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Groundwater Modeling of an Aquifer in Sharqiyah Region, Sultanate of Oman

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Abstract: A proposed bottled water plant in Sharqiyah region, Sultanate of Oman will require extraction of groundwater at the rates of 100 m^3/d to 350 m^3/d in addition to the existing extraction rate of 565 m^3/d. In order to study the technical feasibility of this facility numerical models, namely; MODFLOW and MT3DMS have been implemented. The aquifer was conceptualized as a two-layer aquifer based on the available hydrogeological data. From the available information no source of saline ground water was found in the vicinity of the project site. Therefore, only MODFLOW was calibrated using available ground water level data. The calibrated hydraulic conductivity values were found to be in good agreement with the previous studies of similar nature in Sharqiyah region. After calibration, the model was run considering three pumping scenarios; (1) current pumping rate, (2) current pumping rate plus 100 m^3/d and (3) current pumping rate plus 350 m^3/d. Simulation was carried out for a period of twenty (20) years. Because of the wide extent of the aquifer, the effect of proposed increases in puming rate, on groundwater elevations, was small. The drop in groundwater elevations at the project site was found to be insignificant if the aquifer recharge and groundwater inflow remain unchanged.

Key words: MODFLOW · Groundwater Modeling

INTRODUCTION

The population growth in Sultanate of Oman has increased the demand for freshwater during the past decades. At Al-KamilWalWafi which is a part of Ash-Sharqiya Governorate, a new facility is to be built to supply bottled water to the nearby communities with a minimum daily groundwater extraction rate of 100 m^3/d (current pumping rate from the project site is 565 m^3/d). The peak requirement could reach 350 m^3/d. In order to study the technical feasibility of the groundwater extraction at the proposed pumping rates, the Groundwater Modeling System (GMS) can be used that includes MODFLOW in addition to MT3DMS module (Mass Transport Three-dimensional for Multi-Species) for groundwater transport processes. First, a conceptual model for the study area aquifer was developed based on available hydrogeological data. The next step was the calibration of the model with steady state flow simulation of the groundwater head distribution for the starting simulation year. Then the calibration was conducted for a selected period. After calibration, the model was used to predict water level fluctuations for a period of twenty (20) years. Similar procedures are followed to simulate saltwater intrusion using MT3DMS in order to predict the salinity movement in response to the pumping rates under different scenarios. MT3DMS uses the outcomes of MODFLOW runs as one of its inputs, so MODFLOW has to be run first.

Study Area: This study has been carried out in Al-KamilWalWafi which is one of the provinces of Sharqiyah region, North Eastern Oman. The project site is located about 60 km southwest of Sur which is the capital of Sharqiyah region (Fig.1). The study area is located in the foothills of Al Hajar mountain range and is adjacent to Wadi Baatha and close to Sharqiya (Wahiba) sands.

Topographically, the project site is a plain terrain with the elevation varying between 205 m and 209 m above mean sea level (amsl). This project site is a privately owned farm and has been used for agricultural purposes for several years. This site was previously leased by Ministry of Regional Municipalities and Water Resources (MRMWR), until five to six years ago, to supply water to

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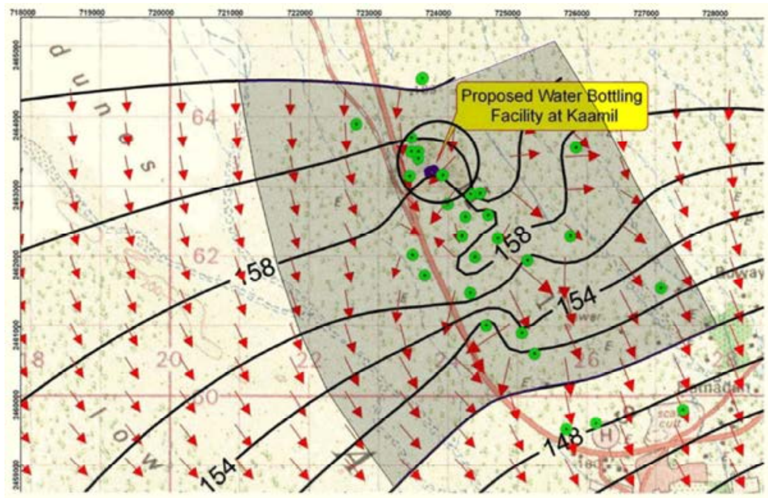

