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Mathematical Model for Water Management of Confined Aquifer in South-western Part of the Baq'a Quadrangle (Hail Province), Saudi Arabia

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Abstract: In Saudi Arabia, groundwater resources are not only limited but also non-renewable. As such, the available water resources need intelligent planning for efficient conservation and management to avoid unwarranted losses. The main objective of this study is to present a simple mathematical model for the management of water wells in an aquifer. The required conditions included the interaction of cone of depression between adjacent wells under a critical and specific of water level and the safe velocity of groundwater which depends mainly on the hydraulic conductivity for flow of water in wells. The variables studied for the confined aquifer were maximum permissible flow rate, velocity and water level. Mean Maximum Permissible Flow Velocity (MMPFV) for different locations came to 5.06, 4.65, 3.48, 4.70, 4.56, 3.92, 5.23, 4.38 and 5.06 m day^{-1} for J, H, G, F, E, D, C, B and A fields, respectively. Mean value of permeability (T, M^2/tor) was 1862.5 and 3475.9 for wells located in G5 and G7, respectively . Mean hydraulic conductivity (K, m day^{-1}) was 5.39 and 4.05 for wells in G5 and G7 locations, respectively. Local variables (maximum permissible flow rate, actual flow rate, residual flow rate) presented in the form of contour maps were used to identify areas with poor management and suggested appropriate preventive measures. In conclusion, implementation of simple administrative water management model was proposed based on the actual field data from Saq sand aquifer in the south-western part of the Baq'a quadrangle in Hail province, Kingdom of Saudi Arabia.

Key words: Cone of depression, groundwater, groundwater management, maximum allowable flow rate, safe velocity, drawdown, Saq aquifer

INTRODUCTION

Groundwater management involves water extraction, its quality for irrigation and the optimal use for the welfare of agrarian community. Such considerations are confined not only to geological and hydrological but also to social aspects. In general, efficient water management includes cost effective groundwater pumping while maintaining the quantity and quality of water for agriculture and drinking. It is an admitted fact that periodic measurement of water level in irrigation wells is important in a particular area or district to determine the quantity of total water extraction and the aquifer flow capacity. This type of information is helpful for determining groundwater depletion, operational cost involved, pumping schedule, design of irrigation system and water management programs for optimizing the use of underground water aquifer and develop water use program for an aquifer. The water sedimentary basin is defined as a natural underground reservoir. However, pumping water from a sedimentary basin at certain sites may affect the quantity of water available to other sites within the basin if good governance and efficient water management program are not followed.

Many people believe that water well should be continuous and permanent productive without interruption. But if water pumping is not properly scheduled and managed it may lead to partially or complete depletion of the aquifer (Powers *et al.*, 1966; Al-Somayien, 1989). The necessary measurements include well discharge, groundwater level (static and dynamic) and frequency of pumping water. In the absence of balance between water availability and the consumption, more water is expected to be pumped from the aquifer which needs monitoring of the unwanted wells. In fact, the water withdrawal at the beginning of any agricultural project begins with a small number of productive wells. But with the passage of time, new wells are drilled to meet the growing demand of water for agriculture expansion, provision of drinking water to houses, industrial uses and landscape development. Therefore, new rules and regulations have to be formulated for drilling new wells to avoid unnecessary depletion of aquifer. Also, the water extraction should not exceed the recharge phenomenon. Because excess pumping of water may lead to aquifer depletion resulting in dryness of the aquifer (Al-Somayien, 1989). It is also important to determine a balance between the water consumption and the rate of groundwater pumping in an arid country like Saudi Arabia (Al-Sagabi, 1978). This could be attributed to un-necessary use of groundwater by pumping from wells installed illegally in the agricultural areas of the Kingdom. It is very difficult to use mathematical models of groundwater management under wetland conditions and directly in dry areas. Therefore, safety and security of an aquifer is very important for sustainability of an arid region of a country. It demands to develop an applicable groundwater management program in an arid zone with little recharge due to arid climate and low rainfall.

Fischer *et al.* (2011) observed that groundwater levels in the capital Hanoi decreased dramatically. In order to manage, they described the "state of the art" and the development of sustainable solutions to maintain and increase the declined groundwater levels in Hanoi. Kenabatho and Montshiwa (2006) stated that water is an essential resource affecting many aspects of development and the natural environment. They concluded that with the current fragmented, uncoordinated institutional and legal arrangements in water resources management, there is an urgent need to adopt integrated water demand management as envisaged in the overall concept of Integrated Water Resources Management (IWRM). Segosebe and Parida (2006) stated that water is one of the most important elements essential not only to attain food and health security, but also for the economic development of a country. They examined the various strategies in a semi-arid country like Botswana to manage the growing demand for water. These strategies encompass the use of tariffs, water reuse/recycling and water restrictions. Other attempts encourage water conservation through rainwater harvesting and implementation of technological innovations with exploration of non-conventional sources. Khadim *et al.* (2013) developed a mathematical formula to assess the rate of tidal sedimentation due to Tidal River Management (TRM) in parts of Khulna and Jessore districts. The study found the evidences of considerable advancements in regional livelihood i.e., flood resistance, cultivated lands, cultivable area, cropping intensities and food security due to Integrated Water Resources Management (IWRM) approaches.

