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Improving phosphorus removal of conventional septic tanks by a recirculating steel slag filter

Short title: P removal from septic tanks by slag filter

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Abstract

The objective of this project was to increase the P retention capacity of a conventional septic tank by adding a recirculating slag filter. Two recirculation modes and recirculation ratios from 5 to 50% were tested in the laboratory with reconstituted domestic wastewater. The best system was recirculation from the end to the inlet of the second compartment of a septic tank with a 50% recirculation ratio in the slag filter, achieving 4.2 and 1.9 mg P/L at the effluent for TP and o-PO_4, respectively, and a pH of 8.8. The calculated size of the slag filter for a 2-bedroom house application was 1875 kg for an expected lifetime of 2 years. The 1 mg P/L level goal was not reached, but P precipitation may be favoured by the relatively high effluent pH reaching the infiltration bed.

Keywords: phosphorus removal, septic tank, steel slag, onsite wastewater treatment

Introduction

In Quebec, the conventional wastewater treatment system for an isolated dwelling consists of a septic tank followed by an infiltration bed (MDDEP 2009). Septical tanks are designed for primary treatment of SS and BOD_5, which are controlled in Quebec regulations. The infiltration bed acts as a secondary treatment system, after which water joins the natural water table. To this day, conventional septic tanks and infiltration beds are not controlled for phosphorus (P), but such systems discharge excess P to the environment via infiltrating water (Robertson et al. 1998), contributing to the eutrophication of freshwaters.

The objective of this project was to improve the P removal capacity of the conventional septic tank - infiltration bed system with a simple and extensive technology. The target total P (TP) concentration of the infiltration water was 1 mg P/L. The selected technology was a steel slag filter fed with the supernatant of the downstream end of the septic tank and recirculating into either the first or the second part of the septic tank. Experimental septic tanks with slag filters were constructed and operated in the laboratory. In this project, focus was given to septic tanks without considering infiltration beds.

Phosphorus removal from wastewater is commonly achieved using intensive processes, as biological treatment (Metcalf & Eddy 2003), coagulation/floculation (Szabo et al. 2008; Evoqua 2014) or membrane filtration (Metcalf & Eddy 2003). Passive technologies for P removal exist, but they are either not reaching 1 mg P/L at effluent (for example constructed wetlands are rapidly saturated, Chazarenc et al. 2007); or very expensive (electrocoagulation system for isolated dwelling, Premier Tech Aqua 2014). Slag was selected for its low cost and its high P removal capacity.

Slag is a by-product of the steel industry that is known to capture P (Yamada et al. 1986; Vohla et al. 2011). Several metallurgic processes result in different slag types and size (National Slag Association 2009). Slag filters are currently operated as tertiary treatment units in research projects for P removal (Chazarenc et al. 2008), but long-term full-scale units are limited to a unique process operated in New-Zealand (Shilton et al. 2006), to the authors' knowledge. A particular application of slag for wastewater treatment is the alkaline slag filter, containing alkaline gravel-size slag. This type of filter raises the wastewater pH to 10-11 and induces P precipitation and filtration (Claveau-Mallet et al. 2012). As a passive and highly efficient P-removal technology, the slag filter is a promising and economical unit to upgrade septic tanks for P removal. However, its high effluent pH complicates its direct application, as a pH 11 is not suitable for discharge or infiltration. It is also possible that the required filter size and replacement cost for a 2-year longevity (MDDEP 2009) may be uneconomical. Recirculation in the slag filter is a strategy that represents a compromise between P removal, effluent pH and filter size. Moreover, addition of a slag filter in the septic tank may favour P precipitation and stabilization in the infiltration bed (Robertson et al. 1998).

Materials and Methods

Experimental Unit

A schematic of the experimental pilot unit is shown in Fig. 1. Septic tank compartments were represented by two covered 26 L plastic boxes. The water volumes in compartments 1 and 2 were 20 L and 10 L, respectively. The outlet of compartments was controlled by overflow tubing. Septic tanks were fed with reconstituted domestic wastewater using a peristaltic pump with intermittent operation (8 feedings per day, for an average flowrate of 14.2 L/d). The total HRT of the septic tank was 2.1 d, according to Quebec requirements (MDDEP 2009). Two slag filter recirculation modes were tested: recirculation from compartment 2 back to compartment 1inlet, and recirculation within compartment 2. Slag filters were fed from the bottom with intermittent operation. Filters had a diameter of 15 cm and a length of 39 cm. The experimental unit was sampled at different points (see Fig. 1) and samples were analyzed for COD (chemical oxygen demand), TSS (total suspended solids), VSS (volatile suspended solids), TP, orthophosphate (o-PO_4), calcium, alkalinity, pH and conductivity. Tests were divided into 6 phases with varying recirculation ratio, as shown in Table 1. They were conducted from June to November 2013.

