Long-term purification efficiency and factors affecting performance in peatland-based treatment wetlands: An analysis of 28 peat extraction sites in Finland

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Abstract

Peatland-based treatment wetlands that purify incoming water by means of natural physical, chemical and biological processes belonging to the peatland ecosystem are widely used at Finnish peat extraction sites. They can comprise either undrained or drained overland flow areas (OFAs or DOFAs), with the OFAs representing the best available technology (BAT) for peat extraction. We analyse here the long-term treatment performance of these OFAs and DOFAs and factors affecting this performance. Data on 14 OFAs and DOFAs in different parts of

Finland were taken from the extensive long-term environmental pollution control databases. Nearly half of these wetlands had been monitored for at least 4 years and seven for 8-23 years. The results indicated that peatland-based treatment wetlands purify drainage water as efficiently as other natural treatment wetlands on soils in general, the common challenge being phosphorus retention. Iron was also efficiently retained. The average reductions were highest in OFAs with good hydraulic function, and these also showed long-term water protection performance. An important factor affecting purification efficiency was the hydraulic loading rate. Important system design elements in this regard were the size of the wetland in relation to its catchment area, its gradient, the length of the water flow route within the wetland, and the efficient flow area of the wetland. The results regarding the latter two design elements strongly indicate that not all the areas potentially suitable in DOFAs for water purification are yet being used efficiently.

Keywords: boreal peatland-based treatment wetland, wetland system design elements, nitrogen, phosphorus, suspended solids, iron

1. Introduction

Peatland-based treatment wetlands that purify incoming water by means of natural physical, chemical and biological processes that occur in the peatland ecosystem are now being widely used as water pollution control methods in

Finnish peat extraction areas. They are built on either undrained or formerly drained overland flow areas (OFAs or DOFAs).

The drainage water from a peat extraction area flows from the sedimentation basin via the outlet and distribution ditches to the OFA, and horizontally through the water-permeable surface moss and peat layers in it (Ihme et al., 1991b; Ronkanen & Kløve, 2008) to the collection ditches downstream of it. There is generally also a sedimentation basin above a DOFA, where water is spread by a ditch or pool, although perforated pipes spreading through the wetland are also often used (Postila et al., 2014). In DOFAs the water flows both in the ditches and in the moss/peat surfaces between the ditches, the ditches being partly blocked with peat or straw dams.

According to the treatment wetland classification of Kadlec & Wallace (2008), these peatland-based wetlands that purify water by means of natural physical, chemical and biological processes inherent in the peatland ecosystem can be viewed as natural systems. In many cases the drainage water to be purified also flows into these wetlands naturally by gravity, although nowadays this is more commonly achieved by pumping.

OFAs are considered to represent the best available water purification technology (BAT) for peat extraction sites in Finland and have been in general use for this purpose since the early 1990s. The Finnish “model” for the method, the OFA of the Kompsasuo peat extraction site in northern Finland (65^{o}45´N, 26^{o}00´E, 110 m a.s.l.), gave good purification results in the early years following its establishment in 1987 (Ihme et al., 1991 a, b; Ihme, 1994) and has also done so in recent times (Karjalainen et al., 2016), to the extent that the official dimensioning and operating instructions for OFAs (Ihme et al., 1991b; Savolainen et al., 1996; Ministry of the Environment, 2013) are largely based on the structural properties of this wetland.

It has been shown that peat extraction water can also be purified using DOFAs (Postila, 2007; Postila , 2016; Postila et al., 2011, Postila et al., 2014). In fact their use in peat extraction areas is increasing, because the Finnish areal planning strategy (Ministry of the Environment, 2007) directs peat extraction operations to already drained peatland areas.

Other water pollution control methods applied in peat extraction areas are careful peat lifting practices, field ditch retainers, peak runoff control and sedimentation basins (Ihme et al., 1991c; Marttila and Kløve, 2009). These methods mainly reduce loading with suspended solids (SS) and the particulate P, N, C and Fe transported by these. In addition to SS, OFAs and DOFAs also reduce loading with dissolved nutrients (PO_4-P, $NO_{2,3}$-N, NH_4-N). Peat extraction water can also be purified by chemical methods (Heiderscheidt et al., 2013).

We examine here the long-term performance of OFAs and DOFAs and factors affecting this, using data taken from the comprehensive, long-term mandatory environmental pollution control databases of Vapo Oy for different parts in Finland. We aim to study i) how peatland-based treatment wetlands operate on a long-term basis, and ii) how the physical properties of wetlands affect the purification results.

2. Water-purifying processes in peatland-based treatment wetlands

The natural physical, chemical and biological processes taking place in the peatland ecosystem that serve to purify the water entering peatland-based treatment wetlands have been studied mainly in the OFAs, the main site for this research being the Kompsasuo OFA in northern Finland (65º45´N, 26º00´E, c. 110 m a.s.l.). It is probable, however, that largely the same processes also occur in DOFAs, especially in the undrained peatland surfaces between the ditches.

The Kompsasuo OFA is situated in a minerotrophic peatland area in the southern aapa mire zone. The mire, which is surrounded by coniferous forests of the mid-boreal type, was prepared for peat extraction in 1986-89, and actual extraction started in 1989. The OFA was taken into use at the beginning of 1987, during the preparation phase.

Kompsasuo is a pine mire, with a typical field layer vegetation for its area, including *Carex spp, Menyanthes trifoliata, Vaccinium spp., Potentilla palustris and Betula nana*. The ground layer vegetation is highly dominated by *Sphagnum spp.* species. A careful survey of its vegetation was conducted at the time of its peak standing crop in mid-August 1992 (Huttunen et al., 1996), when it had been in use for 6 years, the main aim of the survey being to study the role of the vegetation as a nutrient sink (see section 2.1.). Out of the 54 taxa identified in the OFA, 18 are indicators of swamp influence (additional nutrient input from surface flow), among which the projection coverages of *Menyanthes trifoliata* and *Carex lasiocarpa* in particular, being species that favour flooded sites, were highest in the upper part of the OFA, near its distribution ditch. The peat mosses in the ground layer were dominated by *Sphagnum angustifolium*, but also included *S. papillosum, S. warnstorfii* and seven other *Sphagnum* species. The predominant brown moss species in the area were *Aulacomnium palustre, Calliergon stramineum, Plagiomnium ellipticum* and *Warnstrorfia exannulata*. Eleven other brown moss species were also found in the area.

The prevailing peat type in the 0-5 cm surface layer of the Kompsasuo OFA was Menyanthes-Carex-Sphagnum peat with the degree of humification between H1 and H3 on the von Post scale (von Post, 1922) in September 1989, when the OFA had been in use for almost three years. The corresponding properties in the 5–15 cm and 15-50 cm depth layers were Menyanthes-Carex-Sphagnum peat (H3) and the Sphagnum-Carex peat (H4), respectively. In 2001, after 14 years of use for water purification, the prevailing peat types were the Sphagnum-Carex peat in the 0-30 cm layer and Carex-Sphagnum in the 30-80 cm layer (Ronkanen and Klove, 2005) indicating increases in the projection coverages of Carex sp. in the OFA, as could also be seen by visual observation. The degree of humification was H1-H5 in the upper 0-30 cm layer and H4-H5 deeper down, at 30-80 cm.

During the both periods the degree of peat humification in the OFA increased with increasing depth of the peat layer as in other peatlands (Huikari, 1959; Boelter, 1969; Korpijaakko and Radforth, 1972; Päivänen, 1973).

The water flow in an undrained peatland-based treatment wetland (OFA) is lateral, because the hydraulic conductivity (K, in situ) of peat decreases with its increasing degree of humification (Huikari, 1959; Boelter ,1969: Korpijaakko and Radforth, 1972; Päivänen, 1973). This flow is affected also by the microtopography (small forms) of the peatland surface layers. The Kompsasuo OFA is situated in the area of aapa-mires in northern Finland, where this microtopography is formed by higher hummock banks and lower flarks and strings (rimpis, puddles). In this environment water flows across strings and percolates through the surface layers of the peat. During the momentary local high water conditions, after prolonged rain or during spring melt, low strings may become submerged and water movement may occur as sheet flow across broader areas of the wetland. As the water level falls, usual surface flow is continued.

