Application of subsurface wastewater infiltration system to on-site treatment of domestic sewage under high hydraulic loading rate

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Abstract

In order to enhance the hydraulic loading rate (HLR) of a subsurface wastewater infiltration system (SWIS) used in treating domestic sewage, the intermittent operation mode was employed in the SWIS. The results show that the intermittent operation mode contributes to the improvement of the HLR and the pollutant removal rate. When the wetting-drying ratio ($R_{WD}$) was 1.0, the pollutant removal rate increased by $(13.6 \pm 0.3)$% for NH$_3$-N, $(20.7 \pm 1.1)$% for TN, $(18.6 \pm 0.4)$% for TP, $(12.2 \pm 0.5)$% for BOD, $(10.1 \pm 0.3)$% for COD, and $(36.2 \pm 1.2)$% for SS, compared with pollutant removal rates under the continuous operation mode. The pollutant removal rate declined with the increase of the HLR. The effluent quality met The Reuse of Urban Recycling Water – Water Quality Standard for Scenic Environment Use (GB/T 18921-2002) even when the HLR was as high as 10 cm/d. Hydraulic conductivity, oxidation reduction potential (ORP), the quantity of nitrifying bacteria, and the pollutant removal rate of NH$_3$-N increased with the decrease of the $R_{WD}$. For the pollutant removal rates of TP, BOD, and COD, there were no significant difference ($p < 0.05$) under different $R_{WD}$. The suggested $R_{WD}$ was 1.0. Relative contribution of the pretreatment and SWIS to the pollutant removal was examined, and more than 80% removal of NH$_3$-N, TN, TP, COD, and BOD occurred in the SWIS.

Keywords: Domestic sewage; Subsurface wastewater infiltration system; Intermittent operation mode; Hydraulic loading rate; Pollutant removal rate

1. Introduction

In rural areas of Northeast China, conventional centralized sewer systems have become impractical due to the topography and long distances between the connected facilities (Petter et al., 2010; Qian et al., 2007). Water shortage in these areas has created a need for both higher quality and a greater quantity of reclaimed water. Conventional systems, such as activated sludge, biological contactors, and chemical precipitation, are alternatives, but previous studies have shown that it is difficult for them to meet the discharge standard for phosphorus concentration (Arve et al., 2006; Fan et al., 2009). Therefore, there is an urgent need for simple maintainable on-site systems with excellent treatment performance.

A subsurface wastewater infiltration system (SWIS) with pretreatment (e.g., septic tank, biological contractor, and biological filtration) has been pioneered in Northeast China (Li et al., 2011; Qian et al., 2007). Over the past 20 years, the SWIS has gained popularity as an effective and low-cost alternative for wastewater treatment, especially in villages and small communities. The SWIS has shown excellent performance in organics, nitrogen, and phosphorus removal (Kadam et al., 2009). Table 1 summarizes the treatment efficiency of SWISs. Up to now, the main research on SWISs has focused on system design, treatment performance, and pollutant removal mechanisms (Pan et al., 2012; Zhang et al., 2011).
Table 1 Treatment efficiency of SWISs.

<table>
<thead>
<tr>
<th>HLR (m/d)</th>
<th>Wastewater type</th>
<th>Country</th>
<th>Removal efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Municipal sewage</td>
<td>United States</td>
<td>BOD 80.5, COD 74.5, TN 84.1, SS 72.0, TP 82.8</td>
<td>Howarth et al., 2002.</td>
</tr>
<tr>
<td>0.088</td>
<td>Germany</td>
<td>83.6, 79.8, 80.7, 85.5</td>
<td>Qian et al., 2007.</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>China</td>
<td>84.6, 77.7, 97.9</td>
<td>Robertson, 2010.</td>
<td></td>
</tr>
<tr>
<td>0.067</td>
<td>Australia</td>
<td>84.7, 86.0, 59.4, 77.0, 83.8</td>
<td>Stewart and Louis, 2010.</td>
<td></td>
</tr>
<tr>
<td>0.015</td>
<td>Japan</td>
<td>82.9, 78.2, 69.8, 82.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Previous studies have suggested that, although the SWIS is a treatment system with simple mechanisms, the treatment process of pollutant removal is intricate (Zhang et al., 2011). The hydrology, microbiology, and water chemistry are complex and interconnected. Studies have presented relatively high removal efficiency for chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), and pathogens (Stewart and Louis, 2010). However, nutrient removal efficiency is low and variable. Moreover, the nutrient removal decreases with the increase of service age of a SWIS (Robertson, 2010). In addition, compared to the conventional treatment plants, SWISs occupy relatively large areas resulting from the low hydraulic capacity. The cost of SWISs is high due to the size requirement. If the hydraulic loading rate (HLR) could be higher, SWISs could be built smaller, and the initial cost would be lower, which would greatly enhance the market potential and application prospects of SWISs. Therefore, the aims of this study were: (1) to examine the contribution of the intermittent operation mode to the HLR encouragement in the SWIS; (2) to assess the pollutant removal contribution of both the SWIS and pretreatment; and (3) to evaluate the impact of the SWIS effluent on receiving-water quality under a high HLR.

