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Effects of riverbed and lake bottom sediment thickness on infiltration and purification of reclaimed water

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Abstract Municipal wastewater reuse has been an important way to enhance water pollution control and water conservation in China. However, many pollutants, such as N, P, chemical oxygen demand (COD_{Cr}), and 5-day biochemical oxygen demand (BOD_5), are contained in the reclaimed water that can pollute the groundwater environment around rivers and lakes supplied with reclaimed water. Therefore, an environmentally friendly method to control infiltration and purification is quite necessary. Original sediment is one potential option. Therefore, in this study, the effects of sediment thickness at 5, 10, and 20 cm were studied for water infiltration and purification processes in riverbed media. The results indicate that the infiltration efficiency of the riverbed media was reduced when the sediment formed gradually and reached an appreciable level. The thickness was kept at 5–20 cm, and the ranges of the removal efficiencies for BOD_5, COD_{Cr}, ammonium-nitrogen, nitrate-nitrogen, total nitrogen, and total phosphorus were 47.7–69.0, 49.9–62.7, 90.6–92.5, 30.5–45.8, 42.7–63.1, and 62.2–77.9%, respectively, by a sediment and soil pillar of riverbed media. The removal efficiencies increased by increasing the sediment thickness, and the final infiltration rates were over 10^{-4} cm/s. The riverbed infiltration remained steady even when thickness was beyond 20 cm, and the purification effect was obvious. The ammonium-nitrogen removal efficiency of the riverbed filtration system did not appear to have an unlimited increase with the increase in sediment thickness. Generally, the existence of a nitrification and denitrification interface was located in the sedimentary layer, and it remained anaerobic at the bottom over a 10-cm thickness. Because ammonium-nitrogen was involved in nitrification, the nitrate-nitrogen concentration of the percolate tended to increase at the beginning of experiments. As the adsorption and nitrification took place, over 90% of ammonium-nitrogen was removed in the riverbed infiltration system through attachment to sediments. The experimental results could be used as references in river regulation.

Keywords Sediments · Reclaimed water · Riverbed media · Infiltration · Purification

Introduction

Rivers do not function of rivers only for transportation, but also as a major supply of water resources for cities. In recent years, urbanization in China has increased in speed following the initiation of the Chinese economic reform. By the end of 2015, 56% of the total population lived in urban areas, a dramatic increase from 26% in 1990 (CCTV 2016). Meanwhile, the urbanization process increased the overexploitation of water resources, so these years municipal wastewater reuse has been an important way to enhance water pollution control and water conservation in China. City water demand has been rapidly increasing in cities, and water shortage problems continue to emerge from decreased or completely dried out water flows. Municipal wastewater reuse has been an effective measure to alleviate the water resource shortages and enhance water pollution control in cities (Li et al. 2012). The largest reclaimed water consumption occurs in landscape

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environment applications (Huang 2008). In 2011, Document No. 1 of the Central Government of China first explicitly proposed the policy "vigorously promote wastewater treatment and reuse." Beijing pioneered the use of reclamation engineering to keep the ecological landscape in rivers and lakes, such as the Yongding River. Since 2012, several major sewage treatment plants, including the Gaobeidian, Jiuxianqiao, and Qinghe sewage treatment plants, have been put into operation. Now nearly 30×10^4 m^3/day of reclaimed water is used for landscape environment applications in Beijing.

After the free water in sediment is lost, the sediments become dry sand and soil. When dry riverbeds have been exposed for a long time, the infiltration rate of reused reclaimed water becomes high, so it is difficult to maintain flow, while the rapid increases in groundwater level could be dangerous for city underground structures. Contaminants in the reclaimed water pose the risk of groundwater pollution. Therefore, treatments to reduce infiltration are necessary in riverbeds. It has been proven that water infiltration in rivers and lakes is also an important way to supply groundwater to cities with large areas of impervious cement.

Due to limited treatment technologies and funds, many pollutants remain in reclaimed water, such as N, P, chemical oxygen demand (COD$_{Cr}$), and 5-day biochemical oxygen demand (BOD$_5$). As a result, these compounds can cause pollution risks to nearby groundwater in the application area (Li 2012). Thus, it is necessary to take pollutant removal efficiency into consideration when groundwater is being supplied.

Anti-seepage methods for rivers and lakebeds commonly include concrete casting, masonry, or geo-membrane layers, as well as other infiltration reduction methods (Zhou et al. 2004). All of these methods have good impermeability but cannot meet the demands for groundwater recharge. They also have harmful influences on lake natural ecosystems; damage the interrelation of aqueous, soil, gaseous, and biophases; destroy the self-purification ability of the natural ecosystem; and accelerate water deterioration (Chen 2006). Clay or geo-synthetic clay liner can be paved directly for anti-seepage, since it has a much lower impact on natural ecosystem in contrast to the first two. However, refractory foreign bodies will be added to the river that are uncoordinated to the natural river and can separate migration of the microorganisms in the upper and lower infiltration reduction layers, resulting in lower purification ability in the aeration zone. Even so, it is difficult to remove a geo-synthetic clay liner, since geo-membrane degrades. Of all the environmental protection cases during the year 2005 in China, the most influential and controversial was the "Yuan Ming Yuan Lakebed Anti-seepage Project Incident," which had extensive public participation and substantial media reporting (Zhang 2005). The incident had a profound impact not only on environmental protection in China, but also far beyond. The final environmental impact assessment concluded that the formal project of laying geo-membrane had been taken to decrease the water infiltration, and consequently, the total nitrogen and phosphorous of the lake water were effectively segregated. Without sufficient water exchange and biochemical reaction, nitrogen and phosphorous cause water eutrophication (Liang and Yang 2005).

Therefore, ideas must be changed in the process of reclaimed water reuse. Better purification efficiency of the riverbed filtration system will be achieved by means of lacustrine sediments. This paper examined the effects of three large soil column test systems built indoors to simulate the aeration zone. Sediment thicknesses of 5, 10, and 20 cm were deposited above riverbed media and under a 30-cm water head. Infiltration rates and purification characteristics of the riverbed media were studied to provide a reference for the coordination of the lake bottom infiltration rate, groundwater recharge, and water quality safety in the reuse of municipal reclaimed water.

Materials and methods

Sampling sites

Samples were collected from the Beiqijia segment in the Wenyu River, part of which has suffered from the worst eutrophication among Beijing's five major river systems. Three points 100 meters apart were chosen, with 20, 40, and 80 samples of 250 mL taken, respectively, from the three sites. River sands were taken from the riverbed surface at a depth of 1–3 m and sifted at 2 cm. The 0- to 50-cm depth was a priority site for sediment sampling when the flood receded. The undisturbed soil density and initial moisture content were determined by spoon sampling (Dirksen 1999). Group content of the riverbed media was analyzed by sieving test. The basic physical characteristics of the soil materials are listed in Table 1. The experimental reclaimed water was taken from the secondary effluent of the Qinghe Reclamation Plant in Beijing.

