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Prediction of the Effect of Pumping on Al-Wasia Well Field

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Abstract. Al-Wasia Aquifer is one of the major aquifers in Saudi Arabia which is found in the Central and Eastern regions of the country. Al-Wasia well field (62 wells) has been in operation since 1981 to supply water to Riyadh. It is located about 110 km north-east of Riyadh close to Riyadh-Dammam Highway. Amounts and rates of pumping from the well field have been changing during the last few years depending on water demand of Riyadh. The operation of the well field is examined under three different pumping stresses. The choice of a pumping pattern is according to the expected amount of pumped water from the well field to meet water demand of Riyadh. A two-dimensional regional ground water flow model (REGNLGW) is utilized to predict the expected water/piezometric levels in the well field due to the different pumping patterns up to the year 2010. The results of the simulation of the different pumping patterns show that piezometric level, in the year 2010, will not reach the critical depth of 300 m below ground surface. This depth is assumed critical because it is economically infeasible to extract water from depths greater than 300 m.

Introduction

Groundwater constitutes the most important natural water source in the Kingdom of Saudi Arabia. Groundwater aquifers throughout the country can be divided into two major types. The first (mostly unfined) are the type of aquifers found close to the surface and they are recharged easily and quickly by flows into the wadis. The amounts of water existing in these aquifers are limited but they have been sustaining agricultural production in the Kingdom's oases for thousands of years. The second type of aquifers are the deep (mostly confined) aquifers that exist within sedimentary formations in the eastern two thirds of the country. They have been discovered only in the last three decades and most of the vast agricultural development taking place now in the Kingdom depends largely on their water. Many urban centers get their water supply from these aquifers as well.

One of the major aquifers in the Kingdom is Al-Wasia aquifer. It spreads along the Central and Eastern regions of the country as shown in Fig. 1. Due to its good hydrologic properties (Mainly transmissivity and storage coefficient), it is used as one of the resources to supply the capital city, Riyadh, with its water [1]. At the present time, most of the water supply of Riyadh comes from the Jubail desalination plant (on the Arabian Gulf, about 460 km to the east). However, the desalinized sea water is mixed before reaching Riyadh with groundwater from a well field tapping Al-Wasia aquifer.

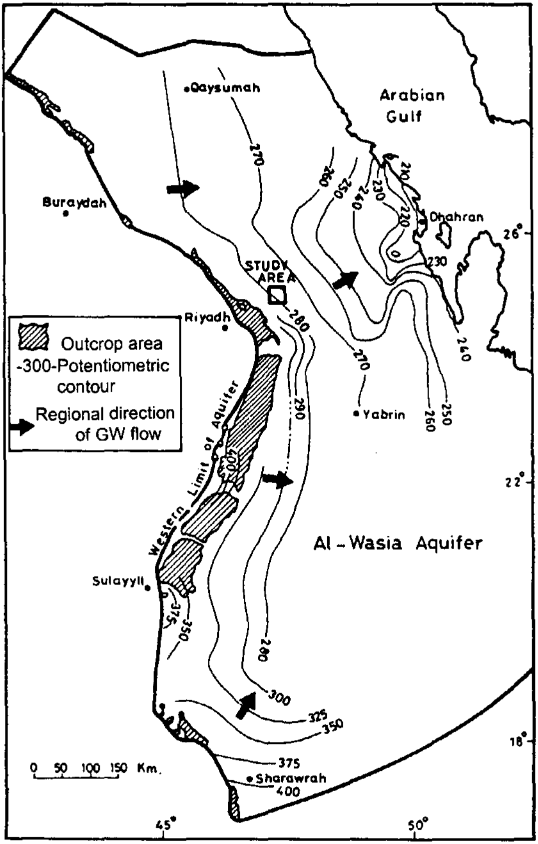

Fig. 3. Al-Wasia aquifer location.

The main objective of this paper is to present the results of the prediction of variations of water/piezometric levels in Al-Wasia well field due to three different pumping patterns. These variations were determined using the numerical regional groundwater model (REGNLGW) proposed by Rushton and Redshow {2}. The critical water level drop in the center of the well field (where the maximum water level drop occurs due to pumping) has also been estimated for the next 20 years under different pumping patterns.

