Development of Groundwater Model for the Rijam Aquifer/ Jafer Basin, Jordan

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ABSTRACT

Rijam Aquifer/ Jafer Basin area (1073 km^2) lies in the southern part of central Jordan plain between 242-279 E longitude and 955-984 N latitude (according to Palestine Grid). Irrigation by pumping groundwater from a shallow unconfined aquifer of Rijam Formation (B4) had been practiced from 1965 up to 1971 when the salinity of the aquifer increased, whereby its yield became unsuitable for irrigation. The sustained yield has been estimated to be less than 2 MCM/Y due to limited recharge through the wadi beds during floods. Consequently, the aquifer balance has been disturbed, leading to a major decline in water level. Therefore, suitable groundwater resource management is required to overcome the problem of overpumping and its effect on groundwater quality.

Three - dimensional groundwater flow model (Processing Model Flow for Windows Pro: PMWIN PRO7, 2010) was used in this study in order to calculate the groundwater budget and aquifer characteristics, as well as to predict the aquifer response under different stresses for the next 20 years (2035). The model was calibrated for steady state conditions by trial and error calibration. The calibration was performed by matching observed and calculated heads for the year 1970. Drawdown data for the period 1990-2005 was used to calibrate transient model by matching the calculated heads with the observed ones. Thereafter, the transient model was validated by using the drawdown data for the period 2006-2013. The hydraulic conductivities of the Rijam aquifer system range between 10^{-4} and 10^{-8} m/sec. The specific yield percentage values ranged between 10% and 15%. The higher values of specific yield appeared in the southern part of the Rijam (B4) aquifer, while the lowest values appeared in the middle of the model area, where the pumping well fields are concentrated..

KEYWORDS: Groundwater modeling, MODFLOW, Hydraulic conductivity, Boundary conditions, Calibration, Conceptual model.

INTRODUCTION

Globally, the shortage of water in arid and semi-arid regions of the world is a major limiting factor in the development of economic and social structures. Since these regions rely mainly on groundwater, which is scarce, almost any development of the aquifers constitutes overdraft conditions. The erratic nature of precipitation in arid countries, such as Jordan. profoundly affects the accumulation and replenishment of groundwater.

Jordan is one of the poorest countries in water resources. About 91% of its area, mostly desert, has a rainfall less than 200 mm per year (Gougazeh and Sharadqah, 2009). As in the rest of the world,

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groundwater has contributed significantly to water resources in Jordan. Increased dependence on groundwater needs improved aquifer management with respect to understanding large recharge and discharge issues, planning withdrawal rates, balancing demands of multiple users, attending water quality problems arising from industrial and agricultural contamination and artificial recharge (Nusier et al., 2002).

In Jordan, rainfall is the main source of water recharge for both surface and sub-surface water resources. It is relatively scarce and varies considerably with location due to Jordan's variable topographic features and climate. Consequently, Jordan suffers from limited water resources. Furthermore, due to the increased demand on fresh water, the actual withdrawal from these aquifers is almost the double of the safe yield, which will eventually lead to depletion of the water resources, deterioration of water quality and increased salinity.

MATERIALS AND METHODS

Study Area

The Jafer Basin is located in the southern part of central Jordan plain and lies to the east of the western highlands, as shown in Figure 1. The basin has an area of 13500 km^2, most of which is classified as an arid desert with an annual rainfall mean of about 50 mm. The basin displays a classic centripetal drainage pattern with all wadis draining from the encircling highlands to the central El-Jafer playa which is the largest conclave in Jordan (El-Naqa and Rimawi, 2012).

