Ecological Engineering 85 (2015) 13–25

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

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ARTICLE INFO

Article history:
Received 19 June 2015
Received in revised form
10 September 2015
Accepted 19 September 2015
Available online 18 October 2015

Keywords:
Constructed wetlands
Cold climate
Peatland
Purification
Winter period
Seasonal frost

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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http://dx.doi.org/10.1016/j.ecoleng.2015.09.066
0925-8574/

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.

Table 1
Properties of the 14 wetlands included in this study. Bold type indicates study sites with ground frost pipes.

Wetland name	Latitude (YKJ-N)	Year of establishment	Wet- land area (ha)	TA/CA (%)[a]	Water distributed by:	Slope (%)	Mean peat thick ness (m)	Mean H-value[b], surface peat	Mean wetland length (m)	Previous drainage	Ice problems
North Ostrobothnia											
Hankilaneva 2	7090400	1992	7.3	3.1	Distribution ditch	0.07	1–1.5	H7	270	Yes	Yes
Korentosuo 1	7197400	2008	10.5	4.9	Distribution ditch	0.38	0.95	n.a.	430	No	Yes
Pehkeensuo 1	7191500	1994	7.6	5.1	Distribution pool	0.5	1.5	H2[c]	800	Yes	Yes
Puutio-suo 2 + 3	7285800	2001	2 + 4.2 = 6.2	6.3	Distribution pool	0.35	2.1	H4[d]	220 + 230 = 550	No	No
Savaloneva	7136500	2005	6.1	7.4	Distribution pool (comp model)	0.06–0.4	0.9	H5	470	Yes	No
Western Finland											
Hormaneva north	6913560	2007	14.1	3.7	Perforated pipes	0.2	2.8	H3[e]	670	Yes	Yes
Kapustaneva	7025766	2008	6.9	4.6	Pipes from distribution pool under embankment to the wetland	0.3	1.4	H4	350	Yes	No[f]
Lammisuo	6785246	2007	7.2	6.5	Perforated pipes	0.4	n.a.	n.a.	260	No	No[f]
Nanhiansuo 1	6795201	2005	3.3	3.8	Perforated pipes	0.4	2.9	n.a.	230	No	Yes
Peuralinnanneva	7002168	2009	6.9	4.7	Distribution ditch	0.25	2.7	n.a.	280	No	No
Ristineva	6895078	2006	8.9	3.7	Perforated pipes	0.1	n.a.	H1[g]	520	No	No[h]
Satamakeidas	6888555	1994	6.9	4.1	Distribution pool	0.07	1.3	H3[i]	300	Yes	Yes
Savonneva	6989355	1999	2.7	2.5	Distribution pool	0.3	0.5–2.0	H5[g]	410	No	Yes
Vittasuo	6797397	2005	2.5	4.2	Perforated pipes	0.65	3.9	n.a.	200	Yes	No[j]

[a] von Post degree of humification (Hobbs, 1986).
[b] Treatment wetland area as % of catchment area.
[c] Only one sample at 10–20 cm depth.
[d] Three samples at 30–65 cm depth.
[e] Only one sample.
[f] However, embankment had to be rectified or raised.
[g] No information on sampling depth or number of samples.
[h] Ice cover on pumping pool had to be broken a few times during the winter.
[i] Only one sample at 30 cm depth.
[j] During some winters some small ice problems were still detected.

Table 2
Purification efficiency of the 14 wetlands in different seasons.