Description of the Study Area

a) Al-Wasia aquifer

The Al-Wasia Formation out-crops about 50 km northeast of Riyadh in a narrow band extending in a northwest-southeast direction, and it dips northeastward beneath younger rocks toward Khurais and the Arabian Gulf as shown in Fig. 1. The formation consists of an upper shale unit and a lower thick sequence of sandstone. Where identifiable, two principal sandstone units are referred to as the Safaniya and Khafji members of the Al-Wasia. The formation is underlain by the Shu'aiba shale and dolomite unit, which separates it from the Riyadh Formation. The Shu'aiba thins toward the west and disappears near the outcrop area where the Al-Wasia and the Riyadh Formations are connected and form a single hydrologic unit [1].

The Al-Wasia aquifer consists of the "main and" unit of the Al-Wasia formation, which is confined between the upper Al-Wasia and the Shu'aiba shale units. The age of this formation is classified as middle ceraceous. The thickness of the aquifer ranges from less than 100 m near the outcrop to more than 250 m west of the Khurais structure.

Along a 5-km to 2-km wide band parallel to the western limit of the quifer, the potentiometric surface is below the top of the aquifer and, hence, the aquifer is unconfined. The western limit of the aquifer lies along the line where the water table meets the bottom of the aquifer. The depth to the water table in this area is about 250 to 300 m. The potentiometric surface slopes very gently to the east, about 0.2 m per kilometer, and after it crosses the top of the aquifer it becomes confined [3,4].

Pumping tests conducted in 1975 by Sir M. MacDonald and Partners (SMMP) [5] indicate that the local transmissivity of the Al-Wasia aquifer ranges from 0.002 m^2/s to 0.070 m^2/s. The storage coefficient of the aquifer is about 0.0002 under confined conditions and 0.13 under unconfined conditions. Their estimation of the recharge to the quifer is 89.4 M m^3/year through outcrop and 11 M m^3/year from flow through wadi Sahaba (south east of Riyadh).

Another Firm (USGS, 1977) has reported that the transmissivity in the unconfined portion of the aquifer ranges from zero at the western limit of the aquifer to about 0.02 m^2/s at the boundary between the confined and unconfined systems and within the confined system the transmissivity ranges from 0.02 m^2/s to 0.06 m^2/s [3].

b) Al-Wasia well field

The Al-Wasia well field was constructed in 1981 to meet the water demand of Riyadh city at that time. It can supply water up to 200,000 m^2/day as it designed. The well field consists of 4 piezometers and 62 production wells in four parallel rows extending northwest-southeast as shown in Fig. 2. Both the rows and wells are 750 meters apart. Wells have depths range from 390 m to 500 m below ground surface. The average static water level in the well field area in mid 1981 was 274 m from average sea level (a.s.l.).

Since the well field started in operation, only half the wells in the well field has been used where the water demand in Riyadh did not reach the maximum supply capacity of the well field pumping rate. The well field is also designed to operate with half capacity while half in stand by situation. Table 1 presents the annual amounts of water supply pumped to Riyadh from different sources from 1973 to 1991 [6].

Model Description

The numerical regional ground water flow model "REGNLGW" by Rushton and Redshaw [2], which is used to simulate the Wasia aquifer in this study, is a two dimensional model based on the finite - difference technique. The method of solution, for the finite-difference equations, is the successive over relaxation (SOR) method. The system of the finite-difference equation of the governing GW flow equation is formulated and solved to produce head at each node of the grid system representing study area at the end of each time step.

In the first steps of the program runs (before the successive over-relaxation routine starts), the program reads data such as the aquifer parameters, grid spacing and boundary conditions. This data is constant throughout the simulation. The successive over relaxation method, as an interactive technique, is used to solve for the heads at each time step. Iteration proceeds until the error criterion is satisfied or until a specified maximum number of iterations is reached. The program is utilized in this study because it is simple to use and simple to change in the source file to suit the study under consideration.

Selection of Pumping Patterns

Three different pumping patterns from Al-Wasia well field were selected based on the predicted water supply to the city up to the year 2010 from the different water sources. The predicted water well field production rates and their required pumping periods are very dependent on other sources of water (CTP&J) to meet the required city demand.

