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DEVELOPMENT OF THREE DIMENSIONAL GROUNDWATER MODEL FOR AL-CORIDOOR WELL -FIELD IN JORDAN

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Abstract. Coridoor area (400 km^2) lies to the north – east of Amman (60 km). It lies between 285-305 E longitude and 165-185 N latitude (according to Palestine Grid). It been subjected to exploitation of groundwater from new eleven wells since the 1999 with a total discharge of 11 MCM in addition to the previous discharge rate from the well field 14.7 MCM. Consequently, the aquifer balance is disturbed and a major decline in water level. Therefore, suitable groundwater resources management is required to overcome the problems of over pumping and its effect on groundwater quality.

Three–dimensional groundwater flow model Processing Modeflow for Windows Pro (PMWIN PRO, 2003) has been usedin order to calculate the groundwater budget, aquifer characteristics, and 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 initial heads for year 2001. Drawdown data for period 2001-2010 were used to calibrate transient model by matching calculated with observed one, after that, the transient model was validated by using the drawdown data for the period 2011-2014. The hydraulic conductivities of the Basalt- A7/B2 aquifer system are ranging between 1.0 and 8.0 m/day. The low conductivity value was found at the north-west and south-western parts of the study area, the high conductivity value was found at north-western corner of the study area and the average storage coefficient is about 0.025. The water balance for the Basalt and B2/A7 formation at steady state condition with a discrepancy of 0.003%. The major inflows come from Jebal Al Arab through the basalt and through the limestone aquifer (B2/A7 12.28 MCMY aquifer and from excess rainfall is about 0.68 MCMY. While the major outflows from the Basalt-B2/A7 aquifer system are toward Azraq basin with about 5.03 MCMY and leakage to A1/6 aquitard with 7.89 MCMY.

Four scenarios have been performed to predict aquifer system responses under different conditions. Scenario no.2 was found to be the best one which indicate that the reduction the abstraction rates by 50% of current withdrawal rate (25.08 MCMY) to 12.54 MCMY. The maximum drawdowns were decreased to reach about, 7.67 and 8.38m in the years 2025 and 2035 respectively.

1 INTRODUCTION

The shortage of water in arid and semiarid regions of the world is a major limiting factor in the development of sound economic and social structures. In these regions, where groundwater is often the major source, almost any development of the aquifers constitutes overdraft conditions. The erratic nature of precipitation in arid countries such as Jordan exerts a profound influence upon the accumulation and replenishment of groundwater. Jordan is one of the poorest countries in water resources all over the world. About 91 % of its area has a rainfall less than 200 mm per year, where most of it is desert land. Groundwater are contributed a significant portion of water resources in Jordan as well as in the rest of the world. Increased dependence on groundwater needs improved aquifer management with respect to understanding large recharge and discharge issues, planning rates withdrawal, balancing demands of multiple users, and attending water quality problems arising from industrial and agricultural contamination, and artificial recharge [1].

The rainfall in Jordan is the main source for water recharge for surface and subsurface water resources. It is relatively scarce and varies considerably with location due to the variable topographic features of Jordan, and due to Jordan's climate. This makes Jordan suffer from limited water resources. Furthermore, due to the increase of demand on fresh water, the withdrawal from these aquifers is almost double that of the safe yield. This will eventually lead to depletion the water resources and deterioration in the water quality as well as increasing the salinity.

Groundwater modeling is an effective tool to get good understanding of groundwater flow and aquifer management. Groundwater modeling begins with the development of conceptual model after enough knowledge of the hydrogeology of the system, followed by the mathematical model, which consists of differential equations for hydraulic head with specification of system geometry, and boundary conditions. Many numerical methods are used to solve these differential equations; however the most common methods are finite difference and finite element method.

2. STUDY AREA

A. Location

The Water Authority of Jordan constructed a new well field (Coridoor Well Field) of 11 wells in the North Badiya region (along the north eastern desert part) in 1997 to 1998. The purpose of the well field is to provide water for domestic supply to Amman City. This well field area lies to the north – east of Amman (60 km) and along a strip N-S beginning from Baghdad Road. It lies between 285-305 E longitude and 165-185 N latitude. (according to Palestine Grid). These wells are expected to produce from 11-22 MCMY (million cubic meters per year) in total which considered as a significant amount of water. Fig. 1 shows the location map of the study area.

