Experimental study on water level and absorption capacity in a radial well flow in a loess area

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ABSTRACT

In this paper, the theoretical basis for flow calculation in an injection well was discussed. It proposed that the flow rate of an injection well could be calculated referring to pumping theory and method. A mathematical model of the rising curve of water level around a radial well was established and the equation for calculating the rising curve was given. The calculation equations selected for the water absorption capacity of injection wells were explained and examples were verified and compared. The results indicated that, under the same injection conditions, the water level value calculated by the analysis method was slightly larger, but the error between the analysis method and the semi-theoretical and semi-empirical methods was small. In the processes of steady flow injection and unsteady flow injection, there was a small difference of water absorption capacity, and the former was slightly larger. The measured values of water absorption capacity were only about one-third of the calculated values based on pumping theory. Overall, the analytical solution method for predicting the rising curve of water level has priority in well injection. The semi-theoretical and semi-empirical equation for calculating water absorption capacity sifted first has priority in steady flow injection, the equation sifted second has priority in unsteady flow injection.

Key words | mathematical model, phreatic aquifer, radial well injection, rising curve, water absorption capacity

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INTRODUCTION

Radial wells in the loess region undertake an important water-supply task in China. More and more attention is being paid to the scientific management of radial wells. How to give the descent curve surface in pumping and the rising curve surface in injection is a major problem to be solved in theoretical calculation and engineering practice.

The radial well can make full use of the permeability characteristics in loess strata, that is, the permeability is weak in the horizontal direction and strong in the vertical direction, and the outflow of water is many times more than in a normal pipe well (Ameli & Craig 2018; Tang *et al.* 2018). The amount of water pumped from a radial well is limited, which is difficult to maintain in most cases (Maroney & Rehmann 2017).

There has been a lack of studies on the theory and method of well injection including radial wells (Zheng *et al.* 2018). It has been found that the injection process can be treated as approximately the reverse of the pumping process (Li *et al.* 2006; Yan 2015; Zhang *et al.* 2017). There have been many researchers engaged in relevant research in pumping, and a few have been worth learning from. Xue & Zhou (2012, 2013) constructed an equation of the descent curve surface in pumping for a single radial tube. Based on the curve surface model of pumping descent, they constructed a water output model for a radial well. Tang *et al.* (2018)

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proposed a new semi-analytical streamline simulation method in the near-wellbore region in polar/cylindrical coordinate systems; by treating each stream tube as a flow unit, it makes streamline simulation a powerful tool. Huang *et al.* (2016) described transient hydraulic head distributions in pumping at a radial well. They employed the governing equation with a point-sink term, and developed a mathematical model for describing head distributions induced by pumping in an unconfined aquifer. Javandel & Zaghi (1975) developed a semi-analytical solution to describe the head distributions from a fully penetrating well in a confined aquifer. Tsou *et al.* (2010) derived analytical solutions to investigate head distributions and stream depletion rate (SDR) induced from pumping in a slanted well in a confined aquifer. Najafzadeh & Saberi-Movahed (2018) used the group method of data handling (GMDH) and group processor and wavelet analysis in studying the seepage diffusion of pipes and tubes, and the calculation accuracy was improved. There have many studies on well flow calculation, but many fewer on water level curves in injection. At present, researchers tend to use off-the-shelf software directly to calculate or predict the curve of groundwater level, though some mathematical models have been established for predictions (Jiang *et al.* 2014).

The goal of this paper is to develop a new way to predict the rising curve of well water level in injection in loess areas. According to the variation of well water level, it is to test the water absorption capacity of the injection well under two injection modes. These are the prospective exploration for groundwater recharge by radial wells in loess areas.

STUDY AREA AND DATA SOURCES

The test site is about 700 metres southwest of Qian County in Shaanxi Province. The altitude of this location is about 650 metres above sea level. The test well is located 300 metres west of the Mogu River. The injection water comes from Qianling reservoir. The water quality is relatively simple. Pressure-free injection was adopted. The location of the injection well and its observation hole are shown below (Figure 1).