Experimental methods

Experimental design

The diagram of experimental apparatus in this study is shown in Fig. 1. After soil samples retrieved from the field were carried back to the laboratory, soil column packing in the aeration zone was simulated, with a packing order of: inverted   filter → riverbed

Table 1 Physical characteristics of riverbed sand in the aeration zone and natural sediments

Item	Group content (%)					Dry bulk density (g/cm^3)	Initial moisture content (%)
	Grit 2–0.5 mm	Medium sand 0.5–0.25 mm	Fine sand 0.25–0.1 mm	Very fine sand 0.1–0.05 mm	Coarse silt <0.05 mm		
Riverbed material	8.6	37.3	24.2	22.79	7.11	2.09	12.60
Sediment	5.21	19.82	25.33	23.40	23.24	1.24	143.58

Fig. 1 Structure of the aeration zone simulation system with dimensions in millimeters: 1—water storage tank, 2—PVC water supply pipes, 3—water pump, 4—Markov bottle, 5—PVC protection box, 6—soil water sampling bottles, 7—groundwater collector, 8—porous clay pipe, 9—large Plexiglas soil column, 10—rubber washer, 11—steel support base, 12—tension meter, 13—steel support frame
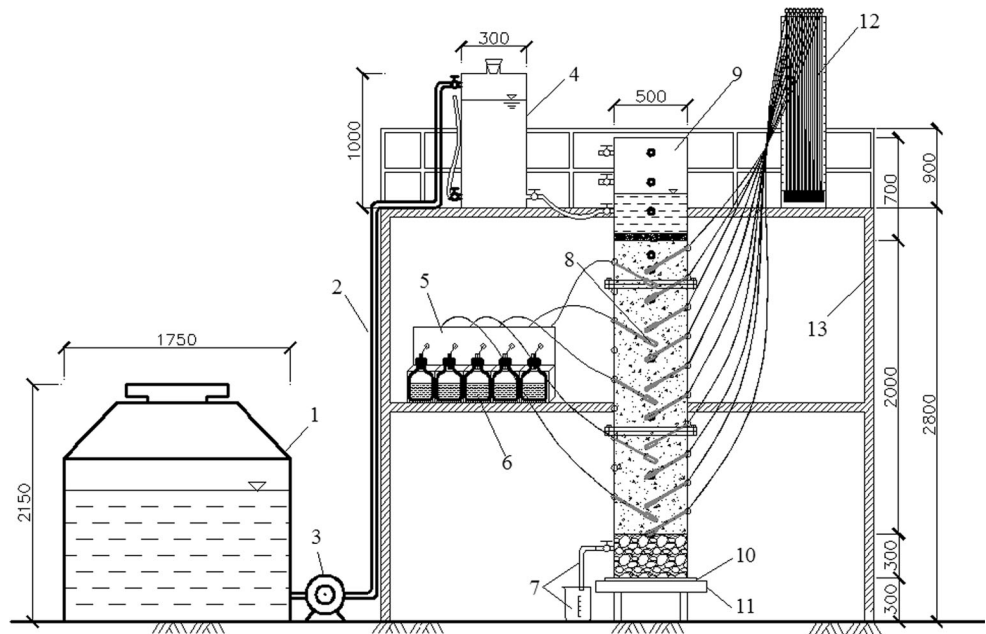
materials → sediments → protective layer. The riverbed was packed according to the initial moisture content, dry density, and soil volume. Packing once every 7.6 cm, the contact plane was scraped roughly to make the upper and lower soil layers contact fully in the adjacent soil filling layer, avoiding obvious stratification. Soil column filling and device assembly procedures are described in Li (2012).

A Markov bottle was used to supply water in the upper end of the soil column, and water was discharged from the bottom. Experiments were run for 155 days, and the water was changed once a month. The experiment was started in late June and ended in early December of 2013 at the Engineering Research Centre of Agricultural Water Saving and Water Conservation of China Agricultural University, Beijing. Ambient temperature and humidity were monitored in synchronization, with results shown in Fig. 2 and Table 2, and all windows were kept open during the experiment. The influent and effluent pollutant concentrations, such as COD$_{Cr}$, BOD$_5$, total nitrogen, total
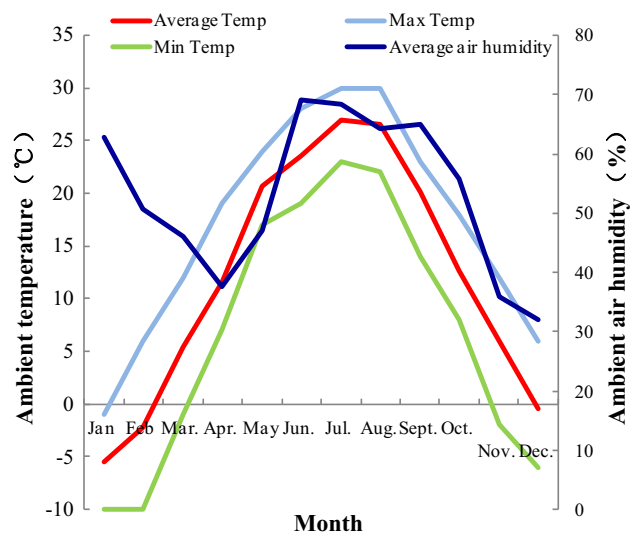
Fig. 2 Ambient environmental factors

Table 2 Environmental factors during the 2013 experiment

Month	Average temp.	Max. temp.	Min. temp.	Average air humidity
January	−5.5	−1	−10	62.8
February	−2.2	6	−10	50.8
March	5.4	12	−1	46
April	11.5	19	7	37.5
May	20.7	24	17	47
June	23.5	28	19	69.2
July	27	30	23	68.4
August	26.5	30	22	64.3
September	20.1	23	14	65.1
October	12.7	18	8	55.8
November	5.9	12	−2	35.9
December	−0.5	6	−6	32.1

Table 3 Experimental design parameters

Soil column number	Loading media	Influent quality	Hydraulic head (cm)
#1	5-cm inverted filter + 200-cm riverbed sand + 5-cm sediment + 5-cm protective layer	Reclaimed water	30
#2	5-cm inverted filter + 200-cm riverbed sand + 10-cm sediment + 5-cm protective layer	Reclaimed water	30
#3	5-cm inverted filter + 200-cm riverbed sand + 20-cm sediment + 5-cm protective layer	Reclaimed water	30

phosphorous, ammonium-nitrogen, and nitrate-nitrogen, were measured monthly. The experiment design parameters are listed in Table 3.

