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Title	Optimising the performance of a lab-scale tidal flow reed bed system treating agricultural wastewater
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Publication date	2004
Publication information	Zhao, Y.Q., Guangzhi Sun, C. Lafferty, and Stephen Allen. "Optimising the Performance of a Lab-Scale Tidal Flow Reed Bed System Treating Agricultural Wastewater" 50, no. 8 (2004).
Publisher	IWA Publishing
Item record/more information	http://hdl.handle.net/10197/3263
Publisher's statement	The definitive peer-reviewed and edited version of this article is published in Water Science & Technology Vol 50 No 8 pp 65–72 and is available at www.iwapublishing.com

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OPTIMISING PERFORMANCE OF A NOVEL REED BED SYSTEM FOR THE TREATMENT OF HIGH STRENGTH AGRICULTURAL WASTEWATER

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ABSTRACT

A gravel-based tidal flow reed bed system was operated with three different strategies in order to investigate its optimal performance for the treatment of high strength agricultural wastewaters. According to the three strategies, individual reed beds of the system were saturated and unsaturated with the wastewaters for different periods while steady hydraulic and organic loadings were maintained. Experiment results demonstrated that the system produced highest pollutant removal efficiencies with relatively short saturated period and long unsaturated period, highlighting the importance of O₂ transfer into reed bed matrices during the treatment of high strength wastewaters. Significant removals of some major organic and inorganic pollutants were achieved with all the three operation strategies. Nitrification was not the major route of NH₄-N removal when the system was under high organic loading. Due to the filtration of suspended solids and accumulation of biomass, gradual clogging of the reed bed matrices took place. The clogging caused concerns over the long-term efficiency of the current tidal flow reed bed system.

KEYWORDS

Agricultural wastewater; constructed wetland; reed bed; tidal flow.

INTRODUCTION

Since the 1980s constructed wetlands in the form of reed beds have been successfully used worldwide as one of the most popular treatment alternatives for a variety of wastewaters, including industrial, domestic and agricultural effluents, urban runoff, mine drainage and landfill leachate (IWA, 2000). As a 'green' technology, reed bed system is considered to be effective, economical and environment-friendly. Tidal flow reed beds emerged in recent years as a novel system in that bed matrix is rhythmically filled with wastewater then drained (Green *et al*, 1997; Revitt *et al*, 1997; Sun *et al*, 1999a,b). During the filling process, air is expelled and the reed bed matrix is gradually submerged with wastewater, providing maximum medium-water contact. When the whole bed is fully saturated, the wastewater begins to drain and air is drawn from the atmosphere into the bed matrix to promote aeration and assist aerobic microbial activities in biofilms attached to the media and roots of the reeds. It has been proved that such tidal flow operation technique enhances oxygen supply and prevents poor water distribution in conventional reed bed systems. However, commercial practices of the tidal flow reed bed have not been carried out due to lack of suitable design criteria and performance data leading to the optimal operation of the system.

In this study, three different operating conditions of a gravel-based tidal flow reed bed system are investigated to discover the optimal operation strategy. The tidal flow system, being used to treat high strength agricultural effluents, consists of five-stages of reed beds with mono-media gravel. The removals of pollutants such as COD, BOD₅, ammonia-nitrogen (NH₄-N), phosphorus (P), and

suspended solids (SS) were analysed. The optimum operating condition is evaluated based on the removal efficiency of these pollutants.

MATERIALS AND METHODS

The reed bed system

The lab-scale reed bed system used in this study is shown schematically in Figure 1. It consisted of five identical beds that were made of Perspex columns of 90 cm in height and 10 cm in diameter. Each bed was filled with 26.4 ± 7.2 mm washed round gravel to a depth of 15 cm as a supporting layer, followed by a top layer of 4.4 ± 1.5 mm washed gravel with a depth of 65 cm. A single common reed, *Phragmites australis*, was planted in the top layer of each bed. The reed bed system was placed in a special experimental area with an overhead air extraction system and a permanent metal rig for holding the beds. This experimental area was fully sealed by a heavy-duty plastic curtain to minimise unexpected odour release to the outside area.

