Short communication

Recirculation on a single stage of vertical flow constructed wetland: Treatment limits and operation modes

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ABSTRACT

Classical French vertical flow constructed wetlands (VFCWs) plant comprises two stages of treatment which the first one nearly respects standard outlet levels. It is therefore attractive to use recirculation on a single vertical stage to reduce its footprint when outlet levels required are not too severe regards to nitrification. The present study aims at evaluating performances and limits of a full-scale experimental plant during one year and a half. The monitoring has been done measuring continuously hydraulic fluxes and treatment performances in different operating conditions. Results showed good performances of the recirculating VFCW according to BOD, COD and SS parameters: mean outlet levels of 14, 73 and 19 mg L^{-1}, respectively. Besides, nitrification is strongly dependant on recirculation rate and seasons (temperature effect). Recirculation over a single stage of VFCW can improve nitrification efficiency while enhancing carbon and SS removal.

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1. Introduction

French Vertical Flow Constructed Wetlands (VFCWs) treat directly raw wastewater and need two stages of filters to achieve complete nitrification (Molle et al., 2005). Mean removal rates are 91 and 95% for COD and SS, respectively, on the whole stages and 90% for nitrification. Regarding the first stage, nitrification efficiency ranges from 50 to 60% only. When outlet requirements are not too stringent, the interest of the second stage can be questioned. A recirculation loop could be an interesting way to reduce investment cost and footprint. Nevertheless, nitrification performances of the French system (raw wastewater applied on the first stage) with recirculation is unknown. Many researchers consider that nitrogen removal in VFCW may be improved by outlet effluent recirculation (Sklarz et al., 2009; He et al., 2006; Platzer, 1999) thanks to an improved water-biomass contact-time (Zhao et al., 2004; Sun et al., 2003), a buffer effect of inlet concentration variations (Moreno et al., 2001; White, 1995) and a greater oxygen consumption (Sun et al., 2005). However recirculation requires the setting up of electromechanical organs (recirculation pumps) leading to additional energy consumption, diminishing the environment-friendly character of the CW process (Stefanakis and Tsihrintzis, 2009).

As French VFCW systems are fed directly with raw wastewaters (Molle et al., 2005), recirculation experiments carried out abroad from France are not easily comparable to the recirculated French system. Recirculating VFCWs usually use a settling tank as primary treatment where the recirculated effluent is introduced (Sklarz et al., 2009; He et al., 2006; Labert et al., 1997). Moreover hydraulic and organic loads are generally much lower than the one used in the first stage of French systems without recirculation (37 cm d^{-1}; 25–30 gKN m^{-2} d^{-1} on the filter in operation). In the same way, the organic deposit layer is generally not present while it plays an important role on ammonia adsorption and can limit oxygen fluxes. Consequently the study aims at assessing the performances a first stage of French system can achieve with a recirculation loop according to the recirculating rate and the load applied. To this purpose a year and a half survey was carried out on a single full scale VF stage fed with raw wastewaters to avoid scaling issues.

2. Materials and methods

2.1. Single stage of vertical filters: design characteristics

Experiments have been done on the Saint-Thibaud plant (Savoie, France, alt. 510 m), designed for 800 p.e. (person equivalent). The plant was monitored over a 18 months period to test different loads and recirculation flow ratio (RFR = daily recirculated effluent volume/daily raw wastewater volume × 100). Vertical reed beds were designed according to French Cemagref recommendations (Molle et al., 2005, Gravel of 2–6 mm on 80 cm of depth with

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an intermediate aeration pipe at 40 cm). The first stage is divided into three filters fed by batches (1.9 cm per batch). Alternation between feeding and resting periods, to prevent the filters from clogging, is of 3.5 days of feeding and one week of rest. The specific areas tested ranged from 1.1 to 1.6 m^2 p.e.$^{-1}$, depending on the load applied.

2.2. Plant monitoring

2.2.1. Hydraulic and RFR

Inlet, outlet and recirculating flows were continuously measured (every minute) by acquisition of pump functioning time. The RFR tested were 50, 100 or 200% over four periods as detailed in Table 1.