Inspection and calculation of cumulative infiltration

At the beginning of the experiment, a constant volume of water and additional water in beakers was accumulated. After the Markov bottle was opened, the cumulative infiltration was observed every 5 min. According to drawdown values of the Markov bottle and the change in the seepage wetting front, the water amount per unit area of soil infiltration was calculated as a function of total time, which had a cumulative infiltration value, I. The infiltration rate, i, is the water amount per unit area soil infiltration per unit time. The advancing distance of the wetting front per unit time is the advancing velocity, V_{zf}.

$$i = \frac{I}{t}$$

Determination of the pollutant concentrations

The concentrations of ammonium-nitrogen, nitrate-nitrogen, total nitrogen, COD_{Cr}, BOD_5, and total phosphorus

were determined. Methods for the analysis of pollutants are listed in Table 4.

Calculation assumptions for total pollutants

1. Water storage of the soil column was basically stable. As the long-running soil column system was also in a stable condition, it can be assumed that the water amount in the soil column remained balanced during a specific time. In another words, the water input at the top was equal to water output at the bottom, according to the law of the conservation of matter.

2. Pollutants in the soil column had no obvious leaching phenomena in the calculation interval, and changes in pollutant residues in the solid phase had negligible effects on removal efficiencies, since the solids were far downstream of the influent pollutants. Hence, only the aqueous pollutant removal efficiency was calculated in this paper.

Calculation of pollutant removal efficiencies

The concentrations of ammonium-nitrogen, nitrate-nitrogen, total nitrogen, COD_{Cr}, BOD_5, and total phosphorus in

Table 4 Methods for the determination of pollutants

No.	Item	Test method
1	BOD$_5$ (biochemical oxygen demand after 5 days)	Dilution and seeding method (HJ 505-2009)
2	COD$_{cr}$ (chemical oxygen demand)	Potassium dichromate oxidation titration
3	Ammonium-nitrogen	Gas-phase molecular absorption spectrometry (HJ/T 195-2005)
4	Nitrate-nitrogen	Spectrophotometric method with phenol disulfonic acid (GB 7480-87)
5	Total nitrogen	Gas-phase molecular absorption spectrometry (HJ/T 199-2005)
6	Total phosphorus	Continuous flow analysis (CFA) and ammonium molybdate spectrophotometry (HJ 670-2013)

the reclaimed water influent and effluent were measured, so that calculation of their removal efficiencies was possible. The effluent leachate was collected ten times in total over 3 days and preserved in a sterile environment at a constant temperature of 4 °C. The cumulative collected water samples were proportionally mixed to 1 L of water based on the water amount. One of the quantity demands of effluent was determined by the following equation:

$$V_{in} = \frac{V_i}{\sum_1^{10} V_i} * L$$

where V_{in} is the water demand for that period, V_i is the effluent amount at the same time, and L is the mixed total water for all i times. The flow concentration was tested by taking samples from the mixed water. The effluent concentration was noted within 30 days.

Results

Water infiltration

The penetration of the infiltration front through the soil column with time is shown in Fig. 3. The penetration time in the riverbed media and frontal advancing rate of the water both indicated that the infiltration tended to be fast at earlier times, and then subsequently slowed. The water breakthrough time was 1623, 3466, and 4825 min with sediment thicknesses of 5, 10, and 20 cm, respectively. Compared to the 10-cm sediment thickness, the penetration time at 5 cm was longer by over 1843 min, with a relative time error of 53.2%. Meanwhile, that for 20 cm was longer by more than 1359 min, with a relative time error of 28.2%. Based on the experimental water infiltration results, the relationship between the depth of the wetting front through the sediments and riverbed media and time was characterized by an exponential growth at first, followed linear growth. However, the duration of the exponential growth was short, and the thicker the sediment, the more obvious were the characteristics of exponential growth indicated by the fitting equations in Table 5. In Fig. 4, for 5-

and 10-cm soil column packing thicknesses, the infiltration rates significantly decreased over time and could be described as a power function (fast at first, then a rapid decrease, until finally reaching stability). At a 5-min infiltration time, the infiltration rates remained at 0.2 and 0.01 cm/min for 5- and 10-cm thicknesses, respectively. At 4000 min, the process tended to be stable with infiltration rates of 0.02 and 0.01 cm/min, respectively. In the soil column with 20 cm of sediment, the infiltration rate sharply decreased in the first 5000 min and then remained at 0.0007 cm/min in a stable infiltration phase.

Pollution interception and analysis

COD$_{Cr}$ and BOD$_5$ removal

The effects of the sediment thickness on COD$_{Cr}$ and BOD$_5$ removal are shown in Fig. 5, with the greatest amount of removal occurring in the 20-cm column. The COD$_{Cr}$ removal efficiencies at 5-, 10-, and 20-cm sediment thicknesses were 9.1–60.8, 44.2–60.8, and 43.5–90.7%, respectively, while the removal efficiencies for BOD$_5$ were 9.1–80, 48.3–80.8, and 44.2–82.8%, respectively.

At monthly cumulative influent and effluent concentrations, the average removal efficiencies of COD$_{Cr}$ and BOD$_5$ with 5-, 10-, and 20-cm thicknesses were 52.5 and 69, 47.7 and 56.5, and 69 and 62.7%, respectively.

Analysis of nitrogen removal efficiency

As observed from Fig. 6, the average removal efficiencies of ammonium-nitrogen were 90.6, 92.5, and 91.6% for 5, 10, and 20 cm, respectively. The best result was found at 10 cm. Results tended to increase slightly with an increase in sediment thickness and were related to influent month. Kopchynski et al. (1996) mentioned ammonium-nitrogen could be nitrated effectively in a soil aquifer at most conditions, but denitrification did not occur at any time.

