



Phosphorus reduction in filters for on-site wastewater treatment

Brenda Vidal*, Annelie Hedström, Inga Herrmann

Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Laboratorievägen 14, 971 87 Luleå, Sweden



ARTICLE INFO

Keywords:

Sand filters
Polonite
Small-scale
Septic system
Composite samples

ABSTRACT

Discharges of phosphorus (P) from on-site wastewater treatment systems generally contribute to eutrophication problems in Swedish freshwaters and, ultimately, in the Baltic Sea. Such concerns have led to a growing interest in improving P removal in treatment facilities. This study investigated the reduction of P in 12 full-scale on-site treatment systems featuring sand filters and alkaline P-filters by sampling and analysing filter influents and effluents. The flow-proportional samples collected were analysed for total and dissolved P, BOD₇, total and dissolved organic carbon (TOC and DOC), and pH. Seven of the eight investigated sand filters did not provide satisfactory total P reduction; the likely explanations are filter clogging and wastewater dilution by extraneous water. In addition, effluents from four of the eight sand filters had total P concentrations higher than 3 mg L⁻¹, which is the Swedish effluent limit recommended for common receiving waters, indicating that a subsequent polishing step would be needed. Six of the nine investigated P-filters reduced P adequately, with total P concentrations in the effluent ranging between 0.1 and 1.9 mg L⁻¹. The three underperforming P-filters had effluent pH values below 9; filter age, clogging, and hydraulic overload were identified as probable reasons for their poor performance. A statistically significant correlation was found between total-P reduction and filtrate pH, but no significant correlation was detected between organic load in the influent and P reduction by the P-filters. The P-filter media replacement frequency could not be established, but filtrate pH appeared to be a good estimator.

1. Introduction

Eutrophication, caused by excess nutrients such as nitrogen (N) and phosphorus (P) in water bodies, is acknowledged as the single largest environmental problem in the Baltic Sea [1]. All Swedish waters—including lakes, rivers and coastal waters—have been identified as sensitive to P discharge [2]. Moreover, the gross discharge of P from private small-scale wastewater systems (septic systems) in Sweden is as large as the discharge from all municipal wastewater treatment plants together, accounting for 15% of the total anthropogenic release of P [3].

The Swedish regulation for small-scale wastewater facilities (< 25 person-equivalents) consists of a set of guidelines recommending certain reductions for P, N, and organic carbon measured as BOD [4]. The suggested criteria are 70 and 90% removal of total P (tot-P) for common and highly sensitive receiving waters, corresponding to tot-P effluent concentrations of less than 3 and 1 mg L⁻¹, respectively. However, it is estimated that less than 50% of the approximately 700,000 existing facilities provide adequate treatment and comply with these guidelines [5,6]. Thus, better understanding of how much P these facilities remove and how long the filters maintain their efficiency after installation is needed.

On-site wastewater treatment facilities in Sweden usually consist of primary treatment in a septic tank followed by secondary treatment; usually either soil-based systems such as sand filter beds or drain fields, or package treatment plants. Both biological and physicochemical processes can occur in secondary treatment. Additionally, where required, a tertiary treatment with an alkaline filter (P-filter) can be added as a final polishing step to remove P. The effluent water is discharged into the subsoil or into receiving water bodies (e.g., ditches, streams, lakes or the sea).

Extensive reviews of P removal and recovery technologies [7] and specifically of reactive filter materials for P sorption [8] have highlighted the potential benefits and development of P removal and recycling. Removal of P in P-filters and sand filters is influenced by the hydraulic and organic load of the incoming wastewater [9,10] and the physical and chemical properties of the filter material, e.g. mineralogy, grain size and pH [10–12]. Biofilm growth and clogging may occur and diminish the efficiency of the filter material. The efficiency of sand filters with respect to hydraulic and biological behaviour such as biofilm development [10], clogging mechanisms [13] and performance under cold-weather conditions [14,15] has been previously studied in laboratory and pilot-scale tests and field conditions [16]. Materials used in P-filters for on-site treatment have been also studied in laboratory-

* Corresponding author.

E-mail addresses: Brenda.Vidal@ltu.se (B. Vidal), Annelie.Hedstrom@ltu.se (A. Hedström), Inga.Herrmann@ltu.se (I. Herrmann).

Table 1

On-site wastewater treatment facilities in the study (table adapted from [25]). The columns Years in use refer to the number of years the treatment units had been in use at the time of sampling.

Facility	Main treatment unit	Years in use	P-filter unit	Years in use	No. of users	Frequency of use
A	Sand filter, Swedish standard	6–7	–	–	3	Year-round
B	Sand filter, with biomodules	2–3	–	–	2	Year-round
C	Sand filter, with biomodules	1	–	–	5	Year-round
D	Sand filter, Swedish standard	1–2	Bag with Polonite, down-flow	1–2	2	Year-round
E	Sand filter, Swedish standard	6–7	Wavin-Labko tank with Filtra P	6–7	5	Year-round
F	Sand filter, with biomodules	5	Bag with Polonite, up-flow	1	2	Summer
G	Sand filter, with biomodules	3	Bag with Polonite, up-flow	1	2	Summer
H	Sand filter, with biomodules	< 1	Bag with Polonite, up-flow	< 1	2	Year-round
I	Biological fibre material in a tank	3	Bag with Polonite, up-flow	2	2	approx. 6 months/year
J	Biop [®] , biofilm treatment without aeration	7	Bag with Polonite, up-flow	< 1	7 ^a	Year-round
K	Biop [®] , biofilm treatment without aeration	7	Bag with Polonite, up-flow	< 1	7 ^a	Year-round
L	Activated sludge with aeration	< 1	Bag with Polonite, up-flow	< 1	2	Year-round

^a Facilities J and K served the same 14 users in total; the wastewater was pumped from the septic tank to a distribution chamber where the flow was diverted into the two separate Biop[®] facilities. Evenly distributed flows to the two P-filters were assumed, thus serving 7 users each.

and pilot-scale tests [17,18], but only few full-scale studies have been published. These full-scale studies include [19], who investigated the performance of nine filter beds containing Filtralite[®] P filter media in several Nordic countries, and [20] who compared the nutrient removal efficiency of 13 different sand filters in Finland.

Despite previous laboratory and pilot-scale studies, there is a lack of full-scale studies on P removal in both sand filters and P-filters. In particular, investigations based on flow-proportional sampling (instead of grab sampling) are rare, probably due to the laborious nature of the methodology [20]. Moreover, grab sampling can result in the collection of non-representative samples due to the varying flow and concentration of wastewater constituents, and can increase the uncertainty range of the results, especially when analysing tot-P loads [21].

The objective of this study was to investigate the reduction of P in full-scale on-site wastewater treatment systems equipped with either sand filters and/or P-filters, using flow-proportional sampling; the analysis focused on filter performance and compliance with current guidelines. The study also examined whether pH can be used as a parameter for deciding when the filter media needs to be changed.

