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Effects of design and operational parameters on ammonium removal by single-stage French vertical flow filters treating raw domestic wastewater

Yoann Millot[a,b,c,*], Stéphane Troesch[a], Dirk Esser[d], Pascal Molle[e], Ania Morvannou[a,e], Rémy Gourdon[c], Diederik P.L. Rousseau[b]

[a] Epur Nature, 12 Rue Toussaint Fléchaire, ZAC les balarucs, Caumont-sur-Durance, 84510, France
[b] Ghent University Campus Kortrijk, Department of Industrial Biological Sciences, Graaf Karel de Goedelaan, Kortrijk, 8500, Belgium
[c] University of Lyon, INSA of Lyon, LGCIE—DEEP Team, 20 Avenue A. Einstein, Villeurbanne Cedex, 69621, France
[d] SINT, La Chapelle du Mont du Chat, 73370, France
[e] IRSTEA, Freshwater Systems, Ecology and Pollutions Research Unit, 5 Rue de la Doua—CS70077, Villeurbanne, 69626, France

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ABSTRACT

Four pilot-scale single-stage vertical flow filters (of 2.25 m^2 each), treating raw domestic sewage, were studied over 20 months in order to assess the impact of different designs and operational conditions on treatment efficiency. One of them was designed and operated as a standard 1st stage "French" vertical flow constructed wetland unit. The other 3 pilots differed from the standard pilot with respect to the filtration depth, the loading rate or the partial replacement of gravel by zeolite (chabazite), respectively. The pilots were monitored by analysing 24-h flow-weighted composite samples for TSS, COD_{tot}, COD_d, ammonium, nitrate and carbonate. All pilots showed a high ability to remove TSS and COD_{tot}, with average removal of 81% and 75%, respectively. Increasing the depth of the filtration layer from 40 to 100 cm allowed to significantly improve ammonium removal (81%), whereas the simultaneous increase in hydraulic and organic loads resulted in a deterioration of ammonium and COD_d removals (44% for both parameters). Using zeolite did not induce any observable improvements in ammonium removal under the conditions of the study.

1. Introduction

Constructed wetlands (CWs) for wastewater treatment met an increasing worldwide interest during the past three decades because of their performances, low investment and operational costs and their environmental friendly image. Moreover, this technique is efficient to treat various kinds of effluents such as domestic wastewater, industrial wastewater or combined sewer overflows, etc. (Ávila et al., 2013; Wu et al., 2015; Meyer et al., 2013).

The classical design of "French CW systems" treating raw domestic wastewater (Molle et al., 2005) consists of two vertical flow constructed wetland (VFCWs) stages operating in a sequential mode of feeding and rest periods (3.5 days and 7 days, respectively). The first stage (1.2 m^2/population equivalent), composed of three parallel filters filled with gravel, is fed by batches of raw screened wastewater. Most of the suspended solids and a part of the dissolved pollution (organic matter and ammonium) are removed at this stage. The second stage (0.8 m^2/pe divided in 2 parallel units) filled with sand ensures a further treatment of dissolved pollution under aerobic conditions. This configuration allows high removal performances on COD_{tot}, TSS and TKN, namely over 90%, 95% and 85%, respectively (Morvannou et al., 2015) and also easier sludge management than other conventional processes. Besides, "French systems" have a high tolerance to variation of hydraulic and organic loads (Molle et al., 2006; Arias et al., 2014).

TKN removal is dependent on various parameters such as wastewater composition, design considerations (media characteristics, design loads...) or external parameters (maintenance, climate). Proper design and optimal operation are needed in order to provide favourable conditions for nitrification. Molle et al. (2005) reported that a minimum surface area of 2 m^2/p.e. was required

* Corresponding author at: Epur Nature, 12 Rue Toussaint Fléchaire, ZAC les balarucs, Caumont-sur-Durance, 84510, France.
E-mail addresses: yoann.millot@epurnature.fr (Y. Millot), stephane.troesch@epurnature.fr (S. Troesch), dirk.esser@sint.fr (D. Esser), pascal.molle@irstea.fr (P. Molle), Remy.Gourdon@insa-lyon.fr (R. Gourdon), diederik.rousseau@ugent.be (D.P.L. Rousseau).