It is important that water is percolated also within the peat matrix, because many processes in the peat have central roles in water purification. On the basis of K-value measurements in 2001 Ronkanen and Klove (2005) calculated the following flow velocities for the different peat layers in the Kompsasuo OFA: 6.1 m h^{-1} in the 0-10 cm surface layer and 5.0 m h^{-1}, 5.3 m h^{-1}, 5.6 m h^{-1}, 3.0 m h^{-1}, 0.6 m h^{-1} and 9.1 mm h^{-1} at depths of 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-60 cm and 60-70 cm, respectively. The authors drew two important conclusions from these results regarding the hydraulic properties of the OFA: 1) The effective flow depth, i.e. that at which water purification occurs in the OFA, can extend to 50 cm, and 2) fairly high hydraulic conductivity is maintained in the OFA despite it having been used for water purification for several years.

On the basis of material balance studies of the Kompsasuo OFA performed by Huttunen et al. (1996; see section 2.1) plant uptake represents only a small annual N and P sink in peatland-based treatment wetlands in undrained peatland areas, as is also generally true of other treatment wetlands (Richardson and Nichols, 1985; Vymazal and Kröpfelova, 2008; Kadlec and Wallace, 2008). This indicates that there are other processes at work in the water-permeable moss and peat surface layers of OFAs that are important for water purification.

One notable sink for N in OFAs is probably biological nitrification-denitrification, as also found generally in horizontal subsurface flow constructed wetlands (HS CWs) (Vymazal, 2010). The surface layers of these undrained peatland-based treatment wetlands show a rapid decrease in redox potential (E_h) with increasing depth, as is common in peatlands (Lähde, 1969; Papendick and Runkles, 1966). In September 1991 the following E_h-values were measured at the different depths of the peat layer in the Kompsasuo OFA, 50 m below the distribution ditch (OFA) and the reference peatland area being situated 25 m from the OFA collection ditches (RA):

The depth of the peat layer (cm)	E_h in OFA (mV)	E_h in RA (mV)
2-6	from 26 to 49	from 81 to 161

8-10	from -31 to -110	from 70 to 134
10-20	from -110 to -305	from 146 to -151
20-30	from -192 to -304	from -131 to -181
30-40	from -122 to -192	from -121 to -136

The results indicate that there is decrease in the E_h –values with increased water flow in the OFA. They also show that aerobic/anaerobic interfaces for sequential nitrification and denitrification are created in OFAs with increased depth of their peat layers, whereupon the air space is diminished and the oxygen content of the soil water reduced. The number of these interfaces is increased further by oxygen transport into the root zone through the air spaces of the stems and roots of aquatic macrophytes growing in the area, as normally found in wetlands (Reddy et al., 1989). There are also plenty of surface moss and peat layers and tissues of vascular plants in the OFAs that offer living environments for the bacterial biofilms involved in the nitrification-denitrification process (Bastviken, 2006). All this data indicates that the role of nitrification-denitrification in reducing N in OFAs should be studied further. More data should be acquired, especially on the effects of soil acidity on denitrification, which proceeds slowly below pH 5.5 (Lance, 1972). During field studies at the Kompsasuo OFA in 1991 the pH values in its 2-10 cm surface layer ranged from 5.6 to 5.7 and those in the deeper 10-40 cm layer from 5.2 to 5.8.

There is also adsorption of NH_4^+ to peat in OFAs (Heikkinen et al., 1995a), although this is mainly temporary, because the adsorbed NH_4^+ is exchangeable and can be mobilized from the peat as a result of nitrification and subsequent N loss through denitrification. NH_4^+ can also be assimilated by plants and peat microbes in the OFA.

The main PO_4 retention process in an OFA is chemical adsorption to the peat (Heikkinen et al., 1995b). There is also retention of organic Fe-P-colloids (Heikkinen and Ihme, 1995) and SS (particulate P, N, Fe and also organic and inorganic matter) from the peat extraction water. In order to obtain good water purification results, an OFA must be planned and constructed so that the purified water is in contact with the surface moss and peat layers of the wetland.

One N and P sink in OFAs could also be the microbial cell tissue. It has been noted in many treatment wetlands (Jenkinson and Ladd, 1981; Nichols, 1983; Jonasson and Michelsen, 1996) that microbial biomass also has a role in annual long-term N and P retention, and this should be clarified further in the case of peatland-based treatment wetlands.

Runoff water from peat extraction sites is characterized by high concentrations of dissolved organic matter (DOM) and Fe. In this water, as in organically coloured river and lake water in general (Heikkinen, 1990; Jones et al. 1993), Fe is bound mainly by the high apparent molecular weight DOM fraction (HAMW DOM) (Heikkinen, 1990). In peat extraction areas the Fe content of this fraction (Heikkinen, 1990), and thus probably also its susceptibility to physical, chemical, and biological precipitation (Kunze, 1982), is elevated, which is likely to be the main reason for the increased sedimentation of fine particulate matter with a high Fe content on stream and river riffle beds downstream from peat extraction areas (Laine and Heikkinen, 2000). This Fe accumulation may be a crucial factor in weakening the conditions for salmonid reproduction (Laine et al., 2001) and growth (Laine, 2001) in these areas. These impacts can be reduced by purifying the water in OFAs and DOFAs, which retain Fe-rich HAMW DOM from peat extraction drainage water (Heikkinen and Ihme, 1995; Heikkinen and Karppinen, 2015).

2.1 The role of plants in water purification

Material balance studies of the Kompsasuo OFA have indicated that plant uptake represents only a small annual N and P sink in the treatment wetlands created on undrained peatlands (Huttunen et al., 1996), as in other treatment wetlands (Richardson and Nichols, 1985; Vymazal and Kröpfelova, 2008; Kadlec and Wallace, 2008). These studies were performed at the time of the peak standing crop in mid-August 1992 (Huttunen et al., 1996), when the OFA had been in use for 6 years, and involved a careful survey of the vegetation of the OFA and its reference area (RA), the latter being situated in a peatland area 25 m from the OFA collection ditches. The work included analyses of above-ground and below-ground plant biomass in 12 quadrats of 1 m x 1 m in the OFA and 8 quadrats of the same size in the RA, the above-ground biomass being classified into three groups: shrubs, sedges plus graminoids, and herbs. Biomass samples of bryophytes were gathered from areas of 0.02 m^2. The below-ground parts (rhizomes and roots) were collected from peat monoliths of volume 2 l (cross-section 10 cm x 10 cm and cut down to a depth of 20 cm, thus comprising the “essential subterranean phytomass”, Sjörs, 1991), and all living parts with a diameter of at least 1 mm were separated out manually. Analyses with two replicates were performed for total N and total P on all the biomass samples. The increases in N and P in the total phytomass of the OFA were estimated by subtracting the values measured in the RA from those measured in the OFA and comparing the results with the figures for the total retention of N and P in the OFA as indicated by hydraulic and water quality monitoring (Ihme, 1994). The main results of this study at the species level are presented in part 2 of this paper.

The results indicate that during the 6 years of using the OFA for water purification there was an increase in the amount of N in its total phytomass, but that this increase accounted for only about 4% of the total inorganic N removal monitored during this period. In the case of P there was a decrease in the total phytomass which accounted for nearly 20% of the PO_4-P retention monitored. There were changes in the amounts of phytomass, but also in their nutrient content. The phytomasses of herbs, sedges, graminoids and below-ground parts of plants increased, but those of shrubs and bryophytes decreased. The average N concentration of the total phytomass in the OFA increased from 1.00 to 1.24% of dry weight, but the average P concentration decreased from 0.26 to 0.22% of dry weight. The highest N and P concentrations were measured in the herbs and the lowest in the below-ground phytomass.

