Effects of earthworms on surface clogging characteristics of intermittent sand filters

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ABSTRACT

Intermittent sand filters (ISFs) are effective and economical in treating wastewater, but they are easy to clog up. To explore a feasible and simple method to alleviate clogging, two pilot-scale ISFs were constructed, one of which contained earthworms and the other did not. During the operation, the effects of earthworms on the hydraulic behaviour of ISFs were investigated. The results showed that both ISFs exhibited good performance in wastewater treatment. However, they showed different hydraulic characteristics although operated at the same organic loading rate (approximately 300 $g\,m^{-2}\,d^{-1}$). The ISF without earthworms clogged only after 53 d operation, and was partially recovered after 7 d resting, but after that, clogging occurred again, and more rapidly than the initial clogging event (40 d). However, water on the medium surface of the ISF with earthworms was not observed during the whole experiments. In addition, 11–13% of effective porosity and 0.015–0.026 $cm\,s^{-1}$ of infiltration rate were measured in the upper 20 cm of the ISF at the end of the experiments. The facts demonstrated that earthworms played a positive role in alleviating clogging and earthworms fed filter could alleviate surface clogging effectively.

Key words | clogging, earthworm, hydraulics, intermittent sand filters

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INTRODUCTION

Intermittent sand filters (ISFs) have been proven to be a cost-effective option with promising organic matter and nitrogen removal performances (Furman *et al.* 1955; Darby *et al.* 1996; Rodgers *et al.* 2004), and have been used widely to treat domestic and industrial wastewaters (Netter 1992; Healy *et al.* 2004). However, clogging, which is the biggest operational problem for the filters, is often observed (Darby *et al.* 1996; Rodgers *et al.* 2004; Ruppe 2005; Leverenz *et al.*

doi: 10.2166/wst.2010.180

2009), and can diminish hydraulic conductivity and reduce both infiltration velocity and oxygen supply, thereby threatening the sustainability of the ISFs.

Clogging is a complex process defined as the processes of reducing porosity and permeability and the accurate mechanisms for clogging have not been completely clarified yet. Baveye *et al.* (1998) summarised the methods for clogging study, and considered that the clogging of porous media was intrinsically a physical phenomenon, formed by three classes: physical, chemical, and biological (microbial). Blazejewski & Murat-Blazejewska (1997) also concluded that the main causes for clogging were the accumulation of wastewater solids, the growth of the biofilm and the deposition of chemical precipitates. Moreover, researchers found that inorganic particulates, organic matter and biofilm growth were mainly accumulated on the upper layer, and described clogging as primarily a surface phenomenon (Rodgers *et al.* 2004; Leverenz *et al.* 2009). Thus, for over a century, removal of surface sand from a clogged filter has been the recommended method for renovation of an ISF. However, this method is difficult for maintenance of the ISF (Leverenz *et al.* 2009).

In early studies, pretreatment and reducing loading rates were found to be able to improve ISF performance and prolong its service life (Furman *et al.* 1955). However, the land area of the treatment systems and the construction cost were increased when using this method, which restricted the method in applications. To balance the loading rates and the clogging problem, many researches were conducted in the past years. It was reported that planting reeds and other macrophytes on top of the retention soil of the filters could mitigate clogging successfully (Brix 1997; Molle *et al.* 2006). Zhao *et al.* (2004) conducted a so-called "anti-sized" system and demonstrated a clear advantage in slowing down the clogging of bed media. Boncolè *et al.* (2003) showed that a low dose per day could make the biofilm develop evenly along the filter bed, while a high dose would result in biofilm accumulation in the upper layers of the filter, which suggested that a lower dosing frequency could delay surface clogging. Similar results were obtained by Ruppe (2005), Molle *et al.* (2006) and Leverenz *et al.* (2009). Furthermore, insights about clogging were investigated with a series of laboratory experiments (Rodgers *et al.* 2004; Siriwardene *et al.* 2007; Pedescoll *et al.* 2009; Soleimani *et al.* 2009; Zhao *et al.* 2009). Although so many investigations about clogging have been conducted, the problem of clogging has not been thoroughly solved and the possibility for filter block still existed.