2. Materials and methods

2.1. Investigated facilities

Twelve on-site wastewater treatment facilities (A–L) were investigated (Table 1): A–C (sand filters), D–H (sand filters with P-filters) and I–L (P-filters). Four of the P-filters were installed in small package plants and five were installed downstream from sand filters. The remaining three sand filters did not have any downstream treatment.

The sand filters in facilities A, D and E were built according to Swedish standards and consisted of a 80 cm layer of filter media (sand and gravel, particle sizes 2–8 mm) with a design load of 30–60 L m⁻² d⁻¹ and a typical surface area of 25 m² [22]. The lifespan of sand filters has been estimated to 15 years [23] however, it is often used for 20–30 years [6]. The wastewater was distributed through slotted pipes and filtered vertically through the filter bed to the bottom of the system, where it was collected in drainage pipes. The sand filters in facilities B and C were smaller in size than the Swedish standard and contained plastic crates (biomodules) to increase their hydraulic capacity. Sand filters F, G and H used a slightly different construction method than the standard, and had a layer of drainage baskets on the top (biomodules) with a triangular cross section, about 0.5 m wide, where the distribution pipe was located. All sand filters were covered with an approximately 30 cm thick layer of soil.

The nine P-filters consisted of bags filled with P-sorbing material. In eight of them, the filter media Polonite was used (supplier: Ecofiltration AB, Sweden), placed in a plastic container installed at ground level, and

Table 2

Summary of the sampling campaigns.

Facility	No. of sampling occasions	Sampling period	Duration of sampling (total hours)	Volume collected (total L) ^a
A	7	Sept 2015–June 2016	25	1124
B	3	May–June 2016	13	41
C	3	May–June 2016	9	95.9
D	6	Sept 2015–May 2016	17	172
E	6	Sept 2015–May 2016	17	274.2
F	3	Aug 2016	7	44
G	3	Aug 2016	8	16
H	4	Aug 2016	9	47.4
I	3	Aug 2016	8	553
J	3	Aug–Sept 2016	10	400.5
K	3	Aug–Sept 2016	11	323
L	3	Aug–Sept 2016	8	368

^a The volume collected during the sampling campaigns varied considerably due to differences in flow and practicalities such as the time of the day and presence of users. Facility I had a water use higher than usual during the sampling days; facility L was sampled only during evening hours.

operated in down-flow (D) or up-flow (F–L) mode. In facility E, the filter media Filtra P (supplier: Wavin-Laboko Ltd) was used and placed in two chambers installed at different levels so the wastewater percolated downwards through the filter media in the first chamber and upwards in the second chamber. Facilities I, J, K and L had P-filters installed inside package plants that functioned as a pre-treatment for the P-filters. Alkaline P-filters should be replaced after 2–3 of years of use, according to the producers [24].

Facility I was a package plant (4evergreen by Biorock[®]) consisting of a trickling filter made of fibre material installed inside a HDPE tank where the wastewater percolated through. Facilities J and K were Biop[®] plants that consisted of a PE unit with multi-stage biological treatment based on attached growth with no aeration and facility L was an aerated activated sludge system installed inside of a HDPE unit (Ecobox Small by Ecotech AB).

2.2. Water sampling and analyses

Sampling was carried out between September and October 2015 and between May and August 2016 (Table 2). For each facility, grab samples were taken in the third chamber of the septic tank or from the distribution/pumping box where the wastewater was transferred to the sand filter. Flow-proportional samples were taken from the outlets of the sand filters, package plants and the P-filters. The samples were taken at different times of the day over a period of several hours, depending on the specific flow (it varied greatly between facilities) and

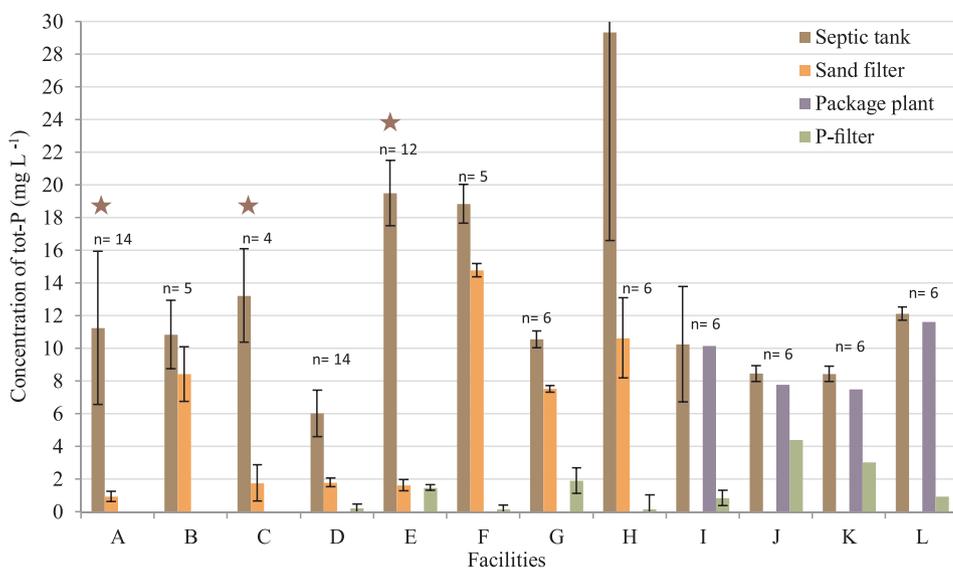


Fig. 1. Average concentrations of tot-P measured in the effluent from the septic tanks (grab samples), and flow-proportional average concentrations of tot-P measured in the effluents from the sand filters, package plants and P-filters in the studied facilities (A–L). Standard deviations are shown as error bars; for facility H the standard deviation (not shown in graph) was 42 mg L^{-1} . The red stars indicate the facilities where dilution was suspected to occur (A, C, E). n = number of samples.

practicalities regarding equipment and location. Flow was measured manually (volumetric flow measurements), using effluent flow for the sand filters and either influent or effluent flow for the P-filters. At each sampling event, two composite samples of approximately 2 to 3 L (depending on flow) were taken from the effluent water collected from the outlets of the sand filters, package plants and P-filters over a period of 1.5–2 h approximately.

Total suspended solids (TSS, not measured on all occasions) and pH were measured on-site. The pH was measured using a WTW pH330 pH meter with a WTW SenTix41 pH electrode. TSS was determined following the European standard EN 872:2005 [26]. The samples for determining total and dissolved P (dis-P), total and dissolved organic carbon (TOC, DOC) and biological oxygen demand (BOD_7) were frozen and stored for later analysis in the laboratory. Samples for DOC and dis-P analyses were filtered through $0.45 \mu\text{m}$ filters before freezing.

BOD_7 was analysed according to the European standard method CSN EN 1899-1 (modified) [27]. Phosphorus was analysed with a Quattro spectrometer and the device-specific method number A-031-04, according to European standards (ammonium molybdate method) with digestion (persulfate oxidation, SS-EN 1189 performance 6.4) [28]. IR detection (based on CSN EN 1484, CSN EN 16192, and SM 5310) was used to analyse TOC and DOC [29,30].

