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ORIGINAL ARTICLE

Effectiveness of riverbank filtration for removal of nitrogen from heavily polluted rivers: a case study of Kuihe River, Xuzhou, Jiangsu, China

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Abstract The Kuihe River is in Xuzhou, Jiangsu, China. It contains high concentrations of nitrogen. The water in the Kuihe River recharges the groundwater via riverbank filtration (RBF) along the Xucun and Huangqiao reaches, which are characterized by unsaturated and saturated percolations, respectively. The two sections were selected to study the effectiveness of RBF to the nitrogen removal from the infiltrating river water. The results showed that the RBF in the saturated percolation had the potential to remove the nitrogen through biochemical processes. The nitrogen-removal rates were more than 95% over the monitoring period. However, the RBF in the unsaturated percolation resulted mainly from the physical process and thus had no efficacy for nitrogen removal.

Keywords Kuihe River · Riverbank filtration · Saturated percolation · Nitrogen removal · China

Introduction

Riverbank filtration (RBF) is a process in which surface water is subjected to underground passage before being collected in a well (Doussan et al. 1997; Hiscock and Grischek 2002; Ray et al. 2002). The physical, chemical, and biological processes in RBF can significantly improve the infiltrating river water quality under favorable conditions (Hiscock and Grischek 2002; Weiss et al. 2005). RBF has been used as a pretreated method to improve drinking water quality for more than 100 years in Europe and China. The experience has demonstrated a number of water quality improvements associated with RBF, including removal of total organic carbon, chemical oxygen demand (COD), and biodegradable organic compounds. However, there are limitations in RBF to purify water. One of the limitations is that some pollutants such as nitrogen (Doussan et al. 1997) and trichloroethylene (Jütter 1999) have low to no removal rates. These pollutants are usually much harmful to human health. Another limitation is that groundwater is vulnerable to surface water pollution. Up to now, primarily the efficacy of RBF to purify the water and remove the pollutants under micro-polluted rivers studies has been studied (Ray et al. 2002; Tufenkji et al. 2002). Few studies were conducted near a heavily polluted river (Kayabalı et al. 1999). Surface water is nowadays polluted widely, and some rivers have been heavily polluted, especially in developing countries. There commonly are diverse pollutants such as nitrogen and trichloroethylene in surface waters. The heavily polluted rivers might affect the groundwater quality via RBF. Therefore, it is important to research effectiveness of RBF in removing pollutants from the infiltrating river water that is heavily polluted.

This study explores whether RBF is efficient in such pollutants' removal and its characteristics under a heavily polluted river in a case study. The study site is in Xuzhou, Jiangsu, China (Fig. 1), where the Kuihe River was polluted heavily by nitrogen. The river water

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recharges groundwater and influences its quality by RBF. The river was selected as a case study to research the efficacy of RBF to remove nitrogen from the infiltrating water, and the effects of several hydrogeological conditions on the efficacy.

Field study

Study site

The Xuzhou region is in the west of Jiangsu province, China. The Old Yellow River flows through the region from west to east, and its riverbed altitude is higher than the ground elevation and divides the region into two surface water systems. The southern surface water system is the Kuihe River watershed and is the study area (Fig. 1). The Kuihe River emanates from the Yunlong Lake in Xuzhou city, and flows through Shilipu, Xucun and Huangqiao, then to Anhui province in a southeasterly direction. The river is approximately 22 km long in the Xuzhou region (Jiang et al. 1997; Li 2001). The river collects most of the industrial wastewater and domestic sewage in the south Xuzhou city, and its average flow rate is approximately 8.0×10^4 m^3/day (Li 2001).

Since 1995, the river has been investigated more than ten times. The water was black with no flora and fauna. The trees on the bank were dying. The monitoring data (Table 1) indicate that although the river water quality has improved from 1995 to 2002, it has been seriously polluted (Jiang et al. 1997; Li and Wei 1998; Li 2001), especially COD and NH_4^+–N. Both concentrations were stable along the whole reach in the Xuzhou region. The river had essentially lost its self-purification capacity (Han and He 2004).