The stratum under the test well is approximately horizontal. Loess-like mild clay of the Middle Pleistocene is the main phreatic aquifer band in this area. The burial depth is about 20 to 30 metres and groundwater flow essentially is controlled by the topography. The hydraulic gradient is usually no more than 1% and water recharge conditions are poor.

The test was divided into two stages. During the first stage, a steady flow was maintained for 160 hours and the recharge flow rate was 9.3 m^3/h. During the second stage, an unsteady flow was maintained for 280 hours and the average recharge flow was 10 m^3/h. The interval was 6 months. Under the conditions of steady flow and unsteady flow, the water levels of well and observation holes were measured.

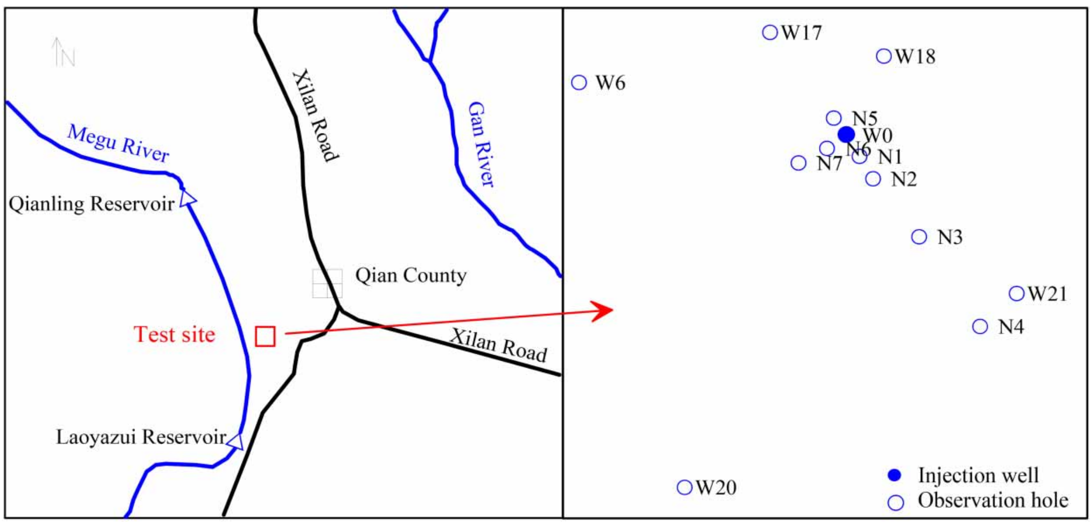

Figure 1 | The position and hole layout of the test site.

METHODS

Mathematical model and analytical solution

The radial tubes are in the same horizontal plane and have a symmetrical layout and are of equal length. Each radial tube has the same water yield. According to the characteristics of the rising curve in steady injection, a water dome will form around the well. The rise of the curve shape is approximately the same through any vertical section. The water level remains unchanged outside the radius of influence. Hence, the problem of finding the general solution for the rising curve in a plane can be simplified as shown in Figure 2.

It can be assumed that the rising curve is controlled by the water height (h) and the horizontal distance (x) from the well. All of the factors are concentrated in the two variables, from which the function $f(h, x)$ can be constructed. At the same time, the supply from the tube is equal to the sum of seepage water of a unit width between two rising curves of water level and the seepage recharge extending beyond the radial tubes (ΔQ). The assumed conditions are:

(a) the rising curve of water level in the seepage field is consistent in all directions;
(b) the two times selected are the times when the water level is stabilized in steady flow injection;
(c) the seepage water extending beyond the radial tubes is approximately constant;
(d) the vertical permeability in the aquifer is significantly greater than the horizontal permeability;
(e) the aquifer is approximately horizontal and the permeability is approximately constant;

where h is the well water level (m); h_w is the starting water level; x is the horizontal distance from observation point to injection well (m); μ is the specific yield of the aquifer; and K is the permeability coefficient (m/h); a is the horizontal section area of the rising water mound centered around the well; ΔQ is the water supply outside the scope of the radial tubes (m^3/h); ω is the unit seepage area in the vertical direction; I is the hydraulic gradient; v is the rising rate of water

