RESEARCH ARTICLE

Development of water quality management strategies based on multi-scale field investigation of nitrogen distribution: a case study of Beiyun River, China

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Abstract

Accurately quantifying the distribution of nitrogen (N) contaminants in a river ecosystem is an essential prerequisite for developing scientific water quality management strategy. In this study, we have conducted a series of field investigations along the Beiyun River to collect samples from multiple scales, including surface water, riverbed sediments, vadose zone, and aquifer, for evaluating the spatial distribution of N; besides, column simulation experiments were carried out to characterize the transport behavior of N in riverbed sediments. The surface water of the Beiyun River was detected to be eutrophic because of its elevated total N concentration, which is 33 times of the threshold value causing the potential eutrophication. The hydrodynamic dispersion coefficient (D) of riverbed sediments was estimated by CXTFIT 2.1, demonstrating that the D of upstream section was lower than that of midstream and downstream sections ($D_{upstream} < D_{midstream} < D_{downstream}$), with the estimated annual N leaching volume of 130,524, 241,776, and 269,808 L/(m^2·a), respectively. The average total N concentration in vadose zone and aquifer of upstream Sect. (297.88 mg/kg) was obviously lower than that of midstream Sect. (402.62 mg/kg) and downstream Sect. (447.02 mg/kg). Based on multi-scale investigation data, subsequently, water quality management strategies have been achieved, that is, limiting the discharge of N from the midstream and downstream banks to the river and setting up the impermeable layer in the downstream reaches to reduce infiltration. The findings of this study are of great significance for the improvement of river environmental quality and river management.

Keywords River pollution · Groundwater · Eutrophication · Sediments · CXTFIT 2.1

Renkuan Liao and Peng Song contributed equally to this work

Highlights
 • A multi-scale field investigation of nitrogen (N) pollution along the Beiyun River was conducted.
 • We have characterized the geological structure and N distributions of vadose zone and aquifer.
 • Determination of hydrodynamic dispersion coefficient of riverbed sediments in different sections.
 • Management strategies have been provided to reduce the N pollution of the Beiyun River.

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Introduction

With the intensification of agricultural and anthropogenic activities, river pollution is getting worse (Han et al. 2014; Mekonnen and Hoekstra 2018; Vareda et al. 2019; Chetty and Pillay 2019). Nitrogen (N), as an important chemical feedstock in industry and fertilizer widely used in agricultural production, is playing an increasingly significant role in driving river pollution (Carpenter et al. 1998; Zhao et al. 2012; Wan et al. 2016; Jarvie et al. 2020). For example, N is one of the main culprits to river eutrophication, which has been recognized by numerous studies (Mekonnen and Hoekstra 2015, 2020; Hobbie et al. 2017; Smith et al. 2017; Jarvie et al. 2018). The 2019 annual frontiers report of the United Nation indicated that the pollution caused by the reactive forms of N is now becoming a grave environmental concern on a global level (UN 2019). In a river ecosystem, N is discharged into surface water from point or non-point sources, causing the degradation of surface water, then N

leaches into riverbed sediments and vadose zone through infiltration, thus further affecting aquifer and groundwater quality (Durand et al. 2011; Burri et al. 2019). Therefore, quantifying the distribution of N in surface water, riverbed sediments, vadose zone, and aquifer can provide a vital prerequisite to develop scientific strategies for reducing N pollution in river ecosystems.

In a context of the immediate challenge caused by N pollution, the investigation and prevention of river N pollution have been the increasing research focus of scholars all over the world in the past decades (Ning et al. 2001; Chiwa et al. 2012; Oita et al. 2016; Yu et al. 2019; Han et al. 2020). Considerable progress has been achieved in identifying potential N pollution sources, studying transport behaviors of N in soils or aquifers, and treating water polluted with N, which is beneficial for developing remediation strategies for N pollution rivers (Vrzel et al. 2016; Yang et al. 2016; Poikane et al. 2019; Worrall et al. 2020; Burt et al. 2020). Among these, accurate identification of the source and type of N contaminants was considered as the premise of setting the targeted goal of N pollution control. In general, point sources can be effectively managed once the source of N emissions has been determined, but non-point sources are still difficult to be completely restricted. In terms of transport behaviors of N and its pollution risks in soils or aquifers, several numerical models and quantitative methods, including HYDRUS, CXTFIT, and GLEAMS as well as nutrient budget models and water quality index, have provided reliable tools for understanding the law of N migration and transformation as well as evaluating its potential hazards (Hendriks et al. 1999; Wallis et al. 2011; Zhou et al. 2011; Wang et al. 2019; Nong et al. 2020; Pan et al. 2020; Torres-Martinez et al. 2021). In order to efficiently treat the N-rich wastewater from point source, industrial treatment processes, including biofilm reactor, ion exchange, electro-photochemical, simultaneous nitrification/denitrification, and anaerobic/anoxic/oxic (A^2/O), have been well-established in previous studies (Leaković et al. 2000; Chen et al. 2003; Sun et al. 2010; Zhao et al. 2017; Tabassum 2019); in addition, constructed wetlands were generally acknowledged as a useful measure for reducing non-point source N pollution in river ecosystems (Wu et al. 2014; Uusheimo et al. 2018; Zhuang et al. 2019). Moreover, in order to realize the prevention and control of nitrogen pollution on a larger scale, many policy measures, such as regional integration and planting structure adjustment, have also been applied to regulate the process of artificial nitrogen input, reducing the intensity of nitrogen pollution in water bodies (Lu et al. 2019; Li and Lu 2020; Shortle et al. 2020). Although these studies have offered a large number of meaningful references for the effective control of river N pollution from various perspectives, most of the studies only focus on a single link of river ecosystem. Limited cases were reported on systematic field investigation of N distribution from multiple scales, particularly the lack of a holistic survey of river systems including surface water, riverbed sediments, vadose zone, and aquifer (Pretty et al. 2006; Barnes et al. 2019). Due to the lack of multi-scale continuous field investigation, it hinders the in-depth understanding of the migration behavior of N pollutants between different environmental media, which is not conducive to the formulation of effective water pollution control strategies.

Beiyun River, which originates from the Jundu Mountain in Beijing and flows south to merge into the Haihe River in Tianjin, is the main sewage drainage channel in Beijing. The water inflow of the Beiyun River includes reclaimed water, domestic wastewater, agricultural irrigation water, and rainwater, resulting in complicated situation of surface water quality. The water quality of the Beiyun River is poor, with more than 80% of water is classified as "class V" (seriously polluted) (BMEPB 2012), and N has been confirmed as a major contributor to water pollution (Yu et al. 2012). The nitrogen in urban sewage discharge and the nitrogen released from riverbed sediments have made a great contribution to the nitrogen pollution of the Beiyun River (Pan et al. 2019; Wu et al. 2020). The objectives of this study were to (1) quantify the spatial distribution of N in surface water, riverbed sediments, vadose zone, and aquifer of the Beiyun River through multi-scale field investigations; and (2) evaluate the impact of N contained in surface water on the distribution of N in riverbed sediments, vadose zone, and aquifer; thus (3) offer effective management strategies to reduce the influence of N on the water environment. The significance of this study lies in the systematic understanding of N distribution in a river ecosystem, which provides a scientific basis for formulating N pollution control strategies.