The overall reduction of tot-P in the 12 treatment facilities was calculated based on P concentrations measured in the last chamber of the septic tank and the effluent from the final treatment step (sand filter or P-filter); hence, the estimated P reduction of the system did not include treatment in the septic tank.

2.3. Tracer tests

In three P-filters (H, J, K) the hydraulic residence time was estimated with tracer tests by using an optical monitoring sonde (YSI 600OMS V2) with a rhodamine probe (YSI 6130). A rhodamine water tracing (WT) solution with a $70 \mu\text{g L}^{-1}$ concentration made from 20% rhodamine WT concentrate was used. Estimations of the required volume of tracer solution were based on the volume (0.7 m^3) and density (730 kg/m^3) of the filter media in the P-filter bag. The 0.5 L of the rhodamine WT solution was added to the inlet pipe of the P-filters, and the rhodamine WT concentration was then measured in the filter effluent. The sonde was left in unattended mode collecting data (concentration of rhodamine WT measured by the optical sensor) over one (J), two (K) and six (H) days in December 2016. The rhodamine WT concentration was measured every two minutes (J, K) and five minutes (H). The data was processed based on time of the first arrival.

2.4. Statistical analysis

The concentrations of tot-P, dis-P, TOC and DOC as well as the pH, were weighted for the water flow. The flow-proportional arithmetic means (\bar{x}^*) and standard deviations (s) were calculated according to Eq. (1) and (2), respectively.

$$\bar{x}^* = \frac{\sum_{i=1}^n x_i w_i}{\sum_{i=1}^n w_i} \quad (1)$$

$$s = \sqrt{\frac{\sum_{i=1}^n w_i (x_i - \bar{x}^*)^2}{(\sum_{i=1}^n w_i) - 1}} \quad (2)$$

Where:

\bar{x}^* = flow-proportional arithmetic mean

n = number of observations

x_i = measured concentration

w_i = volume of wastewater making up the composite sample

s = flow-proportional standard deviation

It was assumed that the influent flow rate to the filter was the same as the measured effluent flow rate and vice versa when the influent flow rate was the one measured instead.

The software Minitab® [31] was used for the statistical analyses. Spearman's rank-order correlation was used to analyse the nonparametric data (normality test Anderson-Darling applied).

3. Results and discussion

Fig. 1 shows the average concentrations of tot-P measured in the effluent from the septic tanks, sand filters, package plants and P-filters in the studied facilities (A–L). The concentrations of tot-P in the septic tank effluent varied greatly among the study facilities, ranging between 6 and 29 mg L^{-1} (Fig. 1), possibly as a result of the different water consumption patterns and contribution by different sources of P in each household such as human waste and the extent of synthetic detergent use. Concentrations ranging between 1.2 and 21.8 mg L^{-1} are normally found in septic tank effluents as reported in a U.S. study [32] modelling the fate and transport of nutrients from on-site wastewater systems.

3.1. Phosphorus reduction in the sand filters

Four (B, F, G and H) of the eight investigated sand filters (A–H) had effluent concentrations for tot-P higher than 7.5 mg L^{-1} (Fig. 1),

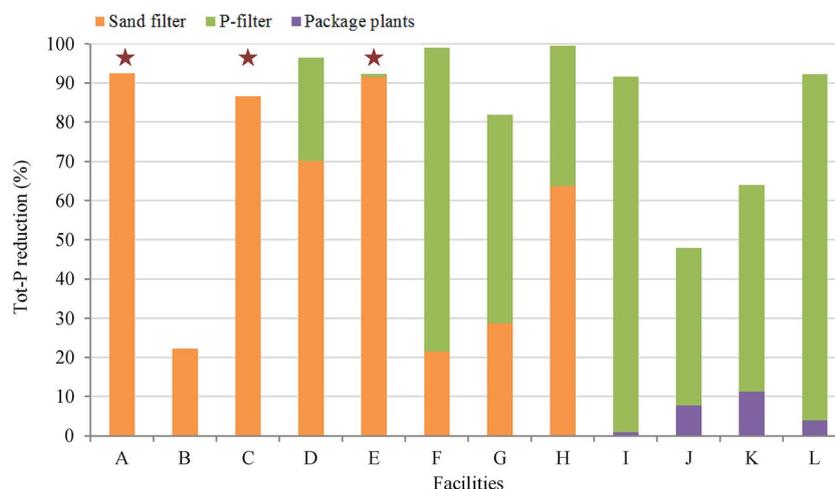


Fig. 2. Reduction of tot-P and relative contribution of each treatment unit to the overall reduction of tot-P for the investigated wastewater treatment facilities A–L. The red stars indicate the facilities where dilution was suspected to occur (A, C and E).

exceeding the Swedish recommended value for common receiving waters (3 mg L^{-1}) and making downstream P-treatment advisable. The highest average concentration of tot-P in the effluent from the sand filter—in facility F—was almost 15 mg L^{-1} (Fig. 1).

The highest tot-P reduction was observed in sand filters D and H, showing a 62 and 70% reduction, respectively (Fig. 2), which is acceptable according to current Swedish guidelines (although both sand filters were quite different with respect to the influent P load). The tot-P concentration in the effluent from sand filter D was 1.8 mg L^{-1} , which is below the recommended value of 3 mg L^{-1} , whereas in sand filter H the effluent concentration was still high (10.6 mg L^{-1}) despite the good P reduction capacity of the sand filter. This was caused by the very high initial concentration of tot-P in the septic tank effluent (29.3 mg L^{-1}). Thus, good tot-P reduction in a sand filter does not necessarily translate into an acceptable tot-P concentration in the effluent.

Low P reduction was observed for three sand filters (B, F and G). In sand filter B (which had been in operation for three years) the measured water flow through the filter was low (3.2 L h^{-1}), with a high suspended solids content at the outlet (TSS = 17 mg L^{-1}), high bacterial concentrations [25], dark colour and strong odour, indicating that this filter was clogged. The main reasons causing clogging are high concentrations of extracellular bacterial slimes in the sand pores, accumulation of suspended solids or precipitation and deposition of compounds such as calcium carbonate [13,33]. Moreover, clogging can persist and increase when ponding of water occurs between the batches [34]. Neither the clogging characteristics nor any obvious malfunction were observed in sand filters F and G (five and three years in operation, respectively). Their inefficiency could be explained by the chemical composition of the sand used. Gill et al. [35] discussed the clear relationship between P removal in subsoils and soil mineralogy after studying on-site wastewater effluent discharge in six sites in Ireland. At $\text{pH} > 6$, as observed in the influent and effluent of the sand filters F and G in this study, the P-removal capacity of the sand is dominated by a combination of physical adsorption to iron (Fe) and aluminium (Al) oxides and precipitation of P as sparingly soluble calcium phosphates [11,35]. According to Evehorn et al. [36], mechanisms for P removal in sand filters were explained by the strong relation between oxalate extractable P and Al. Hence a lack of Al (or Fe) compounds in the sand filters F and G could have hampered the adsorption and mineral precipitation of P. The distribution of wastewater in the filter surface could also affect the P removal, as uneven distribution has been shown to promote preferential flows and decrease the potential to remove P in sand filters [37,38].

