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Optimum Aquifer Yield of Four Aquifers in Al-Kharj Area, Saudi Arabia

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ABSTRACT. Al-Kharj region, in the central part of Saudi Arabia, has been developed mainly for agriculture. Accordingly, the water demand increase resulted in significant depletion of the present aquifers. Therefore, necessary precautions must be taken.

This paper proposes preliminary solutions by evaluating optimum aquifer yield patterns from wells in this region. Also, charts are constructed for different discharges as well as number of wells to estimate the time of depletion in each of the aquifers. It is therefore, possible by use of these charts either to limit the number of wells or discharges as convenient. In fact, these charts provide a basis for simple groundwater management in the Al-Kharj area. Furthermore, the proposed charts provide a significant reduction of the shortfall in the required discharges from about 20% to 8%. However, the correct use of the charts will benefit the future plans of the area in managing the use of the available water.

Introduction

The safe yield is defined by Todd (1959) as the amount of water that can be withdrawn from aquifer annually without producing an undesired result. Any withdrawal in excess of safe yield is an overdraft. The term overdraft may include not only the depletion of the groundwater reserves, but also the intrusion of water of undesirable quality (Domenico 1972 and Kazmann 1972).

Al-Kharj area is a recreational place of Al-Riyadh, capital city of Saudi Arabia (Fig. 1). This area became an important center of growth and agricultural activities. The available water in the four productive multiple aquifers, namely, Biyadh, Wasia, Sulaiy and Arab, should be exploited with an efficient management plan.

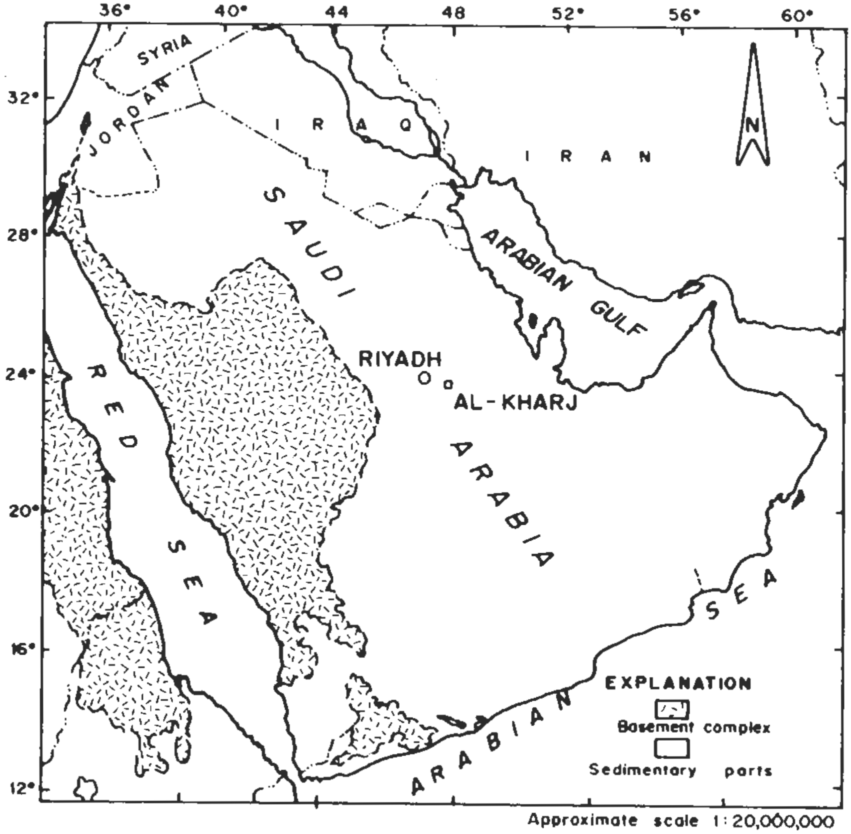

FIG. 1. Location map.

