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Prediction of Water Table in an Alluvial Aquifer Using Modflow

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ABSTRACT

Groundwater is the main source of water in the Kingdom of Saudi Arabia (KSA). A larger part of groundwater is founded in alluvial (unconfined) aquifers. Prediction of water table elevations in unconfined aquifers is very useful in water resources planning and management. During the last two decades, many aquifers in different regions of the KSA experienced significant groundwater decline. The declines in these aquifers raised concerns over the quantity and quality of groundwater, as well as concerns over the planning and management policies used in KSA. The main objective of this study was to predict water table fluctuations and to estimate the annual change in water table at an alluvial aquifer at wadi Hada Al Sham near Makkah, KSA. The methodology was achieved using numerical groundwater model (MODFLOW). The model was calibrated and then used to predict water table elevations due to pumping for a period of 5 years. The output of the model was found to be in agreement with the previous records. Moreover, the simulation results also show reasonable declination of water table elevations in the study area during the study period.

Keywords: Water table, elevations, alluvial aquifer, prediction, validation

INTRODUCTION

Groundwater constitutes the most important natural water resource in the Kingdom of Saudi Arabia. It exists in two different types of formation. The first type is deep confined aquifer that exists throughout the two thirds of the eastern part of the country. These aquifers contain huge amounts of water. The second type is shallow unconfined aquifer. This type is scattered throughout the country and it is mainly found under wadis. They are normally unconsolidated and of limited thickness. Meanwhile, alluvial (unconfined) aquifers have been developed in the country for hundreds of years to sustain agriculture before drilling of wells in the vast confined aquifers which was started only in the last few decades. These supply substantial amounts of water to agricultural areas that are located around many wadis in the Kingdom. Groundwater flow and water table fluctuations in the alluvial aquifer can be numerically simulated if adequate hydrologic and geologic data are available. These models and concepts, on which they are based on, are well-accepted by researchers and engineers dealing with groundwater flow.

A simulation of groundwater flow that takes into consideration the parameters and properties variability of aquifer is only possible through mathematical modelling. Most models that are usually employed to simulate groundwater flow are based on the Partial Differential Equation (PDE) which can be solved numerically through Finite Difference (FD) or Finite Element (FE) techniques. These methods discreet the time and flow domains, and require computing the hydraulic head in each cell

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by dividing the stress periods into smaller time steps. Several studies with the use of the FD and FE methods have been carried out by many researchers (Wang and Chunmaio, 1998; Bakker, 1999; Gupta *et al*., 1984; Mazzia and Putti, 2002).

The development of high speed computers may ease solving the PDE in groundwater modelling using numerically-based models such as MODFLOW. MODFLOW is a fully-distributed three dimensional groundwater model which uses a block-centred approach and a modular structure consisting of a main program and a series of subroutines that are grouped into packages (McDonald and Harbaugh, 1988). MODFLOW has been updated and it comprises different refinements such as the revised version in 1996 (Harbaugh and McDonald, 1996).

MODFLOW is widely used to either predict groundwater flow or head fluctuations (Pulido-Velazquez *et al*., 2007) or to verify other groundwater simulation methods, such as spreadsheet simulation model (Karahan and Ayvaz, 2005). Due to its capability, MODFLOW is widely used to simulate different types of groundwater problems in different geographical regions, such as the arid, semi-arid and tropical areas. It is a well known model in the field of groundwater. In this study, MODFLOW was applied to simulate the fluctuation in water table at the semi-arid region. This is considered as an example to present the capability of the model.

MODFLOW has been used in groundwater simulation and management scenario analysis in Jordan (Al-Kharabsheh, 2000), simulation and well field operation in discontinuous layers in Kuwait (Szekely *et al*., 2000), investigation of possible alternatives for effective groundwater management in eastern Saudi Arabia (Rasheeduddin *et al*., 2001), simulation and modelling of groundwater in multilayer aquifer system in the valley (wadi) area of south-west Egypt (Ebraheem, 2002), and the prediction of the effect of irrigation and water abstractions on the piezometric levels in the Murzuq aquifer in the south-west of Libya (Shaki and Adeloye, 2007).

