Effect of loading rate on performance of constructed wetlands treating an anaerobic supernatant

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F. Chazarenc*,, G. Maltais-Landry*, S. Troesch*, Y. Comeau** and J. Brisson***

*Institut de Recherche en Biologie Végétale, Université de Montréal 4101, rue Sherbrooke Est, Montréal (Québec) Canada H1X 2B2 (E-mail: *florent.chazarenc@umontreal.ca*)

**Department of Civil, Geological and Mining Engineering, Ecole Polytechnique 2900, Edouard-Montpetit, Montréal (Québec) H3T 1J4 Canada

Abstract The effect of organic loading, season and plant species on the treatment of fish farm effluent was tested using three-year old mesocosm wetland systems. During one year, nine 1 m^2 mesocosms (horizontal subsurface flow), located in a controlled greenhouse environment, were fed with a reconstituted fish farm effluent containing a high fraction of soluble components (1,600 μS/cm and in mg/L: 230 ± 80 COD, 179 ± 60 sCOD, 100 ± 40 TSS, 37 ± 7 TKN, 14 ± 2 TP). Combinations of three hydraulic loading rates (30, 60 and 90 $L.m^{-2}\,d^{-1}$) and two plant species (*Phragmites australis, Typha angustifolia*) and an unplanted control were tested for treatment performance and hydraulic behaviour. Loadings higher than 15 g COD $m^{-2}\,d^{-1}$ resulted in a net decrease of hydraulic performances (generation of short circuiting) coupled with low TKN removal. Maximal TKN removal rates (summer: 1.2, winter: 0.6 $g.m^{-2}\,d^{-1}$) were reached in planted units. In all mesocosms, phosphorus was removed during summer (maximal removal rate: 0.3 g TP $m^{-2}\,d^{-1}$) and was released in winter (release rate = ~ half of summer removal rate). This study confirmed that constructed wetlands are susceptible to clogging when treating anaerobic storage tank supernatant rich in highly biodegradable compounds. Contributions of plants to hydraulic efficiency were mainly observed in summer, associated with high evapotranspiration rates. Both plant species gave a similar removal efficiency for all pollutants.

Keywords Anaerobic storage tank supernatant degradation; horizontal subsurface flow constructed wetlands; organic loading rates; *Phragmites australis*; *Typha angustifolia*

Introduction

Constructed wetland (CWs) performance is affected by a range of factors such as operation mode (loading rate, continuous or batch-load) and environmental conditions (climate, season). An improved understanding of these factors enables the design of CWs for a wide range of wastewater types, such as fish farm effluent (Comeau *et al.*, 2001; Lin *et al.*, 2002; Ouellet-Plamondon *et al.*, 2006).

The purpose of this study was to determine the effect of loading rate on plant development, treatment and hydraulic performance of a horizontal subsurface flow constructed wetland (HSSF) treating the supernatant from an anaerobic fish sludge storage tank (high conductivity, high soluble fraction due to an anaerobic sludge hydrolysis; Chazarenc *et al.*, 2006).

Typical organic loads between 8 and 12 g BOD_5 $m^{-2}\,d^{-1}$ are recommended to treat secondary domestic wastewaters under temperate conditions, and this is generally associated with a total suspended solids loading of 1–10 g TSS $m^{-2}\,d^{-1}$ (Kadlec and Knight, 1996). Care must be taken when applying these recommendations to other effluent such as fish farm wastewaters, as several characteristics, such as organic matter (OM) accumulation or salinity, can influence the CW behaviour and longevity.

Accumulation of OM in CW is a consequence of two main mechanisms: external TSS loading (rapid particulate matter deposition) and internal OM loading (biofilm development,

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litter accumulation due to plants; Tanner *et al.*, 1998). When OM production rates exceed degradation rates, significant experimental residence time distribution (*ts*) reduction may occur, as reported in several studies: 50% in Tanner *et al.* (1998), and 30% in Grismer *et al.* (2001).

