

Long-Term Field-Scale Experiment on Using Lime Filters in an Agricultural Catchment

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The River Yläneenjoki catchment in southwest Finland is an area with a high agricultural nutrient load. We report here on the nutrient removal performance of three on-site lime-sand filters (F1, F2, and F3), established within or on the edge of the buffer zones. The filters contain burnt lime (CaO) or spent lime [CaO, Ca(OH)₂, and CaCO₃]. Easily soluble lime results in a high pH level (>11) and leads to an efficient precipitation of soluble phosphorus (P) from the runoff. Water samples were taken from the inflow and outflow of each site in different hydrological situations. The length of the monitoring period was 4 yr for F1, 6 yr for F2, and 1.5 yr for F3. F1 and F2 significantly reduced the suspended solids (SS), total P (PTOT), and dissolved reactive P (DRP) in the treated water. The proportional reduction (%) varied but was usually clearly positive. Filter F3 was divided into two equal parts, one containing burnt lime and the other spent lime. Both filter parts removed PTOT and SS efficiently from the water; the burnt-lime part also removed DRP. The mixed-lime part removed DRP for a year, but then the efficiency decreased. The effect of filters on nitrogen compounds varied. We conclude that sand filters incorporating lime can be used together with buffer zones to reduce both P and SS load to watercourses.

THE RIVER YLÄNEENJOKI CATCHMENT, located in the center of an intensive agricultural area in southwest Finland, is an example of an area with high diffuse nutrient load. The catchment has been the target of an intensive restoration program since 1995, when the Pyhäjärvi Protection Fund was established by local municipalities, private industries, and local associations to promote the protection of the locally important Lake Säkylän Pyhäjärvi, suffering from eutrophication caused by a high external phosphorus (P) load (Mattila et al., 2001; Ventelä and Lathrop, 2005; Ventelä et al., 2007, 2011). The lake's P load originates through 54% from the River Yläneenjoki catchment, 10% from air, 24% from smaller ditches, and 12% from the River Pyhäjoki (Ventelä et al., 2007). Since 1995, nearly all farmers in the catchment have committed to the Finnish agri-environmental program to implement basic water protection measures. The Pyhäjärvi Protection Fund has also been active in promoting wastewater treatment in the rural catchment. In addition, catchment management practices such as buffer zones, sedimentation ponds, and wetlands have been introduced.

The main goal of the catchment work is to reduce the amount of P, the limiting nutrient, in the lake. The P load from agriculture is accentuated in areas with heavy clay soils and sloping fields. In such cases, most of the P is transported in surface runoff due to the low infiltration capacity of the soil. The P is mainly contained in eroded soil, as even slopes exceeding 2 to 3° are vulnerable to erosion. Some 20 to 30% of the P is usually in the form of soluble, algal-available P (Ekholm, 1998; Ekholm et al., 1997).

New, innovative treatment methods, such as filtering ditches and lime-sand filters, together with and in addition to buffer zones and wetlands, have been developed and tested for their ability to remove P from runoff (Kirkkala, 2001). In Finland, this work was first done in the European Union and nationally cofunded Pyhäjärvi LIFE project (1996–2000), and currently in the project financed by ERDF, European Regional Development Fund Program for Southern Finland, “Inventory of water protection measures and the technical innovations of catchment restoration in changing climate” (2008–2011).

Sand filters are primarily known and studied in the area of municipal wastewater treatment. Treatment mechanisms in a sand filter include physical filtering of solids, ion exchange, and decomposition of organic substances by soil-dwelling bacteria. Different reactive materials have been tested and studied

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Abbreviations: DRP, dissolved reactive phosphorus; EC, electrical conductivity; NTOT, total nitrogen; PTOT, total phosphorus; SS, suspended solids.

to intensify nutrient removal, for example, iron or other metals containing side products (Dobbie et al., 2009; Penn and Bryant, 2006; Shilton et al., 2006), or natural deposits (Arias et al., 2001; Renman, 2008; Roseth, 2000; Søvik and Kløve, 2005).

Burnt lime (CaO) reacts with the runoff water to form hydrated lime [Ca(OH)₂] so that over time a typical structure containing sand and hydrated lime, characterized by coarse and durable aggregates, is gradually achieved. Chemically, the improvement of the filter media structure is due to an increase in the Ca²⁺ content of the solution: Ca²⁺ gradually replaces Na⁺, K⁺, Mg²⁺, and H⁺ on the cation exchange sites. The particles thereby coagulate into larger groups or aggregates. The cation exchange process is further amplified by slower pozzolanic reactions known from filter media stabilization with lime. The permeability of a typical lime filter drain is similar to the permeability of sand, being in the range of 10⁻⁴ to 10⁻⁶ m s⁻¹. The surface runoff is thus able to infiltrate and discharge through the subsurface drains or collection pipes, which significantly reduces the amount of suspended solids in the water. The material in the lime filter contains a surplus of easily soluble lime, which results in a high pH (pH > 11) in the treated layer. This leads to an efficient precipitation of both soluble P and most metals contained in the runoff. The reactions, which are well known from normal lime precipitation processes, produce poorly soluble calcium phosphate and metal hydroxides (Oates, 1998). As a consequence of the above reactions, the P and metal load on adjacent watercourses can be significantly reduced (Wepping, 1997).

In the 1990s, the first signs of eutrophication were detected in Lake Pyhäjärvi and thus the filter development work aimed for the development of efficient methods for P load reduction. This has become even more relevant in the 2000s, as the recent climate variation seems to pose new challenges to the load reduction work. In the southwestern part of Finland, the wintertime 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 temperature above zero, lack of snow, and high wintertime rainfall. The open agricultural fields are more vulnerable to erosion, as they have been tilled in late autumn and they lack the protective plant cover. Thus, the risk of erosion and nutrient runoff is high (Puustinen et al., 2005; Ventelä et al., 2011). If most of the nutrient loading occurs outside the growing season, the traditional biological measures, such as wetlands and buffer strips, perform suboptimally in reducing the load. New innovations and enhancement of the old methods are thus needed. The idea of removing nutrients from agricultural runoff water with filters has recently arisen in many countries (Penn and Bryant, 2006; Ballantine and Tanner, 2010; Falk Øgaard, 2010; Kjaergaard, 2010). Therefore, the previously unpublished long-term filter data from the 1997 to 2006 period are now a very valu-

able addition to the current development work and are the subject of this paper. We report here on the nutrient removal performance of three on-site lime-sand filters, two of which were established within the buffer zones and one on the edge of the buffer zone.

