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Modeling the Eocene Aquifer in Northern West Bank

نمذجة الحوض الجوفي الايوسيني في شمال الضفة الغربية

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Abstract

The Eocene aquifer is one of the major groundwater aquifers in Palestine. It is located in the northeastern part of the West Bank covering areas of both Jenin and Nablus districts. The development of the groundwater within the Eocene aquifer is very essential for the Palestinian water supply. This paper simulates for groundwater flow in the Eocene aquifer using MODFLOW as a strong available groundwater model. The groundwater budget, flow computation, and flow path-lines were estimated and calibrated. Groundwater balance has been evaluated. The Modeling results show that a minimum initial level of 340 m above sea level should be applied to model the hydraulics of the aquifer correctly. The recharge and hydraulic conductivity are the most sensitive model parameters. The hydraulic conductivity in some areas has proved to be double than assumed by other literatures. More reasonable recharge coefficients in comparison to other literatures have been obtained. Groundwater balance indicated that the water budget of the Eocene aquifer totals about 72 MCM/yr. The modeling has indicated reasonable matching between the observed and modeled groundwater levels and spring flows. The flow direction within the aquifer is from the south to north and northeast. The Faria spring system located to the southeast is the major sink within the aquifer. It attracts most of the particle tracking lines due to its high discharge rates. It is recommended to monitor the existing wells and springs permanently. It is also recommended to asses the effect of the faults and fractures on the hydraulic conductivity.

Keywords: Groundwater, Modflow, Eocene Aquifer, Hydraulic Conductivity, Recharge.

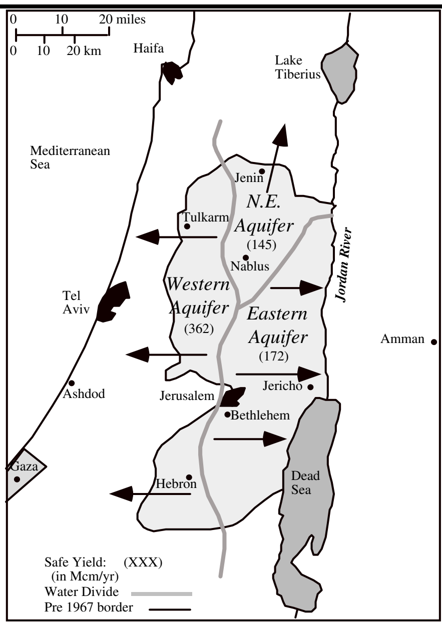
ملخص

يعد الخزان الجوفي الأيوسيني من أهم الخزانات الجوفية في الحوض الشمالي الشرقي في الضفة الغربية من فلسطين، وهو من أهم مصادر المياه الجوفية العذبة في منطقتي نابلس وجنين. وقد أجريت عدة دراسات دعت إلى تطوير مصادر المياه الجوفية ضمن هذا الحوض، ومن هنا فان هذه الورقة تمثل ضرورة عمل نموذج رياضي لدراسة الخزان الجوفي الأيوسيني. تم استخدام برنامج MODFLOW وذلك لتوفره وسهولة التعامل معه، إذ تم تقييم كمية المياه التي يعطيها الخزان سنوياً والميزانية المائية له وكذلك تحديد اتجاهات حركة المياه الجوفية في داخل الخزان الجوفي. أشارت النتائج إلى أن النموذج لا يعمل إلا على مستوى هيدروليكي ابتدائي للمياه الجوفية لا يقل عن ٣٤٠م فوق سطح البحر. وتم حساب حساسية النموذج لعاملي التغذية والنفاذية إذ تبين أنهما أكثر تأثيراً على النموذج للخزان الجوفي الأيوسيني، كما تم معايرة النموذج لكل من مستوى المياه الجوفية وتدفق الينابيع. القيم الابتدائية للنفاذية ارتفعت في بعض المناطق إلى ضعفي تلك الواردة في دراسات أخرى وذلك بسبب إهمال تأثير الفوالق (faults) والإنكسارات (fractures) والكرسته (karstification) في الصخور الموجودة في منطقة الدراسة، كما أن الدراسة أعطت قيماً مقبولة لمعاملات التغذية. بالنسبة للموازنة المائية المتجددة للخزان الجوفي الايوسيني فقد تبين أنها ٧٢ مليون متر مكعب سنوياً. أظهر النموذج تطابق بين مستويات المياه وتدفق الينابيع المقروءة والمحسوبة وتبين كذلك أن خطوط التدفق والمياه الجوفية تتجمع باتجاه الشمال والشمال الشرقي للحوض، وأن خطوط التدفق تتكاثف باتجاه منطقة نبع الفارعة الواقع في المنطقة الجنوبية الشرقية من الحوض ما يشكل حفرة بالوعية (sink hole) هناك. بالاعتماد على النتائج السابقة يوصى بتصميم آبار الحوض وينابيعه بدقة واستمرارية وكذلك الحال فيما يتعلق بتشغيلها وعملها، ويوصى كذلك بتقييم تأثير الفوالق والانكسارات على قيم النفاذية.

Introduction

As many other countries, water in Palestine is the most precious natural resource and its relative scarcity is a major constraint against economic development. Groundwater is the main source of fresh water, thus, it is of primary importance to the Palestinians.

The aquifer systems in the West Bank are divided into three main groundwater basins; the western, the north-eastern and the eastern (Figure 1). The Eocene aquifer is one unit of the north-eastern basin. It extends between the coordinates 165 to 195 km West-East and 180 to 220 South-North (Figure 1). The water of the Eocene aquifer is partially utilized by Palestinians to secure domestic and irrigation needs. The outcrop area of the Eocene aquifer constitutes a vital region for water supply and is highly populated, with a total population of about half a million. This reflects the importance of managing the groundwater within this aquifer, emphasizing the need for its assessment and control of the aquifer.



