Water Supply

Water Supply Vol 22 No 10, 7430 doi: 10.2166/ws.2022.324

Variation characteristics of water and sediment of managed aquifer recharge with the Yellow River water in the piedmont sand gravel channel in the North China Plain

Weidong Zhao[a], Donglai Xu[b], Weiping Wang[a,*], Shuai Liu[a], Shisong Qu[a], Yujie Meng[a] and Xiuxiu Sun[a]

[a] School of Water Conservancy and Environment, University of Jinan, Jinan 250022, China
[b] Shandong GEO-Surveying & Mapping Institute, Jinan 250013, China
*Corresponding author. E-mail: stu_wangwp@ujn.edu.cn

WW, 0000-0002-0780-5448

ABSTRACT

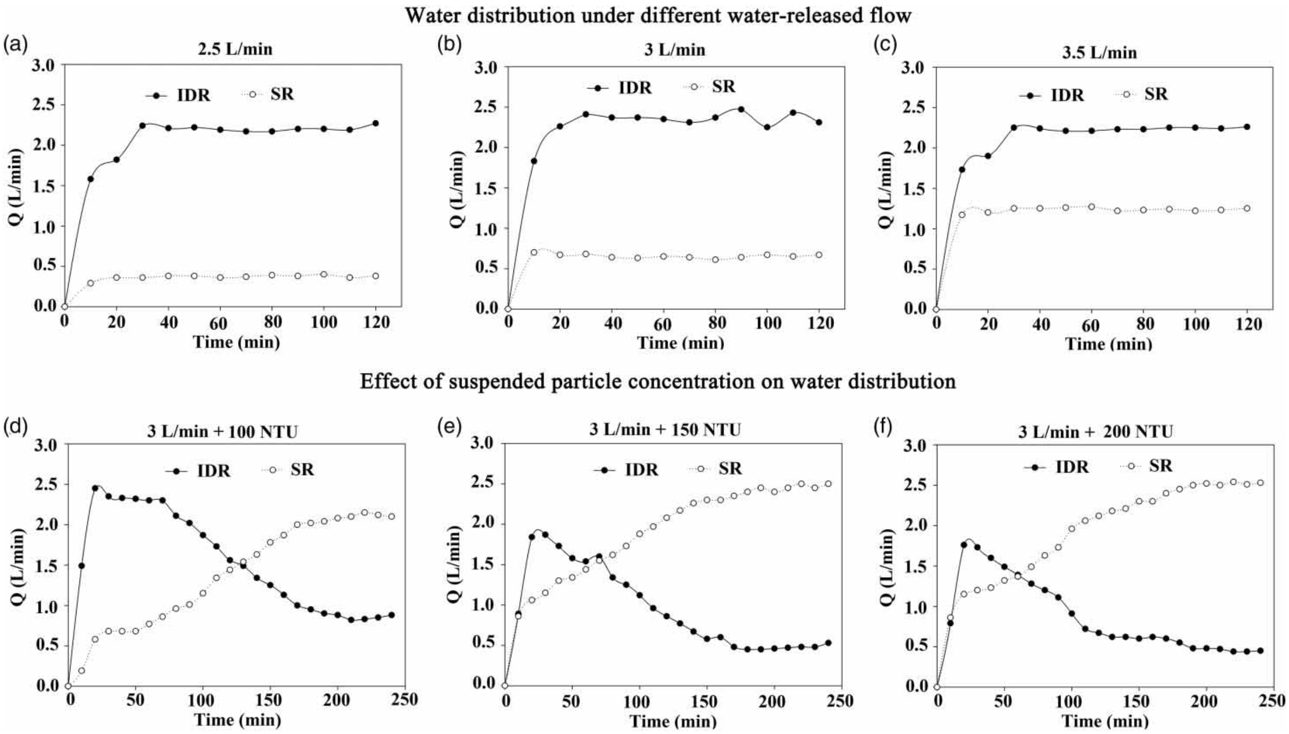
A two-dimensional sand tank model was designed to investigate the water distribution and sediment clogging of the Yellow River water during the seepage recharge process of the piedmont sand gravel channel in the North China Plain. Due to the high permeability of the sand gravel medium, only infiltration deep runoff (IDR) and surface runoff (SR) occurred in the sand tank experiment. The increase in water released did not improve the effective recharge. The IDR accounted for 65–85% of the water released. After clogging appeared, the value decreased to 15–30%. More than 96% of suspended solids were deposited in the surface and upper areas of the sand tank, among which the sand gravel surface covered by the thin clay layer formed by suspended particles was the main cause of the change in the distribution of IDR and SR. A rubber dam can promote the conversion of high velocity SR to low velocity lateral shallow runoff (LSR) by 25–30% while increasing the deposition mass of suspended particles in the sand tank. The rationality of the sand tank model was verified by the numerical model, and the fitting degree between the simulated and the measured results was greater than 0.9.

Key words: managed aquifer recharge, North China Plain, piedmont plain, sand and gravel, Yellow River water

HIGHLIGHTS

- Only infiltration deep runoff and surface runoff appear during recharging of the piedmont sand gravel channel.
- The suspended solids concentration and the medium infiltration capacity have a major effect on water and sediment movement processes in the recharging.
- The rubber dam built on the riverbed surface can promote the conversion of surface runoff to lateral shallow runoff.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The North China Plain (NCP) is a typical case of groundwater depletion due to agricultural development. Groundwater depletion has attracted the attention of many researchers (Cao *et al.* 2016; Zhao *et al.* 2019). Managed aquifer recharge (MAR) is the purposeful recharge of water in aquifer mediums for the recovery of the ecological environment (Dillon 2005). The water from the Yellow River flowing through the NCP can provide recharging water for improving the fragile groundwater environment (Rong *et al.* 2017). Hydrogeological zones in the NCP primarily include the piedmont region and plain area, of which the piedmont channel consists principally of sand and gravel (Wu *et al.* 1996; Zhao *et al.* 2021).

In the piedmont area of the NCP, using the Yellow River water to recharge groundwater through sand and gravel is a crucial measure for solving groundwater overexploitation. The Yufuhe River is located in the southwest of Jinan city in the NCP (Figure 1(a) and 1(b)). To date, a range of MAR projects for increasing groundwater have been built in the upstream channel (Li *et al.* 2019). The riverbed has a slope of 1/200–1/500, belonging to the piedmont channel. In the study region, the river is 50 m wide, and the riverbed is covered by a Quaternary sand and gravel layer with a thickness of 7–30 m and with the underlying permeable limestone aquifer. The impervious shales both upstream and downstream block the infiltration path of river water. Therefore, the reach of the study region belongs to the special 'open window' river channel, with a strong hydraulic connection between the sand gravel layer and limestone layer (Figure 1(c)). The Yellow River water transported by the multistage pumping stations from the Yuqinghu reservoir is released to the channel of the Yufuhe River for recharging (Figure 1(b)).