Information obtained personally, from the Saline Water Conversion Corporation, indicate that there will be another seawater desalination project in the Gulf to supply water to Riyadh. This project, which is called line D, with a capacity water production of 400,000 m^3/day is expected to be completed by the year 2000. From this information and

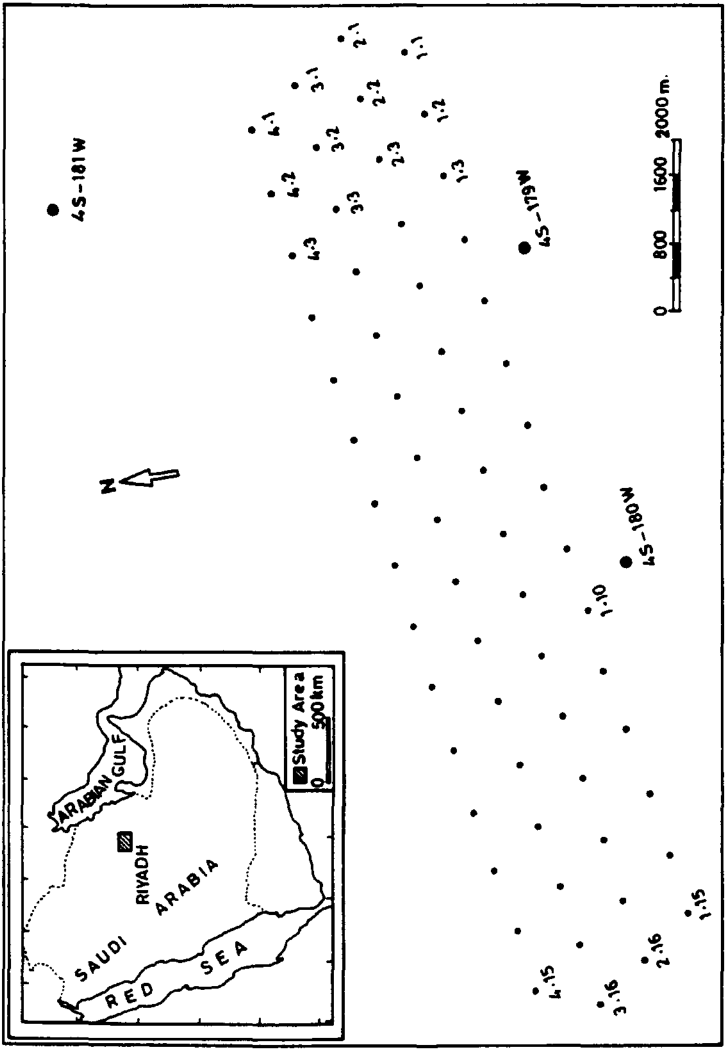

Fig. 2. Al-Wasia well field.

by noticing the annual increase in water supply presented in Table 1, it is expected that the current water supply sources will reach their water production capacity by the year 1999. Based on these expectations, two scenarios are assumed to predict water supply to Riyadh from the year 1992 up to the year 2010 as shown in Fig. 3. Both of them assume a constant annual increase in water supply (i.e. 31041 m^3/day per year) until reaching maximum production rate of all sources in 1999 (i.e. 1,336,000 m^3/day). These values based on historical water demand of Riyadh. From year 2000 to 2010, first scenario assumes that Riyadh is annually supplied with constant discharge (i.e. 1,336,000 m^3/day), while second scenario assumes an annual increase in supply (i.e. 49,450 m^3/day per year) due to new desalination line D.

It should be noted that in the year 2000, when line D in operation, another 32 wells should be introduced in Al-Wasia well field. This assumption is to maintain the mixing ratio of $W/J = 0.25$ of supply water from Al-Wasia well field to that from Al-Jubayl (this ratio is the average mixing ratio for the last eight years as can be found from Table 1.

Based on the forementioned scenarios, three different pumping patterns were chosen from Al-Wasia field to supply water to Riyadh. Table 2 displays these patterns and the total water supply to Riyadh from the year 1991 to 2010. In pattern 1, total predicted

Table 1. Average annual water supply (m^3/day) from different sources to Riyadh from year 1973 to 1991 [6].