2.2.2. Treatment performances

Treatment efficiency was assessed by 24-h flow composite samples spread out throughout the studying periods. Performances of the plant were measured for SS, COD, BOD_5, KN, NH_4-N, NO_3-N, NO_2-N removal, according to French standard methods (AFNOR, 2008). Moreover, NH_4-N, NO_3-N, conductivity and pH were assessed into each 1-h sample in order to evaluate nitrification efficiency according to load variation within the day. Furthermore, online optical analyzers (Royce) monitored inlet and outlet SS concentrations. Gaseous O_2 and CO_2 concentrations were regularly performed (by a DräggerSensor X am 7000© gas analyzer) in order to estimate the aerobic conditions inside the porous media for several depths. Results are expressed in percent of the air phase ($\pm 0.2\%$).

3. Results and discussion

3.1. Removal performances

Mean values of global removal rates and concentrations are synthesized in Table 1. Wastewater characteristic variations are normal for small communities (COD/BOD_5 ratio of 2.8 ± 0.5). Treatment yields achieved by the filter (called "local") were distinguished between those obtained by the treatment plant (called "global"). The later takes into account the inlet dilution impact of recirculation while "Local performances" concern the filter removal rates only. Local and global removal yields are over 80% for SS, COD and BOD except during the starting phase. Despite these good performances, high concentrations are sometimes observed at the output (see Table 1). They are caused by high input raw concentrations. For example, COD parameter varies up to 1500 mgCOD L^{-1}. It is easy to notice the failure to respect outlet quality objectives in phases 3 and 4 when the filter is strongly overloaded. In phase 4, the system recovers with difficulty after winter overloads, even with a low RFR and the return of warmer temperatures. On the contrary, even in winter (phase 2), treatment performances are excellent when the nominal loads are close to 300 gCOD m^{-2} and 0.37 m d^{-1}.

3.1.1. SS

SS are overall well filtered whatever season, hydraulic or organic load conditions. Due to recirculation, SS loads overcome 150 gSS m^{-2} d^{-1}, but filtering performances stay quite stable with global yields of about 90%. When SS loads exceed 250 g m^{-2} d^{-1} and hydraulic loads are high, performances tend to fail in winter. Online SS measurements allowed to state that buffer effect is insignificant for SS; outlet SS concentrations vary with inlet concentration.

3.1.2. BOD5 and COD

Good and stable global removal rates are observed for COD (Table 1) and BOD_5, above 80 and 85%, respectively. This is apparently independent on water temperature: measurements carried out in summer and winter show similar efficiency regardless of the temperature, even during periods of night frost. Performances on local COD removal are equivalent to these obtained by a first VF stage without recirculation (Molle et al., 2005). Up to 450 gCOD m^{-2} d^{-1}, no impact of recirculation is noted on the filter treatment efficiency as COD performances are maintained above 90%. A slight negative impact is pointed out for high loads such as 600 gCOD m^{-2} d^{-1}: removal rates dropped to 82%. Global performances are improved by recirculation diluting effect. Nevertheless, a single stage filters with recirculation can show performance limitations, preventing the respect of the outlet quality level. Despite global yields above 90%, this is observed when raw wastewaters are strongly concentrated.

3.2. Nitrification removal capabilities

3.2.1. 24-h flow composite sample

Local nitrification performances of the filter are consistent to those observed on a classical system (Molle et al., 2008). This is observed even for high hydraulic loads (linked to high RFR) and for nitrogen loads up to 45 gKN m^{-2} d^{-1} (i.e. 35 gNH_4-N m^{-2} d^{-1}): 50–60% KN removal. Because of the variations of operating conditions, sometimes simultaneously, no clear tendency between performances and operating parameters is obtained. Data processing can however provide some interesting conclusions:

- In winter local yields drop to 20–30% for the KN when HL are superior to 0.7 m d^{-1}. Such HL seem to be the limit to maintain nitrification for low temperatures (water temperature <10 °C). Indeed, increasing RFR impacts the oxygen renewal because it reduces drainage times between each batch. In fact, after one week of rest, oxygen level is still under 5% just after phase 3 (KN yields <50%) while it is above 15% in phase 4 (KN yields >65%).
- On the contrary, dilution effect induced by recirculation is of importance in order to reach low outlet levels. Global nitrification performances of approximately 70% over a single stage can be expected by this way. Nevertheless the outlet level it is possible to respect appears to be of 30 mgKN L^{-1}.