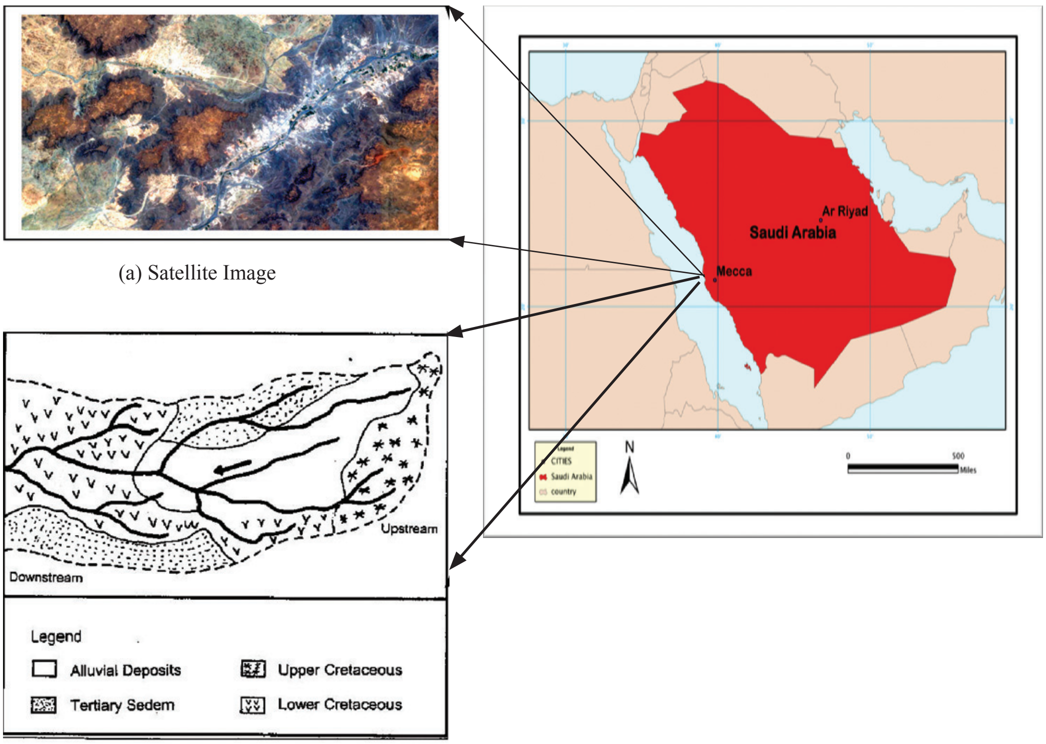
STUDY AREA AND CHARACTERISTICS OF AQUIFER

The application of the groundwater model was done on the unconfined aquifer underneath wadi Hada Al Sham, which is located in north Makkah, Saudi Arabia. The study area is located between the longitudes of 39° 40' and 40° 15' in the east and the latitudes of 21° 45' and 22° 10' in the north, as shown on the location map in *Fig. 1*. Wadi Hada Al Sham flows into wadi Usfan that runs in the east-west direction having its outlet towards the Red Sea at a distance of 105km in the north of Jeddah. It consists of Wadis sub-basins Madrakah, Zabyah, Hishash, and Wadi Al Lusub. The area is bound by Wadi Khulays in the north and Wadi Fatimah in the south.

Agriculture is the main activity in the region, particularly private farms. The main source of water in the area is the groundwater from aquifers. Many wells of different types and diameters are used and most of them are exploiting the unconfined (alluvial) aquifer.

The study area is a part of the Western Arabian Shield which comprises complex of metamorphic and plutonic rocks. The central part of the area consists of sedimentary rocks of Tertiary age which are overlain by basaltic lava flows. The sedimentary rocks cover about 50% of the total surface area. Cretaceous Hada Al Sham formation is composed of sandstone, siltstone, and alluvial deposits. According to Kotb *et al*. (1983), the upstream area of the valley has deposits of layers of pebbles and coarse sand. It gradually changes to silt and clayey silt at the downstream. The thickness of the alluvium deposit in the middle portion varies in the range of 35 to 75 m.