Figure 1. Schematic diagram of the tidal flow reed bed system

Experiment process

The reed bed system was previously started-up via batch and continuous operation for four months for the purpose of establishing a heterogeneous environment in which chemical processes, microorganisms and the reeds constituted the operative substrates (Zhao *et al*, 2003). During the current study, the system was operated in tidal flow strategy that five single reed beds (Stages 1-5) were alternately filled and drained with wastewater. In order to avoid the excessive accumulation of biomass in the beds, the system was rested for one week after each week of operation.

Diluted pig slurry was prepared in a feed tank with SS, COD, BOD₅, NH₄-N and PO₄-P levels up to 894 mg/l, 4254 mg/l, 3150 mg/l, 159.2 mg/l and 50.0 mg/l, respectively. As shown in Figure 1, 2.1 litre of diluted pig slurry was pumped from the feed tank into the first stage of the reed bed system, totally submerging the bed before being pumped out and passed through the system sequentially from the first to the fifth stages. Controlled by pumps and timers, each “tide” was completed in four hours, giving a hydraulic loading of about 1.6 m³/m²d for each reed bed. Details of the three operating conditions applied in this investigation are presented in Table 1. The period of individual reed beds being filled with the wastewater is named as ‘saturated time’, whereas the period of reed beds being drained and unsaturated with the wastewater is named as ‘unsaturated time’.

Table 1. Operating conditions of the reed bed system

Parameters	Operating conditions		
	1	2	3
Pump cycle operation	every 4 hr@6 times/day	every 4 hr@6 times/day	every 4 hr@6 times/day
Bed saturated time (hr per cycle operation)	3	2	1
Bed unsaturated time (hr per cycle operation)	1	2	3
Retention time in the system (hr/d)	15	10	5
Pump flow rate (ml/min)	56	56	56

Sampling and analyses

Samples of influent and effluents from each stage were collected three days a week and analysed on the same day of collection. The COD and BOD₅ were determined according to Standard Methods. NH₄-N was analysed using a Sension II pH/ISE meter and an ammonia electrode. NO₂-N, NO₃-N, P and SS values were measured with an HACH DR/2010 spectrophotometer. A Piccolo II portable pH meter was used for pH measurement.

RESULTS

The overall performance

The overall removal efficiency of pollutants across the whole reed bed system under the three operating conditions is illustrated in Figure 2.

Figure 2. Overall treatment efficiencies in the reed bed system under three operating conditions
Error bars denote SDs

As shown in Figure 2, considerable increases of removal efficiencies in COD, BOD₅ and NH₄-N are observed as the operation strategy was changed from condition 1 to conditions 2 and 3. Such trend is not so clear for the SS removal although condition 3 did produce the highest removal percentage, around 80%. It is noted that the removal efficiency of P remained virtually constant in all three conditions. Overall, results from Figure 2 demonstrate that a shorter saturated time and a longer unsaturated time gives greater pollutant removal efficiency, and aeration by convection and

diffusion in the unsaturated time may have played a controlling role for the removal of pollutants in the current tidal flow reed bed system.

Organic removal

Figure 3 illustrates the variation and removal efficiency of COD and BOD₅ across the reed bed system. During the operation period, pig slurry was diluted with tap water to achieve COD and BOD₅ strengths in the range 3,420-4,254 mg/l and 2,310-3,150 mg/l, respectively. It is noted from Figure 3 that the removal percentages of COD and BOD₅ follow the trend of increase with time during continuous runs under the same operation condition. In addition, the removals increase with the changing conditions from 1 to 3. The increase of removal efficiency under the same operating condition lies in the progressive arrival of a stable treatment status, whereas the improvement of removal efficiency from operating condition 1 to 3 is attributed to the aeration of the reed bed matrices during the prolonged unsaturated time that enhanced the O₂ transfer.

Figure 3. Variation and removal efficiency of COD and BOD₅ in the reed bed system

Figure 4 illustrates typical changes of COD and BOD₅ in different stages of the system. It is evident from Figure 4 that the first three stages of the reed bed system undertake 77.2-92.3 % of the total removals of COD and BOD₅. Under all the three operation conditions, there were no significant further reductions of organic pollutants in 4th and 5th stages. The 5th stage essentially provided only a polishing process for effluents from the pervious stages.