At least three (A, C, E) of the eight investigated sand filters had likely dilution problems, i.e. extraneous soil/ground/rainwater

infiltrating into the filter bed and diluting the wastewater. Dilution was suspected to occur based on field observations, such as high measured water flow through the sand filters, even when the users were not at home and when the pump transporting wastewater from the septic tank was not operating during collection, as well as very clear effluent water. In these facilities, the low P concentration could therefore be explained by the dilution of the phosphorus concentration and not the filters' efficiency. For this reason, correct installation and supervision of sand filters are crucial and highly recommended to ensure that the filter material is properly sealed and there is no infiltration/exfiltration between the treatment facility and the surrounding environment.

P reduction occurring in the septic tank was not investigated in this study, but this reduction has been estimated to be $15 \pm 10\%$ of the incoming quantity [5]. Assuming this percentage of reduction in the septic tank, facilities B, F and G, whose sand filters showed low P reduction, would be estimated to reach only 33–39% tot-P reduction, which is still below the recommended reduction of 70% suggested by the Swedish guidelines. The low P reduction capacity of sand filters had already been shown in previous studies; e.g. Evehorn et al. [36] reported 8–16% P removal in four sand filters by using a mass balance approach, while Vilpas and Santala [20] reported low performance from two conventional sand filters, with tot-P concentrations in the effluent exceeding the Finnish regulation of 3 mg L^{-1} . A similar trend was shown by Wilson [39] who investigated the long-term effects of filter length and wastewater loading on performance of eight sand filters in Canada. In the mentioned study, the P removal decreased with time as adsorption sites in the sand filters became exhausted. The estimated removal of tot-P in sand filters in Sweden, including reduction in septic tank, is $50 \pm 30\%$ [5], which is a wide range that reflects the expected large variations in removal efficiency. Sizeable variation in sand filter performance and their general low P reduction was corroborated in this study.

The four package plants (I–L) reduced P to a lesser extent than the sand filters. The influent tot-P concentrations ranged between 7.5 and 11.6 mg L^{-1} of tot-P (Fig. 1), and the highest reduction rate in the package plants was only about 11% (facility K) (Fig. 2). In contrast to the sand filters, these units have not been designed as stand-alone treatment systems but as a pre-treatment step before the P-filter units to reduce organic matter. Hence residence time is short and P treatment capacity is low.

3.2. Phosphorus reduction in the P-filters

Six out of the nine investigated P-filters generally reduced P satisfactorily and covered for a considerable amount of tot-P removed in

Table 3

Concentrations of pH, tot-P and dis-P measured in the influent and effluent of the P-filters and concentrations of BOD and TOC measured in the influent of the P-filters (flow-proportional average concentrations).

Facility	Influent P-filter ^x					Effluent P-filter		
	pH	BOD ₇ (mg L ⁻¹)	TOC (mg L ⁻¹)	Tot-P (mg L ⁻¹)	Dis-P (mg L ⁻¹)	pH	Tot-P (mg L ⁻¹)	Dis-P (mg L ⁻¹)
D	6.2	1.9	8.2	1.8	1.7	9.4	0.2	0.2
E	4.5	< 1.0–2.4	13.2	1.6	0.8	6.0	1.5	0.8
F	7.4	2.1	19.8	14.8	14.8	12.1	0.17	0.07
G	7.2	2.6	12.0	7.5	6.7	10.5	1.9	0.2
H	6.8	2.9	20.1	10.6	11.7	9.9	0.1	0.03
I	7.2	31.4	39.8	10.1	9.9	9.6	0.9	0.3
J	7.3	18.8	25.3	7.8	7.3	8.6	4.4	3.3
K	7.5	16.0	22.0	7.5	7.4	8.8	3.04	2.7
L	8.0	17.0	29.3	11.6	11.5	9.7	0.9	0.6

the treatment facility. The effluent P concentrations of the P-filters that functioned well ranged between 0.15 and 1.9 mg L⁻¹ (Fig. 1), and the relative contribution to P reduction ranged between 26 and 91% (Fig. 2). Five of the studied P-filters (D–H) had sand filters upstream, while four (I–L) were contained within package plants whose biological treatment unit is not designed to remove P.

Eight out of nine P-filters reduced between 43 and 99% of the tot-P of the influent to the P-filter, but one P-filter (E) reduced only 8% of P (calculated using influent and effluent concentrations shown in Table 3). Most of the P measured in the influent water to the P-filters was in the dissolved phase (dis-P): 93% on average (Table 3). However, the share of dis-P in the effluent was smaller than in the influent (55% on average), which could indicate that some of the dis-P precipitated as bound particles within the filter but to some extent was washed out with the water, possibly because of the small size of the particles, thus escaping from the filter material, as studied by Herrmann et al. [9].

The investigated P-filters that worked well and had tot-P effluent concentrations below 3 mg L⁻¹—namely D, F, G, H, I and L—had varied influent tot-P concentrations. For example, P-filter D had already low concentrations of tot-P in the influent (1.8 mg L⁻¹), while the rest had much higher influent concentrations, ranging from 7.5 to 14.8 mg L⁻¹ (Table 3). This suggests that the filter is able to function adequately and remove most of the tot-P regardless of influent concentration within this range (14.8–1.8 mg L⁻¹).

Three P-filters (E, J and K) did not remove P satisfactorily; J and K had the highest average effluent concentration of tot-P, 3.04 and 4.4 mg L⁻¹, respectively. P-filter E was possibly saturated with respect to P and, because of its construction, some of the influent water bypassed it without passing through the filter material. The pH in the effluent was very low (around 6), and almost no P was reduced. P-filter E was the oldest P-filter in the study (built in 2009) and was more than six years old by the time the samples were taken. The filter medium used was Filtra P, in contrast to all the other investigated P-filters, which contained the filter medium Polonite. Both filter media have been reported to have significant potential for P removal, although

Filtra P has been shown (in column experiments) to be prone to clogging due to structural degradation of the material, which in practice translates into a shorter service life [40].