Soil column #3 was at the bottom of the riverbed vadose zone, which was an aerobic environment preventing
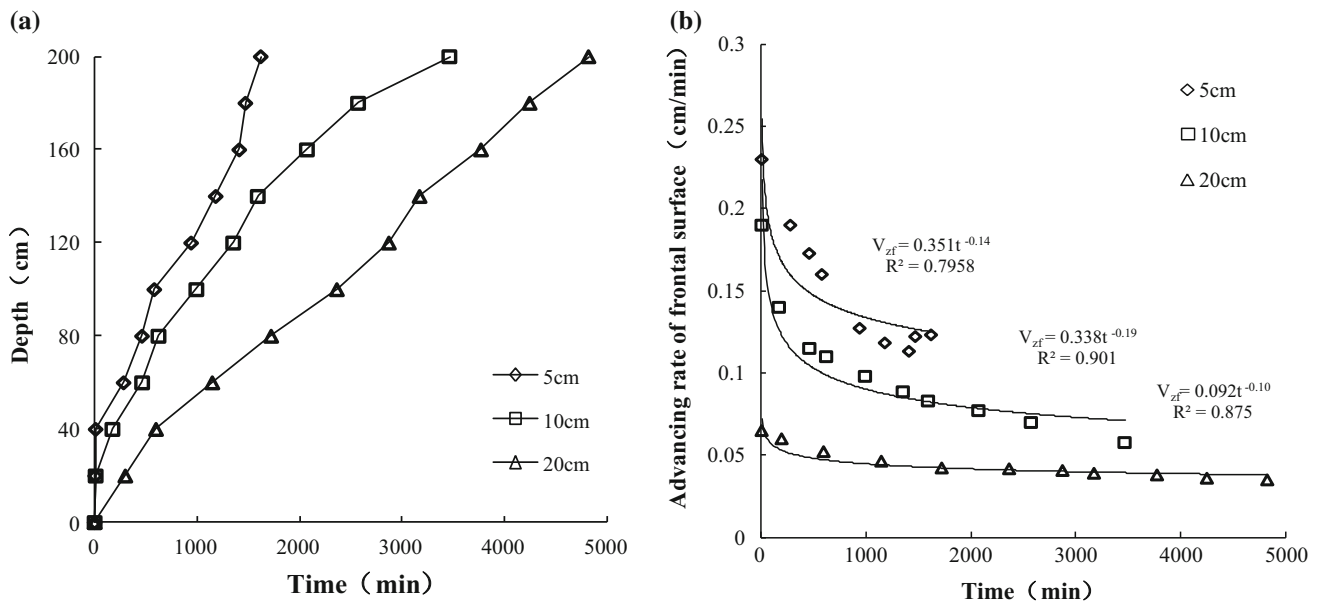
Fig. 3 Wetting front variation characteristics

Table 5 Fitting equations for infiltration

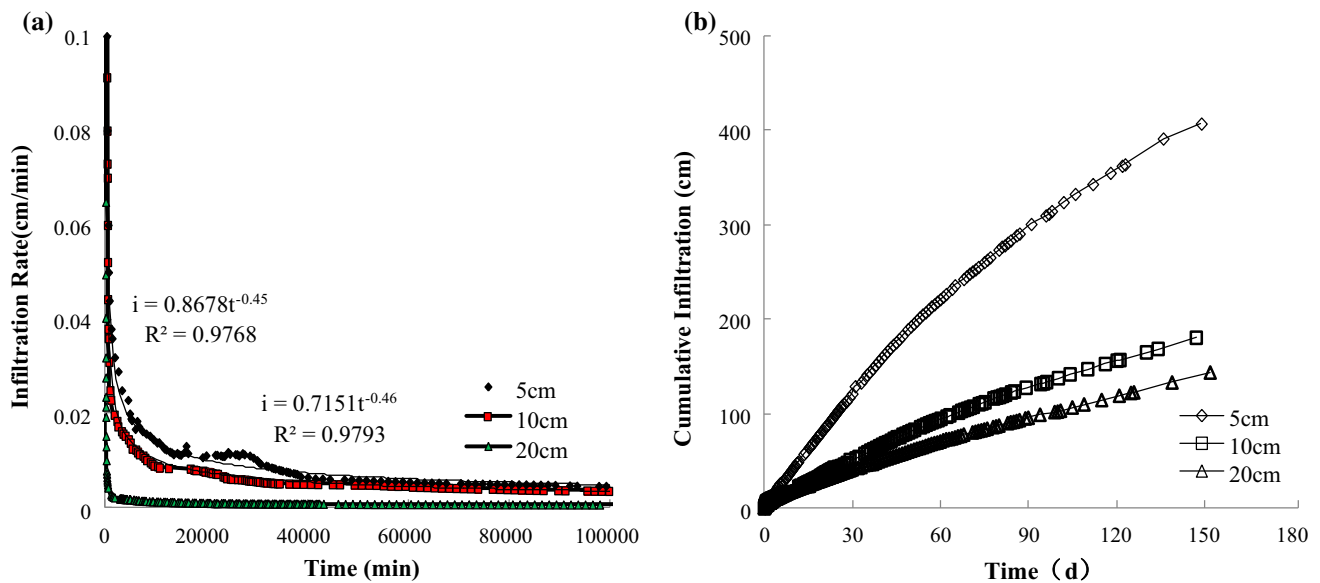| No.	Cumulative infiltration equations at various stages			
	First stage $0 < t < 10$ days	Second stage 10 days $< t < 50$ days	Third stage 50 days $< t < 100$ days	Forth stage 100 days $< t < 160$ days
#1	$I = 14.65t^{0.368}$ $R^2 = 0.960$	$I = 3.785t + 7.925$ $R^2 = 0.999$	$I = 2.551t + 68.96$ $R^2 = 0.998$	$I = 1.812t + 141.2$ $R^2 = 0.994$
#2	$I = 4.962t^{0.758}$ $R^2 = 0.924$	$I = 1.549t + 4.591$ $R^2 = 0.999$	$I = 1.138t + 25.87$ $R^2 = 0.996$	$I = 0.904t + 47.31$ $R^2 = 0.999$
#3	$I = 4.885t^{0.485}$ $R^2 = 0.968$	$I = 1.055t + 8.785$ $R^2 = 0.997$	$I = 0.834t + 20.44$ $R^2 = 0.997$	$I = 0.795t + 23.94$ $R^2 = 0.999$

