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The determination of allowable exploiting yield for the deep groundwater

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ABSTRACT

Deep groundwater can promote the development of local economy, and raise living standards and improve the environment of residents, and reasonable exploiting method can improve groundwater utilization level. Based on Theis's equation of the confined unsteady flow in full well, the principle and the calculation procedure of uniform well arrangement method is provided in this article. The method is suitable for the confined and infinite aquifers with large distribution, horizontal roof and floor, non-close interlayer hydraulic contact, and homogenous pore, which are short of recharge. The allowable exploiting yield and the optimal pumping well numbers of the deep porous groundwater have been calculated by the method in the Kaifeng city, China, and the allowable exploiting intensity and the single-well allowable pumping discharge have also been determined. The calculation results show that the actual exploiting plan of two aquifers, 800–1,000 m and 1,000–1,200 m, in Kaifeng city could be adjusted for reducing the faster groundwater drawdown rate caused by unreasonable exploitation. The method to determine the allowable exploiting yield has the advantages of understandable theory and simplified calculation, and the study contributes a scientific basis for the exploitation and protection of the deep porous groundwater in the North China Plain.

Keywords: Uniform well arrangement method; Deep groundwater; Designed drawdown; Allowable exploiting yield; Optimal pumping well numbers

1. Introduction

Deep porous groundwater exists in the confined aquifers of medium sand, fine sand, and silty sand strata with an over 600 m buried depth, whose temperature is often over 25°C (hereinafter referred to as the deep groundwater). This groundwater resource is widely distributed in the Neogene Minghuazhen (Nm) Formation and the Neogene Guantao (Ng) Formation aquifers in the North China Plain and is no pollution, heat, and mineral [1–4]. More than 2,000 pumping wells are being exploited in the North China Plain, which has promoted the development of local tourist economy, and raised living standards and improved the environment of residents.

As a clean heat water resource, deep porous groundwater is widely concerned by the society. Because the deep groundwater is remote from source area and is short of recharge, the unreasonable distribution and exploitation on pumping wells can bring about a series of issues, such as disorderly drops in groundwater level, pumping costs increasing, outer-water intrusion, and deterioration of water quality [5–13]. Therefore, it is necessary to determine the allowable exploiting yield of the deep groundwater.

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At present, there are many methods to determine the allowable exploiting yield of the deep groundwater in designed drawdown [14–16]. The existed methods include the water balance, the correlation analysis, the exploiting test, the analytic method, the numerical techniques, and empirical formulae [17–25]. The above methods cannot accurately calculate the allowable exploiting yield of the porous confined and infinite groundwater with wide distribution, even roof and floor and non-close interlayer hydraulic connection. The uniform well arrangement method suggested in the article belongs to the analytical methods and is used to calculate the allowable exploiting yield and the optimal pumping well numbers of the deep porous groundwater. By the method, expensive groundwater projects can work fully, the valuable porous confined groundwater can be exploited scientifically, and some environmental hydrogeological problems can be avoided effectively. This study contributes a scientific basis for rational development of the deep groundwater.

2. Methods and materials

2.1. Mathematical model

When the deep groundwater exists in the confined and infinite aquifers with large distribution, horizontal roof and floor, non-close interlayer hydraulic contact, and homogenous pore and is short of recharge, the drawdown of groundwater level in a fully penetration pumping well can be calculated by Theis's equation as follows:

$$S = \frac{Q}{4\pi T} W(U) \tag{1}$$

$$U = \frac{r_{ij}^2 \mu^*}{4Tt} \tag{2}$$

where S is the drawdown of groundwater level at calculation point within the scope of a pumping well, m; Q is the pumping discharge of an exploiting well, m^3/d; T is the transmissibility of aquifer, m^2/d; μ^* is the storativity of aquifer; $W(U)$ is the pumping well function, $W(U) = \int_U^\infty \frac{e^{-y}}{y} dy$; t is the pumping time of one well, d; r_{ij} is the distance from the calculation point to the center point of the pumping well, m. When the calculation point is located inside the pumping well, r is equal to the pumping well radius r_ω, m.