Year	City* treatment plant (CTP)	Al-Wasia well field	Jubayl desalination plant	Total
1973	78,462	-	-	78,462
1974	92,308	-	-	92,308
1975	19,230	-	-	109,302
1976	130,769	-	-	130,769
1977	144,615	-	-	144,615
1978	155,385	-	-	155,385
1979	193,846	-	-	193,846
1980	220,000	-	-	220,000
1981	243,830	15,400	-	259,230
1982	239,718	59,513	-	299,231
1983	228,927	57,874	85,139	371,940
1984	179,510	54,928	227,100	461,538
1985	169,177	87,585	328,153	584,915
1986	148,771	104,338	429,968	683,077
1987	150,337	120,804	507,020	778,161
1988	168,744	135,998	598,335	903,077
1989	156,679	153,152	634,677	944,508
1990	189,303	168,309	657,869	1,015,481
1991	217,860	183,118	686,691	1,087,669

*Source of water to CTP are (Nisah, Namar and Hayir) wells.

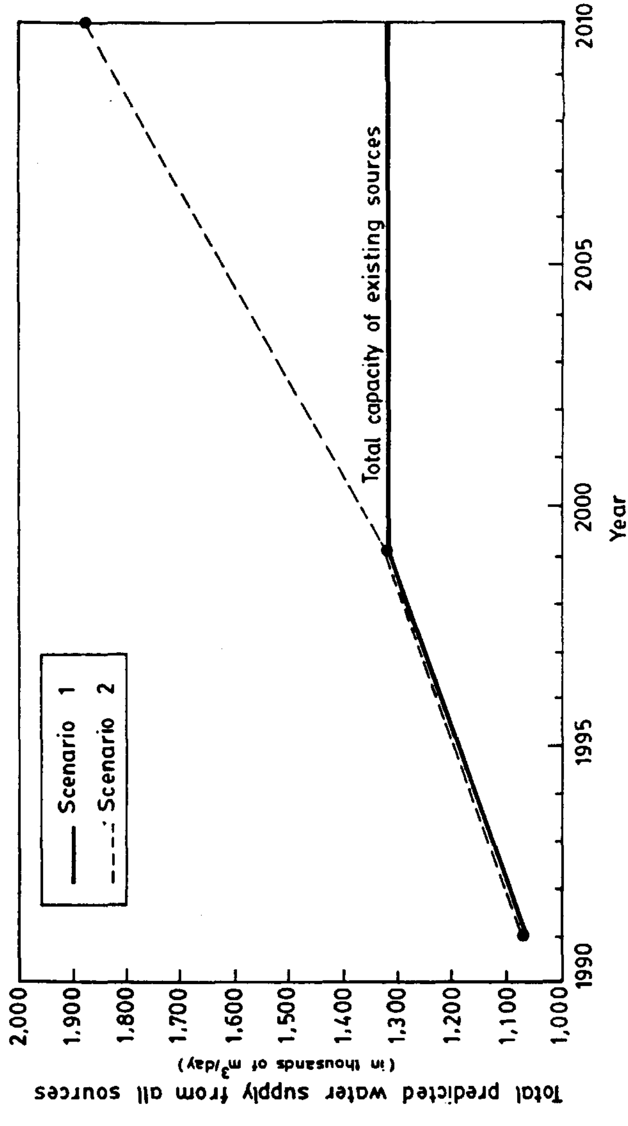

Fig. 3. Riyadh water supply scenarios.

water supply to Riyadh is fulfilled from CTP (where its production capacity or 288,000 m^3/day is reached in 1992 and it remains constant up to 2010) and from Al-Wasia / Al-Jubayl mixed water (with ratio of 0.25) to reach maximum water supply in 1999. Hence the pumping rate from Al-Wasia well field is computed by subtracting CTP rates from the total supply rate then the result is distributed between W/J with 0.25 ratio.

