DESIGN OF DEWATERING SCHEMES USING ANALYTICAL AND NUMERICAL METHODS AT RESIDENTIAL AREAS IN KUWAIT

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ABSTRACT

The water table of the shallow aquifers at many residential areas (e.g., Jaber Al-Ahmad and Al-Qirawan) in Kuwait is close to the ground surface, which has forced a lot of individuals and companies to conduct unplanned dewatering activities. The elevated water table and insensitive dewatering schemes can have negative impacts on the existing buildings and the infrastructure services such as collapse or fracturing. The aim of this paper was to develop an integrated management approach that solves the problem of high water levels through dewatering schemes that deal with environmental consequences and reduce the demand on brackish groundwater well fields by treating the drained water using a new desalination technology consisting of small Reverse Osmosis (RO) units. In this paper, a dewatering system was designed, using field pumping tests, analytical models (Tartakovsky-Neuman and Theis) and a numerical model (the USGS software package, Visual MODFLOW). This paper illustrates that the water table can be reduced to a maximum of four m without causing problems of formation stability and without raising the groundwater salinity above 10,000 mg/l. Based on the results of this study, the Ministry of Electricity and Water (MEW) is planning to use the existing brackish water networks situated in these residential areas to supply it to the main roads and public parks for irrigation, and to implement similar designs of these dewatering schemes and RO units in other residential areas. This paper does not address the RO design and technology used in this project.

Keywords: Dewatering, groundwater flow, numerical modeling, RO technology, Kuwait

1. INTRODUCTION

For many years, rise in the level of water table in residential and commercial areas in Kuwait has been a serious problem causing road instability, subsiding issues and moisture-related problems for building foundations, flooding of basements, over loading of sewer systems, increase of salinity of shallow groundwater, flash floods caused by water logging of soil, and other public health problems.

If the water table is too high, then the hydrostatic pressure against basement walls will be high as well. To remove and prevent this water from entering the basement and/or foundation areas, dewatering schemes are always suggested. It was estimated in Kuwait that a permanent abstraction by vertical wells (at 30 – 50 m total drilling depth) would be required to keep the water table at a
desired level below the foundations in residential areas of Kuwait (Mossaad and Sayed[4] and El-Nahhas et al.[3]).

A balance is needed because both elevated water table levels and the unplanned water table lowering are harmful for building foundations and infrastructure stability. The project areas chosen are Jaber Al-Ahmad and Al-Qirawan (Fig. 1) because the groundwater levels were measured to be close to the ground surface reaching the root zone of some plants(Fig. 2).

The abrupt lowering of the level of the water table is normally a result of the inaccurate design of the dewatering scheme in terms of excessive pumping rates and large drawdown caused by closer distances between dewatering wells. In this study, a dewatering scheme was designed based on the field pumping tests, which helped determine hydraulic properties of the aquifer to be dewatered, optimal pumping rates, number of dewatering wells, maximum drawdown and the distances between the dewatering wells. The Visual MODFLOW software package [7] was used to develop a dewatering numerical model for the study area to confirm that the design limits are not violated.

The method of dewatering that was used in this project is based on vertical dewatering wells. This is a suitable method because vertical wells can be installed relatively quickly and they are very effective in stratified formations such as the Kuwait Group. However, other methods such as well points should be tested because of the limited drawdown that they cause, which might also be suitable for Kuwait’s situation. This project aimed to establish a pilot model to prevent groundwater levels from keep rising on the long run by means of drainage in the residential areas of Jaber Al-Ahmed and Al-Qirawan, and treating the drained water using reverse osmosis (RO) technology for reuse in irrigation and other non-human consumption purposes. The quality of the drainage effluent prohibits direct use for human consumption, livestock consumption and even for irrigation (Al-Wazzan et al. [2]).
Based on the expected quality of the treated water and the robustness of the design and operation of the dewatering scheme in the study area, the Ministry of Electricity and Water (MEW) will plan to implement this pilot project in other residential areas, especially those that lack brackish water networks.

Disposing of the drained water as waste, however, constitutes a great loss that the country cannot afford. Therefore, as a resource, it should be treated and properly utilized. RO Desalination Units are being installed at two well sites in the study area. The use of recovered water for irrigation purposes through brackish water networks is the most viable option. The specific objectives of this paper are given as follows:

- To design a dewatering scheme at the study area using field pumping tests and Tartakovsky-Neuman [5] analytical model so that the decline of groundwater levels does not exceed 4 m and the total dissolved solids (TDS) of the pumped water remains less than 10,000 mg/l.
- To use the numerical model, Visual MODFLOW (McDonald, G., and A. Harbaugh, 1988 [7]) in order to check that the design limits of the dewatering scheme are not violated under different operational scenarios.

During the implementation of this project, the safe disposal of the pumped water (i.e., not treated by RO Units) was provided to avoid negative impacts on the environment.