Study Area

Lake Pyhäjärvi (61°00'04" N, 22°17'29" E) situated in the boreal temperate zone in southwestern Finland, is one of the most extensively studied lakes in Finland. The major inflows to Lake Pyhäjärvi are the rivers Yläneenjoki and Pyhäjoki, which cover 68% of the drainage basin area of the lake. Long-term (1959–2009) average annual precipitation is 590 mm. Because of clay soils, only a minor part (<10%) of rainwater ends up in groundwater. Therefore, groundwater contributions to stream flow are also small, which is reflected by very low discharge values during low-flow periods (in the River Yläneenjoki <0.05 m³ s⁻¹ during 16 summers in the period 1980–2000) (Bärlund and Kirkkala, 2008). The long-term (1979–2008) average monthly temperature for the period October to 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 three on-site lime filters presented in this paper are located in the middle part of the River Yläneenjoki catchment beside ditches flowing to the river. The soils in the river valley and in the catchments of the filters are mainly clay and silt, whereas tills and organic soils dominate elsewhere in the catchment. The main land covers in the River Yläneenjoki catchment are agriculture (27% of the area), forest (48%), and peat land (21%) (Koivunen, 2004). The main forms of agriculture are cereal production and poultry husbandry. According to surveys conducted in 2000 to 2002, 75% of the agricultural area is planted with spring cereals and 5 to 10% with winter cereals (Pyykkönen et al., 2004). The characteristics of the subcatchments of the River Yläneenjoki where the filters are situated are presented in Table 1.

Materials and Methods

The Filters

Sand (particle size < 3 mm) was used as carrier material in the three studied filters (F1, F2, F3) and was moistened to field capacity before lime addition, which amounted to 10% lime of the sand wet weight. Two different kinds of lime were used. Burnt lime (CaO) was used in F1 after renovation, in F2, and in one part of F3. The material used in F1 before renovation and in the other part of F3 was spent lime from the sugar manufacturing process at a nearby sugar refinery and it contained CaO, Ca(OH)₂, and CaCO₃. The latter is called *mixed lime* in this study. The schematic diagrams of the filters are presented in Fig. 1.

Filter 1 (F1) (Mäkilaurla, Kreivilänoja subcatchment): One of the earliest test filters (built in 1997) is a lime filter drain between the field and the buffer zone next to the ditch flowing to the River Yläneenjoki. The furrow was infilled with lime and sand mixed manually and equipped with a drainage pipe at the base (Table 2). The aim of this filter was to reduce the P content in agricultural and domestic wastewater from the farmer's house. The waters were mixed in a collection well and subsequently

Table 1. Properties of the River Yläneenjoki catchment and subcatchment areas, southwest Finland. The flow rates are the mean of the years 1980 to 2009.

Catchment	Filter	Catchment area	Agricultural area	Agricultural area	Flow
		km ²	ha	%	
Total		234	6430	27	2.01
Kreivilänoja (Mäkilaurla)	F1	23.6	681	29	0.24
Vehmasoja	F2	6.3	135	22	0.06
Kiimassuonoja	F3	6.1	119	20	0.06

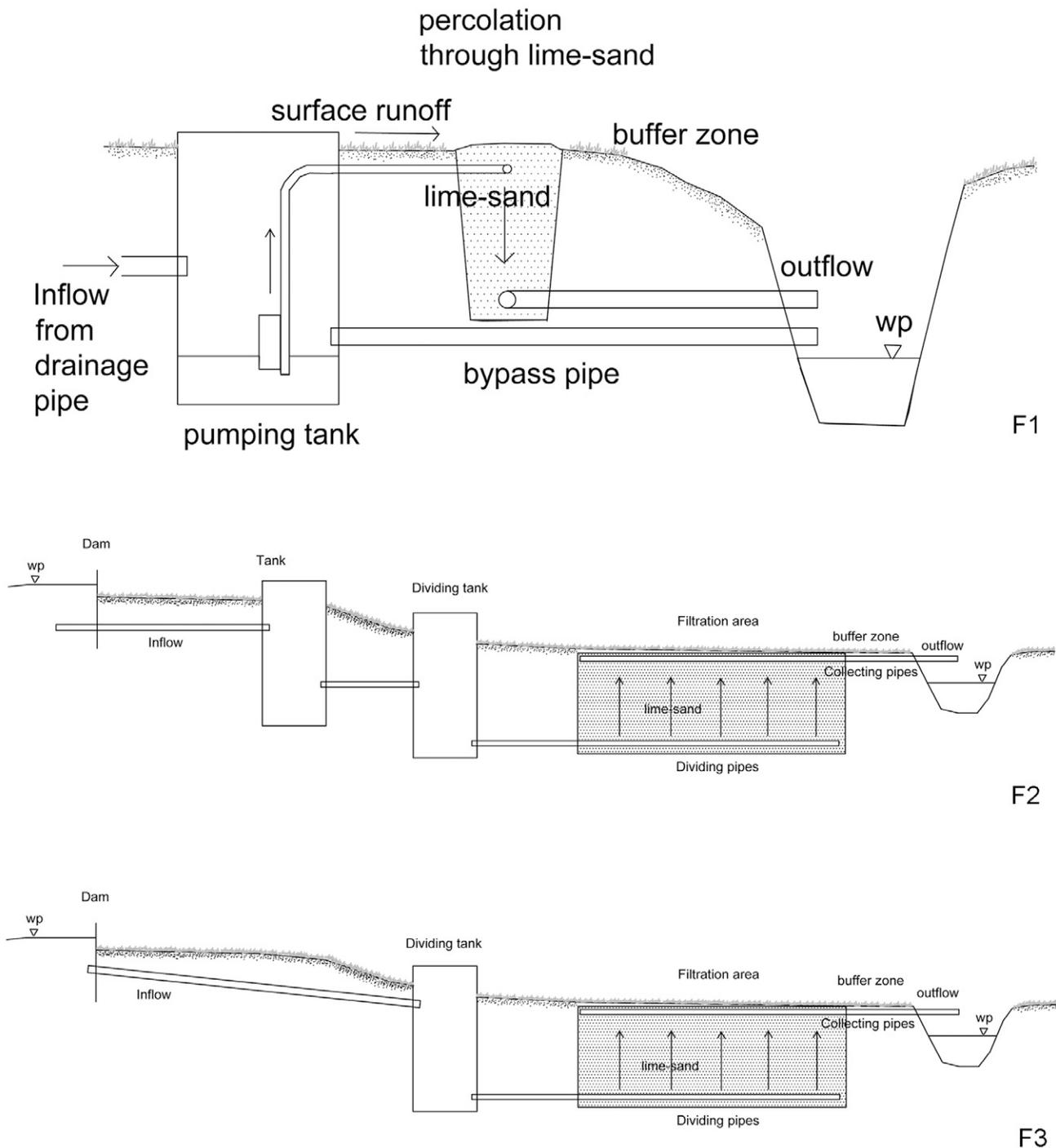


Fig. 1. Schematic diagrams of Filters F1 (Mäkilaurla, Kreivilänoja subcatchment), F2 (Vehmasoja), and F3 (Kiimassuonoja) in the River Yläneenjoki catchment, southwest Finland. wp = water level.