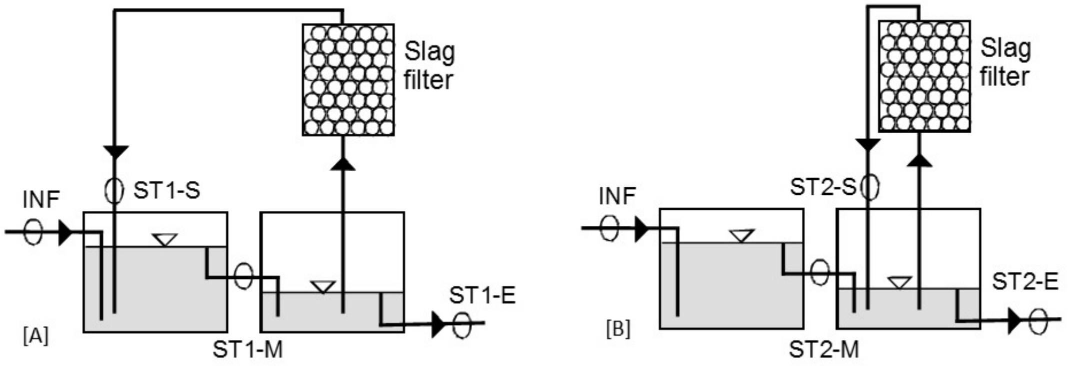

FIGURE 1. Schematic of the experimental unit showing recirculation from compartment 2 to 1 [A] and from compartment 2 to 2 [B]. Sampling points and their label are identified on the schematic by circles

TABLE 1. Experimental program

Phase	Wastewater type[a]	Duration	Slag filter recirculation ratio	Slag filter influent flowrate	Slag filter HRTv
		d	%	L/d	h
1	1	20	5	0.71	118
2	1	20	10	1.42	59
3	1	19	25	3.55	24
4	2	9	25	3.55	24
5	2	19	50	7.11	12
6	2	20	10	1.42	59

a: see Table 2 for Wastewater composition

At the end of all phases, each compartment was homogeneously mixed and sampled in triplicates. Slag filters were emptied, sampled and analyzed for a P mass balance.

Slag Media and Wastewater Characteristics

The slag used in this study was 5-10 mm electric arc furnace slag produced by Arcelor Mittal, Contrecoeur, Quebec. This slag was previously used for P removal filter applications (Lospied 2003; Chazarenc et al. 2007; Anjab 2009; Claveau-Mallet et al. 2012; Mahadeo 2013; Claveau-Mallet et al. 2014). The chemical composition of slag was (% w/w): 40.6 CaO, 18.2 Fe_2O_3, 16.3 SiO_2, 10.2 MgO, 5.1 Al_2O_3, 3.9 MnO, 0.47 P_2O_5, 0.44 TiO_2, 0.41 Cr_2O_3, 0.05 Na_2O and 0.03 K_2O.

Septic tanks were fed with reconstituted wastewater. Primary sludge, KH_2PO_4, K_2HPO_4 and $NaHCO_3$ were added to tap water, resulting in wastewater characteristics presented in Table 2. Two wastewater sludges were used, with a higher suspended solids content for wastewater 2. Feeding was done from a continuously mixed barrel kept at 4°C which was renewed and analysed every 6 days.

TABLE 2. Reconstituted water composition

Parameters	Units	Wastewater 1	Wastewater 2
Sludge origin (wastewater treatment plant)		Auteuil (Laval)	St-Hyacinthe
pH	-	7.6±0.2	7.3±0.1
o-PO_4	mg P/L	10.5±0.6	9.7±1
TP	mg P/L	14±4	22.7±4.5
Calcium	mg/L	30±2	30±2
Alcalinity	mg $CaCO_3$/L	228±3	235±7
Conductivity	µS/cm	598±20	594±5
COD	mg/L	44±6	567±200
TSS	mg/L	16±5	441±190
VSS	mg/L	14±3	283±130

Analytical Determinations

Slag composition was determined by Acmelabs (Vancouver) by ICP-emission spectrometry. Analyses for COD, TSS, VSS, TP, o-PO_4, calcium and alkalinity were conducted following standard procedures: methods 5220-D, 2540-D, 2540-E, 4500-P-F, 3500 and 2320-B (APHA et al. 2012).

Calculations for Full-Scale Application

The full-scale size of a slag filter (mass and volume) was calculated according to equations 1 and 2, that were developed by the authors. These equations are based on the P retention capacity (r_{max}) and P mass balance of the slag filter. The equation parameters are defined in Table 3.

$$m_{slag} = \frac{Q_{slag}\left(c_{i-slag} - c_{o-slag}\right)T_{life}}{r_{max}} \times \frac{(365\,d/year)}{(1000\,g/kg)} \tag{1}$$

$$V_{slag} = \frac{m_{slag}}{\rho_{slag}} \tag{2}$$

Equations 1 and 2 were used to design a full-scale application. Q_{slag} was chosen based on experimental results.