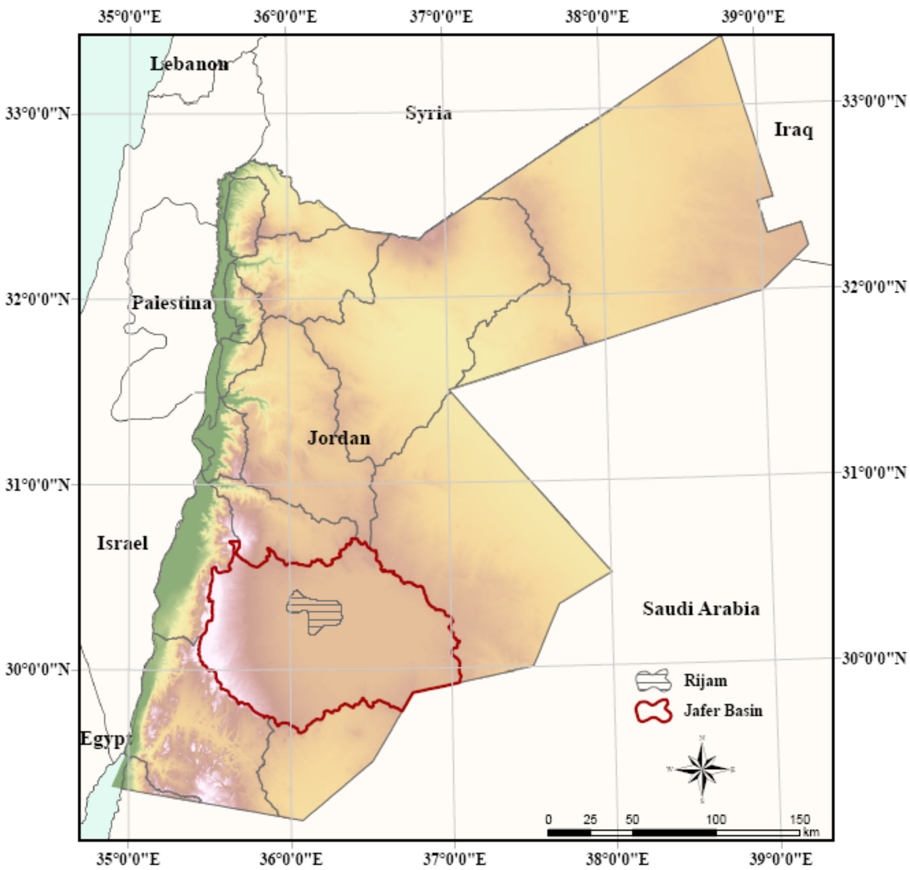

Figure (1): Study area location

Geology of the Study Area

A series of successions of sedimentary origins, ranging in age from Cambrian to recent formations, underlies the Jafer Basin and the Upper Al-Hasa Basin, except the minor areas in the northeastern part of the Jafer Basin, where volcanic rocks of Neogene and Pleistocene ages occur. The sedimentary succession thickness varies from 2000 m to 3000 m on the top of the basement complex. The sedimentary rocks underlying both basins are mainly of sandstones of the Paleozoic and Cenozoic ages in the upper part. Geological groups comprise Disi, Khreim, Kurnub, Ajloun and Balqa. None of the deep test wells drilled in these basins penetrated the groups of Disi, Khreim and Kurnub. The Ajloun group is composed of two formations: lower Ajloun (A1-6) and Wadi Es-Sir (A7), while the Balqa group includes three formations: Amman (B1-2), Muwaqqar (B3) and Rijam (B4). The Ajloun group is collectively referred to as the A1-7 and the Balqa group as the B1-4 (Shawaqfah et al., 2015).

In the southern part of the Jafer Basin to the south of Shidiya phosphate mines, the B2/A7 and A1-6 aquifers are both thin and unsaturated. In the central part of the basin, the B2/A7 aquifer is confined by overlying thick impervious argillaceous unit of the Muwaqqar B3 formation, while the surrounding areas are unconfined. Except the area along the Jafer trough, the confined B2/A7 aquifer has a potential for development. The A1-6 formation is highly confined in the area to the north of the Salwan fault, which is conceived to be a promising aquifer. The B4 aquifer exists in an independent regional shallow sedimentary basin, which overlies the impervoius Muwaqqar formation (B3). In the central part of the sedimentary basin, the B4 is saturated under water table condition, while it is unsaturated in the surrounding areas. This aquifer receives limited recharge through the wadi beds during floods.