2. METHODOLOGY

The methodology used to design the dewatering schemes at the study area is based on using pumping tests in the field, analytical models (such as Tartakovsky-Neuman [5] and Theis [6] to analyze the pumping tests data) and numerical models (such as Visual MODFLOW [7]) to validate design limits.
The Tartakovsky-Neuman Method [5] is an analytical method that is suitable for analyzing pumping data for unsteady flow to a fully or partially penetrating well in a homogeneous, anisotropic, unconfined aquifer with a delayed gravity response. The Tartakovsky-Neuman solution [5] does not allow for instantaneous drainage at the water table. The solution neglects wellbore storage and can be used to analyze both the pumping and recovery data from constant or variable rate pumping tests. Tartakovsky and Neuman [5] developed a Laplace Transform solution for the unsteady flow to a partially penetrating well in an unconfined aquifer with three-dimensional flow in the saturated and unsaturated zones as follows:

\[
s = \frac{Q_t}{2\pi\rho_D} \int_0^\infty \frac{\eta \sinh(\eta)}{\cosh(\eta)\gamma - \eta \sinh(\eta)} e^{\gamma(Z_D - 1)} \frac{\sinh[\eta(1-l_D)] - \sinh[\eta(1-d_D)]}{\eta^2(l_D - d_D)\sinh(\eta)} y J_0(y\sqrt{\beta}) \, dy
\]  

(1)

Where:

- \( s \) is drawdown in [L]
- \( b \) is aquifer thickness [L]
- \( d_D \) is dimensionless depth to top of pumping well screen \((d/b)\)
- \( J_0 \) is Bessel function of first kind, zero order
- \( K_r \) is radial hydraulic conductivity [L/T]
- \( K_z \) is vertical hydraulic conductivity [L/T]
- \( K_D \) is dimensionless Gardner parameter for the unsaturated zone
- \( l_D \) is dimensionless depth to bottom of pumping well screen \((l/b)\)
- \( \rho \) is Laplace transform variable \([T^{-1}]\)
- \( Q \) is pumping rate \([L^3/T]\)
- \( r \) is radial distance [L]
- \( S \) is storativity [dimensionless]
- \( S_y \) is specific yield [dimensionless]
- \( t \) is time [T]
- \( T \) is transmissivity \([L^2/T]\)
- \( y \) is variable of integration
- \( Z_D \) is dimensionless elevation of piezometer opening above base of aquifer \((z/b)\)

And the parameters are related as follows:

\[
\beta = \frac{r^2 K_z}{b^2 K_r}
\]

\[
\mu^2 = y^2 + \frac{\rho_D}{t_s \beta}
\]

\[
v^2 = y^2 + \frac{\rho_D}{t_s \varphi \beta}
\]

\[
\varphi = \frac{S}{K_D S_y}
\]

\[
\gamma = \frac{K_D}{2} - \sqrt{(K_D^2)/4 + v^2}
\]
\[
t_S = \frac{Tt}{S_T^2}
\]
\[
\rho_0 = t_p
\]
\[
S_B = \frac{4\pi T}{Q} - S
\]


\[
S_y \frac{\partial h}{\partial t} = \nabla \cdot (k \nabla h) + q \quad (2)
\]

Where:

- \( q \) is the source and/or sink term; it stands for abstraction from dewatering wells plus the leakage from water and sewerage pipes in addition to irrigation returns, recharge from rainfall and marine discharge flux to the Arabian Gulf.
- \( h \) is the hydraulic head [L].

Other terms are defined above.

The Visual MODFLOW solves equation 2 using a set of initial and boundary conditions including the physical geometry of the aquifer, in the finite difference approximations. The data needed to solve this equation are basically: the inputs and outputs (\( q \)) to the aquifer; the physical geometry of the aquifer; the boundary conditions; the spatial head distribution (\( \nabla h \)); the temporal head distribution (\( \frac{\partial h}{\partial t} \));

The hydraulic conductivity coefficients, \( k \); the storage coefficients (\( S_s \) and \( S_y \)) and the initial conditions. A dewatering model for the study area was developed and calibrated using the Visual MODFLOW software package as described in the next section.

