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Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate

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ABSTRACT

With climate warming, snowmelt and runoff will occur more frequently during winter months. For efficient removal of runoff loads, water pollution protection methods such as constructed wetlands must also function during winter runoff periods. This study evaluated the purification efficiency and function of constructed wetlands in treating peat extraction runoff in all seasons, using collected data on inflow and outflow concentrations and wetland properties from 14 treatment wetlands in Finland. The runoff water flows partly on top of the peat layer as surface flow and partly as horizontal subsurface flow. In three of these wetlands, seasonal ground frost depth was also observed in two winter periods. In winter, the surface peat in constructed wetlands was mostly frozen (0–42 cm depth) but in some parts of the wetland the water flowed as overland or near-surface flow. Chemical oxygen demand (COD_{Mn}) and ammonium nitrogen (NH_4-N) purification efficiency varied seasonally, with NH_4-N purification efficiency being highest during the warm summer period and COD_{Mn} purification efficiency being lowest during summer and winter. For other water quality parameters (N_{tot}, P_{tot}, PO_4-P, Fe, and SS), no influence of season was noted.

1. Introduction

Despite considerable efforts to improve surface water quality, nutrient loading to water bodies and deterioration of the ecological status of water systems continue, e.g., in Finland (Putkuri et al., 2013), Ireland (Department of the Environment, 2014), and the United Kingdom (Department for Environment, Food and Rural Affairs, 2014). Cost-effective methods are needed to treat water from different point and diffuse sources for better water quality and to meet the requirements set in the EU Water Framework Directive (2000/60/EY). Especially scattered load sources, including forestry and agriculture, pose challenges for water treatment due to e.g., high runoff, relatively low nutrient concentrations, and complex water flow routes that are difficult to control.

Constructed wetlands can be an efficient method to decrease nutrients, suspended solids, and harmful elements from different types of point and diffuse sources (Kadlec and Wallace, 2009), even in cold regions (Mander and Jenssen, 2002, 2003). However, low temperature is known to reduce the rate of microbiological purification processes (Feng et al., 2012; Kadlec and Wallace, 2009), which is apparent in low purification efficiency. The role of temperature is not always clear, however, as some field-scale studies show that nutrient and biological oxygen demand (BOD) purification efficiency decreases in periods with low temperatures (Kadlec et al., 2003), whereas others have found no significant differences between seasons (Mæhlum and Stålnacke, 1999).

Due to climate change, winter runoff is predicted to increase (Vehviläinen and Lohvansuu, 1991), which means that nutrient removal in constructed wetlands during winter will also become important. Winter conditions such as frost, ice, and snow have not been well documented for seasonally frozen northern peatlands or constructed wetlands. In lakes and rivers, the maximum ice depth is typically 0.5–0.8 m in central and northern Finland (Korhonen, 2006), and this could be used as a proxy for frost depth in constructed wetlands. In peatlands, as in mineral soils, insulation by snow reduces frost depth (Eurola, 1975; Venäläinen et al., 2001). Eurola (1975) observed that mean ground frost depth in pristine mires in Finland (Northern Ostrobothnia) in 1970 was at maximum around 0.3 m. For constructed wetlands, it can be assumed that with surficial ice in the topmost soil layer, the active flow area is reduced and the flow paths change.

Increased focus on water protection has led to the introduction of new requirements in peat extraction environmental permits for runoff water treatment throughout the year, and not just in the peat extraction period (May–September). As treatment of runoff in cold conditions is not well documented, this study sought to

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determine the seasonal purification efficiency of constructed wetlands treating peat extraction runoff and to identify the main factors controlling the purification efficiency. Key research questions were: (1) Is there seasonal variation in purification efficiency? (2) What are the main factors affecting purification efficiency? and (3) Does frost accumulate and change flow paths in constructed wetlands?

2. Materials and methods

The study included 14 treatment wetlands constructed on peatland in Finland. Six of the wetlands were constructed on drained peatland and eight were constructed on pristine peatlands (Table 1). All these wetlands treat runoff from peat extraction areas year-round. The wetlands are free surface flow systems with some subsurface flow (the water flows on top of the peat layer or within the surface peat layer). More detail schematic description of used structures can be found in Postila et al. (2014). Five of the wetlands are located in North Ostrobothnia (Fig. 1), where the permanent snow cover duration is about 4.5–6 months, and nine are located in Western Finland, where the mean permanent snow cover duration is 3.5–4.5 months. Mean annual precipitation in the study areas varies between 500 and 700 mm, and mean annual evaporation between 300 and 500 mm. Wetland size varies from 2.5 to 14.1 ha and the water is pumped and divided to the wetlands e.g. by distribution pool or perforated pipe (typically there is only one pump that pump water from peat extraction site to the treatment wetland). In two of the wetlands (Savaloneva and Puutiosuo 2 + 3), water flows only by gravity during winter. In Puutiosuo 2 + 3, water is conducted first to wetland 2 and thereafter to wetland 3. In some of the studied wetlands, freezing of the pumping well/basin or distribution system or thick ice layer formation (bulge ice) was observed, and in some cases even caused damage to embankments.

