Experimental study on recharge capacity of a mixed well injection in Xi’an

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Abstract. The over-exploitation of groundwater can be controlled and prevented by using mixed well to recharge groundwater. A seepage model of semi-confined aquifers was established for simulating recharge well in a cone of depression. Two mathematical expression formulas were proposed for estimating recharge capacity. To analyze the response of recharge capacity, stepwise injections were introduced. It can be pointed out that recharge capacity increases with that of injection flow; moreover, it tends to attenuate during steady injection, which is closely related to injection flow. An attenuation equation of recharge capacity was constructed finally. Recharge capacity was not related to injection mode. The results indicate that under similar conditions, recharge capacity of a mixed well was about one-third of pumping capacity. A minimum value of recharge capacity was maintained with constant injection. Mixed wells were used to recharge and recover groundwater from the cone of depression.

1. Introduction

Geological disasters have occurred and groundwater resources have been exhausted in many areas due to over-exploitation of groundwater. To control and prevent over-exploitation of groundwater, pipe well was used and groundwater was recharged. A pipe well crosses more than two aquifers, which constitute a mixed well. A large-scale recharge plan must be conducted to address following objectives: i) determination of recharge feasibility of a mixed well and ii) confirmation of recharge capacity.

Presently, theoretical research studies have been conducted on well recharge. In general, research studies have been conducted to determine recharge capacity of well. These studies encompass following stages: parameter calculation, numerical simulation, clogging mechanism, and application technology. Many research studies have established that injection process is the reverse of pumping; therefore, well pumping and recharge was possible with calculation methods [1-4]. Furthermore, the results of theoretical research studies were emphasized the most. Complex potential theory and Ghyben-Herzberg theory have innovative applications. These applications were used to develop new analytical and computational methods for recharge [5-6]. Numerical simulation studies have been extensively conducted to investigate well recharge. Conclusions can be easily drawn from these research studies: a few semi-empirical and semi-theoretical calculation methods have also been put forward [7-9]. In general, no breakthrough theories or methods were found directly for well recharge.
Well recharge is primarily affected by clogging, which occurs frequently during the injection process. Comprehensive research studies were conducted to investigate the effect and mechanism of physical clogging. The other types of clogging were not mature [10-13]. Clogging problem has some regional characteristics; however, it can be used as a reference in similar engineering applications. Recharge capacity was often estimated in research studies involving clogging [14-16]. However, there was no consensus on definition, calculation, and basic connotation of recharge capacity.

2. Study area and data sources
Test well is a typically mixed well that crosses three confined aquifers, which are located in the southern suburb of Xi'an city in China (Figure 1). Tap water was used to recharge well under no pressure. Test aquifer was approximately horizontal. The depth of injection well was 300 meters. The diameter of injection well was 0.25 meters. Well pipe was equipped with filter pipe. Static water level was less than 121 meters below ground surface. Top confined aquifer was drained. The underground altitude of layers was in the range of 85-92 meters. Groundwater level was formed by over-pumping at an early stage, and a cone of recharge surrounded test well. The pumping test was conducted in advance.

![Figure 1. A schematic diagram of a test well.](image)

Table 1. Design scheme of well injections.

| Stage division | t (hour) | Q (m³/h) |
|----------------|---------|----------|
| 1-1            | 24      | 20       |
| 1-2            | 24      | 25       |
| 1-3            | 24      | 30       |
| 1-4            | 264     | 35       |
| Break          | 48      |          |
| 3-1            | 264     | 20       |

Test site was suitable for several reasons. Test well was located in the cone of depression. A potential injection task was developed in the future. Observation wells have the same pumping-injection conditions, which restore permeability and eliminate clogging. It is feasible to connect test well with tap water network. Recharge aquifers and tap water have the same background values of
water quality, minimizing the degree of chemical clogging. Because of seasonal effect, surplus tap water from rivers was stored for emergency supply.

Injection process was divided into two stages (Table 1). Such a design scheme was used to explore the difference between several injections and to identify a better injection mode.

3. Methods

3.1. Mathematical model of recharge well flow
Most aquifer systems are made of multi-layers. When a pipe well contains multiple aquifers, static water level would appear in a mixed level [17-18]. It is difficult to obtain each aquifer parameter directly by pumping or injecting through a mixed well [19]. An integrated aquifer was formed by using multiple aquifers to understand the complexity of various stages of study. The entire aquifer was represented by water levels of a mixed well. The differences between seepage flows of aquifers were ignored.