2. Materials and methods

2.1. System description

The wastewater was pretreated in a septic unit with a hydraulic detention time of 4 h. The effluent flowed under the action of gravity through the distribution tank to four infiltration tanks. The dimension of each infiltration tank is 20 m long, 15 m wide and 1.5 m deep. Inflowing pipes were 0.5 m underneath (100 mm in diameter with holes of 4 mm in diameter placed in the bottom side every 60 mm). Collecting pipes were 1.5 m underneath (80 mm in diameter with holes of 6 mm in diameter placed in the bottom side every 60 mm). The beds were planted with herbage (Poa annua) and ryegrass, which was mainly for landscape planting. A1, B1, C1, D1, E1, A2, B2, C2, D2, and E2 (0.4 m intervals) were sampling positions for substrate samples and bacteria numbering, as shown in Fig. 1. The substrate samples were taken twice a month from 0.2, 0.4, 0.6, 0.8, and 1.0 m depths at each sampling position, respectively.

2.2. Wastewater characteristics

Field experiments were carried out in Shenyang City, China. The influent to the pretreatment unit was combined wastewater, from toilets, restaurants, etc. The ranges of major water quality indices were 7.2–7.4 for the pH value, 275–360 mg/L for COD, 155–220 mg/L for BOD, 95–126 mg/L for SS, 30–45 mg/L for total nitrogen (TN), 3–4 mg/L for total phosphorus (TP), 20–30 mg/L for ammonia nitrogen (NH3-N), and 0.2–0.3 mg/L for nitrate nitrogen (NO3-N).

2.3. Substrate characteristics

The packed substrate in the SWIS was a kind of novel bio-substrate, which was composed of 5% activated sludge, 65% meadow brown soil, and 30% coal slag mixed evenly in volume ratios. The activated sludge was obtained from the aeration tanks in the Shenyang Northern Municipal Sewage Treatment Plant, China, and air-dried after being centrifuged for 15 min at 1 500 r/min. The meadow brown soil was sampled from the top 20 cm of soil at the Shenyang Ecological Station. Other materials (gravel and coal slag) were purchased from a local market (particle size: 10–25 mm of gravel and 4–8 mm of coal slag). The infiltration rate, porosity, and surface area of the substrate were 0.37 m3/(m2·d), 59%, and 5.21 m2/g, respectively. A previous study (Li et al., 2013) indicated that, in comparison with meadow brown soil, the bio-substrate provided a more favorable micro-environment for the pollutant removal. The maximum adsorbing capacity for NH3-N was 0.724 mg/g, which was 0.253 mg/g higher than that of meadow brown soil.

2.4. Analysis method

The ammonifying, nitrifying, and denitrifying bacteria in the substrate samples were counted using the most probable number (MPN) method twice per month (Nie et al., 2011). The medium components are shown in Table 2. Aliquots (1 mL) were diluted with 12-fold sterile distilled water and transferred
denitrifying bacteria. Meanwhile, 10 g of the substrate samples were oven-dried at 105 °C for 12 h to produce a constant weight.

During the study period, paired samples of raw sewage and effluent were collected every three days, stored at 4 °C, and analyzed within 24 h. The COD, BOD, SS, NO3-N, NH3-N, TN, and TP concentrations of the water samples were analyzed according to the American Public Health Association (APHA, 2003) guidelines. The potassium dichromate method was used for COD determination, and the colorimetric method was used for NO3-N and NH3-N measurements. Hydraulic conductivity was measured according to the method suggested by Lowe and Siegrist (2008). Oxidation reduction potential (ORP) was analyzed through pre-buried sensors, and the readings were recorded every three days. All statistical analyses were carried out using the computer software package Origin 7.5. With respect to surface water quality from different sampling points, a parametric analysis of variance was used to determine the significant difference (p).