The role of the vegetation as a nutrient sink may be more prominent in DOFAs than in OFAs. Silvan et al. (2004) reported a major role for plant uptake in nutrient removal in a restored peatland buffer, i.e, a peatland drainage area restored for water protection purposes to form a buffer between a land used for active forestry and a water body. It is probable, however, that in the long term the role of the vegetation as an annual nutrient sink is also small in DOFAs, as it is in water pollution control wetlands in general.

Although the role of the vegetation as an annual nutrient sink is small in OFAs, it is important that the vegetation should grow well in them, because this accelerates the functioning of water purifying processes in many ways. For example, it provides a substrate for the growth of bacterial nitrification-denitrification biofilms (Eriksson and Weisner, 1997; Toet, 2003; Bastviken, 2006), diffuses oxygen from roots to the rhizosphere, and insulates the bed surface during the cold season (Brix, 1994). As we all know, vegetation is also a prerequisite for the existence of peatlands, since these are formed by the accumulation of organic matter (peat) from dead and decaying plant material under conditions of permanent water saturation.

3. Materials and methods

Data on the peatland-based treatment wetlands to be studied here, together with monitoring data on outflow discharge and the quality of the inflow and outflow water, were taken from the Vapo environmental database, which covers 39 such treatment wetlands. A monitoring period of at least one year was required. On this basis a database covering 28 treatment wetlands in different parts of Finland (Fig. 1, Table 1) was established for further study. Of these wetlands, 14 were undrained (OFAs) and 14 drained (DOFAs).

All the wetlands forming the database (Tables 1 and 2) had been planned and constructed on peatlands according to the existing operating instructions (Ihme et al., 1991b; Savolainen et al., 1996; Ministry of the Environment, 2013), and their plans and realizations had also been checked by the water authorities, because environmental permits are required for peat extraction.

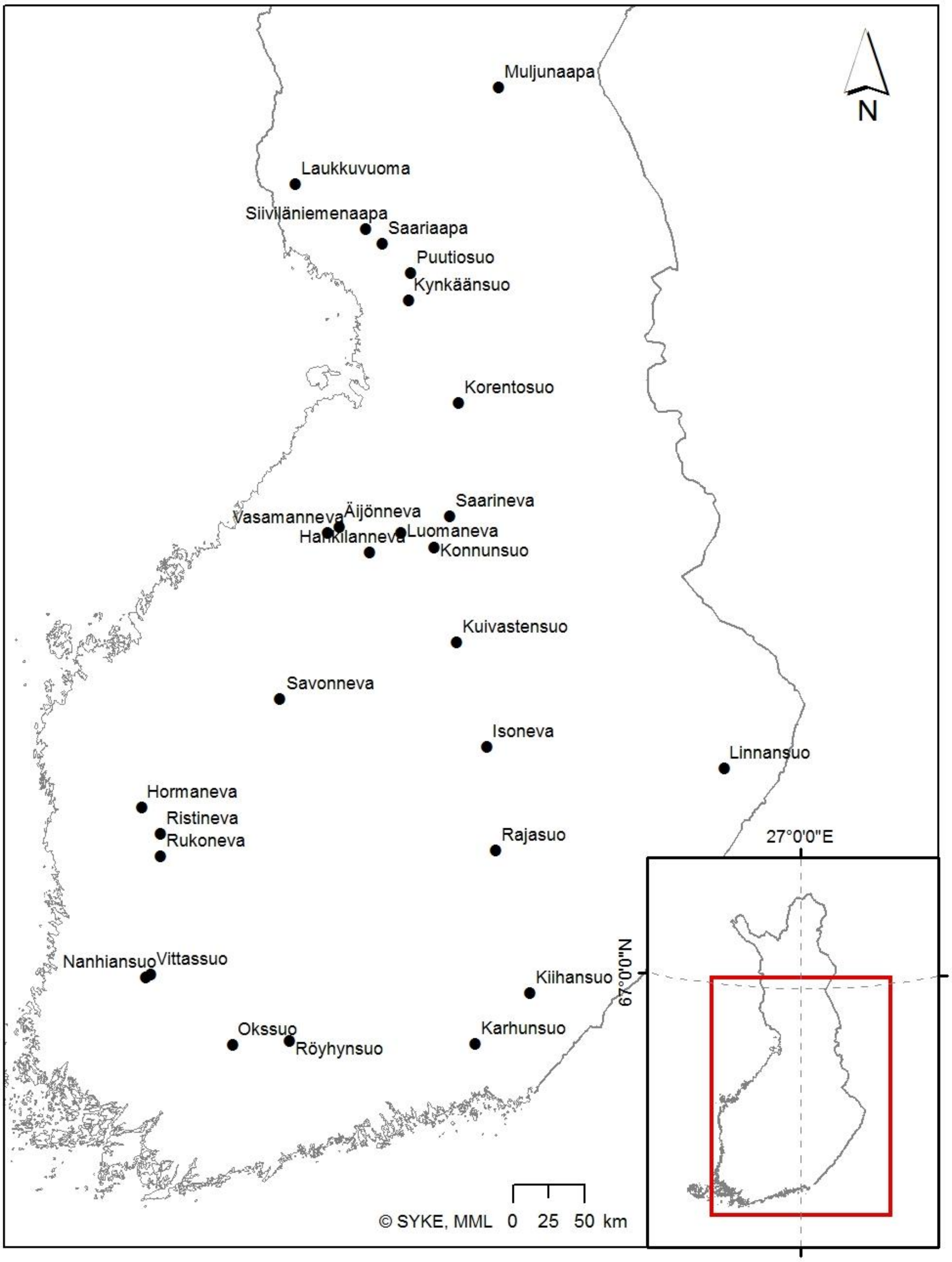

Fig.1. Map of Finland showing the location of the peat extraction areas where the peatland-based treatment wetlands studied are situated.

Table 1. Location, monitoring period and frequency, area, percentage of wetland in relation to catchment area, length/width-ratio, and peat thickness of the wetlands studied. Location: S-F = Southern Finland, M-F = Middle Finland, W-F = Western Finland, E-F = Eastern Finland, N-F = Northern Finland.

Wetland	Location	Monitoring		Area		Length/width ratio	Peat thickness (m)
		Period	n	ha	% of drainage basin		
OFA with good hydraulic function							
Konnunsuo OFA2	E-F	2007-2012	66	24.6	9.8	0.9	1.4
Korentosuo	N-F	2008-2013	35	10.5	5.6	1.2	1.0
Kuivastensuo	E-F	2003-2012	139	2.8	3.4	1.1	3.0
Linnansuo	E-F	2003-2012	158	6.3	9.0	1.6	0.9
Muljunaapa	N-F	2004	10	4.5	3.3	0.8	3.0
Nanhiansuo	W-F	2006-2013	157	3.3	3.8	2.2	2.9
Puutiosuo OFA 2-3	N-F	2001-2012	77	6.2	3.5	2.1	2.1
Ristineva	M-F	2006-2013	122	9	4.1	4.4	
Rukoneva	E-F	2009-2013	90	3.9	5.4	2.5	
Saariaapa	N-F	2012-2013	14	6.9	8.9	1.2	1.5
Siiviläniemenaapa	N-F	2005-2006	20	4.4	2.9	1.3	1.6
Vasamaneva	N-F	2011-2013	23	2.8	4.7	1.1	2.0
OFA with weak hydraulic function							
Laukkuvuoma	N-F	2004-2005	20	1.1	2.6	1.9	0.8
Savonneva	W-F	2001-2004	62	2.7	2.5	6.1	0.5-2.0
DOFA							
Hankilanneva DOFA2	N-F	1991-2012	72	8.6	2.6	0.7	2.1
Hormaneva northern	W-F	2008-2010	48	4.6	4.2	3.0	1.9
Isoneva	E-F	2003-2005	62	10.0	7.9	1.1	2.7
Kapustaneva	N-F	2008-2010	47	6.9	4.4	0.5	1.4
Karhunsuo	E-F	1997-2009	113	7.0	2.8	1.1	2.5
Kiihansuo	E-F	1999-2009	76	2.8	3.8	1.4	3.7
Kynkäänsuo DOFA1	N-F	2007-2011	6	3.9	3.5	1.0	0.7
Luomaneva	N-F	2009-2010	15	3.2	2.7	0.8	2.6
Okssuo	S-F	2002-2008	67	3.0	3.8	3.6	2.0
Rajasuo	E-F	1998-2010	128	22.5	6.4	2.5	1.3
Röyhynsuo	S-F	2008-2010	29	7.8	4.8	0.4	
Saarineva	E-F	2011-2013	22	6.0	5.1	0.8	1.7
Vittasuo	W-F	2005-2009	97	2.5	4.2		3.9
Äijönneva	N-F	2008-2010	47	5.8	5.3	0.5	1.2

