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Fosfilt filters in an agricultural catchment: a long-term field-scale experiment

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Diffuse load mitigation is a prevailing global challenge due to the eutrophication of water bodies. We report here long-term nutrient removal performance of two on-site sand filters (F1 and F2) in southwestern Finland, established in the 1990s. The sand filters were enhanced with a layer of phosphorus binding material Fosfilt-s, a side product of titanium dioxide production. The monitoring periods were 4.5 and 3.5 years for F1 and F2, respectively. F1 only worked for some months due to blockage of the crushed stone layer. After renovation (1999), the filter worked for a year but then the Fosfilt-s layer clogged and the filter increased suspended solids (SS) and dissolved reactive phosphorus (DRP) loads by 36% and 19% on average, respectively. Total P (PTOT) load was not affected. The structure and performance of F2 were more successful due to a better water distribution system. On average, 61% of the inflowing suspended solids, 37% of the PTOT and 45% of the DRP were removed during the monitoring period. We conclude that these filter types have the potential to be further developed into useful tools for nutrient load reduction. Development work should be focused on the treatment of subsurface drainage waters with high concentrations of dissolved nutrients, in particular. Long term field data is needed, because laboratory tests cannot fully simulate natural circumstances.

Key words: filter, lime, nutrient load, nutrient load reduction, water protection method

Introduction

High diffuse nutrient load, causing eutrophication of affected water bodies, is a serious problem in intensive agricultural areas all over the world. In South-West Finland, the River Yläneenjoki and River Pyhäjoki catchments have been the target of an intensive restoration programme, aiming at phosphorus (P) load reduction, since the early 1990s (Mattila et al. 2001, Ventelä and Lathrop 2005, Ventelä et al. 2007, 2010). Farming in the study area is characterized by intensive cereal and vegetable production, which demands intensive use of fertilizers and consequently causes high risk of P losses.

Nearly all farmers in the catchment have committed to the EU's agri-environmental programme (European commission 2005) that requires implementation of basic water protection measures like a reduction in the application of fertilizers. In addition, different types of buffer zones, sedimentation ponds, wetlands and wastewater treatment units have been promoted and implemented by authorities and local projects. As the need for load reduction was urgent in the 1990s, new treatment methods, such as filter ditches and sand filters, in addition to buffer zones and wetlands, were developed and tested for their ability to remove P from runoff (Kirkkala 2001, Kirkkala et al. 2012). The emphasis of the work was in providing field scale monitoring data on effectiveness of load reduction measures for the run-off waters. This kind of field data is needed, because tests in laboratories cannot give proper answers to questions related to run-off waters.

Recently, the need for new load reduction solutions has increased again, as nutrient load reduction has become even more challenging in the 2000s. The recent climatic variation has already affected the timing of the annual external nutrient load. In the southwestern part of Finland the winter mean air temperature is –2.0 °C and the catchment is normally covered with snow in winter. However, in the 2000s, there have been several mild winters with winter mean temperatures above zero, lack of snow and high winter rainfall (Ventelä et al. 2010). When most of the nutrient loading occurs outside the growing season, traditional biological measures such as wetlands and buffer strips are not efficient in reducing the load. New innovations and enhancement of the old methods are thus needed.

Sand filtration is widely used in municipal and industrial water and waste water treatment facilities (Yao et al. 1971, Vohla et al. 2011, Crittenden et al. 2012). Treatment mechanisms in a sand filter include physical filtering of solids, ion exchange and decomposition of organic substances by soil-dwelling bacteria. Different reactive mate-

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rials have been tested and studied to intensify nutrient removal, e.g. side-products containing iron or other metals (Dobbie et al. 2009, Penn and Bryant 2006, Shilton et al. 2006), and natural deposits (Arias et al. 2001, Gill et al. 2011, Renman 2008, Søvik and Kløve 2005). The idea of removing nutrients from agricultural runoff water using filters has recently arisen in many countries (Penn and Bryant 2006, Ballantine & Tanner 2010, Falk Øgaard 2010, Kjaergaard, 2010). Therefore, results from our long-term field scale filter experiment from the Yläneenjoki and Pyhäjoki catchments in the 1997–2006 period may help the current development work (see also Kirkkala et al. 2012). We report here the long-term performance of nutrient removal with two on-site Fosfilt-s filters.