Method

Study area and field sample collection

In this study, the investigation area of the Beiyun River belongs to the Beijing reach, with the total length of 89.4 km. Along the study area, in September 2014, we have collected 15 surface water samples and 13 river sediment samples of 0–45 cm depth to evaluate the nitrogen (N) pollution status at representative sites (Fig. 1a). These representative sites are the key monitoring points for the water quality of the Beiyun River. In addition, we selected three typical sections at the upstream, midstream, and downstream of the Beiyun River, and three wells were drilled to collect soil samples for each section (Fig. 1b). The latitude and longitude coordinates for sample collection are listed in Table S1.

The surface water samples were collected 1 m below the surface of water body and the samples were stored in 500-mL plastic bottles for further analysis. The sediment
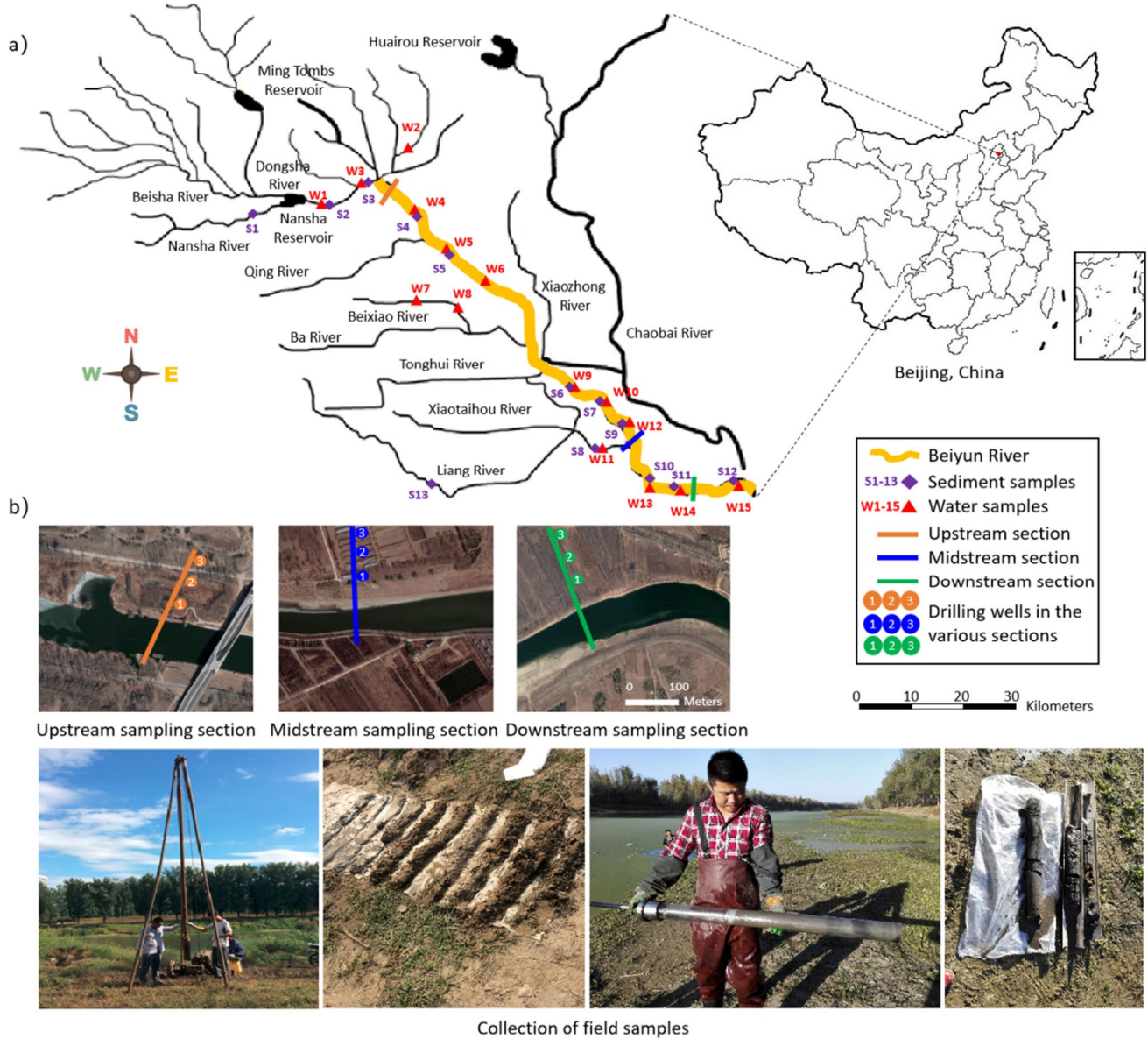
**Fig. 1** Scheme for collecting surface water, sediments, and groundwater samples in the Beiyun River

of 0–45 cm depth was collected and each 15-cm sample (0–15, 15–30, and 30–45 cm) was stored, separately, in zip-lock bags for further analysis. Soil samples of the vadose zone and aquifer were collected by drilling wells (10 m) perpendicular to the river channel, in which the soil samples were collected every 0.5–1 m. The distance from the drilling wells to the river channel is shown in Table S2. All the collecting samples were labeled and carefully transferred to the laboratory. The water samples were stored in a refrigerator at 4 °C until analyses, and the sediment and soil samples were naturally air-dried in the shade and screened by 2-mm steel-wire screen.

Column simulation experiments

To further evaluate the transport characteristics of N contaminants in riverbed sediments, PVC columns (40 cm in height × 10 cm in inner diameter) were used for simulation experiments. A 3-cm gravel filter layer, which was covered with 200-mesh nylon fabrics, was set at the column bottom to reduce clogging and soil loss. The procedure of packing riverbed sediments into columns has been described in our previous study (Liao et al. 2020).

Before the simulation experiment, deionized (DI) water was introduced continuously into the columns from the

Fig. 2 Concentrations of total nitrogen (TN), nitrate nitrogen (NN), and ammonium nitrogen (AN) at different collecting locations of water samples
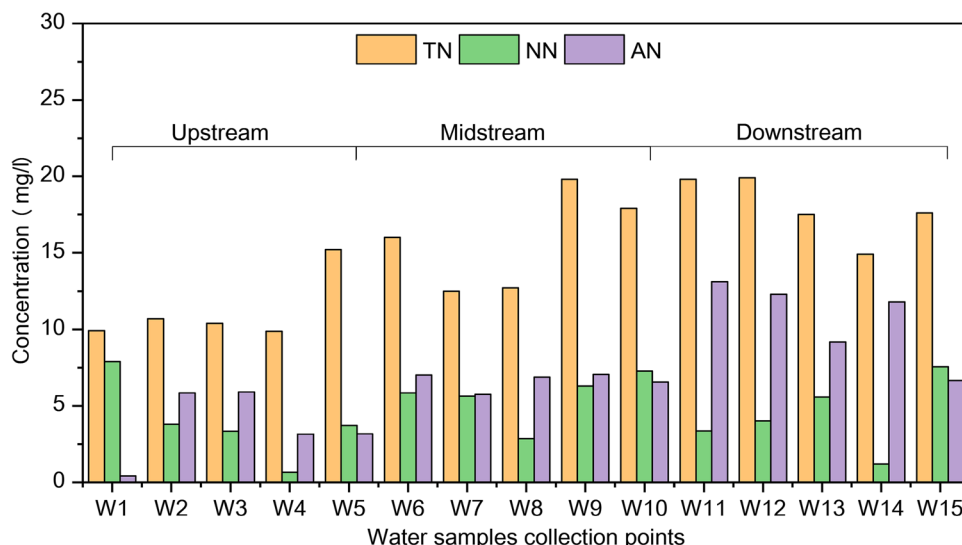
bottom to the top to remove air in the pores of the packed sediments. Thereafter, the leaching direction of DI water was shifted from top to bottom to remove the chemical substances originally contained in the sediments. When the electrical conductivity (EC) of the leachate was measured close to 0, the leaching event was stopped. The EC values were measured by a benchtop pH/conductivity meter (PC300, LabForce). Subsequently, NH_4Cl solution (considered as the N solution) at 0.1 mol/L was used to leach columns from the top to the bottom in free draining manner. The EC values of leachates were measured in real time and the leaching process was stopped when the EC of the leachate was measured close to the initial EC value of N