Table 2. Total water supply to Riyadh and pumping rates from Al-Wasia well field for years (1991-2010)

Year	Total water supply (m3/day)		Pumping rates from Al-Wasia (m3/day)		
	Scenario 1	Scenario 2	Pattern 1	Pattern 2	Pattern 3
1991	1,087,669	1,087,669	183,118	183,118	183,118
1992	1,118,710	1,118,710	166,142	178,994	178,994
1993	1,149,751	1,149,751	172,350	183,960	183,960
1994	1,180,792	1,180,792	178,558	188,927	188,927
1995	1,211,833	1,211,833	184,767	193,893	193,893
1996	1,242,874	1,242,874	190,975	198,860	198,860
1997	1,273,915	1,273,915	197,183	219,132	219,132
1998	1,304,956	1,304,956	216,956	243,965	243,965
1999	1,336,000	1,336,000	248,000	248,000	248,000
2000	1,336,000	1,385,854	248,000	248,000	219,491
2001	1,336,000	1,434,908	248,000	248,000	229,382
2002	1,336,000	1,484,362	248,000	248,000	239,272
2003	1,336,000	1,533,816	248,000	248,000	249,163
2004	1,336,000	1,583,270	248,000	248,000	259,054
2005	1,336,000	1,632,724	248,000	248,000	268,945
2006	1,336,000	1,682,178	248,000	248,000	278,836
2007	1,336,000	1,731,632	248,000	248,000	288,726
2008	1,336,000	1,781,086	248,000	248,000	298,617
2009	1,336,000	1,830,540	248,000	248,000	342,540
2010	1,336,000	1,880,000	248,000	248,000	392,000

In pattern 2, the total predicted water supply is satisfied from the CTP (with an average

In pattern 2, the total predicted water supply is satisfied from the CTP (with an average 20% of the total which is obtained from last six years production) and from Al-Wasia/Al-Jubayl with same mixing ratio (0.25) up to the year 1999. Same procedure to obtain pumping rates that applied in pattern 1 is also applied to pattern 2. From year 1999 up to year 2010 for both patterns 1 and 2, Riyadh is supplied with maximum production rate, or 1,336,000 m^3/day. Therefore, pumping rates for both patterns remain constant as in the year 1999.

In pattern 3, from 1992 to 1999 pumping rates are the same as in pattern 2 where scenarios 1 and 2 are the same in that period. From year 1999 up to 2010, predicted water supply to Riyadh is fulfilled from the CTP (at maximum production rate) and from mixed water of Al-Wasia well field (with 32 new wells) and Al-Jubayl desalination water (with new line D) using the same ratio of W/J = 0.25. Computation of pumping rates from Al-Wasia well field is performed with same procedure done in previous patterns.

Results and Discussion

Model calibration

The ground water model (REGNLGW) has been calibrated in order to determine best fitting aquifer parameters (namely: transmissivity and storage coefficient). It was done in two sequential stages, steady-state calibration followed by a transient calibration. The steady-state calibration was performed using the water level map of Al-Wasia aquifer which was developed by the U.S.G.S. in 1977 [3] before the operation of the well field. The purpose of steady-state calibration is to adjust the transmissivity distribution in the study area. Since the aquifer is assuemd in equilibrium, then the storage coefficient is assigned a vlue equal to zero and the only variable in the governing equation is the transmissivity. Boundary conditions of this calibration are the contours 290 m in the west and 260 m in the east are considered as constant heads. The boundary node in both north and south of the area are assigned a zero value of transmissivity which indicate that there is no flow through these nodes.

Matching between the computed and observed groundwater potentials was obtained after numerous computer runs in a trial and error procedure b changing the transmissivity values in the nodes of the modeled area. The results of the steady-state calibration indicate that the transmissivity of Al-Wasia aquifer at the study area varies from 0.0075 m^2/s near the outcrop area to 0.055 m^2/s east of the well field. The transmissivity at the study area increases from west to east. At the well field area, the transmissivity values were found to be varying from 0.012 m^2/s to 0.017 m^2/s.

