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Treatment and hydraulic performances of the NiiMi process for landscape water

Jian YANG†, Liang-bo ZHANG, Yi-fan WU, Ya-yi WANG, Cui LI, Wen LIU

(*State Key Laboratory of Pollution Control and Resources Reuse,*
School of Environmental Science and Engineering, Tongji University, Shanghai 200092, China)

†E-mail: yj4275@126.com

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Abstract: This paper describes the NiiMi process designed to treat landscape water. The main aim of the research was to investigate the feasibility of NiiMi for removing organic and nutriment materials from landscape water. During the batch-scale NiiMi operation, the removal rates of color ranged from 66.7%–80%, of turbidity from 31.7%–89.3%, of chemical oxygen demand (COD) from 7%–36.5%, of total phosphor (TP) from 43%–84.2%, of soluble phosphate from 42.9%–100%, of total nitrogen (TN) from 4.2%–46.7%, and of NH_4^+-N from 39.3%–100% at the hydraulic loading of 0.2 $m^3/(m^2\cdot d)$. Results showed that the removal efficiencies of COD, TP, soluble phosphate and TN decreased with the decline in the temperature. The NiiMi process had a strong shock loading ability for the removal of the organics, turbidity, TP, soluble phosphate, TN and NH_4^+-N. Three sodium chloride tracer studies were conducted, labeled as TS1, TS2, and TS3, respectively. The mean hydraulic retention times (mean HRTs) were 31 h and 28 h for TS1 and TS2, respectively, indicating the occurrence of a dead zone volume of 12% and 20% for TS1 and TS2, respectively. TS1 and TS2 displayed the occurrence of short-circuiting in the NiiMi system. The comparison results between TS1 and TS2 were further confirmed in the values obtained for some indicators, such as volumetric efficiency (e), short-circuiting (S), hydraulic efficiency (λ) and number of continuously stirred tank reactors (N).

Key words: NiiMi system, Landscape water, Purification efficiency, Hydraulic efficiency, Tracers
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1 Introduction

As one of the ecological treatment technologies, the subsurface wastewater infiltration system (SWIS) is the most commonly used system for the treatment and disposal of onsite wastewater and has been used as one of the conventional intensive sewage treatment technologies (US EPA, 2002; El-Masry *et al.*, 2004; Mohamed *et al.*, 2004; Zhang *et al.*, 2004; Li *et al.*, 2007; Zhao *et al.*, 2007; Lowe and Siegrist, 2008). SWIS is an effective process for wastewater treatment according to the integrated mechanisms of chemical, physical and biological reactions if the system is carefully designed and managed (Healy *et al.*, 2007; Babatunde *et al.*, 2008). As an improved SWIS, the NiiMi process is a kind of integrated technique including the aerobic and anaerobic processes (Kruzic, 1997; Zhang *et al.*, 2005). The NiiMi process developed by Tadashi NiiMi in Japan is a kind of infiltration percolation method backed up by the phenomena of capillary siphoning. The polluted water is transferred into distribution tubes with numerous small holes in them. Because of the capillary activity, the polluted water is drawn up and distributed uniformly in sand. The pollutants in water are then eliminated by filtration and microbial activity. The treated water is then collected with a collection tube implemented below and pumped out into a reclaimed water tank. To avoid a possible shortcut between distribution tube and collection tube, a water-proof trough is implemented between them. And to avoid possible underground water pollution, a water-proof layer is applied in this system. The polluted water body percolates around the circumference through the capillary soakage and soil percolation actions, under the integrated action of soil, microbe and plant together, the organic matter and nitrogen are decompounded, the phosphorus is absorbed by the soil through chemical precipitation and it can be utilized by the lawn or other plants. The removal of effluent contaminants occurs mainly in the upper few centimeters of the bed where a biologically active layer is formed (Beal *et al.*, 2005). Compared to the conventional activated sludge process, this system has many advantages, including the excellent performance of organic matter and phosphorus removal, lower construction and operation costs and easy maintenance (Yamaguchi *et al.*, 1996; Sun and He, 1998; Zhang *et al.*, 2005). Compared to constructed wetland or soil filter, one of the most conspicuous differences of the NiiMi system is its distribution system that distributes water by the capillary siphoning of sand or other fillers.