solution. Thus, the leaching solution was shifted from N solution to DI water, and the leaching event was stopped when the EC value of the leachate was close to 0.

Measurement

All the measurements were conducted following the well-established procedures to ensure the accuracy and reliability of investigations. For the water samples, the concentration of TN was measured using peroxodisulfate oxidation method (Ebina et al. 1983). The concentrations of mineral N (NN and AN) were detected using a continuous flow analyzer (AutoAnalyser-III, Bran + Luebbe, Germany).

Fig. 3 Concentrations of total nitrogen (TN), nitrate nitrogen (NN), and ammonium nitrogen (AN) at different collecting locations of sediments samples. The N concentrations of S13 are not shown here
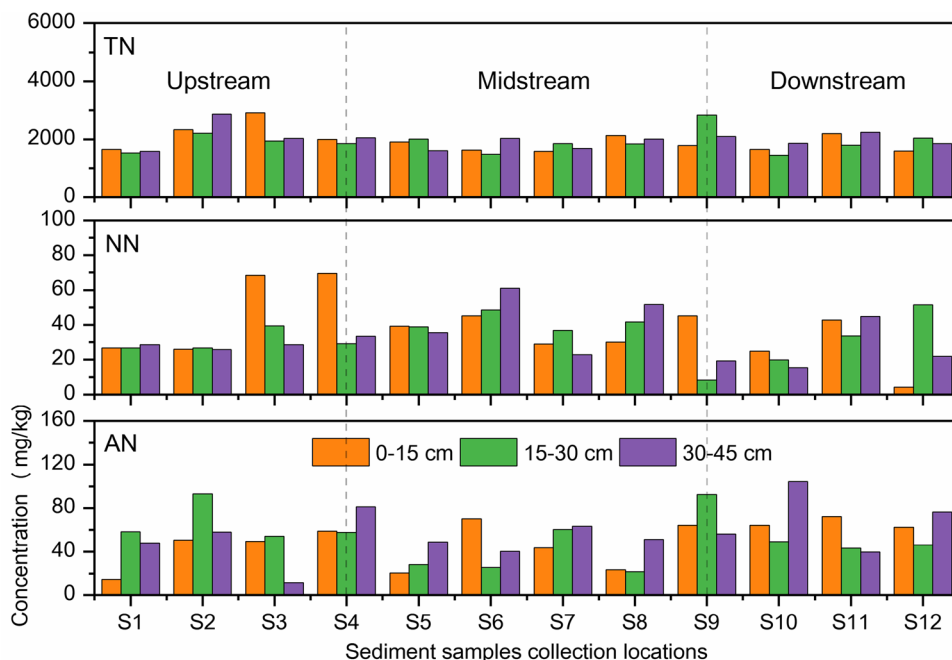
Table 1 Linear regression relationship between N in surface water and N in sediments at different depths

| N in sediment samples | | | | N in surface water samples | | | | |
| Depth (cm) | | TN | | NN | | | AN | |
		Linear regression	R^2	Linear regression	R^2		Linear regression	R^2
TN	0–15	$y = -69.06x + 3060$	0.47*					
	15–30	$y = -2.02x + 1970$	0					
	30–45	$y = -38.78x + 2638$	0.21					
NN	0–15			$y = -5.46x + 63.89$	0.51*			
	15–30			$y = 0.99x + 29.40$	0.04			
	30–45			$y = -1.71x + 40.67$	0.09			
AN	0–15						$y = 0.72x + 47.40$	0.03
	15–30						$y = -1.35x + 61.65$	0.05
	30–45						$y = -0.30x + 59.51$	0

"*" stands for significant linear correlation at 0.05 level. The N data collected from both water and sediment sampling locations were used for linear regression analysis ($n = 11$)
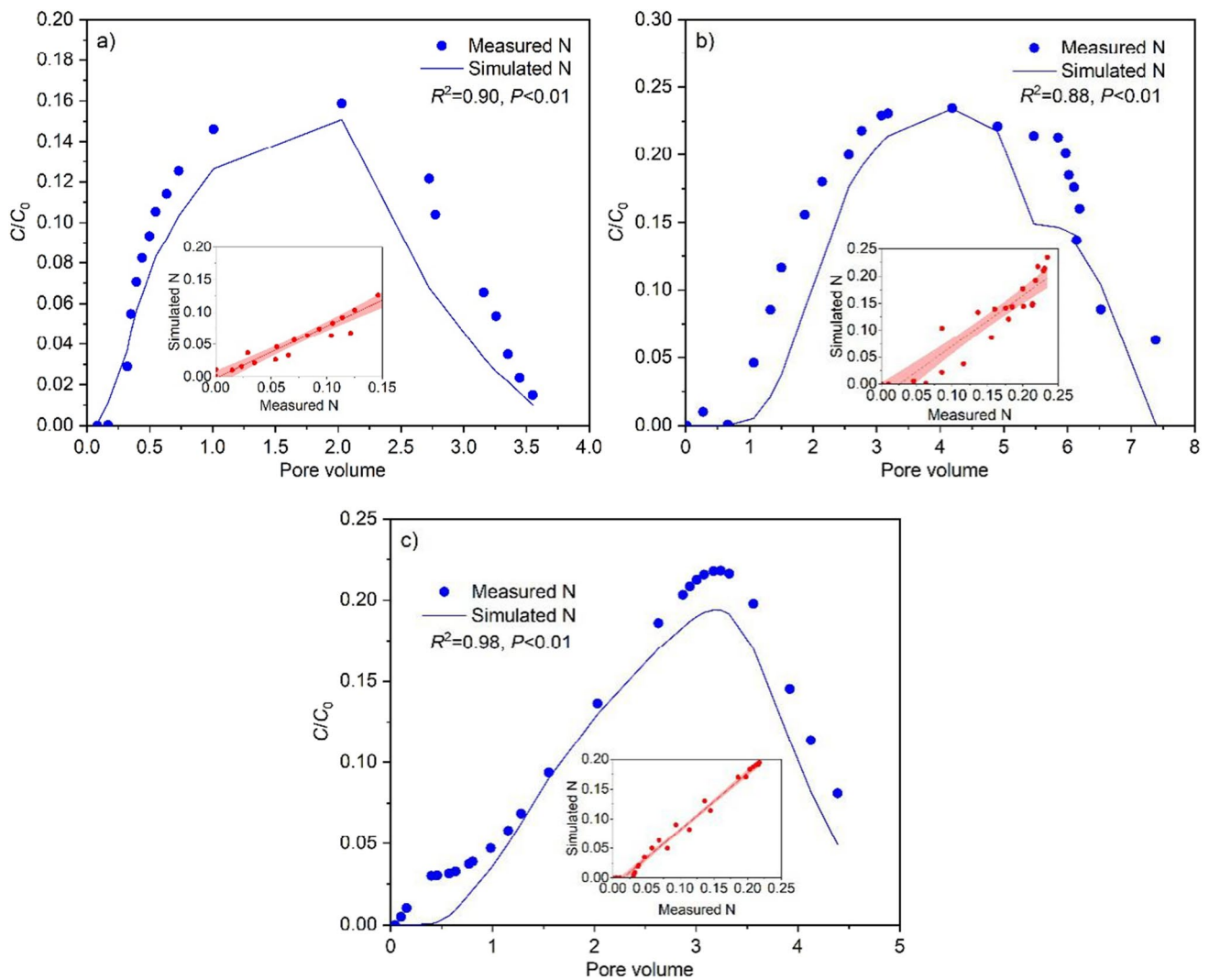