Fig. 1: Study Area Aquifer with polygon (shaded) showing the modeled area.

the region of Al-KamilWalWafi. Recently, the private concern established a RO plant at this site with a groundwater pumping rate of 20 m^3/day. The site and the surroundings are used for farming and the area is covered by dates, mango and Rhodes grass along with some seasonal plantings of short season annual vegetable crops like tomatoes. Currently, to meet the water requirement of agriculture activities, an approximate extraction rate of groundwater at the site is around 565 m^3/d (extraction time = 5 hrs/day).

Numerical Model: A groundwater flow model design consists of the following stages:

- Concept development, which is the most important part of the modeling and the basis for all further activities.
- Selection of a computer code that can most effectively simulate the concept and meet the purpose of modeling.
- Definition of the model geometry (lateral and vertical extent of the area to be modeled defined by model boundaries, grid layout and position and number of layers).
- Definition of boundary array, i.e, cell types (active, inactive, constant-head cells)
- Input of hydrogeologic parameters for each cell such as hydraulic conductivity (horizontal and vertical, including possible anisotropy), transmissivity, storage properties and porosity.
- Definition of boundary conditions (boundaries with known head, known flux, or head-dependent flux).
- Definition of initial conditions (distribution of hydraulic head).
- Definition of stresses acting upon the system such as aerial recharge, evapotranspiration, well pumping, outflow through springs, drains, inflow of water from other sources (recharge wells, adjacent aquifer).
- Model run, which includes choosing a mathematical method for solving the system of algebraic equations, iteration criterion and acceptable error criterion for terminating the iteration process.
- Calibration and sensitivity analysis. This is probably the lengthiest and most demanding part of any modeling process.
- Verification of model validity. The calibrated model is checked against another set of field data that was not used in model design.
- Prediction which is in most cases the purpose of model design.
- Presentation of results that includes both the prediction results and all relevant data documenting stages of model design.

Model Development: In the present study the Groundwater Modeling System (GMS) is used that includes MODFLOW and MT3DMS in addition to other models for groundwater transport processes.

MODFLOW is a computer program that numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method. Although MODFLOW was designed to be easily enhanced, the design was oriented toward additions to the ground-water flow equation. Frequently there is a need to solve additional equations; for example, transport equations and equations for estimating parameter values that produce the closest match between model-calculated heads and flows and measured values.

The governing equation of ground-water flow used in MODFLOW is [1]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the ground-water system and W>0.0 for flow in (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

Equation 1, when combined with boundary and initial conditions, describes transient three-dimensional ground-water flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions.

MT3D is a comprehensive three-dimensional numerical model for simulating solute transport in complex hydrogeologic settings. MT3D has a modular design that permits simulation of transport processes independently or jointly. MT3D is capable of modeling advection in complex steady-state and transient flow fields, anisotropic dispersion, first-order decay and production reactions and linear and nonlinear sorption. MT3DMS is the successor to the modular three-dimensional transport model referred to as MT3D, which was originally developed by [2] and documented for the Robert S. Kerr Environmental Research Laboratory of the U.S. Environmental Protection Agency. MT3DMS was developed by [3] for the U.S. Army Engineering Research and Development Center under the Strategic Environmental Research and Development Program (SERDP).

Like MT3D, MT3DMS simulates solute transport in three-dimensional ground-water systems using multiple solution techniques, including the finite-difference method and the method of characteristics (MOC). New features in MT3DMS include (1) a third-order total-variation-diminishing (TVD) scheme for solving the advection term that is mass conservative but does not introduce excessive numerical dispersion and artificial oscillation; an efficient iterative solver based on generalized conjugate gradient methods to remove stability constraints on the transport time step size; options for accommodating non-equilibrium sorption and dual-domain advection-diffusion mass transport; and a multi-component program structure that can accommodate add-on reaction packages for modeling general biological and geochemical reactions.