Landscape water is one kind of surface water that is applied to beautify the environment, humidify and clean the atmosphere, and improve the climate of a district. Furthermore, it can be a landscape to appreciate. With the rapid economic development of China, urban landscape water including a number of artificial lakes and rivers are being polluted in many places gradually with a low-concentration of organic compounds. Therefore, nitrogen and phosphorus lead to the higher eutrophication of urban landscape waters. In addition, this will result in the propagation of blue-green algae, poor transparency and malodor of the water. Nowadays, the main treatment methods for landscape waters include physical-chemical methods such as coagulative precipitation, filtration and air flotation, traditional biological treatment such as the contact oxidation process, biological aerated filter and constructed wetlands technique (He, 2004). Although some soil infiltration technologies are frequently used to treat landscape water (Eldridge *et al.*, 2000; Siriwardene *et al.*, 2007), the NiiMi process is seldom applied to polluted landscape waters. As a novel attempt, applying the NiiMi process to landscape water treatment has lots of advantages for the urban surroundings. It can not only beautify the environment but the flower-grass planted in the system can purify the landscape water quality.

Factors pertaining to the NiiMi process removal efficiencies should be considered when the system is designed properly, which include bioaugmentation, media depth, grain size distribution, mineral composition of media, the water composition and nutrient concentration, the organic loadings rate and hydraulic performances, etc. As for some influential factors on the treatment effects of wastewater, such as grain size, the compositions of media, were greatly researched, but the influence of hydraulic performances on NiiMi treatment effects was seldom reported (Beach *et al.*, 2005). The key position of the NiiMi process is the biomat, where biological processes, adsorption, filtration and infiltration actions can occur. With the operation of the system, the biomat depth increases with the augmentation of biomass. But the biomat development creates an increased resistance to flow, and therefore, strongly influences the unsaturated flow regime of media. Unsaturated flow conditions are critical for higher effective purification of the water quality. The removal of pollutants is often estimated using an ideal water retention time distribution (plug flow). But this is not necessarily the case. A great amount of research (Persson *et al.*, 1999; Werner and Kadlec, 2000; Persson and Wittgren, 2003; Suliman *et al.*, 2005; Munoz *et al.*, 2006) reported the relations between the removal efficiencies and the hydraulic conductivity and dispersitivity in constructed wetlands. However, such research in SWIS of the NiiMi process is seldom reported.

The aim of this study was to evaluate the purifying performances and the removal efficiencies of all kinds of indexes of the NiiMi process to treat the landscape waters. The experiments were carried out on the bench-scale. In addition, the objective was to assess hydraulic behavior of the NiiMi process with the operation of the system. The research helped further establish how the NiiMi process was a viable tool for treating landscape water.

2 Materials and methods

2.1 Laboratory set up

One container made of Plexiglas, placed in a laboratory, was used to conduct the removal effects and hydraulic performance studies. The container was 1 m long, 0.15 m wide and 1 m high (Fig. 1). The height of filter media was 0.9 m. Landscape water was distributed evenly through a distribution slot. 12 sampling pores were equipped on one side of the container; the treated effluent was collected through a collecting pipe at the bottom of the system. The container was divided into two parts, including distributing water district and filler district. The distribution slot was filled with gravel whose particle size was in the range of 1–2 cm, and the filler district was filled with sand. The particle size ranged from 0.3 mm to 1 mm, the density of sand was 2.59 g/cm^3, the porosity was 42%, and the specific surface area was 0.9361±0.0025 m^2/g. The experiment system flow chart is illustrated in Fig. 1.

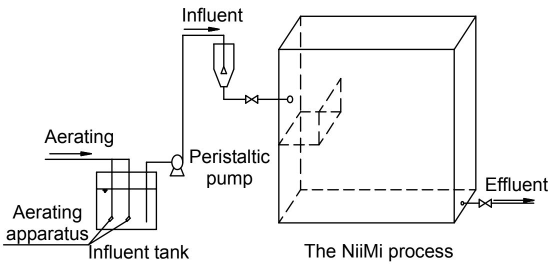

Fig. 1 Schematic diagram of experimental system

In the first stage (S1) over 4 months, the lower influent concentration was distributed into the NiiMi process at a hydraulic loading of 0.2 m/d. In the second stage (S2), which lasted for 2 months, in order to investigate the influence on the removal efficiencies and the hydraulic behavior of the NiiMi process, the higher influent concentration was applied to the system; the hydraulic loading of S2 was the same as that of S1.

2.2 Quality of influent

The quality of influent landscape water used in the study is shown in Table 1. Affected by the rainfall, the influent concentration fluctuated during the operation period.