Due to the large slope of the river channel, the Yellow River water flowing through the study area mainly forms three runoff processes under the influence of gravity and its components along the riverbed, namely infiltration deep runoff (IDR), surface runoff (SR) and lateral shallow runoff (LSR), among which the IDR and LSR belong to underground runoff (Figure 1(c)). Only IDR can actually be recharged to the limestone aquifer, which is an effective recharge. Both SR and LSR eventually flow downstream, on account of the riverbed slope. However, the Yellow River water has an extraordinarily high silt content. Suspended particles deposited in riverbed medium can easily cause aquifer clogging.

Previous research has shown that the risk of porous medium clogging occurs in an aquifer when the suspended solids turbidity is more than 25 mg/L or 3 NTU (Pavelic *et al.* 2011; Cui *et al.* 2021; Rong *et al.* 2017; Zheng *et al.* 2020). During recharging, water is the carrier of suspended particles, and the seepage process can affect the suspended particle movement in the porous

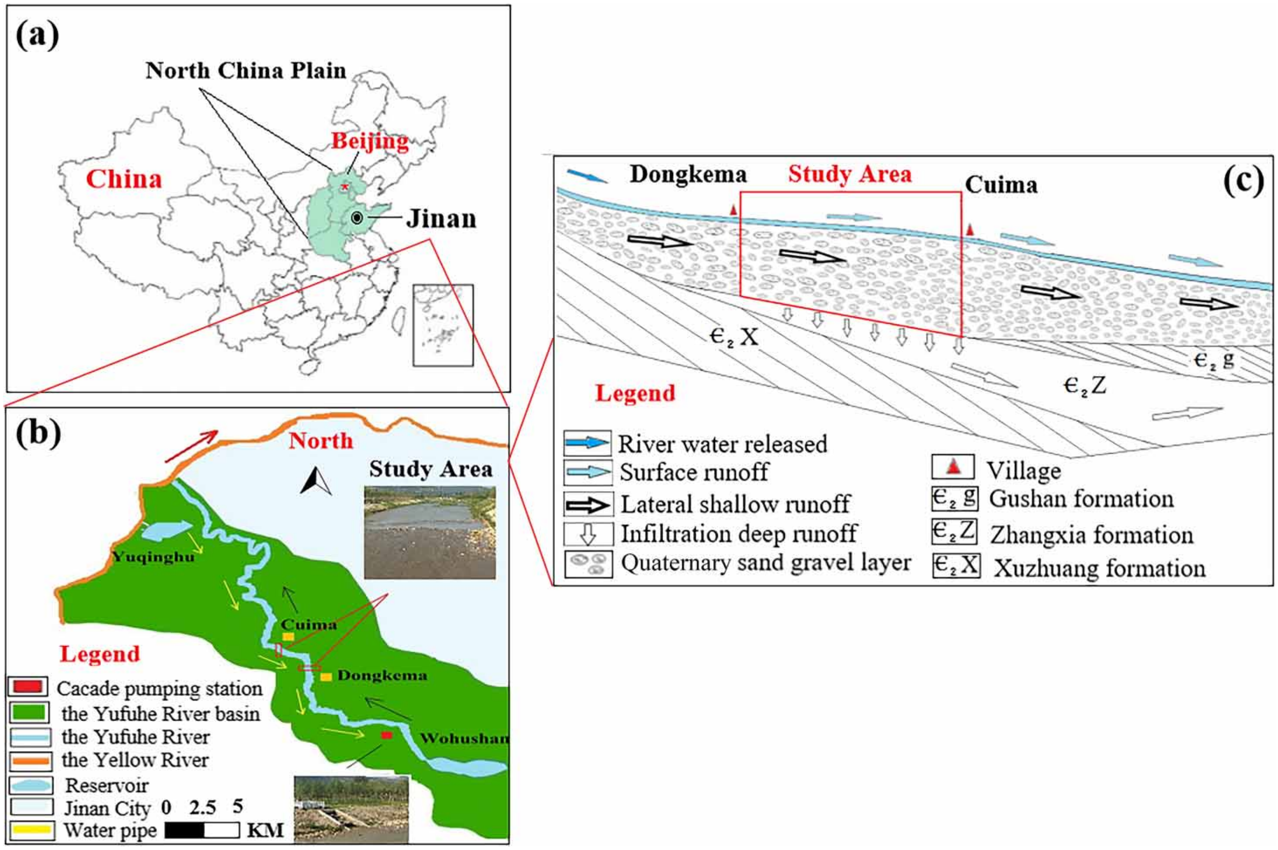


Figure 1 | (a) Location map of NCP; (b) Yufuhe River Basin; (c) riverbed profile in the study area.

medium. Additionally, the process of suspended solids migration in the medium further determines the seepage process variation. The clogging type of MAR projects mainly includes physical, chemical, biological, and combined clogging (Wang *et al.* 2012; Cui *et al.* 2018, 2021; Xian *et al.* 2019). Notably, previous surveys have indicated that aquifer clogging caused by suspended particles is the primary clogging case (Fetzer *et al.* 2017; Xie *et al.* 2020). Physical experiments based on the one-dimensional sand column model are widely used to simulate the aquifer clogging process in groundwater recharge. Zheng further studied the movement characteristics of exogenous and endogenous particles in aquifers during recharging through sand column infiltration experiments (Zheng *et al.* 2020). Through a series of sand column tests, Wang studied the migration mechanism of different sized particles in porous media (Wang *et al.* 2012). Wang investigated the combined effects of suspended particles and bacteria on the permeability of porous media by sand column experiments (Wang *et al.* 2020). However, the sand column model for studying particle blockage still has limitations, especially when describing aquifer clogging in the piedmont areas with large slopes. Furthermore, laboratory experiments focused on the clogging mechanism have frequently occurred in previous articles. Studies on the variation in suspended solids and seepage flow are in short supply.

Zhao explored the mechanism of water distribution and silt clogging in the 'open window' river channel consisting of upper gravel and lower karst layer in the recharge of the piedmont plain (Zhao *et al.* 2021). According to the permeability coefficient of the medium, the double layer medium composed of upper gravel and lower karst layer belongs to the combination of 'upper coarse and lower fine'. Owing to the existence of low permeability limestone medium, the maximum capacity of piedmont sand and gravel riverbed to distribute water and sediment has not been adequately studied (Zhao *et al.* 2021). On the basis of previous research, in this study, the variation characteristics of water distribution and sediment movement were studied by sand tank experiments when the lower boundary of the sand gravel layer was not constrained by the low permeability limestone medium. The conclusions of this research were an effective supplement to the operation theory of MAR projects in the Yufuhe River. Furthermore, in the piedmont region of the NCP, the riverbed surface was generally covered by a sand gravel medium.