Nearly half of the treatment wetlands in the database were monitored for at least 4 years, and in seven cases for even longer, 8 – 23 years (Table 1). In most cases the water samples were taken at two week intervals in summer and autumn, monthly in winter, and weekly in spring, always from the inflow and outflow of the wetland. They were then analysed for total nitrogen (total N), total phosphorus (total P), chemical oxygen demand (COD_{Mn}) and SS. During frost-free periods the concentrations of NH_4-N, $NO_{2,3}$-N, PO_4-P and total iron (total Fe) were also analysed. The analyses were performed in FINAS-accredited laboratories using standard (SFS and ISO) methods.

Discharges were monitored by means of triangular Thompson´s measuring weirs below the wetlands, some of the weirs being equipped with an automatic water level recorder. These discharge values were taken to represent the hydraulic loads imposed on the wetlands, since typically there was no inflow discharge information available.

The OFAs were classified on the basis of their hydraulic function (Table 1), which was assessed in the field. In this classification good hydraulic function was taken as implying an absence of obvious bypass flows and a uniform distribution of water in the wetland.

Data on the design elements of the wetland system were taken or calculated from the environmental permits issued to the peat extraction company, Vapo. These included the size of the wetland in relation to its catchment area, the length of water flow route within the wetland, and the efficient flow area and gradient of the wetland. The efficient flow area was taken to be the proportion (%) of the wetland area over which run-off water is spread in the OFAs and DOFAs in summer. For practical water management purposes this proportion is estimated mainly by eye during the early use of the wetlands and again later as needed. Although this estimation method is quite rough, it gives valuable information on the internal flow patterns of a wetland and possible reconstruction needs.

Nutrient, SS, COD_{Mn} and Fe reductions were calculated as the difference between the periodic mean inflow and outflow concentrations during the frost-free (May – October) and winter (November – April) periods. The effects of hydraulic loading and wetland system design elements on the reduction performance were analysed by Spearman correlation and regression analysis using the OFA, DOFA, and OFA + DOFA data, while the effect of the hydraulic loading rate was also assessed using data for each of the treatment wetlands.

4. Results and discussion

4.1 System design elements, hydraulic loading rate and the quality of water purified

The surface area of the treatment wetlands ranged from 1.1 to 24.6 ha (Table 1), comprising 2.9-9.8% of the drainage basin in the case of the OFAs, and 2.6-7.9% for the DOFAs. Six OFAs were smaller than 3.8% of their drainage basin, the minimum size recommended for OFAs in the present water pollution control regulations (Ihme et al. 1991a, Savolainen et al. 1996, Ministry of the Environment 2013). The length/width ratio of the OFAs ranged between 0.8-6.1, and that of the DOFAs between 0.4-3.6.The peat depth ranged from 0.5 to 2.9 m in the OFAs, and was 0.5 m or over in all cases, as recommended in the regulations. In the DOFAs the peat depth was 0.7-3.9 m.

The hydraulic loading rate ranged from 133 to 1499 $m^3d^{-1}ha^{-1}$ in the OFAs, and from 66 to 1637 $m^3d^{-1}ha^{-1}$ in the DOFAs (Table 2). These values based on outflow discharges are probably slight underestimates in the DOFAs due to evapotranspiration losses and recharging of the ground-water system below some of the wetlands (Postila et al., 2015a). The hydraulic loading rate was mostly controlled by pumps above the wetlands.

The length of the water flow route within the wetland was 170-570 m in the OFAs and 50-600 m in the DOFAs, and the gradient was 0.002-0.8% and 0.003-0.8%, respectively. There were bypass flows in about half of the OFAs and most of the

DOFAs. The efficient flow area, i.e. the active surface area for water purification purposes, was 60–100% in the OFAs and 40–100% in the DOFAs, but estimates of the efficient flow area were not available for six OFAs and seven DOFAs.

The concentrations of suspended solids (SS) are quite high in the peat extraction waters purified (Table 3). The main characteristics of these waters are also high concentrations of dissolved organic matter, Fe and P. Dissolved organic P has been estimated to form approx. 30% of the total P found in the runoff water from the OFA of Kompsasuo in 1989 (Ihme et al., 1991b).

Table 2. Method used for spreading incoming water, average hydraulic loading rate, length of water flow route, gradient, proportion of tussocks, bypass flows and efficient flow area during dry summer periods in the wetlands studied.

Wetland	Method of spreading the water GR=gravitation	Hydraulic loading (l s^{-1} km^{-2})	Length of water flow route within the wetland (m)	Gradient (%)	Obvious bypass flows	Average utilization rate at dry

	PU=pumping					summer period (%)
OFA with good hydraulic function						
Konnunsuo OFA2	PU	183	500	0.002	no	70
Korentosuo	PU	368	400	0.38	yes	90
Kuivastensuo	PU	491	170	0.80	no	90
Linnansuo	PU	581	300	0.50	no	100
Muljunaapa	PU	458	220	0.60	yes	60
Nanhiansuo	PU	355	230	0.40	yes	65
Puutiosuo OFA 2-3		233	430	0.35	yes	90
Ristineva	PU	339	570		yes	
Rukoneva	GR	499	320		no	
Saariaapa	GR	437	260		no	
Siiviläniemenaapa	PU	1734*	225	0.08	no	
Vasamaneva	PU	334	190	0.30	yes	
OFA with weak hydraulic function						
Laukkuvuoma	GR	154	170			
Savonneva	PU	393	380	0.30	no	90
DOFA						
Hankilanneva DOFA2	PU	752	270	0.07	yes	100
Hormaneva northern	PU	828	50	0.25	yes	10
Isoneva	PU	371	225	0.30	no	70
Kapustaneva	PU	333	130	0.30	yes	
Karhunsuo	PU	340	225	0.35		
Kiihansuo	PU	546	200	0.80	yes	90
Kynkäänsuo DOFA1	PU	439	250	0.20	yes	
Luomaneva	PU	139	175	0.80	yes	
Okssuo	PU	514	270	0.14	yes	
Rajasuo	PU	76	600	0.003	yes	100
Röyhynsuo	PU	192	150		yes	80
Saarineva	PU	1894*	210	0.40	yes	
Vittasuo	PU	432		0.65		
Äijönneva	PU	322	135	0.25	yes	40

Table 3. Average quality of the inflow water purified in the peatland-based treatment wetlands at peat extraction areas in Northern (N-F), Southern (S-F), Eastern (E-F) and Western (W-F) Finland.