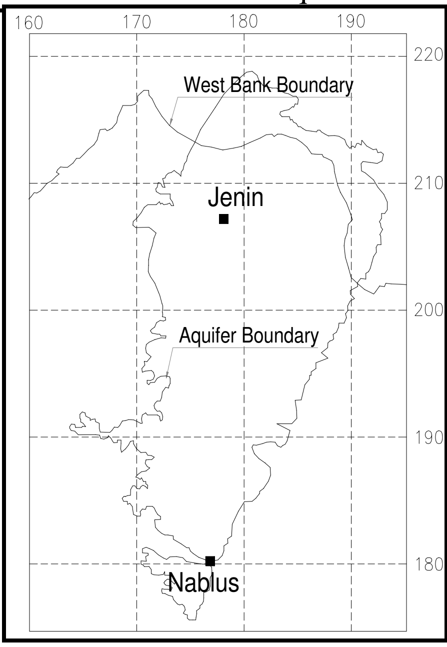


Figure (1): The groundwater basins and the Eocene aquifer boundaries in the West Bank

The Eocene aquifer is of great value for the agricultural sector in Palestine, therefore it is important to model its flow system and estimate its sustainable yield. Modeling will provide the basic information for the managers to simulate the flow within the aquifer and thus influence decision-making process for future development. This paper describes modeling of the flow in the Eocene aquifer, aims at evaluating its sustainable yield, the flow system, and the steady state flow conditions of the aquifer. MODFLOW is used in modeling and calculation of water budget applying porous media approximation.

MODFLOW (PMWIN) is a three-dimensional finite difference flow model and has powerful capabilities for the simulation of regional groundwater flow. It simulates steady and non-steady flow in an irregular shaped system, in which aquifer layers can be confined, unconfined, or a combination of both(1). It is accessible, popular and user friendly.

The Eocene Aquifer

The Eocene Aquifer is located in the northeastern part of the West Bank covering areas of both Nablus and Jenin districts. The outcrop area of the Eocene aquifer is about 520 km^2. It is considered one of the main water supply sources for these areas.

The Eocene aquifer overlies the Upper Cenomanian-Turonian aquifer system, with a transition zone of chalk of variable thickness ranging from 0 to 480 m. This system is represented by the Jenin sub-series of the Tertiary age and exposed in 80% of the Jenin area. It constitutes a fully utilized shallow aquifer which is lithologically composed of reef limestone, numulitic, and limestone with chalk and chalk with numulitic limestone as indicated in Figure 2. In this system, limestone rocks form an aquifer while chalk rocks form an aquiclude(2-3).

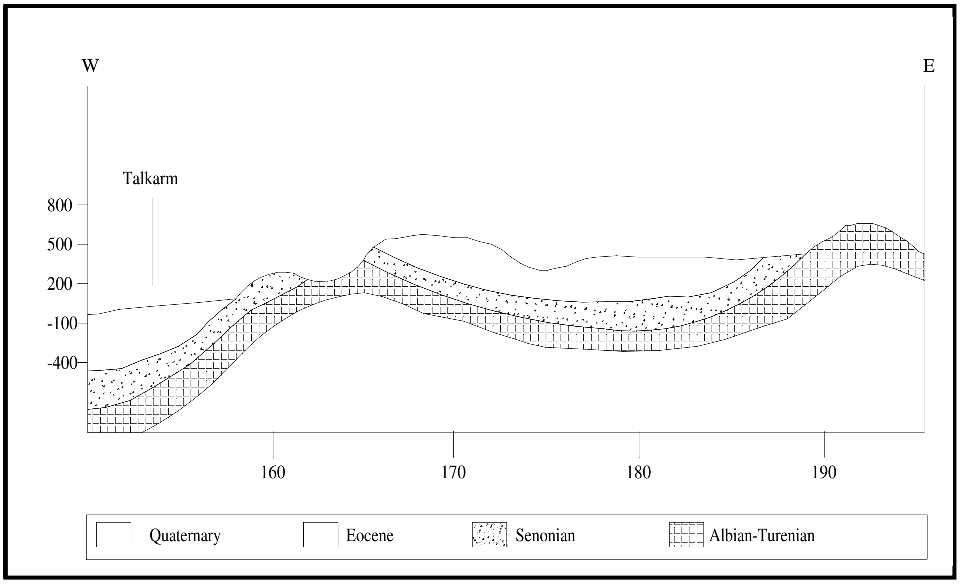


Figure (2): Conceptual Model of the Eocene Aquifer Formation

The springs taping the Eocene aquifer are important as a water resource for most of the villages providing water for domestic use, livestock use, and for irrigation, mainly for cropping in summer(3).

The quantity of recharge depends mainly on climatic conditions including rainfall, temperature, relative humidity, and wind, in addition to the soil type (infiltration capacity), land use and topography. The Eocene aquifer is being recharged through infiltration of rainfall and wadi runoff. It crops out across most of the central parts of Jenin district(4). The water table contours of the Eocene aquifer have been mapped from spring levels and from the elevation of static water in wells. It shows that flow within the aquifer is from the south to north and northeast. At the northern flank of the Gerzim Mountains near Nablus City and in Burin springs, the level is 460 m above sea level. In the vicinity of Jalboun, the gradient steps reflect changes in permeability of the aquifer system. In the north, at Jenin area, the gradient is very small, which reflects a thickening of the saturated section rather than changes in permeability(5).

Modeling of the Eocene Aquifer

A groundwater model is an approximate representation of physical situation using computer software or code. A groundwater model could be represented by a set of boundary conditions, initial conditions, hydrological stresses, and aquifer characteristics[1]. In modeling, simplification is necessary because complete reconstruction of the field is not feasible. The conceptual model is defined by the main hydrostratigraphic units and their boundaries. In this study, the domeninant direction of water movement is represented as a two-dimensional nearly horizontal flow to the north and northeast. Vertical flow to the lower aquifer is neglected, since the separating layer (aquiclude) is of chalk which is almost impervious. The model consists of one hydrogeological layer representing chalk, limestone and chert of the Tertiary rock formation. Its thickness is measured in the range of 50 m to 450 m (Figure 2).

The grid in the model consisted of two parallel lines that are orthogonal. Cells are formed by the intersection of these lines. A node is located at the center of each cell. It is assumed that hydrologic and hydraulic properties are constant all over the extent of the cell area. A cell's node represents the cell. This system is called a "block-centered grid"[1].

