbation	Annual Optimized Withdrawal from Palestinian Wells (m^3)	Annual Spring Yield (m^3)	Outflow from General Head Boundary (m^3)	Increase in Total Pumping (m^3)
+20 %	23,047,109	4,316,845	44,552,004	16,537,877
+10 %	26,284,336	4,622,769	41,012,913	19,775,104
Base conditions	6,509,232	10,407,288	55,005,472	0
-10 %	32,830,323	5,428,122	33,979,129	26,321,091
-20 %	37,272,978	5,892,930	29,343,490	30,763,746

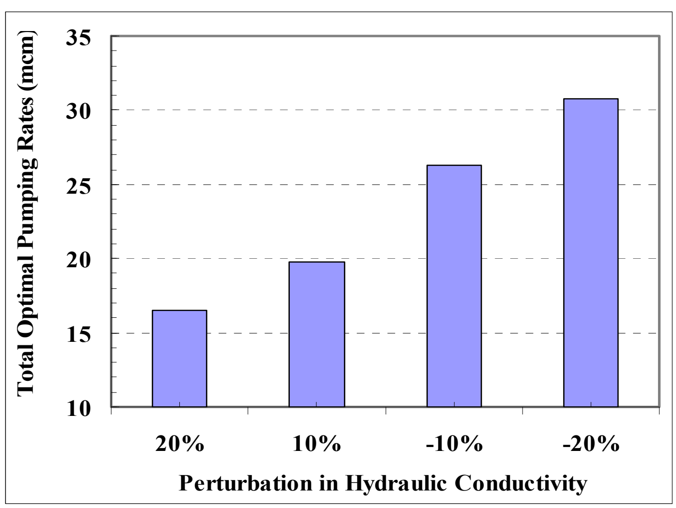


Figure 8.12: Optimal Pumping Rates for Different Perturbation Percentages in Hydraulic Conductivity

8.7.3 Saturated Thickness Requirement

In general, the groundwater-saturated thickness is affected by recharge and the amount of water withdrawn through pumping along with other factors. It can also be said in an opposite way that available saturated thickness affects the amount of water that can be withdrawn from an aquifer. This in other words dictates the optimal pumping rates. As furnished earlier in this chapter, constraints were placed on head based on 50% of saturation thickness (see Figure 8.2). However, the choice of the percentage of 50% from saturation was used to prevent an unrealistic optimal solution (McKee et al., 2004). As such, the optimal pumping rates were determined for different levels of head constraints corresponding to the following percentages of reduction in saturation thickness; 50, 45, 40, 35, 30, 25, and 20%. An infeasible solution occurs for 20% of saturation reduction due to head constraints violation. As can be seen from Figure 8.13, which depicts the sensitivity of the optimal solution to percentage reduction in saturation thickness, the total optimal pumping decreases with increasing the required saturation thickness.

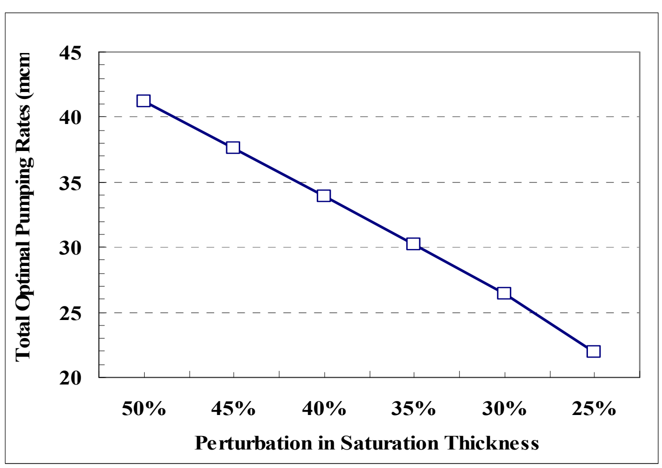


Figure 8.13: Optimal Pumping Rates for Different Reduction Percentages in the Minimum Saturation Thickness Requirement

Chapter Nine
Conclusions and Recommendations

The work furnished in this thesis concentrated on two key tasks. The first is the development of a groundwater flow model for the Eocene aquifer using MODFLOW. The second task is the utilization of the MODFLOW-based flow model in the development of an optimization framework for the Eocene aquifer using GWM software. Optimal pumping rates were determined under existing conditions and different proposed scenarios. The following are the key conclusions and recommendations.