In the late 1949's ARAMCO engaged Dr. G. Brown to report on the geology and groundwater of Al-Kharj District. This also involved the first attempt at defining the stratigraphy of the area, and was done without the benefit of topography control or aerial photographs. The sequence of formations that he defined in Al-Kharj area provided a valuable base for later stratigraphy workers such as Powers and others of the United States Geological Survey in 1966 published an extensive and detailed study of the sedimentary geology of Saudi Arabia.

In 1968, a report was completed by the French consulting firm SOGREAH on the water and agricultural development studies of "Area V" which included Al-Kharj. The purpose of their report was to determine the geologic structure, outline the general stratigraphic sequence and estimate the groundwater resources for possible future development. The SOGREAH report was necessarily of a reconnaissance nature since it extended over a huge region, and was therefore unable to provide detailed assessments of subsidiary areas.

In 1978, another French consulting firm (BRGM) commenced work on a hydrogeological study of Al-Kharj area. In their final report (1981), the BRGM recommended that, more groundwater should be tapped from successively deeper layers, not restricted to the clastic formation, but also utilising limestone units of Lower Cretaceous to Middle Jurassic ages. In addition, they recommended that a detailed evaluation should be made of the productive aquifer system, and the flow conditions between the limestone aquifers. Bazuhair (1986), in his extensive study of Al-Kharj area, recommended continuous monitoring of water-level in the productive aquifers so as to be informed on time the decline of the water table.

This paper is about estimation of the optimum aquifer yield of the productive aquifers in Al-Kharj area. In addition, charts are constructed to estimate the time of depletion of each aquifer provided that the discharges and the number of wells are known. Similar charts could be prepared for any aquifer in other parts of the world.

Geomorphology and Geology

The average altitude of Al-Kharj is some 200 meters above mean sea level. Despite an approximate surface slope of 0.5 toward the north-east and east, the low-lying land is susceptible to flooding after the occasional heavy rains, which might lead to recharge through outcrops to a certain extent. Hills of different geologic formations bound the wadi plain on all sides. Three large wadies meet in Al-Kharj plain area; wadi Hanifah from west, wadi Nisah from the south-west and As-Sulaiy from the north-west. These wadies join to form wadi As-Sahba which flows east out of Al-Kharj.

Al-Kharj area is located on the sedimentary basin of Saudi Arabia. The foundation for sedimentary deposition is the Arabian Shield, which is vast Precambrian complex of igneous and metamorphic rocks. The sedimentary layers cropout in a great curved belt bordering the rigid shield part as in Fig. 2. Here, the landscape is dominated by series of essentially parallel, west-facing escarpments each supported by a resistant limestone cap. The beds dip gently with a slope of about 0.51 to the north-east and south.

Al-Kharj is located at the apex of the curved belt, and it covers about 1800 km^2. The stratigraphic sequence in the basin near Al-Kharj, as described by Powers *et al.* (1966), is shown in Fig. 2 through the legend.

Aquifers and Their Properties

The study of groundwater behaviour underlying Al-Kharj area requires some knowledge of the hydraulic parameters of the productive aquifers, which, in the order of deposition age from younger to older, are Wasia, Biyadh, Sulaiy and Arab.