When n pumping wells are in calculation area, the groundwater drawdown of calculation point, with intersecting pumping influence, can be calculated using the following:

$$S = \sum_{l=1}^{n} \frac{Q}{4\pi T} W(U) \tag{3}$$

where l is numerical order of the pumping well, l = 1, 2, 3 ... n; the meanings of the other symbols is the same in Eqs. (1) and (2).

2.2. Uniform layout of pumping well

To calculate the allowable exploiting yield of an aquifer, it is hypothesized that the pumping wells are distributed in a square grid (Fig. 1). The coordinate origin in Fig. 1 is located in the well at the center of the calculated area. The X-axis is i, $i = -M, ..., -2, -1, 0, 1, 2, ..., M$, and the Y-axis j, $j = -K, ..., -2, -1, 0, 1, 2, ..., K$.

A pumping well can be identified as (i, j), and the distance between pumping well and coordinate origin is as follows:

$$r_{ij} = r_0 \sqrt{i^2 + j^2} \tag{4}$$

$$r_{ij} = r_\omega \ (i = 0, j = 0) \tag{5}$$

$$r_0 = 1000 \sqrt{F/n} \tag{6}$$

where r_{ij} is the distance between pumping well and coordinate origin, m; r_ω is the pumping well radius, m; r_0 is the distance between two adjacent wells (the side length of one square), m; F is the calculated area, km^2; and n is the number of pumping wells.

2.3. Calculation formula of allowable exploiting yield

When all wells are in the uniform well arrangement in a square grid and equal pumping discharge Q, specific discharge (Q/S) can be obtained by Eq. (3).

$$Q / S = 4\pi T / \sum_{l=1}^{n} W(U) \tag{7}$$

Obviously, the value of Q/S is related to the adjacent well spacing r_0 and the number of pumping wells n according to Eqs. (4) and (6). The total exploiting yield Q_a in calculation area is as follows:

$$Q_a = n \times Q \tag{8}$$

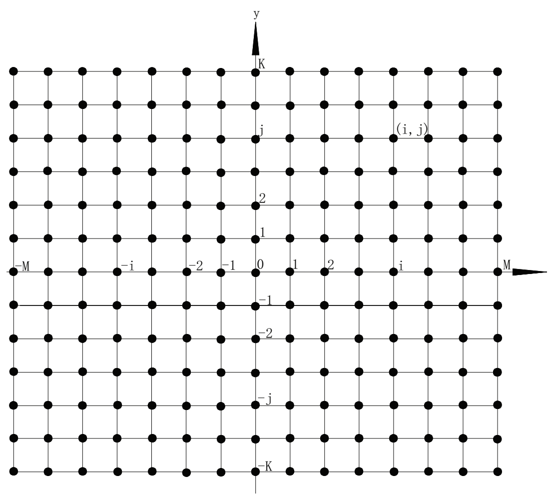

Fig. 1. Square distribution of pumping wells.

According to Eqs. (7) and (8), the formula of the total exploiting yield in unit groundwater drawdown can be obtained.

$$Q_a / S = 4\pi n T / \sum_{l=1}^{n} W(U) \tag{9}$$

When the limit time of exploiting groundwater and the maximum allowable drawdown of groundwater level (design drawdown) are known, the Q_a/S_{max} can be calculated by Eq. (9). Q_a and S_{max} are, respectively, the allowable exploiting yields (m^3/d) and the designed drawdown (m).

2.4. Calculation steps of allowable exploiting yield

Based on Eq. (9), the steps to obtain the n and the Q_a are: (1) The calculated area F, the well radius r_ω, the limit time of exploiting groundwater t and the design drawdown S_{max} are given. (2) The transmissibility T and the storativity μ^* based on the pumping test of steady flow and unsteady flow in single well are obtained. (3) Based on the given number of pumping wells n, the Q_a/S_{max} are calculated, and then the curve of Q_a/S_{max} and n are drawn. (4) According to the curve of Q_a/S_{max}~n, a stationary point where the curve is from sharp to flat is chosen. Then the n and Q_a/S_{max} in the stationary point are, respectively, the optimal numbers of pumping well and the reasonable specific discharge of the calculation area. (5) The allowable exploiting yield Q_a of the deep groundwater in the calculation area can be determined by Q_a/S_{max} and S_{max}.