9.1 Conclusions

- The groundwater model was constructed and calibrated under steady-state conditions. Based on the calibrated steady-state model, the annual discharge from the Eocene aquifer through the general-head boundary (outside the West Bank) is about 55 mcm.

- The flow model was calibrated using trial-and-error approach. The calibrated hydraulic conductivity values of the Eocene aquifer range from 0.013 to 5.94 m/day.

- The model was found to be very sensitive in terms of head, spring yield and general-head boundary to changes in recharge rates and hydraulic conductivity values and of moderate sensitivity to well pumping rates.

- Simulation/optimization techniques are very powerful in figuring out the optimal pumping rates under hydraulic constraints and management scenarios.

- The outcome from the GWM model shows that 23 mcm can be safely pumped out from the Eocene aquifer via the existing Palestinian wells from scenario 1 and about 23 and 22 mcm result from scenario 2 and 3 respectively. These are achieved under the assumption that the Israeli wells tapping the aquifer pumps 11.7 mcm and that the drop in the saturated thickness does not exceed 50%. While the result from scenario 4 (assumes no Israeli wells) showed that about 32 mcm can be safely pumped out from the Eocene aquifer via the existing Palestinian wells.

9.2 Recommendations

I recommend that proposed future work in this regard to consider the following:

- A more comprehensive management framework should have taken economic considerations into account instead of carrying out the analysis under hydraulic constraints, merely.
- It is crucial to determine the best locations for drilling new wells within the Eocene aquifer and to find out the corresponding optimal pumping rates.
- Management constraints should consider maintaining minimum spring yield. This implies that GWM be upgraded/modified to account for this capability.
- This study did not take into account the impact of the illegal wells in Qabatia area. A future study should take this into consideration to find out potential impact on the optimal pumping rates.

- Much of the time spent to accomplish the work was allocated to develop the MODFLOW-based groundwater flow model though a version of it is available at the PWA. Information exchange between the involved parties should be promoted and enhanced.

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Appendix

Table (1) Palestinian and Israeli Abstraction Wells for Eocene Aquifer

Well No.	Well-ID	X (Km)	Y (Km)	Z (m)	Use	Annual Pumping Rate (m3)
1	17-19/001	174.83	198.60	360	Domestic And Agriculture	224,155
2	17-19/002	175.00	198.32	365	Agricultural	55,476
3	17-20/003J	177.96	207.78	136	Agricultural	146
4	17-20/004J	178.88	208.12	130	Agricultural	6,678
5	17-20/005J	178.87	208.05	130	Agricultural	6,458
6	17-20/006J	179.06	207.75	145	Agricultural	114,469
7	17-20/007Q	174.86	205.55	252	Agricultural	34,957
8	17-20/009J	178.76	207.94	140	Domestic And Agriculture	53,001
9	17-20/009Q	174.45	203.30	255	Agricultural	32,886
10	17-20/012J	176.80	208.50	130	Agricultural	76,332
11	17-20/013Q	174.48	204.06	255	Agricultural	23,217
12	17-20/014A	172.10	202.06	255	Agricultural	12,015
13	17-20/014Q	174.08	204.00	260	Agricultural	2,604
14	17-20/015Q	174.60	203.85	260	Agricultural	20,177
15	17-20/018Q	174.62	204.99	242	Agricultural	34,268
16	17-20/019A	172.90	205.05	250	Agricultural	20,656
17	17-20/019J	178.50	207.00	160	Domestic And Agriculture	11,565
18	17-20/020J	178.25	206.10	185	Agricultural	37,284
19	17-20/020Q	175.11	204.75	251.12	Agricultural	11,621
20	17-20/022Q	176.75	201.85	285	Agricultural	51,720
21	17-20/023Q	175.31	204.80	255	Agricultural	16,332
22	17-20/024A	173.35	201.70	280	Agricultural	67,487
23	17-20/024J	178.00	205.75	183.54	Domestic And Agriculture	55,872
24	17-20/026Q	175.72	204.72	250	Agricultural	43,605
25	17-20/028Q	175.28	203.36	276.68	Agricultural	114,853
26	17-20/030Q	175.28	203.14	278	Agricultural	109,624
27	17-20/031Q	175.21	204.34	255	Agricultural	31,505
28	17-20/033J	178.50	207.40	150	Domestic	523,045
29	17-20/035A	174.37	205.32	250	Agricultural	17,632
30	17-20/035Q	176.10	204.95	240	Agricultural	68,327
31	17-20/036A	174.96	206.14	260	Agricultural	18,913
32	17-20/036Q	177.70	202.20	290	Agricultural	105,016
33	17-20/037J	175.26	205.79	261.02	Agricultural	3,702
34	17-20/040A	173.31	201.81	285	Agricultural	54,659
35	17-20/041Q	174.80	203.20	260	Agricultural	46,062
36	17-20/042Q	177.30	201.50	286.34	Agricultural	145,046
37	17-20/043Q	175.60	205.60	270	Agricultural	25,172
38	17-20/044Q	177.41	202.47	288	Agricultural	84,364
39	17-20/046	174.73	209.80	130	Agricultural	153,765
40	17-20/046Q	177.10	201.90	285	Agricultural	53,113