B. Climate

The climate in the working area is of a Sahara type characterized by hot summers and cold winters. There are 5 rainfall stations (AL0048, AL0058, AL0059, AL0049 and F0001) in the vicinity of the study area, only one of them is a metrological station (AL0059 Um Jemal).

The annual average temperature as recorded at AL0059 Um Jemal is 17.3° C. The daily average temperature ranges from approximately 8°C in winter time to 25°C in summer time. Prevailing winds at Um Jemal Metrological station are from the southwest in the winter shifting to the northwest in the summer.

Precipitation occurs periodically during the winter months from October to May and is normally associated with the frontal system moving inland from the Mediterranean Sea. The monthly rainfall distribution shows a start of the rainy season

in October with a peak in December and January (average of 30 mm in December and 28 mm in January). There's a sharp decrease from March to April (19 – 5 mm) to no rain in June.

The average annual rainfall in the vicinity of the site ranges from 83.2 mm in 1992 to 243.2 mm in 1980.

For the preparation of a rainfall distribution map, the average of the time period 1980 – 2014 was used. Generally, rainfall decreases towards east and increases with the topography towards north showing a decrease from NW to SE in the vicinity of the study area.

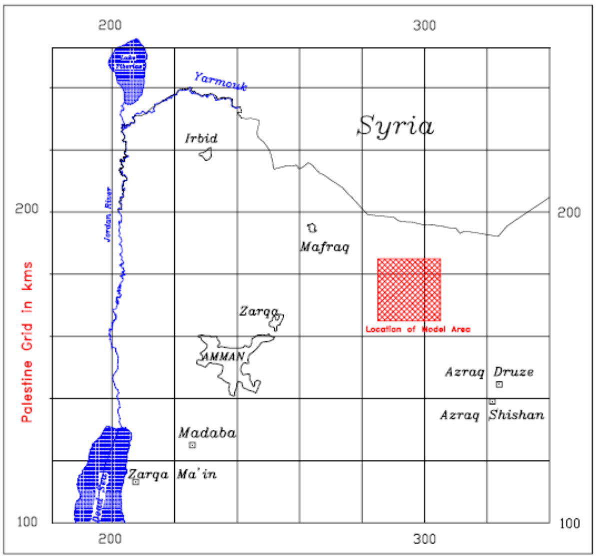

Figure 1. Study area location [2].

C. Evaporation

Evaporation (class-A-pan) is measured at station AL0059 Um Jemal, located 25 km southeast of the study area. Evaporation measurements started in 980. Monthly evaporation rates range from 116 mm to 117 mm in December and January to 268 mm in April and form a peak in July with 315 mm.

Potential evaporation decreases continuously from August to December. For the time period 1980 – 2014 average annual potential evaporation is 2943 mm/year. Average monthly potential evaporation varies between 116 mm in February and 395 mm in July. The average monthly and annual potential evaporation measured at AL0059 Um Jemal during the time period 1980 – 2014.

D. Runoff

Runoff is a function of precipitation, soils type and moisture, groundcover, elevation of catchment, and slope; of these factors the precipitation is the most variable. The shape of the drainage basin also governs the rate at which water enters the streams

In general, the high storm intensities combined with the low field capacities of the soil or even bare rocks in the area provide good conditions for recharge. Unfortunately, the annual amount of rainfall is very low. In addition, rainfall events occur infrequent, with short duration and high intensity. Most of the annual rainfall falls as high intensity storms therefore most of the rainfall comes to the surface during a very short period of time. Flash flood events are a direct result of this type of storm. Under these conditions, the rainfall is unable to infiltrate in the surface layer, resulting in surface flows that propagate rapidly through the watershed. Also if low intensity rainfall events occur: the surface crust that develops on arid watersheds can lead to significant surface runoff. Once on the surface, water in the study area is subject to high evaporation caused by

low humidity and high temperature. In many cases, the surface flows never reach the valley bottom. Therefore the surface water catchment area belongs to a less favorable area for groundwater recharge.