3.2.2. Nitrification variations

Incoming and treated nitrogen loads measured each 1 h step know a nitrification efficiency variability because of operating condition variations (temperature, RFR, loads, seasons, inlet concentrations. . .). As can be seen in Fig. 1, outlet NH_4-N concentrations are quasi-constant while inlet concentrations vary. This smoothing effect of outlet levels has been observed for each sampling periods. It takes place thanks to the filter's water storage. Once reaching a stable saturation state (4–5 h after the beginning of a feeding period), and analyzing only nitrification rate for inlet concentrations higher than 40 mgNH_4-N L^{-1}, we notice a good correlation of nitrification efficiency with the load applied (Fig. 2). In these conditions (100% RFR), schedule nitrification rates are of 61% by mean. But this relation is not valid when input loads vary quickly (linear model in Fig. 1). Then the buffer effect helps to smooth outlet levels, which is positive for high input concentrations but negative otherwise. To better represent nitrification rate with inlet concentration variations, we plotted nitrification yields according to N-NH_4 inlet concentration (ex. for June 2009, Fig. 3a).

Table 1
Tested operation modes, concentrations and removal rates.

				Phase 1			Phase 2			Phase 3			Phase 4		
RFR (%)				200%			100%			100%			50%		
Organic load (gCOD m^{-2} d^{-1})[*]				**250**			**300**			**670**			**350**		
KN load (gKN m^{-2} d^{-1})[*]				–			**25**			**60**			**40**		
HL (m d^{-1})				0.50			0.40			0.75			0.40		
Season				All, 2004–2008			Autumn–winter, 2008			Winter–spring, 2009			Summer, 2009		
Water temp. (°C)				–			9–18			5–15			15–20		
24-h flow composite samples (number)				Punctual samples			4			4			4		
Conc. (mg L^{-1})	Raw	In	Out	Raw	In	Out	Raw	In	Out	Raw	In	Out			
SS	480 ± 173	–	41 ± 31	493 ± 96	383 ± 162	19 ± 2	363 ± 41	304 ± 52	42 ± 4	769 ± 148	430 ± 80	42 ± 4			
COD	1246 ± 309	–	125 ± 64	942 ± 136	736 ± 240	73 ± 7	706 ± 166	708 ± 132	143 ± 20	1465 ± 173	861 ± 127	146 ± 11			
BOD$_5$	681 ± 269	–	37 ± 22	325	215	14	329	237	33	576 ± 10	307 ± 22	42 ± 6			
KN	–	–	32 ± 12	106 ± 16	63 ± 18	19 ± 3	71 ± 12	62 ± 8	37 ± 13	128 ± 5	101 ± 6	41 ± 1			
NH$_4$-N	–	–	–	67 ± 9	48 ± 5	15 ± 2	49 ± 11	42 ± 4	29 ± 10	78 ± 8	70 ± 5	33 ± 10			
NO$_3$-N	–	–	–	0.5 ± 0	4.4 ± 5	23 ± 9	0.5 ± 0	1.9 ± 2	18 ± 21	0.5 ± 0	0.5 ± 0	15 ± 1			
Removal rate (%)	Local		Global	Local		Global	Local		Global	Local		Global			
SS	76 ± 22		88 ± 15	94 ± 2		96 ± 1	84 ± 7		87 ± 3	90 ± 2		95 ± 1			
COD	74 ± 13		89 ± 7	89 ± 4		92 ± 1	80 ± 4		82 ± 4	83 ± 2		90 ± 1			
BOD$_5$	84 ± 11		93 ± 5	93		96	86		90	86 ± 1		93 ± 1			
KN	–		–	67 ± 15		82 ± 1	40 ± 18		46 ± 23	59 ± 2		68 ± 2			
NH$_4$-N	–		–	58 ± 23		77 ± 1	30 ± 20		37 ± 32	53 ± 4		57 ± 5			