The research results of this paper can effectively improve the existing pattern of the Yellow River water used to recharge groundwater in the NCP, especially in the piedmont area of the river channel consisting of sand gravel. Therefore, in the study, the primary study objectives were as follows: (1) to reveal the variation characteristics of water in the sand gravel channel infiltration process of the piedmont area, (2) to explore the variation characteristics of water and sediment in the piedmont channel recharge process, and (3) to simulate the influence of engineering measures such as rubber dams on water and sediment variation in the piedmont sand gravel reach infiltration.

2. METHODS AND MATERIALS

2.1. Experimental materials

To conform to the characteristics of the medium under actual conditions, the sand and gravel used in the sand tank model were obtained from the channel surface in the study area in the experiment. The sand samples were dried and sieved to demonstrate an average granularity (d_{50}), effective grain size (d_{10}), coefficient of permeability (k), and porosity of 8 mm, 0.2 mm, 90 m/d, and 23.9%, respectively. Tap water and suspension were used as reinjection water sources in the experiment. The turbidity of tap water was lower than 0.5 NTU, and it was regarded as a liquid without suspended particles, which is used in the water quantity experiment of the sand tank model. The suspension was used to simulate the Yellow River water. Montmorillonite is the main component of the Yellow River sediment, accounting for more than 40% of the sediment. Montmorillonite and tap water were used to prepare three suspensions with concentrations of 100, 150 and 200 NTU, respectively, for the suspended particles experiment in the sand tank.

The sand tank made of plexiglass was 50 cm long, 10 cm wide and 50 cm high (Figure 2). The whole experimental model mainly comprised four parts: a water supply device (a pump), infiltration part (a plexiglass sand tank), measuring equipment (four water meters and a turbidimeter) and collecting device (several buckets). The water inlet connected with the water pump was located in the upper right of the device, principally simulating the river water release process. The middle area filled with sand gravel from the surface sample of the study region belonged to the infiltration part. Pressure measuring holes connected to the pressure plate were set at the back of the sand tank to monitor the change in the head during the experiment. The dotted line on the left side and bottom of the experimental device was a hard plexiglass plate with 6 mm evenly distributed holes. Two outlet holes were set on the left side of the device from top to bottom to simulate surface

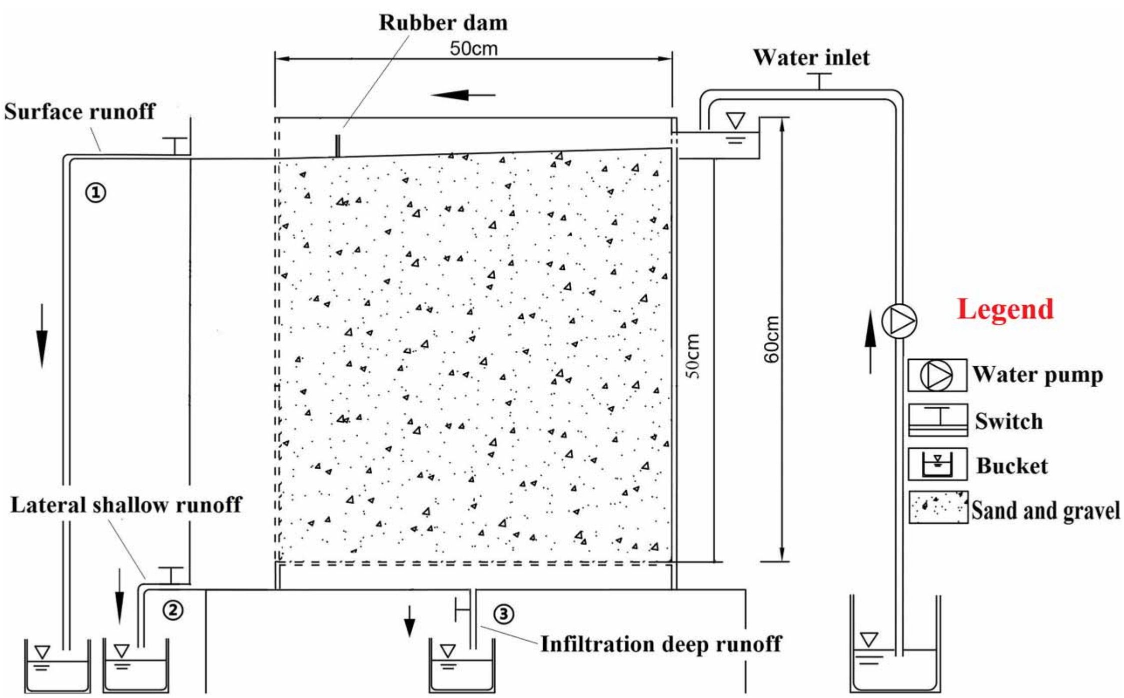


Figure 2 | Sand tank model.

runoff (SR) and lateral shallow runoff (LSR), respectively. The outlet hole simulating the infiltration deep runoff (IDR) was located at the bottom of the device. Entire outlets were wrapped with nylon mesh with an aperture size of 0.074 mm. The flow rate and turbidity of all the outlets and the pressure head of the medium in the sand tank were the three most important indexes in the experiment. The flow was measured by a water meter and a stopwatch. A Hach turbidimeter was used to measure the turbidity of the outflow liquid. The pressure head can be measured by a pressure plate.

2.2. Experimental schemes on water variation characteristics

To eliminate the interference of fine particles with particle sizes less than 0.074 mm in the original sand, the sand samples must be cleaned and dried before filling the sand tank. After completing the sand filling work, the subsequent operation steps were followed:

(1) The experiments were carried out under the conditions of flow rates of 2.5, 3 and 3.5 L/min respectively. When the water pump was turned on, and tap water was injected into the sand tank from the water inlet hole, it marked the beginning of the experiment. The flow of the outlets and the head of the pressure measuring pipe were both measured every 10 minutes. The outlets flow was stabilized, and the experiment was immediately stopped.
(2) A 3 cm-high plexiglass plate was set on the surface of the sand tank device to simulate the impact of the rubber dam on infiltration deep runoff (IDR), surface runoff (SR) and lateral shallow runoff (LSR) during recharging. On this basis, the operation of step (1) was repeated.
(3) A two-dimensional saturated-nonsaturated steady-state flow model established by using HYDRUS-2D software was used to simulate the movement characteristics of the water flow in the sand gravel medium during the sand tank water release experiment. The numerical model simulated the water distribution process under the condition of maximum permeability of the sand gravel medium. The governing equations and the numerical model have been described in detail in previous studies (Zhao *et al.* 2021).