Study area

The River Yläneenjoki and River Pyhäjoki catchments are situated in the boreal temperate zone in southwestern Finland. Long-term (1959–2009) average annual precipitation in this area is 590 mm. The long-term (1979–2008) average monthly temperature for the period October–March is –2.0 °C, varying between –5.4 and +1.9 °C. The warmest month is generally July, when the average temperature is 16.5 °C (1980–2009).

The first Fosfilt-s filter (F1) presented in this paper is located in the lower part of the River Yläneenjoki, in a sub-catchment with a ditch flowing to the river. The soils in the Yläneenjoki river valley and in the filter catchment are mainly clay and silt. The land use in the River Yläneenjoki catchment is distributed between agriculture (27%), forest (48%) and peat land (21%). In this catchment, a high P load originates especially from heavy clay soils and sloping fields as well as soils with low infiltration capacity and high surface runoff.

The second filter (F2) is located beside the main channel of the River Pyhäjoki and the outflowing water runs to the river. The soils in the Pyhäjoki river valley and in the filter catchment are mainly fine sand, sand and till. The main land use in the River Pyhäjoki catchment is agriculture (23%), forest (56%) and peat land (16%). The soil types in the area are permeable and extra nutrients leach into the adjacent water bodies via the subsurface drainage systems.

Materials and methods

The filters

In this study, material called Fosfilt-s was used in two sand filters to enhance the removal of P. Fosfilt-s is a side product of a titanium dioxide production plant situated in the city of Pori in western Finland. Fosfilt-s contains 60−75% SiO_2, 3.0−8.0% Fe, 4.0−6.5% Al, 1.0−3.0% Ti, 0.8−1.3% Ca and 1.3−4.0% C. Grain size of Fosfilt-s is mainly 0.125−0.5mm, but 20% of the material is under 0.125 mm. The schematic diagrams of the filters are presented in Figure 1. Filtration area of F1 is 10 m x 20 m ,volume 240 m^3 and rough estimate of the hydraulic retention time 33 hours. The respective values for the F2 are 5 m x 15 m, 113 m^3 and 16 hours.

Filter 1 (F1), (Imponoja): The filter was constructed in 1997. This filter is situated beside a small ditch, which drains both arable land and forest. Since 1995, ditch water has been dammed upstream of the filter in order to develop a wetland for a purification function. The height difference of the wetland and the filter is approximately 1.4 m, and water was led from the wetland to the filter. The upper distribution layer of the filter contained crushed stones and there were no distribution pipes. The middle layer of the filter consisted of separate layers of sand and Fosfilt-s. The lowest layer of the filter was made of gravel and included perforated collection pipes, with the goal of percolating water downwards through different types of filter layers. The filtered water was returned to the ditch from the bottom layer (gravel) of the filter via collection pipes.

The filter worked properly only for some months after construction because of blockage of the surface macadam layer, and the filter was renovated in 1999. The filter was changed to function inversely so that the old collection pipes in the bottom layer were turned into distribution pipes. The new collection pipes were installed on the top layer of the filter and water was forced upwards through the filter medium under its own pressure as described in Figure 1. This structure worked approximately for one year, after which the Fosfilt-s layer in the middle part of the filter was clogged.

Filter 2 (F2), (Mylly). This filter was constructed in 1999 to catch nutrients from the subsurface drainage waters of a field area (12 hectares), which discharges to the River Pyhäjoki. The subsurface drainage waters are led to the filter's distribution pipe and layer (rough macadam) through a well. The water percolates across the filter (Fig. 1).

The upper and lowest filter layers are composed of sand (< 8 mm). The additional material, Fosfilt-s, is a separate layer in the inner part of the filter, and not mixed with the sand. The filtered water drains to the river through the collection layer and pipe in the lower part of the filter.