Along the Kuihe riverbanks, there is a Quaternary sedimentary layer with 10–30 m thick. The layer is mainly made of clay, sub-clay and fine sand, and contains groundwater. Under natural conditions, the porous aquifer was replenished by precipitation. The groundwater level ranged from 0.5 to 4.0 m deep, which was higher than the water level in the river. Therefore, the groundwater discharged to the river naturally. The hydrochemical type of the groundwater was Ca–Mg·HCO_3. The background concentration for chlorite (Cl^-) was 26–30 mg/L (Wang et al. 2002). The groundwater was of good quality and was collected in a

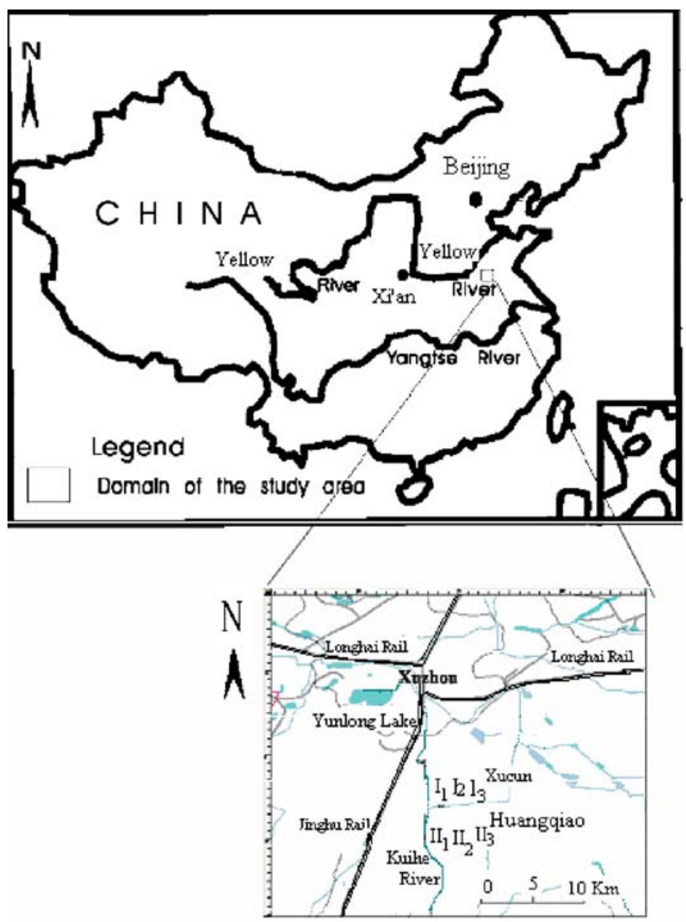


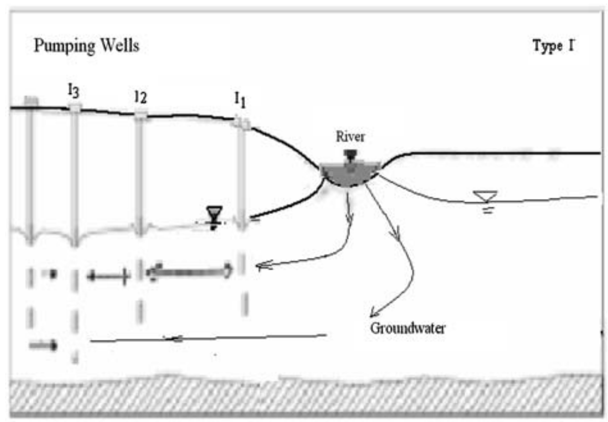
Fig. 1 Location of the study area

Table 1 The concentrations of chemical components in Kuihe river water

Year	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	Total nitrogen (mg/L)	NH_4^+–N (mg/L)	NO_3^-–N (mg/L)	NO_2^-–N (mg/L)	Cl^- (mg/L)
1990	0.0	427	225					
1991	0.1	716	294					
1992	0.1	560	255					
1993	0.1	548	248					
1994	0.0	646	610					
1995	0.0	379	160	17.674	17.09	0.57	0.014	160.2
1999	0.47	109	42.4	39.478	16.64	21.31	1.528	164.8
2002	0.07	116	65.8	17.667	16.42	1.24	0.007	161.4

well by a family along the riverine countryside and used as the main water source for domestic supply. Groundwater is still the main drinking water source in this area today.