Earthworms can accumulate large amounts of organic pollutants from the soil environment by passive absorption through the body wall and intestinal uptake during the passage of soil through the gut, and have been successfully applied in solid wastes treatment and contaminated soil remediation (Contreras-Ramos *et al.* 2009; Suthar 2009). Furthermore, earthworm-created macropores may have a significant impact on soil renovation of wastewater (Hawkins *et al.* 2008). Researches showed that infiltration rates on the surface of soils with earthworms could be 4–10 times greater than those without earthworms (Hawkins *et al.* 2008), and the environmental conditions in the filters were suitable for earthworms to live (Taylor *et al.* 2003). Therefore, it is interesting to assess if earthworms could be applied in ISFs to alleviate clogging. Thus the purpose of this paper was to study the effects of earthworms on the hydraulic characteristics of ISFs, and to estimate the applicability of earthworms in delaying surface clogging of filters.

MATERIALS AND METHODS

Engineering situation

The domestic sewage collected in a freeway toll-gate located in Hunan province, China, was used in this study, and the influent characteristics were as follows: chemical oxygen demand (COD) 142–235 mg L^{-1}, suspended solids (SS) 107–173 mg L^{-1}, ammonia (NH_4^+-N) 18.31–29.26 mg L^{-1}, and phosphorus (P) 2.71–4.05 mg L^{-1}.

Characterisation of the ISFs

The investigations were carried out at two pilot ISFs (called ISF-1 and ISF-2) with a surface area of 0.25 m^2 each. The filters consisted of three layers consisting of peat (40 cm thickness), sand (40 cm thickness, grain size 0–2 mm), and gravel (20 cm thickness, grain size 5–30 mm) from the top down. Four reeds (*Phragmites australis*) were planted in each filter, and a certain number of earthworms (*Eisenia foetida*) were immediately put into the peat layer of ISF2 (about 250 earthworms). Both ISFs were intermittently fed (2 h of dosing and 6 h of resting), and each one received 0.375 m^3 of mechanically settled freeway toll-gate domestic sewage three times per day (hydraulic loading rate (HLR) of 1.5 $m\,d^{-1}$), which resulted in an average organic loading rate (OLR) of approximately 300 $g\,m^{-2}\,d^{-1}$.

Sampling and analytical methods

Chemical analysis

Effluent samples from the ISFs were taken weekly for analysis of COD, SS, NH_4^+-N, NO_2^--N, NO_3^--N and Pi, according to the Chinese National Standard Methods (SEPA of China 2002). NO_X^--N was calculated as the sum of measured NO_2^--N and NO_3^--N.

Effective porosity measurements

Under the saturated condition of the sand filter, the drainage volumes of the whole filters were measured every 10 d and the effective porosity of the total filter was calculated by the following equation:

$$N_e = V_e/V_T$$

where, N_e effective porosity of total filter, V_e the volume of water that can be contained in media, V_T the volume of media. At the end of the experiments, the effective porosity of each layer was also measured.

Infiltration rate measurements

The infiltration rate was measured every 10 d and was based on the constant water head method of Standard for Soil Test Method (GB/T50123-1999). The tube was connected to a bottom sampling port and water would always overflow from the overflow hole to keep the water level constant. When the water level of the tube reached stability, the difference of water level between the tube and experimental column (Δh) could be measured. With a graduated flask and a stopwatch, the infiltrated water volume over a period could be also measured (Zhao *et al.* 2009). The value of infiltration rate K_T (cm/s) could be calculated through the following modified Darcy's equation.

$$K_T = (V \times L)/(t \times \Delta h \times A)$$

where, V (cm^3) infiltrated water volume, t (s) infiltrated time, L (cm) the length of the sand filter (100 cm in this study), Δh (cm) the difference of water level, A surface area of the filter (2,500 cm^2 in this study). In addition, the infiltration rate of each layer was also measured at the end of the experiments.