	Period	n	COD_{Mn}	Total Fe

Peat extraction area	Loca-tion			SS (mg l^{-1})	(mg O_2 l^{-1})	(mg l^{-1})	Total P (µg l^{-1})	PO_4-P (µg l^{-1})	Total N (mg l^{-1})	NH_4-N (mg l^{-1})	$NO_{2,3}$-N (mg l^{-1})
Siiviläniemen-aapa	N-F	2005-2006	20	17.0	17.7	10.0	39	19	2.4	1.2	0.1
Konnunsuo	N-F	2007-2009	36	13.3	27.9	3.5	103	18	1.4	0.2	0.2
Karhunsuo	S-F	1998-2009	112	15.1	70.5	2.7	79	30	2.3	0.6	0.04
Okssuo	S-F	2002-2008	67	18.6	68.4	4.6	120	30	2.6	1.3	
Isoneva	E-F	2003-2005	47	17.9	64.1	5.5	107	18	2.5	1.1	0.1
Linnansuo	E-F	2003-2009	120	17.7	34.1	1.6	40		1.3	0.5	0.1
Hormaneva	W-F	2008-2010	48	8.2	48.1	2.5	100	32	2.9	1.6	
Savonneva	W-F	2001-2004	63	16.6	60.4	3.7	97	15	2.8	0.8	

4.2 Treatment efficiency

The results indicated that both types of peatland-based wetlands remove and retain nutrients and SS from drainage water as effectively as do other natural treatment wetlands on soils in general (Tables 4 and 5). In a study by Fisher & Acreman (2004) collating data on P and N reductions in 57 natural wetlands in 16 countries around the world retention of nutrients was observed in most of these wetlands (80%). Inorganic N and PO_4-P are also reduced effectively in forested (Vikman et al., 2010; Hynninen et al., 2011) and restored (Silvan et al., 2005) peatland buffer zones in Finland. The average reductions in OFAs with good hydraulic function during the frost-free period according to our present data (Table 4) were of the same order as reported for HS CWs treating wastewater: SS 75% (n= 367), total P 50% (n=272) and total N 43% (n=208) (Vymazal, 2010). The reduction levels were also generally similar to those in the Finnish model, the Kompsasuo OFA, at the start of its use for runoff water purification in 1987 -1989: SS 61%, COD_{Mn} 23%, total N 56%, inorganic N 60%, total P 54% and PO_4-P 51%

(Ihme et al., 1991a). This indicates good treatment performance for the OFAs with respect to water protection.

Retention of SS, P, N and Fe was also observed in winter in the OFAs with good hydraulic function (Table 5), although the average N reduction was clearly lower than during the frost-free period and the average SS and P reductions somewhat lower (Tables 4 and 5). The poorer treatment performance of the OFAs in winter was probably mainly due to the low temperatures, at least partial freezing of the surface peat layers, and the lack of nutrient-assimilating vegetation. It is also possible that there may have been a decrease in peat P sorption capacity, as P sorption reactions are endothermic (Jin et al., 2005). The average N reduction in the present DOFAs was markedly smaller in winter than during the frost-free period (Tables 4 and 5), but the average SS, total P, PO_4-P and total Fe reductions were slightly higher. This is probably mainly due to increased SS retention in ditches blocked with ice and snow in winter. Seasonal fluctuations in inorganic N removal have also been reported for many other treatment wetlands (Sutton et al., 1975; Poe et al., 2003; Bastviken, 2006; Hernandez and Mitsch, 2007; Postila et al., 2015b).

Table 4. Reduction (%) in organic matter (COD_{Mn}), suspended solids (SS), phosphorus, nitrogen and iron in the undrained and drained overland flow areas (OFAs and DOFAs) during the frost-free period.

Reductions calculated on the basis of mean concentrations during the period at sampling points upstream and downstream the OFAs and DOFAs. Inorganic N = NH_4-N + $NO_{2,3}$-N

	COD_{Mn}	SS	Total P	PO_4-P	Total N	Inorganic N	Total Fe
OFA with good hydraulic function							
Mean	-1	76	53	57	42	77	51
Min.	-42	52	16	11	26	57	24
Max.	17	92	70	88	58	97	74
n	12	12	12	12	12	9	12
OFAs with negative total reduction (n)	5	0	0	0	0	0	0
OFA with weak hydraulic function							
Mean	5	62	41	49	35	57	34
Min.	3	62	35	26	32	54	26
Max.	6	62	48	73	37	59	43
n	2	2	2	2	2	1	2
DOFA							
Mean	-12	55	27	-5	27	60	24
Min.	-52	16	-3	-135	9	35	-19
Max.	17	87	74	53	45	86	67
n	14	13	14	12	14	8	13
DOFAs with negative total reduction (n)	9	0	1	4	0	0	2

Table 5. Reduction (%) in organic matter (COD_{Mn}), suspended solids (SS), phosphorus, nitrogen and iron in the undrained and drained overland flow areas (OFAs and DOFAs) in winter. Reductions calculated on the basis of mean concentrations during the period at points upstream and downstream the OFAs and DOFAs. Inorganic N = NH_4-N + $NO_{2,3}$-N

	COD_{Mn}	SS	Total P	PO_4-P	Total N	Inorganic N	Total Fe
OFA with good hydraulic function							
Mean	-22	71	46	44	27	55	48
Min.	-125	48	22	-34	-8	36	34
Max.	18	93	69	71	47	82	54
n	10	10	10	8	10	5	6
OFAs with negative total reduction (n)	6	0	0	1	1	0	0
OFA with weak hydraulic function							
Mean	-5	65	-10	-105	25		-43
n	1	1	1	1	1	0	1
DOFA							
Mean	-9	58	30	13	15	26	31
Min.	-21	0	-11	-55	-6	17	-66
Max.	15	94	67	62	39	45	61
n	9	8	9	9	9	4	8
DOFAs with negative total reduction (n)	7	0	1	3	1	0	1

P retention is a challenge in peatland-based wetlands, as in other treatment wetlands (Johannesson, 2011). The average total P reduction was negative in one DOFA and PO_4-P reduction was negative in four DOFAs during the frost-free period (Table 4), while in winter there was a negative average reduction in total P in one DOFA and in PO_4-P in three DOFAs. Leaching of P from DOFAs has been reported previously by Postila et al. (2014). Similarly, one of our OFAs also showed an average negative PO_4-P reduction in winter (Table 5). Monthly negative P reductions coinciding with both high flow and warm low flow periods have been observed in constructed wetlands purifying drainage water from arable land in Sweden, during the former because of the flushing of particulate P straight through the wetland or resuspension of particulate P from deposited sediment, and during the latter because of PO_4-P release from wetland sediments under anoxic conditions (Johannesson, 2011). These are probably also important reasons for the leaching of P from OFAs and DOFAs. Under high flow conditions, however, the purification efficiency of OFAs and DOFAs is also hampered by the decrease in contact between the incoming water and the surface moss and peat layers.

The average total Fe reduction in all OFAs and most DOFAs was positive during the frost-free period and in winter (Tables 4 and 5). There was a positive correlation between SS and total Fe reductions ($r = 0.52$, $p = 0.01$, $n = 26$) in the complete dataset for the OFAs and DOFAs, indicating Fe retention in particulate form, i.e. in SS particles, and most likely also in the Fe-organic precipitates formed after the precipitation of HAMW DOM with an elevated Fe content

(Heikkinen, 1990; Kunze, 1982) in the peat extraction water entering the wetlands. This DOM fraction is probably at least partly precipitated also in the OFAs (Heikkinen and Ihme, 1995) and DOFAs (Heikkinen et al., 2015).

The average total Fe reduction was negative in two DOFAs during the frost-free period (Table 4) and in one DOFA in winter (Table 5). It is probable that this Fe leaching coincided with SS leaching under high flow conditions and with Fe release from the anoxic peat/soil layers during low flow periods.

The average reduction in SS, P, N and Fe was higher in the OFAs with good hydraulic function than in the DOFAs both during the frost-free period (Table 4) and in winter (Table 4), and this was also the case for inorganic N, even though the more intensive change in internal flow patterns and oxygenated/anoxic conditions in DOFAs could be expected to offer better environments for nitrification-denitrification processes than in OFAs. The most probable reason for the weaker purification results in the DOFAs is that the potential water purification capacity of their surface moss and peat layers remains at least partly unutilized because of the ditches. The increase in the water velocity in the ditches (Postila et al., 2015a) will also shorten the nitrogen residence time in the DOFAs. The degree of humification of the surface peat layers is also higher in DOFAs than in OFAs (Postila et al. 2011), probably mainly due to drainage. This in turn would reduce the water permeability and purification potential of the surface peat layers in DOFAs.