pumped into the lime filter drain, where it was dispersed into the filter material through a perforated pipe at 10-cm depth from the surface of the filter. The water was allowed to percolate downward by the force of gravity, and then collected into a discharge pipe that led to the buffer strip (Fig. 1). Spent lime from the sugar refinery was used in the original filter but, when it was renovated in October 2000, burnt lime was mixed with the old filter material.

Filter 2 (F2) (Vehmasoja): This filter is situated in the buffer zone of a small ditch, which drains both arable lands and forests. The large filter contains burnt lime and sand and was built to catch P (Table 2). Ditch water is dammed upstream of the

filter with a height difference of approximately 2 m. From the dam, water is led to the filter through a regulation well. There is another well in the upper head of the filter to distribute the water and pressure evenly. Perforated pipes (diameter 40 mm) were installed at the base of the excavation at horizontal intervals of 2 m to distribute the incoming water evenly over the whole filter area. Water is forced upward through the filter media under its own pressure, and the filtered water is returned to the ditch from the upper layer of the filter via collection pipes (Fig. 1).

Filter 3 (F3) (Kiimassuonoja): A wetland was established in this small ditch in 1995, and the lime filter was constructed

within the buffer zone downstream of the wetland in 1999 (Table 2). In principle the filter is similar to F2, but it was divided into two equal parts with the same inflow. Each part contained a different lime material to study the use and efficiency of two lime types in the removal of nutrients from runoff. One part contained burnt lime and the other spent lime from the sugar refinery. The filtered water is conveyed from both parts to the ditch via separate collection pipes, which enables separate monitoring of the two parts (Fig. 1).

Monitoring

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

In all cases sampling started when the filter was completed. The length of the monitoring period varied and depended on the financial situation. The monitoring period of F1 was 3.5 yr before renovation and 0.5 yr after renovation (from May 1997 to April 2002, $n = 88$). The monitoring period of F2 was ca. 6 yr (from February 1997 to June 2003 and from April 2006 to October 2006, $n = 117$). The monitoring period of F3 was 1.5 yr (from August 1999 to November 2001, but that of inflowing water started in June 2000, $n = 24$).

Samples were taken straight to sterilized plastic sampling bottles, and stored in a portable cooler and refrigerator before analyzing. The analysis started within 24 h after sampling at the latest. Until 2001, water samples were analyzed 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 methods of analyses followed Finnish standard laboratory procedures (Ekholm et al., 1997) and the methods are accepted by the Finnish Accreditation Service. Suspended solids (SS), total phosphorus (PTOT), dissolved reactive phosphorus (DRP), total nitrogen (NTOT), ammonium-nitrogen ($\text{NH}_4\text{-N}$), and nitrate- and nitrite-nitrogen ($\text{NO}_{2+3}\text{-N}$) were analyzed in discrete samples. Samples were digested with $\text{K}_2\text{S}_2\text{O}_8$ before analysis with ammonium molybdate on PTOT, and on NTOT measured as $\text{NO}_3\text{-N}$. Ammonium-nitrogen was analyzed colorimetrically with hypochlorite and phenol, and the sum of $\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$ was determined by reduction of $\text{NO}_3\text{-N}$ followed by $\text{NO}_2\text{-N}$ determination. Electrical conductivity (EC) was determined by the conductometric method (in 25°C) and pH electrometrically. Other samples were passed through a $0.4\text{-}\mu\text{m}$ polycarbonate filter, and SS was determined gravimetrically on the

filter. The filtrate was analyzed for DRP by an ammonium molybdate method with ascorbic acid as the reducing agent.

The outflow rate (flow L s^{-1}) was measured every time the water samples were taken. A container with a known volume was filled with water flowing out of the filter, and the time of filling was measured. On the basis of the measurements of flow and the inflow and outflow concentrations, the masses of inflowing and outflowing SS and nutrients and their percent reduction were calculated. No interpolations were made. The mean of measured inflow and reduction was used to roughly estimate the P mass removal of the filter material (g kg^{-1} lime).

Statistical Analysis

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

The correlation coefficients for reduction rates vs. concentrations of SS, PTOT, DRP, and NTOT in inflow were calculated for all filters, as well as the correlations for reduction rates vs. outflow rate.

Results

Filter 1

The mean of outflow rate was 0.061 L s^{-1} before and 0.158 L s^{-1} after the renovation. The flow rate over time is presented in Fig. 2.

The quality of the inflowing water varied considerably because of the input of domestic wastewater, which usually has high concentrations of nutrients and SS. The filter significantly reduced SS, PTOT, and DRP in the treated water throughout the monitoring period (Fig. 2 and Table 3). The proportional reduction (%) varied but was usually clearly positive.

After renovation, the proportional reduction of SS and nutrients did not change considerably, but the absolute reduction (g d^{-1}) of SS, PTOT, and DRP clearly increased (Table 3). The rough estimation of P mass removal by F1 during the monitoring period was 3.031 g kg^{-1} lime before renovation (3.5 yr) and 0.633 g kg^{-1} lime after renovation (0.5 yr). The lower value after renovation is mainly due to the short monitoring period.

The filter decreased NTOT on average (Fig. 2 and Table 3). The concentration of $\text{NH}_4\text{-N}$ decreased significantly during the filtration, but the $\text{NO}_{2+3}\text{-N}$ concentration increased slightly, perhaps due to the occurrence of nitrification in the filter.

The water pH increased clearly during filtration, especially immediately after the construction and renovation of the filter (Fig. 2). The EC of both inflowing and outflowing water varied

Table 2. Characteristics and properties of the filters in the River Yläneenjoki catchment, southwest Finland. Sand (particle size < 3 mm) was used as carrier material in every filter.