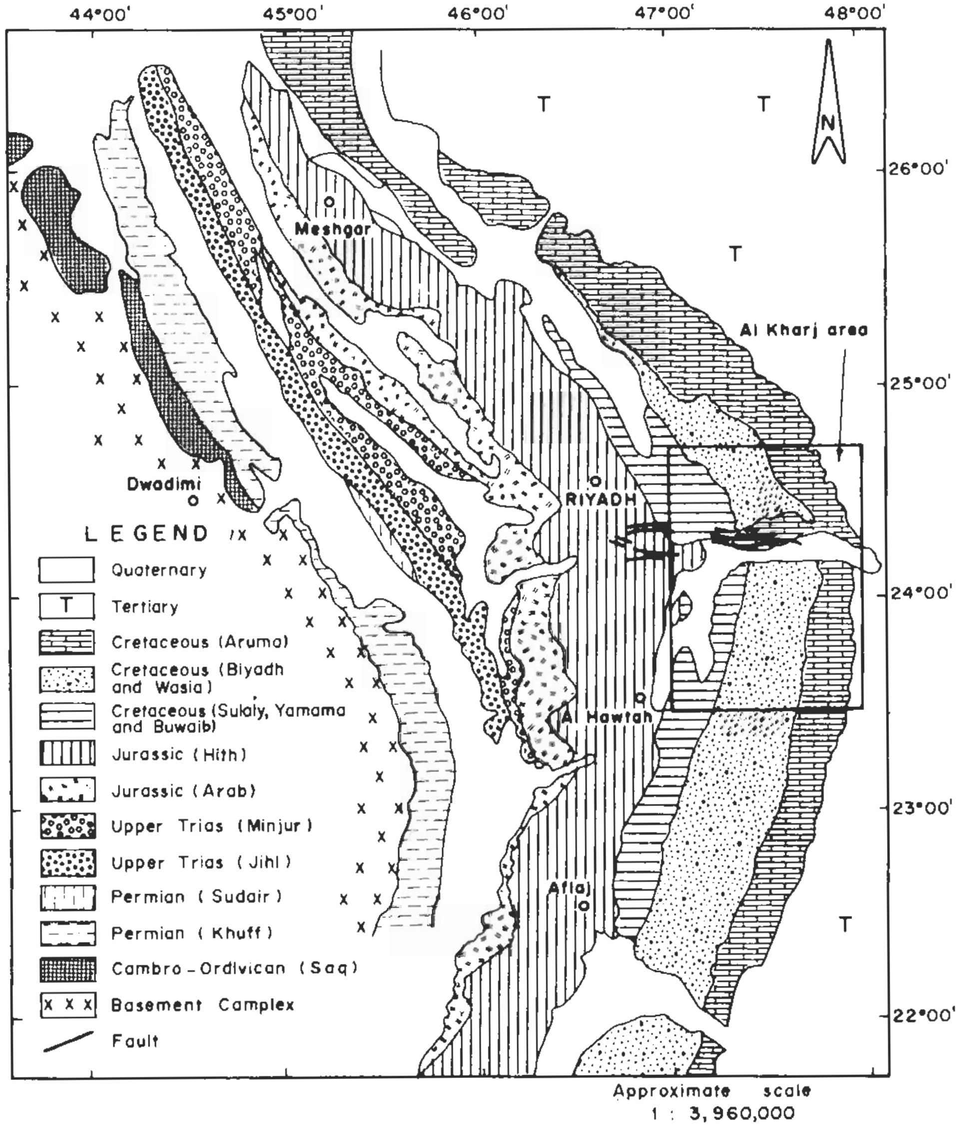

FIG. 2. Regional geology (after BRGM 1981).

Yamama formation is not considered to be aquifer in Al-Kharj area, since it has a relatively impermeable character. Similarly, the nature of the Buwaib formation provides the impermeable substratum to the Biyadh aquifer east of Al-Kharj. On the other hand, the Hith is unseen exposed except in the pits. The Wasia and Biyadh are clastic productive aquifers, whereas the Sulaiy and Arab are non-clastic aquifers. The Sulaiy formation has undergone considerable underground solution to form a Karst topography over some parts of Al-Kharj area. Also, Arab formation is characterized by joints, fractured and solution openings up to one meter in diameter.

Due to difficulty in finding satisfactory observation wells, only ten wells were tested during field work. As the drawdown measurements were made in the pumping well, the determination of storativity would not be representative, because the nominal radius would have been too small. However, fifteen samples of clastic materials from different localities were collected where possible.

The pumping test data are analysed, using different analytical methods such as Theis (1935), Cooper and Jacob (1946) and Boulton (1963). The specific capacity method of Walton (1970) is applied to estimate the transmissivity of the productive aquifers.