Fig. 4 Water infiltration characteristics: infiltration rate (**a**) and cumulative infiltration (**b**)
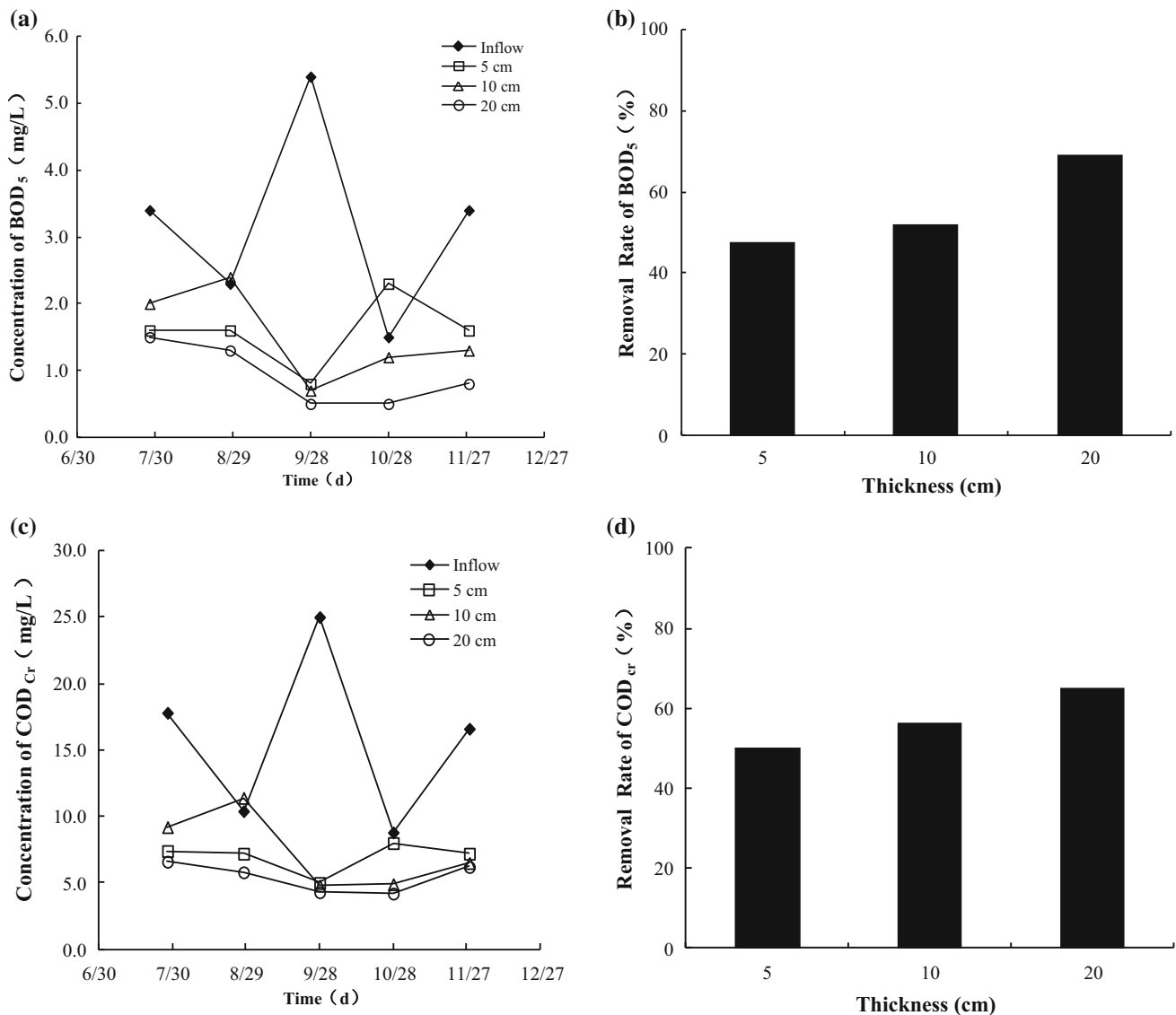
Fig. 5 Oxygen demand removal results: BOD_5 concentrations (**a**) and removal rates (**b**), and COD_{Cr} concentrations (**c**) and removal rates (**d**)

nitrification, so the average removal efficiency of nitrogen declined slightly. The nitrate-nitrogen removal efficiency in soil column #1 was 30.5%, and that in #3 was 45.8%, illustrating that the resulting nitrate-nitrogen removal was more obvious for thicker sediments.

When the total nitrogen concentration of the original influent was 17.1 mg/L, the effluent concentration was 0.22 mg/L, the lowest with the soil column sediment thickness of 20 cm. Because of the initial water, a compacted water film was generated on the surface of the soil column and sediment. After water infiltration reached stability, the oxygen content in the vadose zone was very low. That strongly activated denitrification, causing nitrides to be transformed into N_2O and N_2, and subsequently evaporated. A good denitrification result could be achieved by this decrease in the total nitrogen amount.

Analysis of phosphate removal

As shown in Fig. 7, the total phosphorous removal efficiencies increased with an increase in sediment depth. The removal result was best with sediment thickness at 20 cm. The average removal rates were 0 (the concentration of raw water was 0.22 mg/L), 92.2, −5.6, 44.4, and 90.0%, on 7/30, 8/29, 9/28, 10/28, and 11/27, respectively.