2.3 Analysis items and methods

According to standard methods (Chinese EPA, 2002), a colorimetric method was used for NH_4^+-N, NO_3^--N, NO_2^--N, TN, PO_4^{3-}, and TP analysis. Platinum-cobalt standard dichromate was used for color. A MERCK spectroquant TR420/NOVA60 COD meter (Germany) was used for chemical oxygen demand (COD) analysis, turbidity was measured by HACH2100 turbidimeter (America), dissolved oxygen (DO) was monitored by WTWOxi330 dissolved oxygen analyzer (Germany). Each sample analysis was performed in triplicate.

2.4 Tracer experiments

To evaluate the flow and transport properties of the NiiMi process during the operation time, three sets of tracer experiment were conducted for 3, 4 and 5.5 months after operation. A pulse solute injection experiment performed in the NiiMi system, the pulse source of tracer (C_0=100 g/L from NaCl), was supplied to the container. Samples were carried out from the effluent at 1 h intervals for analysis of Cl^- concentration. The chloride concentration was analyzed with a titration measurement by $AgNO_3$.

2.5 Filter medium hydraulic parameters

Retention time (RT) represents the amount of time it takes for the landscape water to flow through the NiiMi process. Theoretical RT were calculated according to

$$\mathrm{RT_n} = V / Q, \quad (1)$$

where $\mathrm{RT_n}$ is the retention time (d), V is the volume of water in the NiiMi system (m^3) and Q is the volumetric flow rate of water through the NiiMi system (m^3/d).

Mean hydraulic retention time (mean HRT) was computed using the area under the breakthrough curve (the zero moment), the trapezoidal rule and mean travel times.

Table 1 Influent water quality before operation

Item	T (°C)	pH	DO (mg/L)	COD (mg/L)	Turbidity (NTU)	TP (mg/L)	PO_4^{3-} (mg/L)	TN (mg/L)	NH_4^+-N (mg/L)
Range	1.0–31.0	7.5–8.2	4.5–8.2	21–55	0.97–3.32	0.04–0.19	0.01–0.12	0.65–2.90	0.22–1.25
Average	18.8	7.8	6.9	39.1	1.9	0.1	0.05	1.84	0.57

$$\text{Mean HRT} = \frac{\int_0^\infty C(t)t\mathrm{d}t}{\int_0^\infty C(t)\mathrm{d}t}, \quad (2)$$

where $C(t)$ is the tracer concentration (mg/L) at time (t); t the time of sample (d). Volumetric efficiency was calculated using a ratio of mean retention utilized:

$$e = \frac{t_{\text{mean}}}{t_{\text{n}}} = \frac{V_{\text{effective}}}{V_{\text{total}}}, \quad (3)$$

where e is the effective volume ratio, t_{mean} the mean hydraulic retention time, and t_{n} the nominal hydraulic retention time.

It is supposed that the flow state in the NiiMi system is similar to the wetland and pond. Kadlec and Knight (1996a)'s method for calculating the number of continuously stirred tank reactors (CSTRs) was used in the analysis of wetland hydraulic characteristics.

$$N = \frac{t_{\text{n}}}{t_{\text{n}} - t_{\text{p}}}, \quad (4)$$

where N is the number of CSTRs in series and t_{p} the peak time.

Kadlec and Knight (1996b) developed a parameter of short-circuiting value (S) which depicted hydraulic performances.

$$S = \frac{t_{16}}{t_{50}}, \quad (5)$$

where t_{16} and t_{50} is the hydraulic residence time at which 16% and 50% of the tracer is recovered, respectively.

In addition, hydraulic efficiency was calculated with an equation derived by Persson *et al.* (1999), which uses volumetric efficiency and the number of CSTRs

$$\lambda = \frac{t_{\text{p}}}{t_{\text{n}}}. \quad (6)$$

3 Results and discussions

3.1 Treatment performances of the NiiMi process

3.1.1 Color variety between influent and effluent

Color is a very crucial monitoring index for landscape water. The color changed from 15° to 25° of influent into less than 5° of effluent, the removal efficiency varied between 66.7% and 80%, and the average removal efficiency was 76%. It can be interpreted that the colored substances are adsorbed into the filtration material. The transparency increased with the decrease in color.

3.1.2 Turbidity removal effect

Landscape water transparency and turbidity are the main indicators of landscape water quality. Increased transparency can allow sunlight to pass into the water body easily, therefore promoting the growth of submerged plants, which is advantageous to the renovation of the ecosystem, as well as its ability to rebound in terms of the improvement in water quality (He *et al.*, 2007).