In MODFLOW modeling, the grid size is slightly larger than the actual model area. For the Eocene Aquifer, the grid is taken as a size of 30 columns and 50 rows. The cells follow a 1 km by 1 km mesh size. The actual model area of the Eocene aquifer in the Jenin area is 26 km by 41 km relating to maximum distances east west and north south respectively. Active cells cover the modeled area of the formation while inactive cells occupy the rest of the grid area (Figure 3).

Layers are the nucleus of the simulation model. The representation of the conceptual model is helpful to describe how many layers have to be represented in the simulation in addition to their hydrological conditions (confined, unconfined, or semi-confined). The Eocene aquifer is modeled as one layer of variable thickness and unconfined aquifer. The representation of the boundaries has been carried out by assigning to the boundary cells special cell indicator according to the physical behavior of the area.

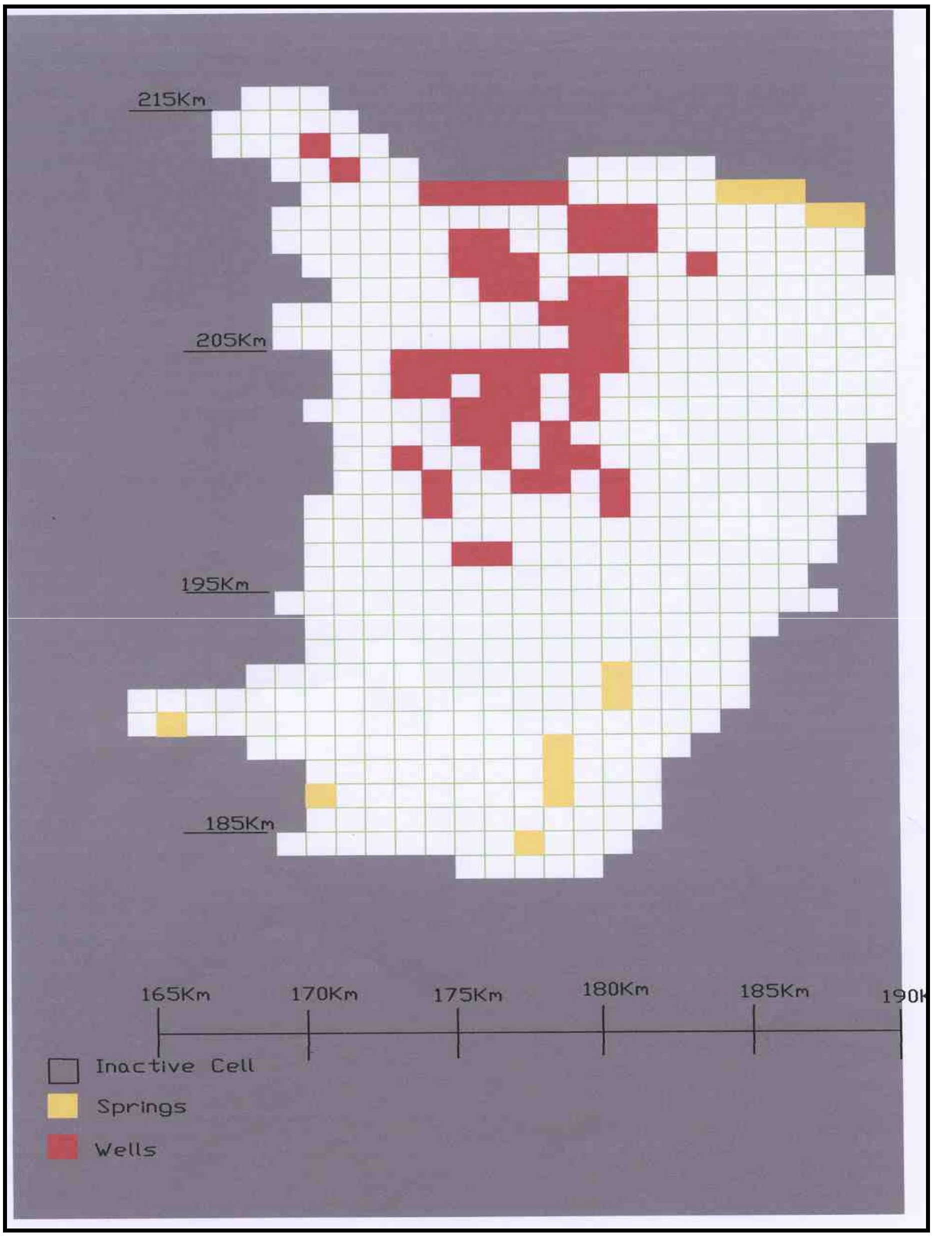


Figure (3): The boundary conditions of the Eocene Aquifer

To describe no-flux boundaries in MODFLOW, the boundary between inactive and active cells can be used. Inactive cells are those for which no flow into or out of the cell occur during the entire simulation. Hydraulic heads and flows from or into the cell are not calculated. On the other hand, active or variable head cells are assigned to the locations of interest inside the studied domain. The hydraulic heads for active cells are calculated by the model and are free to vary during the simulation process. Moreover, constant head cells, which are special active cells (inside the domain of the problem), could be used to describe a model boundary with known heads such as aquifer contacts with surface water bodies like lakes and rivers(1). Such boundaries are not included in the model for the Eocene aquifer.