Because of the development of agriculture and the increase in population, there is a growing water shortage in the watershed. To overcome the shortage, several dams were built to retain water in the river during 1950–1970s. As a result, the river water level was raised to higher than the natural groundwater level, and the hydraulic relation between the river and the groundwater was completely changed. Currently, the river discharges to the porous aquifer via RBF through unsaturated seepage along the Xucun section (Section I), and through saturated seepage along the Huangqiao section (Section II). The locations of Xucun and Huangqiao sections are shown in Fig. 1, and the percolation types of the groundwater flow in the RBF processes at the two sections are represented in Fig. 2. The majority of RBF schemes are of type I, where the groundwater is recharged by the river via RBF in a great flux. However, when the hydraulic conductivity of the riverbed is too small to adapt the groundwater abstraction rates, the formation of unsaturated condition beneath the river occurs, that RBF is called unsaturated RBF. In view of groundwater dynamics (Bear 1988), the quantity of the groundwater recharged by the unsaturated RBF at the Xuncun section is less than that by the saturated RBF at the Huangqiao section, because their hydrogeological conditions have some small differences but the permeability coefficient of the saturated RBF is greater than that in the unsaturated one (Wang et al. 2002). Therefore, the area of the groundwater affected by the river along the Xucun section is smaller than that along the Huangqiao section.



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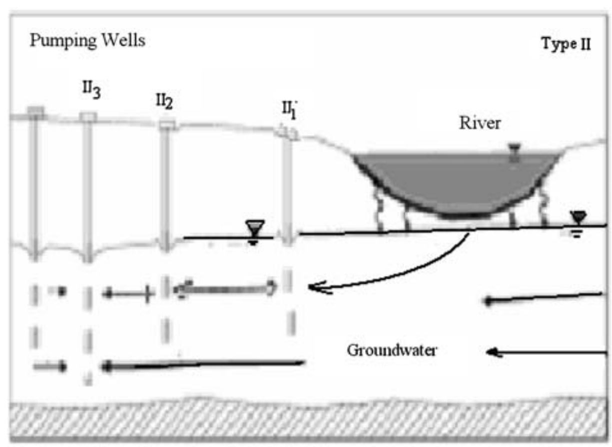

II

Fig. 2 Schematic representation of types of groundwater flow types at RBF sites (*I*: saturated percolation conditions; *II*: unsaturated percolation conditions)

Field monitoring

To study the effectiveness of RBF to remove nitrogen from the infiltrating river water, two sections, where three wells with a depth of 10 m available for each section, were selected on the Kuihe riverbank (Fig. 1). The distances from the wells to the riverbank are given in Table 2. Samples were taken in 2002 from each well and were analyzed by the national standards methods of China (State Environmental Protection Administration of China 1998), and their results are shown in Tables 3 and 4.

Table 2 The distances from the monitoring wells to the Kuihe riverbank

Section	Xucun section			Huangqiao section		
Monitoring Well	I_1	I_2	I_3	II_1	II_2	II_3
Distance to riverbank (m)	19.0	36.0	55.5	40.0	62.6	138.6

Results and discussion

Assessment of the groundwater quality

Tables 1, 3, and 4 indicate that the monitored groundwater quality is superior to the Kuihe River water quality; the groundwater quality exceeds the primary standards for the sewage discharge of China (GB8978-1996; Ministry of Construction of the People's Republic of China 1996), and even the concentrations of several constituents (such as Cl^-, NH_4^+–N, NO_3^-–N, and NO_2^-–N) met the national drinking water standards of China (GB5749-85; Ministry of Health of the People's Republic of China 1985). These show that the RBF, which is in unsaturated or saturated percolation, seem to have a potential to improve the infiltrating river water quality to some extent. Compared with the background concentrations, the concentrations of NH_4^+–N and Cl^- were higher in the groundwater in the belt along the river, where a pollution plume existed in the Xucun section within 19 m. Along the Huangqiao section, the Cl^- concentration of groundwater was much higher. Even in the well 138.6 m from the riverbank, the Cl^- concentration was two times its background concentration. The pollution plume in the Huangqiao section was much larger than that along the Xucun section. These show that the polluted river not only recharged groundwater and affected its quantity by RBF, but also impacted the groundwater quality, especially around the saturated RBF.