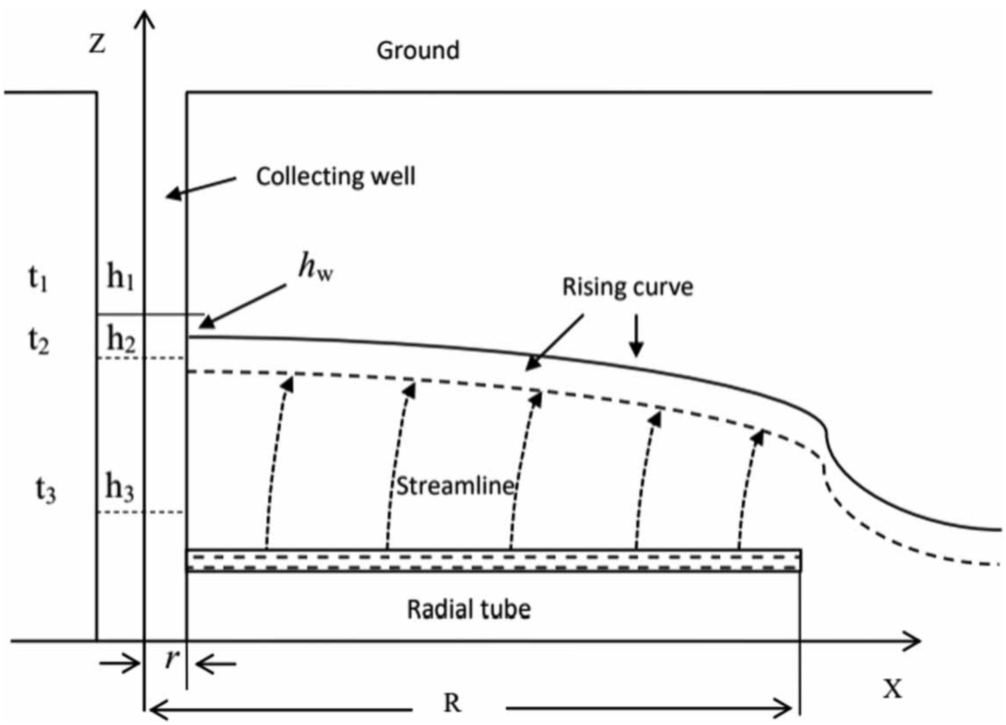

Figure 2 | Schematic diagram of the seepage flow of a radial well in the vertical direction.

level; αt is the interval between two observation times (h); r is the radius of the water-collecting well (m); R is the length of the radial tubes (m); Q is the seepage supply of the radial tubes to the aquifer (m^3/h); and n is the number of radial tubes.

If the expression for the rising curve in the seepage field is:

$$f = f(x, h)$$

Then, the flow rate of the aquifer between the two ascending curves, with a width of dx within a radial tube, is:

$$Q_{\Delta t,\Delta h} = \frac{2\pi\alpha[f(x, h+\Delta h) - f(x, h)]}{\Delta t} xdx$$

The unit width of water from the two ascending curves with r as the inner diameter and R as the outer diameter is given by:

$$Q_{\Delta t,\Delta h} = \int_r^R \frac{2\pi\alpha[f(x, h+\Delta h) - f(x, h)]}{\Delta t} xdx$$

If ΔQ is the water flow rate from the radial tube to the outside, and v is the rising velocity of water level, then:

$$\int_r^R \frac{\partial f(x, h)}{\partial h} xdx = \frac{k\omega I - \Delta Q}{2\pi\alpha v} \tag{1}$$