TABLE 3. Parameters for equations 1 and 2

Description	Symbol	Units
Required lifetime	T_{life}	year
Dry density of slag filter	ρ_{slag}	kg slag/m^3
Total influent flowrate in septic tank	Q	L/d
Influent flowrate in the slag filter	Q_{slag}	L/d
Influent conc. of the slag filter	$c_{i\text{-}slag}$	mg P/L
Effluent conc. of the slag filter	$c_{o\text{-}slag}$	mg P/L
P retention capacity of slag filter	r_{max}	g P/kg slag
Mass of slag filter	m_{slag}	kg slag
Volume of slag filter (including porosity)	V_{slag}	m^3

Results

Wastewater composition monitoring

COD, TSS and VSS results are presented in Fig. 2. Both systems were efficient for settling, as shown in Fig. 2. TSS were reduced below 70 mg/L after the first compartment. The settling efficiency was not changed by the drastic increase of influent TSS related to the change of wastewater. VSS and COD curves were similar to TSS curves.

The effect of the slag filter on P removal is shown in Fig. 3. The slag filter had a negligible effect on the global P and o-PO_4 removal at recirculation ratio of 5 and 10%, while recirculation ratio of 25 and 50% reduced the P concentration at effluent. pH at the outlet of the slag filter was kept at 11 for the whole test duration. The slag filter increased pH in the first and second compartments from 7.5 to up to 9. pH 9 represents a discharge target in the infiltration bed suitable for P precipitation (Robertson et al. 1998; Valsami-Jones 2001). The system was stable, as concentrations of the second 10% phase were similar to concentrations of the first 10% phase. Low o-PO_4 concentrations were related to high pH, as reported in past studies (Vohla et al. 2011; Claveau-Mallet et al. 2012). High pH increases OH^- and PO_3^{4-} concentrations, which results in hydroxyapatite ($Ca_5(PO_4)_3OH$) supersaturation and precipitation (Valsami-Jones 2001; Claveau-Mallet et al. 2014). P concentration at the outlet of slag filter were below 1 mg P/L for TP and below 0.1 mg P/L for o-PO_4.

The slag exhaustion behavior is shown in Fig. 4. Alcalinity, calcium and conductivity curves were similar: the slag effluent concentration was high at the beginning and it slowly decreased. High calcium, alcalinity and conductivity were related to high pH. Concentrations in the other sampling points were constant and similar to the influent concentration. The concentration of the slag filter effluent of system 1 was higher and decreasing faster then the one of system 2. This difference was probably related to the variability of the slag. The slag filter of system 1 may have contained several reactive slag particles. Previous work conducted by the authors showed that slag behavior can be variable (results not shown). In a full-scale application, slag reactivity and its variability should be characterized to ensure a sufficient filter longevity.