Filter	Year built	Size†	Type	Additional material	Drainage area above	Average flowthrough
		m			km ²	L s ⁻¹
F1						
F1, before renovation	1997	30 × 0.5 × 1.0	Downwards	Mixed‡		0.06
F1, after renovation	2000	30 × 0.5 × 1.0	Downwards	CaO		0.15
F2	1997	50 × 10 × 0.9	Upward	CaO	6.3	0.15
F3						
F3 mixed-lime part	1999	50 × 7.5 × 0.9	Upward	Mixed	6.1	0.33
F3 burnt-lime part	1999	50 × 7.5 × 0.9	Upward	CaO	6.1	0.09

† Length × width × depth.

‡ CaO, $\text{Ca}(\text{OH})_2$, and CaCO_3 .

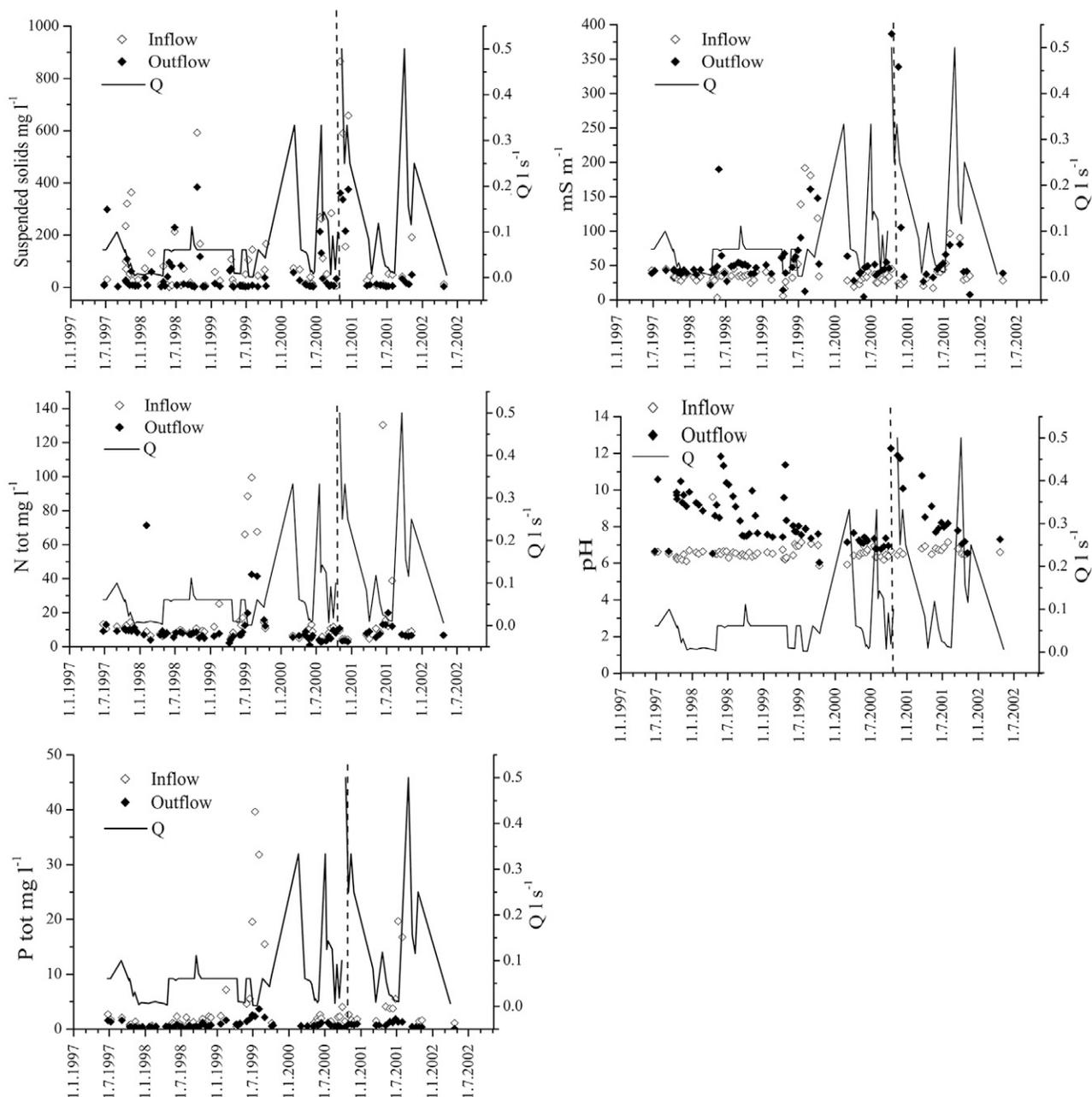


Fig. 2. Concentrations of suspended solids and nutrients, electrical conductivity, and pH in inflowing and outflowing water and the outflow rate (Q) of Filter F1 in the River Yläneenjoki catchment, southwest Finland. The dashed line presents the time of renovation. N tot = total nitrogen; P tot = total phosphorus.

considerably, but the values for filtered water were 25% higher on average than those of the inflow (Fig. 2).

The correlation coefficients (Table 4) show that the SS and nutrient concentrations in inflowing water partly explain the reduction rates. The outflow rate does not have any considerable impact.

The t - and P -values of t -test for SS, PTOT, DRP, NTOT, and pH are shown in Table 5.

Filter 2

The outflow rate was 0.15 L s^{-1} on average for sampling occasions during the observation period. In 2001 and 2006, two exceptionally high amounts of percolated water were observed.

The quality of inflowing water represents the typical quality of runoff waters from southwestern Finnish clay soils with high

concentrations of SS and nutrients. They vary according to seasonal hydrological conditions and short-term events (Fig. 3). The nutrient and SS concentrations are lower during dry seasons than in rainy seasons. Traditionally, there has been a dry period in summer and a rainy season in autumn and spring, but now climatic variation is so high that the timing of the dry and rainy seasons is difficult to generalize.

On average, 67% of the inflowing SS and PTOT and 52% of DRP were removed by the filter during the monitoring periods (Table 6). Summer and autumn 2001 were very unusual periods, as the filter released both suspended solids and P, especially DRP. In May and June 2001, the amount of percolated water was about four times higher than usual. After that, the efficiency of the filter was not as high as before (Fig. 3). It is possible that local rainfalls were so heavy that they did not

Table 3. The average values ± SD of suspended solids, nutrient concentrations, and conductivity, as well as the absolute amounts of suspended solids and nutrients in the inflow and outflow water of Filter F1 (Mäkilaurla, Kreivilänöja) in the River Yläneenjoki catchment, southwest Finland.