Fig. 4 Measured and simulated N breakthrough curves (relative concentration values) in riverbed sediments at **a** upstream, **b** midstream, and **c** downstream. Pore volume: the volume of total pores in each column packed with riverbed sediments. The linear regression relationship is shown in the embedded graphs with the decisive factor (R^2) and the significance test (p). The shadow bands represent 95% confidence intervals

Table 2 N transport parameters estimated from BTCs in the riverbed sediments

River section	D cm^2/h	R	S_r	v cm/h	V L/(m^2·a)
Upstream	7.0	3.57	0.15	1.49	130,524
Midstream	24.0	1.94	0.23	2.76	241,776
Downstream	29.8	1.97	0.19	3.08	269,808

D, the hydrodynamic dispersion coefficient; R, the retardation factor; S_r, the relative ratio of the concentration of N in the leachate to that in the water body; v, the leaching velocity of N in the riverbed sediments; these parameters, including D, R, S_r, and v, were fitted by CXTFIT 2.1. V, the annual leaching volume of N through the riverbed sediments, $V = v \times 365 \times 24 \times 10$

For the sediment and soil samples, the TN was extracted in 2 mol L^{-1} KCl from the sediment and soil samples and their concentrations measured using peroxodisulfate oxidation method (Ebina et al. 1983). The mineral N (NN and AN) was extracted in 2 mol L^{-1} KCl from the sediment and soil samples and their concentrations were detected using a continuous flow analyzer (AutoAnalyser-III, Bran + Luebbe, Germany). The particle size composition of sediment and soil samples was determined using laser particle size analyzer (Malvern Mastersizer 2000, Malvern Instruments, UK), and their texture was classified by International Soil Classification System (FAO 2014).

Data analysis

The linear regression relationships between N in surface water and N in sediments were obtained via origin 2018 (Origin Lab, USA). The one-dimensional solute transport model CXTFIT 2.1 was used to fit the transport parameters of N in column simulation experiments (Toride et al., 1995), and the fitting details can be found in our previous study (Liao et al. 2020). Based on the convection–dispersion equation (CDE), the obtained data were fitted by the non-linear least squares method to inversely determine the solute transport parameters including dispersion coefficient, distribution coefficient, and retardation factor. The governing equation based on CDE for simulating solute transport through porous media was as follow:

$$R\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x} \tag{1}$$

$$R = 1 + \rho K_d / \theta_v \tag{2}$$

where c is the concentration of solute, mg/L; t is the time of solute leaching in the soil column, h; D is the dispersion coefficient, cm^2/h; x is the distance of solute to entry point,

Fig. 5 The distribution of nitrogen in vadose zone and aquifer of ► upstream section. **a** 1# well, 16 m away from the river bank. **b** 2# well, 40 m away from the river bank. **c** 3# well, 82 m away from the river bank

cm; v is the averaged pore water velocity, cm/h; R is the retardation factor; ρ is the dry density of the medium, g/cm^3; θ_v is the volumetric water content of the medium, %; and K_d is the distribution coefficient for linear sorption, L/kg.

In this study, it was assumed that the transport of N in riverbed sediments will be influenced by the adsorption and desorption properties of N. The two-site nonequilibrium model was used to estimate the transport parameters of N in riverbed sediments. This model assumes the sorption mechanism follows two steps: equilibrium sorption isotherm (S_1) and first-order kinetics (S_2).

$$\frac{\partial c}{\partial t} + \frac{\rho}{\theta_v}\frac{\partial S_1}{\partial t} + \frac{\rho}{\theta_v}\frac{\partial S_2}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x} \tag{3}$$

$$\frac{\partial S_2}{\partial t} = \alpha\left[(1-F)f(c) - S_2\right] \tag{4}$$

where c, θ_v, ρ, t, D, v, and x have been described in Eqs. (1) and (2); S_1 and S_2 are concentrations of the solid phase at the equilibrium sites and kinetic nonequilibrium sites, in which $S_1 = Ff(c)$, $S_2 = (1-F)f(c)$, and the total adsorption $S = S_1 + S_2$, mg/kg; F is the fraction of available sites for instantaneous adsorption; and α is the first-order rate coefficient, h^{-1}.

Results

N distributions in the surface water and riverbed sediments

The concentrations of total nitrogen (TN) in surface water of the Beiyun River were 9.88–19.9 mg/L, and the spatial distribution of TN concentrations presented a trend of gradual increase from upstream to downstream reaches, indicating that N pollution of surface water was increasing along the direction of water flow. In addition, except for a few sampling locations (W1, W5, W10, and W15), the ammonium nitrogen (AN) concentrations of surface water were detected generally higher than that of nitrate nitrogen (NN) (Fig. 2). The higher concentration of AN may be caused by the discharge of industrial wastewater and domestic sewage to the Beiyun River.