In order to regulate proper groundwater management, some initial and essential steps such as preliminary survey and geological field surveys are required in the study area. The changes in the groundwater level can be attributed either to the local aquifer flow itself or directly through the influence of pumping wells in the area. The configuration of sandstone aquifer in the North-Center are tangent to the rocks of Arabian shield of Saudi Arabia. Also, the support program defines the maximum permissible allowance as the amount of water that can be pumped from a well without affecting the aquifer and the well conditions. Therefore, water pumpage must be limited to the quantity of flow rate which should be less than or equal to the ideal flow. The current problem in the study area (Hail Agriculture Development Company, HADCO) is that wells are dug in advance and spacing between the wells is either horizontal or vertical direction.

Therefore, the main objective of this study is to calculate maximum permissible allowance, discharge and depletion in groundwater level. Also, to clarify the optimal quantity of pumping water using field data from the sandstone aquifer in the Saq formation south-west of Hail province, Saudi Arabia.

MATHEMATICAL MODEL FOR ADMINISTRATIVE PROGRAM

The Maximum Permissible Flow rate (MPF) is defined as the quantity of water that can be extracted from a well without affecting the aquifer and the productive well. So, pumping of water from a well should not exceed the optimal flow rate in order to avoid excess costs, depletion of water level and the interaction between the radius of influence of two adjacent wells. One of the major problems in the study area (Hail Agriculture Development Co., HADCO) is that wells are dug in advance and the distance between wells is either horizontal or vertical in direction. Maximum Permissible Flow rate (MPF) is an unstable value depending on the value of dry zone, space or distance between wells and physio-chemical properties of subsurface layer of each well. Therefore, the concept of maximum water withdrawal should consider that the well is in good condition and is not damaged from continuous use. Also, there is no effect from interaction between the radius of influence and the cone of depression between adjacent wells. It is also clear that the concept of radius of flow velocity of underground water increases near the center of the well. This increase in flow velocity allows the movement of colloidal particles from the aquifer around the well casing thus increasing the pressure loss due to blockage of pump filter resulting in high drawdown of water in the well (Ali *et al.*, 1997). Furthermore, mathematically the groundwater velocity can be expressed at any point by the movement of groundwater zone through each section of the porous material (solid part and pores) which is equal to the value of specific flow rate (well pumping flow rate, Q) or called Darcy velocity to total cross-sectional area (A) depending on the flow direction as follows:

$$q = \frac{Q}{A} \tag{1}$$

Where q is the actual flow velocity of groundwater to the cross-sectional area and is measured by the space of the porous material of aquifers. Therefore, the actual velocity of groundwater is much more than velocity of Darcy (Nonner, 2003).

The relationship between the actual velocity (V_a) and velocity of Darcy (V) is as follows:

$$V_a = \frac{A}{A_{cap}} \cdot V \tag{2}$$

where, A_{cap} is the sum of cross sectional area of the capillary tubes. The porosity (n) is (A_{cap}/A).

Equation 2 can also be written in another form, after dividing the drainage capacity on porosity (n), as follows:

$$V_r = \frac{Q}{A_{cap}} = \frac{q}{n} \tag{3}$$

where, A_{cap} is the cross-sectional area close to the well in the aquifer. From physical point of view, the velocity near the center of the well depends on the distribution of particle density of aquifer and the hydraulic conductivity than other hydrological factors. All these factors can be obtained by estimation using the empirical correlation. This correlation is based on the observation from a numbers of wells. Driscoll (1986) observed a strong relationship between the hydraulic conductivity (K) and the depletion of ground water. This relationship can also be expressed empirically by using approach velocity (V_a) equation with the introduction of safety factor according to Huisman (1972). This equation can be written as follows:

$$V_a = \sqrt{K / 60}$$

Equation 3 gives accurate measurement of hydraulic conductivity. This can be verified by pumping test or by the measurement of specific flow rate of each well. However, the other alternative approach is Logan (1964) method that was used in the present study for calculating the conductivity coefficient. After that, this coefficient was converted to hydraulic conductivity by dividing the conductivity coefficient by the thickness of aquifer. Equation 3 can be rewritten to determine the Maximum Permissible Flow rate (MPF) as follows:

$$Q_{mi} = 2\pi\, r_{wi} b \sqrt{K_f / 60} \qquad (i = 1,2,3,........,n) \tag{4}$$

where, r_{wi} is the radius of irrigation well, K_i is the hydraulic conductivity, b is the thickness of the ground water reservoir and n is the number of wells in the study area.