Wetland Season	Monitoring years	Purification efficiency (%), inflow concentration (mg/L) and number of samples (n)																				
		Tot.N			NH_4-N			Tot.P			PO_4-P			COD_{Mn}			Fe			SS		
		%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n
Hankilaneva 2																						
Spring	2007, 2009, 2010	27	1.14	9				36	0.07	9				5	20	9				60	20	9
Summer	1992, 2007–2009	18	1.24	18	62	0.39	14	−16	0.07	18	−22	0.04	13	−78	25	18	14	11.3	8	64	15	18
Autumn	1992, 2007, 2009	49	1.36	4	93	1.38	1	9	0.06	4	0	0.02	1	13	26	4				37	9	4
Winter	1991, 2007–2010	35	1.65	22	82	1.65	4	47	0.11	22	−56	0.03	4	1	27	22				−9	48	22
Korentosuo																						
Spring	2010, 2012–2013	45	1.42	8	89	0.75	8	49	0.04	8	62	0.01	7	10	19	8	49	1.4	7	85	9	8
Summer	2012–2013	52	2.15	18	94	1.06	18	54	0.09	18	71	0.04	18	−9	39	18	65	4.8	18	67	13	18
Autumn	2012–2013	53	2.33	3	96	1.60	3	57	0.09	3	77	0.05	3	1	31	3	75	5.8	3	86	25	3
Winter	2010, 2012–2013	18	1.77	11	74	1.44	11	34	0.09	11	68	0.07	9	−119	16	11	68	6.1	9	73	8	11
Pehkeensuo 1																						
Spring	1997, 2008–2010	28	1.31	9				46	0.06	9				17	18	9				71	44	9
Summer	1997, 2005–2009	27	1.26	32	81	0.33	16	40	0.07	32	46	0.03	15	−7	31	32	28	5.8	15	71	18	32
Autumn	1997, 2005–2009	48	2.22	9				32	0.07	9				20	38	9				46	32	9
Winter	1997–1998, 2008–2010	40	1.80	18	45	0.59	5	60	0.09	18	75	0.08	5	18	25	18	42	7.4	5	91	56	18
Puutiosuo 2–3																						
Spring	2002–2005, 2007	26	1.13	10	31	0.47	5	51	0.05	10	60	0.003	1	2	15	10	23	0.6	1	67	5	10
Summer	2001–2004, 2007	53	2.01	35	98	0.87	17	71	0.09	35	70	0.06	10	−38	27	35	61	3.5	10	81	7	35
Autumn	2001,2003–2004, 2007	57	3.72	9	93	1.65	2	61	0.07	9				12	37	9				82	31	9
Winter	2002,2004–2005, 2007–2008	41	2.19	20	72	1.50	6	65	0.09	20				−45	16	20				71	4	20
Savaloneva																						
Spring	2009	−70	1.69	3	−73	0.88	3	−193	0.03	3				−79	25	3				−500	3	3
Summer	2009	−40	2.90	10	−12	1.36	10	−206	0.06	10	−651	0.01	6	−43	53	10	−389	9.4	1	−109	21	10
Autumn	2009	−1	3.03	3	27	1.83	3	−132	0.05	3	−292	0.01	2	−38	41	3				−15	9	3
Winter	2009	−80	2.20	6	−45	1.57	6	−197	0.04	6				−158	33	6				−249	4	6
Hormaneva North																						
Spring	2008–2010	1	1.95	6	6	1.08	4	5	0.05	6	12	0.01	4	−6	34	6	13	1.1	4	20	6	6
Summer	2008–2009	12	2.81	22	23	1.48	8	14	0.14	22	9	0.03	8	−18	57	22	15	2.8	8	28	9	22
Autumn	2008–2009	3	3.56	7	8	2.40	1	−4	0.06	7	14	0.02	1	−7	51	7	5	2.2	1	−6	6	7
Winter	2009–2010	−5	2.89	10	6	2.16	5	10	0.11	10	23	0.05	5	−13	36	10	21	3.8	5	22	9	10
Kapustaneva																						
Spring	2009–2010	11	2.00	7	20	1.21	7	20	0.05	7	50	0.01	7	−9	30	7	42	1.9	7	67	8	7
Summer	2008–2009	14	2.15	12	59	0.86	11	27	0.09	12	47	0.02	11	−28	55	12	63	3.3	11	68	10	12
Autumn	2008–2009	24	3.06	8	48	1.84	5	52	0.10	8	48	0.02	5	−4	61	8	59	3.2	5	81	20	8
Winter	2009–2010	3	2.84	9	17	1.86	7	26	0.10	9	63	0.04	7	−33	50	9	67	4.7	7	84	24	9
Lammisuo																						
Spring	2009–2010	14	4.15	6	15	2.90	4	30	0.09	6	54	0.05	4	3	38	6	44	7.1	4	48	12	6
Summer	2008–2009	13	5.02	13	16	3.57	6	34	0.12	13	41	0.04	6	10	53	13	26	10.6	6	57	29	13
Autumn	2008–2009	12	4.59	8	15	2.70	1	35	0.10	8	−74	0.03	1	9	62	8	29	5.8	1	58	28	8
Winter	2009–2010	14	4.88	5	8	4.45	2	56	0.16	5	33	0.07	2	32	59	5	−238	7.6	2	88	51	5
Nanhiansuo																						
Spring	2006–2010	36	2.49	14	48	0.82	9	55	0.20	14	55	0.06	9	4	62	14	45	5.2	9	72	61	14
Summer	2006–2009	17	2.01	46	39	0.14	17	34	0.26	46	21	0.08	18	2	103	46	21	6.3	17	51	33	46
Autumn	2006–2009	37	2.39	16	53	0.71	4	52	0.13	16	55	0.06	4	11	92	16	30	4.3	4	67	14	16
Winter	2006–2010	27	2.16	14	29	0.65	6	54	0.20	14	35	0.04	6	8	76	14	17	2.7	6	61	22	14

Peuralinnanneva																						
Spring	2010	31	1.93	4	73	1.20	2	60	0.11	4	47	0.03	2	−66	41	4	58	8.1	2	81	125	4
Autumn	2009	38	1.73	4				79	0.14	4				−27	46	4				93	134	4
Winter	2010	46	2.30	4	95	1.40	1	62	0.07	4	85	0.03	1	−58	49	4	80	6.5	1	88	25	4
Ristineva																						
Spring	2007–2009	47	0.96	4	52	0.33	2	60	0.03	4	16	0.01	2	11	32	4	73	1.4	2	85	8	4
Summer	2007–2009	43	1.38	31	72	0.19	10	66	0.07	31	60	0.01	11	9	54	31	75	2.2	11	91	18	31
Autumn	2007–2009	33	1.73	12	58	0.90	3	61	0.04	12	50	0.01	3	2	51	12	55	1.6	3	72	6	12
Winter	2007–2008	25	1.48	4	23	0.52	1	73	0.05	4	74	0.03	1	−10	44	4	44	0.9	1	92	15	4
Satamakeidas																						
Spring	2002–2010	21	1.14	30	51	0.56	13	31	0.08	30	41	0.02	13	0	14	30	31	1.9	13	69	19	30
Summer	2001–2009	5	1.07	90	74	0.39	38	21	0.11	90	39	0.03	38	−37	19	88	23	2.3	38	46	10	90
Autumn	2001–2009	13	1.55	36	33	0.75	12	13	0.09	36	7	0.04	12	−31	19	36	8	2.3	12	38	9	36
Winter	2002–2010	−15	1.18	39	17	0.70	18	−8	0.10	39	−61	0.05	18	−85	11	39	−73	2.6	18	27	12	39
Savonneva																						
Spring	2002–2004	24	1.64	10	49	0.84	3	24	0.05	10	−77	0.01	3	1	29	10	−20	0.8	3	62	7	10
Summer	2001–2004	34	2.81	32	59	1.08	18	28	0.13	32	11	0.02	18	2	72	32	15	4.4	18	40	16	32
Autumn	2001, 2003	24	4.54	9	34	2.33	6	22	0.12	9	−34	0.02	6	11	89	9	3	3.4	6	62	38	9
Winter	2002–2004	16	2.28	11	26	1.44	5	−64	0.05	11	−163	0.02	5	−20	33	11	−59	2.7	5	39	9	11
Vittasuo																						
Spring	2005–2009	20	1.82	14	29	0.84	10	21	0.08	14	27	0.01	10	5	40	14	32	2.0	10	28	32	14
Summer	2005–2009	25	2.28	47	46	1.01	36	16	0.09	48	−47	0.01	38	4	68	48	16	2.1	38	14	17	48
Autumn	2005–2009	32	2.61	20	44	1.37	15	55	0.08	20	25	0.01	15	8	77	20	12	1.3	15	62	10	20
Winter	2006–2010	23	2.13	16	24	1.02	12	47	0.08	16	44	0.02	12	5	59	16	35	1.4	12	62	22	16