Equation (1) is the mathematical model established, according to the research experience of Wang Yufeng, Xu Zhigang and Liu Tao in 2012, and the characteristics of the rising curve in Figure 2 can be described as follows:

$$f(r, h) = hg(r) + \varphi(r)$$

$$\frac{\partial f(r, h)}{\partial h} = hg'(r) + \varphi'(r) = 0$$

and the following functions can be constructed:

$$g(x) = \frac{k\omega I - \Delta Q}{2\pi\alpha vx} e^{(r-x)}$$

$$\varphi(x) = \frac{k\omega I - \Delta Q}{2\pi\alpha vx} h\left(lnx - \frac{1}{x}\right) + h - \frac{k\omega I - \Delta Q}{2\pi\alpha vx} hlnr$$

The expression for the rising curve of water level is:

$$h_x = f(x, h) = \frac{(k\omega I - \Delta Q)e^{(r-x)}}{2\pi\mu vx} + \frac{k\omega I - \Delta Q}{2\pi\mu v} h\left(lnx - \frac{1}{x}\right) + h - \frac{k\omega I - \Delta Q}{2\pi\mu v} hlnr \tag{2}$$

ΔQ is equal to the water yield of the radial tubes that temporarily are in the same condition. The value of h_w is determined by reference to the hydraulic jump value obtained from previous experiments.

Semi-theoretical and semi-empirical equation

The numerical simulation of the groundwater level in the seepage field is 'ideal' and the analytical solution of the mathematical model needs to be simplified. In this way, a certain error in the prediction of the groundwater level in the seepage field will be unavoidable. Therefore, studies of the semi-theoretical and semi-empirical equation would appear to be attractive. Researchers have had positive research experience in quantitative calculation (Tofiq & Guven 2015; Sammartano *et al.* 2016).

On the basis above, it is hypothesized that the injection process will be equal to the reverse process of pumping. By absorbing the experience of predecessors' research, such as that of Qu Xingye and Cai Guozhen, an equation can be proposed to estimate the rising curve of water level as:

$$h_x = nh_R + n(h_0 - h_w - h_R)e^{-\beta(R-x)} \tag{3}$$

$$\beta = \frac{1}{R_2 - R_1} ln\frac{h_2 - h_p}{h_1 - h_p} \tag{4}$$

where h_x is the water level at a distance x from the well (m); h_0 is the water level in the well (m); h_R is the water level at the end of a radial tube (m); β is the experience value of the rising curve; R_1 and R_2 are the horizontal distances of observation holes at a distance from the injection well (m); h_1 and h_2 are the water levels in the observation holes at distances R_1 and R_2 (m) from the injection well. Other parameters are identical to those of Equation (2). The height of each variable in the above Equation (3) is calculated from the well bottom.

Explanation of water absorption capacity

The water absorption capacity of the injection well can be expressed by the ratio of the flow and the head, which is of great reference value in the engineering design and planning of radial wells (Wang *et al.* 2012; Miotliński *et al.* 2014). To the present, there have been various equations for hydrogeological calculations, but the calculation method for the injection of a radial well has not been found. In terms of mechanism, pumping and injection have strong similarity, thus, pumping theory was used to check the calculation of water absorption capacity proximately in this paper.

According to the test conditions and the hydrogeological situation in injection, an expression, based on the principle of the Dupuit equation, can be developed to describe the process as:

$$q = \frac{Q}{h} = 2\pi kMln\frac{R}{l\sqrt[n]{0.25}} \tag{5}$$

where q_0 is the measured value for water absorption capacity (m^3/h.m); Q is the injection flow (m^3/h); h is the value of well water level (m); l is the length of the radial tubes (m); n is the number of radial tubes; M is the aquifer thickness (m); and R is the influence radius (m).

