The comparative analysis of two injection modes and recharge capacity estimation for a radial well in the loess area of China

Xuezhen Zhang1,2,3, Aidi Huo1,2 and Jucui Wang1,2
1 Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, Chang’an University, Xi’an, 710054, China; 2 School of Environmental Science and Engineering, Chang’an University, Xi’an, 710054, China
3 Email:zxz-2000@126.com

Abstract. This study is focused on the theoretical substantiation and practical application of the radial well recharge. Two semi-empirical equations were derived for the estimation of the recharge capacity and clogging coefficient of the recharge well, respectively. Two injection modes were applied to analyze the relations between the recharge capacity, water level, and flow rate. Two methods were used to calculate and verify the recharge capacity and clogging coefficient, with a brief analysis of their variation laws. The recharge capacity of the radial well was found to increase with the injection flow, with the following gradual saturation during two injection stages. The recharge capacity increased with the recharge flow, while the clogging coefficient of the second stage was higher than that of the first stage, and exhibited a different variation pattern. The results obtained strongly indicate that the pumping and recharge are hydrological processes, which differ from each other by their physical essence. The available calculation methods based on the pumping theory were found to overestimate the recharge well flow by more than six times. The refined semi-empirical equation provides a more realistic estimation of the recharge capacity of radial wells.

1. Introduction
The vegetation growth in the loess plateau of China is limited by scarce water resources. Although in rainy seasons the rainwater is intercepted by numerous reservoirs, the intensive evaporation makes these reservoirs unfit for the agricultural irrigation demands during the irrigation seasons. In the past, numerous radial wells have been furnished in the area, to solve the urgent need of water. However, the natural recharge of groundwater in the loess area is quite problematic, which inhibits the sustainable local groundwater exploitation. If the surplus reservoir water in the rainy season was used as the recharge resource through radial wells, it could preserve the groundwater source to be reused and thus reduce the evaporation losses.

The theory and method research on recharge well were in the test stage. Many researchers admitted that a recharge process could be treated as the reverse of a pumping process. Therefore, the flow calculation of injection wells can be carried out by a series of methods applied in pumping [1-2]. There were many factors influencing the calculation of the well flow, and the calculation results tended to have large errors. Currently, the calculation methods are subdivided into two categories: (i) calculation via an empirical equation and (ii) calculation via a semi-theoretical/semi-empirical equation [3-4]. The model simulation study reported quite impressive results, which involved empirical equations for the calculation of water yield of radial wells, water level curve in pumping,
and the equivalent permeability coefficient [5]. Authors studied the radial collector flow rate in a semi-
infinite and unconfined aquifer [6]. They expressed the stream depletion rate as a function of eight
dimensionless parameters.

The clogging problem is one of the main factors influencing the well recharge. The main research
on clogging was mainly focused on the elucidation of its mechanisms. The insights into physical and
mechanical clogging mechanisms seem to be much more successful than those into chemical and
biological ones [7-8]. Experimental research has shown that the clogging of suspended solids and gas
phase occurred mainly in the surface medium in recharge, while the permeability coefficient decreased
exponentially with time, due to the gas phase clogging [4]. Microbial clogging assessments were based
on the growth theory of microorganisms, whereas the potential microbial clogging occurred in the
upper layer of the soil surface. The above studies revealed some regional characteristics, which could
be applied to the engineering practice in similar areas.

The clogging degree is critical for the well injection. Field test results indicated that the capacity of
multi-injection was higher than that of the concentrated one, the optimal capacity of the well injection
being achieved when the water level rose to 40% of the peak one [9]. A plan for a managed aquifer
injection was mainly limited by the physical clogging, whereas the well injection was related to the
quality of injection water and minerals' composition [10]. The effective storage capacity with a proper
storage rate was found to be related to the water volume of injection. An increase in the injection
intensity could efficiently improve the storage capacity, but could also reduce the storage rate [4]. A
support system, which could substantiate strategic decisions on selecting the most appropriate
injection method, was proposed as a suitable tool for sustainable groundwater management, in order to
recover the security of the water supply and reduce the injection cost [11]. An innovative pumping-
injection technology has developed, excavation and injection were conducted nearby the protected
facilities. The feasibility of the well injection has been verified with different pumping and injection
rates [12-13].

The above findings indicate some progress in the theory and practical application of the well
recharge, which promoted the development of groundwater recharge. However, to the best of the
authors' knowledge, no direct estimations of the radial well recharge capacity have been performed yet.