Besides, implementation of the second phase of water management program requires interaction between the drawdown and rate of pumping water from a well at a critical level of 5%. In fact, if water is pumped from two or more adjacent wells from the same aquifer layer, it shows interaction between the drawdown and flow rate of well resulting in more drawdown in groundwater. This interaction between radius of influence among the wells will cause high water level depletion in many wells. As the aquifer in the study area is of closed type, so the flux equation in the steady state for any well can be written as follows:

$$Q_{mi} = \frac{2\,\pi\, T_i S_{wi}}{\log\, ({}^{R_i}\!/_{r_{wi}})} \qquad (i = 1\ ,\ 2\ ,\ 3,\ ....,n) \tag{5}$$

where, S_{wi} is the level of drawdown in irrigation well, R_i is the effective well Radius, T_i is conductivity coefficient, the value of the conductivity coefficient can be expressed by T_i. Equation 5 is the vertical distribution in wells without receiving any recharge from surface sources Al-Naeem (1999) conducted studies that used the effective well Radius as follows:

$$RT_i = 3000 S_{wi} \sqrt{K_i} \tag{6}$$

By substituting Eq. 6 in Eq. 5 we obtained:

$$Q_{mi} = \frac{2\,\pi\, T_i S_{wi}}{\log \dfrac{3000 S_{wi} \sqrt{Ki}}{r_{wi}}} \qquad (i = 1\ ,\ 2\ ,\ 3,\ ....,n) \tag{7}$$

After rearranging Eq. 7, the value of the maximum permissible drawdown in wells can be obtained as follows:

$$S_{wi} = \frac{[r_{wi} b \frac{K_i}{60}(14 + \mathrm{Ln} S_{wi} \frac{K_i}{60})]}{bK_i} \qquad (i = 1\ ,\ 2\ ,\ 3,\ ....,n) \tag{8}$$

All the variables in Eq. 8 are known except the value of water drawdown (S_{wi}) in the wells. Equation 8 can be used to calculate the maximum permissible drawdown for each well. The main advantage of the last method is that it does not consider the distance between the wells. By this way it can be converted to a series of effective well radius (R_{wi}) by using Eq. 6. Also, it is possible to determine the distances between the adjacent wells from the well map. Assuming that D_{ab} indicate the distance between two wells close to each other at location a and b and there are many unknown wells (n). Which means that there are many wells with different distances and interactions with each other. It can be calculated from n (n-1)/2. Each distance must be equal or more than the summation of the effective radius of two close (adjacent) wells. This close distance can be expressed as follows:

$$D_{ab} \geq R_a + R_b \quad (a, b = 1, 2, ..., n) \tag{9}$$

Which represents the algebraic distance in the administrative program. At the critical level Eq. 9 can be rewritten as follows:

$$D_{ab} \geq (1-\alpha) R_a + R_b \tag{10}$$

where, α is the critical level. It is clear that if a critical level is equal to zero (this means that there is no interaction between the wells), Eq. 10 is converted to Eq. 9 after obtaining the effective radius of well. It has to be satisfied for each two wells using Eq. 10. If the algebraic distance in Eq. 10 is unsatisfied, the value of α will be equal to 0.05. In this case, the value of effective radius of a well has to be reduced until the same value of algebra distance is obtained in Eq. 10 and this value is satisfied. Therefore, the value of maximum permissible drawdown in well water can be calculated as follows:

$$S_{wi} = \frac{R_i}{3000\sqrt{K_i}} \quad (i = 1, 2, 3, ..., n) \tag{11}$$

By this method, all the adjacent wells were investigated to obtain final values of water drawdown and the radius of wells. Hence, the permissible groundwater flow velocity can be calculated as follows:

$$V_{mi} = \frac{Q_{mi}}{2\pi\, br_w} \quad (i, j = 1,\ 2,\ 3,\ ...., n) \tag{12}$$

According to the method of Theis (1935), the values of aquifer properties such as hydraulic conductivity (K), water layer storage coefficient (S) and permissibility factor (T) can be estimated. The value of (T) can be obtained from water pumping experiments. Theis (1935) method can be derived from the following equation:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{Kb}\frac{\partial h}{\partial t} \tag{13}$$

Equation 13 can be written in terms of radial coordinator as follows:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial h}{\partial r} = \frac{S}{T}\cdot\frac{\partial h}{\partial t} \tag{14}$$

In 1935, Thiees created a solution to the differential Eq. 14 for unstable flow in two directions based on the symmetry between the groundwater flow and thermal conductivity as follows:

$$h_o - h = \frac{Q}{4\pi T}\int_{\mu}^{\infty}\frac{e^{-u}}{u}du \tag{15}$$

where, the value of u is:

$$u = \frac{r^2 S}{4Tt} \tag{16}$$

Whereas, s = (h_0-h) is the level of drawdown (meter) at any point which is the distance from the observation well to the pumping well at a steady flow rate, Q represents the well discharge in m^3 per unit time ($L^3\ t^{-1}$), r is the radius of influence which is the distance between the pumping well to the observation well. T is the starting time from the beginning of pumping.

MATERIALS AND METHODS

The development and implementation of the mathematical model program for the management of groundwater in Saq sand aquifer was carried in the south-east part of the Hail northern region of Saudi Arabia (Hail Agriculture Development Co., HADCO). The study area is located between longitudes 42°39'-43°E and width of 27°16'-27°23' N. It is about 120 km from the province of Hail. The study area covers an area of approximately 350 km² and is rectangular in shape (Fig. 1).

The land topography of Hail is 980-1000 m above sea level. In this study, the wells were distributed in the study area into a small area as horizontal lines and were named A, B, C, D, E, F, G, H, J, K, L and M and the vertical lines from 1-12 represented the names of wells by the interaction of the horizontal line with the vertical lines, such as (A1, A2, ...etc). as shown in Fig. 2.