Three loads of fish farm effluents with two plant conditions (*Phragmites australis, Typha angustifolia)*, and an unplanted control were tested simultaneously using a well-established pilot system (three years old in a controlled greenhouse). The focus of the study was to simultaneously analyse treatment performances (TSS, COD, sCOD, TKN, NH_4, NO_3, TP), hydraulic performances (NaCl and KBr as conservative tracers) and plant development (biomass, global health). It is hypothesised that shock loads of highly soluble and biodegradable effluents could be treated efficiently.

Materials and methods

Wetland system

Nine mesocosms (1.25 m long, 0.8 m large, 0.3 m deep) located in a controlled greenhouse environment (summer: 25 °C, winter: 5 °C) were used at the Botanical Garden of Montreal. At the end of each unit, a reservoir enabled the collection of daily treated effluent. Two 1,500 L refrigerated bulk tanks were used to store a reconstituted effluent, while peristaltic pumps distributed the effluent at the chosen loading rates (Table 1). Mesocosms were filled with granite river gravel (10–15 mm diameter), with a narrow section at the inlet filled with large gravel (30–40 mm diameter) to facilitate water distribution. The water table was kept 4 cm below the surface. Mesocosms were planted on May 2002 from rhizomes, and fed with 30 L m^{-2} d^{-1} of a reconstituted fish farm effluent until June 2004 (Ouellet-Plamondon *et al.*, 2006).

The reconstituted effluent was created to mimic the supernatant from an anaerobic fish sludge storage tank by diluting decanted fish farm sludge and fish sauce (rich in salt and sCOD) to reach concentrations (in mg/L) of 100 TSS, 300 COD, 200 sCOD and 750 NaCl. Urea ($CO(NH_2)_2$) and KH_2PO_4 were also added to increase TKN and TP concentrations, to 40 mg TKN/L and 15 mg TP/L. From May 2004, three sets of three mesocosms were fed with 30, 60 and 90 L m^{-2} d^{-1} (3, 6 and 9 cm/d) of this effluent. In each set, one bed was planted with *P. australis*, another one with *T. angustifolia* and the third one was left unplanted.

Table 1 Evapotranspiration rate (ET), above-ground biomass and dispersion (Pe number) observed in each mesocosm

	ET (mm/d)				Biomass (kg/m²)	Pe			
	June	July	August	February		June	July	August	February
30 L/d									
Reed	5	5	7	–	1.92	12	8	8	31
Cattail	6	9	8	–	2.21	10	7	7	23
Unplanted	1	2	1	–	–	10	5	5	24
60 L/d									
Reed	11	11	11	–	3.28	7	5	6	24
Cattail	11	13	9	–	2.12	8	5	5	13
Unplanted	4	6	6	–	–	5	5	4	17
90 L/d									
Reed	7	13	12	–	1.82	7	3	4	11
Cattail	12	10	12	–	1.94	8	4	3	7
Unplanted	8	6	4	–	–	3	5	3	6

Treatment and hydraulic performances, plant biomass

Data were collected during campaigns of seven consecutive days, three in summer (June 21–27, July 14–20 and August 5–11) and two in winter (February 16–22, March 1–7). The following parameters were measured daily according to Standard Methods (1998): TSS, COD, sCOD, TKN, NH_4^+, NO_3^- and TP. Evapotranspiration (ET) was estimated by measuring the total inflow and outflow. Removal efficiencies were calculated on a mass balance basis. Hydraulic performances were determined by hydraulic residence time distribution analyses of mesocosms. Pulse input tracer studies were conducted using NaCl and KBr. During each campaign, the tracer was injected in each of the nine mesocosms (15 L of tracer, 6.7 g NaCl/L in summer and 0.4 g KBr/L in winter) within five minutes and analysing outlet concentrations during seven days to draw a normalised E-curve. Experimental residence time distribution (*ts*) and Peclet number ($Pe = Ul/D$ where U is the flow speed [m/s], l the flow length [m], and D the diffusion coefficient [m^2/s]) were calculated according to Levenspiel (1972). Global hydraulic failures were revealed by comparing the theoretical HRT (τ) and the centre of gravity of E-curve (experimental residence time: *ts*) such as:

- $ts > \tau$: the influent flows through the reed bed without reacting, indicating short-circuiting. The fluid follows a preferential path and the first peak is seen at an earlier stage of the curve than in the theoretical curve.
- $ts < \tau$: the fluid stagnates in the reactor and does not participate in reactions. This phenomenon is due to the presence of dead or stagnant zones.