The volume of runoff for the Corridor well field catchment area is calculated using the runoff coefficient estimated for wet, dry and average conditions and is about 0.41 MCMY [3].

E. Aquifer System

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. In general basaltic aquifers are characterized by hydraulic anisotropy and discontinuous heterogeneity. Large contrasts may exist in hydraulic conductivity of basalt aquifer systems. Relatively high permeability's and preferential pathways are related to the boundary layers, between individual basaltic flows and 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 have a higher permeability than older flows, where is decreased by alteration related to weathering and the influx of cementing fluids [4]. A7/B2 is the most important aquifer in Jordan because of its vast extent and its favorable aquifer properties.

The following units are of interest for the current model:

Basalt: This formation outcrops in the model area and forms the main aquifer together with the A7/B2 aquifer. The thickness of this formation varies from more than 300 m in the north-east to less than 100 m in the south-west of the study area.

A7/B2: This unit comprises the A7, B1 and B2 formations. They consist of massive limestone, chalk or dolomite with only minor intercalations of strata with lower permeability.

The investigated aquifer, the A7/B2, is the most important aquifer in Jordan. The thickness of this formation varies from more than 300 m in the eastern part to less than 100 m in the western part of the study area. Since both aquifers (A7/B2 and Basalt) are hydraulically interconnected, they were considered as one unit [5].

A1/A6: In general, the A1/A6 unit has a very low vertical permeability in the model area. It forms the base of the A7/B2 aquifer, separating it from the underlying Kurnub aquifer.

Kurnub: This aquifer is not reached by wells in the model area. It influences the A7/B2 aquifer because it drains the water leaking through the A1/A6 aquitard.

F. Groundwater Occurrence and Movement

Generally, groundwater movement depends on the hydraulic conductivity and hydraulic gradient. It moves from areas of high pressure (head) to areas of low pressure (head).

The initial water levels map in the study area is illustrated by Fig. 2. The water levels map has been drawn according to the drilled wells in the study area. The depth to water table varies from more than 250 meters in the north-east to less than 100 meters in the south- west of the study area. Moreover, the elevation of the water surface varies from more than 525 m (a.s.l.) in the north-east and south-west to less than 520 m (a.s.l) far south-east of the study area. The source of lateral flow running through the plateau basalt to the northeast of the aquifer complex and through the limestone aquifer (A7/B2) to the southwest of the aquifer complex. Therefore, the type of groundwater is water-table conditions over most of the study area, which confirmed by wells drilling. The dominant direction of groundwater flow in the study area from north-east and south-west to the far south-west. The Corodoor well field is located at the north-western boundary of the Azraq basin. The groundwater divide between the Azraq and the Amman-Zarqa basins forms the western boundary of the study area as shown in Fig. 2.

G. Aquifer Characteristics

Only few pumping tests are reported from the Basalt aquifer in the study area. Most of them are from the corridor wells. Transmissivity and conductivity values vary enormously as shown in table 1 , transmissivity shows a range from 4.4 to 5600 m²/d, conductivity varies from 0.01 to 31 m/d. As there're only 6 transmissivity and conductivity values with high variation, no spatial interpretation of the data has been done. The highest permeability was determined in corridor well No. AL3479. No storage coefficients could be obtained from the above mentioned pumping tests since no water level measurements were effected in observation wells. Porosity varies as can be seen from the transmissivity values from around 0.03 (3%) to less than 0.01 (1%). The hydraulic gradient varies from 0.08 (West of the corridor well field) to 0.57 (North of the study area), with an average of 0.29 [3].

Well ID	Conductivity [m/d]	Transmissivity [m²/d]
F1389	4.75	360
AL3479	5.88	1100
AL3481	0.32	62
AL3666	8.64	1300
AL3480	0.63	130
AL3482	0.01	2

Table 1: CONDUCTIVITY AND TRANSMISSIVITY VALUES FOR THE CORRIDOR WELL FIELD [3].