The transient calibration is based on the established steady state pattern of transmissivity distribution over the modeled area. Initial water/piezometric levels are those which were obtained from the steady-state calibration. The model was calibrated according to the available data from the three observation wells shown in Fig. 2 for the period from mid 1981 up to the end of 1989 (a total period of 102 months). Actual pumping rates for every well (in a monthly basis) were fed into the program. The boundary conditions are the same as in the steady state calibration and a uniform value of natural ground water recharge of 35,000 m^3/day (as computed by SMP) was used. A unifrom time step of one month was assigned in the model. After the calibration has been achieved, the maximum absolute difference between the computed and observed water/piezometric levels as 1.9 m for observation well 4S-179W and 2.2 m for OW-4S-181W. Storage coefficient was obtained to be equal to 0.135 for the unconfined part and 0.004 for the confined part of the study area.

Model simulation

After having achieved the model calibration, the program was run to predict water/piezometric levels on an annual basis in different nodes in the well field of the study area. Simulation of the model was performed using the three pumping patterns which were presented in Table 2. Water levels at each node of the model mesh were determined for each pumping pattern.

Figure 4 shows water level at the center of the existing well field under pumping patterns 1 and 2 while Fig. 5 shows the water level at the center of a hypothetical well field under pumping pattern 3. These figures show water levels at the well field center in the year 2010 is: 230.7 m, 230.3 m, 242.6 m for pumping patterns 1, 2 and 3 respectively.

The elevation of ground surface at the well field ranges from 513 to 525 m (from average sea level, a.s.l.) with an average elevation of 520 m (a.s.l.) at the center of the well field. Since the critical depth to water table in the study area is assumed as 300 m, then the critical elevation of water level at the center of the well field will be (520 - 300) or 220 m (a.s.l.). Therefore results indicate that the water levels at the center of the well field in the year 2010 from all patterns did not reach the critical elevation (namely 220 m).

From Figs. 4 and 5 it is noticed that the water level is decreasing gradually as the pumping rate is increased as it should be. The value of drop in water level is changing from year to year and the maximum value occurs at the maximum change in pumping rate. These maximum values of drop in water level were found to be:

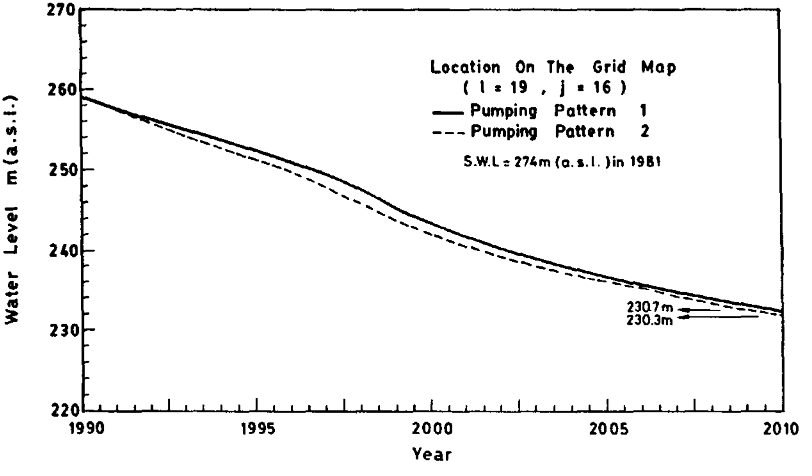

Fig. 4. Water level at the center of the well field.

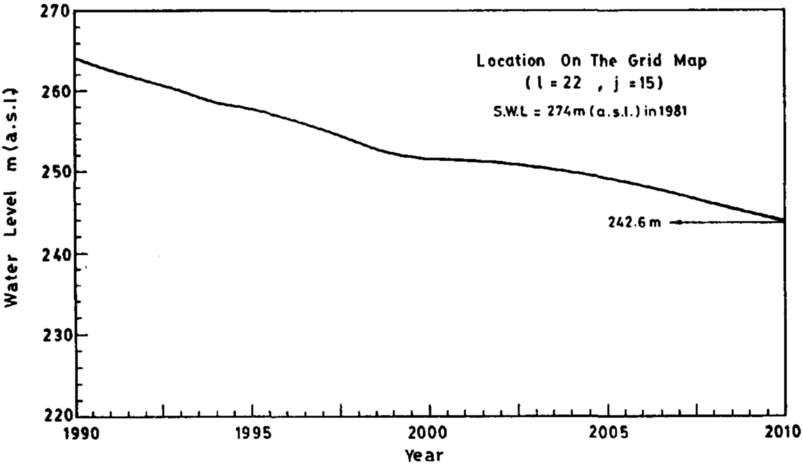

Fig. 5. Water level at the center of the well field.