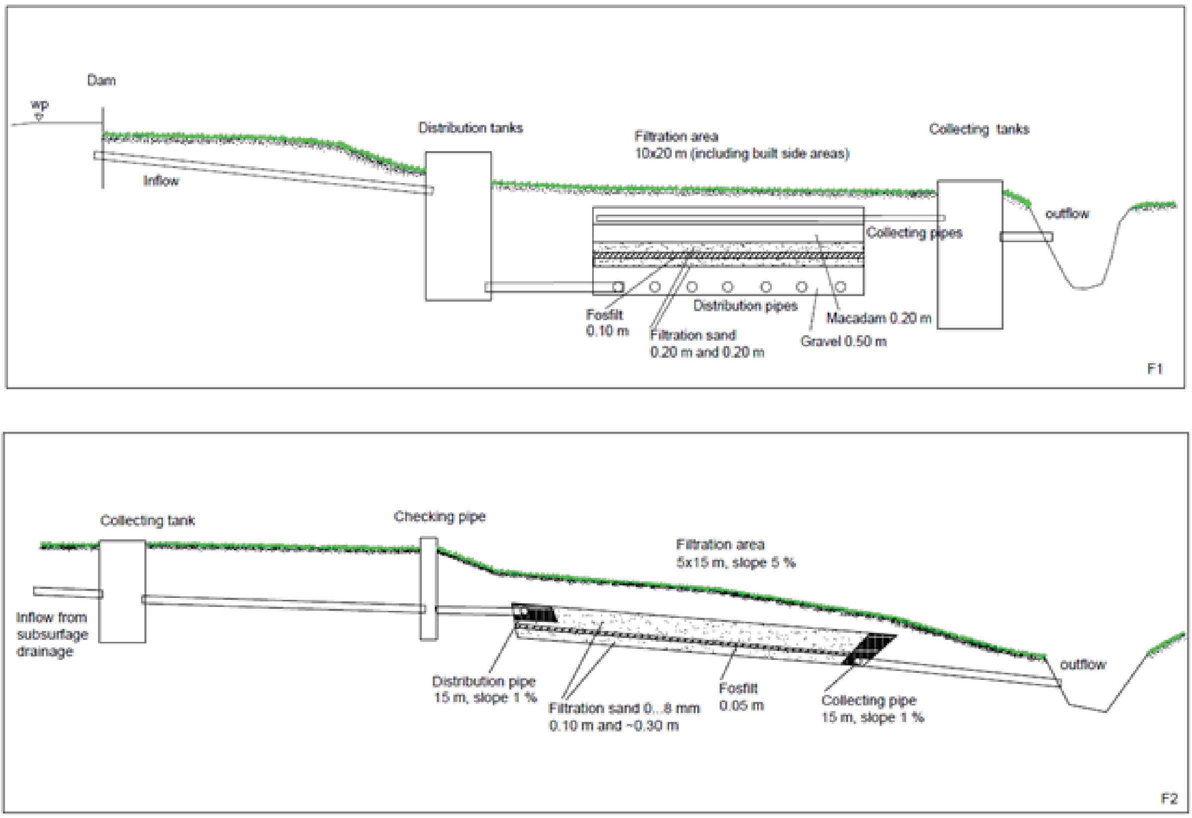

Fig. 1. Schematic diagrams of filters F1 and F2.

Monitoring

Water samples were taken from the inflow and outflow of both sites in different hydrological situations. The aim was to concentrate sampling on high-flow periods, but samples were also taken during low-flow periods.

In both cases, sampling started when the filter was completed. The monitoring period of F1 was 1.5 years before renovation and three years after renovation (from February 1997 to October 2002, n=59). During the first period, the amount of filtered water was measured only twice. Therefore, the absolute amounts of filtered solids and nutrients cannot be calculated for that period. The monitoring period of F2 was c 3.5 years (from April 1999 to November 2003, n=56).

Samples were taken to sterilised plastic bottles, and stored in a portable cooler and refrigerator before analysis (maximum 24 hours). Until 2001, water samples were analysed in the laboratory of the Southwest Finland Regional Environment Centre and after 2001 in the laboratory of Southwest Finland Water and Environment Research Ltd. The analysis methods followed Finnish standard laboratory procedures (Ekholm et al. 1997) and the methods are accepted by FINAS (Finnish Accreditation Service). Suspended solids (SS), total phosphorus (PTOT), dissolved reactive phosphorus (DRP), total nitrogen (NTOT), ammonium-nitrogen (NH_4-N), nitrate- and nitrite-nitrogen (NO_{2+3}-N) were analysed in discrete samples. SS were filtered through a polycarbonate filter (0.4 µm) and analysed gravimetrically. DRP was analysed by an ammonium molybdate method with ascorbic acid as the reducing agent. A polycarbonate filter (pore size 0.4 µg) was used in DRP analysis. PTOT was determined in the unfiltered sample. The sample was digested with $K_2S_2O_8$ before analysis with ammonium molybdate. NH_4-N was analysed colorimetrically with hypochlorite and phenol. The sum of NO_3-N and NO_2-N was determined by reduction of NO_3-N followed by NO_2-N determination. NTOT was analysed as NO_3-N after digestion of the sample with $K_2S_2O_8$. Electric conductivity (EC) was determined by the conductometric method (at 25 °C) and pH electrometrically.