A total of 193 wells were selected from the study area. The location of wells and distribution in the study area is rectangular in shape (Fig. 2). The average horizontal distance between the wells is 1641 m while the average vertical distance is 821 m. The average depth of wells is 509 m in the selected study area. The groundwater levels ranged from 61-71 m in 1982, 68-69 m in 1983, 144-168 m in 1997/1998 and 168 and 186 m in 2011-2012

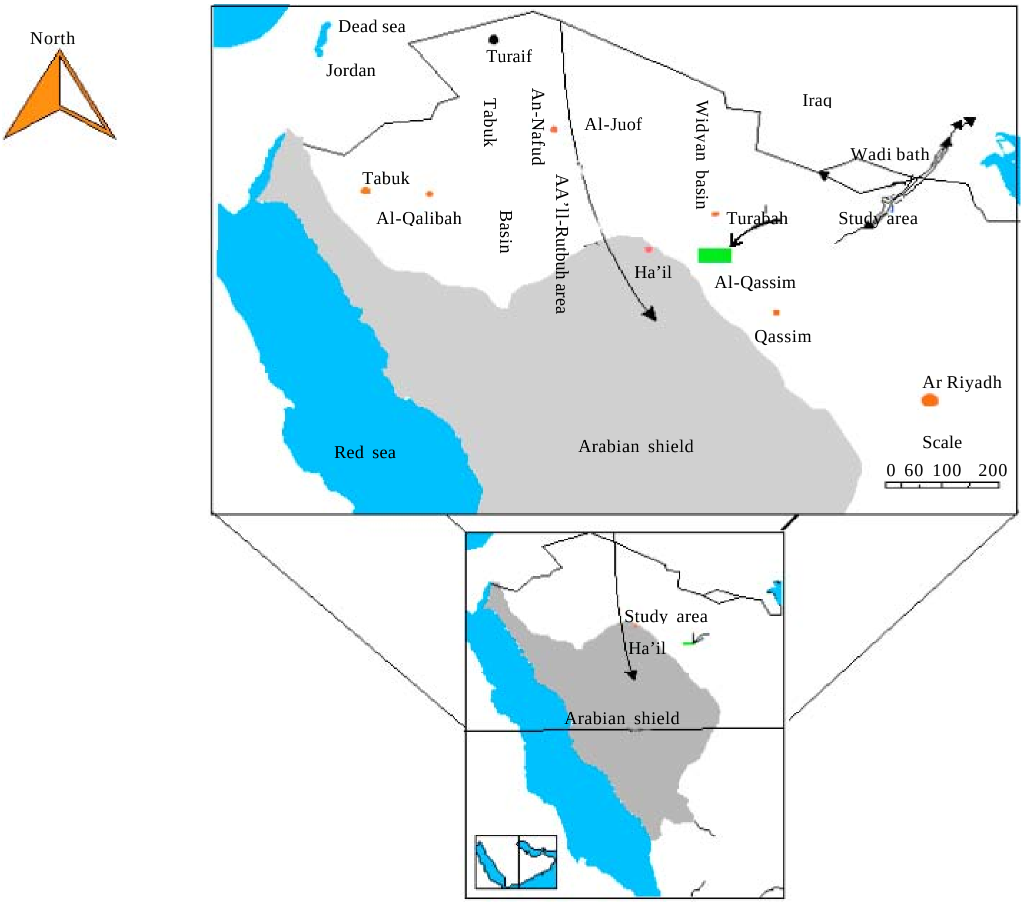

Fig. 1: Location of the study area in Hail region, Saudi Arabia

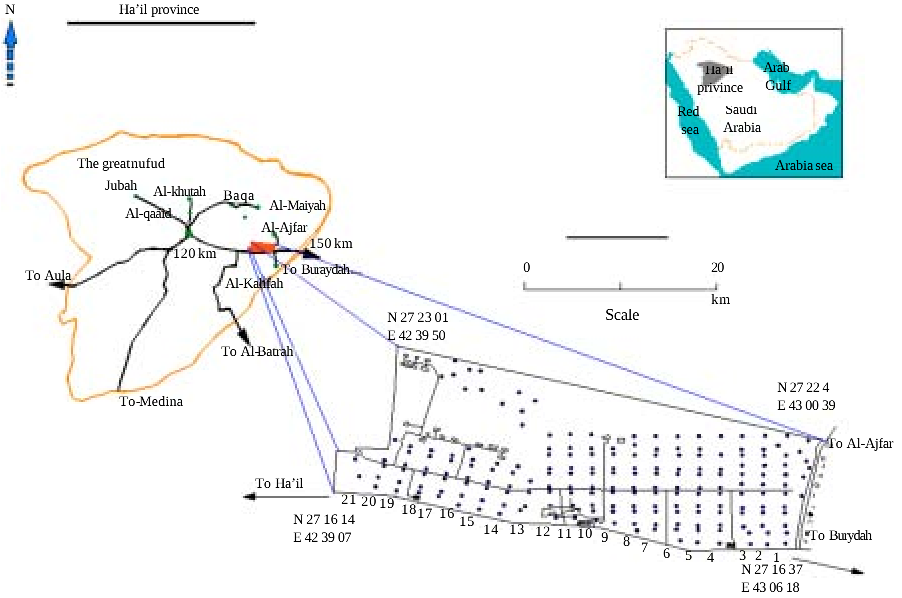

Fig. 2: Location of wells in the study area (Al-Naeem, 1999)