2. Study area and data sources

2.1. Conditions of the test well

The test well is a typical radial well designed for the water injection and pumping. The location of the
well is about 700 meters southwest of Qian County in Shaanxi province of China. The test area
altitude is about 650 m, and the terrain slope is about 1-2%. The test well is located at the distance of
300 m to the east of the Mogu River, which belongs to the backwater of Laoyazui reservoir (Figure 1).
Loess-like mild clay of the middle Pleistocene is the main phreatic aquifer in this area. The burial
depth is from 20 to 30 m. The groundwater flow is controlled by the topography, which implies the
main flow direction from the northwest to the southeast, with a connection to the Mogu River in the
west. The hydraulic gradient is mostly 10%. Groundwater recharge conditions are quite poor.

The test well is a reinforced concrete structure with a radius of 3.5 m and a depth of 40 m. The
water level depth is about 25.5 m. There are eight horizontal radial tubes of 120 m length each, and a
uniform conductivity distribution. The radius of the radial tube is 120mm, and the front end is
equipped with a filter tube. The radial well is located 1.2 m from the bottom of the well, and

2
2.2. Recharge plan

The recharge conditions were close to the actual operational ones of the radial well. According to the actual condition of incoming water, two modes of injection were used for the implementation, namely the intermittent injection and the continuous one. The test was carried out in two stages: (i) in early summer and (ii) in early winter, with the interval of about six months. Given the agricultural irrigation demands, the water from the reservoir could be used intermittently at the first stage, while the injection flow was unsteady at both stages.

It was clear that there was some sporadic pumping for irrigation between the two stages, which was, in fact, conducive to the dredging of well and easing of clogging and recovery. Therefore, the two stages of the recharge test were treated as two independent tests, similar to work, where estimations of the growth and recession processes of a water mound under an infiltration basin were performed for wet and dry cycles. Due to the disturbance of the agricultural irrigation, the water flow of injection was always changing, even after a few days of temporary discontinuity of the injection. The more prolonged injection was beneficial to the cumulative effect of research and the exploration of statistical rules. The intermittent injection is beneficial to the study of the clogging caused by the injection.

3. Methods

3.1. Mathematical modelling of the recharge capacity

Radial well is more complicated than a standard pipe well. Because of a larger number of influencing factors, it is quite problematic to measure its recharge capacity [14]. It is noticed that specific yield and unit water injection depend on the water output capacity of well and the water recharge capacity under pumping and injection conditions. The recharge capacity of an injection well ($E$) can be expressed as follows:

$$E = \frac{Q_1}{h_1} \times \left(\frac{Q_0}{h_0}\right)^{-1} \times 100\%$$

Where, $Q_1$ is the flow rate of injection (m$^3$/s), $h_1$ is the water head of injection well (m), $Q_0$ is the flow rate of pumping (m$^3$/s), $h_0$ is the water head of pumping well (m), and $E$ is the recharge capacity of well (%).
The common advantage of equations (1) is that the recharge capacity can be calculated directly from the experimental observations, avoiding the tedious and controversial analysis and calculation of hydro-geological parameters.

According to the Dupuit–Forchheimer assumption, groundwater flows horizontally in an unconfined aquifer, while the groundwater discharge is proportional to the saturated aquifer thickness. Given this, the recharge capacity of the injection well can be expressed as follows:

\[ E = 2\pi a k M \cdot \ln \frac{R}{l \cdot \sqrt{0.25}} \]  

(2)

where \( l \) and \( n \) are the length (in m) and the number of radial tubes, respectively, \( M \) is the aquifer thickness (m), and \( R \) is the influencing radius (m).

Noteworthy is that equation (2) was derived within the framework of the pumping theory. It can be treated as a mathematical representation of the water absorption capacity, which furnishes a theoretical substantiation for planning and design of a recharge with reasonable injection flow and water level values.

The recharge capacity of wells is often influenced by several factors, which may also be coupled. Given this, theoretical predictions frequently deviate from the actual results. In this paper, based on the analysis of similar test results obtained in the loess area by the Irrigation Research Office of the Shaanxi Institute of Water Resources Science, the water absorbing capacity of an injection well is assessed by the following equation:

\[ E = 2a\beta kr \sum_{i=1}^{n} l_i \]  

(3)

where \( r \) is the radius of a water-collecting well (m), \( \beta \) is the empirical value (dimensionless), while the remaining parameters are the same as in equation (2).