The results clearly demonstrated that the loads of DOM (mainly humic substances) from peat extraction areas cannot be reduced in OFAs or DOFAs as is still surprisingly often expected in practical water management projects. These treatment wetlands are located on peat, which acts as a source of DOM in the drainage basin (Wartiovaara, 1978). Leaching of organic matter occurred from many of the OFAs and DOFAs studied here (Tables 4 and 5).

4.3 Needs and possibilities for increasing P retention

PO_4-P is retained in peat-based treatment wetlands mainly by chemical adsorption in the surface peat layers, and the P sorption capacity of these layers increases with increasing Fe and Al content of the peat (Heikkinen et al., 1995b; Karjalainen et al., 2016; Ronkanen et al., 2016). Similarly, colloidal retention processes typical of naturally coloured waters (Heikkinen, 1990; Jones et al., 1993) exist in peat extraction site runoff water (Heikkinen and Ihme, 1995), where P is also to be found as dissolved organic P carried by HAMW organic-Fe colloids, which is therefore retained along with colloid retention (Heikkinen and Ihme, 1995; Karjalainen et al., 2016). The positive correlation between total Fe and PO_4-P reductions ($r = 0.74$, $p = 0.00$, $n = 26$) in OFAs and DOFAs found in our data indicates that P retention is closely controlled by Fe processes in peatland-based wetlands.

The P retention capacity of the surface peat layers in the OFAs may also be increased by the retention of Fe with SS and organic HAMW colloids (Heikkinen and Ihme, 1995). The Fe concentrations in the uppermost surface layers of the Kompsasuo OFA were markedly higher than those in the reference area after five years of use for the purification of peat extraction water (Heikkinen et al., 1995b). It is also possible that the long-term retention time of P in the microbial biomass (Jenkinson and Ladd, 1981; Jonasson and Michelsen,1996) might be an important factor preventing the leaching of P from peatland-based treatment wetlands, as already suggested by Silvan et al. (2004) for constructed peatland buffers installed for forestry purposes.

The use of material with a high P sorption capacity has proved necessary to increase the P treatment performance of many HF CWs (Vymazal, 2007), and this method has also been applied to DOFAs (Postila et al., 2017). Ronkanen et al. (2016) succeeded in maintaining the P sorption capacity of the peat column in their long-term filtration tests with additions of Al and Fe to the incoming water, and Callery et al. (2015) also found that the adding of Fe and Al to peat increased its P sorption capacity. The use of artificial P sorption materials should still be carefully considered at least in OFAs in natural, undrained peatland areas, where a range of natural processes are involved in P retention. Trials with additives to increase adsorption should be supported with environmental impact assessments.

4.4 Effect of hydraulic loading and wetland system design elements on the purification efficiency of treatment wetlands

4.4.1 Hydraulic loading

The 12 OFAs with good hydraulic function in our dataset typically showed a decrease in pollutant reductions with increasing hydraulic loading rates (Table 6), an effect that has been reported previously for P and N in buffer zones established in peatlands for forestry purposes (Hynninen, 2011; Hynninen et al. 2011). Large amounts of water and high flow velocities limit the contact between the water and the peat, moss and vascular plant layers in OFAs and other peatland-based wetlands, and also shorten the residence time of the water for all purification processes, especially nitrification and denitrification. In addition, an increase in the leaching of elements is possible. A high hydraulic loading rate could also have other negative effects on purification processes, as observed in many treatment wetlands (Bastviken, 2006) and macrophyte-dominated systems (Claret and Fontvieille, 1997; Eriksson, 2000). Limited contact of water with P-adsorbing soil particles has been suggested as the main reason for low P retention in free water surface constructed wetlands (Vymazal, 2010).

Of the 14 DOFAs included in the dataset, one showed a decrease in SS and total Fe reductions with increasing hydraulic loading rates, two a decrease in total P reductions and one a decrease in PO_4-P reductions (Table 6). Inorganic N (NH_4-N + $NO_{2,3}$-N) reductions also decreased with increasing hydraulic loading rates in two of the seven DOFAs monitored for this parameter. The reason for these decreases was probably mainly the same as in the OFAs. There was also a decrease in the average SS reduction with increasing hydraulic loading rates in the whole DOFA dataset (Fig. 2). The SS reduction was about 61% at a hydraulic loading rate of 500 l s^{-1} km^{-2} and about 48% at a rate of 1000 l s^{-1} km^{-2}, although the variation in the average reductions was large.

Table 6. Number of treatment wetlands in undrained and drained peatland-based overland flow areas (OFAs and DOFAs) with a negative (n) and positive (p) correlation ($p<0.05$) between hydraulic loading rate and reductions in COD_{Mn}, suspended solids (SS), phosphorus, nitrogen and iron in the complete database. Inorganic N = NH_4-N + $NO_{2,3}$-N

	n	COD_{Mn}		SS		Total P		PO_4-P		Total N		Inorganic N		Total Fe	
		n	p	n	p	n	p	n	p	n	p	n	p	n	p
OFA with good hydraulic function	12	-	7	3	1	4	2	1 (n=10)	-	-	3	3 (n=9)	-	2	-
OFA with weak hydraulic function	2	-	1	-	2	-	-	-	-	-	-	1 (n=1)	-	-	-
DOFA	14	-	7	1	3	2	1	1 (n=11)	2	1	3	2 (n=7)	-	1	-

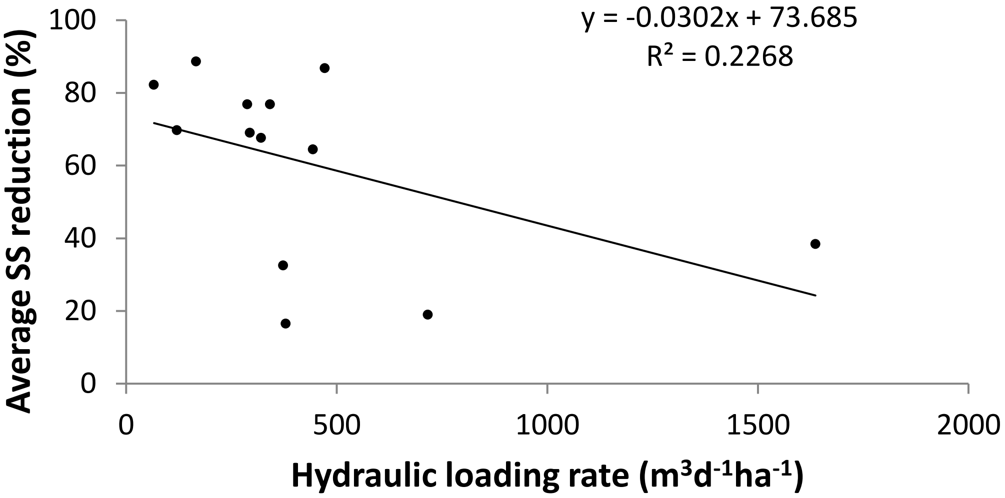

Fig. 2. Effect of hydraulic loading rate on the average suspended solids (SS) reduction in drained overland flow areas (DOFAs).

There were statistically significant increases in COD_{Mn}, SS, total P and total N reductions with increasing hydraulic loading rate in both the OFAs and DOFAs (Table 6). This was probably at least partly due to an increase in the concentrations of these elements in the inflow water, which in turn would lead to better reductions. Another possible reason for these increases observed in DOFAs, however, could be the more effective spreading of water to the peat and moss layers between the ditches at times of high flow conditions. The quite common increase in COD_{Mn} reduction with increasing hydraulic loading rates in both OFAs and DOFAs (Table 6) might also be at least partly a result of enhanced retention of dissolved organic HAMW Fe-P colloids with increasing flow velocity, turbulence and oxygen content of the drainage water. COD_{Mn} values are affected by the concentrations of organic matter, and also by the concentrations of many inorganic substances in the water sample, especially Fe^{2+} (SFS 3036).