The geological formations at outcrop in the study area mainly comprise the upper most Balqa group of upper most to lower Eocene. It consists of massive limestone intercalating with crystalline chert limestone and marly limestone. The formation outcrops extensively in the northern part of the Jafer Basin. The deposit is restricted to the area from the center of the study area to the northwestern Jafer Basin, mainly along the trough. The Rijam (B4) formation is deepest at 800 m elevation in the central Jafer Basin with a thickness of approximately 50 m. The sequence is restricted to the Jafer trough and thickness to the northeast ranges from 50 m to 100 m or more (JICA, 1990).

Climate

There are six climatological stations in Al-Jafer watershed; namely, Hasa, Abur, Shoubak, Udruh, Jafer and Ma’an airport. Climatological data, such as temperature, relative humidity, evaporation, sunshine hours, wind velocity and direction and rainfall are available for the period 1977 through 1993. The average annual minimum temperature is recorded in January and varies from 3.9 ºC at Al-Hasa to -2.6 ºC at Udruh, while the average annual maximum temperature is recorded in July or August and varies from 35.5 ºC at Jafer to 27.4 ºC at Shoubak. Relative humidity is as low as 30-50% during May to October and as high as 60-80% during December to January. The average annual total evaporation measured by U.S. Class A pan varies from 1800 mm at Shoubak to 4200 mm at Jafer. 70% of the annual evaporation at all the stations occurs between April and September.

Hydrogeology of the Study Area

The main aquifer considered in this study is the Basalt aquifer, since it is mainly exploited with the Corridor well field. The underlying A7/B2 aquifer is in direct contact with the basalt aquifer. The basalt aquifer can be described based on the hydraulic conductivity spatial distributions and the direction of these distributions. Anisotropy and discontinuous heterogeneity describe the nature of the basalt aquifer system with high variation in hydraulic conductivity. Relatively high permeability and preferential pathways are related to the boundary layers, between individual basaltic flows to joints and fractures resulting from cooling and tectonic stress. Porosity can be high in vesicular lava flows, but the effective porosity is generally less than 1% in the solid lava flows. Young basalt generally has permeability higher than that of older flows. It is decreased by alteration related to weathering and the influx of cementing fluids (Wagner, 2011). A7/B2 is the most important aquifer in Jordan because of its vast extent and favorable aquifer properties.

Groundwater Aquifer System

Aquifers have been recognized in argillaceous, arenaceous and low carbonate rocks of the Cambrian to Paleogene ages, such as Disi, Kurnub, lower Ajloun (A1/6), Amman –Wadi Es-Sir (B2/ A7) and Rijam (B4). This study focused on B4. The study area includes the Jafer Basin. B2/A7 and A1-6 are both thin and unsaturated in the southern part of the Jafer Basin, to the south of the Shidiya phosphate mines. B2/ A7 is classified as confined/ unconfined aquifer, such that it is confined by overlying thick impervious argillaceous unit of Muwaqqar (B3) formation and unconfined in the surrounding areas (JICA, 1990).

The Rijam (B4) aquifer exists in an independent regional shallow sedimentary basin overlying the impervious Muaqqar (B3) formation. B4 aquifer is saturated with water table condition in the central part of the sedimentary basin, while it is unsaturated in the surrounding areas. The aquifer receives limited recharge through the *wadi beds*, during the occasional floods, the potential of which is evaluated to be limited and small (JICA, 1990).

Conceptual Model

A conceptual groundwater model is a pictorial representation of the groundwater flow system, frequently in the form of block diagram or cross-section to simplify the field problem and organize the associated field data in order to determine the dimensions of the numerical model and the design of the grid (Anderson and Woessner, 1992). It consists of a set of assumptions that reduce the complicated real system to a simplified view to reach the model objectives.