Results and discussion

Hydraulic performances

All E-curves were significantly skewed as reported in other tracer tests conducted in CWs. Evapotranspiration (Table 1) was greatest in 6 and 9 cm/d load (maximum average rate: 13 mm/d) and was in the range (0–50 mm/d) for planted units under temperate climate. A higher ET would have been expected for the 3 cm/d than for the 6 and 9 cm/d loads because of the enhanced contact between plants and water but this was not observed. Hydraulics of similar sized mesocosms ($0.7\,m^2$) planted with *T. angustifolia* was observed to be greatly influenced by high ET rates in summer (from 20 to 40 mm/day), which enhanced residence time and decreased the Pe number (He and Mankin, 2001; Chazarenc *et al.*, 2003). In the study, although the Pe number was always smaller in summer (higher dispersion), it was smaller in unplanted beds (with low ET). It was as if the Pe number followed a decrease between June and August, in all beds, indicating that the ET was not a dominant factor and that biofilm development was more likely to increase dispersion (reduce Pe). In winter, data showed a net increase of Pe in all beds which could have been a consequence of biofilm obstruction reduction in void space, or a consequence of the difference between tracers' behaviour, linked to water temperature and to tracer dispersion (at 25 °C: $NaCl = 1.48 \times 10^5\ cm^2/s$ and $KBr \sim 1.9 \times 10^5\ cm^2/s$). On average, higher Pe numbers were observed in planted wetlands, with differences being mainly pronounced for the 3 cm/d load. Slight differences were measured between above-ground biomass in the different loads, the largest growth being observed for the 6 cm/d load with *Phragmites*. On average, above-ground biomass in our experiments was lower than others reported at 6–8 kg dry plant/m^2 in mesocosms reported by He and Mankin (2001), or 4–22.5 kg dry plant/m^2 for *Typha* and 6–35 for *Phragmites* reported by Kadlec and Knight (1996). These were probably a consequence of the shallow depth of 30 cm and of the cold climate as *T. angustifolia* and *P. australis* are reported to be salinity tolerant until a salinity level of 2.5 g NaCl/L.

Mean *ts* were about 15% higher in planted wetlands (Table 2). Under a 3 cm/d loading, τ was slightly greater than *ts* (indicating the presence of a stagnant region), and experimental residence time remained constant throughout the year, probably less influenced by the smaller ET. In constructed wetlands, *ts* are generally higher than τ (Rousseau *et al.*, 2004) and are mainly associated with water retention by organic litter which was not the case for 6 and 9 cm/d loadings. In 6 cm/d loaded mesocosms, *ts* was always greater than τ as a consequence of a short circuiting amounting to about 30% in reed and 20% in unplanted. τ in the 9 cm/d loaded CW was twice as low as *ts*. This reduction was attributed to the presence of a significant short circuiting of about 50% of the inflow in planted beds in summer and 20% in reed and unplanted in winter, confirmed by observations of free water at the surface of all beds due to clogging. In all cases, it is hypothesised that clogging may result from organic carbon accumulation via biofilm development and exopolymer gel formation. As the short circuiting was greater in planted units, it is also assumed that plant obstruction could play a role. Mesocosm depths were low (30 cm) and enabled plant development across the depth. Little sludge accumulation was observed at the head part of the bed which supported the hypothesis of internal clogging.