The two other P-filters with low P reduction (J, K) were highly loaded ($J = 79.4 \text{ L m}^{-2} \text{ h}^{-1}$; $K = 58.5 \text{ L m}^{-2} \text{ h}^{-1}$) because of the number of users they provided service to as compared to the rest of the facilities. The pH in the effluents of both filters was below 9, although the filters had been installed only around two weeks before sampling started. The low pH could be explained by the washing out of calcium from the filter caused by the high hydraulic load, as previously studied by Herrmann et al. [9]. Furthermore, the high hydraulic load corresponds to short residence time, so that there was probably not sufficient time for the calcium phosphates to precipitate. Another possible explanation would be differences in the pore distribution and the formation of preference channels, which can also affect the sorption efficiency of P-filters, as discussed in [41]. The organic matter concentrations in the influent to the P-filters in facilities J and K were in the same range as for most of the other P-filters with high P reduction rates (Table 3), ruling out high organic matter influent concentrations as a reason for the low P reduction in facilities J and K.

3.2.1. pH dependency of phosphorus reduction in the P-filters

The effluent pH of the P-filters ranged between 6.0 and 12.1 (Table 3). The P-filter with the highest tot-P reduction (F) was also the one with the highest effluent pH (12.1) (Fig. 3). Significant correlation was found between the P reduction in the P-filters and the pH measured in their effluents (Spearman rank correlation coefficient = 0.833, $p = .005$). Higher pH values favour the precipitation of calcium phosphate [42], which is the filters' main retention mechanism [40].

In previous column studies, [12] found a positive correlation and a strong relationship between the P removal in Polonite filters and pH. Nilsson et al. [43] reported the same positive correlation, but only when the P-filters were loaded with high BOD concentrations ($120 \pm 11 \text{ mg L}^{-1}$). In the same study, no significant correlation was found between the P removal and pH when the Polonite filters were

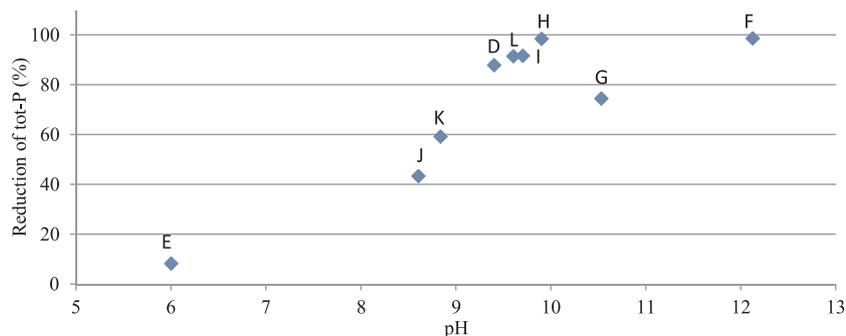


Fig. 3. Relationship between the reduction of tot-P in the P-filters and pH measured in the effluent of the nine P-filters studied (D–L).

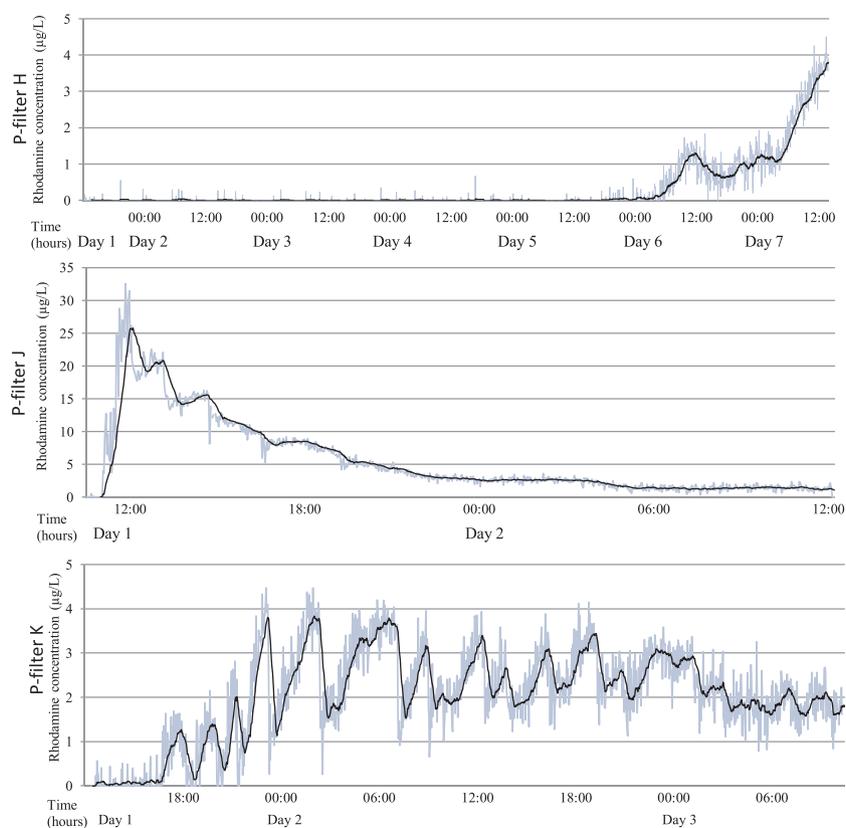


Fig. 4. Rhodamine WT concentrations in the effluent from the P-filters in facilities H, J and K. Negative values (probably due to sensor inaccuracy) were set to zero; the blue line shows the measured concentrations, and the black line shows the trendline (averaged for every 20 (H), 10 (J) and 20 (K) values).

loaded with low BOD concentrations ($20 \pm 5 \text{ mg L}^{-1}$), which is in the range of the corresponding data in the present study (Table 3). However, the positive correlation between pH and P removal in P-filters with influent BOD concentrations ranging from 1.9 to 31.4 mg L^{-1} was confirmed in this study.

The P-filters with an effluent pH of 9.4 or higher had 75% or more tot-P reduction (Fig. 3). However, pH is not the only factor affecting the P reduction in the P-filter, and several facilities showed different rates of P reduction despite similar pHs. For example, in P-filters J and K, with similar pH values of 8.6 and 8.8, respectively, residence times were estimated to be considerably different (Fig. 4), and their P-reductions differed by approx. 16 percentage points. This indicates that the residence time of the wastewater in the P-filter is an important factor governing P removal. An earlier comparative study of various filter materials by Cucarella and Renman [44] concluded that low effluent pH values indicated low P sorption, but higher pH values did not necessarily imply greater P sorption. These findings are in line with the results of the present study when comparing the performance of the P-filter in facility G with the other facilities with effluent pH > 9: e.g. facility G had higher effluent pH than facilities (D, L, I and H), but lower P reduction (Fig. 3).

3.2.2. Effect of organic load on phosphorus reduction in the P-filters

The TOC concentrations in the influent to the P-filters were rather low, ranging between 8 and 40 mg L^{-1} TOC (Table 3). No significant correlation was found between P reduction in the P-filters and the TOC in the influent to the filters (Spearman rank correlation coefficient = 0.150, $p = .700$). Previous studies on the effect of organic matter content in wastewater on P removal in P-filters have shown that higher P removal is achieved when extensive pre-treatment of the wastewater occurs [12,43]. A study with batch experiments [42] found that humic substances negatively affected phosphate removal efficiency when the pH of the solution was 8 but had almost no effect when the

solution had a pH of ≥ 9 . The inhibitory effect of the humic substances on phosphate precipitation was explained by the combination of calcium and humic substances and by the blocking of active growth sites on newly nucleated precipitates of calcium phosphate. Similarly, the lack of correlation between P reduction and influent TOC in the present study could be explained by the fact that effluent pH from only one facility (E) was low (6.0) (Table 3), while effluent pH for the other eight facilities ranged between 8.6 and 12.1. Hence, for the statistical analysis, the inhibitory effect of organic matter on P precipitation might have been small because most of the facilities had a high pH.