3. RESULTS AND DISCUSSION

3.1 Analytical Model

Figure 3 shows the locations of dewatering wells and their associated observation wells at Jaber Al-Ahmad area. At each site, there are two dewatering wells and two observation wells (one observation is located at 11 m deep and the second at 21 m deep). A program of pumping tests was undertaken at all the wells of Jaber Al-Ahmad dewatering sites as follows: Pumping the two dewatering wells (DW-1 and DW-2) for a period up to 6 days on a continuous basis at one dewatering site (JB-A) while one pumping well was operated on other dewatering sites. The decline of the water level during the pumping tests was observed in the two monitoring wells (deep and shallow) at each site. This was then followed by three to six days of recovery tests. Only the results of site JB-A are represented and discussed in this paper. Table 1 represents the results of the pumping tests for other sites. The analysis of a six-day constant pumping rate test followed by a recovery test as shown in Fig. 4 at JB-A shows that \( T = 488 \text{ m}^2/\text{day} \), \( S = 1.6 \times 10^{-4} \), \( S_y = 0.01 \), \( K_r/K_z = 70 \), \( K_r = 31 \text{ m/d} = 3.59 \times 10^{-4} \text{ m/s} \) and \( K_z = 0.443 \text{ m/d} = 5.13 \times 10^{-6} \text{ m/s} \).
Table 1: Summary of results of pumping tests and analysis at all sites at Jaber Al-Ahmad

<table>
<thead>
<tr>
<th>Location</th>
<th>$T^{(1)}$ (m$^2$/d)</th>
<th>LS$^{(2)}$ (m)</th>
<th>SWL$^{(3)}$ (m bgl)</th>
<th>$K^{(4)}$ (m/d)</th>
<th>$K \times 10^4$ (m/s)</th>
<th>$s^{(5)}$ (m)</th>
<th>$R_0^{(6)}$</th>
<th>$Sx10^4$</th>
<th>$Sy^{(7)}$ (%)</th>
<th>$Kr/Kz^{(8)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JB-A</td>
<td>488</td>
<td>15.75</td>
<td>6.34</td>
<td>31</td>
<td>3.6</td>
<td>1.14</td>
<td>65</td>
<td>1.6</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>JB-B</td>
<td>534</td>
<td>15.75</td>
<td>6.09</td>
<td>34</td>
<td>3.9</td>
<td>1.01</td>
<td>60</td>
<td>2.0</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>JB-C</td>
<td>265</td>
<td>15.75</td>
<td>7.30</td>
<td>17</td>
<td>2.0</td>
<td>1.16</td>
<td>50</td>
<td>3.4</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td>JB-D</td>
<td>225</td>
<td>15.75</td>
<td>9.04</td>
<td>14</td>
<td>1.7</td>
<td>1.01</td>
<td>40</td>
<td>0.43</td>
<td>1.5</td>
<td>95</td>
</tr>
<tr>
<td>JB-E</td>
<td>263</td>
<td>15.75</td>
<td>11.38</td>
<td>17</td>
<td>1.9</td>
<td>1.6</td>
<td>66</td>
<td>1.6</td>
<td>2.6</td>
<td>40</td>
</tr>
<tr>
<td>JB-W</td>
<td>No pump installed yet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Transmissivity (m$^2$/d)
(2) LS: Length of Screen (m)
(3) SWL: Static Water Level (m below ground level, m bgl)
(4) Hydraulic conductivity (m/d)
(5) Drawdown (m)
(6) $R_0$: radius of influence (m)
(7) $Sy$: specific yield
(8) $Kr/Kz$: Anisotropy ration

Figure 4 shows the effect of delay yield of unconfined aquifers, although the specific yield value is low at 1% and the general storage coefficient is 1.6x10$^{-4}$, which indicates that although the utilized aquifer is unconfined, but the presence of clay and silt as shown in Fig. 5 has semi-confining effects. The transmissivity values of the utilized (Kuwait Group) aquifer at Jaber Al-Ahmad shows that the Kuwait Group Aquifer is significant in terms of quantity potential and it can be utilized on the national Kuwaiti level. This is confirmed by relatively low drawdown values and high specific capacity values. It is also shown that the average anisotropy ratio is just above 70, which shows that the aquifer is strongly anisotropic. Fig. 6 illustrates the status of water levels under static and dynamic conditions for JB-A wells. It is clear that water will move upwards under static conditions (the lower sections/aquifers have larger hydraulic heads than the upper ones) and downwards under dynamic...
(pumping) conditions. Since, the results of pumping tests at Jaber Al-Ahmad will be used to design the dewatering scheme at Al-Qirawan, Table 1 above shows that SWL at any location is deeper than 4 m and therefore it is needed to design the system at Al Qirawan with only one dewatering well at each dewatering site. This fact was also confirmed by the numerical dewatering model.