The sieve analysis of the clastic samples are plotted to provide cumulative frequency curves. From these curves, different parameters necessary for the determination of the permeability are obtained and substituted in the equation applied of Hazen (1893) and Masch and Denny (1966).

It is known that each of the methods applied has its own limiting assumptions and was expected that there would be different results, but those results, at least, should indicate, comparatively, the same pattern of increase or decrease in aquifer characteristics.

In order to allow a rapid comparison, the permeability values for the four productive aquifers, as well as methods applied in this study, are presented in Table 1. In this table, the big range of Biyadh and Wasia aquifers permeability is due to the differences in grain size, lateral variation, cementation, and/or secondary permeability.

TABLE 1. Summary of K and T results.

Aquifer name	Copper and Jacob method	Recovery straight line method	Theis type curve method	Boulton method	Specific capacity method	Grain size method	
						Hazen's method	Masch and Denny's method
	T in m²/d					K in m/d	
Wasia	2756.2	-	-	1500-2200	1500-2200	13.5 -42.3	14.7-53.4
Biyadh	108.9-604.8	34.6-388.8	96.9-817.7	-	31-1950	2.88-25.92	7.6-15.9
Sulaiy	-	34.6	-	-	28-54	-	-
Arab	2877.12	-	-	666.65	2000-2950	-	-

Şen (1983) derived a solution to determine the storativity S in the absence of observation well. His equation is applicable to confined, and after drawdown corrections to unconfined aquifers. It is defined as the ratio of water volume $V_p(t)$ abstracted from the aquifer at a certain time to the volume of aquifer dewatered zone, *i.e.* depression cone volume $V_d(t)$, which is an imaginary volume in the confined aquifer case. For a discharge, Q, after a certain time duration, t, the drawdown in the main well is $s_w(t)$ have,

$$V_p(t) = Qt - \pi r_w^2 \ s_w(t) \tag{1}$$

in which r_w is the well radius.

The volume of depression cone is, in general

$$V_d(t) = r_w^2 Q \left\{ \frac{[\exp^{(\frac{4 T s_w(t)}{Q})} - 1]}{4 T} - \pi r_w^2 \ s_w(t) \right\} \tag{2}$$

in which T is the transmissivity.

The ratios of Eq. (1) to Eq. (2) yields an approximate estimation of S provided that, t, s_w, Q and r_w measured in the field, and T calculated by some other method such as Theim's method (Theim 1906). The final form of the equation is

$$S = Q(t) - r_w^2 \ s_w(max) / \left\{ r_w^2 Q \ \frac{[\exp^{(\frac{4 \pi T s_w(t)}{Q})} - 1]}{4 T} - \pi r_w^2 \ s_w(t) \right\} \tag{3}$$

The parameters required for the application of this formula as well as the calculated S are shown in Table 2.

TABLE 2. Parameters used for calculation of storativity.

Aquifer name	T (m^2/d)	t (d)	s_{max} (m)	Q Practical discharge (m^3/d)	r_w (m)	S
Wasia P.T. (2)	2758.10	0.260000	1.17	1507.16	0.16	2.30×10^{-7}
Biyadh P.T. (4)	664.00	0.404000	9.19	5443.2	0.16	3.22×10^{-2}
Sulaiy P.T. (6)	34.56	0.29166	7.00	276.5	0.16	2.65×10^{-2}
Arab P.T. (10)	2873.90	0.186100	3.05	5024.0	0.16	1.5×10^{-5}

Optimum Aquifer Yield

In areas, like Al-Kharj, where the groundwater is the only source for supply, the increase in demand will mean abstraction of more groundwater. Therefore, in order to preserve the aquifer safe yield it would be very convenient to have a proper plan, design and operation. In this connection, the optimum aquifer yield determination is one of the significant factors in exploiting the available groundwater in each aquifer of Al-Kharj area.