The sand particles in the river sediments were the largest, accounting for more than 55% of river sediments. The sediments in upstream and midstream reaches were mainly sandy
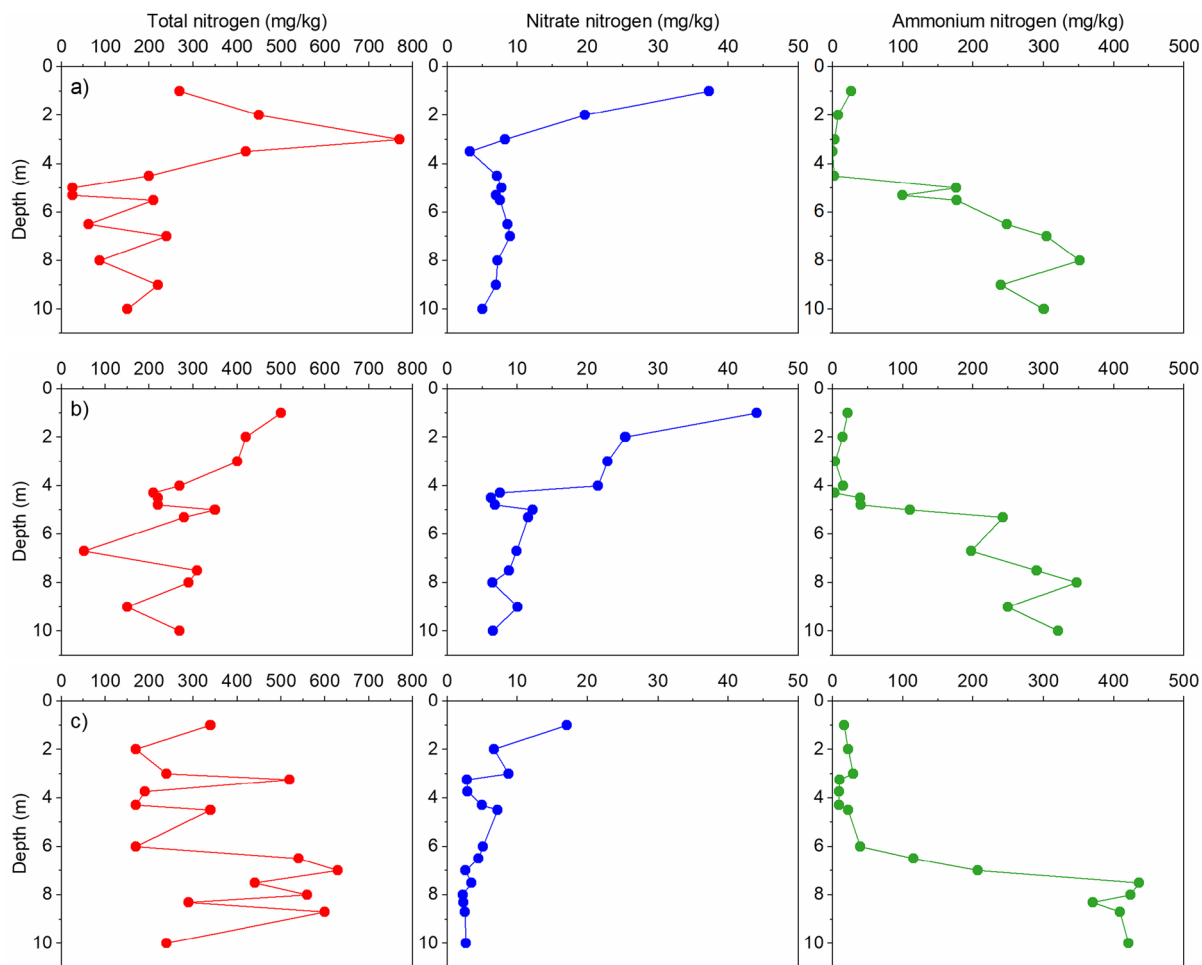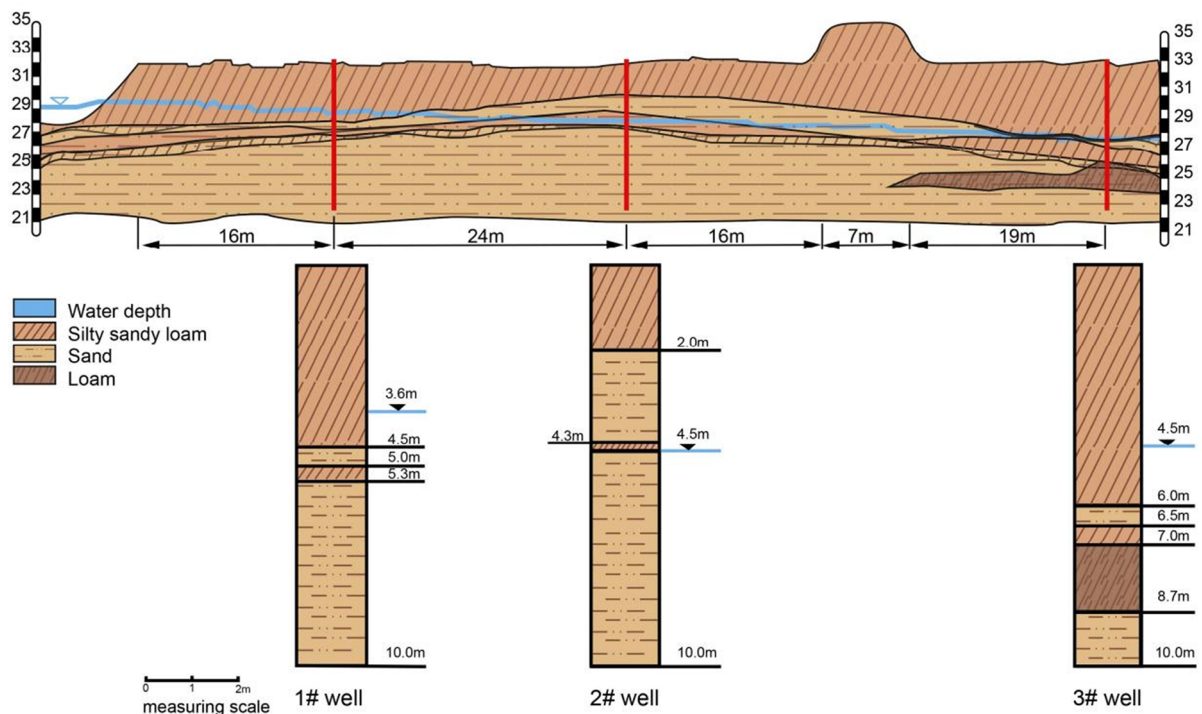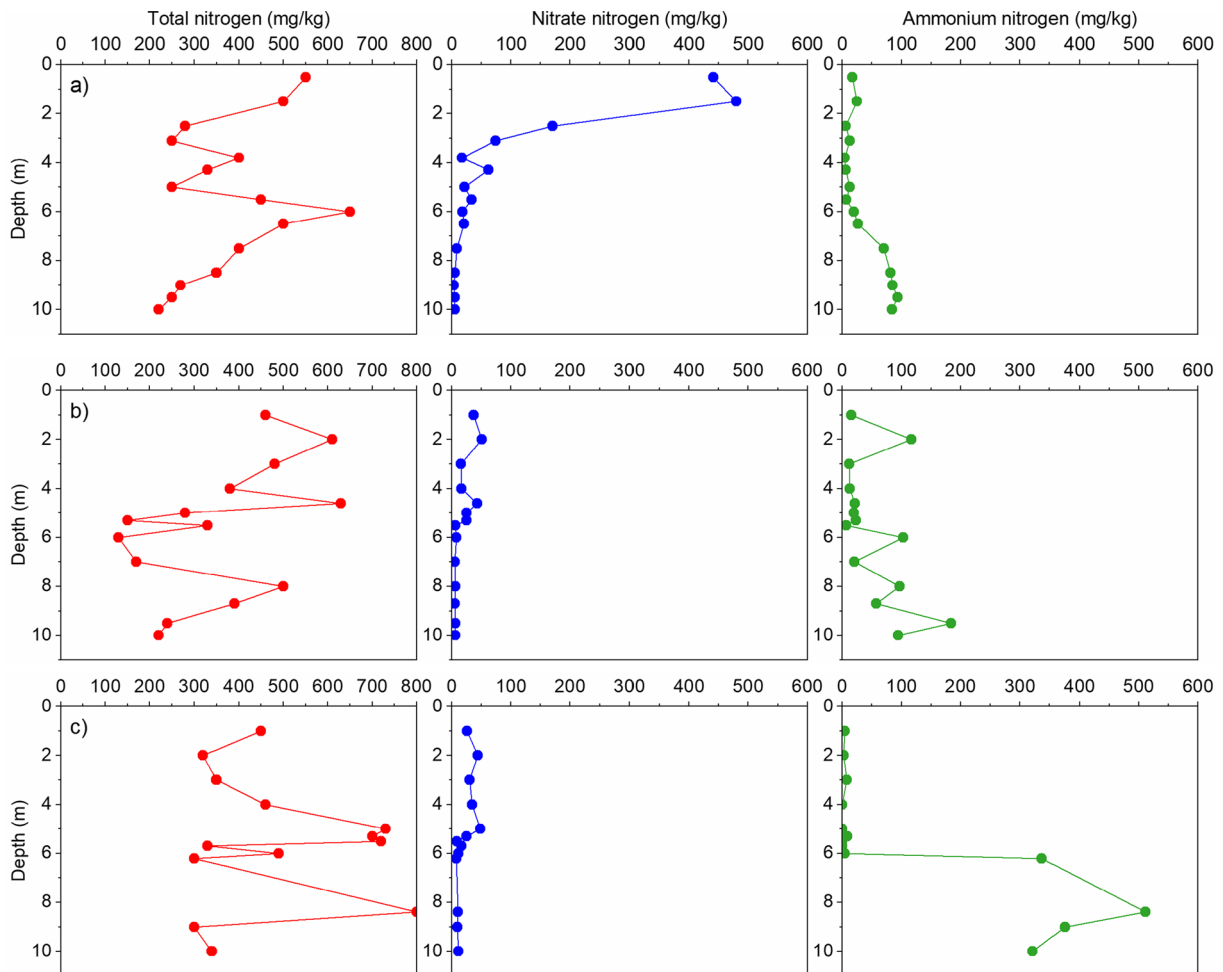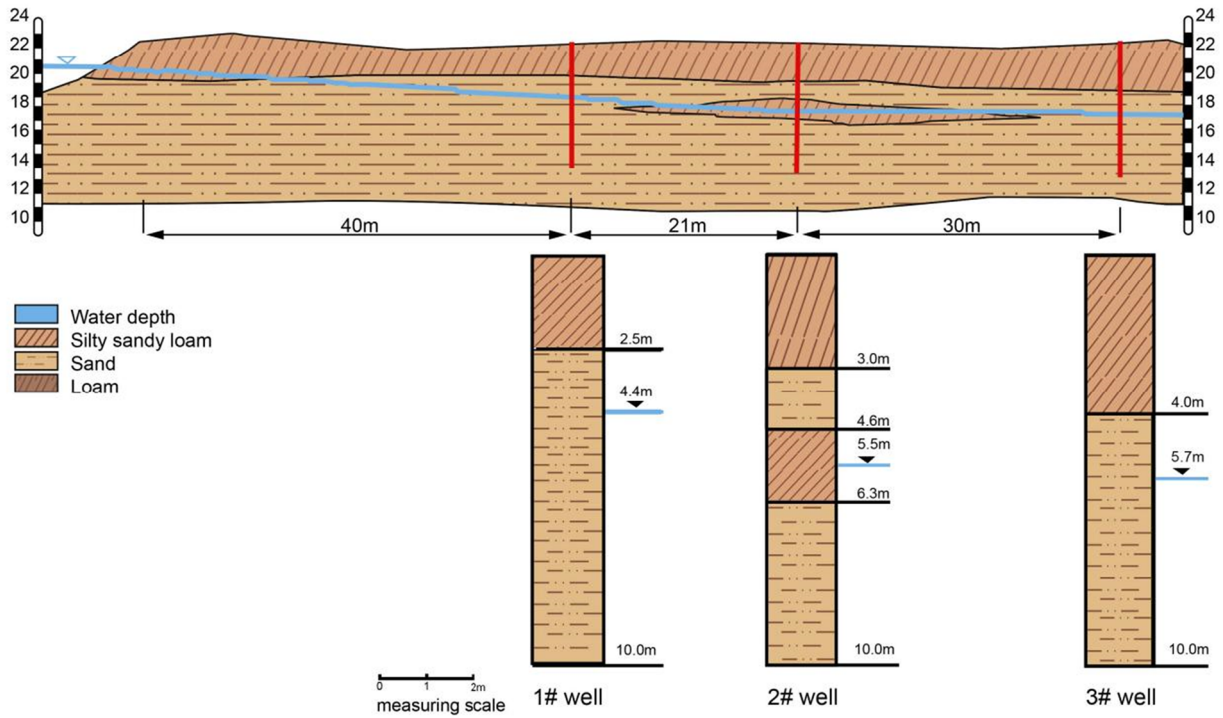
◄**Fig. 6** The distribution of nitrogen in vadose zone and aquifer of midstream section. **a** 1# well, 40 m away from the river bank. **b** 2# well, 61 m away from the river bank. **c** 3# well, 91 m away from the river bank