Table 3 Groundwater quality in the wells along Xucun section

Monitoring date	Well	Total nitrogen (mg/L)	NH_4^+–N (mg/L)	NO_3^-–N (mg/L)	NO_2^-–N (mg/L)	Cl^- (mg/L)
2/21/2002	I_1	1.64	1.42	0.22	0.004	32.6
4/13/2002		3.69	3.10	0.14	ND	31.3
6/29/2002		3.27	2.97	0.19	ND	35.2
8/28/2002		3.27	3.15	0.11	0.008	35.0
2/21/2002	I_2	2.10	1.92	0.18	ND	29.3
4/13/2002		2.60	2.46	0.14	ND	28.4
6/29/2002		0.88	0.67	0.20	0.012	32.3
8/28/2002		2.93	2.81	0.12	ND	72.9
2/21/2002	I_3	0.84	0.61	0.23	ND	32.2
4/13/2002		1.33	1.18	0.14	0.007	27.4
6/29/2002		1.25	0.90	0.35	ND	31.3
8/28/2002		2.02	1.16	0.85	0.012	33.0

ND under the detected limit 0.003 mg/L

Table 4 Groundwater quality in the wells along Huangqiao section

Monitoring date	Well	Total nitrogen (mg/L)	NH_4^+–N (mg/L)	NO_3^-–N (mg/L)	NO_2^-–N (mg/L)	Cl^- (mg/L)
2/21/2002	II_1	0.35	0.29	0.06	ND	142
4/13/2002		0.23	0.15	0.08	ND	130
6/29/2002		0.43	0.39	0.04	ND	146
8/28/2002		0.24	0.13	0.11	ND	145
2/21/2002	II_2	0.35	0.28	0.07	ND	104
4/13/2002		0.18	0.14	0.04	ND	95.9
6/29/2002		0.35	0.31	0.04	ND	64.6
8/28/2002		0.25	0.14	0.11	ND	96.2
2/21/2002	II_2	0.36	0.27	0.09	ND	73.4
4/13/2002		0.19	0.15	0.04	ND	73.4
6/29/2002		0.38	0.34	0.04	ND	99.8
8/28/2002		0.19	0.12	0.07	ND	73.8

ND under the detected limit 0.003 mg/L

Characteristics of RBF in nitrogen removal

As mentioned above, RBF has a potential to improve the infiltrating river water quality by physical (such as dilution), chemical, and biochemical processes (Hiscock and Grischek 2002; Weiss et al. 2005). Generally, the potential from the physical process is limited, because (1) the groundwater in the RBF system usually origins mainly from the river water; and (2) while pollutants go through the RBF system, although they transfer from one place to another place and even their concentrations decrease, their masses conserve in the studied system. In other words, there are no pollutants removed from the studied system by physical processes. During the chemical and biochemical processes, on the other hand, the pollutants transform, and may be removed from the studied system. To explore the pollutant-removal effectiveness of RBF, methods are suggested to amplify the potential from the chemical and biochemical processes, where the objective pollutants are removed, and to minimize that from the physical processes, where the pollutants are not removed.