- 2.5 m under pumping pattern 1 in the year 1999
- 2.4 m under pumping pattern 2 in the year 1998
- 1.7 m under pumping pattern 3 in the year 1998.

It is found that the drawdowns under pumping pattern 3 are less than those under pumping patterns 1 and 2 although the total water production is higher in pumping pattern 3. This is because the total water production in pumping pattern 3 is distributed among a greater number of wells (94 wells) which are spaced at further distances than for the existing wells.

The results of the application of the model under the different pumping patterns as shown in Figs. 4 and 5 can be summarized in the following statements:

1. For the existing well field which consists of 62 wells in four parallel rows spaced 750 m apart, the followings were concluded:
   a. A maximum drop in water level of 43.3 m occurs at the center of the well field when pumping continuously (pattern 1) for 29.5 years (from mid 1981 to 2010) at an average rate of 190,000 m^3/day (computed from Tables 1 and 2).
   b. A maximum drop in water level of 43.7 m occurs at the center of the well field when pumping continously (pattern 2) for 29.5 years (from mid 1981 to 2010) at an average rate of 194,000 m^3/day (computed from Tables 1 and 2).

2. For the hypothetical well field (which consists of the existing wells of 62 wells and another 32 wells in two rows parallel to the existing rows) a maximum drop in water level of 31.4 m occurs at the center of the well field when pumping continously (pattern 3) for 29.5 years at an average rate of 200,000 m^3/day (computed from Tables 1 and 2).

It should be noticed that the above mentioned values, for the drop in water level at the center of the well field, are based on an average pumping rate throughout the year. The drop in water level is higher in summer where the pumping from the well field is at a maximum rate, and it is low in winter where the pumping is at a minimum rate. However, the effect in summer pumping has small effect on water level drop.

The results of this study are slightly different from the prediction which was made by the U.S.G.S. (1977). They predicted a drop of 60 m in water level at the center of the well field when pumping at a rate of 220,000 m^3/day continously for 20 years. This might be because in their study the aquifer parameters were underestimated and the vertical leakage to the aquifer from the upper Wasia formation was not considered. Using (REGNLGW) with physically-based aquifer parameters in this study should give more accurate resutls and predictions of water level drop in the study area.

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التنبؤ بتأثير الضخ على حقل آبار الوسيع

صالح عبدالله الحسون

قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود، ص.ب ٨٠٠،
الرياض ١١٤٢١، المملكة العربية السعودية

(استُلم في ٥/ ١٢/ ١٩٩٥م؛ قبل للنشر في ٦/ ٣/ ١٩٩٦م)

ملخص البحث. يعتبر تكوين (الوسيع) أحد التكوينات الرئيسة في المملكة العربية السعودية والممتد على طول المنطقتين الوسطى والشرقية. تم تشغيل حقل آبار الوسيع (٦٢ بئرا) في عام ١٩٨١م لإمداد مدينة الرياض بما تحتاج إليه من المياه. يقع الحقل على مسافة ١١٠ كلم تقريبا شرق مدينة الرياض. إن كميات ومعدلات الضخ من الحقل قد تغيرت خلال السنوات القليلة الماضية.

في هذه الدراسة تم اختبار أداء الحقل عن طريق تقدير أثر الضخ على منسوب المياه في الحقل خلال العشرين سنة القادمة بفرض ثلاثة أنماط مختلفة من الضخ. وقد تم ذلك باستعمال نموذج للمياه الجوفية يسمى (REGNLGW). وقد دلت نتائج المحاكاة باستخدام النموذج بأن مستوى الماء في الحقل سنة ٢٠١٠م، تحت تأثير أنماط الضخ الثلاثة، لن يصل إلى المستوى الحرج الذي يعادل ٣٠٠م تحت سطح الأرض.