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

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

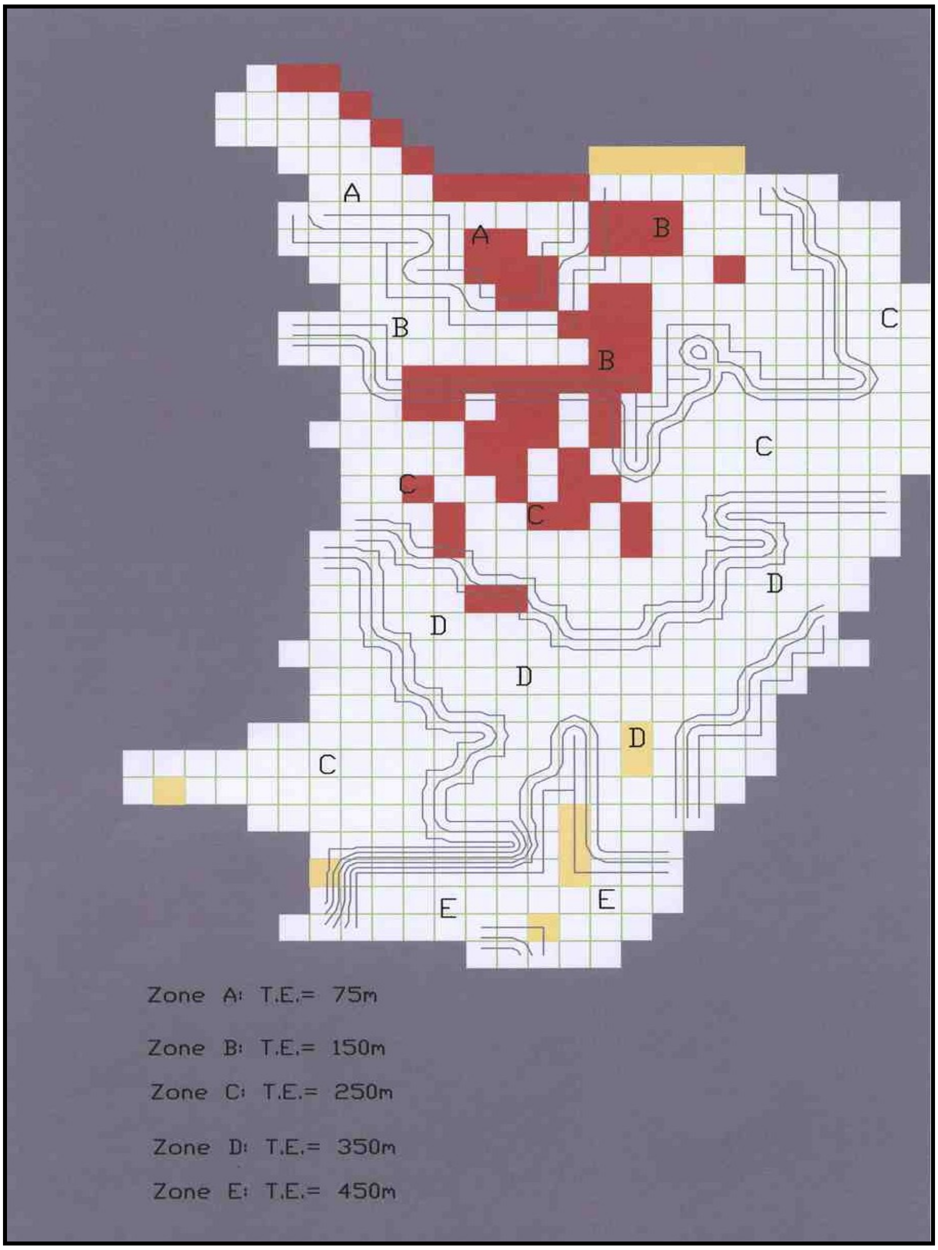


Figure (4): Top elevation (T.E.) of the Eocene layer

Figures 4 and 5 present the top and bottom elevations of the Eocene layer. From the well pumping test carried out by the Palestinian Water Authority (PWA), the horizontal hydraulic conductivity is presented as constant average value equal to 2.5 m/day[6]. It is important to know that the effect of the faults on the hydraulic conductivity was neglected in the PWA study. For the model involving more than one layer, MODFLOW requires the input of the vertical transmission or leakage terms, known as vertical leakance. MODFLOW uses the vertical hydraulic conductivities and thicknesses of layers to calculate the vertical leakance. In this study, one non-leaky layer is considered; therefore, there is no need to assume the vertical hydraulic conductivity.

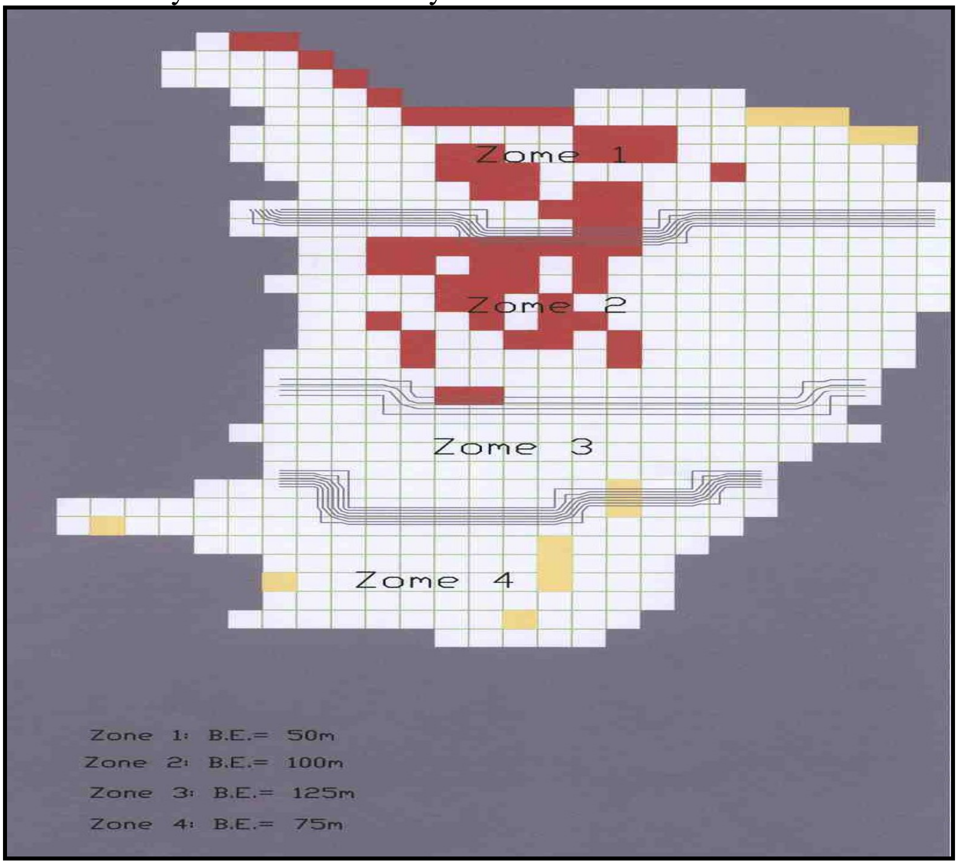


Figure (5): Bottom elevations (B.E.) of the Eocene layer

The initial groundwater level distribution within the model is used to solve the steady state flow problem. The level values are the starting values for the numeric calculations of the equation solvers. The levels for each active cell should be higher than the elevation of the cell bottom[1].