3. Case study

3.1. Aquifer characteristics

Kaifeng city is located in the North China Plain. Its urban area is 165.23 km^2, and the ground elevation is 70 m, with a ground slope of 1:5000. The topography is slightly slopy from west to east. Currently, 600–1,800 m depth groundwater in the Nm aquifers and the Ng aquifers are being exploited in 89 pumping wells. The groundwater temperature and age ranges are from 32°C to 68°C and from 21,140 a to 24,970 a, respectively. The groundwater source area is apart from 60 km to Kaifeng city [26,27]. Area of the 800–1,000 m and 1,000–1,200 m porous aquifers in Kaifeng city is wide, the roof and floor is horizontal, and the interlayer hydraulic contact is not close, which meet the requests of Theis's equation and calculation formula of allowable exploiting yield.

According to their burial conditions, hydraulic characteristics and exploiting status, aquifers have assigned thicknesses of 200 m, namely the 600–1,800 m depth porous strata is often divided into six aquifers. This article takes the 800–1,000 m and 1,000–1,200 m aquifers as the example to calculate the allowable exploiting yield of groundwater because of the complete hydrogeological data. The hydrogeological characteristics of two aquifers are shown in Table 1.

3.2. Data and parameters of aquifers

Based on the local hydrogeological, economic, and technological conditions of Kaifeng city, the designed drawdown of groundwater level is 50 m, the limit time of exploiting groundwater is 30 years, and the pumping well radius is 0.08 m. Then, the transmissibility and storativity of two aquifers were determined by the pumping test of steady and unsteady flow in one well (Table 2).

Table 2
Hydrogeological parameters of two aquifers

Aquifer (m)	**800–1,000**	**1,000–1,200**
Transmissibility (m^2/d)	109.93	113.80
Storativity	0.00065	0.00016

Bold values represent buried depth (m).

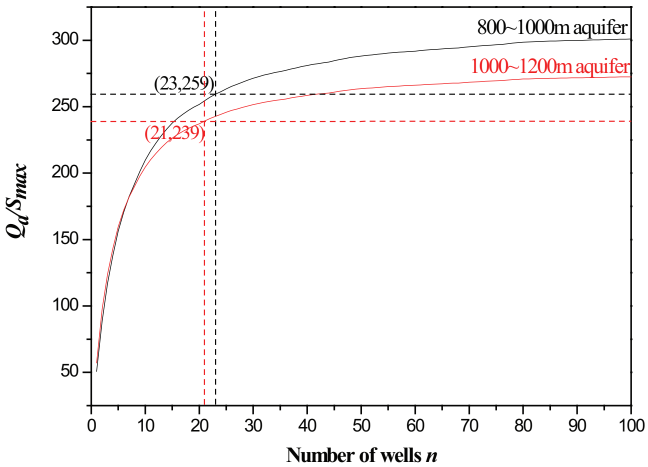

Fig. 2. Q_a/S_{max}~n curves of two aquifers.

Table 1
Hydrogeological characteristic of groundwater aquifers

Aquifer (attribute)	Lithology	Aquifers and thickness (m)	Aquiclude thickness between upper-down aquifer
800–1,000 m (Nm)	Medium sand, fine sand, silty sand with clay layer	7–16 sand layers; 2–18 m thickness of single layer, 67–112 m of total thickness, 94.08 m of average thickness	15–40 m clay layer
1,000–1,200 m (Nm)	Medium sand, fine sand, silty sand with clay layer	6–14 sand layers; 1–20 m thickness of single layer, 36–136 m of total thickness, 75.6 m of average thickness	10–60 m clay layer

Table 3
Allowable exploiting yield in 50 m drawdown

Aquifer (m)	N (optimal well numbers)	Q_a/S_{max} ((m^3/d)/m)	r_0 (m)	Allowable exploiting yield (m^3/d)	Allowable exploiting intensity ((m^3/d)/km^2)	Single-well allowable pumping discharge ((m^3/d)/well)
800–1,000	23	259	2680	12,950	78.38	563.04
1,000–1,200	21	239	2805	11,950	72.32	569.05
Sum	44			24,900		