Based on the compilation and interpretation of topographic, geological and hydrogeological data, the development of conceptual model of Jafer Basin has been set up, as shown in Figure 2.

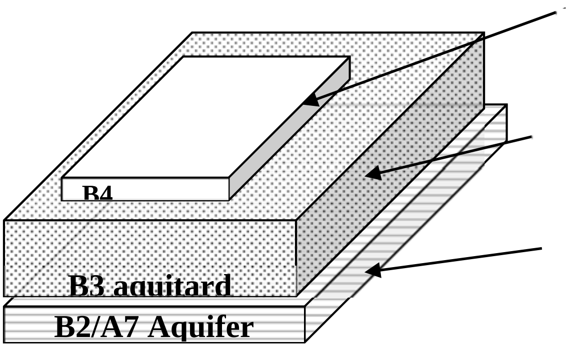

Figure (2): Conceptual model of the study area

Model Domain and Grid

The model domain was selected to cover 1073 km^2 of the watershed. The area of the modeling domain was chosen based on data availability and model boundaries not to be affected by stresses within the modeling domain. The domain is located between 240 and 280 E longitude and between 950 and 990 N latitude (according to Palestine Grid).

The mesh size of the model (0.5 by 0.5 km) was chosen in order to have each production well in one cell and eliminate the superposition of drawdown in the same cell as much as possible. About 1400 square cells are active and used for model calculations in the studied aquifer. Model parameter values have been assigned by two methods: Cell-by-Cell and Polygon. The two methods are part of the model software.

All the required maps have been scanned and converted into GIS maps:

1. Top and bottom elevation of each layer of the study area.
2. Water level maps of Rijam aquifers.
3. Location map of pumping wells and springs.
4. Location map of observation wells.
5. Detailed geological map.

Initial and Boundary Conditions

Based on the conceptual model, the groundwater flow pattern of the upper aquifers and the geological setting of the study area, the boundary conditions of the current study have been built up carefully. For the upper aquifer (Rijam B4), the dry region considered as no-flow boundary in the north and south. On the other hand, the 820 m water level contour is being used as a constant head boundary in the eastern part of the model area. The 900 m water level contour is assumed to be a constant head in the southern part of the study area. In addition, the rest of the model area has been left as specified head boundary. Figure 3 shows the flow model boundaries of the upper aquifer (Rijam B4) of Jafer Basin.