2.3. Experimental schemes on water and sediment variation characteristics

(1) Reinjection water with turbidity of 100, 150, and 200 NTU was respectively injected into the sand tank, and the inlet hole flow was always controlled at 3 L/min through the pump. After the experiment had run for 160 minutes, the suspension was replaced by tap water, and the experiment continued. The flow and turbidity of all outlets were measured every 10 minutes while recording the water head value of the pressure measuring pipe. In a previous article, the measurement method of suspended particle mass in a sand tank is comprehensively described (Zhao *et al.* 2021).
(2) A 3 cm-high plexiglass plate set on the sand tank surface was used to simulate the impact of the rubber dam built on the riverbed surface on surface runoff, underground runoff, and suspended particle movement during recharging. On this basis, the operation of step (1) was repeated.

3. RESULTS

3.1. Variation characteristics of water in the sand gravel channel infiltration

When there was no rubber dam on the surface of the sand tank, only infiltration deep runoff (IDR) and surface runoff (SR) appeared (Figure 3(a)–3(c)). Because the gravel medium is highly permeable, the water flow injected into the sand tank infiltrated through the sand gravel layer, and turned preferentially into IDR under the action of gravity. Therefore, lateral shallow runoff (LSR) was not observed during the experiment. Table 1 showed that when the experiment reached a stable state, IDR and SR values were 2.12–2.36 L/min, and 0.38–1.2 L/min, respectively. The IDR can really be recharged to the aquifer, which is an effective recharge, accounting for 65–85% of the water release of the sand tank. Figure 3(a)–3(c) showed that the IDR did not vary significantly with the increase of water release in the sand tank experiment. Rather, SR increased. According to the results of the sand tank water quantity experiment, it can be seen that the permeability of sand gravel medium can affect the groundwater infiltration process and surface water runoff process in the piedmont sand gravel channel recharge. In addition, when the IDR value exceeded the critical seepage capacity of sand gravel medium, the excessive increase in water-released flow will cause a sharp decrease in recharge efficiency. In order to avoid invalid recharge, the appropriate discharge flow should be selected according to the permeability of sand and gravel medium when making the discharge plan.

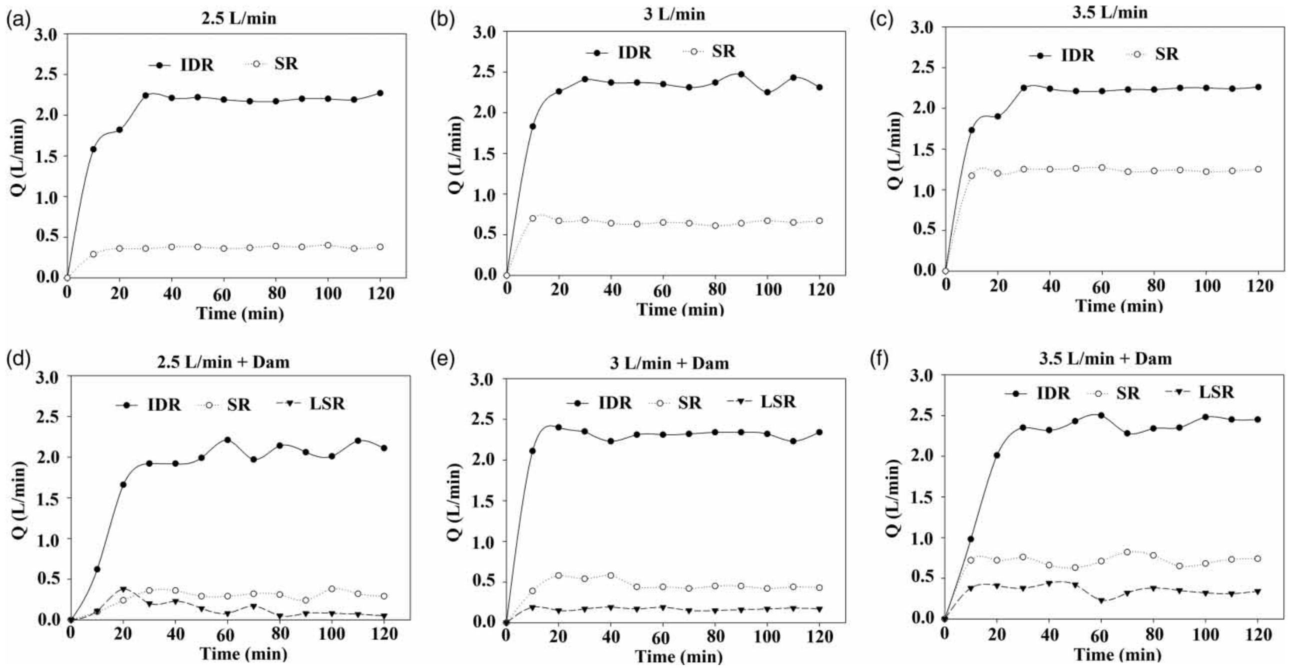


Figure 3 | (a)–(c) show the flow variation of IDR and SR only, and (d)–(f) show the flow variation of IDR, SR, and LSR after the rubber dam is built.

Table 1 | Variation characteristics of water

Serial number	Rubber dam	Turbidity (NTU)	Released water (L/min)	IDR (L/min)	SR (L/min)	LSR (L/min)
①	No	0	2.5	2.12	0.38	0
②			3	2.36	0.64	0
③			3.5	2.3	1.2	0
④	Yes	0	2.5	2.1	0.3	0.1
⑤			3	2.33	0.5	0.17
⑥			3.5	2.4	0.76	0.34

Note: The values of IDR, SR, and LSR in Table 1 were measured when the experiment reached a stable state.

With the existence of the rubber dam, IDR, SR, and LSR occurred concurrently. Compared with before the rubber dam was set, the value of IDR did not increase significantly (Figure 3(d)–3(f), and Table 1). But Table 1 showed that the conversion efficiency of SR to LSR was increased by approximately 25–30%, and the larger the water discharge was, the higher the conversion efficiency. This was of great significance for retaining surface water in the piedmont areas where water resources are scarce. In the piedmont channel with a large slope, the river water flowed downstream quickly. The establishment of a rubber dam can promote the conversion of high-velocity SR into low-velocity LSR, and protect ecological base flow. According to the results of the sand tank experiment, considering the impact of rubber dams on surface runoff and underground runoff, it was necessary to demonstrate repeatedly before building water retaining structures in the riverbed.