Parameter†	n	Inflow		Outflow		Reduction	Reduction
		µg L ⁻¹		g d ⁻¹			
Before renovation							
SS (mg L ⁻¹)	64	76 ± 109	71 ± 72	497 ± 1	314 ± 1	182 ± 1	36.7 ± 765
PTOT	64	3055 ± 6774	792 ± 650	9.8 ± 17	3.9 ± 5	5.9 ± 15	60 ± 39
DRP	60	2642 ± 6417	643 ± 682	7.6 ± 16	2.8 ± 4	4.7 ± 14	62.6 ± 186
NTOT	61	14,116 ± 18,432	9867 ± 10,592	53.4 ± 66	38.5 ± 37	14.8 ± 42	27.8 ± 96
NO ₂₊₃ -N	65	4379 ± 2834	6701 ± 6624	20.8 ± 22	27 ± 31	-6.2 ± 26	-29.6 ± 12,504
NH ₄ -N	65	7454 ± 17,922	887 ± 1626	21.4 ± 55	4 ± 9	17.4 ± 53	81.2 ± 95
EC (mS m ⁻¹)	65	41 ± 32	57 ± 51				
After renovation							
SS mg L ⁻¹	17	162 ± 269	86 ± 139	4448 ± 10	2370 ± 4	2078 ± 5	46.7 ± 50
PTOT	17	4005 ± 5572	848 ± 456	25.3 ± 27	9.8 ± 11	15.5 ± 19	61.1 ± 44
DRP	17	3302 ± 5440	632 ± 537	10.7 ± 9	4.1 ± 4	6.6 ± 9	61.3 ± 78
NTOT	17	17,021 ± 30,331	8417 ± 4296	117 ± 119	92.6 ± 122	24.4 ± 64	20.8 ± 43
NO ₂₊₃ -N	17	2711 ± 1922	6328 ± 4422	54.8 ± 85	64.7 ± 80	-9.9 ± 13	-18 ± 16,305
NH ₄ -N	16	5017 ± 8201	357 ± 454	19.5 ± 17	3.5 ± 4	16.1 ± 18	82.2 ± 62
EC (mS m ⁻¹)	17	39 ± 22	66 ± 74				

† SS, suspended solids; PTOT, total phosphorus; DRP, dissolved reactive phosphorus; NTOT, total nitrogen; EC, electrical conductivity.

affect the other filters. However, our weather monitoring network is not so specific that this could be detected.

The filter reduced the content of NTOT significantly (Fig. 3 and Table 6). The *t*- and *P*-values of *t*-test for NTOT and pH are

Table 4. Correlation coefficients for concentrations vs. reduction rates of DRP, PTOT, NTOT, and SS in inflow and the correlations for outflow rate vs. reduction rates in the inflow and outflow water of Filters F1, F2, and F3 in the River Yläneenjoki catchment, southwest Finland.

Filter	Parameter†	n	r
Concentration in inflow vs. reduction rate			
F1	DRP	76	0.176
	PTOT	80	0.411
	NTOT	78	0.209
	SS	81	0.107
F2	DRP	86	0.035
	PTOT	90	0.300
	NTOT	89	0.421
F3	SS	88	0.298
	DRP	24	0.507
	PTOT	24	0.523
	NTOT	24	0.595
Outflow rate vs. reduction rate			
F1	DRP	76	0.033
	PTOT	80	-0.087
	NTOT	78	0.044
	SS	81	0.017
F2	DRP	86	0.030
	PTOT	90	-0.170
	NTOT	89	0.185
F3	SS	88	-0.065
	DRP	24	0.237
	PTOT	24	0.368
	NTOT	24	0.244
	SS	23	0.346

† DRP, dissolved reactive phosphorus; PTOT, total phosphorus; NTOT, total nitrogen; SS, suspended solids.

shown in Table 5. However, the filter released NH₄-N throughout the whole period. It slightly reduced the content of NO₂₊₃-N on average, but in many situations nitrate was released.

The filter strongly influenced the pH values of runoff. The pH values of untreated water were usually under 7.5; the pH values of treated water were approximately 12 until 2001 (Fig. 3), but then lower values were observed. The EC of inflowing water was 14.9 mS m⁻¹ on average, and that of filtered water was 492 mS m⁻¹. The EC in treated waters gradually decreased over time, being >800 mS m⁻¹ at the beginning of the experiment and <100 mS m⁻¹ at the end (Fig. 3 and Table 6).

The correlation coefficients (Table 4) show that SS, PTOT, and NTOT in inflowing water partly explain the reduction rates, but not considerably in the case of DRP. The outflow rate affects PTOT and NTOT reduction rates, but the correlation is negative for PTOT and positive for NTOT.

Table 5. The dependent *t*-test, *t*-values, and *P*-values.

Filter	Parameter†	n	<i>t</i> -value	<i>P</i> -value
F1	SS	81	2.00	0.025
	PTOT	80	4.48	0.001
	DRP	76	3.52	0.000
	NTOT	78	2.37	0.010
F2	pH	81	-10.15	0.000
	NTOT	89	3.02	0.002
F3	PTOT‡	24	6.11	0.000
	PTOT§	24	6.66	0.000
	DRP§	24	6.67	<0.001
	NTOT‡	24	4.53	0.000
	NTOT§	24	5.22	0.000
	NO ₂₊₃ -N‡	24	2.61	0.008
NO ₂₊₃ -N§	24	3.34	0.001	

† SS, suspended solids; PTOT, total phosphorus; DRP, dissolved reactive phosphorus; NTOT, total nitrogen.

‡ Mixed lime.

§ Burnt lime.