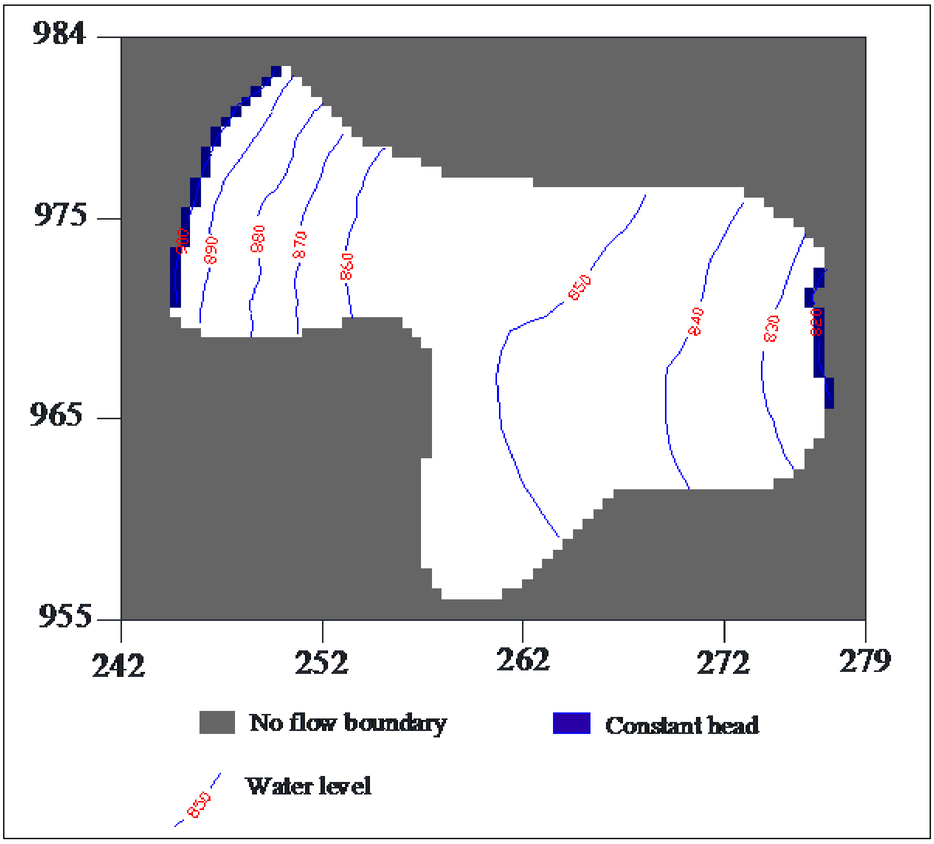

Figure (3): Model boundary and initial conditions

Model Calibration and Validation

Steady State Calibration

The steady state condition is a condition that existed in the aquifer before the occurrence of any development. Matching the initial heads observed for the aquifer with the hydraulic heads simulated by MODFLOW is called steady state calibration, that is done by sequential adjustment of the model parameters.

Model calibration of steady state was done by comparison of observed piezometric heads of the upper and lower aquifers with the calculated hydraulic heads. Calibration of the upper aquifer (B4) was based on the water-table map, which reflects the groundwater situation in the beginning of the seventies. Most of the parameters were considered changing during the steady state to reach the best fit for the model, particularly horizontal hydraulic conductivity and recharge.

Large numbers of hydraulic conductivity matrices have been used to simulate the hydraulic head in the model. The initial hydraulic conductivity used in the Rijam aquifer is 10^{-6} m/sec, which reflects the major structural formation of Rijam (B4) aquifer (BGR and WAJ, 1991). More than 50 sequential runs have been carried out to adjust the horizontal hydraulic conductivity of Rijam aquifer, so that the calculated hydraulic head is relatively equal to the observed hydraulic head. According to the best matching between the observed heads and model-calculated heads as shown in Figure 4, the final values of horizontal hydraulic conductivity ranged between 10^{-4} and 10^{-8} m/sec as shown in Figure 5, while the theoretical values of horizontal hydraulic conductivity of limestone (the major formation of B4) ranged between 10^{-6} and 10^{-9} m/sec (Domenico and Schwartz, 1998). The presence of the values of 10^{-5} and 10^{-4} is due to other formations.