Table (1) Continue

Well No.	Well-ID	X (Km)	Y (Km)	Z (m)	Use	Annual Pumping Rate (m3)
41	17-20/047Q	175.30	204.05	258	Agricultural	16,388
42	17-20/048Q	175.36	204.18	260	Agricultural	23,746
43	17-20/049Q	175.08	204.10	255	Agricultural	12,666
44	17-20/050J	177.85	205.45	203.7	Agricultural	61,510
45	17-20/050Q	178.80	201.50	300.9	Domestic	504,321
46	17-20/051Q	175.18	205.00	253	Agricultural	37,393
47	17-20/052A	173.62	205.75	250	Agricultural	63,519
48	17-20/052Q	178.40	202.60	300	Domestic	312,050
49	17-21/009	176.00	210.80	98	Agricultural	63,920
50	17-21/010	174.48	210.20	120	Agricultural	182,727
51	17-21/012	174.60	210.40	110	Domestic And Agriculture	133,716
52	17-21/013	174.85	210.50	108	Agricultural	28,997
53	17-21/014	175.50	210.14	102	Agricultural	19,089
54	17-21/015	178.50	211.08	104.73	Agricultural	221,614
55	17-21/017	178.73	212.12	95	Agricultural	14,572
56	17-21/022	178.86	211.37	95	Agricultural	282,951
57	17-21/024	178.62	211.35	100	Agricultural	11,191
58	17-21/025	179.15	211.55	100	Agricultural	35,378
59	17-21/032	180.75	188.83	95	Agricultural	202,393
60	17-21/034	174.25	209.85	128	Agricultural	274,902
61	18-18/001	181.05	188.62	220	Agricultural	389,531
62	18-18/004	180.94	188.68	180	Agricultural	220,735
63	18-18/017	182.31	190.12	223	Domestic	182,397
64	18-18/025A	181.67	190.00	220	Agricultural	262,165
65	18-18/033	182.15	190.22	213.32	Agricultural	75,832
66	18-20/007	180.45	200.35	310	Agricultural	5,743
67	18-21/003	182.10	210.40	130.04	Domestic And Agriculture	302,007
68	ISW 1	178.00	213.00	-	Unclassified	1,300,000
69	ISW 2	179.00	214.00	-	Unclassified	1,300,000
70	ISW 3	180.10	214.50	-	Unclassified	1,300,000
71	ISW 4	180.00	217.50	-	Unclassified	1,300,000
72	ISW 5	183.00	217.50	-	Unclassified	1,300,000
73	ISW 6	190.12	211.48	-	Unclassified	1,300,000
74	ISW 7	191.00	212.50	-	Unclassified	1,300,000
75	ISW 8	191.72	212.50	-	Unclassified	1,300,000
76	ISW 9	191.98	212.34	-	Unclassified	1,300,000
Total						**18,209,232**