The groundwater along the riverbank is recharged by the river water and precipitation. Cl^- in the groundwater may come from the river water and (or) precipitation, and also is affected by the human agriculture activities. The Cl^- concentration is more than 126 mg/L in the river water, which is much higher than that from the rain. Of the agriculture activities, irrigation is the main factor affecting the groundwater quality. And in the studied area, irrigation has little effect on the Cl^- concentration in the groundwater (Jiang et al. 1997). Thus, Cl^- in the groundwater mainly comes from the river water. Because Cl^- is generally considered as a tracer, it can be used to determine the percentage (x) of the groundwater coming from the river water based on the formula:

$$x = \frac{C_1 - C_0}{C_s - C_1} \times 100\% \quad (1)$$

where, C_1: Cl^- concentration in the groundwater of the monitoring well (mg/L); C_0: Cl^- background concentration in the groundwater in the study area (mg/L); C_s: Cl^- concentration in the river water (mg/L).

If one objective pollutant has the same action as Cl^-, the theoretical concentrations can be computed for the objective pollutant when x is known, based on Eq. 1, and the calculated concentration is assumed to result from physical processes. In fact, an objective pollutant may be involved in physical processes as well as in chemical and biochemical processes. Comparing the calculated and monitored concentrations of an objective pollutant, the difference between the concentrations is found. Therefore, the difference results from pollutant removal through chemical and biochemical processes, and is used to assess the effectiveness of RBF for removal of nitrogen.

Effect of unsaturated and saturated percolation on nitrogen removal

According to Eq. 1, where Cl^- is used as the tracer, the percentages of the groundwater in well I_1 along the Xucun section coming from the river water are obtained as 20.38, 19.56, 22.0, and 21.88% on February 21, April 13, June 29, and August 28, respectively. These show that the minority of the groundwater comes from the river water and the majority is from its base water flow in the study area, and also prove that the river has less effect on the quantity of the groundwater along the Xucun unsaturated RBF. As discussed above, the nitrogen in the groundwater is mainly from the polluted river water. We assume that nitrogen be involved only in the physical process during RBF, thus the theoretical concentrations of the total nitrogen in the groundwater of well I_1 would also calculate to 3.6, 3.45, 3.89, and 3.86 mg/L for the same sampling times. When calculated and monitored concentrations are compared (Table 3), there is no difference. The similar phenomena are also obtained for other wells along the Xucun section and at the other monitoring times. This proves our assumption and shows that nitrogen is only involved in the physical process. Compared with the river's effect on the groundwater quality, the effects of agriculture activities and precipitation are very limited, and even negligible. Thus, during the unsaturated RBF, nitrogen in the infiltrating water is just mixed with the groundwater and not reduced. The RBF system in unsaturated percolation has no potential to remove nitrogen from the infiltrating polluted water.

Nitrogen is mainly in three forms: NH_4^+–N, NO_3^-–N, and NO_2^-–N. The unsaturated RBF system, which exchanges matter and energy with atmosphere, is in aerobic condition. Usually in the soil environment, NH_4^+–N is reactive and involved in nitrification under an aerobic condition:

$$NH_4^+ - N + 2O_2 \xrightarrow{\text{nitrifers}} NO_3^- - N + 2H^+ + H_2O. \quad (2)$$

From Tables 1 and 3, the ratio of NH_4^+–N/total-nitrogen in the groundwater is lower than that in the river water, and the ratio of NO_3^-–N/total-nitrogen in the groundwater is higher than that in the river water. Nitrogen is also involved in nitrification, which transforms NH_4^+–N to NO_3^+–N. NO_2^-–N also exists and its concentration in the groundwater is higher than that in the river water during 2002 (Tables 1, 3), which is considered as an indicator of nitrification (Zhu 1990). These certify that nitrogen is involved in nitrification, which is one of biochemical processes. Nitrification causes the nitrogen to transform from one form to another, and no nitrogen escapes from the groundwater. Therefore, the RBF system in unsaturated percolation has no potential to remove total nitrogen from the studied system.

Along the Huangqiao section, the RBF system is in saturated percolation. When Eq. 1 is used to the groundwater in the wells, the findings are different from those along the Xucun section. For example, the theoretical concentrations of the total nitrogen of groundwater in well II_1, based on calculation of Cl^- concentration, are 15.67, 14.35, 16.11, and 16.01 mg/L on February 21, April 13, June 29, and August 28, respectively. These concentrations are much greater than the corresponding monitored concentrations (Table 3). This indicates that there is nitrogen removal from the studied system in the saturated RBF. Therefore, the RBF in saturated percolation can remove the nitrogen from the infiltrating river water. For that reason, RBF in the following discussion is for the saturated percolation only.