Seepage characteristics of recharge test field were defined as follows: occurrence conditions of groundwater were approximately in line with semi-confined aquifers, which did not consider water storage rate of a weak permeable layer. Recharge area was limited to the cone of depression within planned time. Surrounding boundary is a rotating surface of a parabola. The wellhead of injection well was the origin, and three-dimensional coordinates were established. Well axis was in z-axis direction, whereas x-axis and y-axis were in horizontal plane. The seepage model of recharge well was established as follows:

\[
\begin{align*}
\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} - \frac{h}{r^2} - \frac{B^2}{r^2} &= \frac{S}{T} \frac{\partial h}{\partial t}, \quad t > 0, \quad 0 < r < R \\
h(r, 0) &= 0, \quad h(R, t) = 0 \\
r &= R \left( \frac{Z}{h_0} + 1 \right) \\
\lim_{r \to r_0} \frac{\partial h(r, t)}{\partial r} &= \frac{Q}{2\pi T}
\end{align*}
\]

Here \( h \) is the water head (m); \( h_0 \) is the initial water head of well (m); \( R \) is the radius of the cone of depression (m); \( r_0 \) is the radius of injection well (m); \( S \) is the storage coefficient (dimensionless); \( T \) is the value of water conductivity (m\(^2\)/h); \( t \) is the time (hour); \( Q \) is recharge flow (m\(^3\)/h); \( B \) is the constant to be determined (dimensionless); \( Z \) is the vertical coordinate (m).

The general solution of above model was established as follows:

\[
h = \frac{Q}{2\pi T} \int_{u}^{R} \frac{1}{y} \exp \left( -y - \frac{r^2}{4B^2y} \right) dy = \frac{Q}{4\pi T} F \left( u, \frac{r}{B} \right)
\]

Where \( F \) is the well function of first leakage system, and \( u \) is the independent variable of well function.

In a stable condition, equation (1) can be written as follows:

\[
h_{\text{max}} = \frac{Q}{2\pi T} K_0 \left( \frac{r}{B} \right)
\]

Here \( K_0 \) is the second kind of zero order virtual volume, which is based on Bessel function. When \( r/B < 0.05 \), derivation equation is expressed as follows:

\[
K_0 \left( \frac{r}{B} \right) \approx -\ln \left( \frac{0.89r}{B} \right)
\]

By substituting equation (3) into equation (2), we obtained equation (4):

\[
h_{\text{max}} = \frac{2.3Q}{2\pi T} \lg \left( \frac{0.89r_0}{B} \right)
\]

The value of \( B \) and \( T \) were obtained by linear graphic method.
3.2. Recharge capacity expression of injection well

It was very difficult to measure recharge capacity based on the factors influencing injection well [20]. When injection flow tends to be stable, water head in well also becomes stable. Recharge capacity \((RC)\) of injection well was directly proportional to flow rate \((Q)\), which was inversely proportional to water head of well \((h)\):

\[
RC = \frac{Q}{\Delta s \times h \times \Delta t} \times 100\% \tag{5}
\]

Here \(RC\) is recharge capacity \((\%); Q\) is injection flow rate \((m^3/h); \Delta s\) and \(\Delta t\) are unit water injection area and unit water injection time respectively. By substituting equation (4) into equation (5), equation (6) is obtained as follows:

\[
RC = \frac{-2.3}{2\pi T \Delta s \times \Delta t} \ln \left( \frac{0.89r_0}{B} \right) \times 100\% \tag{6}
\]

The parameters \(RC\) is an important indicator of water absorption capacity of a semi-confined aquifer, which also represents water injection capacity of whole recharge system.

By considering the design of recharge experiment, the injection mode was used as step flow. Based on approximate solution of Theis formula, equation (7) is written as follows:

\[
h = \frac{Q}{4\pi T} \ln \frac{2.25Th}{sr^2} \tag{7}
\]

Parameter meaning is same as above.

In initial stages of injection, conditions were as follows: if \(Q_i\) is injection flows, then \(t_i\) is injection time. There are two assumptions:

\[
\Delta Q = Q_2 - Q_1 = Q_3 - Q_2 = \ldots = Q_n - Q_{n-1}
\]

\[
t_1 = t_2 - t_1 = t_3 - t_2 = \ldots = t_n - t_{n-1}
\]

Using equations (8–9), an approximate analytic solution and superposition principle of groundwater level were obtained:

\[
h_2 = \frac{Q_1}{4\pi T} \ln \frac{2 \times 2.25T t_1}{sr^2} + \frac{\Delta Q}{4\pi T} \ln \frac{2.25T t_1}{sr^2} \times 2! \tag{10}
\]

Similarly, we obtained equation (11):

\[
h_3 = \frac{Q_1}{4\pi T} \ln \frac{2 \times 2.25T t_3}{sr^2} + \frac{\Delta Q}{4\pi T} \ln \left( \frac{2 \times 2.25T t_1}{sr^2} \right)^2 \times 2!
\]

\[
h_n = \frac{Q_1}{4\pi T} \ln \frac{n \times 2.25T t_n}{sr^2} + \frac{\Delta Q}{4\pi T} \ln \left( \frac{(n-1) \times 2.25T t_1}{sr^2} \right)^2 \times (n-1)! \tag{11}
\]

Parameter meaning is same as above.