MT3DMS can be used to simulate changes in concentrations of miscible contaminants in groundwater considering advection, dispersion, diffusion and some basic chemical reactions, with various types of boundary conditions and external sources or sinks. The chemical reactions included in the model are equilibrium-controlled or rate-limited linear or non-linear sorption and first-order irreversible or reversible kinetic reactions. It should be noted that the basic chemical reaction package included in MT3DMS is intended for single-species systems. MT3DMS can accommodate very general spatial discretization schemes and transport boundary conditions, including: confined, unconfined or variably confined/unconfined aquifer layers; inclined model layers and variable cell thickness within the same layer; specified concentration or mass flux boundaries; and the solute transport effects of external hydraulic sources and sinks such as wells, drains, rivers, areal recharge and evapotranspiration.

Pollutants move in the soil and groundwater by three mechanisms; (1) convection (advection) transport- carried by water, (2) diffusion transport- due to concentration gradient and (3) hydrodynamic dispersion- due to non-uniformity of flow velocity.

Mathematical Formulation: The governing equation used in MT3DMS is [3]

$$R\frac{\partial C}{\partial t}=D_x\frac{\partial^2 C}{\partial x^2}+D_y\frac{\partial^2 C}{\partial y^2}+D_z\frac{\partial^2 C}{\partial z^2}-V\frac{\partial C}{\partial x}-\mu RC \tag{2}$$

where, C is concentration of the solute and D_x, D_y, D_z : Dispersion coefficients in x, y and z directions where:

$$D_x=\alpha_L V+D_d$$
$$D_y=\alpha_{TH} V+D_d$$
$$D_z=\alpha_{TV} V+D_d$$

α_L : Longitudinal dispersivity
α_{TH} : Horizontal transverse dispersivity
α_{TV} : Vertical transverse dispersivity
V : Average pore water velocity
D_R : Molecule diffusion
R : Retardation factor
μ : Decay coefficient

For saline water simulation by MT3D the decay constant is equal to zero, therefore, $\mu RC = 0$.

Conceptual Model of the Aquifer: First of all, a conceptual model for the aquifers in the study area is developed. The conceptual model is a three-dimensional representation of the groundwater flow and transport systems based on all available geologic and hydro-geologic data for the study area. A complete conceptual model includes geologic and topographic maps of the area, bore-logs depicting the physical and chemical parameters associated with the aquifers and the salinity data.

The next step is model construction that is primarily the conversion of the conceptual model into the input files for the numerical model then running the model under steady state to demonstrate that the model can predict the aquifer flow properties. After that the calibration is done in order to demonstrate that the model is capable of producing field measured heads and flows, which are used as calibration values or targets. After the calibration the model can be used for future prediction of groundwater elevations in the study area.

The salient features of the conceptual model of the study area aquifer are as follows:

- The aquifer is considered to be consisting of two layers. The upper layer (Layer 1), which comprises of Aeolianite, is estimated to be 100m thick and the second layer, gravel alluvium (Layer 2) is estimated to be 160m to 600m thick [4]. The base of the aquifer is defined as the bedrock which is classified as Tertiary Fars.
- The aquifer area is approximately 1600km^2 [4]. However, a small part of this aquifer is modeled in the present study.
- The eastern and western boundaries of the aquifer are assumed to be no-flow boundaries. The northern boundary is considered to be constant head boundary and the hydraulic head is estimated to be 162m above mean sea level (amsl) and the salt content is considered to be constant at 500ppm.
- The southern boundary is also a constant head boundary at 150m amsl and the concentration is considered to be 500 ppm as well.
- The direct rainfall recharges are considered to be very small. The recharge through rainfall is only about 3% of the annual rainfall whereas total annual rainfall is less than 50mm) [4].
- The major groundwater abstraction is by well field close to the northern boundary of the model area. The pumping well for the new facility is obtained from the requirements of the client.
- A subsurface recharge is found to exist as described in the previous studies [4]. The value of this recharge has to be found from model calibration.

The conceptual model was implemented in GMS to be used for MODFLOW and MT3DMS using Map module. The model consists of the following coverages under steady flow condition:

- Model boundary
- Sources and sinks (abstraction wells and, upstream and downstream boundary conditions)
- Recharge (due to rainfall and bed rock)
- Layer 1 (hydraulic properties of top layer)
- Layer 2 (hydraulic properties of second layer)
- Observation wells

Model Grid: In order to run MODFLOW a 3D grid was generated. The number of cells in x, y and z directions were 129, 114 and 2, respectively. In other words, it is a two-layer model grid simulating the actual situation in the field. The total number of active cells in the grid was 19450. The lengths of the model domain in x and y directions were 6200m and 7000m, respectively. The model grid is shown in Figure 2. The ground elevations are shown in meters above mean sea level. In order to ensure no groundwater flow takes place from the eastern and western boundaries, the grid was aligned with the groundwater flow direction that can be found from the water table contours.