Water quality data for inflow and outflow water were obtained from peat extraction load monitoring programs. In these programs, water samples are taken for analysis of total nitrogen (N_{tot}), ammonium nitrogen (NH_4-N), total phosphorus (P_{tot}), phosphate-phosphorus (PO_4-P), chemical oxygen demand (COD_{Mn}), iron (Fe), and suspended solids (SS) during different periods (Table 2). The sampling interval varies from once per week (typically spring time) to once per season. The samples are from the inlet and outlet at the same time, which produces some bias as retention time is not considered (in these systems the retention time is highly variable and difficult to consider in sampling design). In this study, the purification efficiency was calculated separately for every wetland, every year, and every season (winter, spring, summer, and autumn), based on concentration reduction in the wetlands. First, the mean inflow and outflow concentrations for each season during one year were calculated, and then these mean values were used to calculate purification efficiency. Using mean purification results for different years, wetland total mean purification efficiency was calculated (Table 2). The load from peat extraction was calculated based on measured outflow from the treatment wetland and outflow water quality data (Table 3). The outflow from treatment wetland was typically measured continuously all wetlands by V-notch weir and pressure sensors, which had sampling interval 15 or 30 min. Some manual recordings were made or sometimes data from the other treatment wetland close to the studied ones were used as runoff estimates. At North Ostrobothnia sites with missing data records, the common practice is to use Finnish Environment Institute hydrological watershed model system (WSFS; Finnish Environment Institute, 2013) to estimate the discharge. The above practice is generally accepted in peat extraction water load monitoring.

Based on their location, the wetlands were divided into two groups, North Ostrobothnia and Western Finland, which are about 550 km apart at the most (Table 1; Fig. 1). In the North Ostrobothnia region, autumn and winter usually start earlier and spring and summer usually start later than in Western Finland depending on the weather conditions (Table 4; Fig. 2). In the present study, the start day of spring was taken as the day when outflow from the wetland was observed to increase due to snowmelt and it changed depending on year and wetland. The start day of summer, when the outflow was reduced to the level typical for the site in summer, also changed depending on outflow values in the year and wetland in question. The results are reported for the hydrological year, which is based on the start day of winter (Table 4). Thus the hydrological year 2008 started in North Ostrobothnia areas on 11 November 2007 and ended on 31 October 2008, while in Western Finland it ran from 1 December 2007 to 30 November 2008.

In order to understand seasonal frost dynamics, three ground frost pipes were installed in each of three studied wetlands on January 2010 and left for two years (Fig. 3). One of these wetlands (Kapustaneva) is located in Western Finland and the others (Pehkeensuo 1 and Korentosuo 1) in North Ostrobothnia (Fig. 1 and Table 1). On October 2010, one more ground frost pipe (pipe 4) was installed near point 1 in the Pehkeensuo 1 wetland (Fig. 3c), in an area where some flowing water was observed while point 1 was frozen.

The ground frost pipes consisted of 2.5 m long transparent plastic tubes (diameter about 1 cm) filled with methylene blue solution. The solution color indicated presence of frost: blue when there was no frost and uncolored with frost (Fig. 4). The pipes were installed with about 1 m of pipe extending above the soil surface.

Data on mean daily temperature (T) and precipitation (P) in the study years (Tables 4 and 5, Fig. 2) were obtained from Finnish Meteorological Institute (2015). These values were based on 10 km x 10 km grid interpolated daily precipitation and temperature averages for the period 1 January 1961–31 December 2011 (PaiTuli database). Interpolation daily temperatures are quite reliable but spatial variations in daily precipitation are smoothed, and for this reason there is about 17% systematic underestimation in the long-term yearly average (Venäläinen et al., 2005). Snow cover data, as snow water equivalent (SWE), were taken from the OIVA database (2015). The data were collected from snow lines at Perho (near Kapustaneva) and Vaala (near Korentosuo 1 and Pehkeensuo 1), where SWE is usually determined twice per month by measuring the depth and weight of snow (Finnish Environment Institute, 2014). Between the measurement days, SWE was calculated using a model based on weather observations. Based on the values obtained, continuous snow cover duration for the Kapustaneva, Korentosuo 1, and Pehkeensuo 1 wetlands was determined.

Different statistical tests were used to study factors and compare purification efficiency in different seasons. The factors examined were structural or design parameters for treatment wetland in national guidelines set by the environmental authority and the presence of icing problems. The analysis was performed using SPSS statistical software (IBM version 22), with $p < 0.01$ taken as the limit for statistical significance in every test. The selected tests were non-parametric, i.e., can be used without assuming normal distribution of data.

- Using non-parametric Kruskal–Wallis one-way analysis of variance, differences in purification efficiency, inflow concentration, and load between different seasons were compared. Every year, season, and wetland was included separately in these tests.
- Using Spearman correlation, the effects on purification efficiency of structural and design parameters such as slope of treatment wetland, average wetland length (m), treatment wetland area as % of catchment area, average degree of humification of surface peat (von Post, Hobbs, 1986), and inflow concentration were studied.