Hölting (1980) used the following equation to obtain the aquifer discharge.

$$Q_q = \frac{2\pi r_w b\,(k^{1/2})}{15} \tag{4}$$

where b = saturated thickness or screen length. Furthermore, the Thiem (1906) equation can be used to determine the maximum allowable drawdown as follows :

$$Q_p = \frac{2\pi T\,(s_2 - s_1)}{\log \frac{r_1}{r_2}} \tag{5}$$

where Q_p is the well pump discharge, r_1 and r_2 are the respective distance of the observation wells, s_1 and s_2 are the respective steady state drawdowns in these observation wells. If the pumped well is used as an observation well, then $s_2 = s_w$ and $r_2 = r_w$ and the equation simplifies to :

$$Q_p = \frac{2\pi T\,(s_w - s_1)}{\log \frac{r_1}{r_w}} \tag{6}$$

However, if the radius of influence R is adopted as (Hölting 1980)

$$R = 3000\, s_w\,(k^{1/2}) \tag{7}$$

then, substitution for R_{max} the final form of Eq. (6) becomes

$$Q_p = \frac{2\pi T\, s_w}{\log \frac{R_{max}}{r_w}} = \frac{2\pi T\, s_w}{log\, \frac{3000\, s_w\, k^{1/2}}{r_w}} \tag{8}$$

Using the above equation, the calculations lead to the optimum aquifer yield of the productive aquifers which are shown in Table 3. The results indicate that the aquifer yields used during pumping test are the optimum range except for Biyadh aquifer, *i.e.* the field discharges in m^3/h are 63, 227, 12 and 209 for Wasia, Biyadh, Sulaiy and Arab, respectively, while the calculated optimum aquifer yields of the same sequence are: 1296, 151, 34 and 575 (m^3/h).

The permissible drawdown (s_w) can be determined also, from Eq. (8) provided that, the other parameter are available. The maximum radius of influence is useful to obtain the allowable maximum number of wells in each aquifer to produce without interference. This can be estimated by dividing the total aquifer area by the influenced area of the well as πR^2_{max}.

TABLE 3. Parameters used to determine R_{max} and the optimum aquifer yield.

Aquifer name	Average thickness h (m)	K (m/d)	$\sqrt{K}$ (m/s)	r_w (m)	s_{max} (practical) (m)	R_{max} (m)	πR^2 (m²)	Optimum aquifer yield (m³/h)
Wasia P.T. (2)	235	40.0	0.0220	0.16	1.17	77.2	18713.9	1296.0
Biyadh P.T. (4)	39	17.0	0.0160	0.16	9.19	441.1	610947.3	151.2
Sulaiy P.T. (6)	30	1.8	0.0046	0.16	7.00	96.6	29301.1	33.5
Arab P.T. (10)	164	18	0.0144	0.16	3.05	131.8	54545.7	575.0

P.T. (10) Pumping Test number.

The previous results and concepts are applied in the following two cases: In reducing the shortfall in the required discharge in SAADCO Company at Al-Kharj area, and to estimate the time to deplete the productive aquifers in the study area.

Reduction of the Shortfall in the Required Discharge in SAADCO Area

Saudi Arabia Agricultural Dairy Company (SAADCO) project is a big integrated dairy, located in Al-Kharj area. This area has been selected for application of equations developed in this study, due to availability of the necessary data as well as the existing serious problem with regard to drawdown.

Value of the parameters used are summarized as follows :

Parameters	Values and units
Total area A_t	25,000,000 m²
Irrigated area A_r	23,000,000 m²
Aquifer Biyadh average saturated thickness (b)	65 m
Transmissivity (T)	664 m²/d (well No. 4)
Hydraulic conductivity (K)	10.22 m/d = 0.000118 m/s
Well radius (r_w)	0.16 m
Maximum drawdown (s_{max})	9.19 m
Radius of influence (R_{max})	303.27 m
Optimal discharge (Q_{opt})	2900 m³/d
Area of influence (A_1)	288794 m²
Existing daily discharge	198995 m³
Required daily discharge	250720 m³
Existing wells	55