Equation (5) is based on pumping theory, which absorbed the research results of predecessors' research in 1975 and 1978, such as that of Qu Xingye and Cai Guozhen. It can be considered as a kind of description of water absorption capacity or recharge ability. When injection is stable, the value change of k over a certain period of time can be neglected. Equation (5) can be used to plan and design a water recharge unit with reasonable injection flow for a range of water levels.

According to the research status of radial wells, the water absorption capacity is influenced by many factors. Considering the complexity of the problem, the research needed to be combined with actual references. In this study, the test results from the Irrigation Research Office of Shaanxi Institute of Water Resources Science were used for reference. In the loess area, under the condition of a phreatic aquifer, the water absorbing capacity of an injection well can be described as:

$$q = \frac{Q}{h} = 2\alpha kr\sum_{i=1}^{n} l_i, \quad \alpha = 1.27n^{-0.418} \tag{6}$$

The parameters in Equation (6) are the same as in Equation (5).

It was noted that the theoretical basis of Equations (5) and (6) was pumping theory. The transformed equations above were modified to some extent in order to test their feasibility, and would be used to predict injection flow problems.

RESULTS AND DISCUSSION

Value verification of water level in steady flow injection

In steady flow injection, when the water level observed became stable, the range of water level change was within a 200-metre radius of the injection well. By comparing with the measured value of water level, the means of the relative errors between the predicted values and observed value were about −5%. The predicted result from using Equation (3) was slightly larger than that from Equation (2). In the observation range, the relative errors of water level range predicted by using Equations (2) and (3) were −4.376% to −6.166% and −4.574% to −6.223% (Table 1).

Table 1 | Comparison of calculated and observed water level values in steady injection

Project	W_0	N_1	N_2	N_3	N_4	N_5	N_6	N_7	Average value
r (m)	0	10	50	117	217	10	10	50	
h_{s0} (m)	4.921	3.742	1.400	0.251	0.040	3.410	3.421	1.010	
h_{s1} (m)	4.618	3.535	1.326	0.238	0.038	3.258	3.268	0.966	
h_{s2} (m)	4.615	3.523	1.322	0.239	0.038	3.250	3.258	0.964	
$(h_{s1}-hs_0)/h_{s0}$ (%)	−6.166	−5.539	−5.286	−4.992	−4.821	−4.463	−4.485	−4.376	−5.016
$(h_{s2}-hs_0)/h_{s0}$ (%)	−6.223	−5.859	−5.571	−4.802	−4.576	−4.698	−4.777	−4.574	−5.135

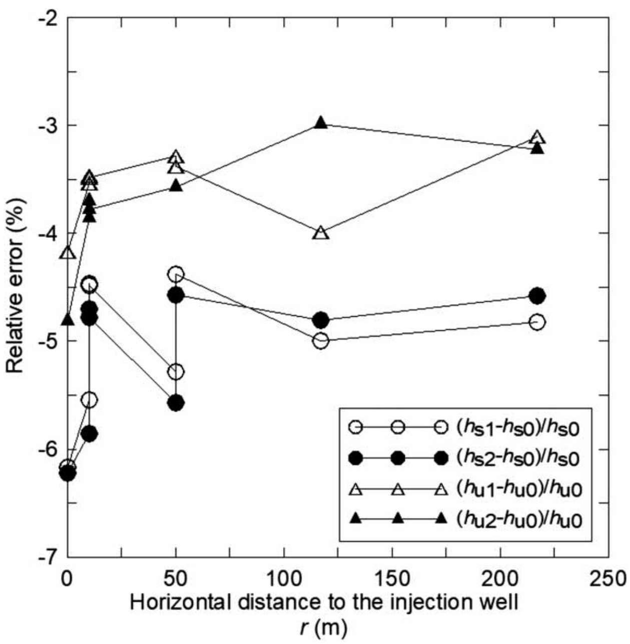

Figure 3 | Relative error of radial water level calculation.