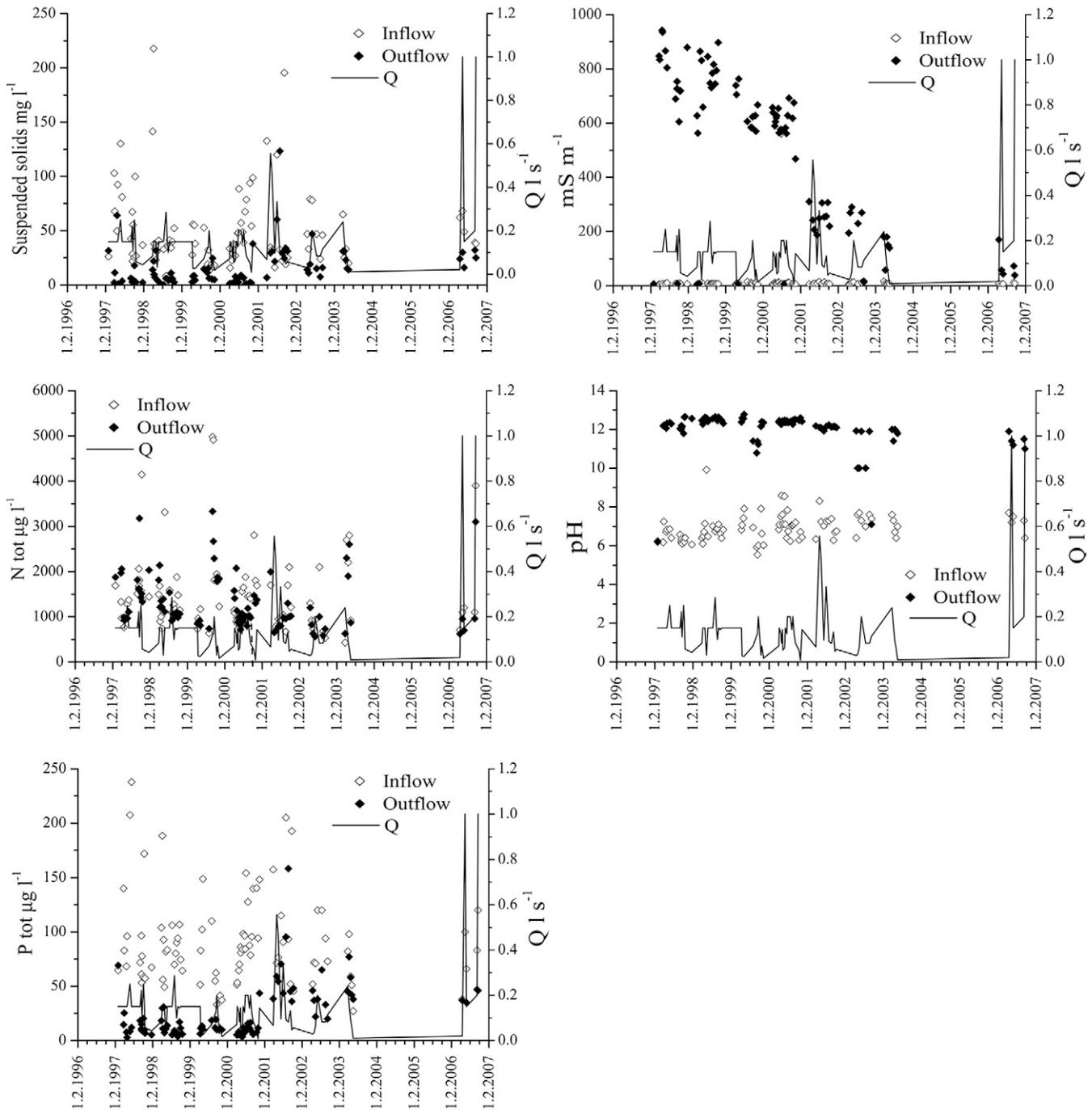


Fig. 3. Concentrations of suspended solids and nutrients, electrical conductivity, and pH in inflowing and outflowing water and the outflow rate (Q) of Filter F2 in the River Yläneenjoki catchment, southwest Finland. N tot = total nitrogen; P tot = total phosphorus.

Table 6. The average values \pm SD of suspended solids, nutrient concentrations, and conductivity, as well as the absolute amounts of suspended solids and nutrients in the inflow and outflow water of Filter F2 (Vehmasoja) in the River Yläneenjoki catchment, southwest Finland.

Parameter†	n	Inflow	Outflow	Inflow	Outflow	Reduction	Reduction
		$\mu\text{g L}^{-1}$		g d^{-1}		%	
SS (mg L^{-1})	89	51 ± 37	14 ± 18	691 ± 895	231 ± 453	460 ± 635	67 ± 55
PTOT	91	90 ± 41	25 ± 25	1.21 ± 1	0.40 ± 0.7	0.81 ± 0.8	67 ± 33
DRP	87	11 ± 6	6 ± 15	0.15 ± 0.1	0.07 ± 0.2	0.08 ± 0.2	52 ± 133
NTOT	90	1469 ± 851	1303 ± 601	19.49 ± 21	16.29 ± 14	3.20 ± 0.0	16 ± 10
$\text{NO}_{2+3}\text{-N}$	90	784 ± 745	771 ± 501	10.51 ± 15	9.37 ± 10	1.15 ± 0.0	11 ± 500
$\text{NH}_4\text{-N}$	91	16 ± 23	126 ± 94	0.21 ± 0.4	1.49 ± 2	-1.28 ± 2	-618 ± 6710
EC (mS m^{-1})	89	15 ± 59	492 ± 288				

† SS, suspended solids; PTOT, total phosphorus; DRP, dissolved reactive phosphorus; NTOT, total nitrogen; EC, electrical conductivity.

Filter 3

The outflow rate was 0.33 L s^{-1} for the part with burnt lime and 0.39 L s^{-1} for the part with mixed lime (Fig. 4).

The concentrations of SS and N of inflowing water were quite similar to those at Filter 2, but the concentrations of P were lower (Fig. 4). The reduction of SS was excellent (94%) as an aggregate of both filter parts (Table 7). Both filter parts removed PTOT from the water efficiently (Fig. 4 and Table 7). The burnt-lime part also removed DRP (ca. 75%). The mixed-lime part removed DRP for a year but after autumn 2001, DRP was released from this filter part. Until October 2000, the removal of PTOT and DRP was equally efficient in both filter parts. Since then, the efficiency of the mixed-lime part decreased (Fig. 4).

The two parts of the filter also removed $\text{NO}_{2+3}\text{-N}$ from the water but mainly released $\text{NH}_4\text{-N}$ (Fig. 4 and Table 7). However, the release of $\text{NH}_4\text{-N}$ seemed to gradually decrease over time.

The pH value of inflowing water was approximately 6.5 to 7.0. The pH values of treated waters were >11 from the mixed-lime and >12 from the burnt-lime part (Fig. 4). The EC of inflowing water was 7.7 mS m^{-1} on average, and that of outflowing water was close to 800 mS m^{-1} at the beginning of the experiment. The EC in treated waters gradually decreased over time, being $<30 \text{ mS m}^{-1}$ in the water treated with mixed lime and $<400 \text{ mS m}^{-1}$ in the water treated with burnt lime (Fig. 4).