Table (2) Palestinian Discharge Springs at Eocene Aquifer

Spring No.	Spring-ID	X (Km)	Y (Km)	Z (m)	Name	Use	Pumping rate (m3/yr)
1	AQ/030	181.40	188.35	160	Al Far'ah	Domestic And Agriculture	5,053,852
2	AQ/032	181.88	187.92	155	Al Dlaib	Agricultural	1,189,865
3	AQ/036	179.95	185.49	240	Sedrah	Agricultural	1,274,837
4	BA/020	175.03	181.30	620	Ras Al 'Ein	Domestic	427,743
5	BA/021	175.11	181.37	575	Al 'Asal	Domestic	169,221
6	BA/022	175.34	181.57	550	Qaryun	Domestic	539,837
7	BA/023	174.83	181.52	510	Shrai`sh	Agricultural	242,764
8	BA/025	174.93	181.64	510	Fu'ad	Agricultural	172,484
9	BA/026	174.93	181.80	540	Al-Kufeir	Unclassified	10,463
10	BA/028	173.63	182.45	458	Beit Al Ma'	Agricultural	616,648
11	BA/035	169.50	185.78	445	Harun	Domestic	192,752
12	BA/036	170.58	186.32	435	Ijnisinya	Domestic	43,905
13	BA/040	171.10	187.55	380	Al Sharqiyyah	Domestic	40,615
14	BA/041	170.85	187.50	390	Al Khadr	Unclassified	4,532
15	BA/043	170.94	187.60	380	Muwaziyyah	Domestic	81,174
16	BA/044	171.03	189.02	410	Al Balad	Domestic	8,144
17	BA/046	168.70	189.70	480	Burqa Group	Domestic	79,522
18	BA/050	167.80	191.10	500	Zakariyya	Domestic	1,897
19	BA/051	168.25	190.98	475	Hud	Domestic	25,272
20	BA/055	169.18	191.55	410	Al Hawuz	Agricultural	11,708
21	BA/056	169.44	191.58	460	Al Balad	Agricultural	10,319
22	BA/057	171.60	192.25	370	Al Sharqiyyah	Agricultural	37,359
23	BA/058	170.91	192.02	390	Al Juzah	Agricultural	22,446
24	BA/060	178.62	207.60	215	Jenin Al Balad	Unclassified	100,704
25	BA/062	175.12	207.35	195	Birqin Al Balad	Agricultural	42,805
Total							**10,400,868**

التنظيم الامثل لضخ المياه الجوفية

حالة الحوض الجوفي الايوسيني/فلسطين

اعداد: رنا امين سليمان خرمه

اشراف: د. محمد نهاد المصري

الملخص

تم عمل نموذج للمياه الجوفية لمنطقة الحوض الجوفي الايوسيني. تم اعداد النموذج وتطويره بواسطة برنامج MODFLOW و GWM. تم ايجاد اقصى كمية مياه يمكن سحبها لعدة حالات.

يعتبر الحوض الجوفي الايوسيني من اهم مصادر المياه الجوفية لمحافظتي جنين ونابلس. يستخدم هذا الحوض الجوفي غالبا للاغراض الزراعية.

تم اعداد النموذج ومعايرته في حالة الاتزان. ونتج عن ذلك ان هناك كمية مياه مقدارها 55 مليون متر مكعب تخرج من الحوض الجوفي الايوسيني خارج حدود الضفة الغربية وتتجه باتجاه اسرائيل.

برنامج GWM استخدم لتنظيم وادارة الحوض الجوفي لعدة سيناريوهات. نتج عنه انه يمكن ضخ كمية مياه في الوضع الامن مقدارها حوالي 23 مليون متر مكعب زيادة عن ما يتم ضخه بالمعدل بواسطة الابار الفلسطينية. وهذه القيمة ممكن الحصول عليها على اعتبار ان الابار الاسرائيلية تسحب 11.7 مليون متر مكعب والانخفاض في منسوب المياه الجوفية لا يقل عن 50%.

جامعة النجاح الوطنية

كلية الدراسات العليا

التنظيم الامثل لضخ المياه الجوفية

حالة الحوض الجوفي الايوسيني/فلسطين

اعداد الطالبة

رنا امين سليمان خرمه

اشراف

د. محمد نهاد المصري

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

2007