3.2. Rationality verification of the sand tank model

In the sand tank experiment, it was found that when the inlet flow rate was 2.5, 3 and 3.5 L/min, the change of sand tank water level was not obvious. Thus, the numerical model was used to simulate the water quantity experiment with inlet flow of 3 L/min. In the sand tank experiment, the distribution of the pressure head in the medium is shown in Figure 4. With the experiment, the pressure head in the sand tank gradually increased and finally tended to be stable. The pressure

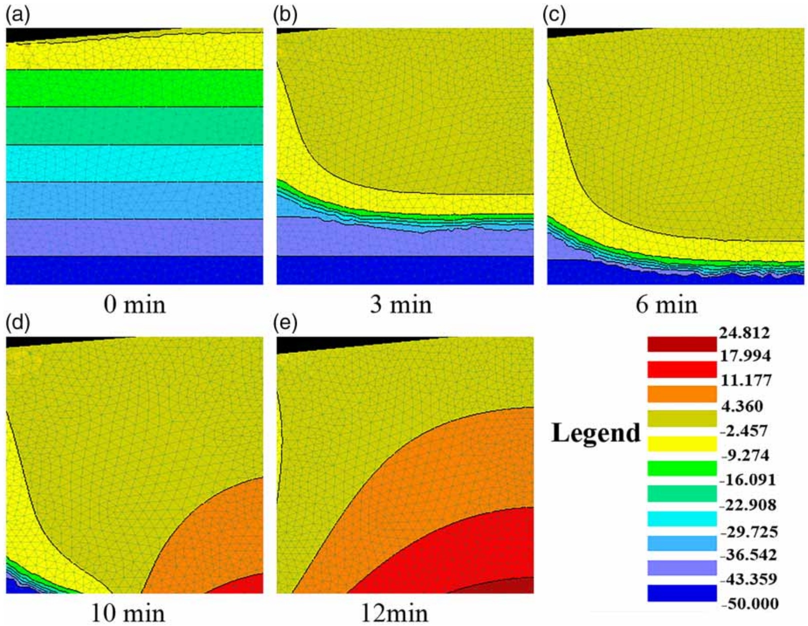


Figure 4 | (a)–(e) Simulation results of the pressure head in the sand gravel medium when the water release time of the sand tank model reaches 0, 3, 6, 10 and 12 minutes, respectively.

head on the right side of the sand tank was obviously larger than that on the left side, mainly because the right side is closer to the water inlet. When water was injected into the sand tank, the right side can get water supply preferentially. Figure 4 also shows that when the sand tank reached a stable state, the pressure head at the bottom of the sand tank was much larger than the left side. The pressure head on the left side of the sand tank was very small and it was difficult to form lateral shallow runoff. At the same time, LSR was not observed in the sand tank experiment, too. According to the numerical simulation results of the pressure head in the sand tank model, due to the high permeability of sand gravel medium, the water injected into the sand tank was preferentially converted into IDR, which is strongly proved by the results of the sand tank water quantity experiment. Figure 5 shows the fitting degree of measured and simulated values of pressure head close to IDR outlet with time. By comparing the results of physical and numerical models, the fitting degree of pressure head with time change was more than 0.9. Based on the simulation results of the numerical model, it can be proven that the sand tank model established

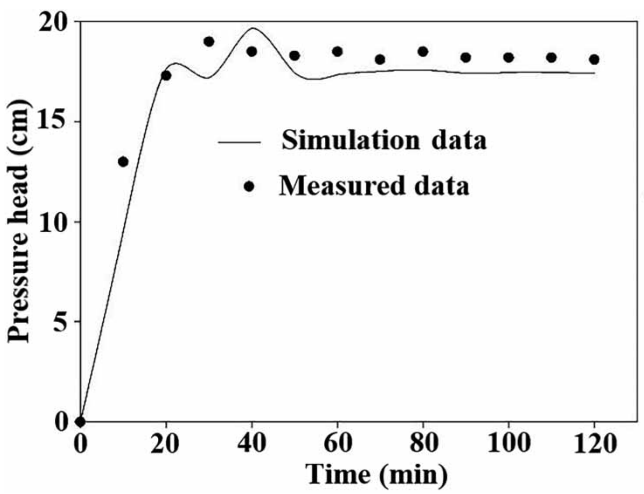


Figure 5 | Fitting curve between the simulated and measured results.

in this paper is feasible to describe the water amount variation during the recharge process of piedmont sand and gravel channels.

3.3. Variation characteristics of water and sediments in the sand gravel channel infiltration

3.3.1. Variation in surface runoff and underground runoff

Figure 6 shows that only IDR and SR occurred in the suspended solids experiment. And when the experiment reached a steady state, the IDR and SR values were 0.45–0.88 L/min, and 2.12–2.55 L/min, respectively (Table 2). As can be seen from Table 2, with the increase of turbidity in the recharge water, IDR values accounted for 29.3, 15.7 and 15% of the water flow of the sand tank, respectively. SR increased gradually with time (Figure 6(a)–6(c)). Compared with the sand gravel medium permeability, the suspended particle concentration had a more direct impact on the surface runoff and the underground runoff. The changes in the IDR and SR values showed the medium was blocked due to suspended particle deposition. The occurrence of clogging means that the original pore structure of the sand gravel medium has been changed, and the flow process of the IDR has also changed. As the recharge process continued, more suspended particles were deposited in the pores of the medium, resulting in a sharp decrease in the pores. When the path of the IDR was blocked, the water flow injected into the sand tank mainly flowed downstream in the form of SR due to the large slope.

Whether the clogging process of the sand tank occurs in advance depends on the time at which the intersection of IDR and SR appears. Apparently, with an increase in the suspended particle concentration in the recharge water, the blockage time of the sand tank occurred earlier. The establishment of a rubber dam did not lead to the early occurrence of the medium clogging process (Figure 6). In the suspended particles experiment, the rubber dam can effectively increase the IDR, but due to clogging, this value was only 24–31% of water release flow of the sand tank (Table 2). Consequently, controlling the suspended particle concentration was the primary factor in improving the MAR operation efficiency.