2.5. Sampling and experimental operation

The whole system was operated from June 2009. Sampling for this study was conducted from April to September 2013. The water quality of the stream adjacent to the SWIS was monitored every three days to assess the impact of the SWIS effluent on receiving-water and verify that the SWIS was not polluting the receiving-water under a high HLR. The stream was located next to the SWIS, as shown in Fig. 2. The stream water was sampled at four locations, one upstream of the discharge point and the other three approximately 100, 300, and 500 m downstream of the discharge point; these locations are labeled a, b, c, and d, respectively. Mean concentrations of BOD, SS, NH3-N, TN, TP, and COD in the upstream water during the experimental period were 3.3, 10.4, 0.5, 10, 0.3, and 38.2 mg/L, respectively. During the experimental period, the intermittent operation mode was adopted as a method of encouraging the HLR. Each cycle of the intermittent operation included a continuous flow period of 24 h (between 9:00 AM and 9:00 AM the next day) and a drying period of 0, 24, 48, 72, and 96 h, indicating a wetting-drying ratio (RWD) of ∞ (termed a continuous operation mode), 1.0, 0.5, 0.33, and 0.25, respectively. All experiments were repeated three times.

As for the HLR values, there is no exact information indicating what extent of the HLR is high. According to Sun and Li (2006), a value of the HLR lower than 8 cm/d is suggested for long lifespan of the SWIS. In this research, the intermittent operation mode was adopted to improve the HLR. Therefore, the HLR was gradually increased from 4 cm/d to 6 cm/d, 8 cm/d, 10 cm/d, and 12 cm/d.

3. Results and discussion

3.1. Effects of intermittent operation mode and HLR on treatment efficiency of SWIS

Table 3 shows pollutant concentrations and removal rates at the discharge point under continuous and intermittent operation modes. The HLR was 8 cm/d for both operation modes. When the RWD was 0.25, the intermittent operation mode improved pollutant removal rates by (23.3 ± 0.2)% for NH3-N, (10.7 ± 0.3)% for TN, (19.5 ± 1.1)% for TP, (12.7 ± 0.3)% for BOD, (11.4 ± 0.5)% for COD, and (37.8 ± 2.5)% for SS, compared with pollutant removal rates under the continuous operation mode. As a general rule, the pollutant removal efficiency declines with the increase of the HLR. Experiments showed that when the average HLR increased to 12 cm/d, the packed substrate in the SWIS clogged due to the excessive inflow of sewage and the permeability decreased quickly to a small value. The significant elevation of NH3-N concentration in effluent in this condition was attributed to deterioration of nitrification caused by substrate clogging. Under the intermittent operation mode, the NH3-N removal rate rose from (86.2 ± 1.5)% at a RWD of 1.0 to (95.9 ± 0.4)% at a RWD of 0.25, indicating that the oxidative condition of the substrate was improved through the drying period of the alteration operation, which was favorable for the nitrification process. In contrast, the TN removal rate decreased with the RWD decline. Furthermore, Table 4 shows that hydraulic conductivity, ORP, and the number of nitrifying bacteria increased with the RWD decline. On the other hand, the changes in water content and

<table>
<thead>
<tr>
<th>Table 2: Medium components list for three kinds of bacteria.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td><strong>Ammonifying bacteria</strong></td>
</tr>
<tr>
<td><strong>Nitrifying bacteria</strong></td>
</tr>
<tr>
<td><strong>Denitrifying bacteria</strong></td>
</tr>
</tbody>
</table>

Fig. 2. Sketch of SWIS and monitoring sites in stream.
the number of denitrifying bacteria showed an opposite trend. According to Li et al. (2013), there was no significant difference in the ammonifying bacteria number with the changing in RWD.