loam while that in the downstream reaches were mainly sand (Table S3), which may lead to different hydraulic characteristics. With the increase of profile depth, the average value of NN gradually decreased from 37.59 to 32.76 mg/kg, while the AN gradually increased from 52.32 to 57.78 mg/kg (Fig. 3). The linear regression analysis showed that the concentrations of TN and NN in surface water were significantly ($p < 0.05$) correlated with the that of TN and NN in sediments at the depth of 0–15 cm (Table 1), suggesting that the TN and NN in surface water have a direct impact on the surface sediments.

The simulation of N distribution in riverbed sediments

The measured BTCs of the N in riverbed sediments are shown in Fig. 4, and AN was selected as the representative N for simulation experiments. The transport parameters, including hydrodynamic dispersion coefficient (D), retardation factor (R), and relative ratio of the concentration of N in the leachate to that in the water body (S_r), were fitted by CXTFIT 2.1, which are displayed in Table 2. The D of upstream section was lower than that of midstream and downstream sections ($D_{upstream} < D_{midstream} < D_{downstream}$), showing that the riverbed sediments in midstream and downstream sections were of higher hydrodynamic dispersion characteristics. Moreover, the annual leaching volume of N through the riverbed sediments was estimated to be 130,524, 241,776, and 269,808 L/(m²·a) for upstream, midstream, and downstream sections, respectively. The results obtained from simulation experiments indicated that the riverbed sediments in midstream and upstream sections of the Beiyun River were stronger in releasing N, which may increase the distribution of N in vadose zone and aquifer.

