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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.

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 and 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 and 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°45′N, 26°00′E, 110 m a.s.l.), gave good purification results in the early years following its establishment in 1987 (Ihme et al., 1991a,b; Ihme, 1994) and has also done so in recent times (Karjalainen, 2016; Karjalainen et al., 2016a,b), 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

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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, 2016; Postila et al., 2011, 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 (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 (65°45′N, 26°00′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 Kløve, 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 Kløve (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