In column experiments, [43] reported a significant positive correlation between TOC removal in Polonite filters and pH concentration in the effluent, for low concentrations of BOD ($20 \pm 5 \text{ mg L}^{-1}$). However, this was not confirmed in the present study, which found no significant correlation (Spearman rank correlation coefficient = 0.133; $p = .732$) when comparing effluent pH and TOC reduction in the P-filter.

3.2.3. Estimating hydraulic residence time in the P-filters

Tracer tests were carried out to estimate the arrival times of the influent water in three P-filters (H, J and K). In P-filter H, the rhodamine WT was detected in the effluent after approximately 5.5 days (Fig. 4). In P-filters J and K, the rhodamine WT was detected in the effluent after 1.5 h and 4.5 h, respectively (Fig. 4).

The water flow was not measured during the tests, but average flows from previous sampling campaigns were 5.3, 39.9 and 29.4 L h^{-1} in P-filter H, J and K, respectively. In P-filters H and K, the end transit pulse of the rhodamine was not reached, hence no estimations of the flow rate were made. However, the end transit pulse of the rhodamine was reached in P-filter J. The peak concentration of rhodamine was achieved after approximately 80 min, decreasing asymptotically afterwards. The calculated average flow for this facility, based on the measured rhodamine concentrations and assuming complete recovery of the rhodamine WT, was 0.23 L h^{-1} . The twofold difference between

the measured flow during the sampling campaign (39.9 L h^{-1}) and the calculated average flow (0.23 L h^{-1}) may be due to several reasons. Explanations include the lack of pumping cycles during night hours, the uncompleted mixing of rhodamine with the influent water which would, consequently, affect the detection and/or the presence of holes or cracks in the bag that would allow the water outflow without being detected by the sensor. The oscillations observed in the graph for P-filter K may show the system's pumping cycles.

The observed time of arrival was inversely related to the previously measured wastewater flow, although the flow measurements were carried out during limited time periods (Table 2). Higher P reduction occurred in the filter with the longest arrival time (H), and lower reduction in the filter with the shortest arrival time (K), possibly because high loading rates have washed out more P precipitates or reactive calcium ions, and the short residence time was insufficient to form calcium-P precipitates.

Previous column experiments with Filtralite P® have shown that a short residence time (15 min when wastewater was used) was sufficient for P removal in P-filters [9]. However, more time might be needed for P that has already reacted to be retained in the filter material. The short residence time in P-filters J and K and the higher flows may possibly have had a negative effect on the binding capacity of the P-filters.

3.2.4. When and how often should P-filter media be changed?

According to the manufacturers of Polonite (Ecofiltration Nordic AB), P-filters are built to maintain high P reduction during the first 2–4 years, depending on load, with decreasing reduction during the remainder of the filter's life cycle. Based on data obtained and the field observations in this study, it is difficult to determine how often the P-filters should be changed. Both old (E, 6 years) and new P-filters (J, K, 2 weeks) showed low P reduction, but for different reasons; age and clogging were assumed to account for the poor performance of P-filter E, while the high hydraulic load hindered the performance of P-filters J and K. The pH in the effluent to all these P-filters (E, J and K) was below 9, suggesting that pH is a good indicator for estimating filter performance.

P-filters showed high reduction rates, both when the influent P concentrations were high (e.g. facility F, 14.78 mg/L) and when they were low (e.g. facility D, 1.80 mg/L), indicating that the influent P concentration is not decisive for their functioning, at least for the concentration range covered in this study. A review of sorption filter materials [44] found a clear tendency for higher P sorption capacity of the materials investigated with increasing initial P concentration. However, the studies selected in the review [44] included a wide variety of materials, such as blast furnace slag, fly ash, Filtralite P® and Shell sand, and the initial P concentrations ranged from normal values of $0\text{--}30 \text{ mg P L}^{-1}$ to very elevated concentrations of $10,000 \text{ mg P L}^{-1}$.

Pratt et al. [45] argued that the complex relation between the P-filters lifespan and the hydraulic retention time (HRT) makes it difficult to estimate the filters lifespan, as flow dynamics, weathering reactions and removal mechanisms must be taken into account. Continuous-flow conditions are needed to predict the long-term performance and lifespan of the P-filters, conditions that are often not met in full-scale systems.

4. Conclusions

This study evaluated the reduction of P in 12 full-scale on-site wastewater facilities with two general types of filters used individually and in-combination—sand filters and P-filters—and compared the effluent concentrations of tot-P to current Swedish guidelines.

Only one sand filter (D) of four was confirmed to remove P satisfactorily (effluent concentration below 3 mg P L^{-1}). The inefficiency of the four sand filters that did not function adequately (discharged more than 3 mg P L^{-1}) indicates that a downstream treatment step is needed. The remaining three sand filters were suspected to have

dilution problems. This means that correct installation and proper sealing of the filter must be ensured to prevent mixing wastewater with other water sources in order to achieve adequate P reduction within the treatment unit.

Six out of nine of the investigated P-filters generally removed P well (75–99% P reduction) and accounted for a considerable amount of tot-P reduced in the treatment facilities, with the exception of one filter that was old and clogged, and two other filters that had to cope with high hydraulic loads.

The analysis found a significant positive correlation between P reduction in the P-filters and pH measured in the effluent, indicating that pH could be used as an indicator of P-filter efficiency. In the three P-filters that worked insufficiently, with effluent concentrations higher than 3 mg P L^{-1} (J, K) or 0.7% tot-P reduction (E), when pH was 8.8 or less.

No significant correlation was found between the reduction of P in the P-filters and the TOC measured in the influent to the filters. It may be that the low incoming TOC concentrations and the high pH found in the majority of the P-filters prevented this effect from reaching quantifiable levels. With the low incoming TOC, the inhibitory effect of organic matter on P precipitation was probably small.

It was difficult to determine how often the filter media in P-filters should be changed, possibly due to the variation in the data in this study and because the filters included in it were rather new (except for P-filter E). With proper installation, the P-filters in the study that handled a moderate load, had a pH above 9.4 and not too many years of use (2–4 years as suggested by manufacturers) functioned well and reduced the incoming concentration of tot-P to below 1.9 mg P L^{-1} .