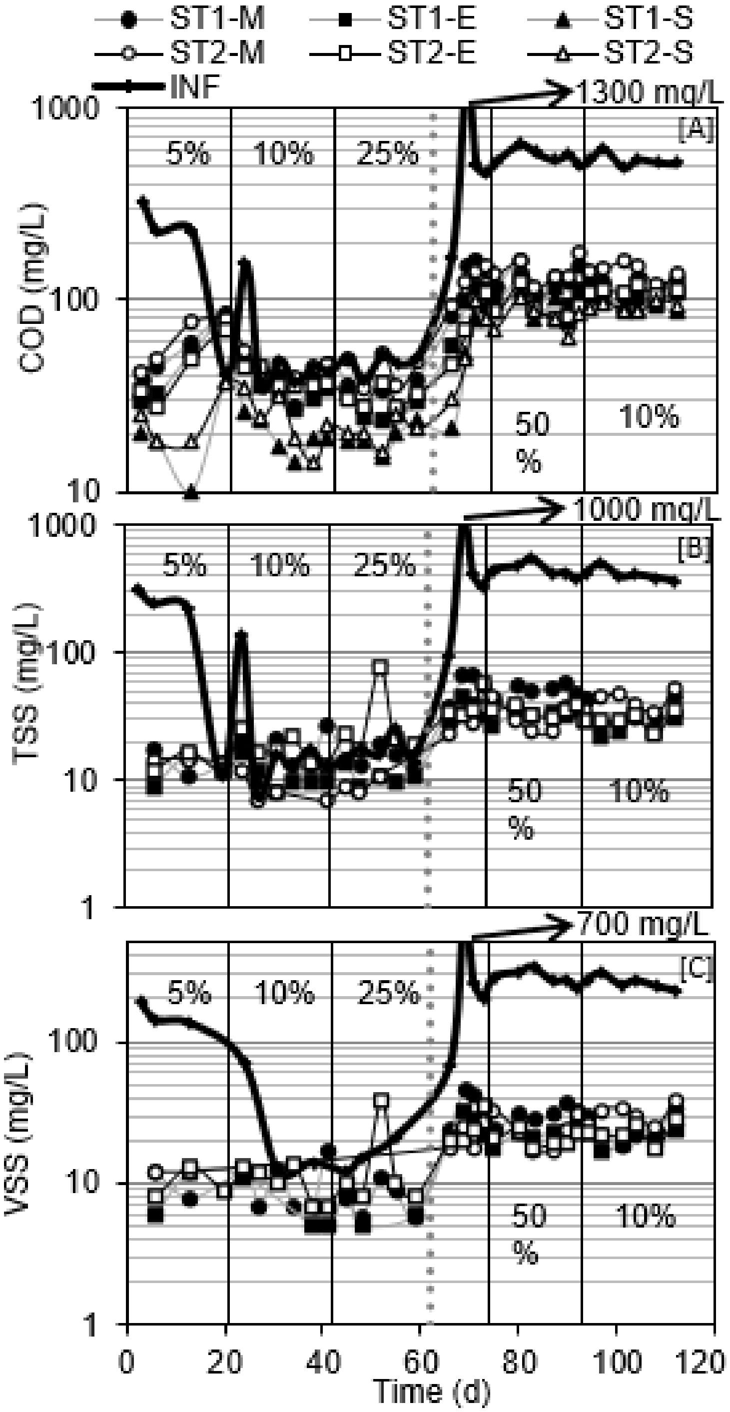

FIGURE 2. COD [A], TSS [B] and VSS [C] monitoring of the pilot unit. Recirculation phases (5, 10, 25, 50 and 10%) are indicated with vertical lines. The transition from wastewater 1 to wastewater 2 is indicated by the grey dotted line

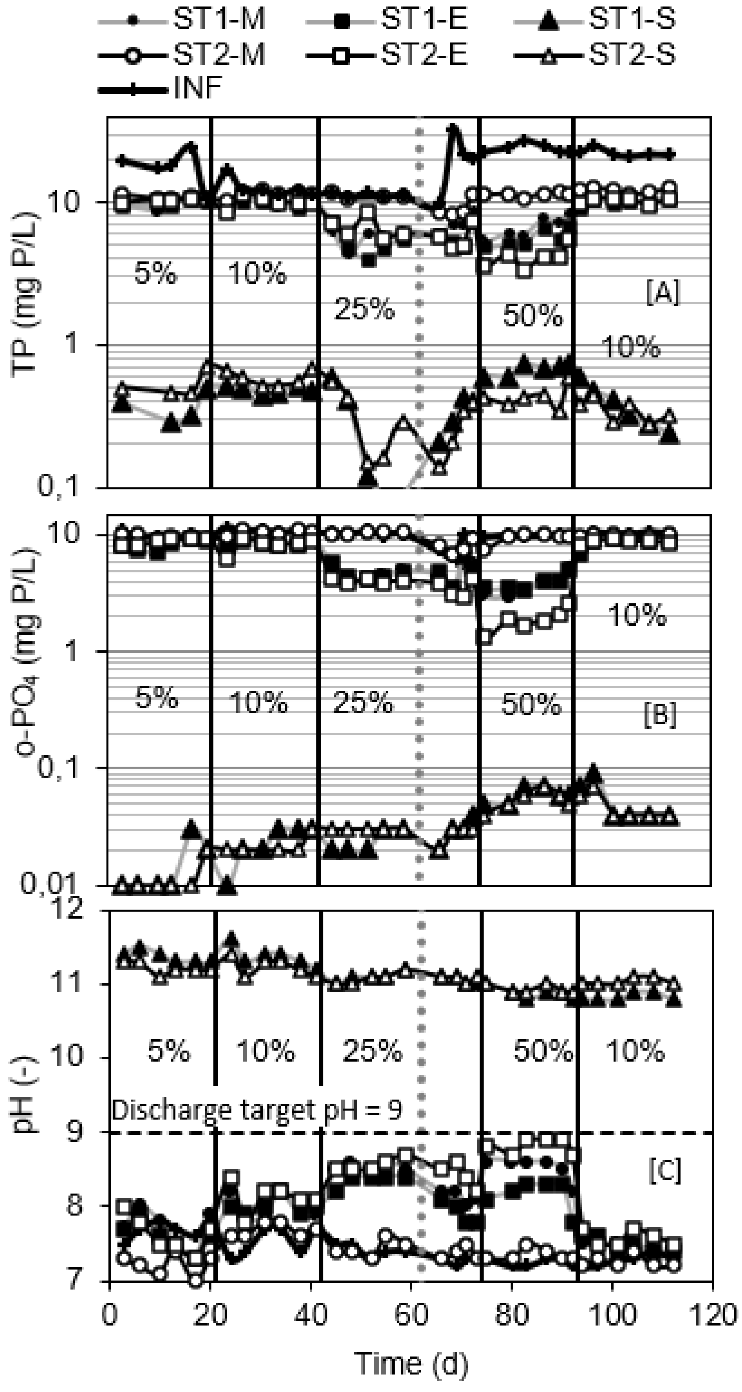

FIGURE 3. TP [A], o-PO$_4$ [B] and pH [C] monitoring of the pilot unit. Recirculation phases (5, 10, 25, 50 and 10%) are indicated with vertical lines. The transition from wastewater 1 to wastewater 2 is indicated by the grey dotted line