RESULTS

Summary of performances of the two measured ISFs

Performances of the two measured ISFs during 100 d operation period were summarised in Table 1. During monitoring, both ISFs showed good performances of pollutant removal. Thirty-two milligrams per litre of COD, 17 $mg\,L^{-1}$ of SS and 36 $mg\,L^{-1}$ of COD, 15 $mg\,L^{-1}$ of SS were respectively measured in effluent of ISF-1 and ISF-2, which indicated that the average removal efficiencies for COD and SS were 89.2% and 90.2% in ISF-1, respectively, while those in ISF-2 were 87.9% and 91.3%. In addition, both ISFs were effective at removing NH_4^+-N (83.6% of average removal rate in ISF-1 and 88.7% of average removal rate in ISF-2), with NH_4^+-N concentration in both effluent $\leq$ 4.18 $mg\,L^{-1}$. However, retention of Pi was low, only 46.4% and 58.1% of Pi were respectively removed in ISF-1 and ISF-2, and similar results were observed in sand filters by other researchers (Hylander *et al.* 2006; Torrens *et al.* 2009).

Table 1 | Summary of performances (average concentrations in effluent) of the ISFs during 100 d operation period

Item	ISF-1 Effluent ($mg\,L^{-1}$)	Removal ($mg\,L^{-1}$)	%	ISF-2 Effluent ($mg\,L^{-1}$)	Removal ($mg\,L^{-1}$)	%
COD	32	265	89.2	36	261	87.9
SS	17	156	90.2	15	158	91.3
NH_4^+-N	4.18	21.32	83.6	2.89	22.61	88.7
NO_2^--N	0.41			0.56		
NO_3^--N	4.73			6.35		
P	1.93	1.67	46.4	1.51	2.09	58.1

Hydraulic characteristics during the operation period

Although both filters performed efficiently during the operation period, evident differences of hydraulic parameters were measured. Figure 1 showed the changes of infiltration rate and effective porosity of ISF-1 during the operation period. It could be found that the effective porosity decreased quickly in ISF-1, and rapid decrease of infiltration rate was also observed. Zhao *et al.* (2009) defined critical infiltration rate K_T of around 1.61×10^{-3} cm s^{-1} to quantify the occurrence of clogging, and Rodgers *et al.* (2004) defined this value as $3.5 \times 10^{-3} \pm 7.5 \times 10^{-4}$ cm s^{-1}. On 30 Mar. 2008, the measured infiltration rate was just 1.1×10^{-3} cm s^{-1}, which indicated that clogging occurred. Simultaneously, serious ponding in the surface of substratum also confirmed the occurrence of clogging. To recover the filtration capacity, 7 d of resting period was operated. However, the filter porosity was only partially recovered after the 7 d resting and failure of ISF-1 occurred more rapidly than the initial clogging event. This appeared to confirm the work of Leverenz *et al.* (2009), who suggested that once filter clogging had occurred, resting would not allow the filter bed to recover fully to the initial conditions, even when operated under reduced loading conditions. The facts showed that the ISF-1 respectively clogged at a rate of 1.5 m d^{-1} after 53 and 40 d in operation for the first and second time, even when operated under the operational strategy recommended by other researchers (for example, plant reeds on top of the substratum and control a low dosing frequency).

As expected, ISF-2 showed much better hydraulic characteristics than ISF-1 although the same HLR and OLR were conducted (Figure 2). 13–18% of effective porosity and 0.011–0.025 cm s^{-1} of infiltration rate could be respectively maintained during the final two months though obvious decreases of those characteristics were also observed. In addition, water on the medium surface was not observed during the whole experiments. All the above facts strongly demonstrated that the surface clogging did not occur and earthworms could play a positive role in alleviating clogging.

Hydraulic characteristics of each layer at the end of experiments

Since the pollutants in wastewater were mostly eliminated in the upper layer of ISFs (Rodgers *et al.* 2004; Zhao *et al.* 2004), it is necessary to investigate the variations of pore