3.2. Clogging coefficient

Although pumping and injection can be treated as two opposite (and thus, similar) processes, their physical essence is somewhat different. Pumping is the process of water release in an aquifer, while recharge is a more complicated process of water injection. Due to the complexity of the clogging mechanism, involving multiple factors and pre-requisites, the robust theoretical and practical research results are quite scarce yet [15].

A concept of clogging coefficient (CC) is proposed in this study. Assume that under the perfect conditions, there is a stable linear relationship between the injection flow and the well water level, while the water absorbing capacity (\( E \)) of the recharge well is constant.

Consider the clogging effect, which occurs at the time \( t \), under a constant injection flow rate. Then the clogging coefficient (CC) of the recharge well at time \( t \) is defined as a ratio of the difference between the initial water absorption capacity \( E_{w0} \) of the recharge well and the ideal water absorption capacity \( E_{i0} \), to the initial water absorption capacity \( E_{w0} \) as follows:

\[ CC = \frac{E_{w0} - E_i}{E_{w0}} \]  

(4)

According to the proposed approach, the extent of the recharge well clogging is controlled by the clogging coefficient derived via equation (4).

4. Results and discussion

4.1. Diachronic change of the recharge capacity

According to the above mathematical representations, the recharge capacity or water absorbing capacity of an aquifer is comprehensively reflected by equations (2) and (3), while \( E \) is as a measure of the recharge capacity of wells.

In two stages, it founded that no matter how the flow rate of injection changed, no matter how intermittent the injection interval, the recharge capacity \( RC \) fluctuated and tended to stabilize at 0.9

\[ RC = 0.9 \]
In different interval of injection, the recharge capacity was attenuated all the time, but it could be restored to some extent with an injection interval. After 11 days' injection, the recharge capacity of both stages tended to be the same.

4.2. Water level responds to the recharge

At the first stage, the main experimental finding was a strong variation of the injection flow rate. With an increase in the injection flow, the water level also exhibited a gradual increase. The flow rate of the injection sharply dropped with the following sharp drop of the water level, which indicated that the radial well was well-permeable, and the injection water flow was quite rapid (Figure 3a). After 11 days of injection, the maximum deviation between the flow rate and water level variation rate was observed. The accumulation effect of the clogging was strongly manifested.

At the second stage, the injection flow fluctuation and time interval were relatively small, but the flow rate and water level relationship were quite similar to that of the first stage: the maximum deviation was also observed after 11 days of injection (Figure 3b).

The common feature of both stages was that, irrelevant of the particular injection process, flow rate and water level exhibited nearly synchronous variations, while the maximum deviation was observed.
after 11 days of injection, which implied the identical cumulative effects of clogging. Thus, the injection method did not influence the time window of the clogging effect peak manifestation.

### 4.3. Validation of recharge capacity and clogging coefficient

The recharge capacity and clogging coefficient of the recharge well can reflect the water absorption performance and well recharge variation. Equations (2) and (3) are based on the pumping theory and, especially, on the assumption that clogging was stable during the injection process. Five representative flows from two recharge stages were selected to assess the variation patterns of the recharge capacity and clogging coefficient. The respective calculated and measured values are listed in Table 1.

Here, $E_0$ is the measured recharge capacity; $E_1$ and $E_2$ are calculation results obtained via equation (2) and (3), respectively; the clogging coefficient ($CC$) are results calculated via equation (4) for the first and second stages, respectively. The initial injection capacities $E_{0i}$ of the two stages are equal to 3.132 and 4.974, respectively.

#### Table 1. Experimental and calculated results on the recharge capacity and clogging coefficient.

| stage | project | Injection flow rates $Q$ (m$^3$/h) | value range |
|-------|---------|-----------------------------------|-------------|
| 1     |         | 1 2 3 4 5                          |             |
|       | $E_0$   | 0.374 0.760 0.949 1.025 1.194      | 0.860       |
|       | $E_1$   | 6.056 6.056 6.056 6.056 6.056      | 6.056       |
|       | $E_2$   | 6.282 6.282 6.282 6.282 6.282      | 6.282       |
|       | $CC$    | 0.881 0.757 0.697 0.673 0.619      | 0.725       |
| 2     |         | 1 2 3 4 5                          |             |
|       | $E_0$   | 0.143 0.389 0.586 0.660 0.674      | 0.490       |
|       | $E_1$   | 6.056 6.282 6.282 6.282 6.282      | 6.282       |
|       | $E_2$   | 6.282 6.282 6.282 6.282 6.282      | 6.282       |
|       | $CC$    | 0.971 0.922 0.882 0.867 0.864      | 0.901       |

By comparing the calculation results for both stages, it was found that the recharge capacity of the injection well increases with the injection flow. The assessment of water absorption capacity of the recharge via the pumping theory yields more than six-fold overestimation of the actual (measured) value. The clogging coefficient at the second stage is higher than that at the first stage. The clogging coefficient decreases with the recharge flow.