4.4.2 Wetland size in relation to catchment area

There was no interdependence between wetland size in relation to its catchment area ($A_{wetland}/A_{catcment}$, A_w/A_c ratio) and the reductions observed for the OFAs and DOFAs in the dataset. This was probably mainly due to the quite small variation in A_w/A_c values in the data because of the existing system design instructions (Ihme et al., 1991b; Savolainen et al., 1996), but it may also be related to the fact that water was being pumped to most of the wetlands (25 wetlands out of the 28 studied) (Table 2), the pumps being used to control the amount of water released onto the wetlands. Increases in total-N and total-P reductions with increasing A_w/A_c ratios have been reported in constructed wetlands (Kadlec and Knight, 1996), in water pollution control wetlands in agriculture (Puustinen et al., 2007) and in peatland buffer zones used in forestry (Vikman et al., 2010; Hynninen et al., 2011).

The A_w/A_c ratio is nevertheless an important system design element for OFAs and DOFAs intended for treating drainage water from peat extraction areas, as it determines the magnitude of the hydraulic load that is introduced onto the wetland (Kadlec and Knight, 1996) and indicates the extent of the chemical and biological sinks contributing to nutrient retention and the residence time available for the water-purifying processes. In order to achieve good water pollution control at peat extraction sites, it is recommended that the size of an OFA should be at least 3.8% of that of the drainage basin (Ihme et al., 1991b; Savolainen et al., 1996) and that of a DOFA at least 5% (Ministry of the Environment, 2013). In the set of wetlands studied here theOFAs were mainly larger than the minimum size recommended, but the DOFAs were mainly smaller (Table 1).

4.4.3 Length of water flow route within the wetland

There was an increase in the average reduction in inorganic N (NH_4-N + $NO_{2,3}$-N) with increasing length of the water flow route in the OFAs (r = 0.812, p <0.01, n = 8) and DOFAs (r = 0.843, p <0.01, n = 8) (Fig 3), as also in the whole dataset of OFAs and DOFAs (r = 0.804, p <0.01, n = 16). This could be seen also in total N reduction (r = 0.585, p <0.01, n = 27) and total P reduction (r = 0.393, p <0.05, n = 26) in the OFA + DOFA datasets (Fig. 3). It is probable that there was an increase in nitrogen residence time with increasing length of the water flow route in these peatland-based wetlands, as also reported for many other treatment wetlands (Sutton et al., 1975; Phipps and Crumpton, 1994; Ishida et al., 2006). Increasing length of the water flow route will also increase the area of the biofilm surface that removes inorganic N from the water. An increased rate of inorganic N (Vikman et al. 2010) and NH_4-N (Hynninen et al., 2011) removal with increasing peatland buffer width has also been reported in a forestry context in central Finland. It is also probable that there was increased retention of particulate P and PO_4-P (Heikkinen et al., 1995b) with increasing contact between the drainage water and the moss and peat surface layers of wetlands.

The increase in inorganic N reductions with increasing length of the water flow route was more intensive in the DOFAs than in the OFAs (Fig. 3). Doubling of the route length in the DOFAs also doubled the inorganic N reduction, indicating strongly that not all the environments that are potentially suitable for inorganic N removal in these wetlands, especially the peat and moss surface layers between the ditches, are yet being used effectively. Also, the N residence times in DOFAs under high flow conditions may be too short for effective nitrogen removal, because of the ditches. Inorganic N as a proportion of total N is high in peat extraction site water, e.g. it averaged 66% in the runoff water from the Kompsasuo peat extraction area in 1988-1989 (Ihme et al., 1991). It is thus important to develop strategies and methods for planning and constructing long water flow routes for efficient N removal, especially for DOFAs.

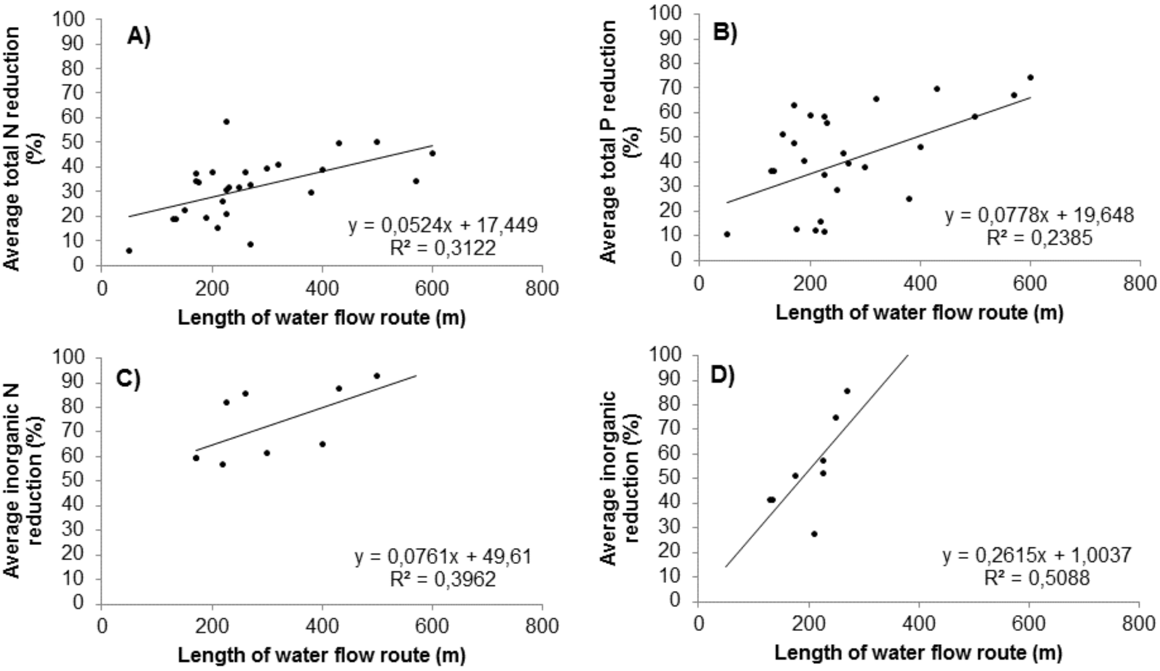

Fig. 3. Effect of the length of the water flow route within the wetland on reductions in total N (A) and total P (B) in the whole database of undrained and

drained overland flow areas (OFAs and DOFAs), and on reductions in inorganic N (NH_4-N + $NO_{2,3}$-N) in OFAs (C) and DOFAs (D).

4.4.4 The efficient flow area of a wetland

There was an increase in the total N ($r = 0.937$, $p < 0.01$, $n = 7$) and total P reductions ($r = 0.811$, $p < 0.05$, $n = 7$) with increasing efficient flow area in the DOFAs (Fig. 4). As in the case of the water flow route within the wetland, the results indicate that not all the environments potentially suitable for N and P removal in DOFAs are yet being used effectively, because of the ditches. This especially involves use of the peat and moss surface layers between the ditches. There were no other statistically significant regressions between the wetland system design elements and the water quality parameters in the DOFAs and OFAs in the database.