3.3.2. Migration of suspended particles

During the experiment, the suspended particles moved synchronously with the water flow. In the sand tank model, through the statistics of the mass of suspended particles, it was found that the suspended particles in the recharge water are allocated to the IDR and SR. And the remainder was retained in the sand tank. The SR turbidity did not change significantly compared to the recharge water. However, the IDR turbidity was 0–3 NTU, and the turbidity value decreased by more than 96%

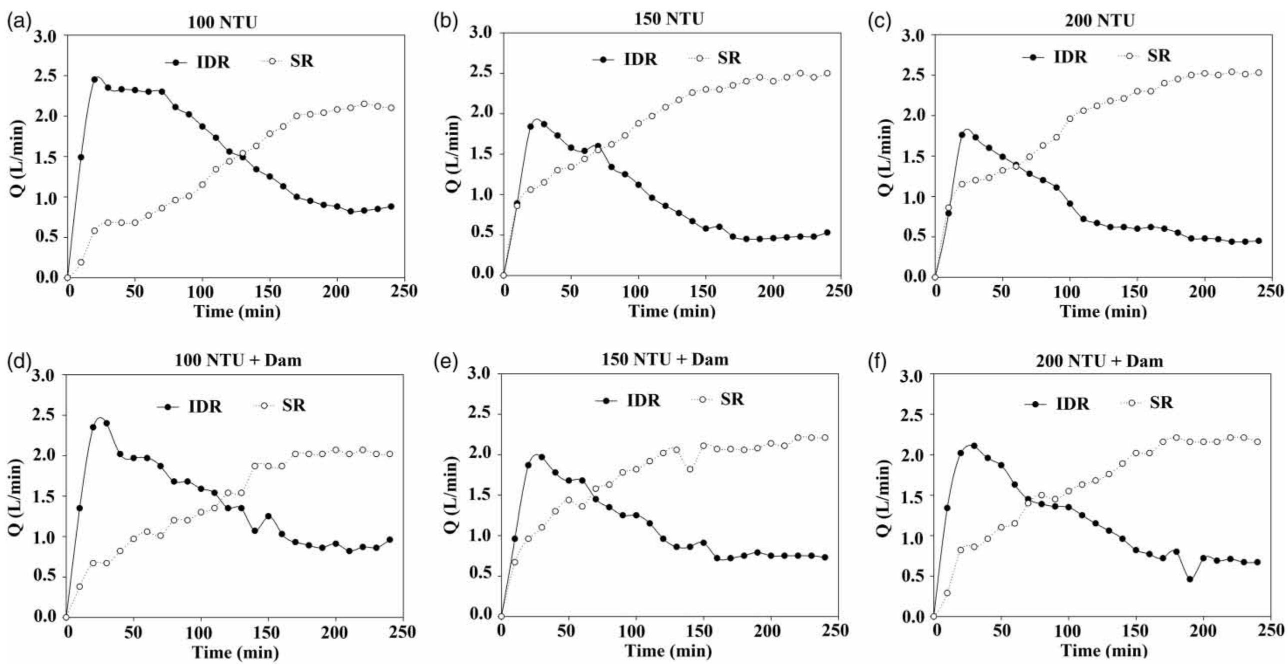


Figure 6 | (a)–(c) show the flow variation of IDR and SR only, and (d)–(f) show the flow variation of IDR and SR after the rubber dam is established.

Table 2 | Variation characteristics of water in the presence of suspended particles

Serial number	Rubber dam	Turbidity (NTU)	Released water (L/min)	IDR (L/min)	SR (L/min)	LSR (L/min)
①	No	100	3	0.88	2.12	0
②		150		0.47	2.53	0
③		200		0.45	2.55	0
④	Yes	100	3	0.93	2.07	0
⑤		150		0.82	2.18	0
⑥		200		0.73	2.27	0

Note: The values of IDR and SR in Table 2 were measured when the experiment reached a stable state.

(Figure 7(a)–7(c)). Therefore, it can be seen that a large number of suspended particles were removed after the sand gravel medium filtration, and the water quality was significantly improved. Additionally, the rubber dam built on the sand tank surface did not affect the turbidity of the IDR and SR in the experiment.

3.3.3. Deposition of suspended particles

The higher the suspended particle concentration in the reinjection water source, the more particles were deposited in the sand tank (Table 3). When the suspended particles experiment starts, many suspended particles follow the water flow and enter into the sand gravel medium. And the medium pores of the sand tank are blocked due to the deposition of suspended particles. The higher the suspended solids concentration increased in the recharge, the faster the sand gravel medium was blocked. After the experiment the distribution of the suspended particles in the sand tank was analyzed and suspended particles were mainly deposited in the surface and upper layers of the sand tank. A thin clay layer caused by suspended particle deposition was clearly observed on the sand tank surface, which is the main reason for the sharp reduction in IDR.

The existence of a rubber dam can promote the deposition of suspended particles in the sand tank (Table 3). Because of the retaining surface water effect of the rubber dam, the suspended solids were heavily intercepted, and flowed into the sand tank with water flow. After the clogging of the sand tank was formed, the scouring of the medium was simulated by the sudden