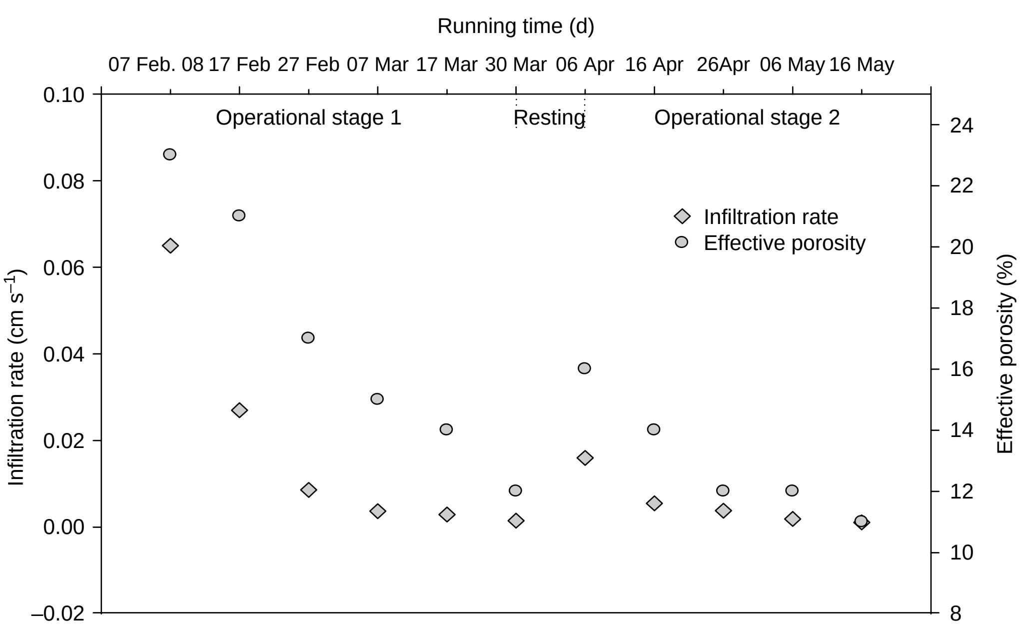

Figure 1 | Variations of infiltration rate and effective porosity of ISF-1 during 100 d operation period, experiments were started on 07 Feb 2008.

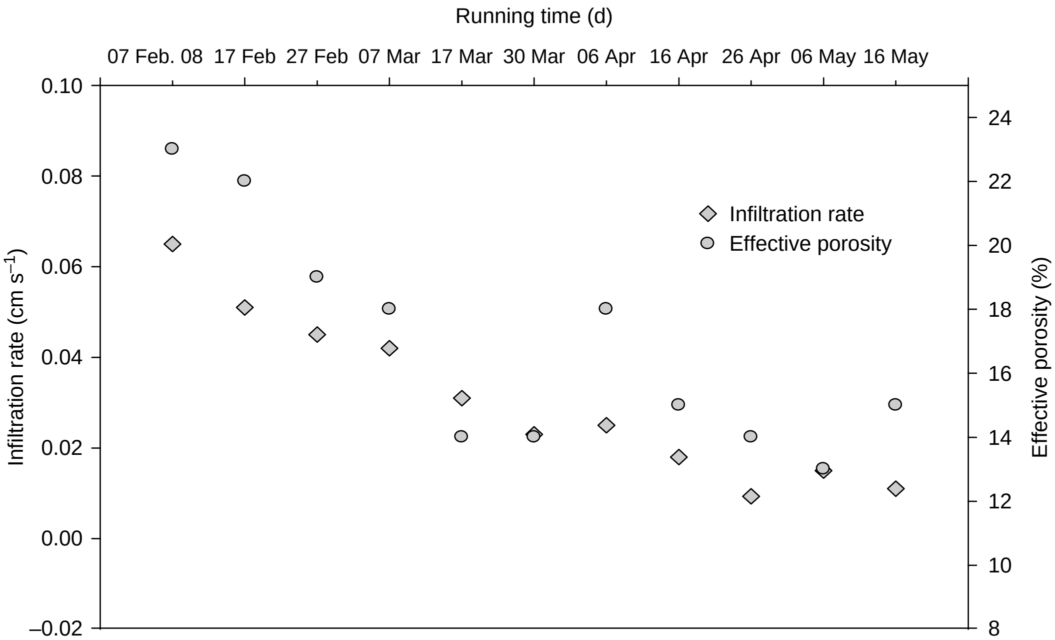

Figure 2 | Variations of infiltration rate and effective porosity of ISF-2 during 100 d operation period, experiments were started on 07 Feb 2008.

spaces and infiltration rate at different depth of the filters to deeply understand the effect of earthworms on the clogging characteristics.