Figure 4. Profile of COD (a) and BOD₅ (b) concentrations in the reed bed system

Nutrients removal

Figure 5 presents variations of nitrogen forms, including $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$, across the reed bed system. Figure 5 shows clearly that a significant reduction of $\text{NH}_4\text{-N}$ was achieved during the operation of the system, especially in condition 3 as there is a big “gap” between the two lines of $\text{NH}_4\text{-N}$ concentrations of the influent and effluent. Also from Figure 5, changes of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ between influent and effluent over the reed bed system can be observed. Under conditions 1 and 2, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ levels in the effluents are mostly higher than that in the influents, indicating that the nitrification process was occurring during the experiment. Under condition 3, nitrification and denitrification processes may have occurred simultaneously in the reed bed system; this resulted in a decrease of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ level. Calculated average removals of the total nitrogen mass of $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ under conditions 1, 2 and 3 are $23.5 \pm 3.0\%$, $25.0 \pm 1.8\%$ and $40.1 \pm 9.5\%$, respectively.

Figure 5. Variations of $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ across the reed bed system

Figure 6 illustrates a typical profile of nitrogen and phosphorus in each stage of the system. It is noted that continuous reduction of $\text{NH}_4\text{-N}$ through each reed bed is observed (Figure 6a). In reed beds the reduction of $\text{NH}_4\text{-N}$ usually results in increases of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ levels as $\text{NH}_4\text{-N}$ can be bio-oxidized by nitrifying bacteria to nitrite ($\text{NO}_2\text{-N}$) and further to nitrate ($\text{NO}_3\text{-N}$). This can be evidenced by inspecting $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ profiles shown in Figure 6 (b,c). As removal of $\text{NH}_4\text{-N}$ largely depends on oxygen supply, the peak values of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ appeared as early as in the 2nd stage in condition 3, demonstrating significant oxygen flux obtainable under this operating strategy. However, from Figure 6 (b,c), it is reasonable to believe that the nitrification did not produced a great amount of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ since the peaks of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ are not remarkably high. In addition, the pH level increased from 6.7 in the feed tank to 7.8 in the final effluent, whereas extensive nitrification normally prompts the pH to drop.

The trends of phosphorus reduction follow a certain pattern in all operation conditions (Figure 6d), and the percentage removal of phosphorus remains largely constant regardless of the operating conditions. The removal of phosphorus in the current reed bed system may be attributed to the adsorption of P by the bed media, uptake by the reeds and chemical precipitations. The biological activities taking place in the reed bed matrices may only have a very limited impact on the phosphorus removal from the wastewater.

Figure 6. Typical profile of $\text{NH}_4\text{-N}$ (a), $\text{NO}_2\text{-N}$ (b), $\text{NO}_3\text{-N}$ (c) and P (d) in the reed bed system

Removal of suspended solids and clogging of bed matrices

As demonstrated in Figure 2, significant removal of SS, 60.6-80.8%, were achieved under the three operating conditions. Part of the reason for the scattering of SS data was that the SS levels of diluted pig slurry in the feed tank fluctuated irregularly with time. In spite of this, the reed bed system under investigation showed a high SS removal ability. Figure 7 provides a profile of SS in different stages of the system under operating condition 3. It is observed that most of the SS are removed in the first two stages. In particular, the first stage contributed up to 57.6% of the total SS removal. However, considerable clogging of bed matrices was observed under all operating conditions, and such clogging was most serious in the first two stages. A direct evidence of the clogging is the detection of progressively increasing water level in the first two stages during the saturated time of the tidal flow operation. Originally, water level in each reed bed was set to precisely reach the top of bed matrix when 2.1 litre of wastewater was pumped into it. Undoubtedly, evolution of water level during the saturated time was an indication of the resistance to filtration and was most likely to be caused by the accumulation of solids and growth of biomass. Visual observation found that the first stage was heavily blocked by visible particles and some unidentified substances linked with slimes.

Figure 7. Profile of SS in the reed bed system under operating condition 3 (error bars denote SDs)

DISCUSSION

One of the unique advantages of the tidal flow reed bed system is the enhancement of oxygen supply (Sun *et al.*, 1999b). Intensified oxygen flux into reed bed matrices is highly desirable in the treatment of high strength wastewaters because a large amount of oxygen is essential for aerobic microbes to decompose organic pollutants (quantified by BOD₅ or COD) and for nitrifying bacteria to convert NH₄-N into NO₂-N and NO₃-N. The ability of a reed bed system to transfer oxygen and to produce a high pollutant removal efficiency is considered an important parameter in evaluating the system. From the current study, the optimum operating condition has been identified by comparing pollutant removal efficiencies when three different operating strategies were adopted. The results clearly support the strategy of a short saturated time and a long unsaturated time.