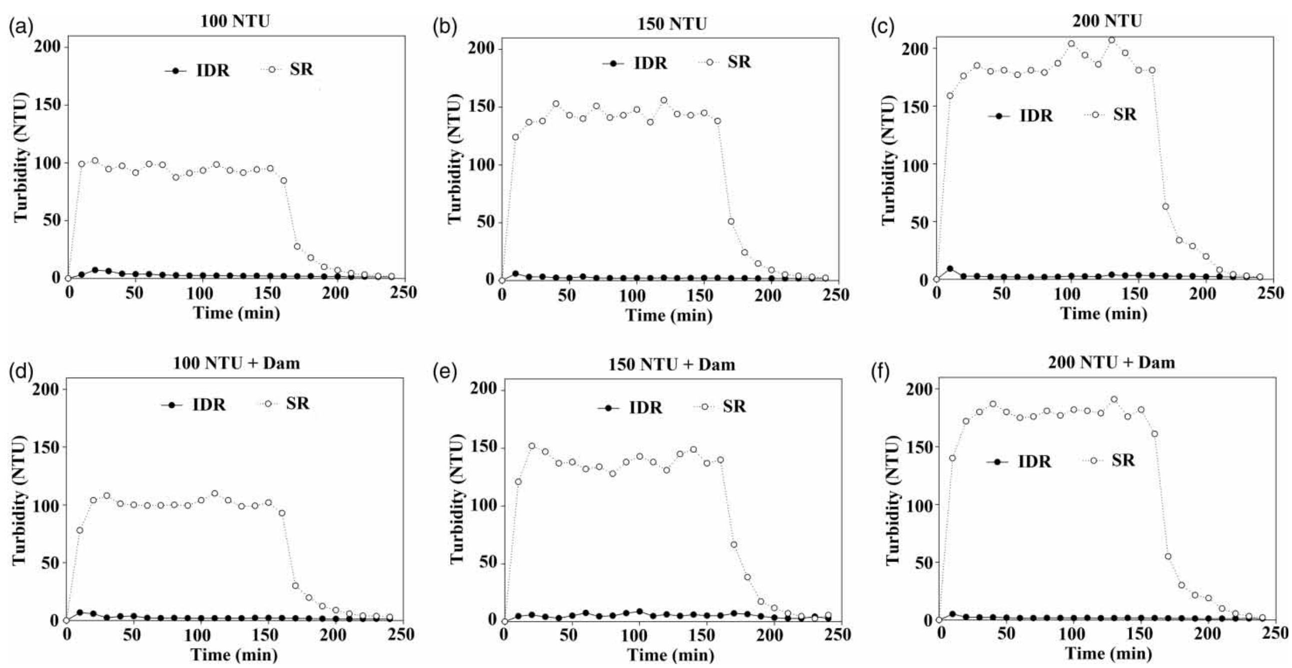


Figure 7 | (a)–(c) show the turbidity variation process of IDR and SR only, and (d)–(f) also show the turbidity variation of IDR and SR after the rubber dam is established.

Table 3 | Mass distribution of suspended particles

Serial number	Rubber dam	Turbidity (NTU)	Total (g)	IDR (g)	SR (g)	LSR (g)	Retained (g)
①	No	100	39.8	0.9	13.7	0	25.2
②		150	56.4	0.4	32.5	0	23.5
③		200	75.2	0.4	42.8	0	32
④	Yes	100	39.8	0.7	16.6	0	22.5
⑤		150	56.4	1	30.3	0	25.1
⑥		200	75.2	0.4	33.3	0	41.5

removal of the rubber dam, but the clogging degree of the medium did not change significantly. After the suspended particles test, the surface sand gravel was washed and then backfilled to the sand tank model for the recharge test again, under the condition that the recharging water is tap water. And the monitored value of the IDR can almost recover to the critical value of the medium IDR.

4. DISCUSSION

Riverbed filtration can not only improve groundwater, but also purify water quality, which is a simple and efficient MAR type (Bertelkamp *et al.* 2016; Hamann *et al.* 2016; Cartwright & Irivine 2020; Yenehun *et al.* 2020). However, during the recharge, the river located in the piedmont area had completely different characteristics compared with the plain river. In this study, the permeability of the riverbed, and suspended particle turbidity had a serious influence on effective recharge of groundwater in the piedmont sand gravel channel infiltration. According to the research results of this paper, when IDR reached the critical seepage capacity of the riverbed, an excessive increase in water release would reduce the recharge efficiency. Furthermore, the suspended particles in the recharge water can also cause a greater reduction in the recharge efficiency of the gravel channel. In terms of the plugging position, it was easy to form plugging on the surface of the medium, especially physical clogging, whether it was a two-dimensional tank or one-dimensional sand column (Wang *et al.* 2012; Zheng *et al.* 2020; Zhao *et al.* 2021). To improve the recharge efficiency of groundwater, the rubber dam built on the riverbed surface had no obvious effect. However, it can promote the conversion of surface runoff with high speed into lateral shallow runoff with low speed, which has a positive significance for storing surface water in areas with low rainfall. Additionally, particles were carried into the riverbed by water flow, which is a potential hidden danger for the operation efficiency of recharge projects, due to the existence of the rubber dam. Therefore, before the construction of a rubber dam on riverbed surfaces, it should be fully demonstrated.

The piedmont channel in the NCP is dominated by sand gravel, which is an excellent recharge site for restoring groundwater because of its high permeability. One of the most effective ways to control groundwater overexploitation in the NCP is to recharge groundwater by the seepage of water from the Yellow River in the piedmont sand gravel channel. In this paper, a sand tank model filled with sand and gravel was designed to simulate the characteristics of water distribution and sediment migration during managed aquifer recharge by Yellow River water in the piedmont sand gravel channel of the NCP. The research results of this paper can provide a new idea for groundwater restoration in the NCP. The Yellow River is an important water source flowing through the NCP. Clogging of the recharge projects caused by suspended particles in the Yellow River water seriously affects the recharge efficiency of groundwater. The way to study aquifer clogging should not be limited to physical models, and the COMSOL Multiphysics software has great advantages in simulating the movement of water and suspended particles in porous medium. The next step is to focus on the biological clogging and physical-biological clogging mechanisms in the sand gravel infiltration of the piedmont area through numerical models.

5. CONCLUSIONS

A two-dimensional sand tank experiment was carried out to investigate the variation characteristics of water and sediment during the Yellow River water recharge in the piedmont sand gravel channel of the North China Plain. The water variation process was simulated using HYDRUS-2D software to verify the rationality of the sand tank model compared with the results of the physical model. The main conclusions were as follows:

(1) Only infiltration deep runoff and surface runoff existed in the sand tank experiment. The IDR of the sand gravel medium accounted for 65–85% of the total recharge water. A reasonable released water plan was necessary in advance because the remaining released water was considered an invalid recharge when the IDR reached the critical value of the medium IDR. The rubber dam had no obvious effect on improving IDR, but could promote the transformation from SR to LSR.
(2) The thin clay layer formed by suspended particle deposition on the medium surface reduced the IDR value. After clogging, the surface sand gravel was washed and then backfilled into a sand tank for the tap water recharge test again. The IDR value can almost recover to the critical value of the medium IDR. The increase in suspended particle concentration promoted the suspended particle deposition in the sand tank. After filtration by the sand tank, the recharge water turbidity was reduced by at least 96%. The rubber dam can increase the suspended particle deposition mass in the sand tank.
(3) By comparing the physical and numerical model results, the fitting degree of the pressure head with time change was more than 0.9. Thus, the sand tank model can be used to simulate the water variation in the piedmont sand gravel channel.
(4) The research conclusions of this paper can provide a new recharge method by using the Yellow River water in the piedmont areas of the North China Plain.

ACKNOWLEDGEMENTS

This paper was supported by the Natural Science Foundation of Shandong Province (No. ZR2021ME069). We sincerely thank the editors and anonymous reviewers for their detailed and constructive comments on this article, which has greatly improved the quality of the article.