Effect of loading on TSS, COD and sCOD removal

On average, the maximal TSS loading was associated with the 9 cm/d hydraulic load rate and amounted to 9.4 g TSS m^{-2} d^{-1} ($\sim$70% volatile) which is in the high range of commonly recommended TSS loadings. Mean summer and winter TSS removal of almost 80% was recorded irrespective of loading rate and plant presence, as observed in similar experiments (Tanner *et al.*, 1995). With a hydraulic loading of 9 cm/d, the maximal TSS removal rates were associated with high COD and sCOD removal rates (Table 3) compared to other fish farm effluents (Lin *et al.*, 2002), where removal rates of 7.2 g TSS m^{-2} d^{-1} associated with 11.6 g COD m^{-2} d^{-1} were reported.

Mass removals of COD and sCOD were proportional to mass loading rates with a slight decrease observed in unplanted mesocosms. In the study, the sustainable COD removal, especially for the sCOD in the 9 cm/d loading, was due to the easily degradable nature of the effluent. As the TSS to COD ratio was smaller than for domestic effluents, it seemed unlikely that the commonly assumed COD removal mechanism of TSS accumulation followed by OM decomposition was the dominant mechanism for COD degradation. The principal OM removal mechanism is normally rapid biological assimilation, producing biofilm, followed by slow mineralisation within this biofilm. The removal decrease observed in winter was mainly due to sCOD seasonal trends, associated with a decrease of both internal loading and biodegradation rate (Barber *et al.*, 2001).

Effect of load on TKN and TP removal

As expected, TKN removal rates were maximal in summer and in planted units (Table 3), similar for both plant species, and superior in planted units in winter (Ouellet-Plamondon *et al.*, 2006). TKN removal was mainly attributed to NH_4^+ removal, except for unplanted beds in winter when NH_4^+ appeared to be released. In unplanted units, TKN removal was probably limited by oxygen availability, and NH_4^+ release was probably due to TKN ammonification followed by partial inhibition of nitrification. Nitrate concentrations were always lower than 0.01 mg N-NO_3/L at the outlet of all beds (results not shown), indicating that nitrification was poor and possibly also that denitrification was not inhibited. TKN removal did not increase proportionally with loading in planted mesocosms, and was maximal in 6 cm/d loaded units. Lower winter TKN removal rates were probably linked to decreased nitrifying activity associated with lower temperatures (Spieles and Mitsch, 2000). Wiessner *et al.* (2005) observed a rapid sulphide production associated with nitrification inhibition in

Table 2 Theoretical and experimental residence time and associated hydraulics dysfunction

	HRT*				*ts*** d				% short circuiting				% dead volumes			
	June	**July**	**August**	**February**	**June**	**July**	**August**	**February**	**June**	**July**	**August**	**February**	**June**	**July**	**August**	**February**
30 L/d																
Reed	3.2	3.2	3.3	2.9	3.0	3.4	3.0	3.1	–	7	–	7	7	–	11	–
Cattail	3.2	3.5	3.4	2.9	2.8	3.3	2.6	2.8	–	–	–	–	12	5	23	4
Unplanted	3.0	3.0	3.0	2.9	2.7	2.3	2.4	2.6	–	–	–	–	9	23	19	11
60 L/d																
Reed	1.6	1.6	1.6	1.5	2.2	2.6	2.3	2.1	28	37	31	30	–	–	–	–
Cattail	1.6	1.6	1.6	1.5	2.3	2.3	2.0	1.7	29	30	21	12	–	–	–	–
Unplanted	1.5	1.5	1.5	1.5	1.8	1.8	2.0	1.9	16	13	25	23	–	–	–	–
90 L/d																
Reed	1.0	1.1	1.0	1.0	2.1	2.0	1.6	1.2	51	47	37	21	–	–	–	–
Cattail	1.0	1.0	1.0	1.0	2.1	2.0	1.9	0.9	50	47	45	–	–	–	–	3
Unplanted	1.0	1.0	1.0	1.0	1.3	1.4	1.4	1.3	24	30	30	24	–	–	–	–

*HRT: τ theoretical hydraulic residence time distribution ($\tau = Vv/Q$ or determined according to Chazarenc *et al.*, 2006 in presence of ET); ***ts*: experimental residence time distribution