The rate of inflow (flow l s^{-1}) was usually measured every time the water samples were taken but that of F1 was measured only twice before renovation. A container with a known volume was allowed to fill with water flowing out from the filter, and the time was recorded. On the basis of the flow rate and the inflow and outflow concentrations, the masses of inflowing and outflowing SS and nutrients and their reduction were calculated. No interpolations were made to estimate total flow.

Statistical analysis

The dependent t-test for concentrations in the paired samples was used for statistical comparison of the removal efficiency of nutrients and suspended solids in the different filter types.

The correlation coefficients for removal efficiency vs. concentrations of SS, PTOT, DRP, NTOT, NO_{2+3}-N and NH_4-N in inflow were calculated for the filters, as well as the correlations for reduction rates vs. inflow rate.

Results

Filter 1

The mean flow rate could not be calculated before renovation because there were only two flow rate observations. After the renovation, the mean flow rate for sampling occasions was 0.135 l s^{-1}. The flow rate over time is presented in Figure 2. The problems were encountered quite soon after the filter started its operation in 1997. The amount of filtered water was very low, and by autumn 1998, it had nearly stopped.

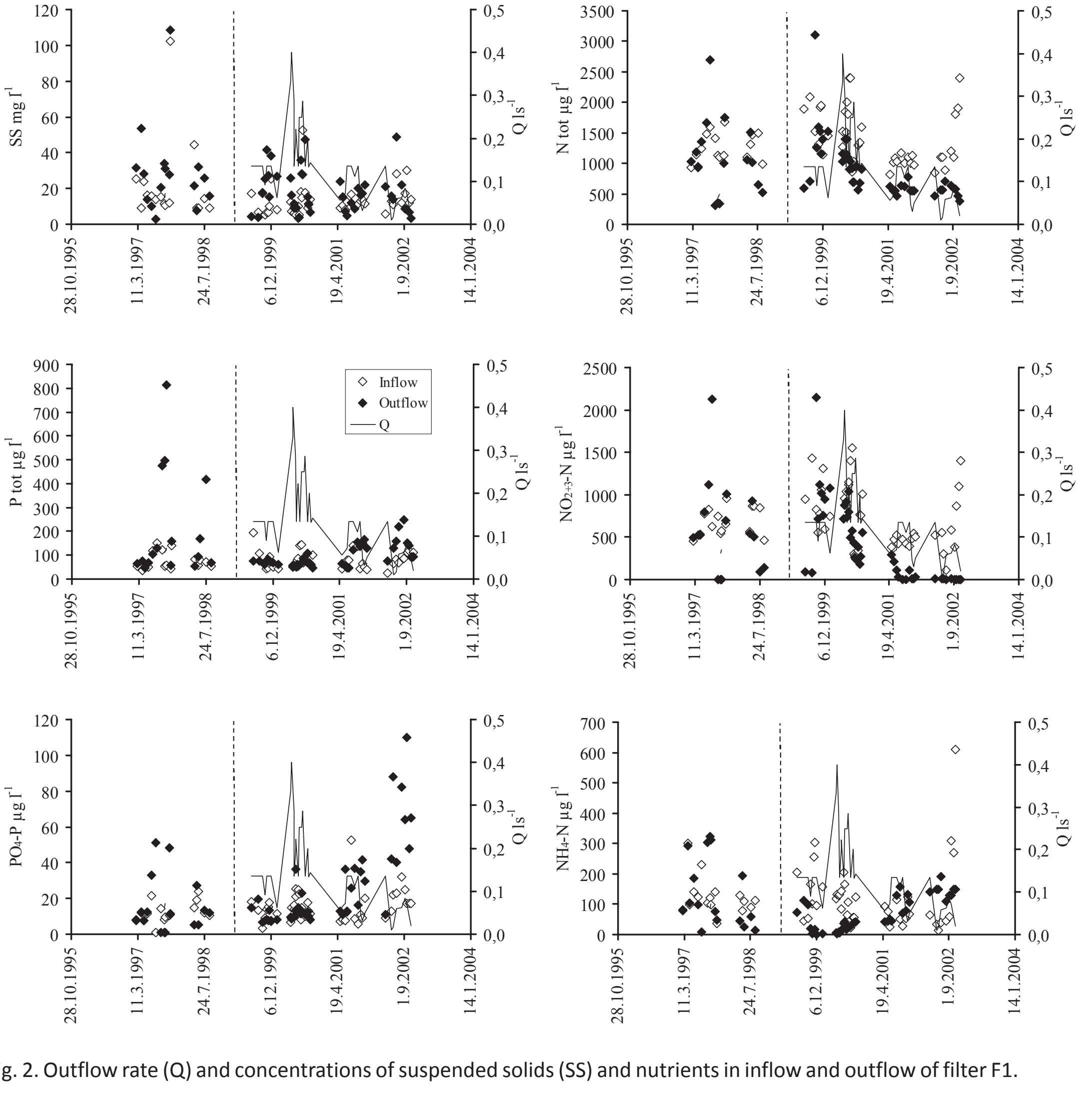

Fig. 2. Outflow rate (Q) and concentrations of suspended solids (SS) and nutrients in inflow and outflow of filter F1.

The quality of the ditch water represents fairly typical quality of runoff waters from southwestern Finnish clay and silt soils. Ditch waters are usually very turbid, but in this case the concentrations of SS and nutrients in the inflowing water were moderate due to the constructed wetland and sedimentation pond upstream. The wastewaters of dispersed settlements increase the concentrations of inorganic NO_{2+3}-N and NH_4-N, in particular.

For SS and DRP, the filter did not work as was intended and usually increased the concentrations throughout the whole monitoring period (Fig. 2, Table 1). On average, the filter increased SS and DRP loads by 36% and 19%, respectively, but did not affect the PTOT load.

Table 1. The average concentrations ± SD of suspended solids (SS) and nutrients and values of electric conductivity (EC), as well as the absolute amounts of SS and nutrients in the inflow and outflow water of F1 (Imponoja).