Sand is a traditional material used for water filtration for the removal of turbidity (Mulligan *et al.*, 2009). During the operation period, the influent turbidity ranged from 0.97 to 3.32 NTU, the average influent turbidity was 2.2 NTU; the effluent turbidity varied between 0.33 and 0.98 NTU and the average effluent turbidity was 0.55 NTU. The removal efficiency of turbidity ranged from 31.7% to 89.3% (Fig. 2) and the average removal efficiency was 66.6%.

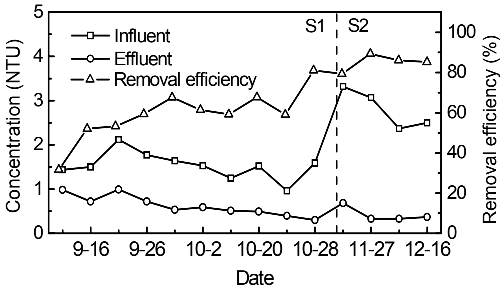

Fig. 2 The change curve of turbidity and its removal efficiency

As shown in Fig. 2, the turbidity removal efficiency could reach higher. It can be interpreted through the absorption and filtration action of filler and, in addition, the finer sands removed the lower landscape water turbidity properly. Previously, He *et al.* (2007) used constructed wetland to treat polluted river water with proper turbidity removal. Compared to constructed wetland, the NiiMi system had a better removal effect of turbidity without producing clogging. It was explained that the grain size of the NiiMi system filler was smaller than that of constructed wetland filler.

The turbidity removal efficiencies of the S1 and S2 stages were 31.7%–81.1% and 79.3%–89.3%, respectively, the average removal efficiency was 59.3% and 85%, respectively. Because the suspended substance concentrations of S2 were larger and the removal efficiency of S2 was higher than that of S1, the NiiMi system had higher buffering ability.

3.1.3 COD removal effect

During the operation period, influent COD ranged from 21 to 55 mg/L, the average concentration of COD was 39.1 mg/L; effluent COD varied between 15 and 47 mg/L, the average concentration of COD was 29.8 mg/L. The removal efficiency of COD ranged from 7% to 36.5% (Fig. 3), the average removal efficiency was 20.4%.

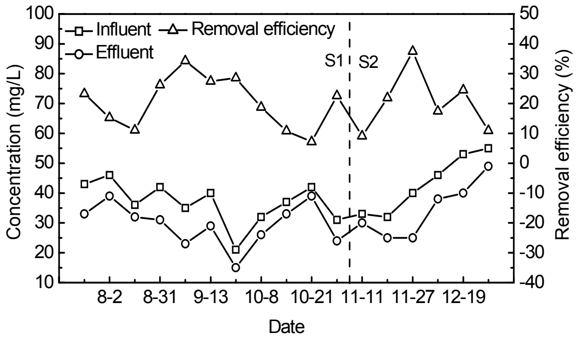

Fig. 3 The change curves of COD and their removal efficiencies

Influent and effluent COD data are presented in Fig. 3. It was concluded that COD can be degraded to a certain degree, but the removal effect was not conspicuous. Because the influence concentration of the organic substance and the B/C value (B/C is the ratio of BOD to COD of polluted water, it represents the biodegraded ability of water) were lower, the COD removal efficiency was not very high. The organic loading of the NiiMi process ranged from 4 to 12 g COD/(m^2·d) in this experiment. The average organic loading of influent was about 10 g COD/(m^2·d). Due to the low organic loading, the removal efficiency was not evident. In fact, the NiiMi process could attain higher COD removal with higher organic loading (Sun and He, 1998; Jarboui *et al.*, 2008).

Zhang *et al.* (2005) drew the conclusion that the COD average removal of the NiiMi system to treat wastewater could reach 82.7%. This might be due to the higher B/C value of wastewater compared to that of landscape water. A similar conclusion could be drawn applying other technologies to treat polluted landscape water. Jing *et al.* (2001) indicated that the average removal rate of COD ranged from 13%–51% using constructed wetland to treat the polluted river water.

According to Fig. 3, the COD removal efficiencies of the S1 and S2 stages were 7%–34% and 9%–36.5%, respectively, the average removal efficiencies were 20.5% and 20.2%, respectively. The COD removal efficiency had no evident variety, although the temperature varied from August to October in 2008. The microbe activities had not decreased with the decrease in temperature, so the NiiMi system has a higher buffering ability for COD removal.