According to previous studies (Candela et al., 2007; Kadam et al., 2009), the biological material attaches to the substrate surface as the influent passes through the SWIS. As the operation time goes on, the packed substrate tends to be choked by the microbial metabolites, which shorten the lifespan of the system. Thus, periodic resting is an effective method for removing the microbial metabolites and restoring the hydraulic capacity. The substrate surfaces are rested by removing them from service for an extended period of time (Moreno Escobar et al., 2005). Second, the main reason for the low hydraulic conductivity in conventional systems is that, during the pollutant removal process, especially the nitrogen removal process, the produced gases, such as N2, CO2, and N2O, congest in and clog the packed substrate pores, thus reducing the hydraulic capacity. It is generally accepted (Nie et al., 2011; Wang et al., 2009) that the feasible hydraulic conductivity between 8.0 × 10⁻⁶ and 7.2 × 10⁻⁵ cm/s is essential in order for the SWIS to run smoothly and efficiently. Therefore, another function of the intermittent operation mode is to encourage the gases to escape from the system. According to the experimental results of pollutant removal (Table 3) and hydraulic conductivity (Table 4), the intermittent operation mode with a RWD of 1.0 was suggested, and the HLR was chosen to be 10 cm/d.

### 3.2. Relative contribution to pollutant removal in pretreatment and SWIS

Fig. 3 shows the overall pollutant removal efficiencies in the pretreatment and SWIS when the RWD is 1.0 and the HLR is 10 cm/d. The results show that the hydrolytic acidification cell was relatively more efficient in the removal of SS than the removal of other pollutants. The average SS removal rate was (60.2 ± 0.3)% in the pretreatment, but NH3-N, TN, and TP concentrations changed little during this procedure.

The overall removal rates of NH3-N and COD are 87.3% and 92.1%, respectively. More than 80% of the removal occurred in the SWIS, even though the HLR was 16.8%–50% higher than that described in previous reports (Nie et al., 2011; Wang et al., 2009). Such a high rate of removal was attributed to the intermittent operation mode and the packed substrate in the SWIS. Periodic resting is conducive to the relatively high oxygen availability in the packed substrate surface and the NH3-N removal. The bio-substrate around the inflowing pipes was favorable to the growth of microorganisms, as well as ammonia adsorption (Li et al., 2013). After the sewage flowed in, the substrate first absorbed refractory organic matter, and then adsorbed organic matter was gradually converted into

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**Table 3**
Effect of continuous and intermittent operation modes on pollutant removal.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Continuous operation mode</th>
<th>Intermittent operation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RWD of 1.0</td>
<td>RWD of 0.5</td>
</tr>
<tr>
<td>NH3-N</td>
<td>17.0 ± 0.2</td>
<td>4.6 ± 0.3</td>
</tr>
<tr>
<td>TN</td>
<td>14.5 ± 1.2</td>
<td>8.2 ± 0.5</td>
</tr>
<tr>
<td>TP</td>
<td>1.1 ± 0.2</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>BOD</td>
<td>12.3 ± 0.4</td>
<td>8.0 ± 0.4</td>
</tr>
<tr>
<td>COD</td>
<td>55.8 ± 0.4</td>
<td>25.5 ± 0.2</td>
</tr>
<tr>
<td>SS</td>
<td>7.6 ± 0.2</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