[*] Loads are based on the filter in operation.
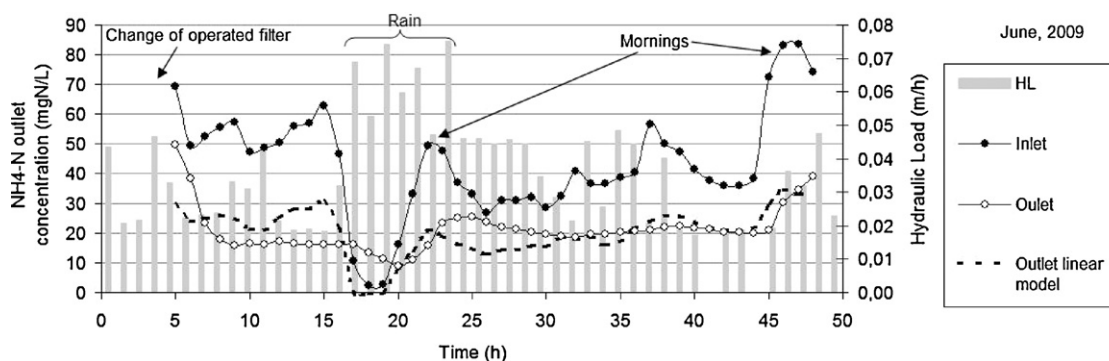
Fig. 1. NH$_4$-N concentration during two successive 24-h flow composite samples, 100% RFR (June 2009).

3.3. Design and limits

To give some design guideline on French VFCW with recirculation we fit a first order equation inspired from biodegradability models (Gillot and Choubert, 2010):

$$\text{Removal yield} = R_{max} \times (1 - \text{Exp}^{(-k(C_{in} - C_{min}))}) \qquad (1)$$
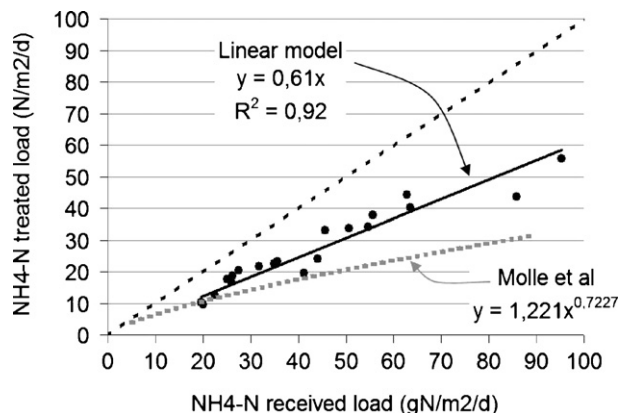
Fig. 2. Treated NH$_4$-N, 100% RFR and $C_{in} > 40$ mgNH$_4$-N L^{-1} (June 2009).

where R_{max} represents the maximum of nitrification removal rate (%), k is a constant, C_{in} and C_{min} the inlet and outlet minimum NH$_4$-N concentration, respectively. The model was safely adjusted and validated for each sample date, in the aim to take into account the removal rate variability. C_{min} was of 25 mgNH$_4$-N L^{-1} and k value was fitted to the data (Fig. 3a). This model is used to give some trends of outlet ammonium concentrations according to design and recirculation rates. To maintain satisfactory nitrification a compromise has to be done between improving recirculation rate (dilution effect) and not overpass hydraulic load greater than 0.7 m d^{-1} on the filter in operation (lack of oxygen for nitrification). The impact of different design and RFR configurations on nitrification efficiency at nominal load (150 L p.e.$^{-1}$ d^{-1}; 12 gKN p.e.$^{-1}$ d^{-1}) is presented in Fig. 3b, assuming:

- an inlet flow and NH$_4$-N concentration variations as observed on Saint-Thibaud plant (see Fig. 3b)
- theoretical nitrification efficiency based on efficiency measured on Saint-Thibaud plant (see Fig. 3a).