Geological age		Geological composition	Stone properties	Thickness (m)
Paleozoic age	Permian age	Alkhif layer composition	Limestone and clay and the majority is sand stone	
	Devonian age	Alj of layer composition	The upper part of the color from white to mica tan color is clay and limestone	229
	Alerfeache and silurian age	layer composition	Light gray color and sandstone fall into three separate units. blue and gray color and resides between the modules are limestone. Hanader clay at the bottom of Tabuk sand composition	1072
	Cambrian age	Alsag layer composition	Sand stone soft particles to medium with alternating layers of the clay. Weak isolate sandstone and soft particles to medium alternate with the clay. Coarse sandstone and a light brown color layerd with small particles in the bottom part of the layer	+600
Pre-cambrian age			Granitic rocks of alondisi with gray color and rosy	

Fig. 3: Geological layer series of Saq sand aquifer in the Arabian shield of Saudi Arabia (Powers *et al*., 1966)

below the ground surface. The total No. of wells used in the study were 117 representing about two third of the total number of wells in the whole area.

The study area consist of a sedimentary layer of quaternary age and covers most of the area. These deposits consist of silt, sand stones and gravel layers with a thickness of 2-15 m. It is known that sandstone layers of Saq aquifer cover large area of the region. The Saq sand layer composed of the coastal lower part of the Tabuk layer with a thickness of 800 m and mostly consists of sandstone. The bottom layer of Tabuk aquifer is separated from Saq sand aquifer by Alhanadr clay which is impermeable with approximate thickness of 20 m as given in Fig. 3.

The thickness of Saq sand aquifer in the study area is identical. The aquifer is horizontal and its eastward slope is about 0.01. The selected location of wells in Saq aquifer is from a well in location A1 to the well in location G9. The total number of wells in the study area were 68 and mostly used for agricultural purposes. The groundwater level was measured through the observation wells. The pumping experiments were carried to a constant flow rate and recovery of well located in G5 and G7 locations where the water level drawdown was monitored with time. Then, Theis (1935) method was applied to determine the aquifer properties namely hydraulic conductivity (k), coefficient storage(s) and permissible coefficient (T) using Groundwater For Windows (GWW) computer program. The results of pumping tests were analyzed to estimate the values of different properties of aquifer. The values of different aquifer properties are presented in Table 1. Besides, Surfer program was used to draw contour maps for various aquifer properties.

Data analysis: Data were analyzed by ANOVA and regression techniques for treatment evaluation at 5% level of significance according to SAS (2001).

RESULTS AND DISCUSSION

Mean values of permeability (T, M^2/tor) was 1862.5 and 3475.9 for wells located in G5 and G7, respectively (Table 1). Mean hydraulic conductivity (K, m day^{-1}) was 5.39 and 4.05 for wells in G5 and G7 locations, respectively in the study area. Whereas, the storage factor (S) was 0.0025 and 0.0029 for wells in G5 and G7 locations, respectively. These values were determined by well pumping tests in the study area. The maximum permissible velocity was calculated using Eq. 12 and ranged between 2.1-7.7 m day^{-1}.

Data in Table 2 show the mean maximum permissible flow velocity (MMPFV) for different locations in the study area. The values of MMPFV came to 5.06, 4.65, 3.48, 4.70, 4.56, 3.92, 5.23, 4.38 and 5.06 m day^{-1} for J, H, G, F, E, D, C, B and A fields, respectively in study area. The results indicated the aquifer homogeneity with respect to water storage characteristics as all these values are very close and the difference among these seems to be insignificant. While looking on the values of velocities, it infers that losses through aquifer cracks is bare minimum according to Driscoll (1986). It is also expected that under these aquifer conditions, the rate of scaling and corrosion of well casing is minimum.

Table 1: Different properties of sub-surface reservoir calculated by Theis (1935) method

	Well pumping		
Factor	G5	G7	Mean value
Permeability (T) (m^2/tor)	1862.5	3475.9	2669.5
Hydraulic conductivity (K) (m day^{-1})	5.39	4.05	4.72
Storage factor (S)	0.0025	0.0029	0.0027

Table 2: Mean maximum permissible velocities in the study area (m^2 day^{-1})

	Field of study								
Parameter	A	B	C	D	E	F	G	H	J
Maximum permissible velocities	5.06	4.38	5.23	3.92	4.56	4.70	3.48	4.56	5.60

Table 3: Mean values of actual flow rate, maximum permissible flow rate and residual flow rate for the study sites in the study area (m^3 sec^{-1})

Study field	Mean actual flow rate (m^3 sec^{-1})	Maximum permissible flow rate calculated (m^3 sec^{-1})	Residual flow rate, (m^3 sec^{-1})
A	0.058	0.013	0.045
B	0.048	0.007	0.041
C	0.070	0.016	0.053
D	0.077	0.011	0.066
E	0.079	0.017	0.063
F	0.083	0.012	0.071
G	0.067	0.011	0.056
J	0.098	0.013	0.085

A contour map was prepared for the values of maximum permissible velocities for the wells in the study area (Fig. 4). The contour map shows that local variation in the maximum permissible velocity ranges between 2.4×10^{-5} to 8.89×10^{-5} m sec^{-1}. Based on the distance between contour lines, values of the maximum velocities for a particular area in Saq sand aquifer were used for all the agricultural related activities especially the irrigation in the study area. The actual flow rate of wells ranged between 0.048-0.049 m^3 sec^{-1}. While, the values of Maximum Permissible Flow rate (MPF) calculated by using Eq. 7 ranged between 0.007-0.017 m^3 sec^{-1}.