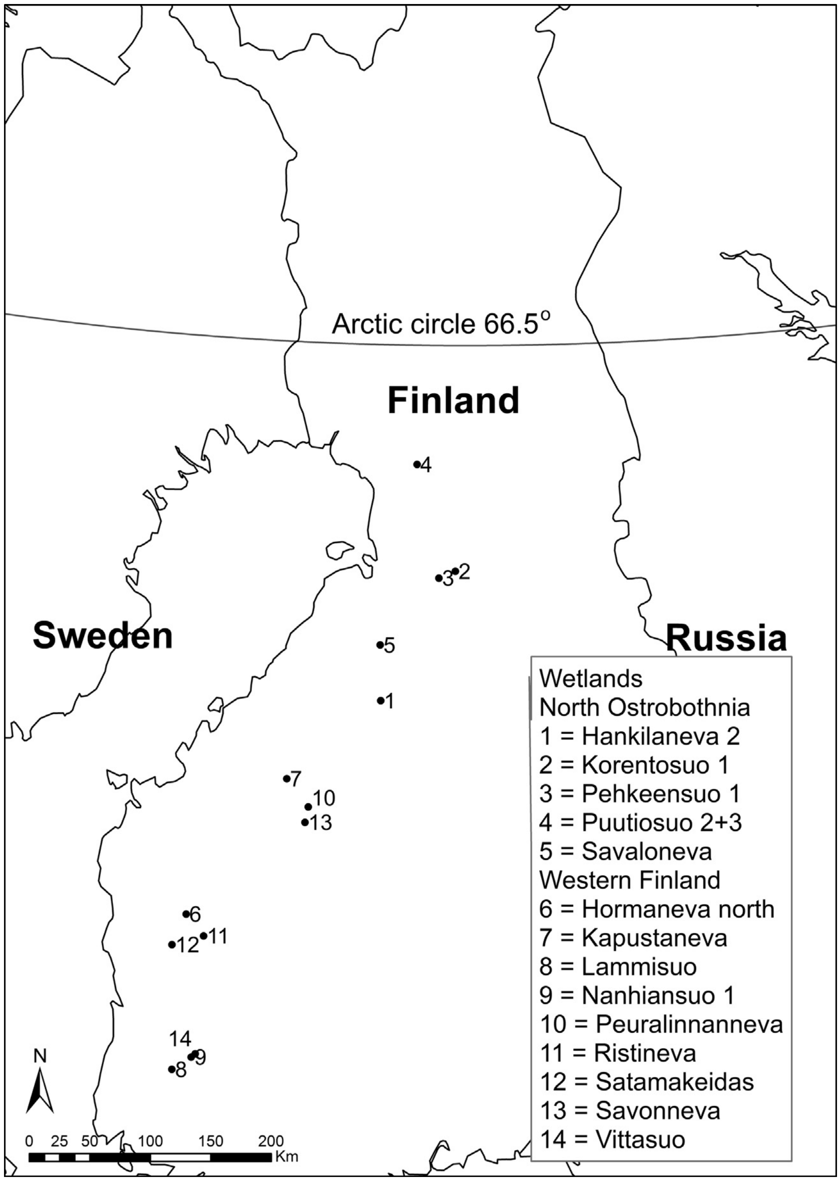

Fig. 1. Location of the 14 treatment wetlands in northern and western Finland included in this study.

Table 3
Seasonal median purification efficiency (%) and load (g/ha d) for different compounds and runoff (q, L/s km^2) of all 14 wetlands and of wetlands located in North Ostrobothnia and Western Finland, calculated using mean values for individual sites and years.

	N_{tot}		NH_4-N		P_{tot}		PO_4-P		COD_{Mn}		Fe		SS		q
	%	g/ha d	%	g/ha d	%	g/ha d	%	g/ha d	%	g/ha d	%	g/ha d	%	g/ha d	L/s km^2
Whole dataset (14 wetlands)															
Spring	25	29	39	8.1	40	1.0	47	0.2	3	625	36	26	67	126	26
Summer	26	7	73	0.5	42	0.3	40	0.1	−8	261	28	11	61	27	6
Autumn	31	21	44	10.0	49	0.5	43	0.2	4	508	27	21	65	62	13
Winter	22	18	24	5.2	51	0.6	35	0.2	−12	362	29	18	74	54	11
North Ostrobothnia (5 wetlands)															
Spring	30	28	75	4.7	43	0.8	60	0.1	8	561	45	24	66	124	38
Summer	31	6	91	0.2	48	0.2	52	0.1	−24	220	28	18	76	30	8
Autumn	49	8	93	0.8	53	0.3	35	0.2	9	248	75	12	72	33	10
Winter	36	11	72	2.3	60	0.4	68	0.2	−18	245	59	14	80	30	9
Western Finland (9 wetlands)															
Spring	21	29	37	9.8	34	1.0	39	0.3	1	634	36	28	68	139	23
Summer	20	8	59	1.2	24	0.3	27	0.1	−1	275	27	8	39	25	6
Autumn	24	34	43	11.1	46	0.7	43	0.2	2	959	26	25	62	76	15
Winter	14	28	23	8.8	35	0.9	33	0.3	−6	610	27	21	70	70	12

Table 4
Regional characteristics of climate (T = temperature, P = precipitation) and season classification in the 14 wetlands in the period 2009–2011.