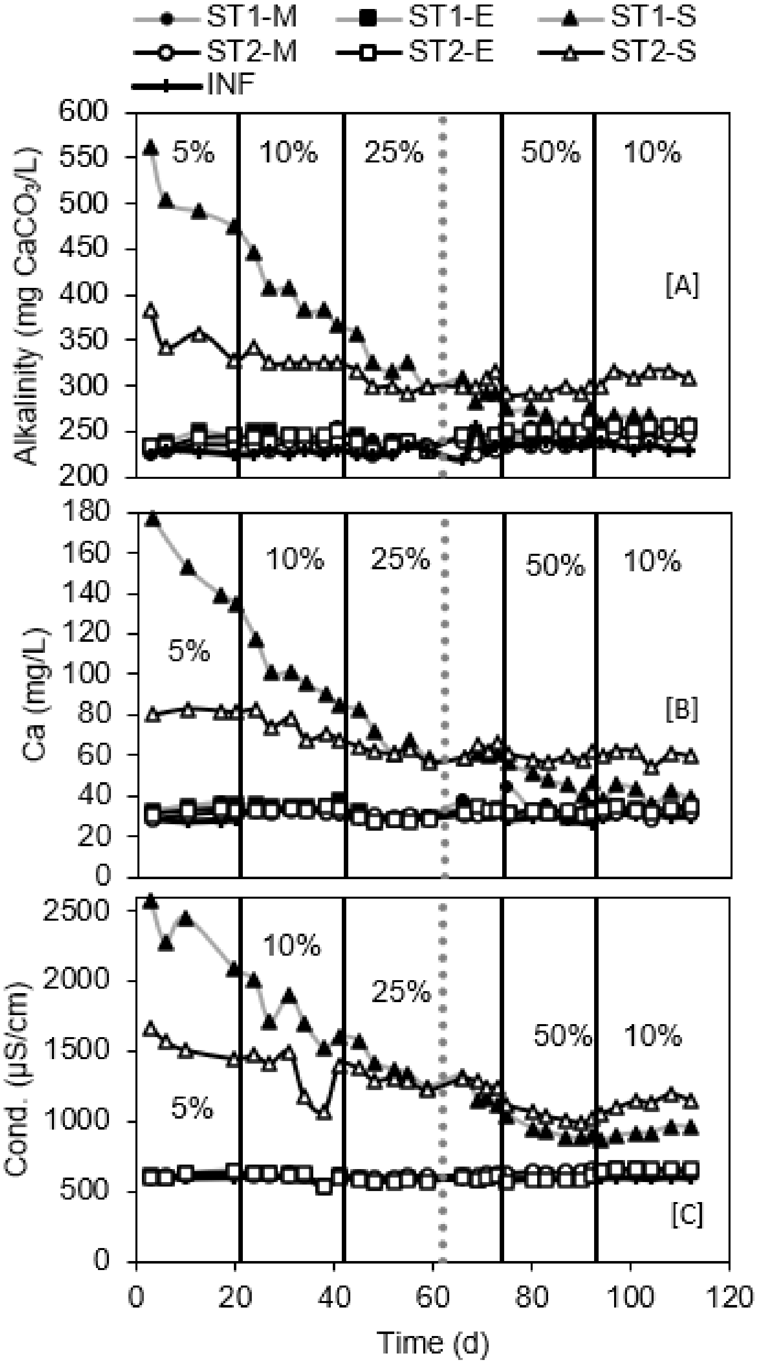

FIGURE 4. Alkalinity (A), calcium (B) and conductivity (C) monitoring of the pilot unit. Recirculation phases (5, 10, 25, 50 and 10%) are indicated with vertical lines. The transition from wastewater 1 to wastewater 2 is indicated by the grey dotted line

Phosphorus mass balance

A mass balance of TP was performed on both systems at the end of the experiment. The amount of P accumulated in the first compartment, second compartment and slag filter was determined by experimental measurement at the end of the experiment. The amount of total P that passed each tubing section was calculated according to equation 3.

$$AP_z = \sum Qc_i\Delta t_i \tag{3}$$

where AP_z is the amount of P in tubing section z (g P), Q the influent flowrate (L/d), c_i is the concentration of P in interval i (mg P/L) and Δt_i is the duration of interval i (d). Accumulated amounts of P in each unit or tubing section are shown in Fig. 5. The mass balance was calculated according to the following equation:

$$Mass\ balance\ (\%) = \frac{Accumulated\ P + Outlet\ P}{Inlet\ P} \tag{4}$$

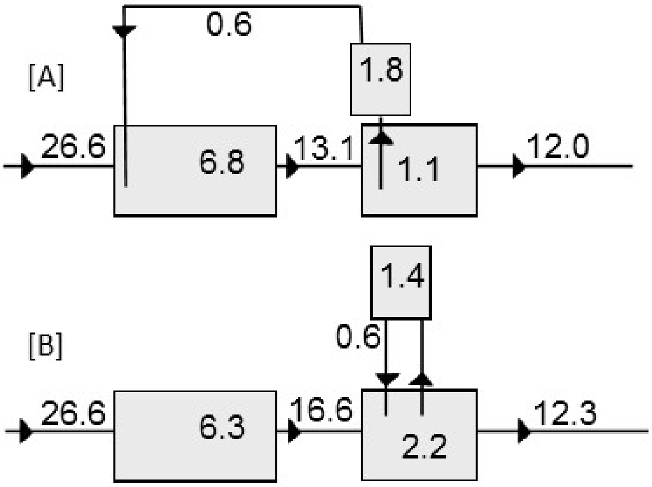

FIGURE 5. TP fluxes (units in g) for the whole duration of the experiment in system 1 [A] and 2 [B]. Fluxes are indicated next to arrows. Accumulated P measured at the end of the experiment is indicated in each compartment