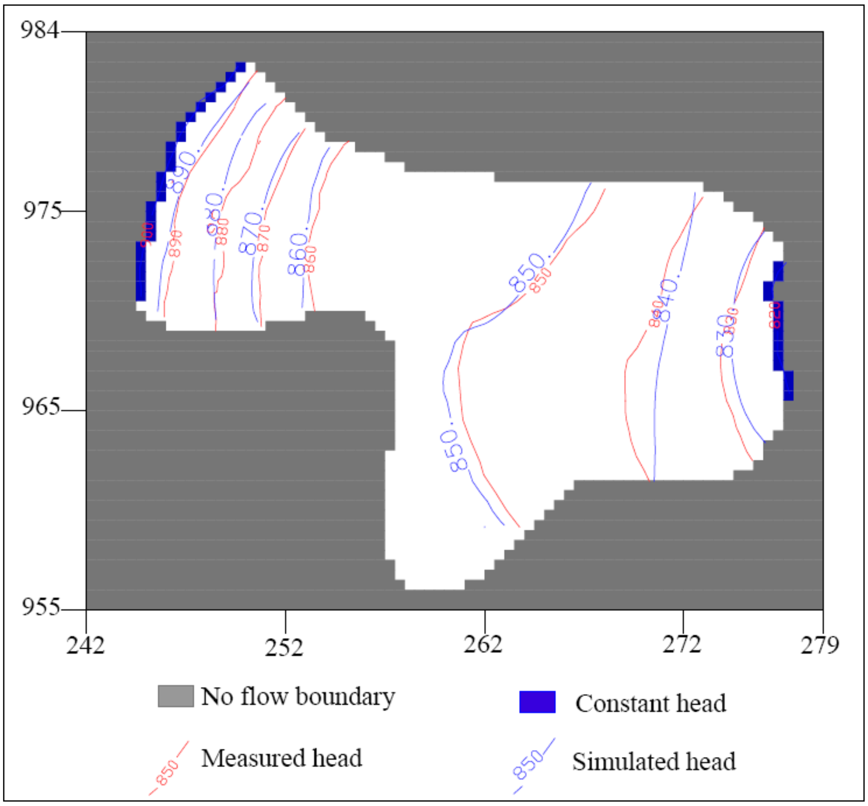

Figure (4): Map of the measured and simulated water levels for the B4 formation (steady state calibration)