3.1.4 P element removal effect

Excess phosphorus can stimulate the production of algae, leading to undesirable states of eutrophication in lakes, reservoirs and rivers (Jiang *et al.*, 2008). Excess algae can lead to taste and odor problems, and also contribute to human health problems. Therefore, the P removal is crucial for landscape water. TP and soluble phosphate were investigated in this study.

During the operation period, influent TP and soluble phosphate concentrations varied from 0.04 to 0.19 mg/L and from 0.01 to 0.12 mg/L, respectively. The average concentrations were 0.1 mg/L and 0.05 mg/L; effluent TP and soluble phosphate concentrations varied from 0.01 to 0.06 mg/L and from 0 to 0.04 mg/L, respectively. The average concentrations were 0.03 mg/L and 0.01 mg/L. The removal efficiencies of TP and soluble phosphate ranged from 43% to 84.2% (Fig. 4a) and from 42.9% to 100% (Fig. 4b), respectively, and the average removal efficiencies of them were 67.1% and 77.2%, respectively. Similar conclusions could be drawn by Zhang *et al.* (2005) and Hu *et al.* (2007) using the NiiMi process to treat wastewater. Cheung and Venkitachalam (2000) already proved that sand infiltration had high P removal efficiencies.

The removal efficiencies of the P element were conspicuous in the NiiMi process (Fig. 4). It was due to the absorption, interception, surface reaction and chemistry deposition of organic and inorganic phosphorus. Large specific surface areas of the sand resulted in higher phosphorus absorption. In addition, the pH of the filler circumference has a significant influence on the mechanism of P removal. Influent pH 7.5–8.2 and effluent pH 7.7–8.1 could create the alkaline cultures. In this environment, cation inside fillers could react with soluble P, Ca-P produced. Furthermore, colloid adhering to the surface of fillers could react to exchange and adsorption with the $H_2PO_4^-$, so the removal effects were conspicuous. The P-removal rates varied with the variation in temperature; however, the NiiMi system maintained relatively consistent removal rates during the operation period. It may be concluded that media sorption played an important role in the NiiMi system. Nevertheless, the sorption capacity of media is limited (Sakadevan and Bavor, 1998) and the stability of phosphate compounds is affected by the redox potential and the pH of the media environment (Kadlec and Knight, 1996). Therefore, altering pH could improve the removal effects of P.

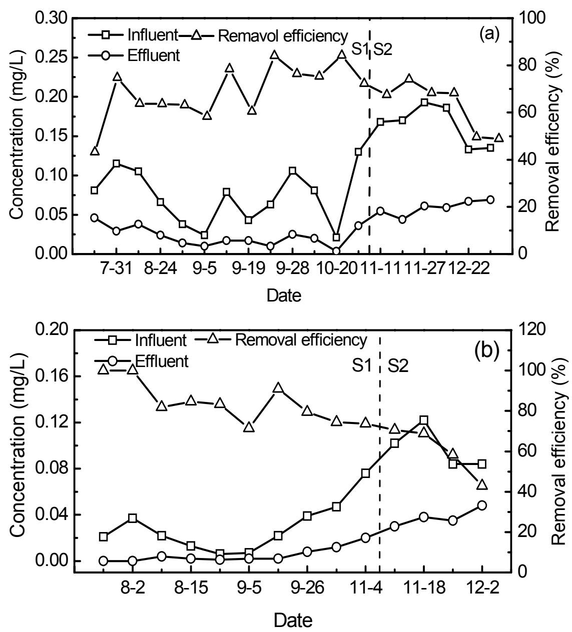

Fig. 4 The change curves of TP (a), soluble phosphate (b) and their removal efficiencies

According to Fig. 4a, the TP removal efficiencies of the S1 and S2 stages varied from 43% to 84.2% and from 48.9% to 74.1%, and the soluble phosphate removal efficiencies of S1 and S2 stages varied from 73.7% to 100% and from 42.9% to 70.6%, respectively. The TP average removal efficiencies of S1 and S2 were 69.1% and 62.8%, respectively, and the soluble phosphate average removal efficiencies of S1 and S2 were 83.9% and 60.2%, respectively. The TP removal efficiency in the S2 decreased a little compared to that of S1, and the variety was not obvious. This indicated that the NiiMi system had higher buffering ability for TP removal. However, reduction of soluble phosphate removal efficiencies was conspicuous between the S1 and S2 stages (Fig. 4b). This was explained by its physico-chemical nature. During the operation time, the adsorption quantities of P on the filler decreased gradually. Furthermore, according to Gibbs adsorption formulas (Chen, 2000), $\Gamma = -\frac{C}{RT}\frac{\mathrm{d}\delta}{\mathrm{d}c}$, the surface adsorption capacity of fillers was affected by temperature to a certain content and decreased with the decrease in temperature.