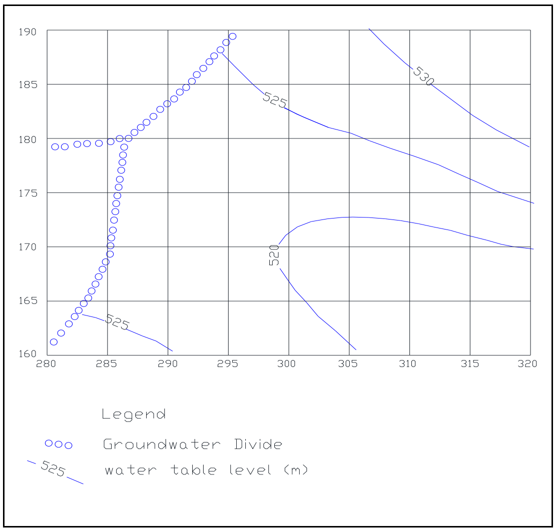

Figure 2. Initial water levels map in the study area.

H. Groundwater Withdrawal

The amount of groundwater abstraction from private wells exceeds the amount of groundwater abstraction for domestic purposes. Until recently, the amount of groundwater abstraction from private wells could only be roughly estimated. In 1993, the Water Basin Project has been created in the Water Authority to collect and monitor field data on groundwater abstraction from private wells by installing flow meters. Another task of this project is the land and the detection of illegal drilling. The agricultural development in the study area started mainly at the beginning of 1990s, except some few areas where the drilling and exploitation of groundwater started before that. According to Water Authority, the amount of groundwater abstraction in 1990 was around 9 MCM and reached 17 MCM in 1997 [3].

I. Recharge

Estimation of the natural recharge is probably the most difficult parameter to estimate due to the many factors that affect on this process. Although there are many methods to estimate the recharge quantity but most of them required detailed and accurate data to get an acceptable estimation. The annual average rainfall ranging from more than 140 mm in the north-western part to less than 110 mm in the south-eastern parts of the study area. In 1996, Ta'any, assumed that a recharge of 2% and 4% of the precipitation for the aquifer in Corridor well field. BGR/MWI, 2007 calculated the groundwater recharge using the hydrological approach for the surface water catchment area, and they found it to be 2.4% from the precipitation.

3. METHODOLOGY (MODELING)

A. Purpose of the Model

The processing Modflow Pro. Version 7.0 [6]. was selected to simulate the behavior of groundwater flow for the Coridoor well field. This model simulates three dimensional groundwater flow by using finite difference techniques.

B. Conceptual Model

Two major aquifer can be recognized in the Corridor well field, the Basalt-B2/A7 Aquifer and Kurnub aquifer, which are separated by the A1/6 Aquitard. The only abstractions until the near time are from the Basalt-B2/A7 aquifer, while Kurnub aquifer is not utilized because it is deep in most parts in the Corridor well field, and so the study will be performed only on the Basalt-B2/A7 aquifer, another reason for excluding the Kurnub aquifer is the absence of any observation well for this aquifer.

The A1/6 Aquitard, which has very low hydraulic conductivities, is considered as an impervious layer in the model, which means that no leakage occurrence between Basalt-B2/A7 layer and Kurnub layer, while in reality; the leakage could happen depending on the hydraulic gradient between the two layers. Fig. 3 shows the hydrogeological layers of the Corridor Well field.

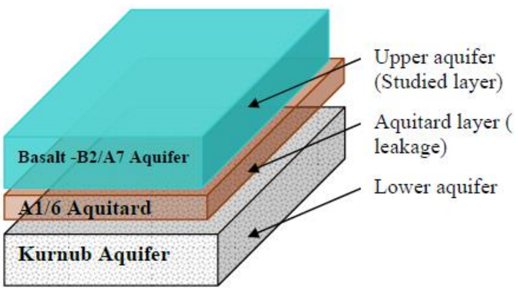

Figure 3. Conceptual model of the study area

C. Model Domain and Grid

The model domain was selected to cover 400 km^2 of the total area (600 km^2) of the Corridor 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 185000 PGE, 165000 PGN (left lower corner) and 310000 PGE, 190000 PGN (upper right corner) according to the Palestinian coordinate.