SAADCO is in need of more water to meet their current irrigation requirements. The deficiency is 21% of present extraction. However, the total optimum aquifer yield from the existing 55 wells would be 2900 × 55 = 159500 m³/d, which is 20% less than the existing extraction. Adaptation of the optimum aquifer yield from the existing wells will increase the water shortage to about 36%. However, the theoretically calculated number of wells, which should be installed in the irrigated area, is $\frac{A_y}{\pi R^2_{max}} = 79$ wells. From this number, the expected daily extraction using the optimum aquifer yield would be 79 × 2900 = 229000 m³, and this would increase the present daily discharge by 15% and reduce the shortfall in the required discharge to 8%.

Obviously, meeting of the required optimum aquifer yield will need more wells to be drilled, and if the optimum aquifer yield is retained, then there is a need for extra 7 wells to bring the total required number to 86. This, in turn, needs an extra area of 2 km².

Estimation of Time to Deplete Al-Kharj Aquifers

There is a definite and logical relationship between the aquifer water volume, pumping discharge, number of wells and time. The aforementioned optimum aquifer yield can be generalized into a graphical form which leads to charts as shown here in Fig. 3-6. Those charts are achieved by assuming various quantity of discharges from which the yearly consumption is calculated for different numbers of wells. In the mean time, the number of years for depletion are calculated by dividing the total amount of water by the yearly consumption. However, the daily hours of discharge are considered as summer and winter 10 to 20 hours, respectively. In calculation, the considered operational area is 1800 km². The saturated thickness, necessary to calculate the total volume of the aquifer, is the average one, and the formations are considered as homogeneous. The total volume of water for each aquifer is equal the operational area (A) multiplied by the average saturated thickness (b) and the estimated storativity (S).

The application of the charts, for obtaining the time of depletion, is possible after deciding the amount of discharge and also the number of wells required to discharge for 10 or 24 hours. For example, if 100 wells penetrate Biyadh aquifer and each discharges 1280 m³/h continuously (24 hours), the water of the aquifer will deplete after 80 years (Fig. 6). On the other hand, for the same condition, except that the discharges are for 10 hours per day, the water depletion might be after 100 years.

Conclusion

The continuous demand on water in Al-Kharj increased the use of the groundwater which is the only source. The alluvium water, which was the main source in Al-Kharj, is depleted since 7 years. Recently, the extensive use of the productive aquifers, Wasia, Biyadh, Sulaiy and Arab are unsafe and requires quick solutions. The

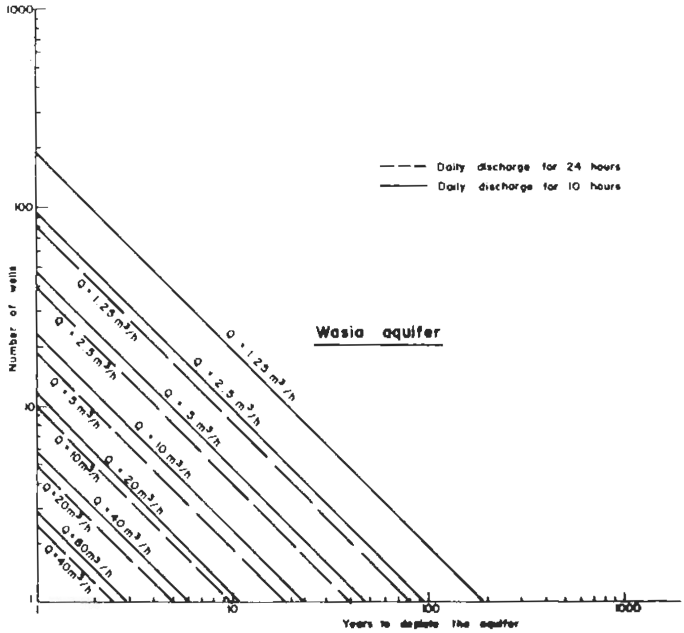

FIG. 3. Groundwater depletion chart.