3.1.5 N element removal effect

With the rapid agricultural development in recent years, nitrogen pollution in some surface water has been rising greatly (Wang *et al.*, 2009). The nitrogen contaminant has drawn more attention. The removal effects of TN and NH_4^+-N were investigated in this study. During the operation period, the influent TN and NH_4^+-N were 0.65–2.90 mg/L and 0.22–1.25 mg/L, respectively, the average concentrations were 1.84 mg/L and 0.57 mg/L; the effluent TN and NH_4^+-N were 0.46–2.4 mg/L and 0–0.27 mg/L, the averages were 1.48 mg/L and 0.1 mg/L. The removal efficiencies of TN and NH_4^+-N were 4.2%–46.7% (Fig. 5a) and 39.3%–100% (Fig. 5b), the average removal efficiencies were 19.8% and 77.1%, respectively. Recently, much research (Tanık and Comakoğlu, 1996; Kuschk *et al.*, 2003; Zhang *et al.*, 2005) has been carried out to study nitrogen removal performance in SWIS. Kuschk *et al.* (2003) concluded that the efficiency obtained for N removal varied between 46%–93%, and the efficiency for nutrients was reduced with an increase in the effective size of porous media. Considering the above conclusion, fine sand was selected in this experiment.

The TN removal effect was not ideal, because the vast majority of practical nitrogen-removal systems employed nitrification and denitrification biological reactions. Although the NiiMi process could provide a preferable nitrification environment, it could not create a denitrification environment; the influent DO ranged from 4.5 to 8.2 mg/L and the effluent DO ranged from 9.3 to 10.5 mg/L, so the system could provide a better aerobic environment favorable to the nitrification effect. However, because of a worse anaerobic environment and carbon source deficiency at the bottom of the NiiMi process equipment, TN removal efficiency requires further improvement.

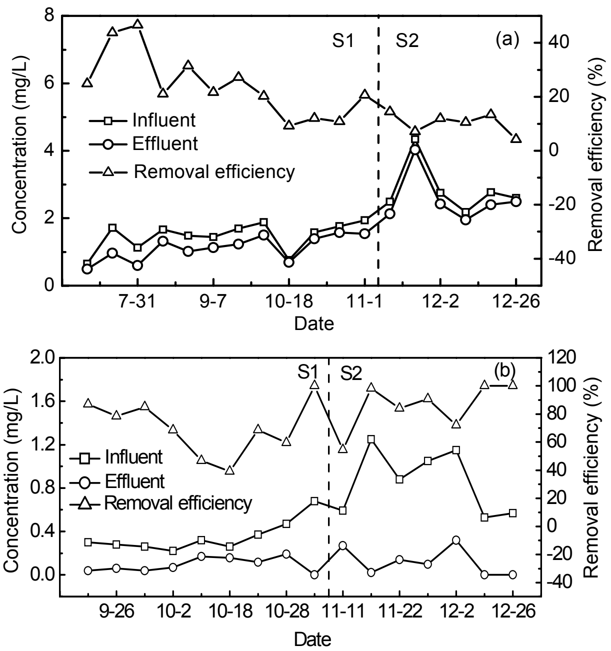

Fig. 5 The change curves of TN (a), NH_4^+-N (b) and their removal efficiencies

According to Fig. 5a, the TN removal efficiencies of the S1 and S2 stages ranged from 9.2% to 46.7% and from 4.2% to 14.4%, respectively. The average removal efficiencies were 24.1% and 10.3%, respectively. The TN removal efficiency of S2 decreased a little compared to that of S1, because the optimum temperature of the nitrification reaction was 20–32 °C. When the temperature decreased below 15 °C, the nitrification rate decreased, so the nitrification effect declined and the TN removal efficiency decreased accordingly.

In addition, the S1 stage on Oct. 18, 2008 can be divided into two sub-stages, which were S1A and S1B. The S1B TN removal efficiency decreased conspicuously compared to that of S1A. Although the temperature decreased, the S2 TN removal efficiency declined compared to S1A. The declination was not evident, which indicated that the TN removal efficiency had no enormous variation with an increase in the TN initial concentration. As for the TN load, the NiiMi system had a higher buffering ability for TN removal.