Input Data: The elevations of ground and bottom of layer 1 and layer 2 were interpolated to the model grid. The ground elevations were available from the topographic maps. The bottom elevations of layer 1 and layer 2 were assigned based on the information given in the previous studies [4, 5]. The thicknesses of layer 1 and layer 2 were considered to be 100m and 150m, respectively. Moreover, the recharge was considered to be 2.4×10^{-6} m/d. Available pumping data was used and minor adjustment had to be done in pumping rates during calibration. After calibration, the horizontal hydraulic conductivity for layer 1 and layer 2 were obtained as 3.5m/d and 16.5m/d, respectively, whereas vertical anisotropy of 4 was used in both the layers. These values agree well with the findings in the previous studies [5].

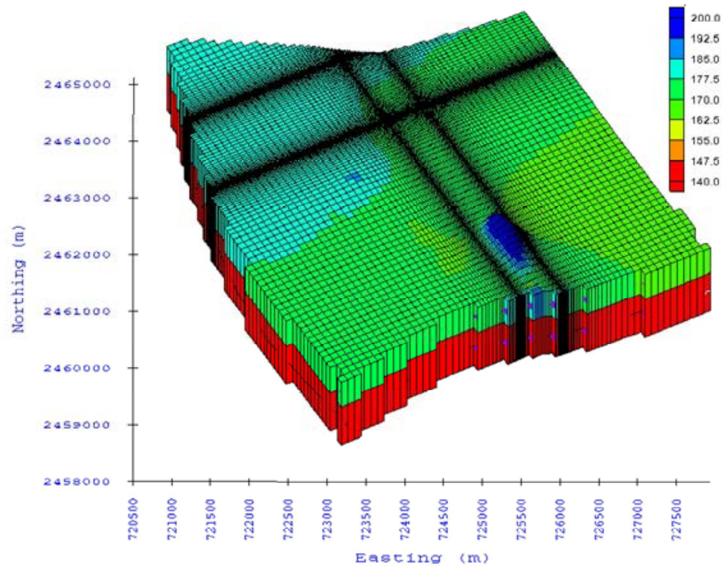

Fig. 2: MODFLOW grid with ground elevations in meters above MSL.

Table 1: Pumping well data.

Well ID	Easting (m)	Northing (m)	Pumping rate (m^3/d)
Local-Well	723764	2463187	-565
245/818	725011	2460365	-268
242/892	726241	2460812	-268
242/891	726484	2460744	-268
245/811	726443	2461906	-268
242/893	726581	2461075	-268
243/025	726746	2460533	-268
243/148	722898	2463344	-328
243/147	722835	2462981	-328
245/801	725721	2460952	-328
243/151	723078	2463048	-328
245/844	725642	2461336	-328
245/802	725749	2461095	-328
245/812	725904	2461927	-328
243/145	723147	2462630	-328
242/882	726133	2460318	-346
245/807	726098	2461640	-397
245/800	726139	2460980	-397
243/144	723450	2462844	-467
242/888	726337	2460650	-467
245/814	726022	2462044	-467
243/143	723589	2462073	-536
245/806	726245	2461277	-536
245/841	725765	2460456	-536
243/149	722788	2463777	-1123

Table 2: Observation well data

Well ID	Easting (m)	Northing (m)	GW El. (m) amsl
NE-12	723501	2462025	154.75
OBW-04	723996	2462724	155.12
OBW-01	724314	2462849	155.42

Boundary Conditions: First of all steady flow computation had to be done to calibrate the model using observed groundwater elevations. For this prevailing condition, northern and southern boundaries were considered to be constant head boundaries. The values of groundwater elevations available from the measured data were used at these boundaries. The eastern and western boundaries were considered to be no flow boundaries as stated above.