The global mass balances were 82% and 83% for systems 1 and 2, respectively. Mass balances for each unit are less accurate but they remain satisfying considering the technical challenges for representative sampling of coarse media. Amounts of accumulated P were similar in both systems, except for the second compartment, where P was more retained in system 2, which is advantageous (Fig. 5). Accumulated P is divided in two fractions: stabilized organic matter in septic tanks (~84%), and precipitates of calcium phosphate in the slag filter (~16%). In a full-scale application, P from the slag filter could be recovered in agricultural uses (Bankole et al. 2011), while P from the septic tank would be sent to subsequent treatment facilities according to the routine emptying of the tank.

Discussion

P Removal Performance and Selection of the Best System

A comparison of TP and o-PO_4 concentration at the effluent of the pilot unit for all recirculation phases and both systems is presented in Fig. 6. Recirculation ratio of 5 and 10% did not result in satisfying P removal, with concentration at effluent of ~8 mg P/L o-PO_4 and ~10 mg P/L TP. The 25% and 50% recirculation ratio were better with ~5 and ~6 mg P/L at effluent, but they did not achieve the objective of 1 mg P/L. The 50% ratio for system 2 resulted in the lowest P concentrations of ~3 and ~4 mg P/L for o-PO_4 and TP and it was the recommended system (Fig. 7).

The recommended system achieved 4.2 mg P/L and 1.9 at effluent for TP and o-PO_4, compared to 10 and 9 mg P/L with a 5% recirculation ratio. This result represents a significant amount of P removal, but it did not reach the initial objective of 1 mg P/L TP.

The objective may be reached by the following infiltration bed, where filtration and precipitation should occur (Robertson et al. 1998). As the pH entering the infiltration bed is raised by the slag filter to 8.8, calcium phosphate precipitation could be favoured in the infiltration bed (Metcalf and Eddy 2003). Stable calcium phosphates as hydroxyapatite could form and stop P migration (Valsami-Jones 2001). Thus, the combination of the recommended system with the infiltration bed could result in water infiltrating in the natural soil with less than 1 mg P/L of TP. The subsequent step of this project would be to install the system in a real septic tank and monitor water properties in the infiltration bed.

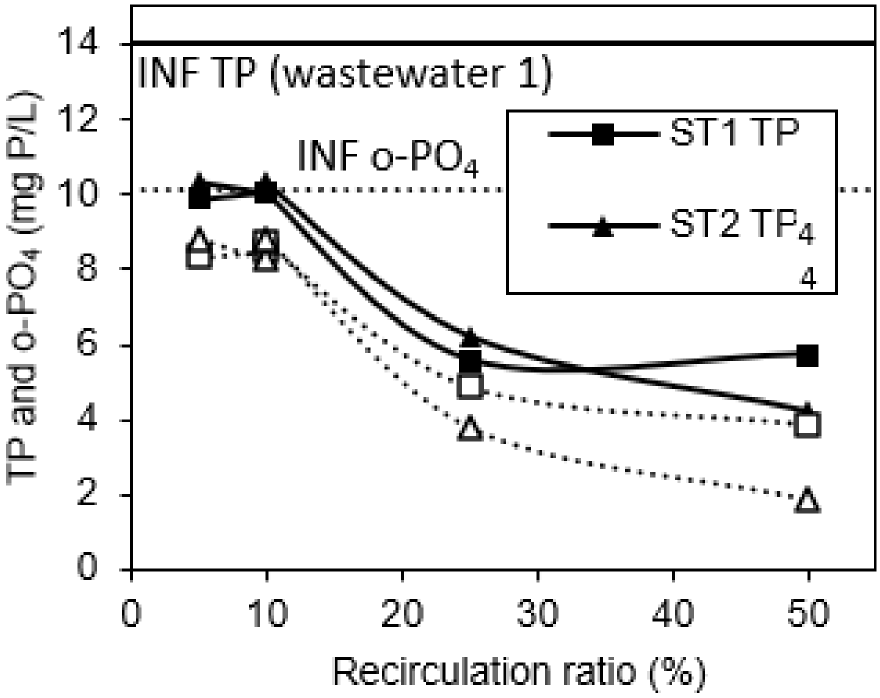

FIGURE 6. Relationship between mean P concentration at the effluent of the pilot unit and recirculation ratio