AUTHOR CONTRIBUTIONS

This paper was composed by collaboration among all authors. W.W. and S.L. designed this study and helped improve its progression and clarity. W.Z. wrote this paper. S.Q., D.X., X.S. and Y.M. helped in revising the paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Bertelkamp, C., Van der Hoek, J. P., Schoutteten, K., Hulpiau, L., Vanhaecke, L., Vanden, B. J., Cabo, A. J., Callewaert, C., Boon, N., Lowenberg, J., Singhal, N. & Verliefde, A. R. D. 2016 The effect of feed water dissolved organic carbon concentration and composition on organic micropollutant removal and microbial diversity in soil columns simulating river bank filtration. *Chemosphere: Environmental Toxicology and Risk Assessment* **144**, 932–939. https://doi.org/10.1016/j.chemosphere.2015.09.017

Cao, G. L., Scanlon, B. R., Han, D. M. & Zheng, C. M. 2016 Impacts of thickening unsaturated zone on groundwater recharge in the North China Plain. *Journal of Hydrology* **537**, 260–270. https://doi.org/10.1016/j.jhydrol.2016.03.049

Cartwright, I. & Irivine, D. 2020 The spatial extent and timescales of bank infiltration and return flows in an upland river system: implications for water quality and volumes. *Science of The Total Environment* **743**, 140748. https://doi.org/10.1016/j.scitotenv.2020.140748

Cui, X. C., Chen, C. L., Sun, S., Zhou, D. D., Ndayisenga, F., Huo, M. X., Zhu, S. Y., Zhang, L. L. & Crittenden, J. C. 2018 Acceleration of saturated porous media clogging and silicon dissolution due to low concentrations of Al(III) in the recharge of reclaimed water. *Water Research* **143**, 136–145. https://doi.org/10.1016/j.watres.2018.06.043

Cui, R. J., Ye, X. Y. & Du, X. Q. 2021 Coupled effects of bacteria and suspended solids on clogging during managed aquifer recharge. *Journal of Hydrology* **600**, 126543. https://doi.org/10.1016/j.jhydrol.2021.126543

Dillon, P. 2005 Future management of aquifer recharge. *Hydrogeology Journal* **13** (1), 313–316. https://doi.org/10.1007/s10040-004-0413-6

Fetzer, J., Holzner, M., Plotze, M. & Furrer, G. 2017 Clogging of an Alpine streambed by silt-sized particles: Insights from laboratory and field experiments. *Water Research* **126**, 60–69. https://doi.org/10.1016/j.watres.2017.09.015

Hamann, E., Stuyfzand, P. J., Greskowiak, J., Timmer, H. & Massmann, G. 2016 The fate of organic micropollutants during long-term/long-distance river bank filtration. *Science of the Total Environment* **545-546**, 629–640. https://doi.org/10.1016/j.scitotenv.2015.12.057

Li, W. L., Sun, Q., Wang, W. P., Qu, S. S., Zhang, Z. X. & Xu, Q. Y. 2019 Effective water quantity of multi-source water recharging aquifers in Yufuhe River based on groundwater and surface water semi-coupled modeling. *Water Supply* **19** (8), 2280–2287. https://doi.org/10.2166/ws.2019.109

Pavelic, P., Dillon, P. J., Mucha, M., Nakai, T., Barry, K. E. & Bestland, E. 2011 Laboratory assessment of factors affecting soil clogging of soil aquifer treatment systems. *Water Research* **45** (10), 3153–3163. https://doi.org/10.1016/j.watres.2011.03.027

Rong, Q., Wang, W., Qu, S. S., Li, J. C., Li, F. L., Xu, Q. Y., Huang, Q. & Deng, H. Y. 2017 A MAR to address the water with high content of suspended solid with a case study in the Yellow River flood plain, China. *Agricultural Water Management* **182**, 165–175. https://doi.org/10.1016/j.agwat.2016.09.026

Wang, Z. J., Du, X. Q., Yang, Y. S. & Ye, X. Y. 2012 Surface clogging process modeling of suspended solids during urban stormwater aquifer recharge. *Journal of Environmental Sciences* **24** (8), 1418–1424. https://doi.org/10.1016/S1001-0742(11)60961-3

Wang, H., Xin, J., Zheng, X. L., Li, M., Fang, Y. H. & Zheng, T. Y. 2020 Clogging evolution in porous media under the coexistence of suspended particles and bacteria: insights into the mechanisms and implications for groundwater recharge. *Journal of Hydrology* **582**, 124554. https://doi.org/10.1016/j.jhydrol.2020.124554

Wu, C., Xu, Q. H., Zhang, X. Q. & Ma, Y. H. 1996 Palaeochannels on the North China Plain: types and distributions. *Geomorphology* **18** (1), 5–14. https://doi.org/10.1016/0169-555x(95)00147-w

Xian, Y., Jin, M. G., Zhan, H. B. & Liu, Y. F. 2019 Reactive transport of nutrients and bioclogging during dynamic disconnection process of stream and groundwater. *Water Resources Research* **55** (5), 3882–3903. https://doi.org/10.1029/2019WR024826

Xie, Y., Wang, Y., Huo, M. X., Geng, Z. & Fan, W. 2020 Risk of physical clogging induced by low-density suspended particles during managed aquifer recharge with reclaimed water: evidences from laboratory experiments and numerical modeling. *Environmental Research* **186**, 109527. https://doi.org/10.1016/j.envres.2020.109527

Yenehun, A., Nigate, F., Belay, A. S., Desta, M. T., Van Camp, M. & Walraevens, K. 2020 Groundwater recharge and water table response to changing conditions for aquifers at different physiography: the case of a semi-humid river catchment, northwestern highlands of Ethiopia. *Science of The Total Environment* **748**, 142243. https://doi.org/10.1016/j.scitotenv.2020.142243

Zhao, Q., Zhang, B., Yao, Y. B., Wu, W. W., Meng, G. J. & Chen, Q. 2019 Geodetic and hydrological measurements reveal the recent acceleration of groundwater depletion in North China Plain. *Journal of Hydrology* **575**, 1065–1072. https://doi.org/10.1016/j.jhydrol.2019.06.016

Zhao, W. D., Wang, W. P., Liu, S., Qu, S. S., Sun, X. X. & Meng, Y. J. 2021 Water distribution and silt clogging in the strong-seepage zone infiltration process of Yufuhe River from Yellow River water based on the two-dimensional sand tank model. *Water* **13** (9), 1200. https://doi.org/10.3390/w13091200

Zheng, Q., Wang, W., Liu, S. & Qu, S. S. 2020 Physical clogging experiment of sand gravel infiltration with Yellow River water in the Yufuhe River channel of Jinan, China. *Frontiers of Earth Science* **14** (2), 306–314. https://doi.org/10.1007/s11707-019-0772-x

First received 6 April 2022; accepted in revised form 1 September 2022. Available online 9 September 2022