Acknowledgements

We thankfully acknowledge the financial support provided by the Swedish Agency for Marine and Water Management (grant 1:12, Measures for Sea and Water Environment) and the Swedish Research Council Formas (project number 942-2015-758). We also thank Kerstin Nordqvist, Gesche Reumann, Snezana Gavric and Katharina Lange for their support in the laboratory and in the field, as well as the staff of the participating municipalities of Robertsfors, Skellefteå, Umeå and Vännäs, and the Development Centre for Water (Utvecklingscentrum för vatten) in Norrtälje for support with the identification and inspection of the facilities. We are grateful to Jiri Marsalek for valuable comments and feedback on the manuscript.

References

- [1] HELCOM, *Eutrophication Status of the Baltic Sea 2007–2011. A Concise Thematic Assessment, Baltic Sea Environment Proceedings No. 143*, (2014).
- [2] Swedish EPA, *Wastewater Treatment in Sweden*, Swedish EPA Publications, Stockholm, 2014.
- [3] H. Ejhed, M. Olshammar, G. Brånvall, A. Gerner, J. Bergström, H. Johnsson, K. Blombäck, J. Nisell, H. Gustavsson, C. Persson, G. Alavi, *Beräkning av kväve – och fosforbelastning på vatten och hav för uppföljning av miljökvalitetsmålet Ingen övergödning [Estimating nitrogen and phosphorus load to water and sea to monitor the environmental quality objective Zero Eutrophication]*, Swedish Environmental Emissions Data Report 56, Swedish Meteorological and Hydrological Institute, 2011, pp. 1–54 Norrköping, (In Swedish with English summary).
- [4] SwAM, *Havs- och vattenmyndighetens allmänna råd om små avloppsanordningar för hushålls-spillvatten [Swedish Agency for Marine and Water Management's general advice on small sewer systems for domestic wastewater]*, Swedish Agency for Marine and Water Management, 2016 (In Swedish).
- [5] M. Olshammar, M. Ek, L. Rosenquist, H. Ejhed, A. Sidvall, S. Svanström, *På uppdrag av Havs- och vattenmyndigheten Uppdatering av kunskapsläget och statistik för små avloppsanläggningar [The state of knowledge and statistics for small sewage plants. Swedish Agency for Marine and Water Management]. Report 166*, Swedish Meteorological and Hydrological Institute, 2015, pp. 1–34 Norrköping, (In Swedish).
- [6] O. Palm, L. Malmén, H. Jönsson, *Robusta, uthålliga små avloppssystem. En kunskapsmanställning [Robust and durable small wastewater systems A knowledge compilation]*, Swedish Environmental Protection Agency (EPA), 2002, pp. 1–117 Stockholm, (In Swedish with English summary).
- [7] G. Morse, S. Brett, J. Guy, J. Lester, *Review Phosphorus removal and recovery*