Figure 3 showed the pore spaces at different depth of ISFs at the end of the experiment. It could be found that the main difference of pore spaces between the two ISFs was detected in the upper 20 cm layer where 2–5% of effective porosity was measured in ISF-1, further illuminating that clogging was a surface phenomenon. The main cause for pore space congestion was attributed to the removal of SS

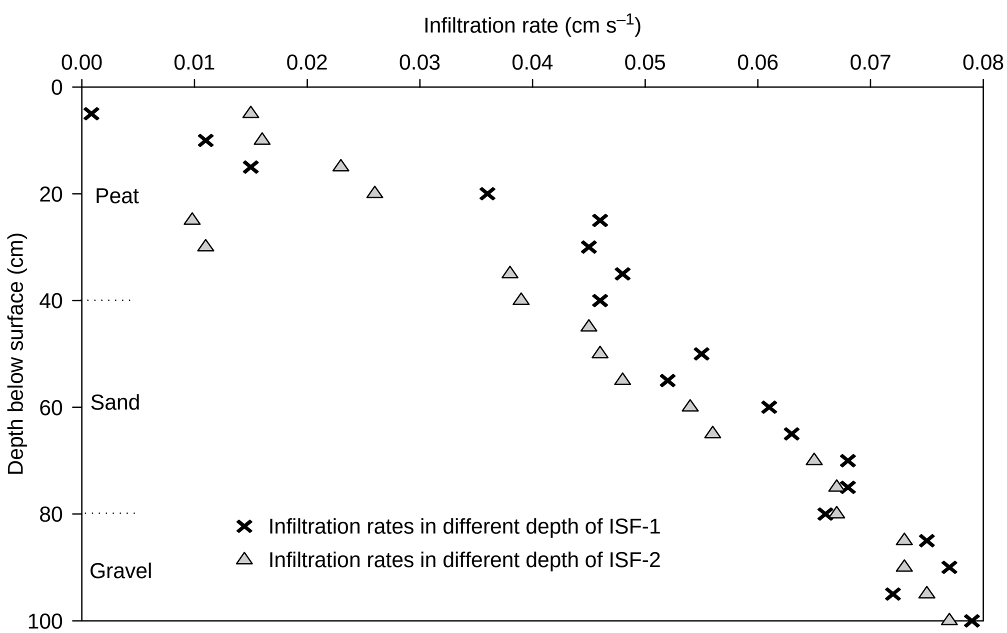

Figure 3 | Variations of pore spaces of ISFs at the end of the experiment.

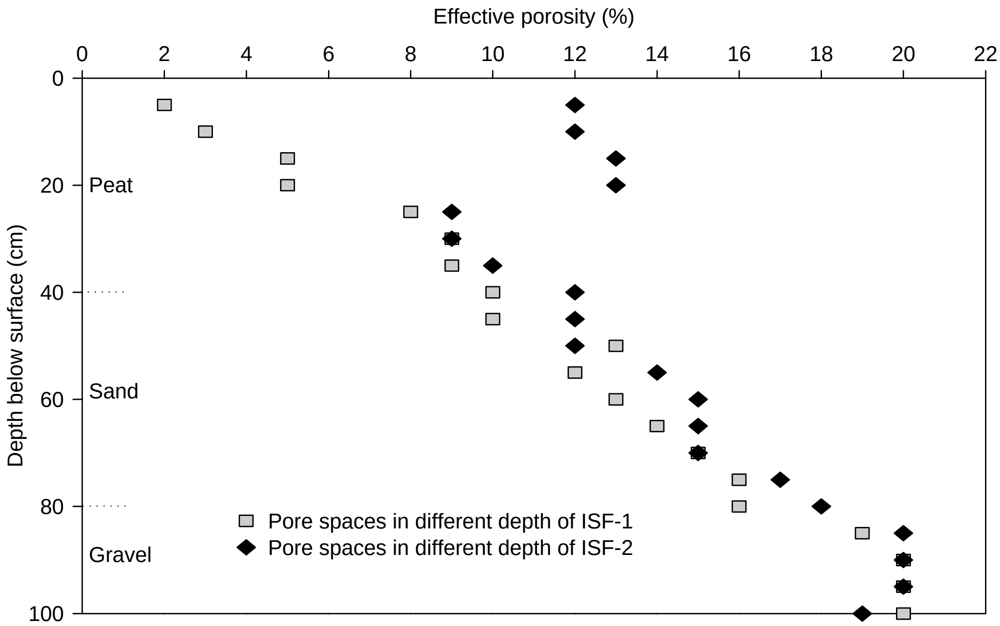

Figure 4 | Variations of infiltration rates of ISFs at the end of the experiment.