Table 3 shows the mean values of actual flow rate, maximum permissible flow rate and residual flow rate of wells in the study area. The ranges of different flow rates (m^3 sec^{-1}) were 0.041-0.085, 0.007-0.017 and 0.048-0.098 for residual flow rate, mean maximum permissible flow rate and mean actual flow rate, respectively for all the investigated wells in different study sites. These values were calculated to determine the quantity of groundwater available and to know the change in the volume of this water with time. In other words, on permanent basis, the quantity of water available and the actual characteristics of the subsurface Saq aquifer tied with the possible side effects during pumping.

Data in Fig. 5, 6 and 7 represent the contour maps of distributions of maximum permissible flow rate, actual flow

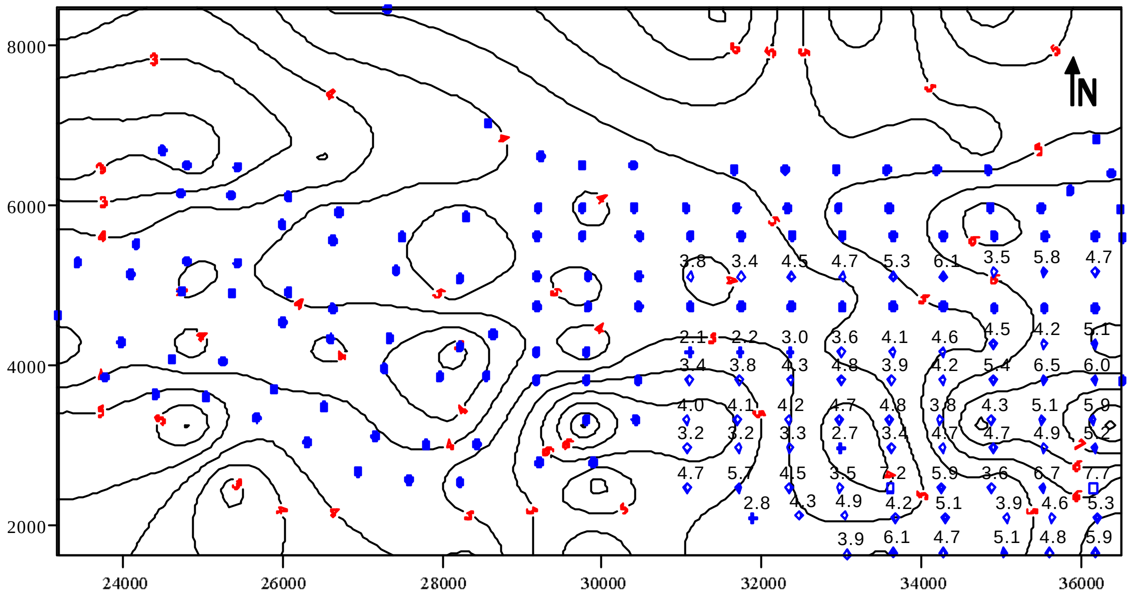

Fig. 4: Contour map showing the maximum permissible velocity in the study area (m day^{-1})

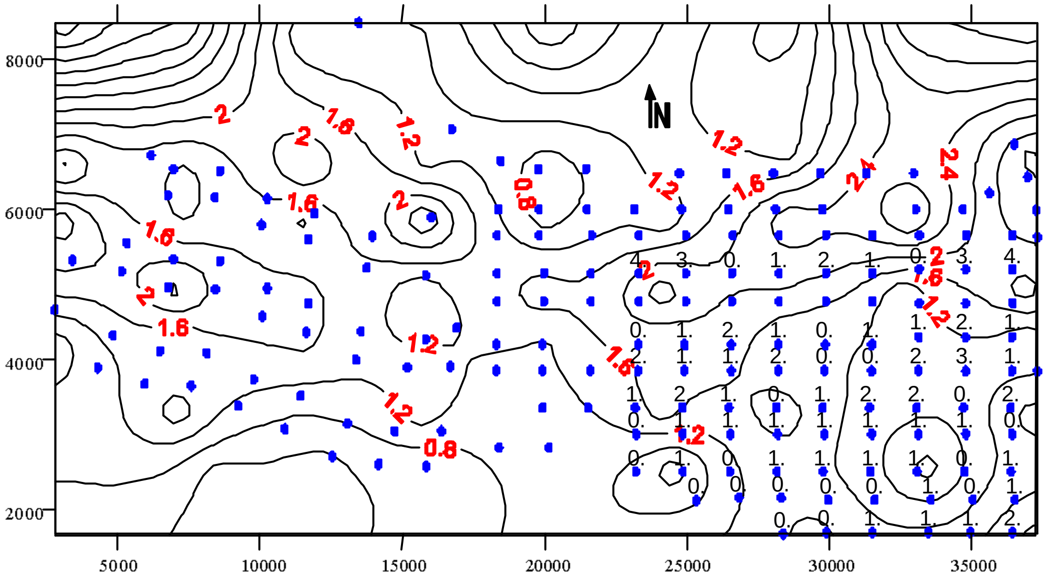

Fig. 5: Contour map shows the maximum permissible flow rate of wells in the study area (10^{-2} m^3 sec^{-1})