Despite variations of the wastewater retention time in the current reed bed system, the hydraulic and organic loadings were kept reasonably constant under all the three operating conditions; therefore the energy requirement of the tidal flow operation remained largely unchanged. When the energy consumption rate is fixed, improvement in the overall efficiency of the system has to be made through optimizing the operation strategy, and the key for the optimal operation is an appropriate balance between the period of wastewater-bed media contact (saturated time) and the period of aeration of the reed bed matrices (unsaturated time). The highest pollutant removal efficiencies achieved in operation condition 3 indicate that organic pollutants are retained inside the reed beds when their matrices are saturated with the wastewater. When the wastewater is drained and the matrices become unsaturated the pollutants are aerobically decomposed by microorganisms using oxygen transferred from the atmosphere into the beds. As the diffusion rate of oxygen in gaseous phase is much higher than in aqueous phase, a longer unsaturated time should certainly draw a higher amount of oxygen flux into the reed bed matrices. It is not clear how the pollutants are retained inside the beds during the saturated time. This behaviour, however, may be hypothetically described as “adsorption”, which is a rapid process (Sun *et al.*, 1998). Overall results from the current study suggest that each tide should be completed quickly during the tidal flow operation, leaving the bed matrices aerated for a longer period.

It is generally believed that the most likely manifestation of the removal of NH₄-N is the production of NO₂-N and NO₃-N, which is widely known as the nitrification process. However, it appears that nitrification in the current study is not the predominant process since the amount of NH₄-N being removed is much greater than the amount of NO₂-N and NO₃-N being generated. The reason may be attributed to the high organic pollutant content of the wastewater in this study. It has been reported that significant nitrification could not take place until the BOD₅ was reduced to 200 mg/l or even well below this value (Gray *et al.*, 1996; Sun *et al.*, 1999a). The removal of NH₄-N in the current study may result from a combination of numerous processes, which include nitrification, adsorption, assimilation associated with decomposition of organics, volatilization and plant uptake.

With regard to the SS removal, the results are adequate to suggest that significant removal of SS leads to considerable clogging of the reed beds, particularly in the first two stages of the system. To date, there is only very limited information concerning mechanisms of clogging in reed bed systems (Blazejewski and Murat-Blazejewska, 1997; Bihan and Lessard, 2000). Nevertheless, it has been recognised that settled and trapped SS in reed bed matrices and the accumulation of biomass associated with the reduction of BOD₅ are the two main factors to cause the clogging. In addition, under normal conditions operating the tidal flow reed beds for a prolonged period can cause change of evolution of the resistance to filtration in the bed, thereby accelerating the clogging (Bihan and Lessard, 2000). To reduce the clogging, a resting period for the reed beds was adopted in this study. Such resting has been proved effective, to a certain degree, in triggering the self-consumption of microorganisms inside the reed beds to avoid excessive biomass accumulation.

CONCLUSIONS

With enhanced oxygen transfer ability, tidal flow reed beds can be used to substantially reduce levels of pollutants in high strength agricultural wastewaters. In the current lab-scale trial of a tidal flow system percentage removals of 85.5% and 78.3% were achieved for COD and BOD₅ from initial levels of 4,254 mg/l and 3,150 mg/l, respectively, under hydraulic retention time of five hours per day. Significant removals of inorganic nutrients were also achieved. Nitrification did not appear to be the predominant process for the NH₄-N removal.

It was clearly demonstrated that with shorter saturated time (one hour per 'tide' in this study) and longer unsaturated time (three hours per 'tide') the tidal flow reed bed system was more efficient in the removal of various pollutants due to enhanced oxygen supply into the reed bed matrices. However, the removal efficiency of phosphorus was found to be independent of the system's operating strategy. Extensive removals of the SS and organic pollutants caused the problem of clogging of the reed bed matrices. Further study is needed to identify mechanisms of the clogging and establish appropriate tactics to overcome this operational problem.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support from the EPSRC, UK for this work. Hall's Farm is thanked for providing wastewater materials.

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