- technologies, *Sci. Total Environ.* 212 (1998) 69–81, [http://dx.doi.org/10.1016/S0048-9697\(97\)00332-X](http://dx.doi.org/10.1016/S0048-9697(97)00332-X).
- [8] A. Hedström, Reactive filter systems for small scale wastewater treatment a literature review, *VATTEN* 62 (2006) 253–263.
- [9] I. Herrmann, A. Jourak, A. Hedström, T.S. Lundström, M. Viklander, The effect of hydraulic loading rate and influent source on the binding capacity of phosphorus filters, *PLoS One* 8 (2013) e69017, <http://dx.doi.org/10.1371/journal.pone.0069017>.
- [10] L. Rolland, P. Molle, A. Liénard, F. Bouteldja, A. Grasmick, Influence of the physical and mechanical characteristics of sands on the hydraulic and biological behaviors of sand filters, *Desalination* 248 (2009) 998–1007, <http://dx.doi.org/10.1016/j.desal.2008.10.016>.
- [11] C.A. Arias, M. Del Bubba, H. Brix, Phosphorus removal by sands for use as media in subsurface flow constructed reed beds, *Water Res.* 35 (2001) 1159–1168, [http://dx.doi.org/10.1016/S0043-1354\(00\)00368-7](http://dx.doi.org/10.1016/S0043-1354(00)00368-7).
- [12] A. Renman, G. Renman, Long-term phosphate removal by the calcium-silicate material Polonite in wastewater filtration systems, *Chemosphere* 79 (2010) 659–664, <http://dx.doi.org/10.1016/j.chemosphere.2010.02.035>.
- [13] R. Kristiansen, Sand-filter trenches for purification of septic tank effluent: i. The clogging mechanism and soil physical environment, *J. Environ. Qual.* 10 (1981) 353–357.
- [14] S.H. Christopherson, J.J. Anderson, D.M. Gustafson, Evaluation of recirculating sand filter in a cold climate, *Water Sci. Technol.* 51 (2005) 267–272.
- [15] A. Kauppinen, K. Martikainen, V. Matikka, A.-M. Veijalainen, T. Pitkänen, H. Heinonen-Tanski, I.T. Miettinen, Sand filters for removal of microbes and nutrients from wastewater during a one-year pilot study in a cold temperate climate, *J. Environ. Manage.* 133 (2014) 206–213, <http://dx.doi.org/10.1016/j.jenvman.2013.12.008>.
- [16] P. Havard, R. Jamieson, D. Cudmore, L. Boutilier, R. Gordon, Performance and hydraulics of lateral flow sand filters for on-site wastewater treatment, *J. Hydrol. Eng.* 13 (2008) 720–728, [http://dx.doi.org/10.1061/\(ASCE\)1084-0699\(2008\)13:8\(720\)](http://dx.doi.org/10.1061/(ASCE)1084-0699(2008)13:8(720)).
- [17] L. Johansson Westholm, Substrates for phosphorus removal—potential benefits for on-site wastewater treatment? *Water Res.* 40 (2006) 23–36, <http://dx.doi.org/10.1016/j.watres.2005.11.006>.
- [18] C. Vohla, M. Köiv, H.J. Bavor, F. Chazarenc, Ü. Mander, Filter materials for phosphorus removal from wastewater in treatment wetlands—a review, *Ecol. Eng.* 37 (2011) 70–89, <http://dx.doi.org/10.1016/j.ecoleng.2009.08.003>.
- [19] P.D. Jensen, T. Krogstad, A.M. Paruch, T. Mæhlum, K. Adam, C.A. Arias, A. Heistad, L. Jonsson, D. Hellström, H. Brix, M. Yli-Halla, L. Vråle, M. Valve, Filter bed systems treating domestic wastewater in the Nordic countries – Performance and reuse of filter media, *Ecol. Eng.* 36 (2010) 1651–1659, <http://dx.doi.org/10.1016/j.ecoleng.2010.07.004>.
- [20] R. Vilpas, E. Santala, Comparison of the nutrient removal efficiency of onsite wastewater treatments systems: applications of conventional sand filters and sequencing batch reactors (SBR), *Water Sci. Technol.* 55 (2007) 109–117, <http://dx.doi.org/10.2166/wst.2007.134>.
- [21] J. Audet, L. Martinsen, B. Hasler, H. De Jonge, E. Karydi, N.B. Ovesen, B. Kronvang, Comparison of sampling methodologies for nutrient monitoring in streams: uncertainties, costs and implications for mitigation, *Hydrol. Earth Syst. Sci.* 18 (2014) 4721–4731, <http://dx.doi.org/10.5194/hess-18-4721-2014>.
- [22] O. Palm, E. Elmefors, P. Moraeus, P. Nilsson, L. Persson, P. Ridderstolpe, D. Everbom, Läget Inom Markbaserad Avloppsvattenrening – Samlad Kunskap King Reningstekniker för Små Och Enskilda Avlopp [State of the Art in Soil-based Wastewater Treatment – Review of Treatment Techniques for Small-scale Wastewater Treatment], Swedish EPA Report 6484, Swedish Environmental Protection Agency (EPA), 2012, pp. 1–35 Stockholm, (In Swedish with English summary).
- [23] P. Weiss, D. Everbom, E. Kärrman, J.P. Gustafsson, Environmental systems analysis of four on-site wastewater treatment options, *Resour. Conserv. Recycl.* 52 (2008) 1153–1161, <http://dx.doi.org/10.1016/j.resconrec.2008.06.004>.
- [24] Ecofiltration Nordic AB, Polonite® – The Sustainable Treatment for Phosphorus Removal and Recovery, (2018).
- [25] I. Herrmann, B. Vidal, A. Hedström, Discharge of indicator bacteria from on-site wastewater treatment systems, *Desalin. Water Treat.* 91 (2017) 365–373, <http://dx.doi.org/10.5004/dwt.2017.21416>.
- [26] European Committee for Standardization, CEN/TC 230. EN 872. Water Quality – Determination of Suspended Solids – Method by Filtration Through Glass Fibre Filters, (2005).
- [27] European Committee for Standardization, CEN/TC 230. EN 1899-1. Water Quality – Determination of Biochemical Oxygen Demand After N Days (BOD_n) – Part 1: Dilution and Seeding Method with Allylthiourea Addition (ISO 5815:1989, Modified), (1998).
- [28] European Committee for Standardization, CEN/TC 230. EN ISO 6878. Water Quality – Determination of Phosphorus – Ammonium Molybdate Spectrometric Method, (2004).
- [29] European Committee for Standardization, CEN/TC 230. EN 1484. Water Analysis – Guidelines for the Determination of Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC), (1997).
- [30] European Committee for Standardization, CEN/TC 444. EN 16192: Characterization of Waste – Analysis of Eluates, (2011).
- [31] Minitab®, Minitab® 17 Statistical Software, State College, Minitab, Inc, PA, 2010 (17.2.1. [Computer software]), www.minitab.com.
- [32] J.E. McCray, S.L. Kirkland, R.L. Siegrist, G.D. Thyne, Model parameters for simulating fate and transport of on-site wastewater nutrients, *Ground Water* 43 (2005) 628–639, <http://dx.doi.org/10.1111/j.1745-6584.2005.0077.x>.
- [33] R. Blazejewski, S. Murat-Blazejewska, Soil clogging phenomena in constructed wetlands with subsurface flow, *Water Sci. Technol.* 35 (1997) 183–188.
- [34] M. Spychala, R. Blazejewski, Sand filter clogging by septic tank effluent, *Water Sci. Technol.* 48 (2004) 153–159.
- [35] L.W. Gill, N. O’Lunaigh, P.M. Johnston, B.D.R. Misstear, C. O’Suilleabhain, Nutrient loading on subsoils from on-site wastewater effluent, comparing septic tank and secondary treatment systems, *Water Res.* 43 (2009) 2739–2749, <http://dx.doi.org/10.1016/j.watres.2009.03.024>.
- [36] D. Everbom, D. Kong, J.P. Gustafsson, Wastewater treatment by soil infiltration: long-term phosphorus removal, *J. Contam. Hydrol.* 140 (2012) 24–33, <http://dx.doi.org/10.1016/j.jconhyd.2012.08.003>.
- [37] A.J. Gold, B.E. Lamb, G.W. Loomis, J.R. Boyd, V.J. Cabelli, C.G. McKiel, Wastewater renovation in buried and recirculating sand filters, *J. Environ. Qual.* 21 (1992) 720–725, <http://dx.doi.org/10.2134/jeq1992.00472425002100040030x>.
- [38] R.B. Reneau, C. Hagedorn, M.J. Degen, Fate and transport of biological and inorganic contaminants from on-site disposal of domestic wastewater, *J. Environ. Qual.* 18 (1989) 135–144, <http://dx.doi.org/10.2134/jeq1989.00472425001800020001x>.
- [39] J. Wilson, L. Boutilier, R. Jamieson, P. Havard, C. Lake, Effects of hydraulic loading rate and filter length on the performance of lateral flow sand filters for on-site wastewater treatment, *J. Hydrol. Eng.* 16 (2011) 639–649, [http://dx.doi.org/10.1061/\(ASCE\)HE.1943-5584](http://dx.doi.org/10.1061/(ASCE)HE.1943-5584).
- [40] J.P. Gustafsson, A. Renman, G. Renman, K. Poll, Phosphate removal by mineral-based sorbents used in filters for small-scale wastewater treatment, *Water Res.* 42 (2008) 189–197, <http://dx.doi.org/10.1016/j.watres.2007.06.058>.
- [41] C. Nilsson, R. Lakshmanan, G. Renman, G.K. Rajarao, Efficacy of reactive mineral-based sorbents for phosphate, bacteria, nitrogen and TOC removal-column experiment in recirculation batch mode, *Water Res.* 47 (2013) 5165–5175, <http://dx.doi.org/10.1016/j.watres.2013.05.056>.
- [42] Y. Song, H.H. Hahn, E. Hoffmann, P.G. Weidler, Effect of humic substances on the precipitation of calcium phosphate, *J. Environ. Sci.* 18 (2006) 852–857, [http://dx.doi.org/10.1016/S1001-0742\(06\)60004-1](http://dx.doi.org/10.1016/S1001-0742(06)60004-1).
- [43] C. Nilsson, G. Renman, L. Johansson Westholm, A. Renman, A. Drizo, Effect of organic load on phosphorus and bacteria removal from wastewater using alkaline filter materials, *Water Res.* 47 (2013) 6289–6297, <http://dx.doi.org/10.1016/j.watres.2013.08.001>.
- [44] V. Cucarella, G. Renman, Phosphorus sorption capacity of filter materials used for on-site wastewater treatment determined in batch experiments—a comparative study, *J. Environ. Qual.* 38 (2009) 381–392, <http://dx.doi.org/10.2134/jeq2008.0192>.
- [45] C. Pratt, S.A. Parsons, A. Soares, B.D. Martin, Biologically and chemically mediated adsorption and precipitation of phosphorus from wastewater, *Curr. Opin. Biotechnol.* 23 (2012) 890–896, <http://dx.doi.org/10.1016/J.COPBIO.2012.07.003>.