The model domain was discretized using 40 rows × 40 columns rectangular cells. This discretization produces 1600 cells in the model layer. The width of the cells along rows (ΔX) 500 m and along columns (ΔY) 500 m.

The orientation of the model grid is dependent highly on the hydrogeological features of the study area such as faults, and the predominant groundwater flow direction [7], as a result of that the grid of the model domain can be oriented in the horizontal direction (W-E).

D. Boundary Conditions

Depending on the map of the groundwater flow pattern of the B2/A7 aquifer, and the structural maps, the 526 and 523 m water level contours were being used as a constant head boundary in the north-eastern and south-western parts of the model area, respectively. The 520 m water level contour is assumed as a constant head boundary in the south-eastern part of the model area to control the flow towards Azraq Basin. A flow line (groundwater divide between Amman-Zarqa and Azraq Basin) in the aquifer represents the western part of the model area.

E. Initial Conditions

The initial conditions describe the distribution of heads (or pressures) and concentrations throughout the model domain at the start of the simulation. The initial condition in steady state condition is the head distribution within the model area at initial time. The initial conditions supplied to a transient run should be the result of a steady state flow or transient flow and transport simulation of background flow and transport conditions, which will gave a mass balance starting point.

F. Steady State Calibration

The steady state condition is a condition that existed in the aquifer before any development had occurred. Match 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.

Hydraulic conductivities, those estimated from previous studies and from pumping tests were used as initial values for the steady state simulation. By using the trail and error calibration, the horizontal hydraulic conductivity was adjusted during many sequential model runs until the match between the observed and simulated heads were obtained. Also minor adjustments were done on the boundary conditions that are firstly used in the initial runs. It is clearly shown that there is a good match between the simulated and measured heads. The values of the calibrated horizontal hydraulic conductivity, ranged between 1 m/d and 8 m/d. The A1/A6 aquitard is characterized by horizontal and vertical conductivities of 0.0086 m/d and $8.6*10^{-6}$ m/d, respectively. This leads to a leakage of about 7.89 MCM/year of the total recharge from the Basalt-A7/B2 aquifer through the A1/A6 aquitard to the sandstone aquifer (Kurnub).

Fig. 4 shows the water balance for the Basalt-B2/A7 aquifer system in Coridoor well field at steady state condition with a discrepancy of 0.3%. Table 2 summarized the major inflows and outflows in the modelled area.

Flow Term	IN	OUT	IN-OUT
Constant Head	12.28	5.03	7.25
Recharge	0.68	0.0	0.68
Leakage	0.0	7.89	-7.89
Sum Of The Year	12.96	12.92	0.04

Table 2: MAJOR INFLOWS AND OUTFLOWS IN THE STUDY AREA.

A comparison of measured and simulated water level contours of the Baslat-B2/A7 aquifer is presented in Fig. 5.

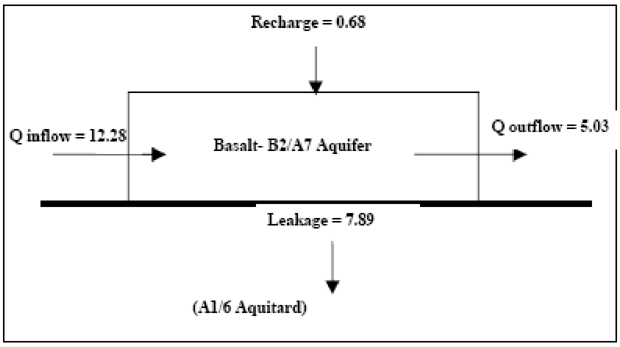

Figure 4. Water Balance of the model domain at the steady state conditions (units in MCMY).