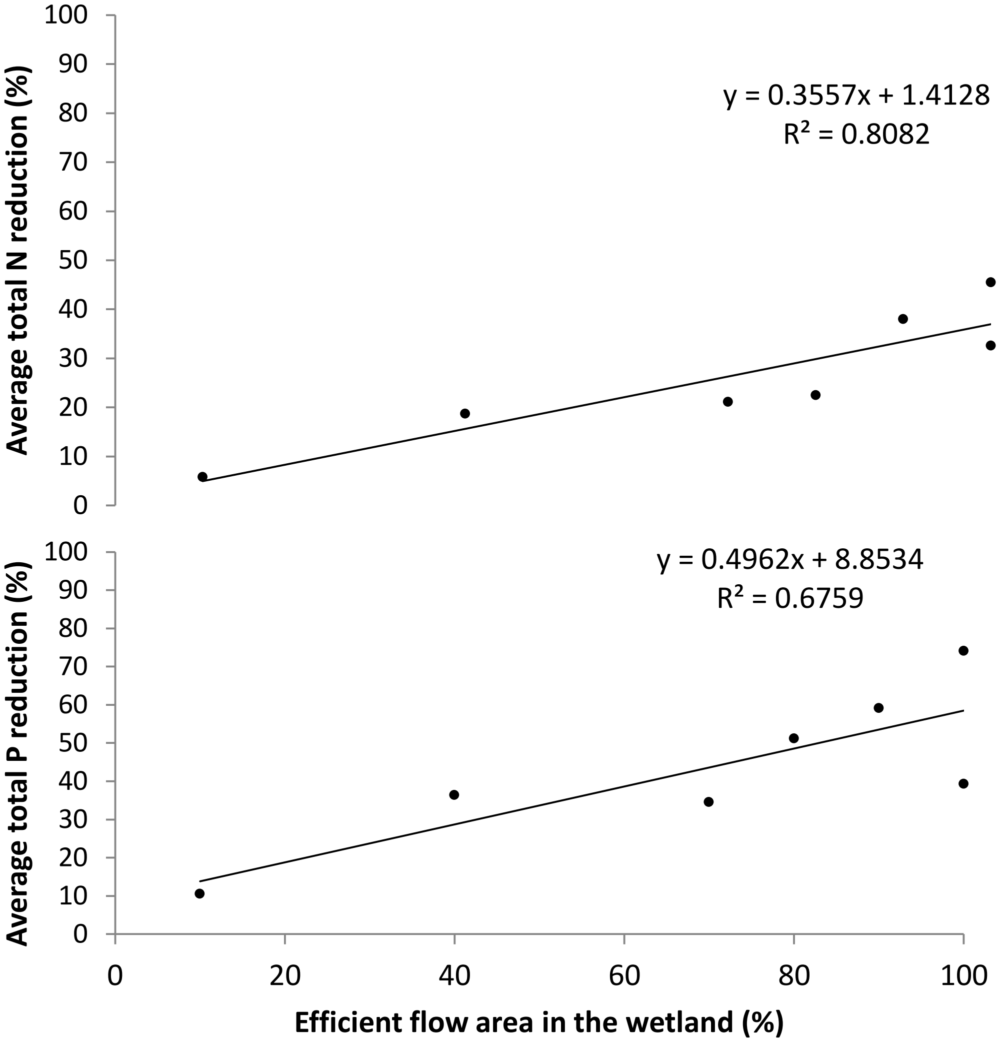

Fig. 4. Effect of efficient flow area on total N and total P reductions in drained overland flow areas (DOFAs).

4.4.5 Wetland gradient

Of the water quality parameters studied, only inorganic N (NH_4-N + $NO_{2,3}$-N) showed a statistically significant regression with the wetland surface slope or gradient. This could be seen in the OFAs, where the average inorganic N reduction increased with decreasing gradient ($r = -0.929$, $p < 0.01$, $n = 7$) (Fig. 5). The main reasons for this were probably the increased water flow rate and reduced nitrogen residence time resulting from an increased gradient.

The gradients of the OFAs ranged from 0.002 to 0.8% (Table 2), i.e. they were less than the maximum of 1% recommended by Ihme et al. (1991b). The inorganic N (NH_4-N + $NO_{2,3}$-N) treatment performance of the OFAs was good in this gradient range (Tables 4 and 5), indicating that there is no need to change the maximum gradient recommendation.

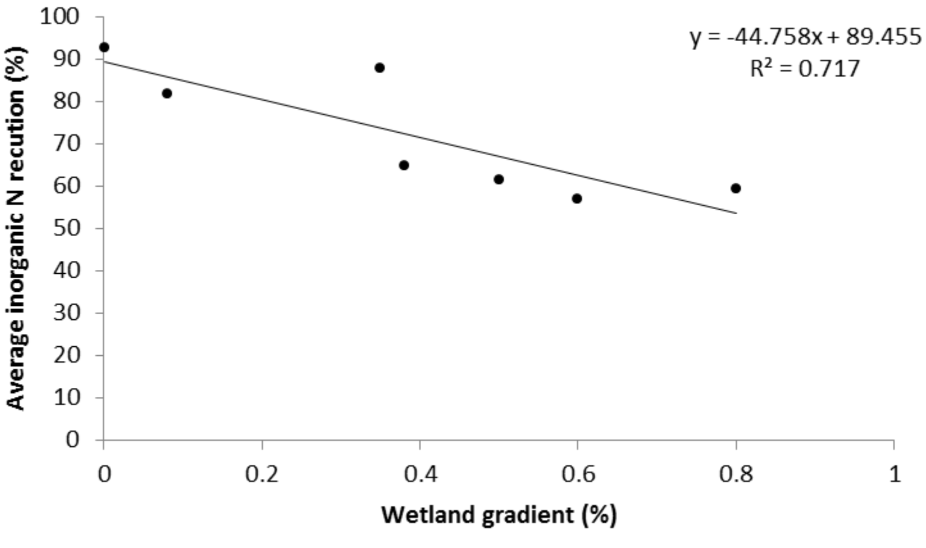

Fig. 5. Effect of wetland gradient on the reductions in inorganic N (NH_4-N + $NO_{2,3}$-N) in overland flow areas (OFAs).

5. Conclusions

The long-term data recorded during mandatory water pollution control monitoring at the peat extraction sites considered here indicate that peatland-based treatment wetlands can remove and retain nutrients and SS from drainage water just as effectively as natural soil-based treatment wetlands in general.

The average reductions in SS, P, N and Fe were higher in the OFAs on undrained peatlands with good hydraulic function than in the DOFAs on drained peatlands both during the frost-free period and in winter. The OFAs also showed good long-term treatment performance with respect to water protection.

There was some leaching of P from the peatland-based treatment wetlands, particularly from the DOFAs. The leaching of P from many constructed wetlands has been reduced by using a material with a high P sorption capacity, and a similar method has been developed for DOFAs. The use of additional sorption materials in the case of OFAs on undrained peatlands, where a variety of natural processes are involved in P retention, nevertheless requires careful consideration. The environmental impacts of these sorption materials on water bodies further downstream should also be considered.

The loads of DOM, mainly humic substances (HS), in drainage water from peat extraction areas cannot be reduced by means of OFAs and DOFAs, despite the common expectations of practical water managers. It is possible, however, to reduce the environmental impacts of Fe-rich HS in water bodies downstream of peat extraction areas by using OFAs or DOFAs.

The hydraulic loading rate is an important factor in water purification using OFAs and DOFAs. In the individual treatment wetlands studied here, there were generally decreases in the SS, P, N, COD_{Mn}, and Fe reductions with increasing hydraulic loading rates, but also some increases. It is probable that there is a decrease in the contacts between the discharge water and the moss and peat layers of the wetland with increasing hydraulic loading rate, which would in turn reduce the physical, biological and chemical retention processes that are dependent on this contact and contribute to the efficiency of water purification. The main probable reason for the increases is that a greater hydraulic loading rate will increase the concentrations of inflow water and thus also the magnitude of the reductions. On the other hand, the increase in COD_{Mn} reduction observed quite frequently with increasing hydraulic loading rates might at least partly be the result of enhanced retention of dissolved organic HAMW Fe-P colloids with increasing flow velocity, turbulence and oxygen content of the drainage water.

There was an increase in inorganic N (NH_4-N + NO_3-N) reductions with increasing length of the water flow route within the OFAs and DOFAs. This was more intensive in the DOFAs, where the reductions in total N, inorganic N, and total P also increased with the efficient flow area of the wetland. These results strongly indicate that not all environments that are potentially suitable for water purification, especially in the moss and peat layers between the ditches, are yet being used efficiently in DOFAs. Methods for spreading the incoming water more efficiently in DOFAs and for planning and constructing longer water flow routes in them should be developed.

In the OFAs there was an increase in the average reductions in inorganic N (NH_4-N + NO_3-N) with decreasing gradient. The gradients of the OFAs were within the maximum recommended value of 1% (Savolainen et al. 1996), ranging from 0.002 to 0.8%. The results regarding inorganic N removal in this gradient range indicate that there is no need to change the maximum gradient recommendation. It is also probable that choosing peatland areas with smaller gradients for OFAs would increase P and Fe leaching from these wetlands.

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