For all pollutants, the efficiencies were better in July and August. It could be inferred that the removal efficiencies had a strong relationship with the temperature and humidity (Cui 2010). The trends in the ambient environmental factors are shown in Fig. 2 and Table 2. A significance level of $\alpha = 0.05$ was adopted, and the effects of riverbed media sediment thickness on pollutant removal were analyzed by one-way ANOVA (Table 6). The
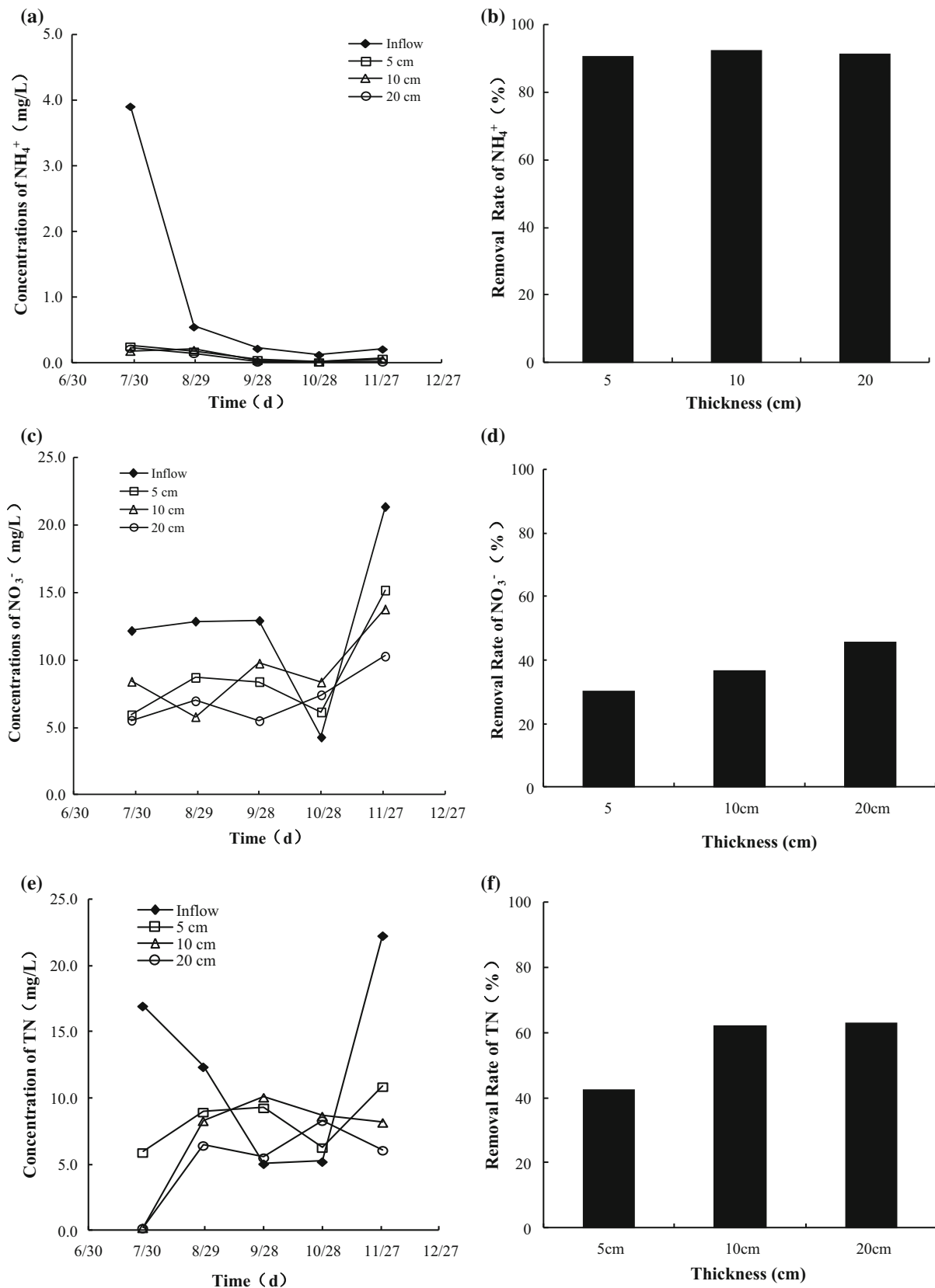
Fig. 6 Nitrogen removal results: NH_4^+ concentrations (**a**) and removal rates (**b**), nitrate-nitrogen concentrations (**c**) and removal rates (**d**), and total nitrogen concentrations (**e**) and removal rates (**f**)
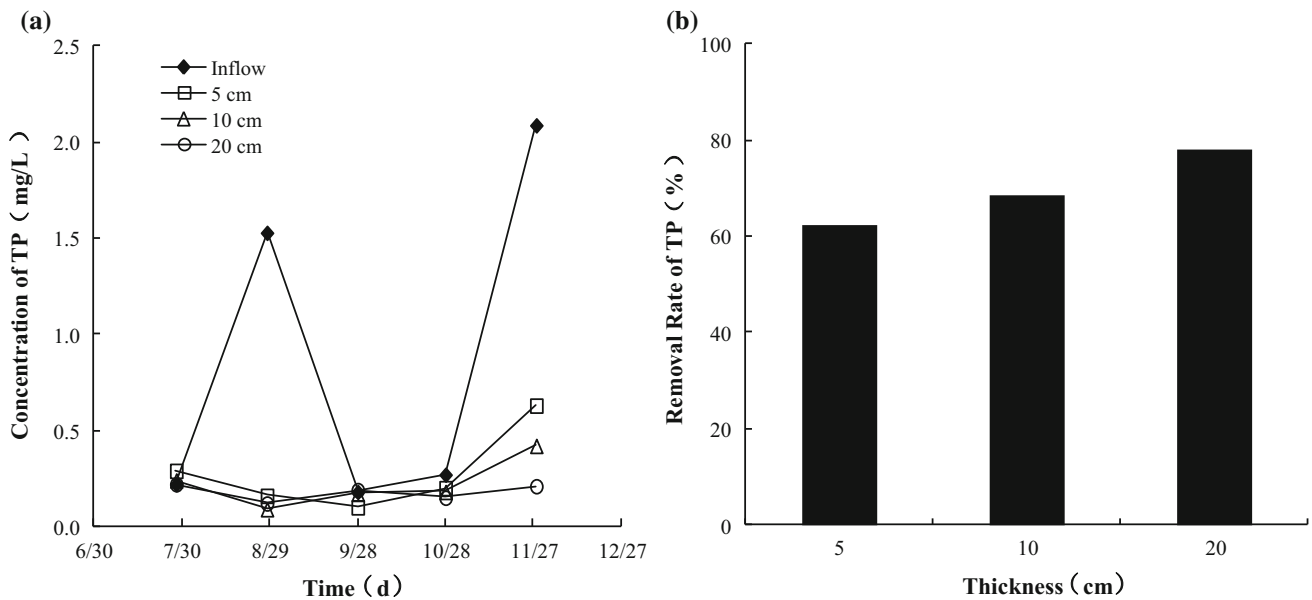
Fig. 7 Phosphorous removal results: total phosphorous concentrations (**a**) and removal rates (**b**)

Table 6 ANOVA results for the pollutant removal efficiencies

Item	BOD$_5$	COD$_{cr}$	NH$_4^+$	Nitrate-N	TN	TP
F	1.031	0.552	0.993	3.892	3.893	25.481
P value	0.443	0.763	0.431	0.000	0.000	0.000
F-crit	3.891	3.892	3.882	0.155	0.184	3.482

$\alpha = 0.05$ significance level

thickness did not have a statistically significant effect on the pollutants in the study when sediment thickness was more than 5 cm.

Discussion

According to the dynamic change curves of water infiltration, the infiltration rates were all large during early infiltration for the three columns. As the water potential gradient decreased throughout the infiltration process, porous media channels were blocked by particles in the reclaimed water. In addition, a vacuum created by air bubbles in the soil pores prevented water infiltration, which led to a rapid decrease in the infiltration rate. The relationship between the depth of the wetting front and time was linear early on, followed by an index change. However, time spent in the index phase was short, which can be explained by a typical generalized model for layered soil infiltration of thorn covered sand (Zhang and Wang 2008). In this model, after the infiltration front penetrates sediments and enters the homogeneous soil, the nonlinear

process converted to a linear process. The thicker the natural sediment, the longer the residence time of the infiltration front in the sediment layers; thus, the characteristics of index infiltration were obvious during the early infiltration (Zhang and Wu 2009). The study showed that sediments had effects on stagnant water, as the sediment compositions were mainly clay minerals and the structure was relatively dense. When the thickness becomes large enough, the water control efficiency is expected to increase significantly.