Group	Number of wetlands	T (°C)	P (mm/d)	Start of season			
				Winter	Spring	Summer	Autumn
North Ostrobothnia	5	−2.0	1.6	November 1	Snowmelt start, apparent as increased outflow from wetlands (usually mid-April)	Snowmelt end (usually during May)	September 20
Western Finland	9	−0.3	1.6	December 1	Snowmelt start, apparent as increased outflow from wetlands (usually early April)	Snowmelt end (usually early May)	October 1

Mean season purification efficiency of every wetland in different years was included in these tests.

- Using the Mann–Whitney *U*-test, differences in water purification owing to icing problems during winter (yes/no) and previous drainage of the area (yes/no) were compared. Mean season purification efficiency of every wetland in different years was included in these tests.

3. Results and discussion

3.1. Influence of seasonal frost depth on water flow paths

Seasonal maximum frost depth varied from 0 to 42 cm, with a mean maximum depth of 20 cm at the three sites studied (Figs. 5–7). All three wetlands were mainly frozen with no apparent water flow, but at two of the sites some surface flow was also observed. This typically occurred when water was pumped to the wetlands in winter. In periods with low runoff the pump runs occasionally causing high inflow fluctuation, the wetland was totally frozen. The seasonal frost layer was deeper in more northerly wetlands, due to smaller snow depth at northern sites in 2010 and in early winter in 2011, and perhaps partly to slightly colder winters (mean temperature 1 October 2009–30 April 2010 of −9.4 °C at southern sites and mean temperature 1 October 2010–30 April 2011 of −10.5 °C at northern sites). There was no difference in snow cover duration between northern and southern sites during the observation period.

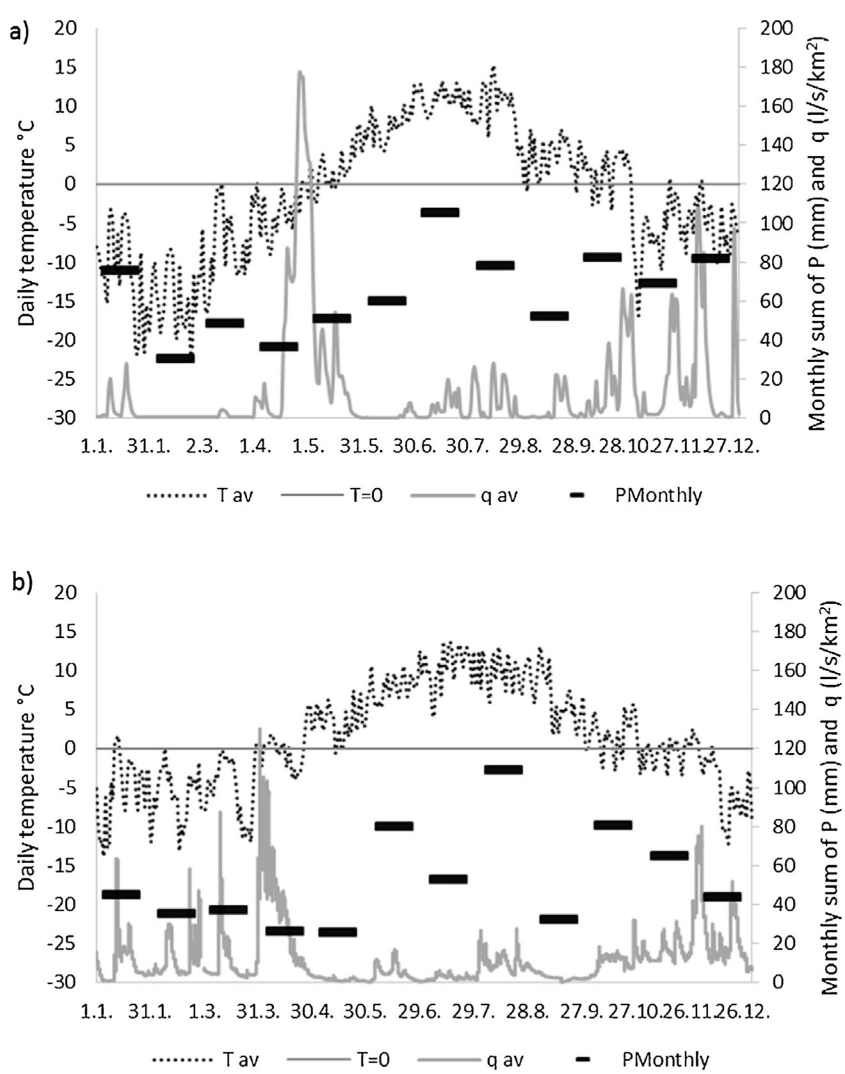

Fig. 2. Mean temperature, precipitation (P) and runoff (q) in (a) Puutiosuo wetland, representing the North Ostrobothnia group, and (b) Nanhiansuo wetland, representing the Western Finland group. The Puutiosuo data are for hydrological years 2007 and 2008 and the Nanhiansuo data for hydrological years 2008 and 2009.