The region of the study area is presumed as an arid basin with a low precipitation of about 100-300 mm annually. The meteorological data (mainly rainfall) were measured and collected by the Ministry of Water (MoW) from seven stations covering the region of the study area. There are two stations located with the basin of the study area. The potential evapotranspiration is at its maximum in July, i.e. around 300 mm. It decreases to 130 mm in December and January.



(a) Satellite Image

(b) Geo-Topographic Map

Fig. 1: Map showing the location of Wadi Hada Al-Sham Aquifer

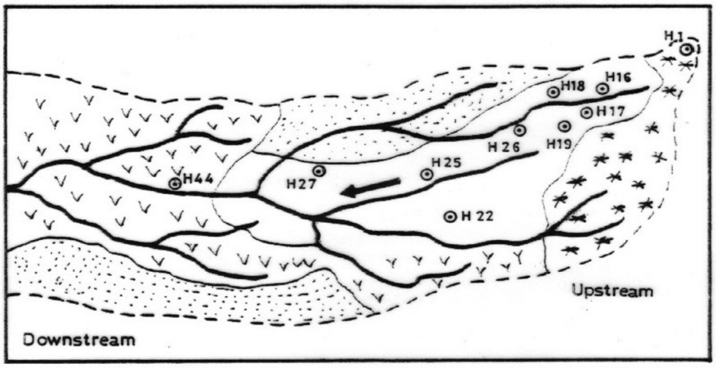
Groundwater occurs in the area within two geological units, namely the alluvial deposits of the wadi system and the classic members of Cretaceous-Tertiary sedimentary succession (Hussien *et al*., 1993).

In this study, the application of MODFLOW was only done for the alluvial (unconfined) aquifer. The aquifer properties were investigated by MoW and found to be (on average), as follows:

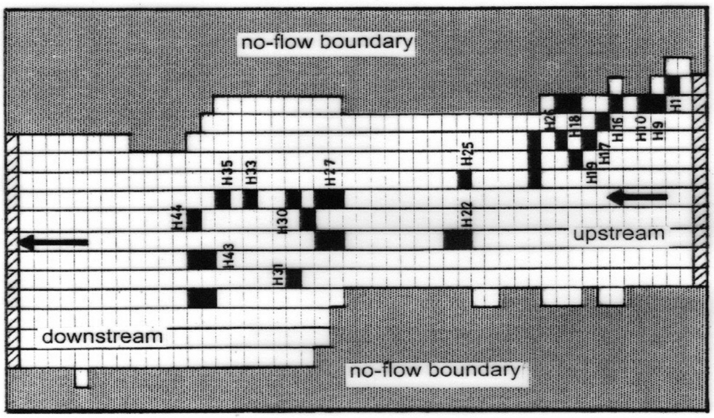
- The effective porosity (Φ)= 0.18
- The vertical hydraulic conductivity (k) = 0.56 m/day
- The aquifer transmissivity (T) = 212 m^2/day
- The specific yield (S_y) = 0.15
- The average thickness of the aquifer (b) = 380 m

MODELLING SETUP

The numerical finite-difference model (MODFLOW) was used to simulate groundwater flow with initial and boundary conditions. The input data for the simulation model may be classified as spatial and temporal. The spatial input includes aquifer characteristics, such as water levels, boundaries, hydraulic conductivity, storage coefficient, location of wells, recharge area, drainage area, etc., whereas the temporal input includes time dependent data. The period of simulation is divided into a series of "stress periods" within which specified stress calculates an overall water budget and controls model output according to user's specification.