Natural riverbed media are recognized as a water purifier and consist of sediments and the vadose zone. The sedimentary layer is thin, about 20–50 cm, and has limited effects on the filtration purification of water. Therefore, the filtration purification function mainly depends on deep riverbed filtration media in the vadose zone. Pollutants from leachates could be removed by riverbed media through a series of physical and biochemical effects (Drzyzga and Blotevogel 1997; Quanrud et al. 2003; Rauch-Williams and Drewes 2006), and the purification result is closely related to the lithology and structure of riverbed media, hydraulic retention time, microbe species and quantity, etc. (Shuang 2008; Liu and Wang 2009; Wu 2009). The study by Grischek et al. (1998) showed that microbial activity in the summer was high and enhanced the nitrate-nitrogen removal, whereas Yu et al. (2011) thought that with a higher hydraulic retention time the pollutant removal efficiencies would improve.

The COD$_{Cr}$ and BOD$_5$ removal efficiencies tended to increase at first and then decreased over different months. They were highest in September. The removal mechanism primarily depended on microbial degradation in the vadose

zone excluding interception adsorption. Microbial growth also requires a certain temperature to maintain activity. The indoor temperature in September was moderate, so microbial growth was the most exuberant and activity was strongest; thus, degradation results were obvious. Meanwhile, COD_{Cr} and BOD_5 in the media of the vadose zone could be removed by volatilization, adsorption, chemical transformation, biodegradation, and so on. Microorganism degradation was the main removal mechanism, since over 50% of organic matter was degraded via biodegradation, and the removal efficiency of aerobic microorganisms was better than anaerobic bacteria (Banton et al. 2010). A study produced COD_{Cr} and BOD_5 removal efficiencies over 100% by the unsaturated zone at 3.3 m (Bouwer and Rice 1989). Li (2012) built soil columns to simulate riverbed media and studied the properties of reduced infiltration materials. As a result, they demonstrated that the COD_{Cr} removal efficiency had a positive correlation with the formation of sediments, i.e., thicker sediments contributed to the removal of COD_{Cr}.

Studies have indicated that thicker sediments showed more obvious decontamination effects for ammonium-nitrogen. Wu et al. (2003) came to a similar conclusion with a simulation experiment of the soil column assembled using riverbed sediment and aquifer soil, namely that there were biochemical reactions in riverbed sediments. According to the speculation of Doussan et al. (1997), riverbank percolation includes oxidation and reduction environments. The interface was located in the riverbed sediments or nearby, and the aerobic environment in the riverbank infiltration system was limited; thus, nitrogen removal is mainly dependent on nitrification.

The nitrate-nitrogen removal efficiencies increased with increasing influent concentration; however, the concentration was negative in November, and especially so in the maximum sediment thickness. This result was due to the lower influent background value of 4.3 mg/L in November, as the nitrate-nitrogen stranded in the vadose zone early on leached via water infiltration during this period. In October, the vadose zone was in an unsaturated condition and aerobic environment. The study showed that aerobic and anaerobic environments exist in the riverbank filtration system—while the riverbed sediments were mainly in an aerobic environment, the others were anaerobic (Wu et al. 2003). Nitrogen disposition was directly finished by denitrification due to the riverbank filtration; as a result, the denitrification rate may be a limiting factor for nitrogen removal. Denitrification was restrained by the aerobic environment, resulting in an increase in nitrate concentration and a decrease in the removal efficiency.

Huang et al. (2006a, b) also had similar results in experiments using an indoor soil column. The ammonium-nitrogen concentration in the influent was 18.27 mg/L, and

its filtration process was simulated in a vertical riverbed; the removal efficiency reached 87%. This indicated that the ammonium-nitrogen was involved in adsorption and nitrification during the riverbed filtration process. In this paper, the removal of ammonium-nitrogen in the reclaimed water also achieved good results in the riverbed media under the action of sediments, i.e., up to 90%. Huang et al. (2006a, b) also increased the concentration of the potassium nitrate solution leachate stepwise and studied the environmental behavior of nitrate-nitrogen in the riverbed vertical infiltration system. The results showed that nitrate-nitrogen was involved in dissimilation and denitrification during the riverbed filtration process, causing an increase in the ammonium-nitrogen concentration in the groundwater, which illustrates that there was transformation between the nitrogen species.

Some research suggests that the phosphorus in the vadose zone is removed mainly through media adsorption, chemical precipitation, and microbial accumulation (Guo and Li 2004; Yuan et al. 2005). The purification results in the vadose zone were better with higher influent concentrations. In August and November, the influent concentrations were 1.53 and 2.09 mg/L, respectively. Correspondingly, the removal efficiencies reached 89.5, 94.1, and 92.2% in August and 69.9, 79.9, and 90.0% in November for soil columns #1, #2, and #3, respectively. When the phosphorous concentration of the influent was lower than 0.22 mg/L, the results had no significant change among the soil columns, indicating that the removal did not reach a maximum capacity due to the low phosphorous concentration. There was even a phenomenon where the effluent concentration was higher than that of the influent, demonstrating that the reaction mechanisms included adsorption and desorption caused by external factors.

Conclusions

In conclusion, this paper studied the purification of common pollutants by riverbed media of three sediment thicknesses, as well as the river water infiltration as supplied by reclaimed water. Since various nitrogen forms were present and their mutual transformations were complex, it is suggested that the nitrogen transformation problem should be more carefully considered in further studies. Moreover, only certain sizes of soil columns were tested to explore the effects on pollutant removal efficiencies by riverbed media caused by changes in the reclaimed water and leachate. The effects of different longitudinal spatial scales also need to be assessed to provide reference for ecological river regulation.

1. The relationship of the advancing depth of the water infiltration front with time showed a linear change early on, followed by an index change. However, the duration in the index phase was short and followed by stable infiltration. After the reclaimed water reached stable infiltration in the 20-cm riverbed sediments, the stagnant water accumulation was more than 10^{-4} cm/s, so the infiltration time of reclaimed water could be lengthened by increasing the thickness of sediments.

2. With the existence of a nitrification/denitrification interface, the ammonium-nitrogen removal efficiency in the riverbed filtration system did not indefinitely increase with the thickness of sediment. This interface was generally located in the sedimentary layers, and the bottom of the riverbed sediment was generally in an anaerobic condition when the thickness was greater than 10 cm. Because ammonium-nitrogen was involved in the nitrification, the nitrate-nitrogen concentration in leachate tended to increase at the beginning of the experiments. However, the nitrate-nitrogen removal efficiency was not obvious. The removal efficiencies of ammonium-nitrogen in the riverbed filtration systems were all above 90% due to adsorption and nitrification.