Table 5
Mean, minimum, and maximum seasonal temperature and precipitation, based on daily data for the 14 wetlands in different years. Only years with purification data were included in the calculations.

	Temperature (°C)												Precipitation (mm)											
	Spring			Summer			Autumn			Winter			Spring			Summer			Autumn			Winter		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
North Ostrobothnia wetlands																								
Hankilaneva 2	−1.5	−3.3	0.8	6.9	5.4	8.3	−0.9	−3.4	2.4	−8.2	−12.6	−6.1	1.2	1.1	1.4	2.2	1.5	2.4	1.5	1.3	1.8	1.2	1.0	1.4
Korentosuo 1[a]	−0.5	−0.5	−0.5							−12.4	−12.4	−12.4	1.1	1.1	1.1							1.4	1.4	1.4
Pehkeensuo 1	0.1	−1.2	1.6	8.0	6.4	9.7	0.6	−1.6	2.7	−10.2	−12.3	−7.2	1.2	1.0	1.5	2.0	1.2	2.3	1.9	0.9	3.0	1.4	1.0	1.8
Puutiosuo 2–3	0.3	−2.3	2.5	8.6	7.6	9.1	1.3	0.3	3.2	−9.7	−11.6	−7.9	1.3	0.3	2.3	2.1	1.6	2.8	1.9	1.4	2.6	1.5	0.9	2.0
Savaloneva	−0.8	−0.8	−0.8	7.6	7.6	7.6	−0.8	−0.8	−0.8	−7.8	−7.8	−7.8	0.8	0.8	0.8	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
Mean	***−0.5***	***−1.6***	***0.7***	***7.8***	***6.8***	***8.7***	***0.1***	***−1.4***	***1.9***	***−9.7***	***−11.3***	***−8.3***	***1.1***	***0.9***	***1.4***	***1.9***	***1.5***	***2.3***	***1.7***	***1.3***	***2.2***	***1.3***	1.0	***1.5***
Western Finland wetlands																								
Hormaneva North	−1.3	−2.5	0.6	6.4	6.2	6.6	−0.3	−1.2	0.6	−8.7	−11.0	−6.4	0.7	0.3	1.1	1.8	1.5	2.1	2.5	1.7	3.3	0.9	0.8	1.0
Kapustaneva	−2.3	−2.5	−2.1	6.5	6.4	6.6	−1.1	−1.9	−0.4	−11.6	−15.2	−8.1	1.0	0.8	1.3	2.2	1.4	2.9	2.0	1.6	2.3	1.0	0.9	1.0
Lammisuo	−1.2	−1.9	−0.6	8.1	8.0	8.3	1.1	0.3	1.9	−7.7	−9.8	−5.6	1.0	0.6	1.4	2.0	1.6	2.4	2.5	1.7	3.2	1.1	1.0	1.2
Nanhiansuo	−0.9	−2.4	0.4	8.0	6.8	8.7	0.8	−0.2	1.4	−6.6	−12.1	−2.6	1.2	0.7	2.2	1.9	1.5	2.2	2.5	1.6	3.7	1.3	1.0	1.9
Peuralinnanneva	−2.9	−2.9	−2.9				−2.1	−2.1	−2.1	−15.1	−15.1	−15.1	1.2	1.2	1.2				1.6	1.6	1.6	1.1	1.1	1.1
Ristineva	−0.3	−1.4	0.3	6.9	6.2	7.4	−0.4	−1.4	0.6	−5.5	−7.3	−3.8	0.9	0.8	1.1	2.1	1.7	2.4	2.4	1.7	3.5	2.0	1.9	2.0
Satamakeidas	−0.5	−2.1	0.8	8.0	6.5	8.7	−0.6	−5.6	1.9	−8.1	−11.8	−3.4	0.8	0.1	1.5	2.1	1.5	2.8	2.2	1.0	3.8	1.3	0.7	2.2
Savonneva	0.8	−0.1	1.5	8.3	7.5	8.9	−1.2	−1.3	−1.0	−9.9	−11.7	−8.9	1.0	0.4	1.5	2.0	1.8	2.5	1.6	1.5	1.7	0.9	0.6	1.2
Vittasuo	0.2	−0.4	0.8	8.2	6.8	8.7	1.0	−0.2	2.0	−6.7	−10.8	−2.6	0.9	0.2	2.2	2.0	1.5	2.4	2.4	1.6	3.7	1.3	1.0	1.9
Mean	***−0.9***	***−1.8***	***−0.1***	***7.5***	***6.8***	***8.0***	***−0.3***	***−1.5***	***0.5***	***−8.9***	***−11.6***	***−6.3***	***1.0***	***0.5***	***1.5***	***2.0***	***1.6***	***2.5***	***2.2***	***1.6***	***3.0***	***1.2***	1.0	1.5

Note: The values in bold and italics used to highlight the mean values of Western Finland and North Ostrobothnia for better reading.
[a] Data only from 2010.