Table 4
Comparisons with allowable and actual exploitation

Aquifer (m)	Optimal well numbers	Actual well numbers	Allowable exploiting yield (m^3/d)	Actual exploiting quantity (m^3/d)	Allowable exploiting intensity ((m^3/d)/km^2)	Actual exploiting intensity ((m^3/d)/km^2)
800–1,000	23	14	12,950	2,645.68	78.38	0.24–106.30
1,000–1,200	21	43	11,950	7,298.20	72.32	16.17–141.76
Sum	44	57	24,900	9,943.88	–	–

3.3. Allowable exploiting yield and optimal layout of wells

According to Eq. (9), the Q_a/S_{max}~n curves of the two aquifers in Kaifeng city can be drawn (Fig. 2). The n and Q_a/S_{max} of the stationary points where the curves are from sharp to flat are, respectively, obtained in Fig. 2. So the optimal numbers of pumping well of two aquifers are, respectively, 23 and 21, and the reasonable specific discharge of two aquifers are, respectively, 259 and 239 (m^3/d)/m. In the 50 m designed drawdown, the allowable exploiting yield of two aquifers is, respectively, 12,950 and 11,950 m^3/d (Table 3).

The results shown that when the exploiting time and designed drawdown are, respectively, 30 years and 50 m, the optimal numbers of pumping well of the 800 to 1,200 m aquifers in Kaifeng city are 44, and the allowable exploiting yields are 24,900 m^3/d. The allowable exploiting intensity of the aquifers and the single-well allowable pumping discharge are listed in Table 3.

3.4. Adjusting in actual layout of pumping wells

At present, there are 57 pumping wells between 800 and 1,200 m aquifers in Kaifeng city. The total actual exploiting quantity is 9,943.88 m^3/d, and other actual exploiting data of two aquifers are shown in Table 4. Obviously, the actual exploiting quantity of two aquifers did not exceed the allowable exploiting yield in the 50 m designed drawdown. However, the actual pumping well numbers of the 1,000–1,200 m aquifer exceed that of the allowable ones. And in some local areas, the actual exploiting intensity of two aquifers is larger than the allowable exploiting one. Because of unreasonable actual layout and exploiting intensity, the average drawdown of the 800–1,200 m aquifers is 3.25–3.77 m per year in Kaifeng city.

Based on the allowable exploiting plan of two aquifers in Kaifeng city, the actual exploiting plan could be adjusted for reducing the faster groundwater drawdown rate caused by unreasonable exploitation. First, because the actual pumping well numbers of 1,000–1,200 m aquifer exceed the allowable well numbers, the actual well numbers should be reduced according to the wells' applied situation. Second, when the actual exploiting intensity is larger than the allowable exploiting one, it is necessary to cut down the exploiting quantity of single well or reduce the number of the pumping wells. Third, the newly built pumping wells should meet the following three targets, namely, allowable pumping well numbers, allowable exploiting intensity, and single-well allowable pumping discharge.

Obviously, the uniform well arrangement method has the advantages of understandable theory and simplified calculation. When other aquifers (except the 800–1,000 m and 1,000–1,200 m aquifers) in Kaifeng city have complete hydrogeological data, the allowable exploiting yield and the optimal pumping well numbers could be calculated according to the above method. In short, the method could be used to determine the allowable exploiting yield and the optimal pumping-well numbers, and provides a scientific basis for the rational development in the deep porous groundwater in the North China Plain.

4. Conclusions

- When the deep groundwater exists in the confined and infinite aquifers with large distribution, horizontal roof and floor, non-close interlayer hydraulic contact, homogenous pore, and is short of recharge, and the drawdown of groundwater level in a fully penetration pumping well can be calculated by Theis's equation.
- The method could be used to calculate the allowable exploiting yield and the optimal well numbers of the deep porous aquifers and has the advantages of understandable theory and simplified calculation. While improving the calculation accuracy need continue to study.
- Using the method, the allowable exploiting yield and the optimal well numbers of 800–1,200 m depth aquifers were calculated in Kaifeng city, and the allowable exploiting intensity and single-well allowable pumping discharge were given. This result provides a scientific basis for exploitation and protection of the deep porous groundwater in the North China Plain.

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