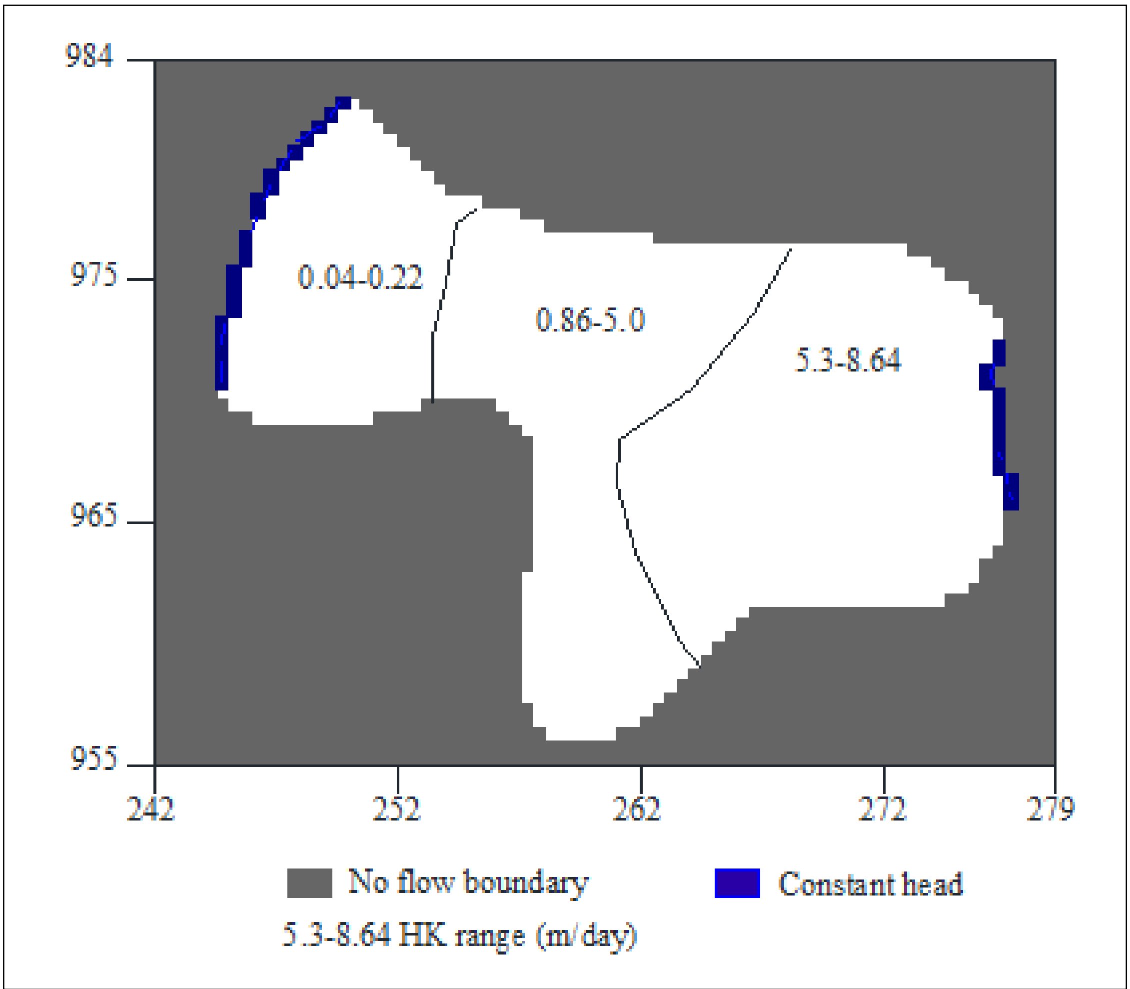

Figure (5): Map of the calibrated horizontal hydraulic conductivity of the B4 formation system

Figure 6 shows the water balance for the Rijam formation at steady state condition with a discrepancy of 0.006%, where the calibrated outflow exceeded the inflow by 0.002 MCM. The calculated total recharge amount to the area was 1.658MCMY (the inflow from eastern boundary is 0.993 MCMY and from the return irrigation flow and excess rainfall is 0.665 MCMY). The outflow across the western boundary reaches 1.66 MCMY, which will be considered the safe yield.

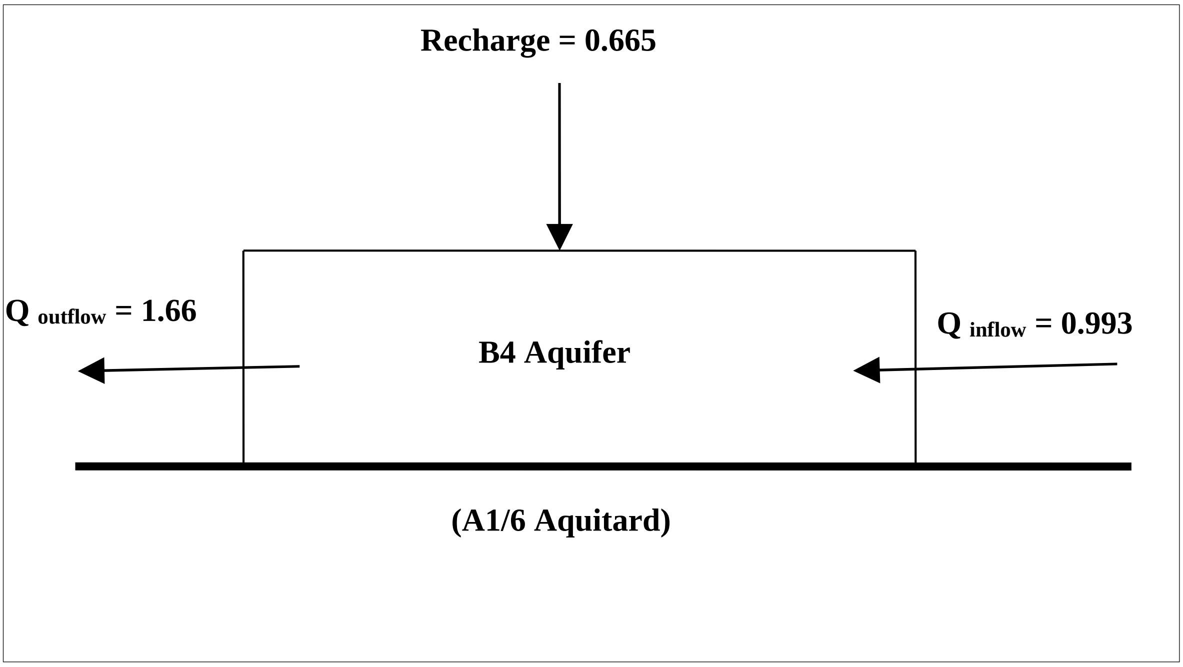

Figure (6): Water balance of the model domain at the steady state conditions (units in MCM/year)