In summary the dewatering scheme can be designed analytically by following these parameters:

- Distance between any two dewatering sites ≥ 500 m
- Distance between any two pumping wells at the same site ≤ 66 m
- Distance between the dewatering well and its observation well ≤ 50 m
- Pumping rate of any dewatering well should be between 1,000 and 1,500 m³/day.
- The radius of influence ≤ 66 m
- The steady state drawdown ≤ 1.6 m which is less than four m (the maximum limit)
- The pump of any dewatering site should be used with the specifications of Q= 42 m³/hr, Total Dynamic Head (TDH) = 30 m and efficiency of pump ≥ 70%

Fig. 4 Analysis of pumping and recovery data using Tartakovsky-Neuman method for JB-A

3.2 Numerical Model

The numerical model was used to demonstrate that applying the above design elements does not violate the condition of a maximum drawdown of 4 m. The boundaries of the Jaber Al-Ahmad&Al-Qirawan Areas model are presented in Fig. 7. The dewatering wells are located in the upper first 30 m of the Kuwait Group Aquifer. Fig. 8 is a geological cross section in the study area.
Fig. 5. Well log at site JB-A
The southern boundary was simulated as specified flux by assuming recharge wells at this boundary as shown in Fig. 9. The numerical techniques require a grid to be imposed upon the model domain. Finite difference grids are generally composed (Fig. 9) of smaller cells in the proximity of the dewatering wells, where the water levels are expected to decline quickly. The next step is calibration, which is the process by which the model is systematically turned to represent the true aquifer conditions. Table 2 represents the water level data used for steady state calibration. It should be noted that the data from Jaber Al-Ahmad dewatering wells (in particular, the Static Water Levels, SWL) were used to calibrate the model under static conditions and data from the pumping tests were used to calibrate the model under dynamic conditions. The numerical model will be recalibrated when the construction of the wells at Al-Qirawn area will be completed and pump-tested.
Fig. 7. Boundary conditions of JBQ flow model

Fig. 8. Geological cross section in the study area (Fadlelmawla, A.; F. Al-Yamani; A. Mukhopadhyay; K. Rakha; M. AlSenafy; and H. Bhandary [8])
The steady state calibration matching results are presented in Fig. 10 which show that the match between observed and simulated water levels is good, as they are within 95% confidence interval. The calibration results using pumping tests data are presented in Fig. 11. The match captures the trend and is considered to be good. The calibrated model was then run to detect that drawdown at any location and it is shown that the maximum drawdown was about 1.5 m which means it does not exceed 4 m. The design of the dewatering scheme at Jaber Al-Ahmad with acceptable quality (Al-Odwani et al.[1]) requires that the TDS does not exceed 10,000 mg/l. A massive water sampling campaign was carried out during pumping tests and all field analysis confirmed that (Fig. 12) the maximum value of Electrical Conductivity (EC) under dynamic conditions is 12,500 uS/cm which is about 8000 mg/l which is less than the limit of 10,000 mg/l. The distribution of water levels after four days of pumping is presented in Fig. 13.
Fig. 10. Steady state calibration using JB wells

Fig. 11. Transient calibration using the pumping and recovery data at well JB-D
Fig. 12. EC versus drawdown at monitoring well JB-E1-LMW under dynamic conditions

Fig. 13. Distribution of groundwater heads after four days
4. CONCLUSIONS

This paper shows that the dewatering scheme by vertical wells to a total depth at 30 m is efficient and can be designed using both analytical and numerical models in order to solve the problem of continuous water rising in residential areas in Kuwait.

The analysis of the pumping tests show that the Kuwait Group Aquifer at Jaber Al-Ahmad study area has moderate to significant transmissive properties and the values of storativity can be attributed to unconfined aquifers with clear effect of confining materials of clay and silt.

Also, the analysis of the pumping tests shows that the Kuwait Group aquifer at the project area has considerable anisotropic properties and weak heterogeneous properties.

This paper shows that the quality of the drained water under pumping conditions is below the upper limit of 10,000 mg/l and thus it can be treated by the RO Desalination Units.

The paper also concluded that the reuse of a blended RO treated water (TDS< 10,000 mg/l) for irrigation purposes through brackish water networks is the most viable option.

The dewatering numerical model using visual MODFLOW was developed and calibrated under static and transient conditions. The calibrated model was used to simulate the drawdown at Jaber Al-Ahmad and it’s been shown the results of the analytical model match the results of the numerical model. However, the numerical model will be recalibrated when the rest of the dewatering wells and their observation wells are constructed and tested.

The proper design of the dewatering scheme at the residential area in Kuwait requires the distance between any two dewatering sites to be about 500 m; distance between the dewatering well and its observation well is less than 50 m; the pumping rate of any dewatering well between 1,000 and 1,500 m³/day in order to achieve drawdown at equilibrium less than 4 m; and finally the pump of any dewatering site should be used with the specifications of pumping rate around 40 m³/hr and a total dynamic head about 30 m with a pump efficiency about 70%.

ACKNOWLEDGEMENTS

The authors would like to extend their appreciation to the Ministry of Electricity and Water (MEW) of the State of Kuwait for funding this project. The active involvement of the Groundwater Resource Development and Management Department of MEW is highly appreciated. The unlimited support of KISR’s management was pivotal in carrying out the various tasks of the project. The constant encouragement and support by the efficient management of the Water Research Center of KISR is highly appreciated as they kept the morale of the project team always at a high level.
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