N distributions in the vadose zone and aquifer

Based on the distribution of soil particle composition in the vertical profile, we have drawn the geological structure map of each typical section (Figs. 5, 6 and 7). The average thickness of sandy loam in the surface layer of upstream section is approximately 4 m, and the average thickness of sandy soil at the bottom is approximately 5 m. A small amount of loam interlayer was found in the local stratum. The average thickness of sandy loam in the surface layer of midstream section is approximately 3.5 m, and the average thickness of sandy soil at the bottom is approximately 6 m. The stratigraphic structure changes in the downstream section are relatively complex, with a small number of loam and silty loam layers. Generally, sandy loam layers alternate with sandy soils and loamy sandy soils.

N distributions in the vertical profile of different sections are shown in Figs. 5, 6 and 7. The obvious variations were observed for three sections because of the different geological structure of sections. The average TN content of upstream Sect. (297.88 mg/kg) was lower than that of midstream Sect. (402.62 mg/kg) and downstream Sect. (447.02 mg/kg), suggesting higher N accumulations in the midstream and downstream sections. In addition, the average NN content (9.76–69.91 mg/kg) was obviously lower than that of AN content (59.56–151.62 mg/kg) for three sections, with the characteristics showing more NN distribution in 0–4 m profile (vadose zone) and more AN distribution in > 4 m profile (aquifer). The difference of distribution of NN and AN in the vadose zone and aquifer is directly related to oxygen content. Large amounts of oxygen are stored in the vadose zone (0–4 m profile), which facilitates the formation of NN by nitrification.

Discussion

The surface water of the Beiyun River was detected as serious nitrogen (N) pollution because of its elevated total nitrogen (TN) concentrations of 9.88–19.9 mg/L, which was 33–66 times of the threshold value (0.3 mg/L) causing the potential eutrophication (Zeng et al. 2016). Previous studies have obtained similar conclusions that the surface water of the Beiyun River was serious polluted by various contaminants including N (Yu et al. 2012; Jing et al. 2013; Liu et al. 2018; Zhang et al. 2020a). Since the Beiyun River is located in a metropolis with a population of more than 20 million, the land use types, domestic sewage discharge, industrial wastewater emission, and agricultural non-point source pollutants resulting from frequent anthropogenic and agricultural activities have been considered to be major contributors to the river pollution (Chen et al. 2015; Dai et al. 2015; Wu et al. 2020). The dominant role of ammonium nitrogen (AN) in causing the water quality degradation of the Beiyun River has been recognized by previous studies (Guo et al. 2012; Yu et al. 2012), which is related to the large amount of domestic sewage and industrial wastewater that the Beiyun River receives. This study has also confirmed the main role of AN to river pollution, suggesting higher concentration of AN in surface water of the Beiyun River. Furthermore, the pollution situation along the Beiyun River is variable, which has been reported to be interannual variation features because of the changes in annual meteorological, hydrological, and human activities (Guo et al. 2012; Jing et al. 2013; Chen et al. 2015).

Although the textures of riverbed sediments may affect N distributions (Schilling et al. 2009; Yang et al. 2014), no
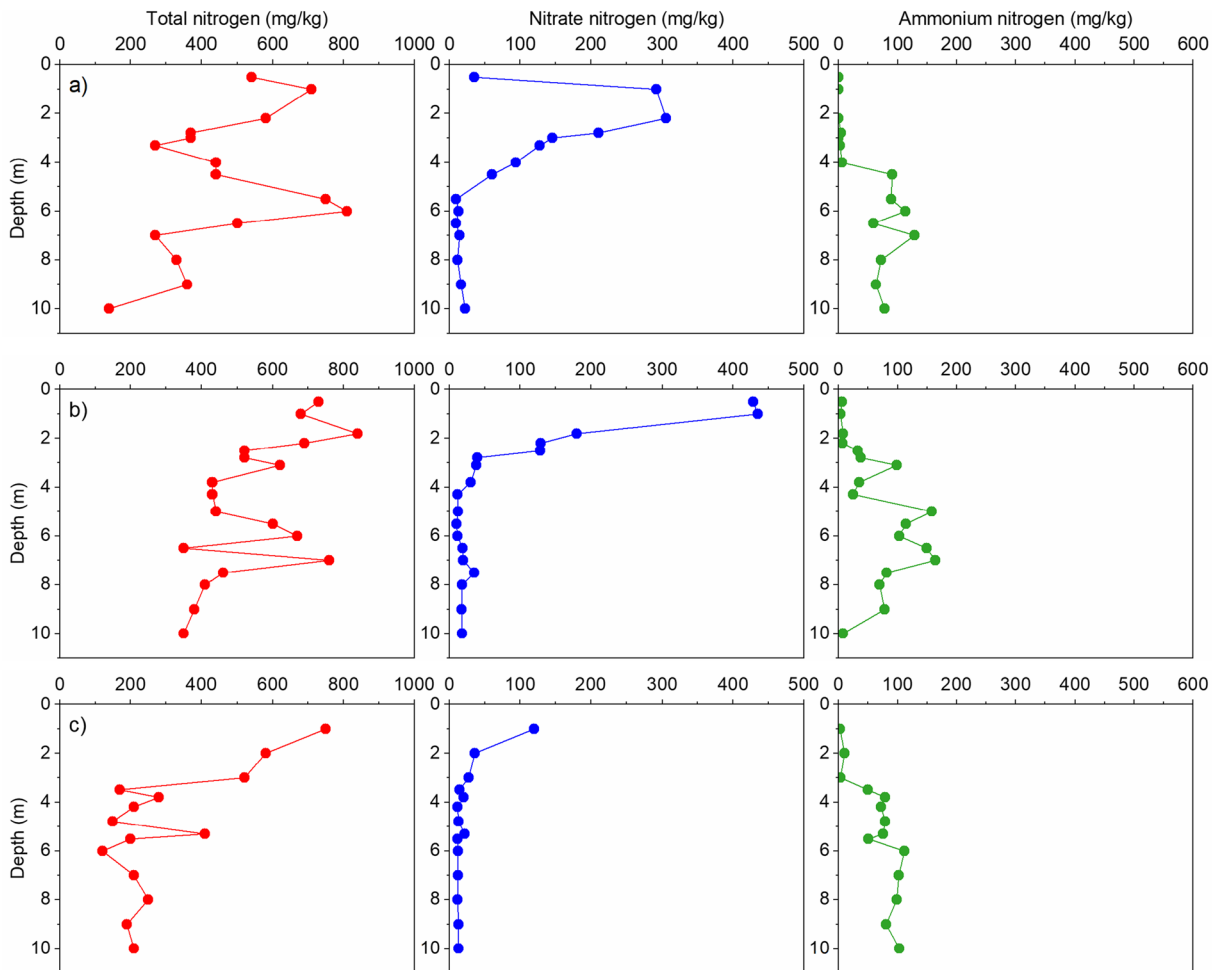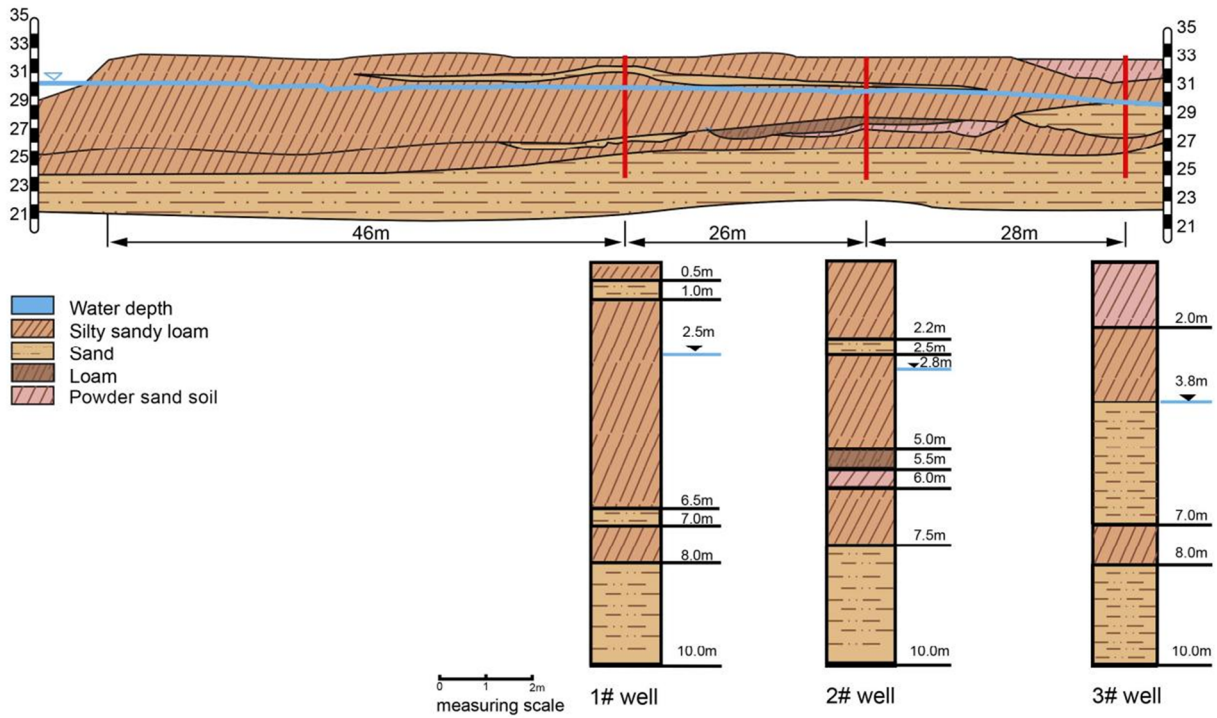
◄**Fig. 7** The distribution of nitrogen in vadose zone and aquifer of downstream section. **a** 1# well, 46 m away from the river bank. **b** 2# well, 72 m away from the river bank. **c** 3# well, 100 m away from the river bank