For future prediction transient simulation was carried out using three scenarios. The transient boundary conditions were used for these simulations. In order to simulate the fall of groundwater elevations at the boundaries, a constant rate of fall of 0.2m/year was assigned to the northern and southern boundaries. This rate of fall was based on the measurements reported in previous studies [5].

Pumping Wells Data: There are a number of pumping wells in the model domain. The pumping well locations and pumping rates used in the model are shown in Table 1. The minus sign with the pumping rate shows that groundwater abstraction is taking place. The pumping well existing on the project site is named as Local Well.

Model Calibration: The model was calibrated under prevailing conditions using the observed groundwater elevations at three monitoring wells. Salient features of these wells are given in Table 2.

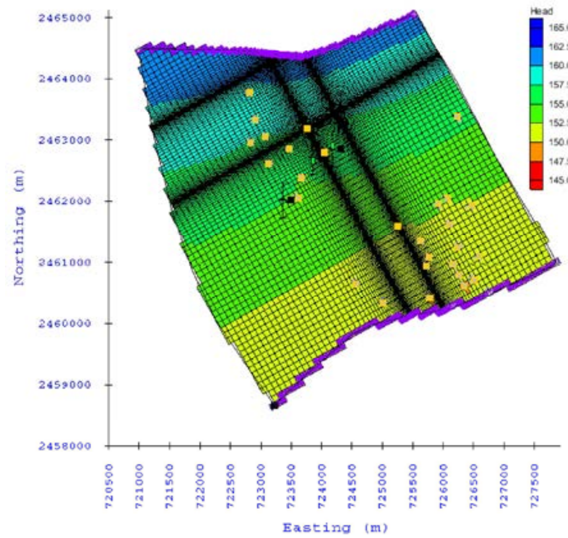

Fig. 3: Calibration of the aquifer parameters using the prevailing conditions, (Q = 565m^3/d).

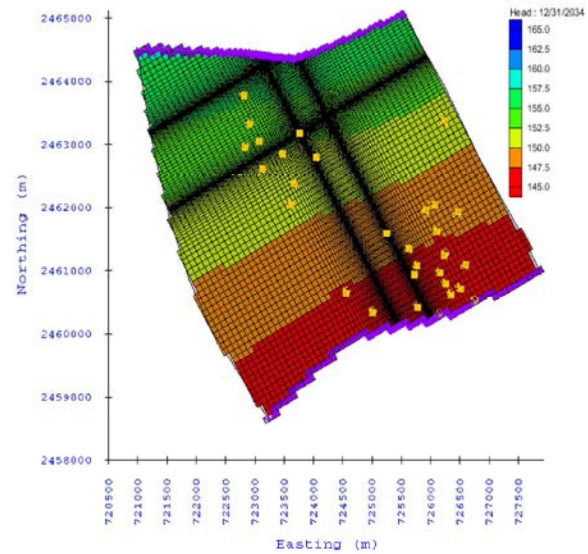

Fig. 5: Groundwater elevations after 20 years of pumping for Scenario 2 (Q = 665m^3/d).

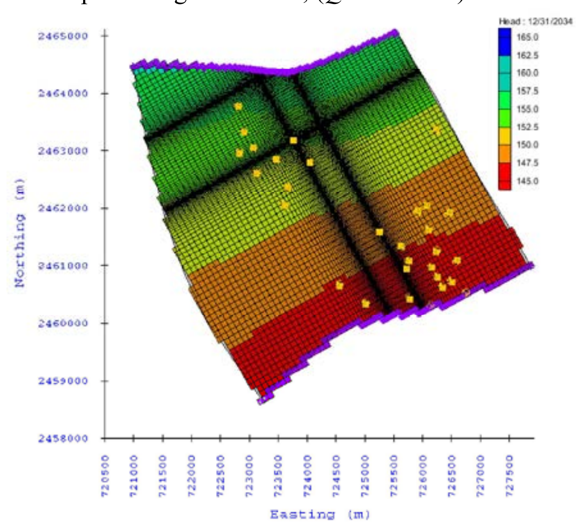

Fig. 4: Groundwater elevations after 20 years of pumping for Scenario 1 (Q = 565m^3/d)