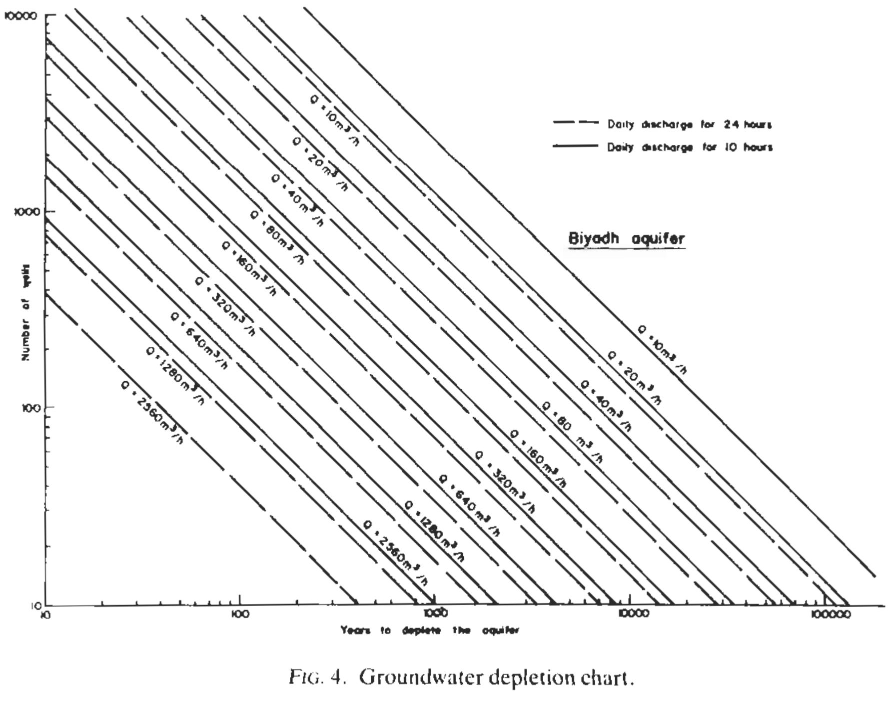

FIG. 4. Groundwater depletion chart.

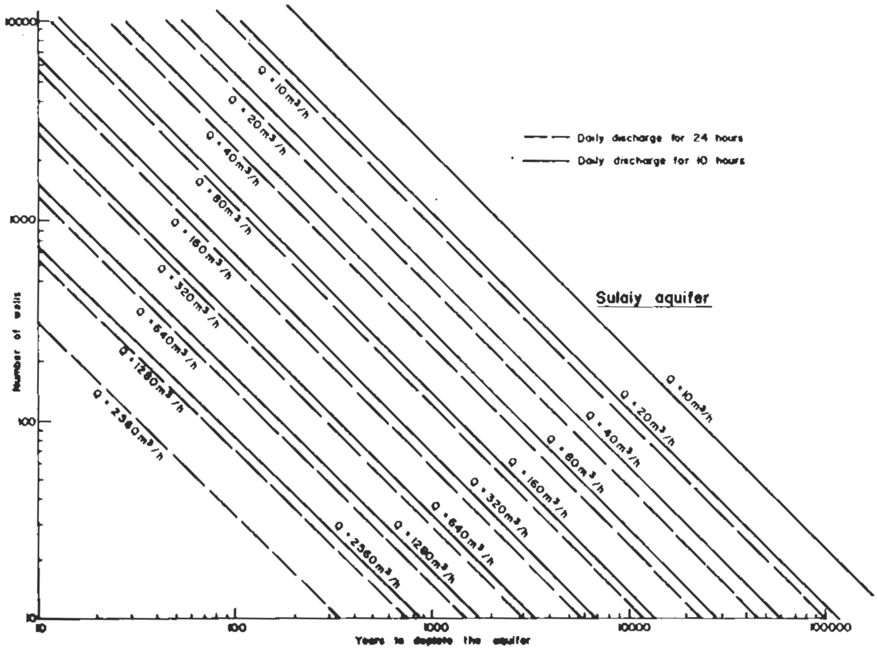

FIG. 5. Groundwater depletion chart.