(a) Location of wells before converting the area to grids

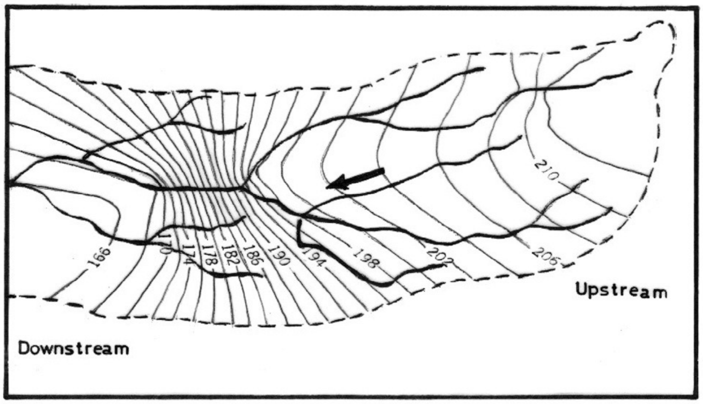


(b) Location of wells after converting the area to grids

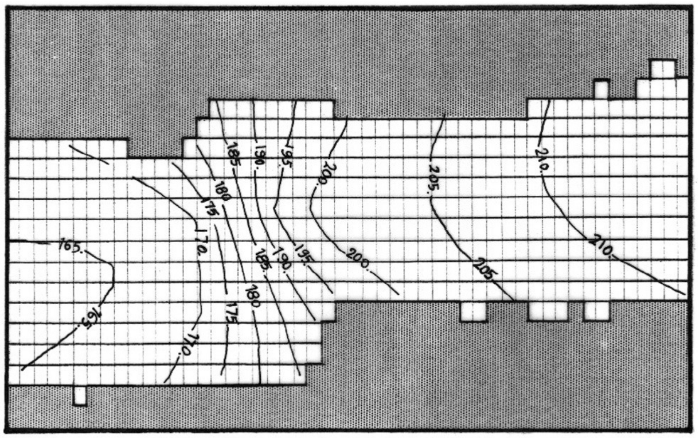
Fig. 2: The location of the wells

The modelled area is replaced by a set of discrete nodes in a grid pattern covering the modelled area. The grid consists of 50 rows and 20 columns (1000 cell) overlaying on the (50 x 30 km) or 1500 km^2 study area, as shown in *Fig. 2a*. The model area is divided into cells, with each consisting of 1.0 x 1.5 km (see *Fig. 2b*). The necessary data for each cell were entered, i.e. top and bottom of the aquifer, hydraulic conductivity, specific yield coefficient, and porosity of the formation, etc.

The initial (i.e. at the beginning of the simulation) water table levels, obtained from the observation wells in the study area, were used to retrieve the initial water level contour map, as shown in *Fig. 3*. Meanwhile, the discharge pumping rates from the 18 wells in the area are presented in Table 1.



(a) Observed



(b) Simulated

Fig. 3: The initial observed and simulated water table contours (in m)

TABLE 1

The pumping rates from the different wells

Well no. (H-)	1	7	8	9	10	16	17	18	19	22	26	27	30	31	33	35	43	44
Q (m^3/day)	280	420	400	370	380	400	450	420	400	350	430	450	500	510	470	400	450	510

These values were included in the model to predict the water table elevations in the aquifer. On the other hand, the recharge to the aquifer in the area was estimated as 0.41 mm/day or 0.00041 m/day, reflecting the annual average infiltration depth due to the flow in the wadi.

Meanwhile, the boundary conditions used in the model simulation and calibration include the upstream and downstream of the wadi that were assumed to be constant head boundary, where head fluctuation is minor. The upstream inflow was estimated as 300 m^3/day, and this was 200 m^3/day for the downstream outflow. The banks of the wadi are assumed as no-flow boundary. These boundaries are displayed in *Fig. 2*.

The simulation of the model was started in 1998 and ended in 2003, with a stress period of 5 years (1825 days). The time step that was used in both calibration and simulation was set as one day.