G. Transient Calibration and Validation

The year of 1990 was considered as the year in which the transient calibration started for Coridoor area. Twenty five stress periods were selected to cover the time period of 25 years (1991–2014), where as each stress period consists of one year in one time step. The available data from 2001 to 2010 were used for calibration processes and the rest data were used for the validation purposes since there is one monitoring well in the study area for the period (2001-2014).

Time dependent model simulations for a time period of 6 years (1991- 1996, without Coridoor wells) with known withdrawal rates (14.7 MCM/year) have been carried out, then for the period of (1997-2000) with withdrawal rate of 17MCM/year, after that for the period of (2001-2014) the withdrawal rate is considered the Coridoor wells to reach the current drawdown in the study area.

The available data of the monitoring well was used in the calibration process. The calibration was done by changing the specific yield values and then several computer runs were performed until reasonable matches were obtained between the observed and simulated heads.

One observation well is available in the model area (AL 3482, coridoor 11). Time dependent model simulations for a time period of 10 years with well-known withdrawal rates have been carried out in order to compare between the observed and calculated head. In addition, further model runs were carried out for hydraulic heads validation for the time period of 5 years based on continuous groundwater withdrawal rates. The average calculated specific storage was about $2.0{*}10^{-4}$ m^{-1} and the average specific yield about 0.025 some values were 0.015.

H. Model Evaluation

Transient calibration is also evaluated quantitatively where some measures of goodness of fit between observed and predicted drawdown for calibration stage are presented in table 3. These quantitative measures give another way to evaluate transient calibration results over the visualized one presented in the previous Fig. Generally, these measures show that the fit between measured and simulated heads for the calibration stage is better than validation stage which is expected because of in the calibration stage the specific yield values was changed till the best fit was reached, while in the validation stage the specific yield values was used from the calibration stage.

ID	R_h Max.	R_h Min.	ME	MAE
AL 3482 C	0.133	-0.4	- 0.168	0.234
AL 3482 V	-0.33	-0.53	-0.43	0.43
Ideal value	0	0	0	0

Table 3: SUMMARY OF SOME MEASURES OF FIT BETWEEN OBSERVED AND PREDICTED HEADS FOR TRANSIENT STATE (C = CALIBRATION, V= VALIDATION).

After checking the model and obtaining the calibrated parameters, the model was run to get the water level map of year 2015 which is shown in Fig. 6.

I. Model Prediction

A model may be used to predict some future groundwater flow or contaminant transport condition, pump and treat or natural attenuation, and to assist with risk evaluation. In order to perform these tasks, the model, whether it is a groundwater flow or solute transport model, must be reasonably accurate, as demonstrated during the model calibration process. However, because even a well-calibrated model is based on insufficient data or oversimplifications, there are errors and uncertainties in a groundwater-flow analysis or solute transport analysis that make any model prediction no better than an approximation. For this reason, all model predictions should be expressed as a range of possible outcomes which reflect the uncertainty in model parameter values.

The following scenario was conducted to predict the drawdown for the Basalt B2/A7 formation of the Coridoor area during the period (2015-2035).

In this scenario, it is assumed that the pumping rates of year 2014 which is 25.08 MCMY are constant for 10, and 20 years. The maximum drawdown were concentrated in north part of the area, and reached about 23.1 and 23.35 m in 2025 and 2035 respectively. Fig. 7 shows the drawdowns maps for year 2035.