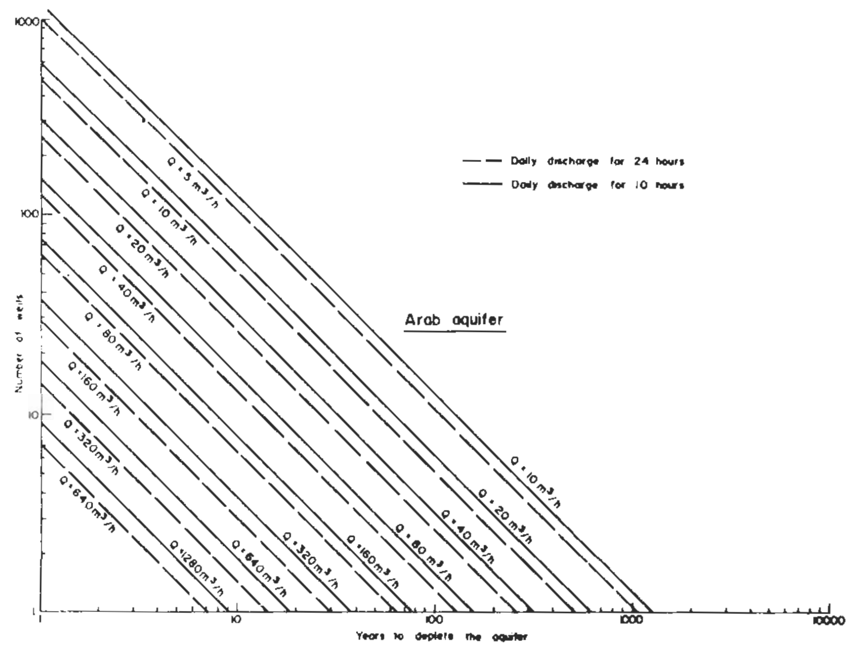

FIG. 6. Groundwater depletion chart.

proposed optimum aquifer yield of each formation could be the initiative solution for the desired management and arrangement of the wells. However, the suggested charts, or similar ones, may be a help for the future plans of Al-Kharj groundwater.

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الإنتـاج الأمثـل لأربع متكونات في منطقـة الخرج بالمملكة العربية السعوديـة

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مستخلص . تقـع الخـرج في الجـزء الأوسط من المملكة العربية السعودية . وكنتيجة للتـطور الزراعي بمدينة الخرج ، فقد ازداد الطلب على المياه الجوفية مما أدى إلى إجهاد المتكونات الحامله للمياه .

في هذا البحث سيعـالج الحل المبدئي لتلك المشكلة ، وذلك بتقويم الإنتاج الأمثل للآبـار في منطقة الدراسة . ونتيجة لهذه الدراسة ، فقد اقترحت مجموعة من الرسومات البيانية والتي من خلالها يمكن إيجاد الزمن اللازم لنفاد المياه في المتكونات من خلال تقدير كمية ضخ الآبار وكذلك عدد الآبار المستخدمة . ومن خلال هذه الرسومات أيضًا يمكن تحديد عدد الآبار أو كمية الضخ . وفي الحقيقة ، فإن هذه الرسومات البيانية تُعتبر قاعدة أولية للتخـطيط للمياه الجوفية في منطقة الخرج ، والتي عن طريق استخدامها يمكن أن ينخفض النقص في المياه المـطلوبـة من ٢٠٪ إلى ٨٪ علمًا بأن الاستخـدام الصحيح لاستخدام تلك الرسومات ستفيد التخطيط المستقبلي للمياه المتوافرة بمنطقة الدراسة .