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in order to achieve full nitrification for a two-stage VFCW configuration. This may be a problem for larger units or when land availability is limited. Recirculation has been reported to improve TKN removal performance (Prigent et al., 2013). Nevertheless, recirculation increases hydraulic loads and can thus negatively affect oxygen transfers. Prost-Boucle and Molle (2012) proposed to limit the hydraulic load to 0.7m/d on the filter in operation in order not to affect nitrification. Oxygen transfer can be increased by implementing passive or active aeration systems (e.g. tidal flow (Sun et al., 2005) or forced bed aeration (Boog et al., 2014; Foladori et al., 2013; Nivala et al., 2013)). However, such intensifications lead to additional operating costs (Austin and Nivala, 2009).

Current methods for design improvement appear to favour more complex and more intensified systems. The objective of the present study was to assess the extent of removal performance improvement by adapting design parameters without increasing energy consumption. Since nitrification is known to be highly sensitive to several operational conditions such as oxygen transfer into the filter, hydraulic and organic loads or the feeding strategies, it was used as an indicator for design optimisation. Four pilot-scale French VFCWs were monitored over 20 months for this purpose. One of them was designed and operated as a standard 1st stage filter according to the French guidelines (Molle et al., 2005) in order to serve as a reference. The design parameters tested were the filter depth (0.4–1.0 m), the use of zeolite (chabazite) as filter media and the hydraulic and organic loading rates.

2. Materials and methods

2.1. Experimental setup

Four vertical flow pilot filters of 2.25 m^2 each were monitored for 20 months, from March 2014 to October 2015. One of them, denoted as Vertical Flow Standard (VFSt), was designed and operated as a standard 1st stage "French" VFCW unit. The other 3 pilots differed from the standard pilot with respect to the filtration depth (Vertical Flow Gravel$^+$, VFG$^+$), loading rate (Vertical Flow High Load, VFHL) or a partial replacement of gravel by zeolite (Vertical Flow Zeolite, VFZ), respectively.

The pilots were all composed, from bottom to the top, of a 15-cm-deep drainage layer made of 16/22 mm grain size cobbles and a filtration layer whose characteristics are given in Table 1. To avoid particulate migration from the filtration layer to the drainage layer in the VFHL pilot, a 10-cm-deep transition layer (grain size 16/22 mm) was implemented above the 15-cm-deep drainage layer which was composed of 20–50 mm cobbles as shown in Fig. 1.

The pilots were operated outdoors on an experimental site located at the site of a domestic wastewater treatment plant (Jonquerettes, south east of France). This facility allowed us to assess the performance of VFCWs for the treatment of real raw domestic wastewater screened at 20 mm under Mediterranean climate.

A sludge deposit layer was progressively formed at the surface of the filters by accumulation of filtered particles (up to a thickness of 3 cm at the end of the monitoring period). The pilots were planted in September 2013 with one year old plantlets of *Phragmites australis* at a density of 6 plants m^{-2}. According to French guidelines, the pilots were fed for 3.5 days and rested for 7 days. During the feeding periods, 18 batches of 2 cm were applied daily (2 $m^3 h^{-1}$), except for the high load pilot VFHL where 32 batches a day were applied which was considered as the highest acceptable hydraulic load based on full-scale observations. The monitoring started after a commissioning period of five months which was meant to allow for the establishment of microorganisms and reeds.

Table 1
Characteristics of the pilot design.

Pilot units	Studied parameters	Filtration layer			Passive aeration location (cm)[a,c]	Hydraulic load ($m^3 m^{-2} d^{-1}$)[b]	Organic load (gCOD $m^{-2} d^{-1}$)[b]
		Material	Depth (cm)	Sampling systems (cm)[a]			
Standard (VFSt)	Unit of reference	Gravel 2/6 mm	40	10 and 30	Bottom	0.36	234 (62)
Deep Filtration (VFG+)	Effect of filtration depth	Gravel 2/6 mm	100	10, 20, 40, 60, 80	Bottom, 30 and 60	0.36	240 (80)
High Load (VFHL)	Effect of hydraulic and organic loads	Gravel 2/6 mm	30	10	Bottom and 30	0.64	536 (276)
Zeolite Chabazite (VFZ)	Effect of sorbent materials	Gravel 2/6 mm Zeolite 2/5 mm	30 + 10	30 and 40	Bottom	0.36	237 (71)

[a] Depth from the filter surface.
[b] Loads are calculated for the filter in operation.
[c] All drains are connected to the atmosphere, resulting in a passive aeration from the bottom on the length of the filter. The intermediate passive aeration systems consist of drilled pipes, with connection to the atmosphere, which are crosswise implemented in the filtration layer of the pilot.