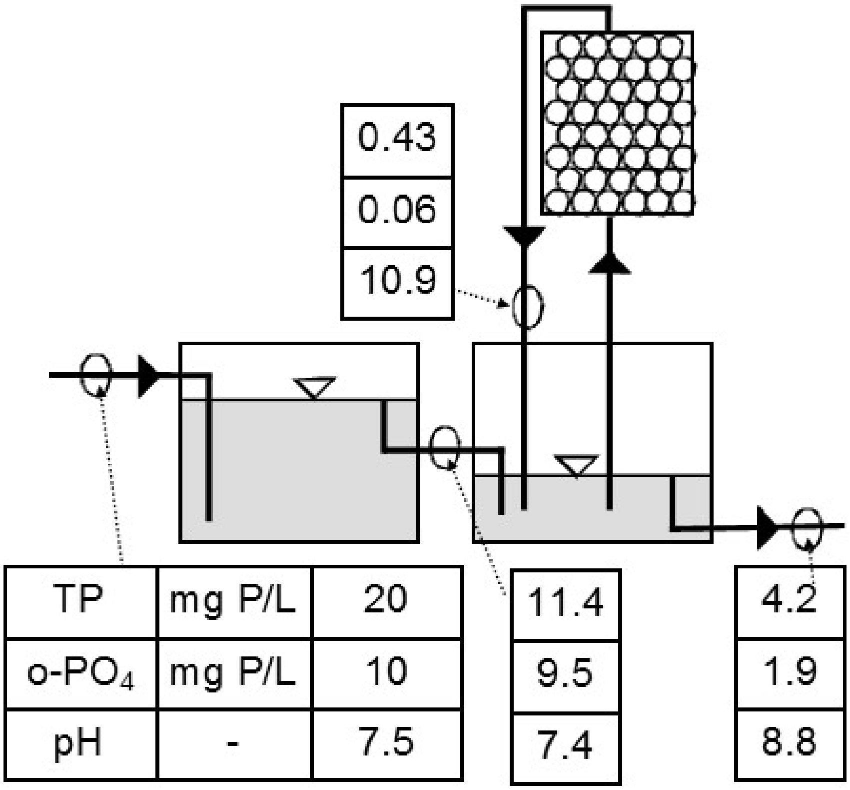

FIGURE 7. Recommended system (system 2 with 50% recirculation in the slag filter) and selected wastewater characteristics

Application to a Full-Scale System

The application of the recommended system to an isolated two-bedroom dwelling is presented in Table 4.

TABLE 4. Application of the proposed system to an isolated two-bedroom dwelling

Description	Parameters	Units	Value			Comments
Input						
Required lifetime	T_{life}	years	2			From Quebec requirements (MDDEP 2009)
Dry density of slag filter	ρ_{slag}	kg slag/m^3	1800			Estimated assuming 50% porosity
Total influent flowrate	Q	L/d	1080			For a 2-bedroom house
Influent flowrate in the slag filter	Q_{slag}	L/d	540			50% recirculation
TP concentration at the inlet of the slag filter	$c_{i\text{-}slag}$	mg P/L	10			From this study
TP concentration at the outlet of the slag filter	$c_{o\text{-}slag}$	mg P/L	0.5			From this study
Scenarios for 3 assumptions						
P retention capacity of the slag filter	r_{max}	g P/kg slag	2	3	4	see Table 5
Calculation						
Slag filter mass	m_{slag}	kg slag	1875	1250	938	From Equation 1
Slag filter volume	V_{slag}	m^3	1.04	0.69	0.52	From Equation 2
Validation						
Voids hydraulic retention time of the slag filter	HRT_V	h	23.1	15.4	11.6	Ok if HRT_V high enough (see text)
Filter longevity	FL	pore volumes	758	1143	1516	Ok if longevity low enough (see text)
Similar calculations for a 6-bedroom house						
Slag filter mass	m_{slag}	kg	5610	3740	2805	Corresponds to Q = 3240 L/d (MDDEP 2009)

Calculations presented in Table 4 illustrate an iterative process: 1- choice of r_{max}, 2- calculation using equations 1 and 2, and 3- validation of the HRT_V and filter longevity. If the HRT_V is too low or the longevity too high, then r_{max} is not realistic and a lower value must be used. Criteria values for longevity and HRT_V can be determined following past experimental work or modelling. The choice of r_{max} is critical, as it influences directly the filter mass. r_{max} has to be estimated according previous studies (c. f. Table 5). r_{max} is influenced by the HRT_V, influent P concentration and presence of buffers in the water to treat (Claveau-Mallet et al. 2014). The authors recommend to use the *P-Hydroslag* model (Claveau-Mallet et al. 2014) for the determination of r_{max}. This model considers the specific influent composition of each wastewater and the HRT_V of the filter. It also facilitates the validation step, as the model uses a known HRT_V and it calculates the filter longevity. According previous work using the P-hydroslag model with similar conditions, the authors recommend r_{max} = 2 g P/kg slag (second line of Table 5: the model results in r_{max} = 2.3 g P/kg slag, HRT_V = 16 h and longevity = 820 pore volumes). The validation criterion provided by the model is respected: 23.1 h > 16 h and 760 pore volumes < 820 pore volumes. The corresponding filter mass is 1875 kg. The *P-Hydroslag* model is a useful tool, as it considers the specific composition of the wastewater and of the slag. It is also possible to evaluate the sensitivity of given parameters (HRT_V, P concentration, etc.) on r_{max} and longevity.