	n	Inflow µg l^{-1}	Outflow µg l^{-1}	Inflow g d^{-1}	Outflow g d^{-1}	Change g d^{-1}	Change %
SS	43	13085 ± 8383	17633 ± 11861	156 ± 200	211 ± 212	-56 ± 176	-36 ± 124
PTOT	43	79 ± 35	93 ± 48	0.9 ± 1	0.9 ± 1	0 ± 1	0.5 ± 84
DRP	43	15 ± 9	26 ± 24	0.2 ± 0.1	0.2 ± 0.2	0 ± 0	-19 ± 143
NTOT	43	1395 ± 456	890 ± 485	17 ± 13	11 ± 10	5 ± 7	32 ± 32
NO_{2+3}-N	43	729 ± 363	402 ± 465	9 ± 8	6 ± 8	3 ± 6	33 ± 59
NH_4-N	43	118 ± 108	66 ± 56	1 ± 1	0.5 ± 0.4	0,8 ± 1	60 ± 200
EC mS m^{-1}	43	11 ± 4	14 ± 4				

However, the filter clearly decreased the NTOT and NO_{2+3}-N concentrations (Fig. 2, Table 1), especially after the renovation. On average, 38% of inflowing NTOT and 64% of NO_{2+3}-N were removed after the renovation. The filter usually decreased concentrations of NH_4-N, but during the period from June 2001 to August 2002, the filter increased NH_4-N concentration. However, the mean proportional reduction of NH_4-N load was 40%.

The pH of water decreased slightly during filtration. The EC values for filtered water were 30% higher on average than those of the inflow, but were still low (Table 1).

The correlation coefficients (Table 3) show that the removal efficiencies relate to SS and nutrient concentrations (except for NO_{2+3}-N) in inflowing water. Moreover, the removal efficiencies of PTOT, DRP, NTOT, NO_{2+3}-N and NH_4-N relate to the outflow rate, the correlation being negative for NTOT and NO_{2+3}-N. The t-test shows that the difference between the amounts of SS, NTOT, NO_{2+3}-N and NH_4-N in the inflow and the outflow was statistically significant (Table 4).

Filter 2

The mean flow rate during samplings was 0.16 l s^{-1}. The inflowing waters were subsurface drainage waters from the field area of silty soils and intensive vegetable growing. The concentrations of SS were low while the concentrations of nutrients were high (Fig. 3). In the inflowing water, the proportion of dissolved nutrients varied between 40 and 100%.

On average, 61% of the inflowing suspended solids and 37% of the PTOT and 45% of DRP were removed by the filter during the monitoring periods (Table 2). When very high PTOT and DRP in the inflowing water occurred, high reduction rates (over 80%) were also observed. Also, the filter decreased concentrations of NH_4-N significantly.