MODEL CALIBRATION

The calibration of a groundwater model can be defined as a trial and error procedure which is done by matching the computed groundwater potentials from the simulation with the observed potentials in the field. The process is completely based on the availability of historical field data of water level in the aquifer. The calibration was done for the adjustment of the aquifer parameters. These parameters are initially imperfectly known and there is usually a certain range of possible values for them that may be valid. The model is said to be calibrated when the difference between the computed and observed potentials is less than a certain specified value.

Once the field has been discretized, the model grids must be initialized. This involves assigning the starting values of the hydraulic parameters and specific yield. The initial value of the hydraulic conductivity was 0.56 m/day, while the specific yield was 0.15. The other data that are necessary for the MODFLOW calibration process are aquifer type (in the case of the present study, it is unconfined), initial water levels, top and bottom elevations, porosity and other aquifer properties and temporal data (discharge rates and general boundary head).

The model was run with a steady state calibration for the study area, with a one day simulation period. The values of the hydraulic conductivity, i.e. K, were chosen in the range from 0.10 up to 1.0 m/day. A comparison of the water level contour maps, using different values of K, was then performed until it was found from the trials that the K value of 0.60 m/day had produced the best matching between observed (*Fig. 3a*) and calibrated water level contours map. This map was achieved as shown in *Fig. 3b*.

RESULTS OF THE MODEL SIMULATION

Water Level Contour Maps

The groundwater flow model MODFLOW was used, with calibrated parameters, to predict and map water table contours of the study area after different durations (1, 2, 3, 4, and 5 years), as respectively shown in *Figs. 4* through *8*. The predicted water table levels were found with a reasonable distribution in the area. Meanwhile, a continuous declination in water table levels can be attributed to the continuous extraction of water from the aquifer through different wells in the study area. However, there are small differences in the contour lines from year to year which indicate that the groundwater storage in the area is huge and the impact of exploitation (by pumping wells) is not significant. A comparison between the observed and predicted water table elevations for the study area was also conducted. It was found that the absolute error between the observed and MODFLOW could predict the ranges from 0 to 6 m, as shown in Table 2.

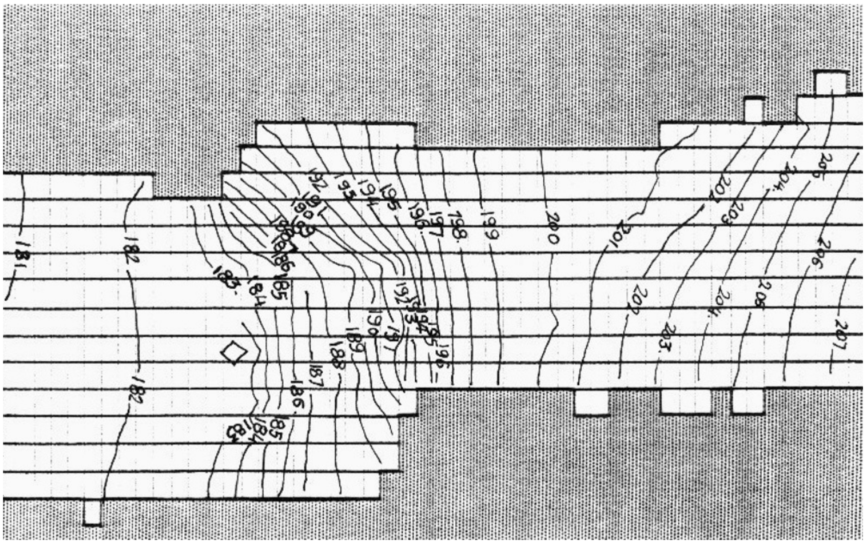


Fig. 4: The predicted water table contours (in m) at the end of Year 1

TABLE 2
Observed and predicted water table elevations for the study area

Distance form down stream border (km)	Observed water table elevation (m)	Predicted water table elevation (m)	Absolute error (m)
8	210	210	0
14	205	205	0
18	202	200	2
21	194	195	1
28	185	186	1
31	176	170	6
39	165	166	1

Well Water Levels

As shown in *Fig. 2*, there are many wells located in the study area. The water table in the selected wells at the study area was predicted. Table 3 and *Fig. 9* show the model output for the 5-year period.