from the wastewater, i.e. the filtration and sedimentation of SS inside the bed matrix, because organic matter can be decomposed by microorganisms and biomass may decay endogenously during the resting period. However, the filtration and sedimentation of SS inside the bed matrix could not be disassembled during the resting period, which well explained that clogging still existed in ISFs even when operated under optimal operational strategy. As we expected, 11–13% of effective porosity was measured in the upper 20 cm of ISF-2, which assured 0.015–0.026 cm s^{-1} of infiltration rate at that layer (Figure 4). The facts proved that earthworms could ameliorate the effective porosity of the upper layer, thus improving the infiltration rate. Surprisingly, a low infiltration rate (0.01 cm s^{-1}) was measured in the 2,030 cm layer of ISF-2, probably due to the low activity of earthworms in this layer.

DISCUSSION

Clogging is a surface phenomenon and is usually attributed to permeability reduction and microbial cell mass and exopolymers production. The permeability reduction results from surface or interstitial accumulation of inorganic particulate matter present in influent or pore narrowing. Thus clogging is mainly considered to be the result of excess accumulation of inorganic particulate matter and growth of microbial cells. As summarised, ISFs operated at low dosing frequencies have been shown to be able to operate for long periods without maintenance. Low dosing frequency increases the endogenous decay phase. From a practical standpoint, biofilm decay is the justification for the common practice of removing a filter from operation when experiencing clogging. The resting period allows endogenous decay and desiccation to partially recover the filter's porosity (Leverenz *et al.* 2009). Moreover, reeds mediate the transfer of oxygen to the rhizosphere by leakage from roots and increase aerobic degradation of organic matter, thus alleviating filter clogging (Brix 1997). However, the above approaches just mitigate clogging caused by excess growth of microbial cells. When SS accumulates in pore spaces of media to a certain extent, clogging still occurs, such as ISF-1 operated in this study. Because the SS sunk inside pore spaces can not be disassembled aerobically, Winter & Goetz (2003) suggested that SS loading rate should not exceed 5 g m^{-2} d^{-1} to completely avoid clogging.

In this study, feeding earthworms to filters has been proved to be an attractive approach to alleviate clogging, and the mechanism was probably based on their burrowing and feeding habits. Earthworms are a heterotrophic species;

they do not consume mineral soil, but organic matter. However, they can excavate galleries, which increase the porosity and the permeability of the medium. Furthermore, earthworms are usually found in the upper 10–15 cm of soil (Hawkins *et al.* 2008); this habit can enhance earthworms' population in the upper layer of the filters, thus improving the infiltration rate of the upper medium. On the other hand, when the surface clogging of the filters is to come, both infiltration velocity and oxygen supply will reduce, earthworms will be forced to burrow desperately to ensure enough oxygen transfer, avoiding death due to lack of oxygen. Accordingly, the surface clogging of filters is alleviated.

From our observations, we demonstrated that earthworms played a positive role in alleviating clogging. However, the results obtained in the experiment are of an indicative nature because of the size of the sand filters used, the short time of experimentation and the lack of replication, Further researches (with bigger systems, longer study periods and under replicated conditions) are needed to assess the true potential of worms on reducing the clogging in sand filters and to make a clear estimate of the life span of the earthworms fed system, and work is under way.

CONCLUSIONS

This study investigated the effects of earthworms on hydraulics characteristics of ISFs and the applicability of earthworms in delaying surface clogging of ISFs. Both ISFs showed good performances of pollutants removal, but ISF-2 showed better hydraulic characteristics than ISF-1 although the same HLR and OLR were conducted, suggesting that earthworms play a positive role in alleviating clogging. The results indicated that feeding earthworms to filters might be an attractive and effective treatment solution for alleviating the surface clogging which has been considered as the biggest operational problem for ISFs so far.

ACKNOWLEDGEMENTS

This research was financially supported by the program for NCET in University (0770). The authors would like to thank Bo Yang and Xiang Tang for assistance with sampling collection and analysis, and their useful suggestions.

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