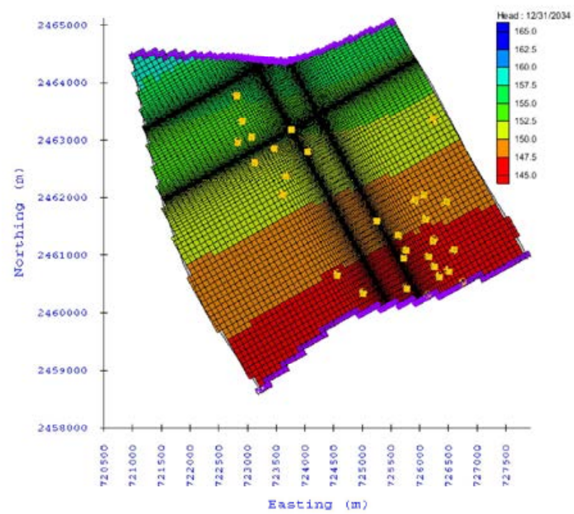

Fig. 6: Groundwater elevations after 20 years of pumping for Scenario 3 (Q = 915m^3/d).

These wells are shown in Figure 3. The dark green color bar with each of these wells shows that the difference between the computed and observed groundwater elevations is less than 0.5m. In other words, the calibration target has been achieved.

Model Prediction: In order to observe the effect of increased demand of pumping on the groundwater elevations, three scenarios were considered as follows:

Scenario 1: The existing pumping rate (Q = 565m^3/d) from the Local Well was used for a period of 20 years. The pumping rates for other wells in the model domain were kept constant for this period.

Scenario 2: The pumping rate from the Local Well was increased by 100 m^3/d (Total puming rate, Q = 665m^3/d) for a simulation period of 20 years. The pumping rates for other wells in the model domain were kept constant as in Scenario 1.

Scenario 3: The pumping rate from the Local Well was increased by 350 m^3/d (Total puming rate, Q = 915m^3/d) for a simulation period of 20

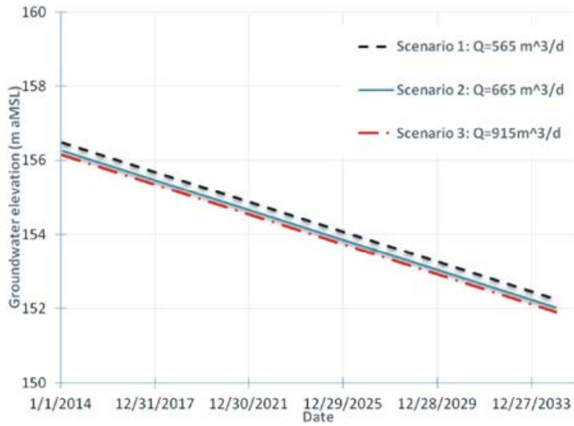

Fig. 7: Comparison between the three scenarios for groundwater elevation change over a period of 20 years from January 2014.

years. The pumping rates for other wells in the model domain were kept constant as in Scenario 1.

The groundwater elevations after 20 years of pumping as per Scenario 1, Scenaro 2 and Scenario 3 are shown in Figure 4, Figure 5 and Figure 6, respectively.

Considering the wide extent of the aquifer, effect of the increase in puming rate of Local Well is found to be rather small. No significant drop in the groundwater elevations at the project site is evident from these figures even for Scenario 3 (Q = 915 m^3/d).

In order to compare the three scenarios the groundwater elevation at the location of Local Well (project site) is shown over a period of 20 years from January 1, 2014 (Figure 7). The decrease in groundwater elevations in three scenarios is due to the fall of groundwater elevations at the model boundaries at a constant rate of 0.2m/year.

A source of saline water is not found to be in the vicinity of the modeled area, therefore, the salinity remains the same as the input value at the boundaries. The previous studies have not shown any concern about the saline water intrusion into this aquifer [5].

CONCLUSIONS

As a result of the present groundwater modeling study the following can be concluded:

- MODFLOW can be utilized for future prediction of the groundwater elevations in the present study area since the model has been calibrated using the existing measured data.
- The future prediction of groundwater elevations by the calibrated model show minimal effect of the increased pumping rates at the project site. It can be inferred that an increase of 350 m^3/d in the pumping rate can be sustained at least for 20 years if no drastic change occurs in the groundwater recharge and inflow patterns of the aquifer.
- The salinity intrusion, as a result of the increased pumping rates, at the project site is not a concern, as reported by the previous research in this region.

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