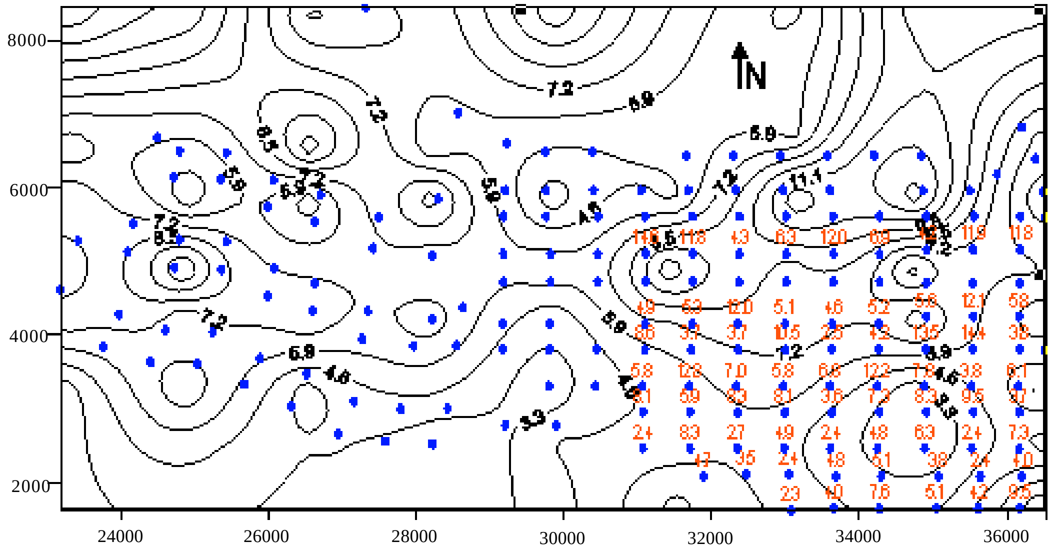

Fig. 6: Contour map shows the actual flow rate of wells in the study area (10^{-2} m^3 sec^{-1})

rate and the residual flow rate, respectively. The values of actual flow rates shown in the contour map were estimated based on the actual field data. It was noticed that the values of actual flow rate measured in the field were higher than the calculated values of Maximum Permissible Flow rate (MPF).

This point is clear from the range of actual flow rate and the maximum permissible flow rate when compared with the average flow rate in the study area as given in Table 3. It can be concluded that actual flow rates of wells in the study area are higher than the maximum permissible flow rate by about 90%. Also, the actual flow rates for two wells is more than the optimal production of wells in the study area. The residual flow rate is the difference between the actual flow rate and the maximum permissible flow rate. From the study results, it was found that the residual flow rates of wells tend to change from one location to another location as shown in Fig. 5 and

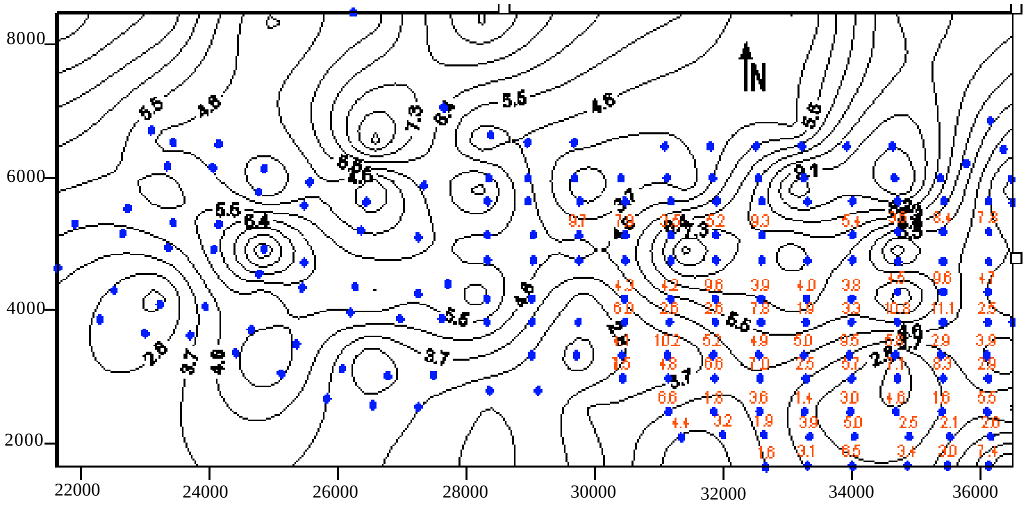

Fig. 7: Counter map shows the residual flow rate of wells in the study area (10^{-2} m^3 sec^{-1})

Table 4: Values of mean maximum permissible drawdown of some wells in the study area