It appears that recirculation on a single vertical flow filter cannot deliver a complete nitrification. If RFR has an impact on NH$_4$-N outlet level, it can be stated that using surface of 1.0–1.2 m^2 p.e.$^{-1}$

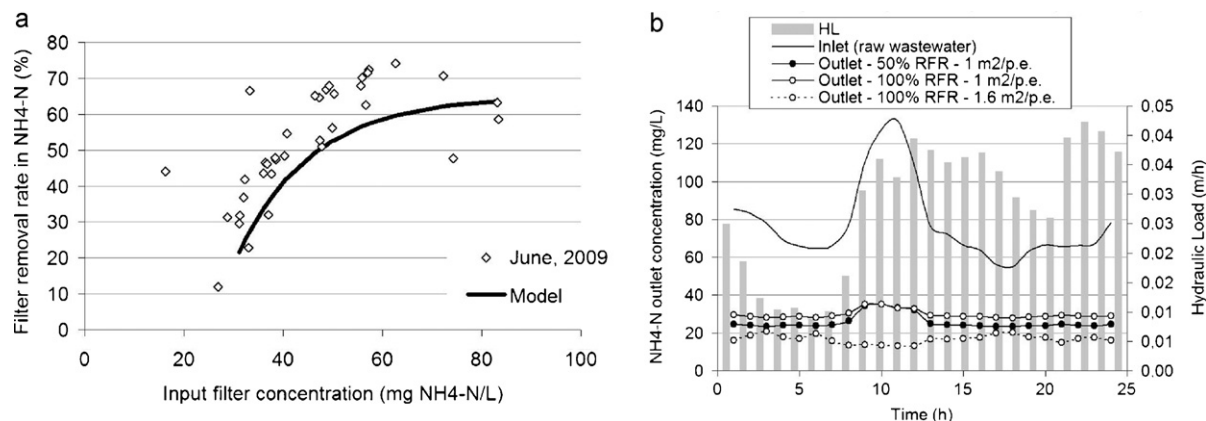**Fig. 3.** (a) Schedule nitrification yields linked to NH$_4$-N inlet concentrations and (b) evolution of the theoretical outlet NH$_4$-N concentrations according to different design and RFR conditions.

is too small to respect 30 mg KN L^{-1} (Fig. 3b). It is preferable to use total surface of about 1.5 m^2 p.e.$^{-1}$ and 100% of RFR.

4. Recommendations and conclusion

Considering a total surface of 1.1–1.6 m^2 p.e.$^{-1}$ on this studied recirculated single stage VFCW, global removal yields are over 80% for SS, BOD and COD, similar to those obtained on a classical French system (two successive stages VFCWs for a total surface of 2 m^2 p.e.$^{-1}$). Dilution effect induced by recirculation is of importance to reach low outlet levels. Filtering performances stay quite stable with global yields about 90% even when SS loads exceed 250 g m^{-2} d^{-1}. Results suggest that high loading rates up to 600 gCOD m^{-2} d^{-1} can be treated by the system without drastically affecting COD performances. Despite good and stable performances over the course of a year, the outlet concentrations sometimes exceed quality levels due to particularly high raw wastewater concentrations (e.g., BOD$_5$ > 350 mg L^{-1}). In such conditions, a final and simple treatment step can be implemented to retain outlet SS (e.g., vegetative filter strip, vegetated ditches).

The system shows nitrification limitation when HL is superior to 0.7 m d^{-1}, particularly in winter. The minimum outlet level on which it is possible to achieve appears to be of 30 mg KN L^{-1} according to the following design recommendations (i) a total surface (for the 3 parallel VF filters) of 1.5 m^2/p.e., (ii) a 100% RFR, (iii) feeding/resting periods of 3.5/7 days, respectively. Recircluation allows to smooth outlet levels which is positive while input concentrations vary significantly in the course of the day.

Acknowledgments

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