3. The purification results of the river lake media were obvious when the sediment thickness reached a certain level. The removal efficiencies of BOD_5, COD_{Cr}, ammonium-nitrogen, nitrate-nitrogen, total nitrogen, and total phosphorous were 47.7–69.0, 49.9–62.7, 90.6–92.5, 30.5–45.8, 42.7–63.1, and 62.2–77.9%, respectively, by riverbed media with thicknesses of 5–20 cm. The thicker sediments showed higher removal efficiencies.

References

Banton O, Join J, Cabioch G (2010) Evaluation of effective groundwater recharge of freshwater lens in small islands by the combined modeling of geoelectrical data and water heads: recharge of freshwater lens in small islands. Water Resour Res 46(6):6601

Bouwer HG, Rice RC (1989) Effect of water depth in groundwater recharge basins on infiltration. J Irrig Drain Eng 115(4):556–567

CCTV (2016) China urbanization rate reached 56% in 2015. IOP China central television web. http://english.cntv.cn/2016/01/30/VIDEf3nCcpAiITmx5J17brHD160130.shtml. Accessed 20 Aug 2016

Chen XR (2006) Brief discussion on urban river course eco-restoration. J China Inst Water Resour Hydropower Res 4(3):226–231

Chinese Standard GB 7480-87 (year) Water quality-determination of nitrate-spectrophotometric method with phenol disulfonic acid. Environmental Protection Standards

Chinese Standard HJ 505-2009 (year) Water quality-determination of biochemical oxygen demand after 5 days (BOD_5) for dilution and seeding method. Environmental Protection Standards

Chinese Standard HJ 670-2013 (year) Water quality-determination of orthophosphate and total phosphorus-continuous flow analysis (CFA) and ammonium molybdate spectrophotometry. Environmental Protection Standards

Chinese Standard HJ/T 195-2005 (year) Water quality-determination of ammonia-nitrogen by gas-phase molecular absorption spectrometry. Environmental Protection Standards

Chinese Standard HJ/T 199-2005 (year) Water quality-determination of total-nitrogen by gas-phase molecular absorption spectrometry. Environmental Protection Standards

Cui F (2010) Study on the temperature effects of constructed wetland treatment for urban lakes. Water Conserv Sci Technol Econ 16(9):982–985

Dirksen C (1999) Soil physics measurements. In: GeoEcology paperback. Catena Verlag, Reiskirchen

Doussan C, Poitevin G, Ledoux E, Detay M (1997) River bank filtration: modelling of the changes in water chemistry with emphasis on nitrogen species. J Contam Hydrol 25(1):129–156

Drzyzga O, Blotevogel KH (1997) Microbial degradation of diphenylamine under anoxic conditions. Curr Microbiol 35(6):343–347

Grischek T, Hiscock KM, Metschies T, Dennis PF, Nestler W (1998) Factors affecting denitrification during infiltration of river water into a sand and gravel aquifer in Saxony, Germany. Water Res 32(2):450–460

Guo W, Li PJ (2004) Research advances on rapid infiltration land treatment system for wastewater. Tech Equip Environ Pollut Control 8:1–7

Huang WW (2008) Research on characteristics of eutrophication in urban landscape water body supplemented by reclaimed water. Dissertation, Hebei Polytechnic University

Huang RH, Wu YG, Yang BC, Miao Y (2006a) Environmental behavior of NH_4^+-N in system of vertical river bank filtration. J Earth Sci Environ 28(1):92–95

Huang RH, Wu YG, Li YF, Yang BC (2006b) Simulating experiment of NO3–N in vertical system of riverbank filtration. J Earth Sci Environ 28(3):92–96

Kopchynski T, Fox P, Alsmadi B, Berner M (1996) The effects of soil type and effluent pre-treatment on soil aquifer treatment. Water Sci Technol 34(11):235–242

Li PX (2012) Purification effect of vadose zone on the contaminant in reclaimed water under the river reducing infiltration. Dissertation, China Agricultural University

Li YK, Yang PL, Liu PB, Lin J, Li JM, Zheng FD, Liu CC, Jiang G (2012) Environmental impact of recycled water to Yongding River for ecological use and key technology study. China Water Resour 5:30–34

Liang CJ, Yang DP (2005) The China environment yearbook: crisis and breakthrough of China's environment (review). China Rev Int. doi:10.1353/cri.2009.0027

Liu XM, Wang XG (2009) Primary research on the self-purification of contamination in unsaturated zone. Groundwater 31(5):79–82

Quanrud DM, Hafer J, Karpiscak MM, Zhang J, Lansey KE, Arnold R (2003) Fate of organics during soil-aquifer treatment: sustainability of removals in the field. Water Res 37(14):3401–3411

Rauch-Williams T, Drewes JE (2006) Using soil biomass as an indicator for the biological removal of effluent-derived organic carbon during soil infiltration. Water Res 40(5):961–968

Wu WY (2009) Research on groundwater vulnerability experiment of reclaimed wastewater district and irrigation allocation. Dissertation, China University of Geosciences

Wu YG, Wang C, Wang HM (2003) Experimental research on nitrogen-removal and its mechanism during riverbank filtration. Urban Environ Urban Ecol 16(6):298–300

Yu ZM, Yuan XY, Liu SL, Guo J, Li ZF, Zhu WL, Cui LH (2011) Effect of hydraulic conditions on treatment of polluted river water by hybrid constructed wetlands. Chin J Environ Eng 05(4):757–762

Yuan DH, Jing LJ, Gao SX, Yin DQ, Wang LS (2005) Analysis on the removal efficiency of phosphorus in some substrates used in constructed wetland systems. Environ Sci 26(1):51–55

Zhang Y (2005) Debate analysis of seepage control engineering of Yuan Ming Yuan-looking for the juncture of landscape and ecological effective protection under the reality of water shortage in Beijing. Beijing Plan Rev 3:136–139

Zhang JF, Wang WY (2008) Experimental study of finger flow occurrence in loess soil. Trans Chin Soc Agric Eng 25(5):357–358

Zhang H, Wu ZG (2009) Experimental research on the effect of entrapped air on one-dimensional ponded water infiltration. Rock Soil Mech 30(2):132–137

Zhou WB, Li LX, He WQ, Lv HG (2004) Advances in canal seepage control techniques in China. Adv Sci Tech Water Resour 24(5):60–63