In F3, the correlation coefficients (Table 4) show that SS, PTOT, NTOT, and DRP concentrations in inflowing water affect the reduction rates considerably. Also, the correlations between the outflow rate and the reduction rates are stronger than in the other filters.

The significant *t*- and *P*-values for F3 are shown in Table 5.

Discussion

The results of these three experiments indicate that the lime filter technique is applicable in situations where diffuse pollution, especially P load, has to be reduced. The method is highly efficient in decreasing the amounts of SS and total and soluble P in accordance with the results from other studies (Renman, 2008). In relation to the filter size, the P removal was the most efficient in F1. The P concentrations of inflowing water in this filter were very high. It is known that a sand filter alone can be used for the removal of SS and particulate P, but reactive materials can be added to also remove dissolved P. The chemical reactions involved are well known from the lime treatment of wastewaters (Hammer, 1977; Weppling, 1997).

Cucarella and Renman (2009) made a comparative study on P sorption capacity of filter materials and found that it is very difficult to compare published data. The results can be strongly influenced by batch experimental parameters, and it is obvious that in field-scale experiments the results are influenced by different parameters as well. Dobbie et al. (2009) studied an ochre (iron hydroxide) wastewater treatment system, which achieved a removal rate of up to 24 g P kg^{-1} ochre during 3 yr of experiment. Another system achieved 195 mg P kg^{-1} ochre d^{-1} during 9 mo (53 g P kg^{-1} ochre). Søvik and Kløve (2005) studied the suitability of shell sand as a P sorbent both with laboratory batch experiments and in a subsurface-flow shell-sand filter treating municipal wastewater from a single household. The average total accumulated P concentration in the entire filter bed was 0.335 g kg^{-1} . Because of

high hydraulic load, 1 yr of operation was assumed to equal 4 to 8 yr of normal operation. Shilton et al. (2006) found a P retention of 1.23 g kg^{-1} slag in a wastewater treatment plant. For the filters in this study we estimated the P mass removal as 3.03, 0.63, 0.028, 0.018, and 0.021 g kg^{-1} for filters F1 before renovation, F1 after renovation, F2, F3 mixed-lime part, and F3 burnt-lime part, respectively. The P mass removals of Filters F2 and F3 seem to be low compared with those in other studies. However, comparing mass removals and P binding capacity of different filters is difficult because of the varying duration of monitoring periods, variation in concentrations in inflow water, and because there still seemed to be P binding capacity left when the monitoring ended.

The visual observation showed that, in many situations, preferential flow paths developed and water was not evenly distributed in the filter. This may be caused by a gradual loss of the porous structure and by clogging of the filter material. In F2, preferential flow paths started to appear in the fourth year of functioning and in F3 after 1 yr, especially in the mixed-lime part. It was observed that the EC values of the outflowing water decreased simultaneously with changes in the flow routes, indicating decreased retention times in the filters. Thus, the development of preferential flow paths reduced the P removal in the filters. The decline in EC values may also indicate leaching out of the reactive components.

The high SS content of the water may clog filters, as found by Dobbie et al. (2009) in their iron ochre-based P filters. They also found that 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 other sites (Kirkkala, unpublished data, 2003), it seems that clogging of the filters can be prevented by installing sedimentation ponds or a wetland before the filter. As much of the solids as possible should be settled before the water enters the filter.

Our results show that the nitrogen removal ability of these types of filters is limited. The filters removed 16 to 28% of the total incoming nitrogen load. Filter F1 removed $\text{NH}_4\text{-N}$ efficiently but released $\text{NO}_{2+3}\text{-N}$. On the contrary, Filters F2 and F3 removed some $\text{NO}_{2+3}\text{-N}$ and released $\text{NH}_4\text{-N}$. In F3, more nitrogen was released in the filter part containing burnt lime than in the one containing spent lime.

The pH of the inflowing water was mostly close to neutral or slightly acid. Lime in the filters increases the pH significantly, and the filtered water is alkaline. The highest observed pH values were close to 12, which may cause problems in the receiving water body, especially if the filtered water volume is high compared with the size and volume of the receiving water body. It is generally known that aquatic organisms may suffer from a high or suddenly varying pH. Fish deaths have been detected both in high- and low-pH regimes. In this experiment, the high pH values were not a problem as the waters drained into ditches where the filtered water was strongly diluted. In the case of F1, the filtered water flowed into the buffer zones.

However, the filter materials still seem to have capacity to remove P, and further monitoring is needed to find out the life span of the filters. Soil-buried sand-lime filters of this type differ from the wastewater treatment plants with lime precipitation in that the precipitated matter remains in the filter, whereas in wastewater treatment plants, sludge (with precipitated P) is continuously removed from the system. There is a risk of release of precipitated P when the filters age, and the pH and the