Table 2. The average concentrations ± SD of suspended solids (SS) and nutrients and values of electric conductivity (EC), as well as the absolute amounts of SS and nutrients in the inflow and outflow water of F2 (Mylly).

	n	Inflow µg l^{-1}	Outflow µg l^{-1}	Inflow g d^{-1}	Outflow g d^{-1}	Change g d^{-1}	Change %
SS	56	9383 ±19256	3460 ± 10122	114 ± 229	44 ± 140	69 ± 222	61 ± 78
PTOT	53	698 ± 1287	366 ± 1146	8 ± 17	5 ± 16	3 ± 5	37 ± 43
DRP	54	666 ± 1410	322 ± 987	8 ± 19	4 ± 14	4 ± 13	45 ± 55
NTOT	56	16347 ± 9009	14976 ± 8522	226 ± 225	217 ± 217	9 ± 77	4 ± 25
NO_{2+3}-N	55	11910 ± 5533	12419 ± 5993	176 ± 189	181 ± 189	-6 ± 31	-3 ± 58
NH_4-N	55	2293 ± 4827	647 ± 2841	22 ± 52	8 ± 39	13 ± 46	76 ± 64
EC mS m^{-1}	56	58 ± 23	56 ± 30				

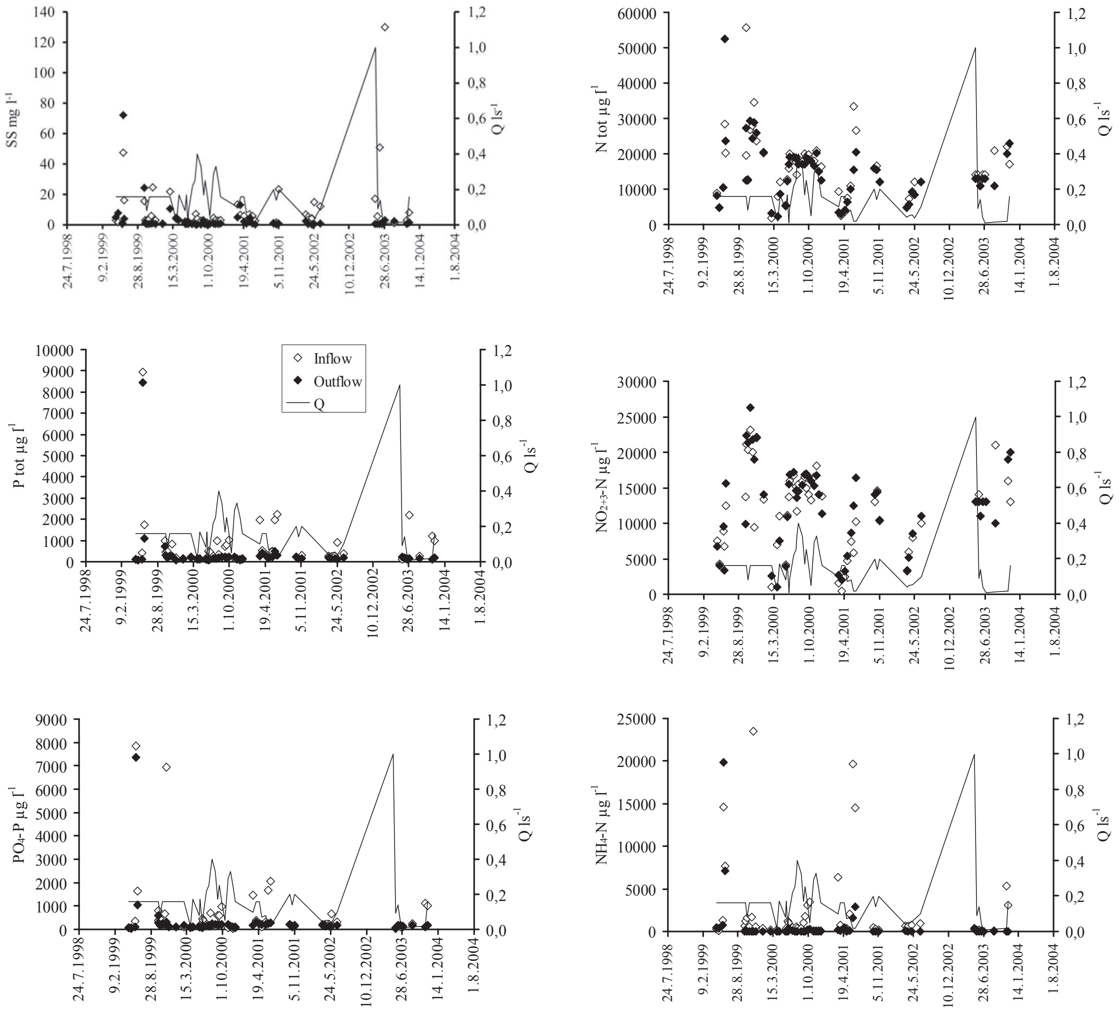

Fig. 3. Outflow rate (Q) and concentrations of suspended solids (SS) and nutrients in inflow and outflow of filter F2.