To calibrate the model, and in view of the relative scarcity of data, the groundwater level maps prepared by the PWA[5] have been used to generate the observed water level maps. In this model the initial water levels were not related to the observed values. Using trial and error, a water level of 340 m above sea level was taken.

The primary source of groundwater recharge in the Eocene aquifer is considered to be rainfall. Recharge values are taken as percentages of rainfall as considered by Ba'ba'[6] (Table 1). These percentages vary according to the distribution of rainfall intensity, topography, and soil characteristics comprising the outcropped zone in addition to the land cover and urbanization. Accordingly different values of recharge coefficients for each of the different sub-regions have been considered in the model. These sub-regions are the areas between different rainfall isohyets.

Table (1): Recharge Coefficient for Different Values of Rainfall[6]

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

The eastern part of the aquifer has a relative low percentage of recharge indicated by the relative low amount of rainfall (75 mm/yr)[7]. At the western side, the recharge coefficients are relatively high due to the high-volume of yearly rainfall (650 mm/yr). After the computation of the recharges, the values have been applied for various sub-regions of the model. The representation of the recharge shows that the values range between 2.877×10^{-5} to 8.192×10^{-4} m/day (Figure 6). Such high variation in recharge values is due to the variation in rainfall amounts.

A pumping well is a point sink or source represented in a 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[1]. Abstraction wells have to be assigned negatively, while recharge values have to be assigned positively. Recharge or discharge wells, are identified when their location and flow rate are specified. The model considers a full penetration of the well for the layer and the well usually represents a single layer. In the Eocene aquifer, there are 67 wells with available data about location and abstraction rates as indicated in Figure 7.

The model simulates the flow from a spring by representing the point of emergence of the spring (the land surface) as the drain elevation. The drain nodes will be activated only in the case that the water table rises up to the level of the drain.

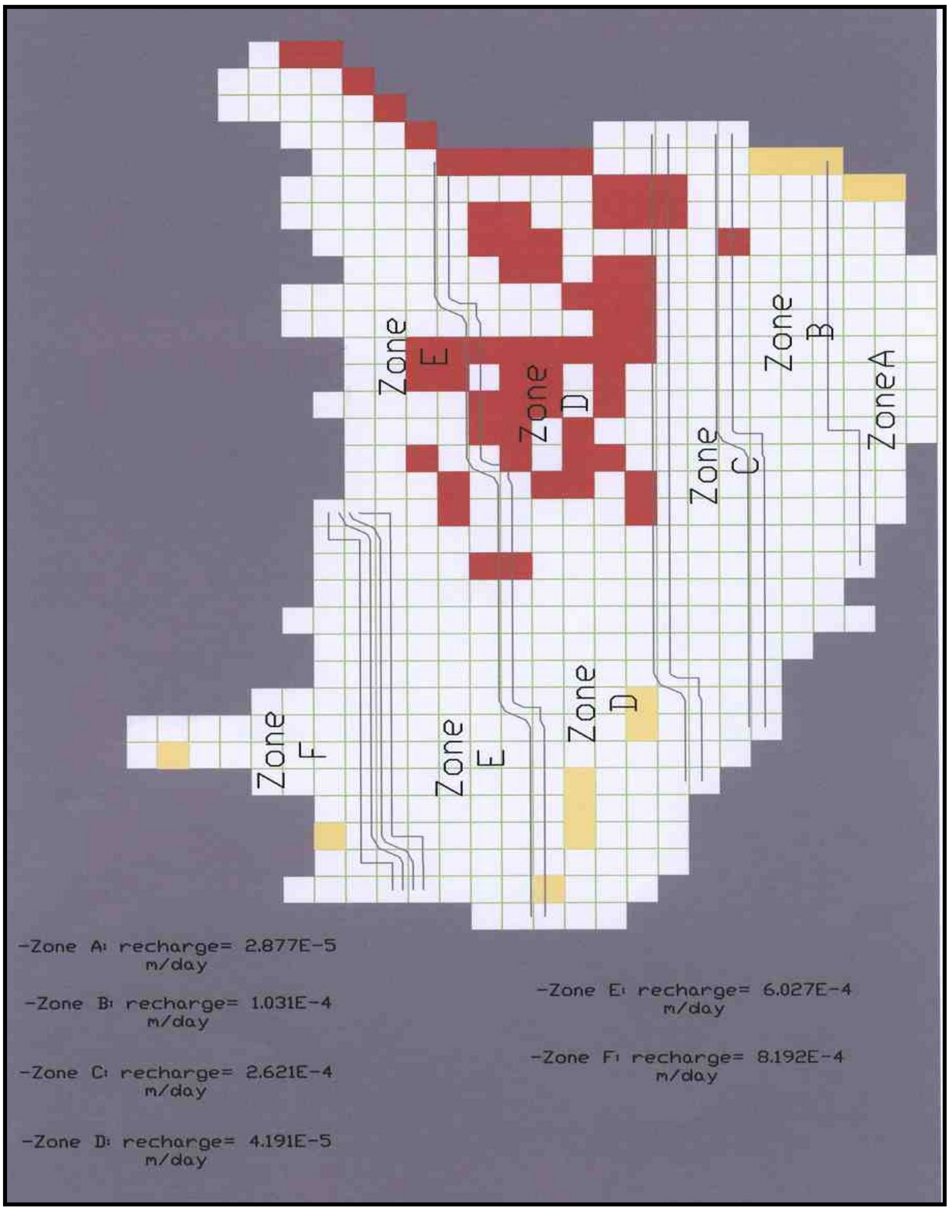


Figure (6): Rainfall recharge values applied in the Model

Springs are represented as wells for simulation purposes during the calibration process. Practically, the best representation of the springs depends on the simulation model's performance and the geometrical settings of the model. During model calibration, the positive outflow at each spring is verified.