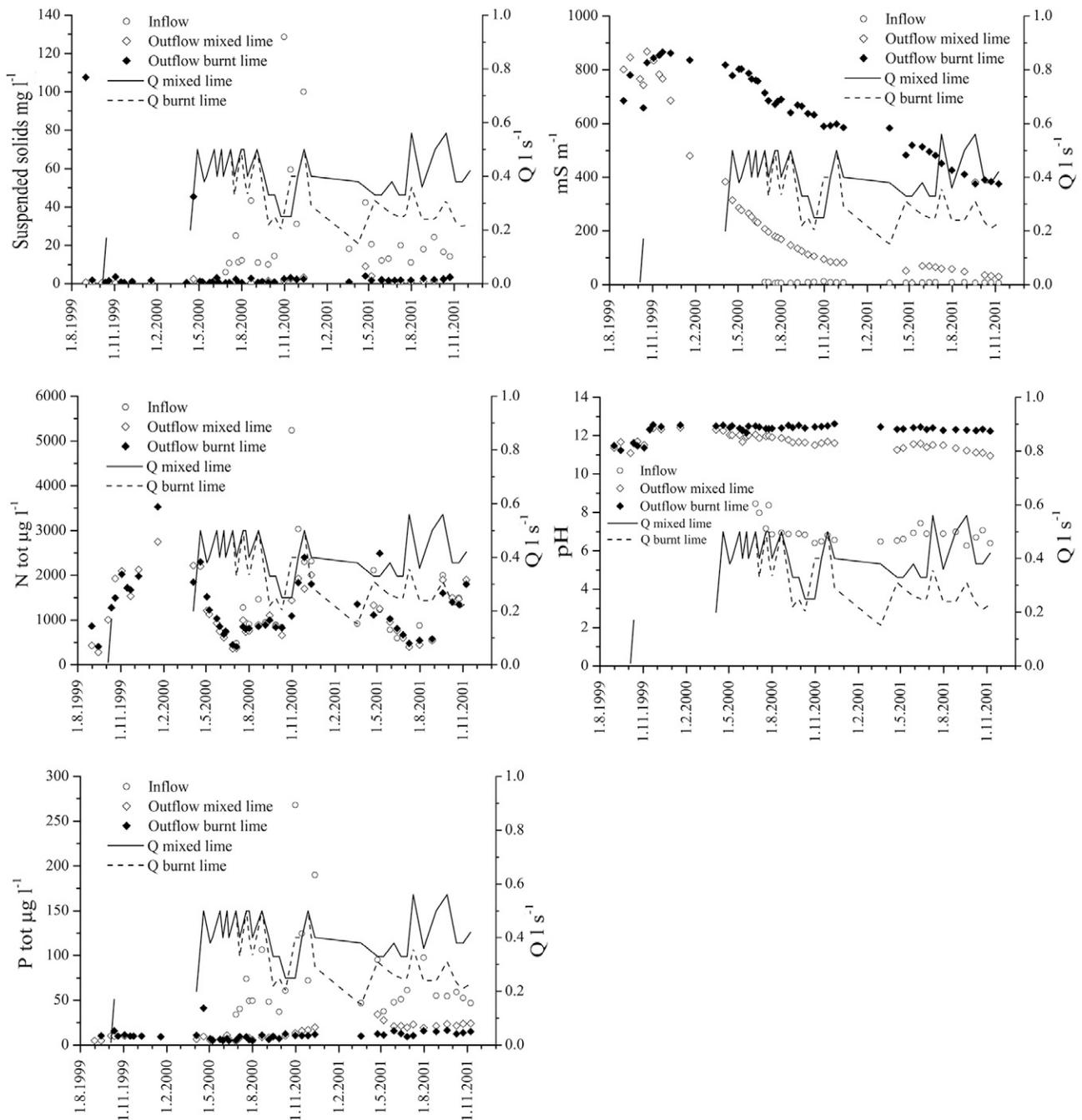


Fig. 4. Concentrations of suspended solids and nutrients, electrical conductivity, and pH in inflowing and outflowing water and the outflow rate (Q) of Filter F3 in the River Yläneenjoki catchment, southwest Finland. N tot = total nitrogen; P tot = total phosphorus.

concentration of Ca diminish. Diaz et al. (1994) conducted laboratory studies to determine the influence of pH and Ca on inorganic P precipitation and solubility relationships in the water column. Precipitation of soluble P was influenced by the initial Ca concentration of the water. Precipitation of inorganic P increased at Ca concentrations $> 100 \text{ mg L}^{-1}$ and at $\text{pH} > 9.0$. Effective P removal from surface waters by means of precipitation requires Ca concentrations $> 100 \text{ mg L}^{-1}$ and $\text{pH} \geq 8$.

One goal of these experiments was to evaluate the life span of these types of filters. It is clear that the efficiency and the life span of the filters depend on the inflow rate and the water quality. In the filters, the structural changes and new internal preferential flow routes of the water decreased the ability to remove

P. Formation of preferential flow paths would be prevented if a very high inflow is avoided, for example, with bypass pipes. To prevent clogging, sedimentation of SS should be done before water reaches the filter. Water should be distributed evenly within the filter, and granule composition should be optimal for water percolation. It is probable that the filter media are frozen during winters, leading to anoxic conditions, stimulating the release of P. More information is needed on the removal capacity of the filters, especially under specific conditions.

Conclusions

Three lime-based sand filters were built to remove P from runoff waters and enhance the treatment effectiveness of buffer zones and

Table 7. The average values \pm SD of suspended solids, nutrient concentrations, and conductivity, as well as the absolute amounts of SS and nutrients in the inflow and outflow water of Filter F3 (Kiimassuonoja) in the River Yläneenjoki catchment, southwest Finland. n = the amount of samples for conductivity inflow/outflow.

Parameter†	n	Inflow	Outflow‡		Inflow	Outflow‡		Reduction	Reduction
			$\mu\text{g L}^{-1}$			g d^{-1}			
SS (mg L^{-1})	24	29 \pm 30	1.8 \pm 2	1.9 \pm 1	1793 \pm 1829	60 \pm 57	53 \pm 35	1681 \pm 1795	94 \pm 6
PTOT	24	76 \pm 54	16 \pm 8	11 \pm 3	4.7 \pm 3	0.56 \pm 0.3	0.29 \pm 0.1	3.86 \pm 3	82 \pm 13
DRP	25	9 \pm 6	7 \pm 5	3 \pm 2	0.58 \pm 0.4	0.24 \pm 0.2	0.07 \pm 0.0	0.27 \pm 0.4	46 \pm 54
NTOT	25	1444 \pm 1058	1097 \pm 528	1135 \pm 581	91.17 \pm 68	38.32 \pm 22	31.87 \pm 21	20.98 \pm 49	23 \pm 26
NO ₂₊₃ -N	25	853 \pm 940	786 \pm 481	752 \pm 445	53.25 \pm 57	27.37 \pm 19	21.01 \pm 14	4.86 \pm 42	9 \pm 65
NH ₄ -N	25	29 \pm 47	32 \pm 14	70 \pm 20	1.66 \pm 2	1.11 \pm 0.6	1.92 \pm 0.8	-1.37 \pm 3	-83 \pm 1697
EC (mS m^{-1})	25/44	8 \pm 2	287 \pm 278	646 \pm 151					

† SS, suspended solids; PTOT, total phosphorus; DRP, dissolved reactive phosphorus; NTOT, total nitrogen; EC, electrical conductivity.

‡ Mixed lime.

§ Burnt lime.

wetlands. The results show that sand filters incorporating lime can be used together with buffer zones to reduce both P and SS load to watercourses. These types of filters are especially suitable for the treatment of phosphorus-rich waters, but their ability to remove N is limited. A potential problem may be caused by lime due to the high pH values of filtered waters. If filtered waters constitute a large proportion of the waters in the receiving watercourse, this may disrupt the flora and fauna. In that case, neutralization should be arranged before transfer of the treated waters to a watercourse. The long-term effects of full-scale applications are not yet known. The fate of P trapped in the filter has not been studied in detail in situations where pH gradually drops toward neutral. The dimensioning criteria are not fully understood for all applications, and it may sometimes be very difficult to ensure a sufficient contact between the water and the filter material in varying field conditions. Yet the filters can be seen as a useful tool for load reduction, and the development of filters should be continued.

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