By substituting equation (10) into equation (5), we obtained equation (12):

\[
RC = \frac{Q_n}{4\pi T} \ln \frac{n \times 2.25T t_n}{sr^2} + \frac{\Delta Q}{4\pi T} \ln \left( \frac{(n-1) \times 2.25T t_1}{sr^2} \right)^2 \times (n-1)! \times 100\% \tag{12}
\]

Equation (11) is the general solution of stepped flow recharge. Results of RC were compared and verified with equation (6).

4. Results and discussion

4.1. Comparison of two modes of injection

It was practical and convenient to theoretically explore flow design of recharge well. Flow rates were 20 m\(^3\)/h, 25 m\(^3\)/h, and 30 m\(^3\)/h in the first three days of continuous injection; moreover, water levels increase gradually and recharge capacity decreases every 24 hours. Recharge capacity minimized with an increase in flow rate. This indicates that both recharge capacity and injection flow increased (Figure 2a). When the period of injection was longer, flow rate was 35 m\(^3\)/h. Thereafter, flow rate was continuous and steady for 264 hours. Recharge capacity was gradually stabilized after 250 hours, and a minimum value \((RC = 30\%)\) appeared several times (Figure 2b). Golden Software Grapher10 was
used for iterative debugging; attenuation function of recharge capacity was determined by using equation (13):

$$RC = 56.589 - 0.178 \times t + 2.96 \times t^{-8} \quad (13)$$

According to equations (6) and (7), the theoretical value of $RC$ should be constant. The measured value of $RC$ has attenuation trend, which indicates that there was still a clogging effect.

![Figure 2. Capacity contrast between two injection periods.](image)

Previous studies have shown that minimum capacity of recharge well and maximum water head exist synchronously under stable injection condition. It is feasible to use mixed well and injection groundwater in a cone of depression. In general, a larger injection flow must be used first. Recharge capacity was attenuated but negligible in magnitude. In similar areas, aforementioned attenuation equation was used to estimate the capacity of other wells and to arrange injection plan of groundwater in an economical manner.

### 4.2 Verification of calculation value of recharge capacity

Two different formulas were proposed for calculating recharge capacity. The proposal was based on the theory of pumping. The purpose of comparison was to verify pumping theory of well recharge. It was observed that water head of injection well fluctuated significantly within the first hour of injection flow. It stabilized rapidly thereafter. For each injection flow, water level in the corresponding well was the observed value after an hour of injection.

For comparison, the measured value of $RC$ was represented by the code $RC_0$; moreover, code $RC_1$ represented the value obtained from equation (6), and code $RC_2$ represented the value obtained from equation (12) (Table 2).

| Injection mode | Stepwise injection | Long injection |
|----------------|--------------------|----------------|
| Injection flow ($m^3/h$) | 20 | 30 | 20 |
| $RC_0$ | 35.400 | 62.700 | 66.400 |
| $RC_1$ | 89.491 | 155.810 | 166.398 |
| $RC_2$ | 71.083 | 128.096 | 133.796 |
| $RC_1/RC_0$ | 2.528 | 2.485 | 3.567 |
| $RC_2/RC_0$ | 2.008 | 2.043 | 3.250 |
In theory, well recharge capacity must be approximately equal to pumping capacity. By analyzing Table 2, it was found that $RC$ values were 2.5 times and 2 times of measured $RC$ values, respectively. Under current conditions, groundwater was recharged with tap water in order to reduce blocking effect. Recharge capacity of injection well was significantly less than that of theoretically calculated values.

5. Conclusions
Theory and method of well recharge are still in the exploratory stage, hard work needs to do constantly. Conclusions are as follows:
(1) Two formulas were proposed for calculating recharge capacity.
(2) Recharge capacity of well was attenuated, a minimum value still existed.
(3) Under similar conditions, recharge capacity of a mixed well was about one-third of pumping capacity.
(4) Well recharge was calculated with pumping theory of well, which has great uncertainty. The conclusions of this study are significant for recharge and restoration of groundwater environment in similar areas.

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