To assess the effectiveness of RBF to remove nitrogen, the following equation is used to calculate the objective pollutant removal rate (R_x):

Table 5 Nitrogen-removal rates to the wells along Huangqiao section

Monitoring date	II_1 (%)	II_2 (%)	II_3 (%)
2/21/2002	97.78	96.98	95.56
4/13/2002	98.38	98.30	97.65
6/29/2002	97.33	95.09	96.55
8/28/2002	98.50	97.65	97.67

$$R_x = \frac{C_s - C_x}{C_s} \times 100\% \qquad (3)$$

where C_s stands for the objective pollutant concentration in the river water (mg/L), and C_x for the objective pollutant concentration of groundwater in a well with x (m) distance to the riverbank.

From Eq. 3, the nitrogen-removal rates are calculated as 97.78, 98.38, 97.33, and 98.50% for well II_1 along Section II on February 21, April 13, June 21, and August 28, respectively. The calculated rates for other wells are also calculated and shown in Table 5. These data indicate that the RBF in saturated percolation is effective in nitrogen removal from the infiltrating river water.

Effect of the seasons on nitrogen removal

Effectiveness of RBF in pollutant removal is mainly from the microbiological process (Jütter 1999; Hiscock and Grischek 2002). Microbiological activity is affected by temperature. The temperature changes with the annual seasons. Therefore, the effectiveness of RBF in pollutant removal may be affected by the seasons. For microbiological activity, there is an optimal temperature during which the microbiological activity is lasting and stabilizing (Maier et al. 2000).

Generally, in the RBF environment, the temperature is high during the summer, and low during the winter. Table 5 shows the nitrogen-removal rates for the groundwater of the wells along the Huangqiao section. Based on Table 5, the effectiveness of the RBF to nitrogen removal does not vary with the seasons, and the nitrogen-removal rates are more than 95% consistent. This perhaps results from that the temperature in the RBF environment, especially 10 m below ground, does not change significantly with the seasons.

Effect of the interface thickness between the river and groundwater on nitrogen removal

The interface between the river and groundwater is the soil layer between the top surface of the riverbed sediments and the underlying groundwater table (Gunten and Zoberist 1993), as shown in Fig. 2. As proved in many studies (Schwarzenbach and Westall 1981; Schwarzenbach and Giger 1985; Gunten and Zoberist 1993), the interface has an important role in the efficacy of RBF for pollutant removal. The interface is rich in organic matter and contains plenty of microbes.

Along the Huangqiao section, the buried depth of the groundwater table varied from 1.7 to 2.6 m. The interface thickness fluctuated approximately 0.9 m. As shown in Table 3, the concentrations of NH_4^+–N and NO_3^-–N in the groundwater were small and hardly changed during 2002. The concentrations of NH_4^+–N and NO_3^-–N in the Kuihe River were stable in 2002, and the nitrogen-removal rates hardly varied during 2002 (Table 5). The efficacy of RBF in the saturated percolation in nitrogen removal was not affected by the interface thickness.

Conclusion

The Kuihe River located in Xuzhou region, Jiangsu, China, is heavily polluted by nitrogen. The river water recharges the groundwater via RBF in unsaturated percolation along the Xucun section, and in saturated percolation along the Huangqiao section. The Xucun and Huangqiao sections were both selected as study sites to explore the effectiveness of RBF in nitrogen removal from the heavily polluted river. This study indicates that the RBF in the saturated percolation has potential to improve the infiltration water quality and to remove nitrogen from the infiltrating water. The potential of nitrogen removal at this site is not affected by the seasons and the interface thickness. The RBF in the unsaturated percolation did not have the potential. For nitrogen removal, the RBF in the saturated percolation may be a good choice to treat nitrogen-polluted water and control the groundwater nitrogen pollution.

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