Transient Calibration of Rijam (B4) Aquifer

The values of hydraulic head of the Rijam (B4) aquifer simulated from steady state calibration are used as initial hydraulic head for transient calibration of Rijam (B4) aquifer. The transient calibration of B4 aquifer is carried out using the available water-level data from two wells for the period 1990 – 2005. The other available data for the same wells in the period 2006 – 2013 is used for the model validation. When the simulated values of hydraulic heads (water level) are relatively close or matched to the values and trend of observed water levels, the transient calibration is completed. More number of wells used in transient calibration, more satisfied data resulted from transient calibration.

The transient calibration of Rijam (B4) aquifer has been initiated by assigning the initial value of the specific yield as 12% according to the general formation of aquifer system. Then, several values of specific yields were used through several computer runs until satisfactory difference between observed and calculated water level values was obtained.

The final values of specific yield after calibration ranged between 10% and 15%. The higher values of specific yields appeared in the southern part of the Rijam (B4) aquifer, while the lowest values appeared in the middle of the modeled area.

Model Prediction

Groundwater models were developed to predict the effects of groundwater abstraction and analyze the impacts of different groundwater management options on the behavior of the aquifer system.

Four different scenarios were carried out to predict the drawdown for the shallow aquifer of the Jafer Basin during the period 2015–2035, focusing on the years 2015, 2025 and 2035. In the first scenario, the pumping rates were assumed to be constant. In the second, third and fourth scenarios, the pumping rates were assumed to be increased by 25%, 50% and 100%, respectively.

- ***Scenario No.1*** (the current withdrawal rate (1.3 MCMY))

The present abstraction rates will be kept the same. The maximum drawdowns were noticed to reach about 13.48, 13.66 and 13.80 m in the years 2015, 2025 and 2035, respectively. In this scenario, it can be noticed that there is some kind of increase in water drawdown in the two periods.

- ***Scenario No.2*** (25 % increase in the current withdrawal rate (1.3 MCMY))

The present abstraction rates will be increased by 25%. The maximum drawdowns were almost fixed as in the first scenario and reached about 13.48, 13.66 and 13.80 m in the years 2015, 2025 and 2035, respectively. In this scenario, it can be noticed that there is good agreement between the safe yield (1.66 MCMY) which was calculated from the steady state calibration and this scenario abstraction rate (1.625 MCMY).

- ***Scenario No.3*** (50 % increase in the current withdrawal rate (1.3 MCMY))

The present abstraction rates will be increased by 50%. The maximum drawdowns were increased to reach about 13.48, 13.69 and 15.92 m in the years 2015, 2025 and 2035, respectively. In this scenario, it can be noticed that there is some kind of increase in water drawdown in the two periods.

- ***Scenario No.4*** (100 % increase in the current withdrawal rate (1.3 MCMY))

The present abstraction rates will be increased by 100 %. The maximum drawdowns were increased to reach about 13.52, 23.95 and 27.68 m in the years 2015, 2025 and 2035, respectively. In this scenario, it can be noticed that there is considerable increase in water drawdown in the two periods.

SUMMARY AND CONCLUSIONS

The Rijam aquifer system (the upper aquifer) of the Jafer Basin is investigated in this study, which is an unconfined aquifer. Processing MODFLOW (version 7.0) was used to simulate the three-dimensional groundwater flow for the upper aquifer systems under both steady and transient conditions. The results of the model calibration and verification showed sensible agreement between observed and simulated drawdown for the observation wells. The model is also used to predict the drawdown for the period from 2015 to 2035 under four different scenarios. The scenarios assumed that the abstraction rates will be 1.3, 1.63, 1.95 and 2.60 MCMY, respectively. Under these scenarios, the maximum predicted drawdown at the wellfield area in 2035 would be 13.8, 13.8, 15.92 and 27.68 m, respectively. The second scenario showed that the safe yield for the upper aquifer system was about 1.63 MCMY.

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