W_0 is the code for injection well; N_1 to N_7 are the codes for observation holes; r is the distance between observation hole and injection well (m); h_{s0} is the water level measured in steady injection (m); h_{s1} and h_{s2} are the rising water levels calculated by using Equations (2) and (3) respectively (m); $(h_u - h_u)/h_u$ is the relative error.

The comparison of results in Table 1 shows that the results from using Equations (2) and (3) to predict the water level were close, and the error was acceptable. The closer the water injection well was, the greater the relative error of water level prediction (Figure 3). If the accuracy requirement is considered, the use of Equation (2) should be given priority. If convenience, the use of Equation (3) should be given priority.

Value verification of water level in unsteady flow injection

The purpose of unsteady flow injection was designed to verify whether this kind of injection method is beneficial for relieving the well clogging. The well water levels are shown in Table 2. The average value of the parameters is the same as in Table 1; h_{u0} is the water level measured in unsteady injection (m); h_{u1} and h_{u2} are the rising water levels calculated by using Equations (2) and (3) respectively (m). The other parameters in Table 2 have the same meaning as in Table 1.

By comparing with the measured value of water level, the average value of the relative errors between the predicted values and observed value was about −3.5%. The predicted result from using Equation (3) was slightly larger than that from Equation (2) similarly. In the observation range, the relative errors of water level range predicted by using Equations (2) and (3) were −3.376% to −4.166% and −3.574% to −4.816%. The closer the water injection well was, the greater the relative error of water level prediction.

The comparison of results in Table 2 shows that, compared with the steady injection, the relative error of water level prediction was small in the unsteady injection (Figure 3).

Value verification for water absorption capacity in steady flow injection

Steady water injection can be achieved by controlling the injection flow. From theoretical analysis, it is easy to understand that the unit injection flow can represent the water absorption capacity of a well and the value should be

Table 2 | Comparison of calculated and observed water level values in unsteady injection

Project	W_0	N_1	N_2	N_3	N_4	N_5	N_6	N_7	Average value
r (m)	0	10	50	117	217	10	10	50	
h_{u0} (m)	7.601	5.010	1.441	0.260	0.050	4.611	4.620	1.051	
h_{u1} (m)	7.284	4.833	1.394	0.250	0.048	4.451	4.459	1.016	
h_{u2} (m)	7.235	4.817	1.390	0.252	0.048	4.440	4.446	1.013	
$(h_{u1}–h_{u0})/h_{u0}$(%)	−4.166	−3.539	−3.286	−3.992	−3.101	−3.463	−3.485	−3.376	−3.551
$(h_{u2}–h_0)/h_{u0}$(%)	−4.816	−3.859	−3.571	−2.989	−3.225	−3.698	−3.777	−3.574	−3.689

Table 3 | Comparison of the water absorption capacity in steady flow injection

Project	Calculated value						Average value
q_{s0}	0.389	0.704	0.656	0.660	0.674	0.709	0.620
q_{s1}	1.111	1.956	1.503	1.784	1.982	1.866	1.700
q_{s2}	1.255	2.011	2.021	2.200	2.042	2.132	2.010
q_{s0}/q_{s1}	0.350	0.360	0.390	0.370	0.340	0.380	0.365
q_{s0}/q_{s2}	0.310	0.350	0.324	0.300	0.330	0.333	0.310

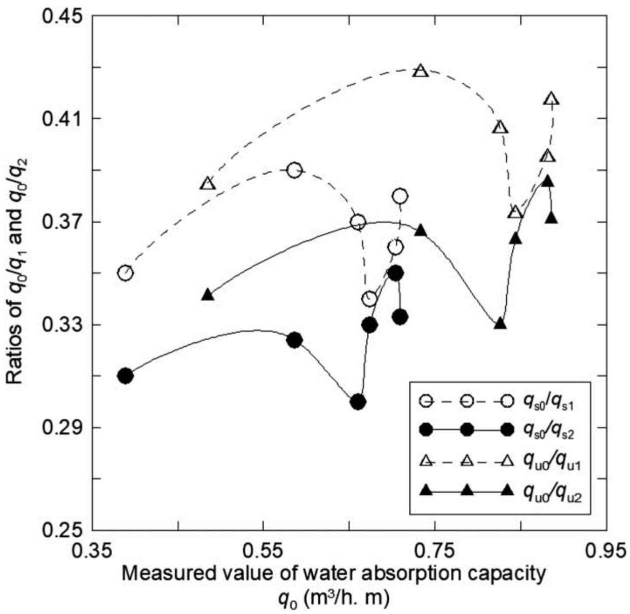

Figure 4 | Comparison of well water absorption.