The NH_4^+-N removal efficiency was high. It was because the NiiMi process could provide a preferable nitrification environment. It is well known that biological nitrification is the most effective process for nitrogen removal. Achak *et al*. (2009) drew a similar conclusion applying a sand filter to olive mill wastewater, to achieve a 97% removal of NH_4^+-N. Nitrification is generally carried out by aerobic, autotrophic bacteria that oxidize NH_4^+ to NO_2^- and NO_2^- to NO_3^- with molecular oxygen as an electron acceptor. A large, special surface area of filler was beneficial for the organic matter remaining and microbial survival (Zhang *et al.*, 2005). In turn, that was advantageous for biological nitrification. Biological nitrification was the highest for ammonia removal in the NiiMi system as time went on.

According to Fig. 5b, the NH_4^+-N removal efficiencies of the S1 and S2 stages ranged from 39.3% to 100% and from 54.5% to 100%, respectively. Average removal efficiencies were 70.4% and 85.7%, respectively. It indicated that the NH_4^+-N removal efficiency had no conspicuous variation when the temperature decreased. Simultaneously, although the influent NH_4^+-N concentration increased, the NiiMi system can maintain higher removal performance. It could be interpreted that the NiiMi system can bear an impact load for NH_4^+-N.

In all, the NiiMi system can clearly be an effective treatment facility for polluted water in natural reservoirs such as rivers landscape water. It could effectively remove some indexes, including sense and conventional indexes. Therefore, it was feasible to utilize the NiiMi process for the removal of organic matter, nitrogen and phosphorus in landscape water, simultaneously improving the landscape situation.

3.2 Tracer study

Tracer studies were conducted on the NiiMi system. Tracer concentration response curves of different operation periods are shown in Fig. 6 and a summary of tracer response characteristics and hydraulic parameters are presented in Table 2. Cl^- tracer relative concentrations were plotted against monitoring time. Fig. 6 indicated the equipment operation situation after 3 months, 4 months and 5.5 months, which were labeled as TS1, TS2 and TS3, respectively. C was the effluent concentration of Cl^-, C_{total} was the total concentration of Cl^-.

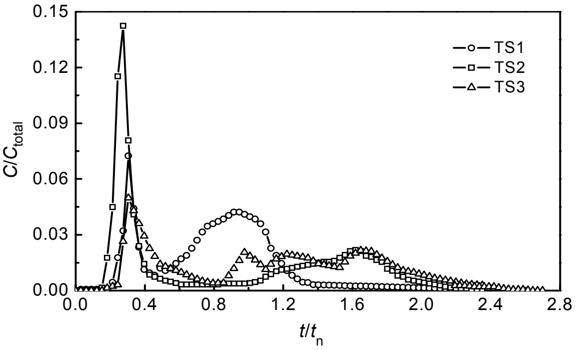

Fig. 6 Tracer concentration response curves for TS1, TS2 and TS3 tracer studies

Table 2 Tracer study response curve characteristics for the NiiMi system

Tracer study item	TS1	TS2	TS3
Average flow rate, Q (l/d)	30	30	25
Nominal retention time, t_n (h)	35	35	38
Peak time, t_p (h)	9.5	8.0	10
Mean hydraulic retention time, t_{mean} (h)	31	28	60
Time at 16% tracer response peak, t_{16} (h)	10	9.5	10
Time at 50% tracer response peak, t_{50} (h)	31	28	60
Volumetric efficiency, e	0.88	0.80	–
Number of CSTRs, N	1.37	1.29	1.37
Short-circuiting, S	0.32	0.34	0.17
Hydraulic efficiency, λ	0.27	0.23	0.26

As for TS1 and TS2, normal retention time (NRT) was $V\times\frac{\varepsilon}{Q}=35$ h, however, NRT was 38 h for TS3. After 3 months, 4 months and 5.5 months, the mean HRT was 31 h, 28 h and 60 h, respectively. After 3 and 4 months, mean HRTs were shorter by about 4 h and 7 h compared to NRT, respectively, which indicated the occurrence of a dead zone volume of 12% and 20%, respectively. It was because the biofilm produced with operation time accumulated, that accordingly a short-circuiting phenomenon was produced. The longer the operation time, the more serious the short-circuiting before clogging was produced. As known, with the operation of the NiiMi system, the filler matrix promoted the settling of suspended solid and provided surfaces for biofilm growth and ion exchange. Growth of biofilms within void spaces further reduced the effective interstitial volume. The functional sustainability of the NiiMi process, both in terms of treatment performance and operational lifetime, was then dependent on the net accumulation of particulate matter and biofilms within the void spaces. As the matrix porosity gradually decreased, both its hydraulic conductivity and the effective retention time of the flowing water were reduced, affecting flow pathways. However, after 5.5 months, mean HRT lengthened by about 22 h compared to NRT. It was mainly due to the inlet of the NiiMi system equipment that clogging occurred, produced by the larger particle size suspended solids. Because of the accumulation of suspended solids, inlet resistance enhanced, the water flow rate decreased, so the mean HRT was longer than NRT.