The results show the declining levels of the water table in most wells. Pumping from the wells has been found to produce drawdown in the aquifer. However, the decline in the water levels is not significant, suggesting that the groundwater storage at the area is very large as compared to the discharge pumped from the wells (low use to yield ratio).

TABLE 3

Simulated water table in the wells (m)

Well year	H-1	H-16	H-17	H-18	H-19	H-22	H-25	H-26	H-27	H-44
1	203.73	204.30	204.02	203.31	203.43	202.05	198.99	203.31	191.75	193.80
2	201.92	202.55	202.33	201.71	201.84	200.67	197.11	201.50	191.22	191.99
3	201.36	202.01	201.81	201.21	201.34	200.24	196.59	200.94	191.12	191.53
4	201.19	201.83	201.64	201.05	201.18	200.10	196.43	200.76	191.10	191.39
5	201.11	201.76	201.57	200.98	201.11	200.04	196.37	200.69	191.09	191.33

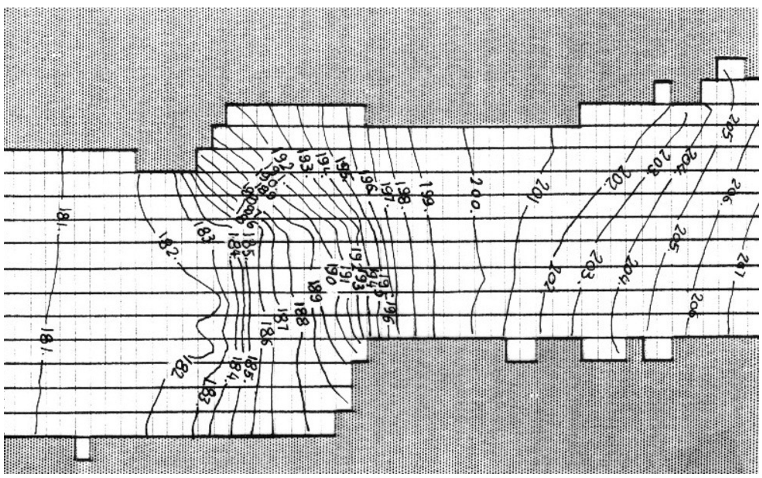


Fig. 5: The predicted water table contours (in m) at the end of Year 2

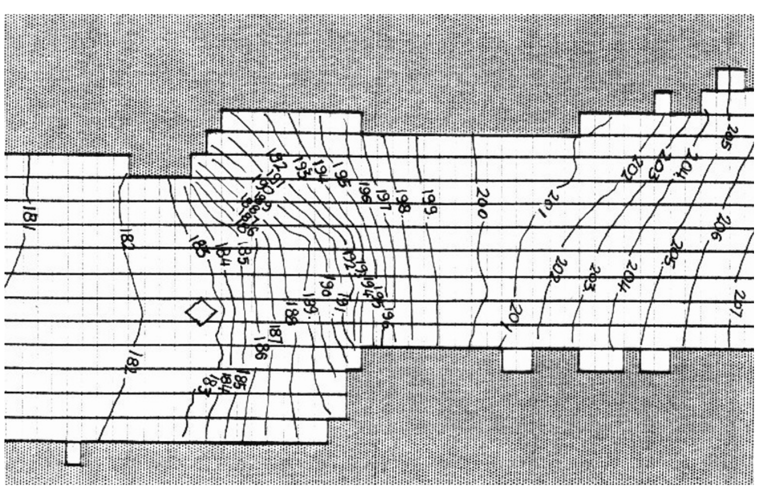


Fig. 6: The predicted water table contours (in m) at the end of Year 3

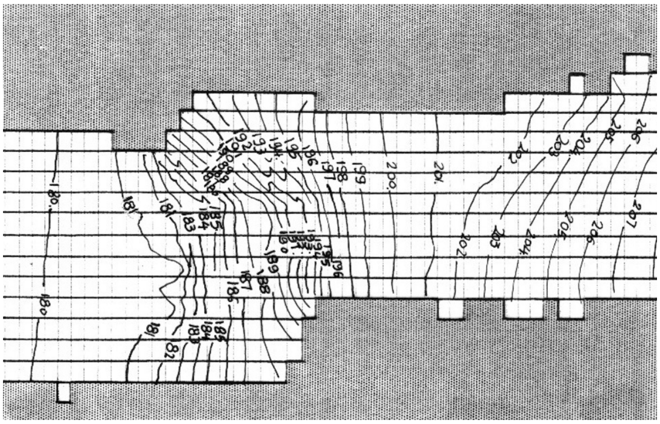


Fig. 7: The predicted water table contours (in m) at the end of Year 4

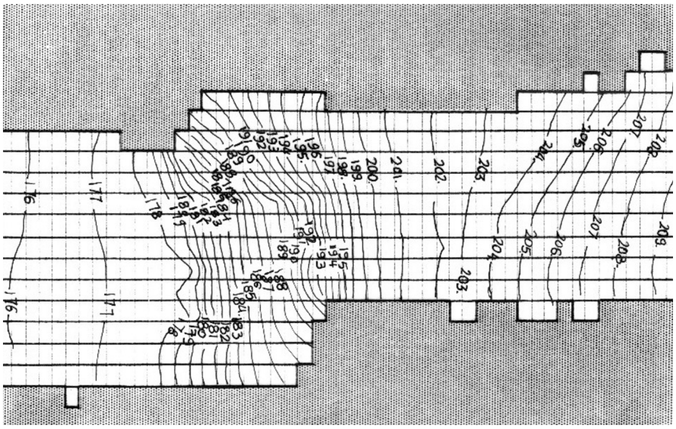


Fig. 8: The predicted water table contours (in m) at the end of Year 5