evident difference was observed for TN concentrations of riverbed sediments both along the river and the vertical profile (0–45 cm). The content of clay particle was considered as an important component to hold N due to its high specific surface area (Wang et al. 2009; Alhaj Hamoud et al. 2019); therefore, the lower clay content (< 14%) may be responsible for this phenomenon. The variations of AN and NN in riverbed sediments showed an opposite trend, i.e., the AN increased with the increase of depth, while the NN decreased with the increase of depth, which was influenced by oxygen content, microbial community, as well as nitrification and denitrification process in riverbed sediments (Béline et al., 1999; Nurk et al., 2005). Although the TN and NN in surface water have been observed to have a direct impact on the surface sediments, the results obtained on the distribution of N in riverbed sediments cannot provide strong evidence for evaluating its influence on N distribution in vadose zone and aquifer.

In order to find more stronger evidence, therefore, column simulation experiments were carried out to quantify the hydraulic characteristics of riverbed sediments. Similar examples, using column experiments, have been widely reported effective in estimating the hydraulic characteristics of riverbed sediments (Pholkern et al. 2015; Shuai et al. 2017; Jin et al. 2019). In this study, the specific hydraulic parameters (D, R, and S_r) were estimated, suggesting that the hydraulic dispersion of riverbed sediment increased gradually from upstream to downstream sections. The rule of fitted hydrodynamic dispersion coefficient (D) for N is generally consistent with that for phosphorus obtained in the previous study (Liao et al. 2020), both of which revealed the similar increase trend from upstream to downstream sections. The results achieved in simulation experiments can well explain the spatial distribution characteristics of N observed in the vadose zone and aquifer. The hydraulic dispersion of the riverbed sediments in midstream and downstream sections is stronger than that in upstream section, leading to more release of N from riverbed sediments into the vadose zone and aquifer. Due to the lack of relevant studies on the Beiyun River (Yuan et al. 2020; Zhang et al. 2020b), we speculate that this effect accumulates over a long period, which may be the main reason for the higher distribution of TN in the midstream and downstream sections. On the other hand, the geological structure of different sections also affected the distribution of N. Based on the obtained data, in the formulation of water quality management strategy of the Beiyun River, targeted control strategy shall be carried out according to the characteristics of different river sections. The discharge

of N pollutants should be restricted in the whole reach of the Beiyun River, especially in midstream and downstream reaches with serious pollution. That is to say, the untreated discharge of domestic sewage and aquaculture wastewater in these areas needs to be prohibited. Meanwhile, due to the greater hydrodynamic dispersion property of riverbed sediments in the downstream reach, appropriate anti-seepage treatment should be carried out. Therefore, two preliminary strategies are suggested to manage the water quality of the Beiyun River: one is to strictly limit the discharge of N from the midstream and downstream banks to the river, and the other is to set up the impermeable layer in the downstream reaches to reduce infiltration.

Conclusion

In this study, we have assessed the nitrogen (N) distribution characteristics in surface water, riverbed sediments, vadose zone, and aquifer of the Beiyun River. The N concentration of surface water in the midstream and downstream reaches is higher than that in the upstream reach, and the ammonium nitrogen (AN) concentration is generally higher than nitrate nitrogen (NN). The discharge of domestic sewage and aquaculture wastewater from the midstream and downstream reaches may be the main cause of this situation. The elevated N concentration in surface water will directly affect the distribution of N in 0–15 cm riverbed sediments because the significant correlation ($p < 0.05$) between each other was detected. In addition to the N contained in surface water, the hydrodynamic dispersion property of riverbed sediments and the geological structure of vertical profile will also impact the spatial distribution of N in the vadose zone and aquifer, showing higher N distribution in midstream and downstream sections. Based on the characteristics of N spatial distribution, management strategies have been developed to elevate the water quality of the Beiyun River, which helps to alleviate the water pollution of the Beiyun River. The causes of N distribution in the vadose zone and aquifer require further investigations, and the optimal strategy should be determined from the perspective of the combination of feasibility, economy, and effectiveness.

Author contribution Renkuan Liao: writing—original draft, writing—review and editing, formal analysis, visualization. Peng Song: writing—original draft, writing—review and editing, data curation, software. Jia Wang: writing—original draft, methodology, investigation, formal analysis. Jieyun Hu: writing—original draft, investigation, formal analysis. Shuqin Li: project administration, methodology, supervision, writing—review and editing. Yunkai Li: project administration,

funding acquisition, methodology, conceptualization, resources, writing—review and editing.

Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All the authors have read and approved the manuscript and accorded the consent for publication.

Competing interests The authors declare no competing interests.

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