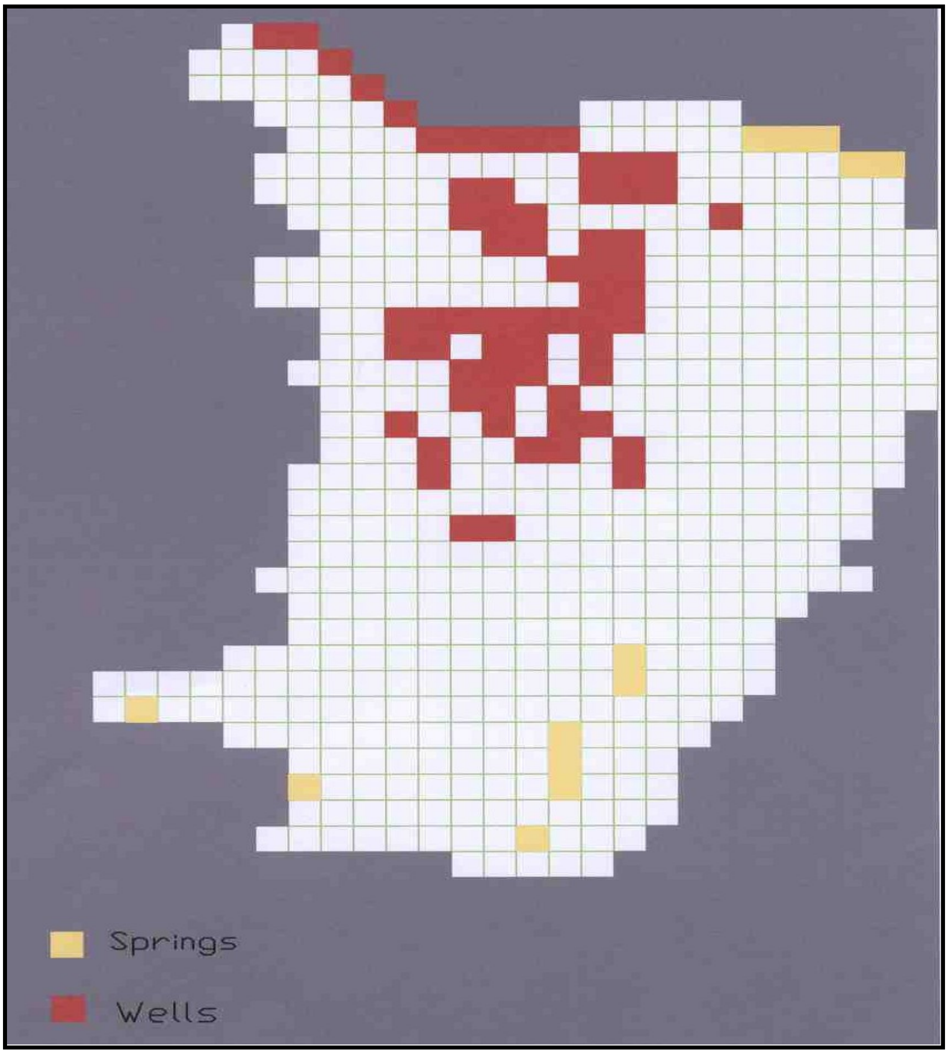


Figure (7): Location of wells and springs in the Model Cells

Figure 7 presents the location of the wells and springs in the model cells. The main objective of modeling is to obtain results nearly compatible with the real case. Iteration is done to achieve this objective by changing the sensitive parameters until the suitable results are determined and performed. Three main packages have been applied; flow simulation package, results extract package, and water budget package. Water levels, draw downs, and water flows in each cell, have been modeled. The amount of water that enter to or discharge out of the Eocene aquifer has been evaluated to determine the water balance for the aquifer.

Sensitivity Analysis

The simplest form of sensitivity analysis is a visual graphical comparison of changes in parameter values versus the effect on the groundwater levels. Some spatially well-distributed cells over the area have been chosen and groundwater levels have been recorded for each trial or change of the calibrated parameter. Sensitivity analysis for this simulation model focused on recharge and hydraulic conductivity. They were found to be the most sensitive model parameters. It was also found that hydraulic conductivity is more sensitive than recharge (Figures 8 and 9).

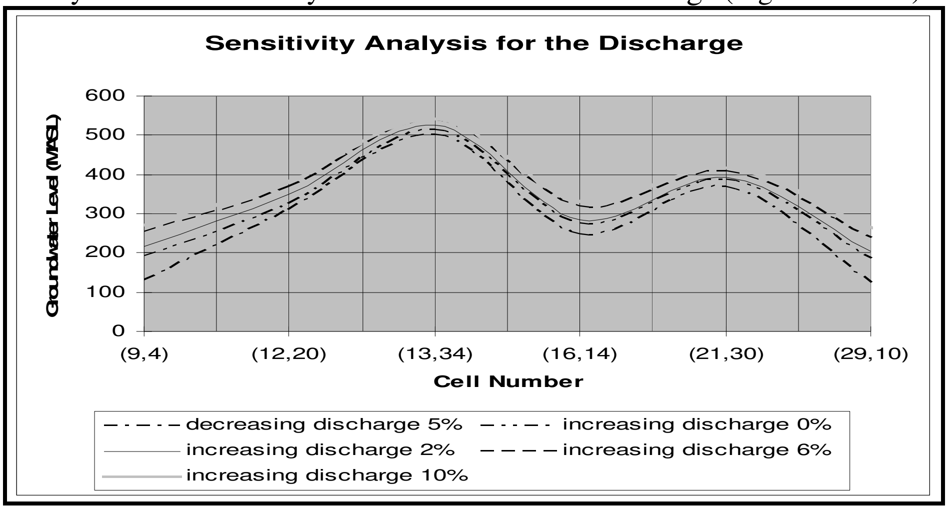


Figure (8): Sensitivity analysis of the discharge for the Eocene Aquifer.

As indicated by the graph for the discharge sensitivity analysis of Figure 8, the groundwater level increases gradually with the increase of the recharge rates. The change of groundwater level is nearly linear. The recharge is less sensitive than hydraulic conductivity for high range of discharge percentages. For more selected cells, the groundwater levels start mild and then become steeper for higher ratios. This is caused by the complex aquifer geometry. The hydraulic conductivity has larger effect when its values are increased from moderate to high or from moderate to low values (Figure 9).