constant. However, the results from theoretical prediction are not the same as the measured ones (Table 3); q_{s0} is the measured value of water absorption capacity in steady injection (m^3/h.m); q_{s1} and q_{s2} are the calculated values of water absorption capacity in steady injection from using Equations (5) and (6) respectively (m^3/h.m).

Comparing the data in Table 3, it shows that the results from using Equations (5) and (6) to predict the water level were close, being 1.111 to 1.982 and 1.255 to –2.532. Equations (5) and (6) were based on pumping theory. The ratios of q_{s0}/q_{s1} and q_{s0}/q_{s2} indicate that the water absorption capacity was only one-third of the pumping capacity (Figure 4). If the accuracy requirement is considered, the use of Equation (5) should be given priority.

Value verification for the water absorption capacity in unsteady flow injection

The realistic recharge condition usually is unsteady flow injection. Compared with the condition of unsteady water injection, the results for q_{ui} from using Equations (5) and (6) had little change (Table 4); q_{u0} is the measured value of water absorption capacity in unsteady injection (m^3/h.m); q_{u1} and q_{u2} are the calculated values of water absorption capacity in unsteady injection from Equations (5) and (6) respectively (m^3/h.m).

Comparing the data in Table 4, it shows that the results from using Equations (5) and (6) to predict the water level were 1.223 to 2.190 and 1.382 to –2.785. The predicted result from using Equation (6) was slightly larger than that

Table 4 | Comparison of the water absorption capacity in unsteady flow injection

Project	Calculated value						Average value
q_{u0}	0.485	0.881	0.733	0.826	0.844	0.886	0.775
q_{u1}	1.223	2.151	1.654	1.962	2.190	2.054	1.870
q_{u2}	1.381	2.212	2.003	2.42	2.246	2.385	2.211
q_{u0}/q_{u1}	0.385	0.396	0.429	0.407	0.374	0.418	0.402
q_{u0}/q_{u2}	0.341	0.385	0.366	0.330	0.363	0.371	0.341

of Equation (5) similarly. Equations (5) and (6) were based on pumping theory. The ratios of q_{u0}/q_{u1} and q_{u0}/q_{u2} indicate that the water absorption capacity was no more than one-third of the pumping capacity (Figure 3). If the accuracy requirement is considered, the use of Equation (5) should be given priority.

CONCLUSIONS

This study proposed a mathematical model for predicting the rising curve of water level in a radial well. The concept of water absorbing capacity was explained. The rising level values and water absorption capacity of the radial well from two methods were verified and compared. The following conclusions can be drawn based on the present study:

(1) A mathematical model was established for the prediction of the rising curve of well water level, and an analytical solution equation has been proposed.
(2) In steady and unsteady injections, compared with the measured values, the relative errors of the prediction results by Equations (2) and (3) were smaller. The precision of Equation (2) was slightly better than that of Equation (3), but the difference between them was small. The closer the water injection well was, the greater the error of water level prediction.
(3) The calculation of water absorption capacity was slightly more accurate by using Equation (5). The measured values of water absorption capacity were only about one-third of the calculated values.
(4) It shows that the proposed method for predicting the water level rise curve is feasible. The variation characteristics of water absorption capacity are favorable for guiding the optimization of water injection mode.

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DISCLOSURE STATEMENT

The authors do not report any potential conflicts of interest.

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