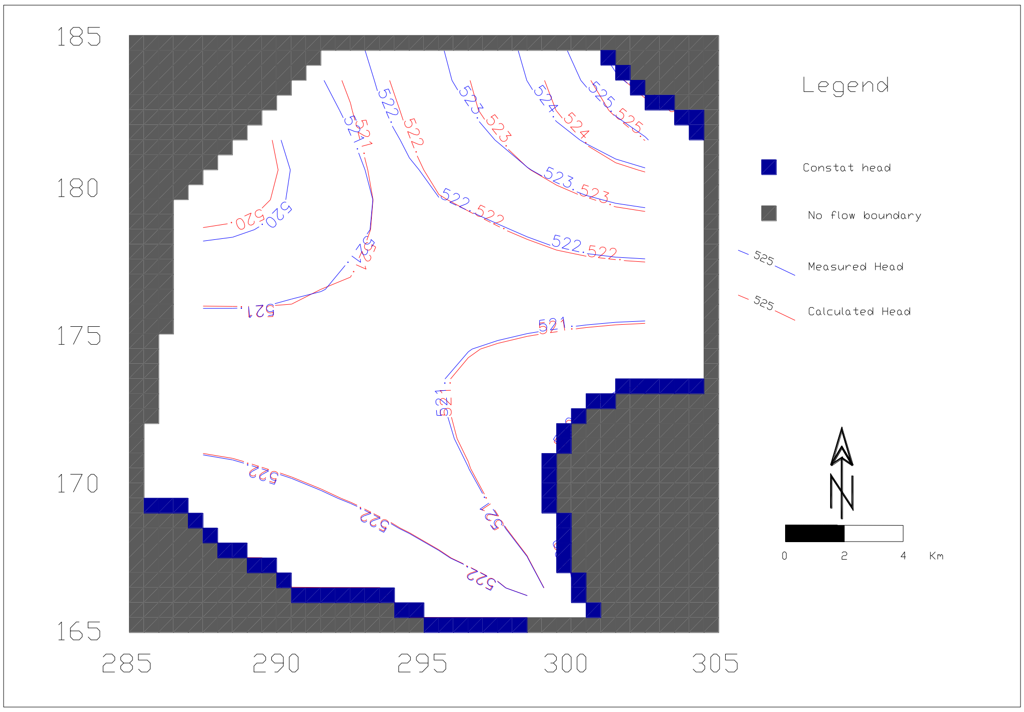

Figure 5. Map of the measured and simulated water levels for the Basalt- B2/A7 aquifer (Steady state calibration).

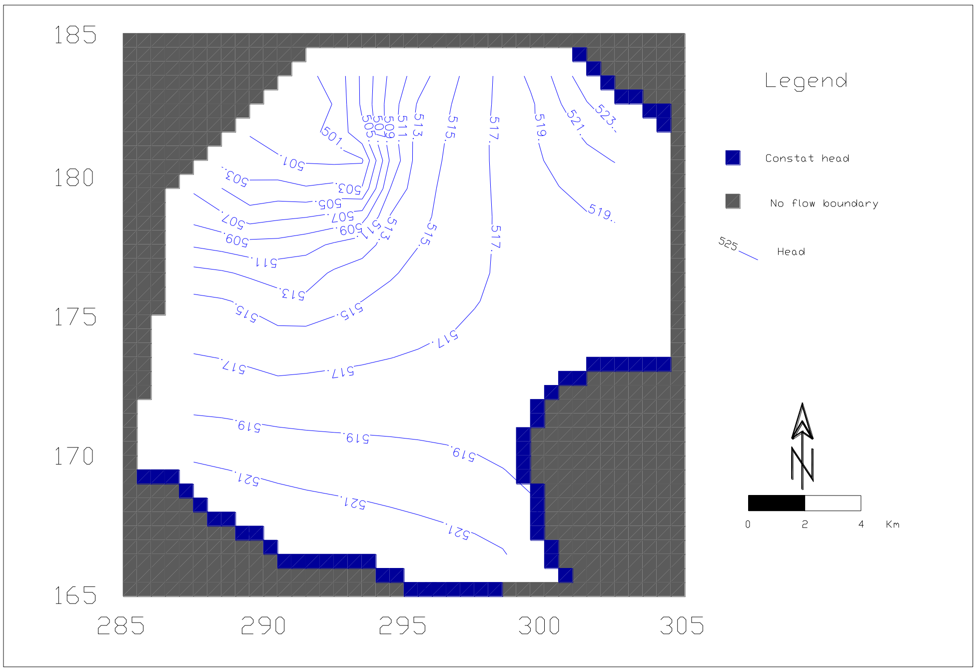

Figure 6. Simulated groundwater level of year 2015.