**Table 4**
Effect of RWD on substrate characteristics.

<table>
<thead>
<tr>
<th>RWD</th>
<th>Hydraulic conductivity (cm/s)</th>
<th>Water content (%)</th>
<th>ORP (mV)</th>
<th>Nitrifying bacteria number (MPN/g)</th>
<th>Denitrifying bacteria number (MPN/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>(7.0 ± 0.5) × 10⁻⁵</td>
<td>35 ± 1.7</td>
<td>160 ± 3.8</td>
<td>(1.5 ± 0.7) × 10⁷</td>
<td>(7.8 ± 0.5) × 10¹¹</td>
</tr>
<tr>
<td>0.5</td>
<td>(9.8 ± 1.0) × 10⁻⁵</td>
<td>30 ± 2.0</td>
<td>190 ± 7.7</td>
<td>(7.5 ± 0.1) × 10⁷</td>
<td>(2.4 ± 0.8) × 10¹¹</td>
</tr>
<tr>
<td>0.33</td>
<td>(2.0 ± 0.6) × 10⁻⁴</td>
<td>24 ± 2.7</td>
<td>220 ± 10.3</td>
<td>(2.1 ± 0.8) × 10⁸</td>
<td>(4.5 ± 0.4) × 10¹⁰</td>
</tr>
<tr>
<td>0.25</td>
<td>(6.1 ± 0.7) × 10⁻⁴</td>
<td>18 ± 1.8</td>
<td>255 ± 9.0</td>
<td>(8.2 ± 0.9) × 10⁶</td>
<td>(1.2 ± 0.6) × 10¹⁰</td>
</tr>
<tr>
<td>∞</td>
<td>(8.9 ± 0.4) × 10⁻⁶</td>
<td>43 ± 1.0</td>
<td>110 ± 5.4</td>
<td>(2.2 ± 0.4) × 10⁶</td>
<td>(8.9 ± 0.2) × 10¹⁴</td>
</tr>
</tbody>
</table>
low-molecular weight matter by microorganisms, which were easily utilized by the denitrifier and other heterotrophs. Therefore, the removal rate of COD always gradually decreased because of adsorption saturation (Pavelic et al., 2011; Toze, 2006). In this experiment, under the intermittent operation mode, the mean removal rate for COD was (92.4 ± 1.2)%, 16.8%–21.8% higher than in the continuous operation mode, as reported in other studies (Petter et al., 2010; Zhang et al., 2007). The SS removal process in the SWIS is based on sedimentation, adsorption, and biological processes. Previous studies have revealed that the permanent removal of SS usually occurs in the subsurface with the effect of aluminum/iron compounds (Olaboja and Ademoroti, 2006; Yang et al., 2007; Ye et al., 2008). Furthermore, studies have shown that the SS reduction capacity decreases with time because the mineral sediments become fully saturated within the infiltration system (Hand et al., 2008; Morkved et al., 2007; Zhang et al., 2005). High influent SS concentration becomes the main reason for the SWIS clogging. Therefore, one encouraging method was to prolong the hydraulic detention time in pretreatment to remove more SS. Influent SS concentration less than 20 mg/L was suggested, as it can ensure a long lifespan of the SWIS (Sun and Li, 2006).

3.3. Receiving-water quality

The stream, which is adjacent to the SWIS, was monitored for over seven months. The average values of variables are shown in Table 5.

At the discharge point, mean concentrations of water quality indices in the effluent were 8.2 mg/L for BOD, 25.3 mg/L for COD, 1.2 mg/L for SS, 4.8 mg/L for NH₃-N, and 0.9 mg/L for TP. According to Table 5, although the pollutant concentrations of point b were slightly higher than that of point a, the differences were not statistically significant (p < 0.05). Likewise, no significant differences were found between the pollutant concentrations in point a, point c, and point d. These results indicate that the stream has sufficient assimilative capacity, and that the SWIS effluent had little negative influence on the water quality of the stream even though the HLR was as high as 10 cm/d.

4. Conclusions

This study demonstrated the performance of a full-scale SWIS in treating domestic sewage. The contribution of the intermittent operation mode to the鼓励 for the HLR was examined. Relative contribution of the pretreatment and SWIS to the pollutant removal were examined. Finally, the impact of SWIS effluent on the receiving-water quality was assessed.

The results indicate that intermittent operation of the SWIS significantly encouraged the pollutant removal. When the R_{WD} was 1.0, the intermittent operation mode improved pollutant removal rates by (13.6 ± 0.3)% for NH₃-N, (20.7 ± 1.1)% for TN, (18.6 ± 0.4)% for TP, (12.2 ± 0.5)% for BOD, (10.1 ± 0.3)% for COD, and (36.2 ± 1.2)% for SS, compared with pollutant removal rates under the continuous operation mode. The pollutant removal efficiency declined with the increase of the HLR. With the drying days prolonged, hydraulic conductivity, ORP, the number of nitrifying bacteria, and the NH₃-N removal rate increased, while water content, the number of denitrifying bacteria, and the TN removal rate decreased. There was no significant difference (p < 0.05) between TP, BOD, and COD removal rates under different R_{WD}s. The intermittent operation mode with a R_{WD} of 1.0 was tested. Under this condition, the HLR increased to 10 cm/d. More than 80% of the removal occurred in the SWIS for NH₃-N, TN, TP, COD, and BOD. The main function of the pretreatment was to remove more SS to minimize the clogging risk of the SWIS. The analysis of receiving-water quality indicated that the SWIS had little negative influence on the nearby stream.

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References