Table 3 COD, sCOD and TKN removal rates (g m^{-2} d^{-1}) according to season

	COD		sCOD		TKN		NH_4	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
30 L/d								
Reed	6.5	5.2	5.4	4.3	0.9	0.5	0.7	0.3
Cattail	6.7	5.3	5.4	4.4	0.8	0.4	0.6	0.2
Unplanted	6.1	5.1	4.9	4.1	0.4	0.1	0.1	− 0.1
60 L/d								
Reed	13.4	10.5	10.3	8.8	1.3	0.6	0.9	0.2
Cattail	13.1	10.0	10.4	8.2	1.2	0.6	0.7	0.2
Unplanted	13.2	10.4	10.1	8.1	0.7	0.3	0.2	− 0.1
90 L/d								
Reed	19.0	15.1	14.1	11.8	1.5	0.7	0.8	0.2
Cattail	19.1	15.4	14.0	11.9	1.4	0.9	0.7	0.3
Unplanted	18.3	14.2	13.1	10.6	0.8	0.5	0.2	− 0.1

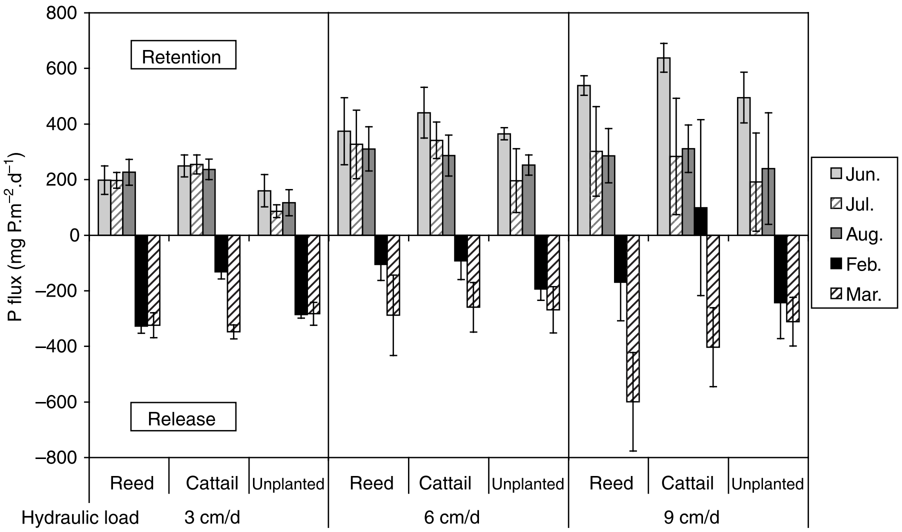

Figure 1 P removal or release rates (error bars represent standard deviation for 7 samples)

CW microcosms fed at 13 g BOD_5 m^{-2} d^{-1}, and it is assumed that a similar behaviour occurred in 9 cm/d loaded mesocosms (fed with 20 g COD m^{-2} d^{-1}). Indeed, a typical odour of rotten eggs and a black layer development were observed in these units. In all mesocosms, TP was retained in summer and released in winter (Figure 1). P removal and release rates seemed to be proportional to the loading over time. P fluxes were more probably linked to biofilm growth cycles rather than plant storage/mineralisation, since aerial biomass was harvested in autumn 2004 and considering that above-ground plant storage is assumed to be minor after three to four years. P was probably retained mostly for heterotrophic biofilm growth in summer and released in winter by biofilm decay.

Conclusion

Higher organic loads of a highly soluble effluent can be treated without decrease in treatment performances of TSS, COD and sCOD. However, since higher organic loads resulted in hydraulic dysfunctions via internal clogging, treatment performances could be altered in the long term, especially TKN removal. Short-circuiting can be accentuated by plants via root growth in the case of the 30 cm depth. Summer TP removal rates increase as TP loading rates increase. However, winter TP release rates were equivalent to summer retention rates, confirming that well-established CWs are only temporary TP sinks.

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