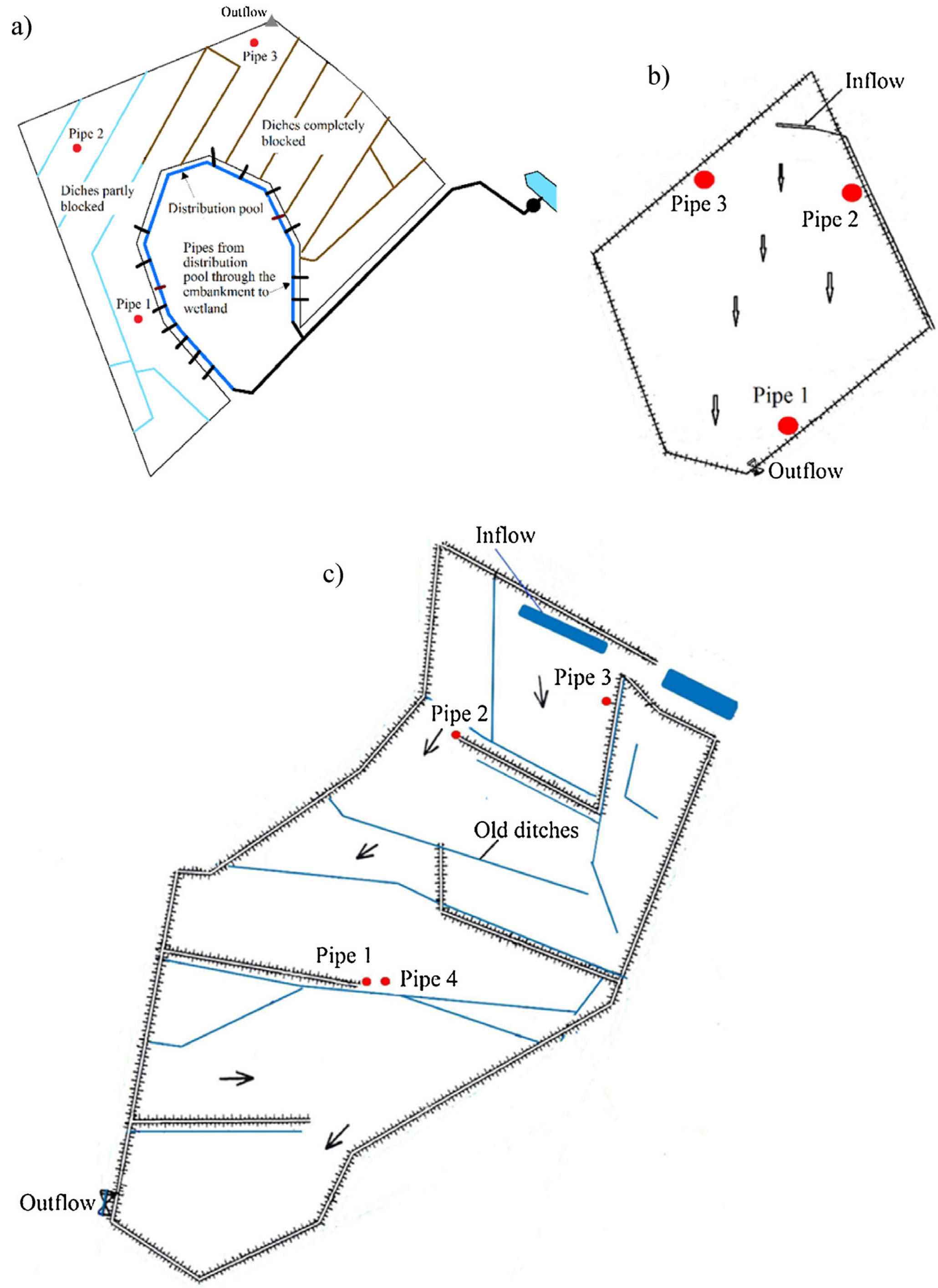

Fig. 3. Location of ground frost pipes in (a) Kapustaneva, (b) Korentosuo 1, and (c) Pehkeensuo 1 wetlands.

When water is pumped to the wetland in cold winter conditions, different flow paths can occur. For example, water can flow through preferential flow paths that remain unfrozen throughout the winter. As the peat layer (acrotelm) with its high hydraulic conductivity is typically deeper than the frost layer, and can extend to 50–60 cm depth (Ronkanen and Kløve, 2005), some flow can also occur in the peat below the frozen layer. At some sites, bulge ice formed on the wetland surface, probably as water flow was partly prevented by frost within the wetland. Differences observed between sites could have been caused by different pumping regimes and wetland designs. Changing the pumping regimes, e.g. by using two lower capacity pump instead of one higher capacity pump could decrease the flow fluctuation improving winter time performance of treatment wetlands. A previous survey of treatment wetlands showed that ice influenced flow conditions occasionally (Kantonen, 2011). In spring, frost in the wetland resulted in overland flow, as the ground frost disappeared after the snowmelt season.

3.2. *Seasonal variation in purification efficiency*

There was a clear seasonal variation in removal of NH_4-N ($p = 0.000$) and COD_{Mn} ($p = 0.004$) in all 14 constructed wetlands (Table 3). The NH_4-N purification efficiency was typically lowest during winter and highest during summer. The variable removal of

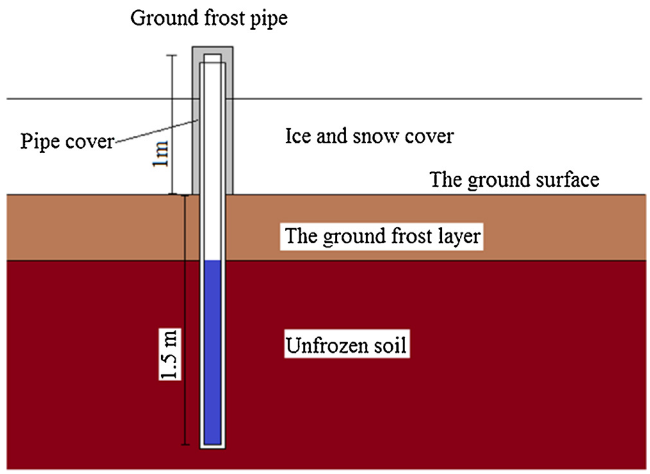

Fig. 4. Set-up of the ground frost pipes, which consisted of transparent plastic tubes filled with methylene blue solution. The pipe section above the ground surface was lagged using polyurethane pipe insulation.