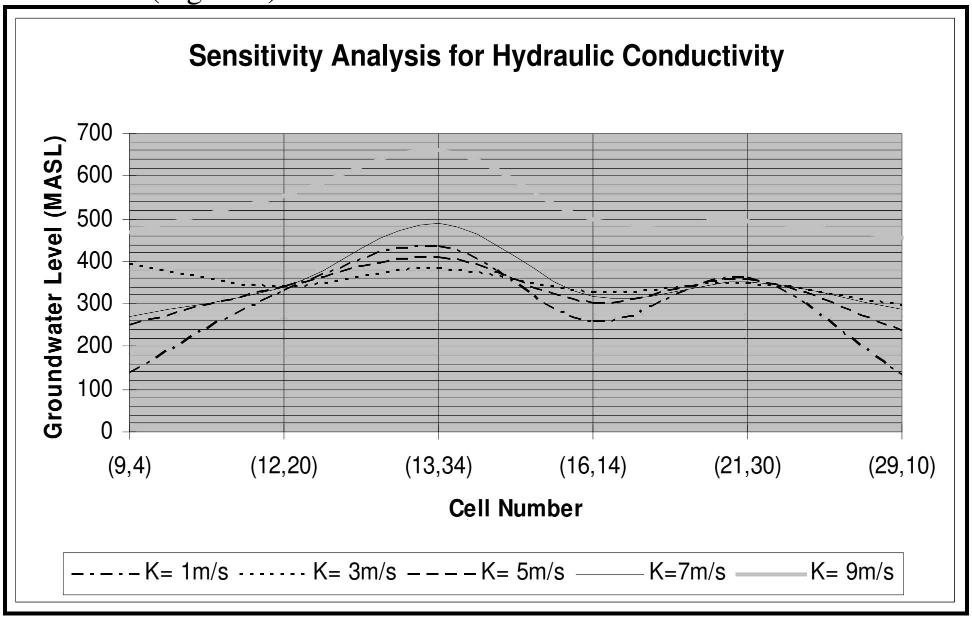


Figure (9): Sensitivity analysis of Hydraulic Conductivity for the Eocene Aquifer

Model Calibration

The simulated values of the groundwater levels and spring flows are compared with those collected by PWA. After error analysis, the model input data (calibration parameters) are changed within a reasonable range until the simulated outputs and observed values fit within a chosen tolerance. Model calibration for this study has been done by trial and error adjustment, considering both errors in groundwater levels and flows at springs in the area.

The calibration process has been done to compare the simulated and the observed groundwater levels. A tolerance of 5 m in water head is applied due to the high variation in water levels[8]. The hydraulic conductivity is the main calibration parameter in addition to the spring recharge. An adjustment for the water level elevations at the springs has been applied. The hydraulic conductivity has substantially increased during the calibration process, being the most uncertain parameter. Recharge was slightly adjusted. Figure 10 shows the calibrated groundwater levels and Table 2 presents the observed and simulated groundwater levels for certain wells in the model.

Simultaneous to the calibration that is based on groundwater levels; the calibration of spring flows was carried out. The calibration results are presented in Figure 11. The figure indicates a reasonable match between the observed and computed spring flows. Reasons for spring flow discrepancies are similar to those between the observed and computed groundwater levels in addition to the uncertain elevations of the springs.