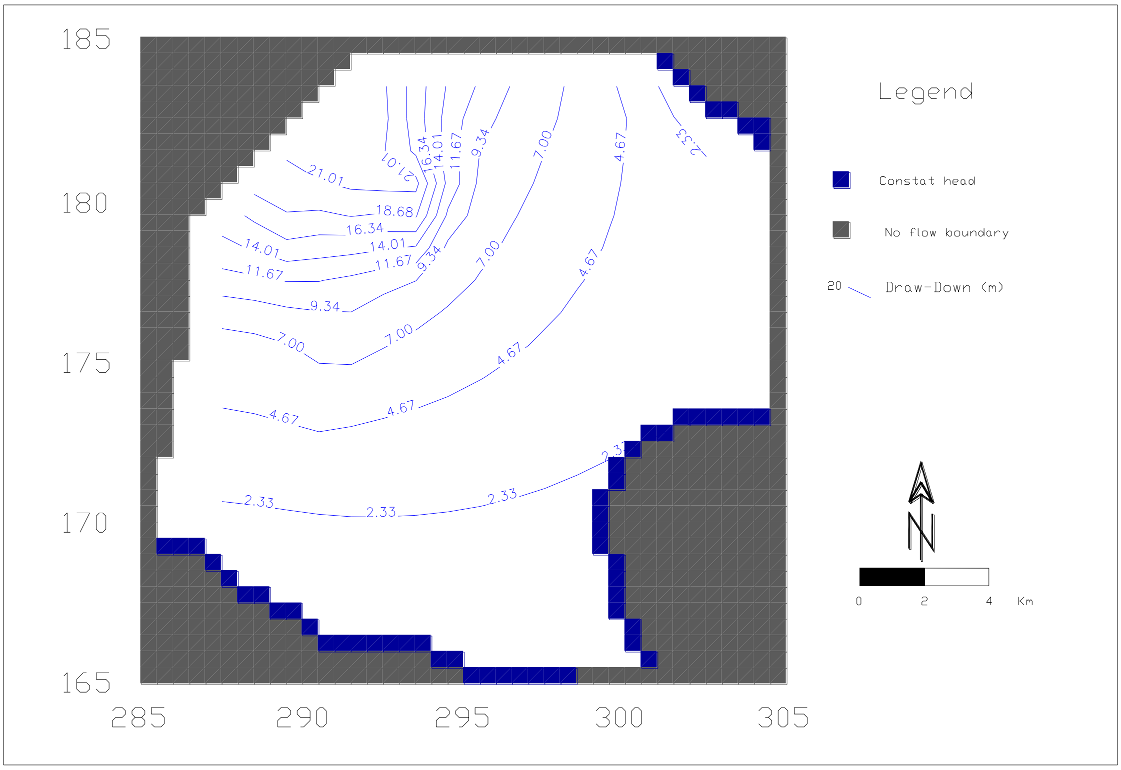

Figure 7. Predicted drawdown at year 2035.

4. Conclusions and Recommendation

Processing Modflow Pro version 7.0 (PMWIN PRO) is used in this study to simulate the groundwater flow for the Basalt-B2/A7 formation system in Coridoor area for both steady and transient conditions, to predict the future changes occurred under different stresses and to investigate different scenarios and evaluate their efficiency and effect on the water table level.

The results of the calibrated groundwater flow model (steady and transient states) indicated that the horizontal hydraulic conductivity (K_h) of the Basalt-B2/A7 aquifer system in Coridoor area basin ranges between 1-8 m. The vertical hydraulic conductivity (K_v)was $1.72*0^{-2}$ m/d The average calibrated specific yield value was 0.025. Regarding the A1/6 aquitard, the K_h was $8.6*10^{-3}$ m/d and the K_v was $4.32*10^{-5}$ m/d.

The major inflows and outflows are 12.96 MCMY and 12.92 MCMY respectively in the study area based on the model results.

Based on this study it is highly recommended to establishing more observation wells, especially near the boundary to detect the water level drawdown so as to implement that in the simulation. Also the abstraction rates from each well need to be recorded for an improved future modelling. In addition, Total groundwater withdrawal in the model area should be reduced to about 9-15 MCM/year in order to reach a sustainable use of the groundwater resources.

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