NH_4-N with temperature indicates that nitrification was the purification process (Vymazal, 2007). The observed wintertime removal could be partly due to cation exchange (Heikkinen et al., 1995; Wittgren and Mæhlum, 1997). In addition, the nitrifying microbial community can be partly adapted to regional and seasonal climate conditions (Wittgren and Mæhlum, 1997), and thus purification via nitrification can also occur in winter.

The COD_{Mn} purification efficiency was typically negative during winter and summer, while during spring and autumn it was on average positive (Table 3). Positive retention in spring can be caused by overland flow on the frozen wetland preventing leaching from the peat. Weak organic matter removal efficiency and leaching of organic materials is common in treatment wetlands constructed on peatlands (Kløve et al., 2012).

For the other water quality parameters (N_{tot}, P_{tot}, PO_4-P, Fe, and SS), no seasonal variation in retention was observed. This could indicate that removal is controlled by chemical (e.g., sorption) and physical (e.g., filtration) processes that are not temperature dependent. The N_{tot}, P_{tot}, and Fe in runoff from peat extraction areas may be bound with SS (Ihme, 1994) and dissolved organic P, and Fe also with high molecular weight humic substances (Heikkinen and Ihme, 1995). Our results confirm previous findings for other types of constructed wetlands and buffer zones of no seasonal variations in P_{tot} and PO_4-P (e.g., Syversen, 2005; Züst and Schönborn, 2003).

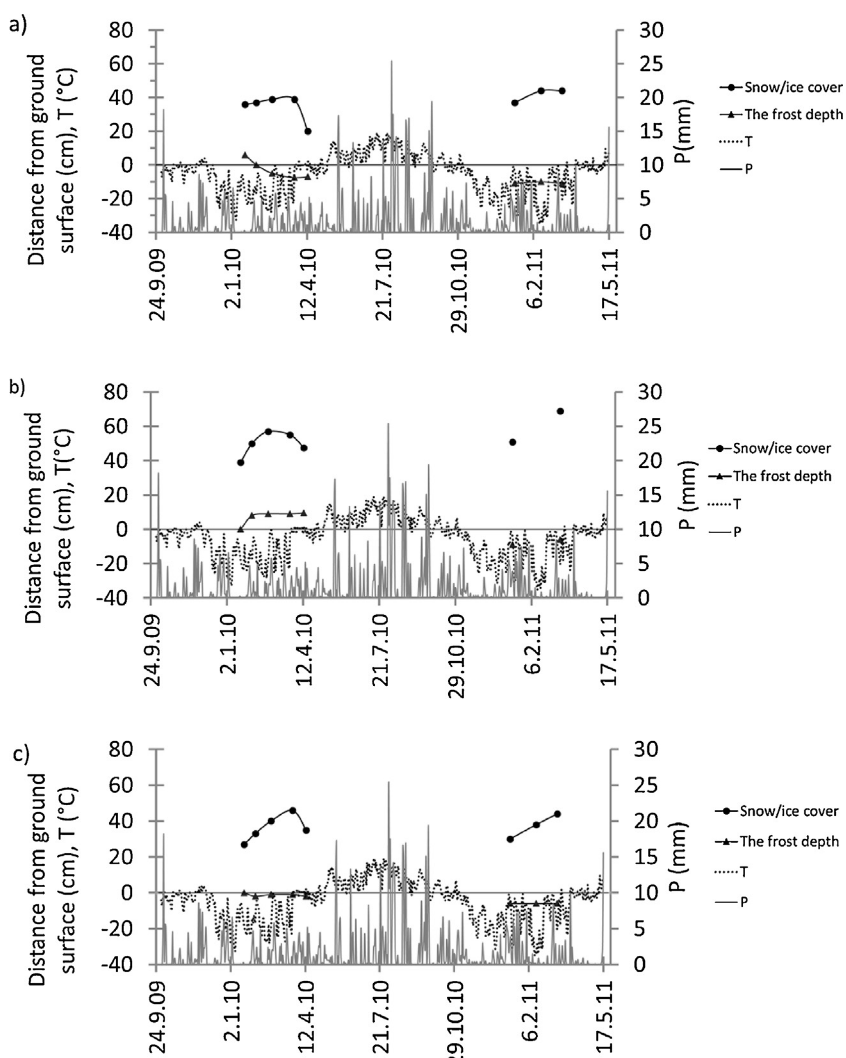

Fig. 5. Daily mean air temperature (T, °C), daily precipitation (P, mm), ground frost, and snow/ice cover in the three measuring pipes in the Kapustaneva wetland: (a) pipe 1, (b) pipe 2, and (c) pipe 3. Mean daily temperature was −9.0 °C for the measuring period 1 October 2009–30 April 2010 and −9.7 °C for the measuring period 1 October 2010–30 April 2011, while mean daily precipitation was 1.2 mm and 1.1 mm, respectively.