The recommended value for r_{max} (2 g P/kg slag) may seem prudent when compared to other past experimental values (up to 6 g P/kg slag, Claveau-Mallet et al. 2012). However, these slag filters were fed with synthetic solutions containing only o-PO_4 salts. If inorganic carbon, particulate matter or other buffers were added to the influent, r_{max} would probably be lower. Past work showed that the presence of inorganic carbon reduces r_{max} (Claveau-Mallet et al. 2014). Ideally, the *P-Hydroslag* model should be run with data obtained from a representative wastewater sample.

On a full-scale application, the slag filter effluent composition should be monitored to insure that pH is kept above 10. pH monitoring as a control method is a challenge, as pH may drop suddenly with a corresponding decrease in P removal efficiency as have been observed with slag filters (Claveau-Mallet et al. 2012, 2014). One way to overcome this problem would be to monitor slag filter by conductivity. As the conductivity decrease is regular (Fig. 4) and is related to high pH, it would be possible to define a conductivity criteria after which the filter is not any more efficient. The development of such a methodology will be part of future work.

TABLE 5. P Retention capacity obtained in previous studies conducted with the same slag

Influent o-PO_4	HRTv of slag	Retention capacity[a]	Longevity[a]	Type of water	Ref	Notes
mg P/L	h	mg P/g slag	pore volumes			
10	16	3.2	1200	Num. simulations	Claveau-Mallet et al. 2014	P as o-PO_4 only in distilled water
10	16	2.3	820	Num. simulations	Claveau-Mallet et al. 2014	P as o-PO_4 only, water contained 0.5 mM $NaHCO_3$
10	?	>2	?	Fishfarm effluent	Chazarenc et al. 2007	On-site pilot unit
26	16.3	>6.3	>911	Synthetic	Claveau-Mallet et al. 2012	P as o-PO_4 only in distilled water
27	3.8	1.1	200	Synthetic	Claveau-Mallet et al. 2012	P as o-PO_4 only in distilled water
2-8	15	>0.5	>677	Fishfarm effluent	Brient 2012 Mahadeo 2013	On-site pilot unit preceded by slag filter
2-8	6	0.9	1722	Fishfarm effluent	Brient 2012 Mahadeo 2013	On-site pilot unit preceded by slag filter
20 to 120	24	2.2	113	Synthetic	Lospied 2003	P as o-PO_4 only in distilled water
26 to 130 TP	31	>3.6 (for TP)	>209 (for TP)	Reconstituted fishfarm effluent	Abderraja Anjab 2009	Preceded by 93 void volumes of tap water feeding

[a]: Retention capacity and longevity reached when the effluent concentration exceeds 1 mg P/L o-PO_4

Conclusion

The objective of this project was to improve the P retention capacity of a conventional septic tank by adding a recirculating slag filter. The best tested system at bench scale with a reconstituted wastewater influent was by recirculating within compartment 2 with a 50% recirculation ratio in the slag filter, achieving 4.2 and 1.9 mg P/L at the effluent for TP and o-PO_4, respectively, and pH 8.8. The calculated mass of the slag filter for a 2-bedroom house application was 1875 kg. The 1 mg P/L goal was not reached, but P precipitation should be favoured by the relatively high effluent pH reaching the infiltration bed. This study will be followed by a full-scale project in a septic tank, including monitoring of the infiltration water.

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List of Abbreviations

COD	Chemical oxygen demand (mg/L)
$c_{i\text{-}slag}$	Concentration at the inlet of the slag filter (mg P/L)
$c_{o\text{-}slag}$	Concentration at the outlet of the slag filter (mg P/L)
FL	Slag filter longevity (pore volumes)
HRT_V	Hydraulic retention time of voids of slag filter (h)
INF	Influent
m_{slag}	mass of the slag filter (kg)
o-PO_4	Orthophosphate
P	Phosphorus
ρ_{slag}	Dry density of slag filter (kg slag/m^3)
Q	Total influent flowrate in the septic tank (L/d)
Q_{slag}	Influent flowrate in the slag filter (L/d)
r_{max}	P retention capacity of the slag filter (g P/kg slag)
ST1-E	Septic tank 1 - effluent sampling

ST1-M	Septic tank 1 - middle point sampling
ST1-S	Septic tank 1 - slag filter effluent sampling
T_{life}	Required longevity of the slag filter (years)
TP	Total phosphorus (mg P/L)
TSS	Total suspended solids (mg/L)
V_{slag}	Volume of the slag filter including porosity (m^3)
VSS	Volatile suspended solids (mg/L)