The rough estimation of P mass removal of F2 during the monitoring period was 2.03 g kg^{-1} Fosfilt-s. The estimation of N removal was 6.50 g kg^{-1} Fosfilt-s.

The pH value of inflow varied between 5.8 and 7.6, and the filter did not change it considerably. The electric conductivity did not change (Table 2).

The correlation coefficients (Table 3) show that the removal efficiencies for SS, PTOT, DRP, NTOT and NO_{2+3}-N are related to the concentrations in inflowing water, but not in the case of NH_4-N. The removal efficiencies of SS, PTOT, DRP, NTOT and NH_4-N were slightly related to the outflow rate, but the correlation was positive only for SS and negative for the nutrients. The dependent t-test for F2 shows that the difference between the amounts of SS, PTOT, DRP and NH_4-N in the inflow and the outflow was statistically significant (Table 4).

Table 3. The correlation coefficients for concentrations vs. removal efficienies of nutrients and suspended solids in inflow and the correlations for outflow rate vs. removal efficiencies.

		n	*r*
Concentration in inflow vs. removal efficiency			
F1	DRP	43	0.140
	PTOT	43	0.518
	NO_{2+3}-N	43	-0.037
	NH_4-N	43	0.391
	NTOT	43	0.270
	SS	43	0.337
F2	DRP	54	0.301
	PTOT	53	0.198
	NO_{2+3}-N	55	0.409
	NH_4-N	55	-0.032
	NTOT	56	0.197
	SS	56	0.139
Outflow rate vs. removal efficiency			
F1	DRP	43	0.512
	PTOT	43	0.403
	NO_{2+3}-N	43	-0.382
	NH_4-N	43	0.414
	NTOT	43	-0.207
	SS	43	-0.064
F2	DRP	54	-0.297
	PTOT	53	-0.259
	NO_{2+3}-N	55	0.039
	NH_4-N	55	-0.189
	NTOT	56	-0.179
	SS	56	0.127

Table 4. The dependent t-test, t-values and *p*-values for the difference between the amounts of SS, PTOT, DRP, NTOT, NO_{2+3}-N and NH_4-N in the inflow and the outflow for different filter types.

		n	t-value	*p*-value
F1	SS	43	-2.08	**0.022**
	PTOT	43	0.06	0.477
	DRP	43	-1.44	0.079
	NTOT	43	4.81	**0.000**
	NO_{2+3}-N	43	3.52	**0.000**
	NH_4-N	43	3.90	**0.000**
F2	SS	56	2.34	**0.012**
	PTOT	53	4.35	**0.000**
	DRP	54	2.05	**0.023**
	NTOT	56	0.88	0.193
	NO_{2+3}-N	55	-1.37	0.089
	NH_4-N	55	2.15	**0.018**

Discussion

The results of these two experiments indicate that the Fosfilt-s filter technique is applicable in certain situations where diffuse pollution has to be reduced. F2 diminished P and partly also N load quite successfully during the study period. However, the method is not always applicable as F1 diminished N load only to some extent and totally failed in reducing the P load.

The structure of Filter 1 (Imponoja) was unsuccessful. One reason for this was that the water first percolated through the original construction of F1 relatively rapidly. After that the distribution layer of macadam was clogged due to fine-sized suspended solids carried by the inflowing water and downward infiltration was restricted. The filter was renovated to function in the opposite direction, and the water was led to the bottom layer and the collection pipes were turned into distribution pipes. The filter worked for a year, but then percolation declined again, probably due to blockage of the Fosfilt-s layer. In this case, the concentrations of SS were not extremely high, but the filter still clogged up. The P reduction rate was already modest in the beginning, but in time the filter started to release P. However, the filter seemed to remove N, especially NO_{2+3}-N.