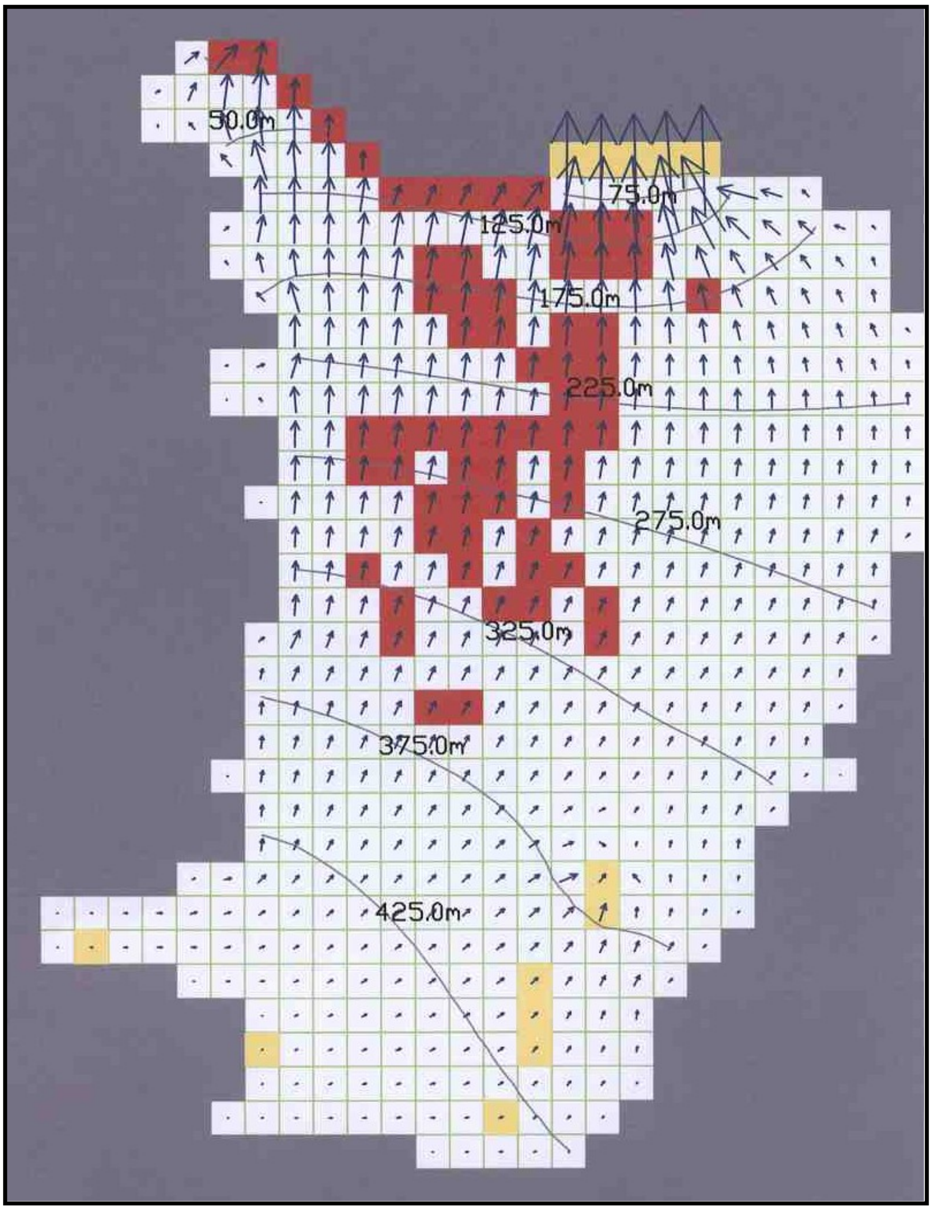


Figure (10): Groundwater levels, Particle Tracking and flow direction.

Table (2): Calibrated and observed Groundwater Levels for monitored Wells

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

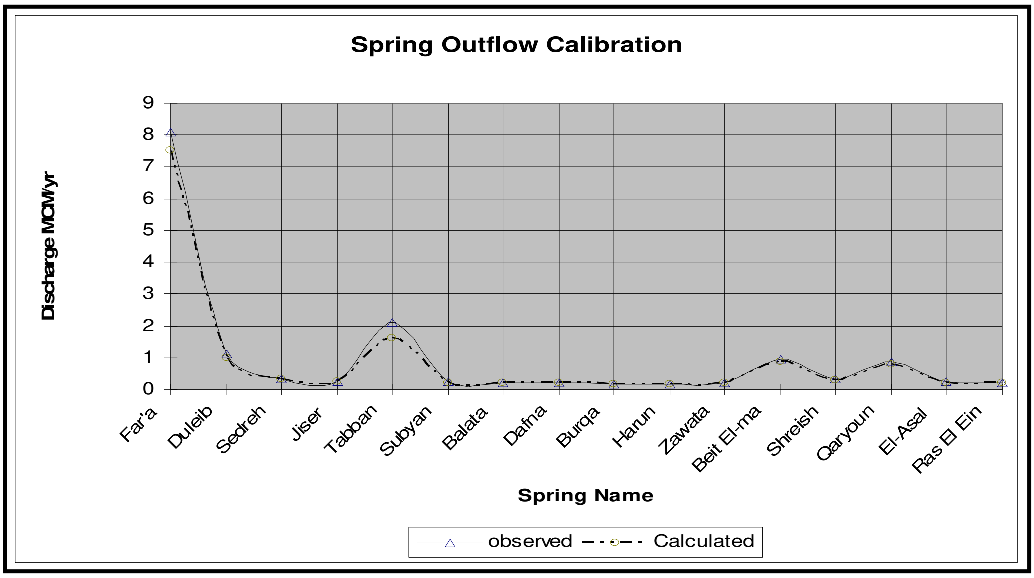


Figure (11): Calibrated versus observed springs discharge.

Groundwater Balance

The particle tracking results of the Eocene aquifer indicates that the main groundwater flow is from the south to north and the northeast (Figure 10). The Faria spring system is the major sink point within the aquifer since it attracts most of the particle tracking lines and has the highest flow rates.

The particle simulation result has identified the protection zones for the wells and the springs. This could be employed in the water resources management and the groundwater quality control.

To determine groundwater availability and sustainable yield of the Eocene Aquifer, the water balance is applied. The balance (Table 3) describes the inflow and outflow quantities of the aquifer system. The balance can be set up when the groundwater recharge and discharge mechanism of the groundwater aquifer are known. The amount of groundwater that can be abstracted from the aquifer is determined from the components of the long-term groundwater balance.

The recharge coefficients estimated by Ba'ba'[(6)] using annual rainfall data has resulted overestimated inflows. The model has calibrated these coefficients and consistent inflow values are obtained.

The water balance of the Eocene aquifer has indicated a sustainable yield value of about 72 MCM/yr. Table 3 presents the model calibration results and the water balance of the Eocene aquifer.

Table (3): Water Budget of the model domain of the Eocene Aquifer

Flow term	In (m3/d)	Out (m3/d)	In (MCM/yr)	Out (MCM/yr)
Spring	0.0	1.037E+05	0.0	37.37
Wells	0.0	1.29E+04	0.0	4.74
Sub-Surface Outflow	0.0	8.22E+04	0.0	30.1
Recharge from Precipitation	1.988E+05	0.0	72.27	0.0
SUM	1.988E+05	1.988E+05	72.27	72.21
Discrepancy (%) = 0%				

Conclusions

In this paper, the groundwater data of the Eocene aquifer located in the northern West Bank are modeled. MODFLOW is used in the analysis. The groundwater levels obtained by the model are higher than those presented by the maps of PWA. It has been shown that initial levels should be higher than 340 m above sea level in order to obtain reasonable results. Groundwater levels less than 340 m has resulted dry cells.

The hydraulic conductivities of the hydrological formations, which were reported in previous studies, are underestimated. The modeling has proved that double these values should be assumed to get more accurate results. This is mainly due to the faults and karstifications that characterize the Eocene aquifer.

The annual sustainable yield of the Eocene aquifer is determined from the model at 72 MCM. The groundwater wells located or proposed near the anticlinorium of the Eocene aquifer should be designed and operated carefully. This is due to the sensitivity of the anticlinorium to groundwater level variations, both seasonal and long term.

Substantial quantity of groundwater flow across the eastern and the northeastern boundaries, materialized as lateral subsurface outflow, is about 30.1 MCM/yr. These estimated good quality water could be tapped and exploited. The existing wells and springs should be monitored considering the construction of a reasonable monitoring network. The Particle Tracking obtained by the model is useful in modeling and controlling the groundwater quality of the aquifer.

In the model it was assumed that the flow in the aquifer is essentially horizontal and no vertical flow component has been considered. The effects of the fractures due to the faults are neglected. It is recommended to assess the faults carefully and determine their effect on the hydraulic conductivity.

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