Well No.	Maximum permissible drawdown (m)
A1	4.70
A3	4.25
A6	3.86
B3	4.08
B5	4.12
C4	3.61
C8	3.04
F7	4.82
F9	6.20
|G3	5.02
G7	4.58
J2	4.45
J4	4.03
J6	6.34
J8	6.63

Table 3. The results in Figures and Tables explain the values of the residual flow rates with the maximum quantity of groundwater and justify the maximum permissible flow rate. In fact, unnecessary consumption of groundwater can be seen from Table 3 and is likely to affect the aquifer water storage in future. Consequently, this will increase the slope of the pizometeric water level in future thus making it impossible for the hydraulic conveyance of the aquifer to recharge the aquifer flow rate in the area. Similar views were reported by Qahman *et al.* (2005). Who reported that water problems occur when excessive pumping at certain individual wells lowers the potentiometric surface locally and causes up-coning of the inter-face between fresh water and saline water. They researchers investigated the optimal and sustainable extraction of groundwater from a coastal aquifer under the threat of seawater intrusion. The physical model is based on the density-dependent advective-dispersive solute transport model.

The study of the contour maps (Fig. 5, 6 and 7) show that if the counter line is high, this means that the actual flow rate is high. Therefore, it is easy from the counter maps to determine the high and low flow rates of wells in the study area which is verified from the distance between different counter lines.

Lastly data in Fig. 7 show the simulation of counter maps for actual flow rate and the maximum permissible flow rate of wells in the study area. The intersection of contour lines for the two maps at any point represents the residual flow rate. The study of a similar map indicates that if the values of the counter lines are positive, then the actual flow rate is more than the maximum permissible flow rate of wells in an aquifer.

The above classification for the actual flow rate, the optimum flow rate and the residual flow rate gives an indication of good administrative process for drawing the counter map of groundwater pizometric level during the irrigation interval in the irrigated agriculture project in the study area. In general, the water consumption is less than recharge in the study area. It is an admitted fact that when water is pumped from a well, the water stored is consumed around the well resulting in decreasing the piezometric water level. Above all, data of groundwater piezometric level such as vertical flow and horizontal flow is required for calculating the capacity of an aquifer. Because, this data is an important part of input data in developing the mathematical model in the computer. The mathematical model, so developed, will be used to predict the effect of the recent pumping flow rates on long-term basis and to draw optimal plan of future groundwater development.

The maximum permissible water drawdown was calculated from Eq. 10 and presented in Table 4. Table 4 shows that the mean maximum permissible water drawdown was 4.65 m which is the drawdown required to produce the desired flow rate partially for possible determining the natural hydraulics of the aquifer. Also, it will further help to develop and design productive wells. Besides, if the drawdown in the well is greater than the maximum permissible drawdown, then disturbance occurs in the flow rate of wells. The tendency of specific capacity of a well is gradual when the increase in the flow rate is above the Maximum Permissible Flow rate (MPF). Moreover, the intersection occurs between the effective radius of counters. Data in Fig. 5 shows the counter map of maximum permissible flow rate. The data in Fig. 5 can help to observe local variation and to estimate the maximum permissible drawdown in well water at any desired point in the study area. The study findings agree with those of Qahman *et al*. (2009) applied two multi-objective management models in a coastal aquifer to maximize the total volume of water pumped, minimizing the salt concentration of the pumped water and controlling the drawdown limits on a part of the aquifer with 9 existing pumping wells located at various depths. The study showed that the optimum pumping rate is in the range of 26-34% of the total natural replenishment and the proposed technique is a powerful tool for solving this type of management problems. Soni and Pujari (2010) analyzed the hydro-chemical data of groundwater samples of three different limestone mine sites which are in close proximity and covers a tract along the Gujarat coast of Indian peninsula. They found sea water intrusion in the coastal aquifer in the study area and recommended measures for sustainable use of groundwater by the mining companies and other stake holders.

CONCLUSION

A mathematical model was developed consisting of easy and simple steps to formulate a procedure for aquifer management in dry regions. Since the aquifers represent the national wealth of Saudi Arabia, therefore this program was designed to manage the water wells located at irregular distances. The variables for the mathematical computer program include flow velocity and the maximum permissible drawdown. The developed program is useful to satisfy the principal variables such as hydraulic conductivity of aquifer related to each well location, well diameter, distance between wells and the aquifer thickness. The effective administrative program was executed without using local continuity equation. The application of this computer program requires actual field data including the properties and composition of Saq aquifer formation. Overall, the variables studied were very effective for the establishment of aquifer administrative program for efficient utilization in agriculture.

RECOMMENDATIONS

In order to apply a simple and effective aquifer management program, the following points need consideration:

- Monitoring of aquifer water level by using a simple and sophisticated administrative rules as suggested in the study
- The interaction between the radius of influence of wells must be minimized and should be less than 5% for introducing aquifer administrative program
- To avoid any problems in the pump filters and the stones around the well casing, the aquifer velocity must be less than the maximum permissible flow rates
- It is required to modify the actual flow rate and should be equal to the maximum permissible flow rate as suggested in this study
- Additional requirements such as quantity of water pumped and its actual use must to be compared or matched for better utilization of aquifer

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