The trace studies conducted on TS1 and TS2 displayed the occurrence of short-circuiting in the NiiMi system. According to Table 2, the t_{16} of TS2 was less than that of TS1. It illustrated that the extent of TS2 short-circuiting was larger than that of TS1, which could be attributed to the biofilm accumulation. Furthermore, TS2 indicated more serious short-circuiting compared to TS1. This was further confirmed by the mean HRT in TS2, which was 7 h shorter than NRT. However, the mean HRT in TS1 was shorter by 4 h than NRT. Similarly, other parameters (the peak time, number of CSTRs and λ) also confirmed that TS2 had lower λ than TS1. The TS1 peak time was 9.5 h, while the TS2 response peak occurred in an earlier period of 8 h. The poorer hydraulic efficiency of the NiiMi system during TS2 was further confirmed in the values obtained for the number of CSTRs: during TS2 it was 1.29, smaller than the CSTRs number for TS1 (Table 2). Kadlec and Knight (1996) used the number of CSTRs to investigate flow hydrodynamics and hydraulic efficiency. Comparatively, a smaller number of CSTR indicated a less efficient system. Furthermore, hydraulic efficiency in TS2 was 0.23, lower than TS1.

Compared to TS1 and TS2, TS3 had the smallest short-circuiting value. It was possibly due to inlet clogging produced by the larger particle size suspended solids.

In addition, during TS1 and TS2, the NiiMi system had a dead zone for treating landscape water. It was concluded through volumetric efficiencies (e) of TS1 and TS2, which were 0.88 and 0.80, respectively. This situation can display the occurrence of short-circuiting in the NiiMi system during TS1 and TS2 studies.

All in all, as for TS1 and TS2, the biofilms were produced gradually with the operation time, the matrix porosity of the area where the water flowed by gradually decreased, so part of the water flow might detour the area where biofilms were produced. As a result, the local flow rate increased and, consequently, the short-circuiting phenomena were produced. Moreover, both its hydraulic conductivity and the effective retention time of flowing water reduced, affecting flow pathways. However, for TS3, because of the accumulation of suspended solids, system inlet resistances were enhanced, the average water flow rate decreased, so the mean HRT was longer than NRT.

The tracer response curves of TS1 and TS2 were similar; there were only some differences between some parameters which indicted the different degree between TS1 and TS2, including t_{16}, λ, e, N, S, etc. However, the tracer response curve of TS3 differed from those of TS1 and TS2, because the flow state and the mechanism of TS3 were not the same as those of TS1 and TS2. Because of the accumulation of suspended solids, system inlet clogging occurs; it prolongs the mean HRT compared to NRT.

4 Conclusion

The NiiMi process in this study represented a feasible treatment for landscape water, to remove organics and nutriments. The efficiency and life span of the treatment process were associated with the extent of organic loading. To optimize effluent quality and the length of treatment of landscape water, a lower organic loading should first be employed. As the operation proceeded, higher organic loading influent water occupied the NiiMi system.

Excellent performance was achieved with an average 76% of color, 66.6% of turbidity, 20.4% of COD, 67.1% of TP and 19.8% of TN removal efficiencies at hydraulic loading 0.2 $m^3/(m^2 \cdot d)$, respectively. Thus this study demonstrated the feasibility of the NiiMi process. In addition, the results revealed that the removal efficiencies of COD, TP, soluble phosphate and TN decreased with the declination in temperature. Furthermore, the NiiMi system had a strong shock loading for the removal of the organics, turbidity, TP, soluble phosphate, TN and NH_4^+-N.

With the NiiMi process operating, the results revealed the occurrence of a dead zone volume of 12% and 20% for TS1 and TS2, respectively. With the biofilm accumulating, short-circuiting occurred simultaneously. Furthermore, the extent of short-circuiting increased as time went on.

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