### 5. Conclusions

The above analysis made it possible to draw the following conclusions:

1. Two mathematical representations of the radial well recharge capacity were proposed. It was difficult to obtain some radial replenishment rules because of much interference factors.

2. The concept of clogging coefficient and its assessment method were introduced.

3. The recharge capacity of a radial well was found to be close to the flow rate for both injection modes under study.

4. A maximum stable value of the recharge capacity was achieved during the injection period.

### Acknowledgments

This work was supported by the Project of Science and Technology of Social Development in Shaanxi [grant No. 2016SF-411]. The authors gratefully acknowledge all helpers and the anonymous reviewers who substantially improved the manuscript.

### Disclosure statement

No potential conflict of interest was reported by all authors.
References

[1] Ganot Y, Holtzman R, Weisbrod N, Nitzan I, Katz Y, Kurtzman D 2017 Monitoring and modeling infiltration-recharge dynamics of managed aquifer recharge with desalinated seawater Hydrology and Earth System Sciences 21(9) 4479-4493 DOI:10.5194/hess-21-4479-2017

[2] Zhang Y, Wang J, Chen J, Li M 2017a Numerical study on the responses of groundwater and strata to pumping and recharge in a deep confined aquifer Journal of Hydrology 548 342-352

[3] Lu C, Werner A D, Simmons C T, Adrian D, Robinson N I, Luo J 2013 Maximizing net extraction using an injection-extraction well pair in a coastal aquifer Groundwater 51(2) 219-228

[4] Xu Y, Shu L, Zhang Y, Wu P, Eshete A, Mabedi E 2017 Physical experiment and numerical simulation of the artificial recharge effect on groundwater reservoir Water 9(12) 908 DOI: 10.3390/w9120908

[5] Huang C, Chen J, Yeh H 2016 Approximate analysis of three-dimensional groundwater flow toward a radial collector well in a finite-extent unconfined aquifer Hydrology and Earth System Sciences 20(1) 55-71 DOI:10.5194/hess-20-55-2016

[6] Maroney C L, Rehmann C R 2017 Stream depletion rate for a radial collector well in an unconfined aquifer near a fully penetrating river Journal of Hydrology 547 732-741

[7] Zheng X, Shan B, Chen L, Sun Y, Zhang S 2014 Attachment-detachment dynamics of suspended particle in porous media: Experiment and modeling Journal of Hydrology 511 199-204 DOI: 10.1016/j.jhydrol.2014.01.039.

[8] Huo A, Peng J, Chen X, Deng L, Wang G, Cheng Y 2016 Groundwater storage and depletion trends in the loess areas of China Environmental Earth Sciences 75(16) 1167

[9] Wang J, Wu Y, Zhang X 2012 Field experiments and numerical simulations of confined aquifer response to multi-cycle recharge-recovery process through a well Journal of Hydrology 464 328-343

[10] Du X, Fang Y, Wang Z, Hou J, Ye X 2014 The prediction methods for potential suspended solids clogging types during managed aquifer recharge Water 6(4) 961-975

[11] Masciopinto C, Vurro M, Palmisano V N, Liso I S 2017 A suitable tool for sustainable groundwater management Water Resources Management 31(13) 4133-4147 DOI:10.1007/s11269-017-1736-0.

[12] Miotliński M, Dillon P J, Pavelic P, Barry K, Kremer S 2014 Recovery of injected freshwater from a brackish aquifer with a multiwell system Groundwater 52(4) 495-502

[13] Zhang Y, Li M, Wang J, Chen J, Zhu Y 2017b Field tests of pumping-recharge technology for deep confined aquifers and its application to a deep excavation Engineering Geology 228(13) 249-259

[14] Biswas H, Sena D R, Kumar G, Lakaria B L, Raizada A, Kumar S, Mishra P K 2017 Effect of water storage structures on groundwater recharge in India Groundwater for Sustainable Development 4 49-56

[15] Zheng G, Cao J R, Cheng X, Ha D, Wang F J 2018 Experimental study on the artificial recharge of semi-confined aquifers involved in deep excavation engineering Journal of Hydrology 557 868-877 DOI:10.1016/j.jhydrol.2018.01.020.