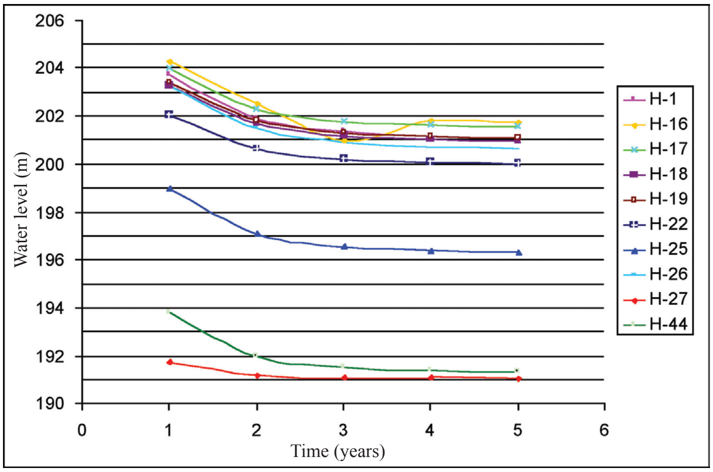


Fig. 9: The simulated water levels in different wells

CONCLUSIONS

The groundwater model MODFLOW was performed to predict the water table in alluvial aquifer located in the Kingdom of Saudi Arabia known as Hada Al Sham region. Based on the findings of the present study, the following conclusions can be drawn:

1. MODFLOW can successfully simulate the elevations of water table for an alluvial aquifer in the semi-arid region with reasonable accuracy.
2. Model calibration indicates that the predicted hydraulic conductivity of the aquifer is 0.60 m/day, which is not radically different from the observed one, i.e. given as 0.56 m/day.
3. The absolute errors between the observed and predicted water table elevations were found to be between 0 – 6 m.
4. Model simulation results for a period of 5 years confirm the low use to yield ratio for the studied aquifer (Hada Al Sham).
5. The simulated maps for 5 years water table counters confirm the abundant groundwater storage in the studied area and the possibility of digging more well without any serious impact on the storage. This can be attributed to the minor changes in the elevations of water table at the study area.

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