The results for this filter indicate that Fosfilt-s can be used to reduce concentrations of runoff nutrients if the SS contents are low, mainly below 10 mg l^{-1}. Dobbie et al. (2009) observed similar effects in their iron ochre-based P filters. P removal rates by concentration were inversely related to flow and declined during the different phases of the experiments, probably due to clogging. Based on our results from this and other sites (Kirkkala, unpublished), it seems that clogging of the filters can in some cases be prevented by upstream sedimentation ponds or a wetland, but it is very difficult to settle fine-sized sediment.

Filter 2 was constructed to treat subsurface drainage waters from sandy soils with concentrations of SS mainly under 5 mg l^{-1} and those of PTOT and DRP very high, usually above 200 µg l^{-1} and sometimes even above 1000 µg l^{-1}. The structure of the filter seems to be successful, since water percolated evenly through the filter and no clogging was encountered. P removal was moderate with removal efficiencies of 37% and 45% for PTOT and DRP, respectively. While the filter reduced concentrations of DRP and NH_4-N efficiently, concentrations of NO_{2+3}-N were higher in the outflowing water than in the inflowing water.

Only F2 caught P from the inflowing water, and the P reduction was significant. So the Fosfilt filter seems to be efficient in situations where the concentrations of SS are low but the concentrations of total and dissolved P are high.

Based on our results, the nitrogen removal ability of these types of filters can be moderate but variable. Filter F1 removed 32% and Filter F2 removed 4% of the total incoming nitrogen load. The reduction rates for NH_4-N were 60% and 76%, respectively. The reduction rate for NO_{2+3}-N was 64% in F1, but F2 did not catch NO_{2+3}-N. Apparently, the nitrogen removal was caused by microbiological processes rather than by chemical processes, but the microbiological activity was not measured in our study. Possibly nitrification occurred in the filter, nitrification bacteria changing ammonium into nitrite and nitrate, followed by denitrification.

Other types of lime filters have also been tested in the Yläneenjoki catchment (Kirkkala et al. 2011). The lime filters were quite efficient in removing SS and P (60–82%), but the nitrogen removal ability was limited (28%). Lime filters tested in the Yläneenjoki catchment increased the pH significantly, and the outflowing filtered water was alkaline (Kirkkala et al. 2012). It is generally known that aquatic organisms may suffer from high pH or sudden pH variation. No such problems were observed with Fosfilt-s filters. There the pH of the inflowing water was mostly close to neutral or slightly acidic, and the filters slightly decreased the pH value. This is an advantage when compared to lime.

In the case of F2, monitoring is needed in order to find out the lifetime of the filter. There is always a risk of release of precipitated P when filters age. The results from this study and the previous lime filter study show that in order to prevent clogging, sedimentation of suspended solids should be carried out before the water reaches the filter. Because of its fine-coarsed structure, Fosfilt-s seems to be more sensitive to clogging than lime.

The estimated PTOT removal of F2 was 2.03 g P kg^{-1} Fosfilt-s during the monitoring period. The estimation of PTOT mass removals of lime filters in the Yläneenjoki catchment varied from 0.02 g kg^{-1} to 3.03 g kg^{-1} (Kirkkala et. al. 2012). For example, Dobbie et al. (2009) found that an ochre (iron hydroxide) wastewater treatment system achieved a removal of up to 24 g PTOT kg^{-1} ochre during a three-year experiment while for another system it was 0.19 g PTOT kg^{-1} ochre d^{-1} during 9-month experiment. For slag, Shilton et al. (2006) reported P removal of 1.23 g kg^{-1} slag in a wastewater treatment plant.

Conclusions

Two Fosfilt-s based sand filters were built in order to remove P from runoff waters. F1 was built to enhance the effectiveness of a sedimentation pond and wetland and F2 to treat subsurface drainage waters. The results show that sand filters incorporating Fosfilt-s can reduce nutrient load to watercourses, but the method has some limitations.

Due to its fine-coarsed texture, Fosfilt-s is not applicable if the inflowing water contains high levels of suspended solids. The Fosfilt-s filter seems to be useful for the treatment of waters from subsurface drainage systems where the concentrations of SS are low. While Fosfilt-s does not seem to remove phosphorus as efficiently as lime filters, it was better in removing nitrogen but the processes were apparently microbiological rather than chemical. The lime compounds increase the pH of the filtered water, but Fosfilt-s decreases it slightly.

The development of this type of filters should be continued to treat subsurface drainage waters in particular with high concentrations of dissolved nutrients. Both the dimensioning criteria and the texture of the filter medium need to be developed. There is a need for field experiments on nutrient removal by sand filters from runoff waters, as most studies are implemented in the laboratory and field experiments often involve wastewater treatment.

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