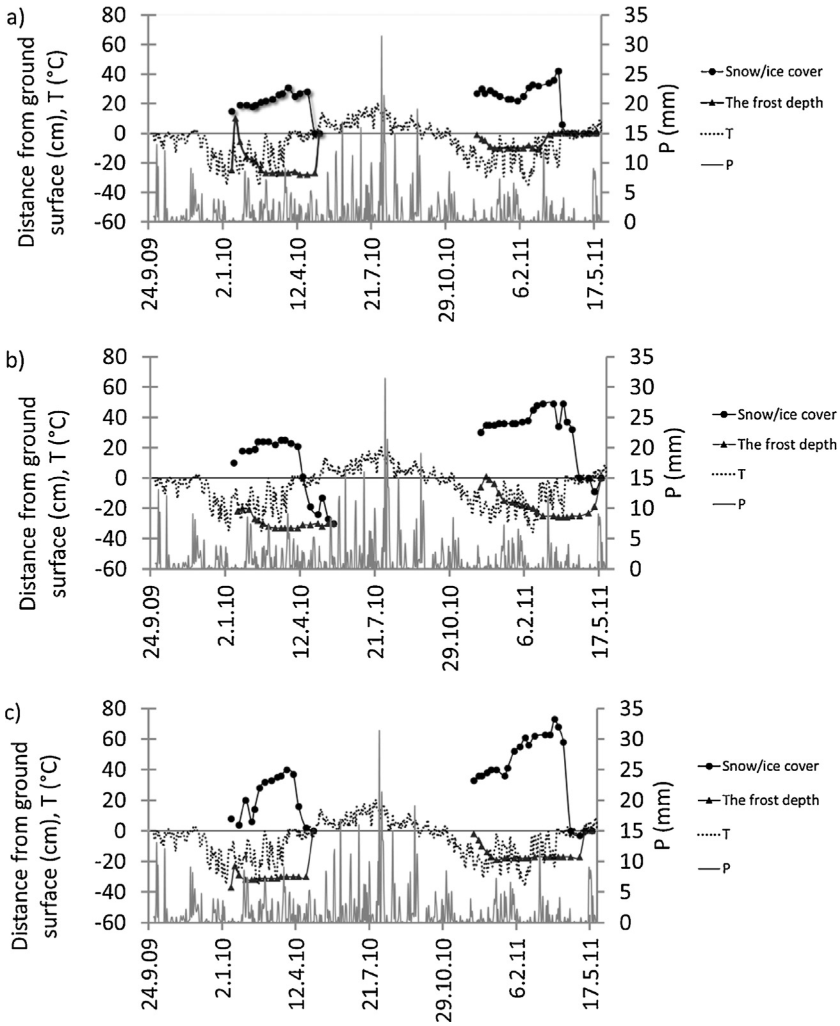

Fig. 6. Daily mean air temperature (T, °C), daily precipitation (P, mm), ground frost, and snow/ice cover in the three measuring pipes in the Korentosuo wetland: (a) pipe 1, (b) pipe 2, and (c) pipe 3. Mean daily temperature was −10.4 °C for the measuring period 1 October 2009–30 April 2010 and −10.9 °C for the period 1 October 2010–30 April 2011, while mean daily precipitation was 1.4 mm and 0.9 mm, respectively.

There was a significant seasonal fluctuation in water quality inflow concentrations ($p < 0.001$), except for SS ($p = 0.502$). During summer, the P_{tot}, PO_4-P, COD_{Mn}, and Fe concentrations were high and the N_{tot} and NH_4-N concentrations were low. The N_{tot}, NH_4-N, and COD_{Mn} concentrations were high in autumn and the NH_4-N inflow concentration was high in winter. In spring, all inflow concentrations except SS were low, but total loads were usually high due to high discharge rates (Table 3). In general, the purification efficiency for P_{tot} ($r_s = 0.23$, $p = 0.002$), PO_4-P ($r_s = 0.37$, $p = 0.000$), COD_{Mn} ($r_s = 0.38$, $p = 0.000$), Fe ($r_s = 0.27$, $p = 0.002$), and SS ($r_s = 0.39$, $p = 0.000$) was correlated with the inflow concentration of each compound, showing that higher inflow concentrations result in better removal efficiency. The increased retention with inflow concentration was not seen for all seasons, however. For example, for PO_4-P a correlation between purification efficiency and inflow concentration was observed only during summer.

3.3. Wetland design criteria and properties influencing purification efficiency

Some design criteria of the treatment wetlands, such as slope and peat type parameters, were found to influence purification in some seasons and some regions. The slope of the treatment wetlands was positively correlated with COD_{Mn} purification efficiency ($r_s = 0.45$, $p = 0.001$). However, because it in turn was positively correlated with COD_{Mn} inflow concentration ($r_s = 0.36$, $p = 0.007$), the higher inflow concentration may have been the main reason for the better purification results. Degree of humification of surface peat was significantly correlated with the purification efficiency for P_{tot} ($r_s = -0.46$, $p = 0.005$), PO_4-P ($r_s = -0.59$, $p = 0.001$), and SS ($r_s = -0.48$, $p = 0.003$), with purification efficiency decreasing with increasing degree of humification. The treatment wetland area as % of catchment area was correlated with PO_4-P purification efficiency in spring ($r_s = 0.79$, $p = 0.004$). The purification efficiency was not significantly influenced by average wetland length. The reason for this unexpected result is probably that the flow path length does not relate well to the average length of the wetland (or residence time) as old ditches and wetland topography result in preferential flow. Another reason could be leakage to the subsurface mineral layer which was observed at one of the study sites.

Initial wetland drainage status (drained or pristine) had some effect on purification efficiency for N_{tot} ($p = 0.001$), P_{tot} ($p = 0.000$), and SS ($p = 0.000$). The retention efficiency was higher in wetlands constructed on pristine peatland, as reported previously by Postila et al. (2014). In general, the factors which might lower purification efficiency for P_{tot}, and SS were: (1) Lower inflow concentration, (2) higher average degree of humification of the surface peat, and (3) previous drainage of the wetland area. At the sites with reported

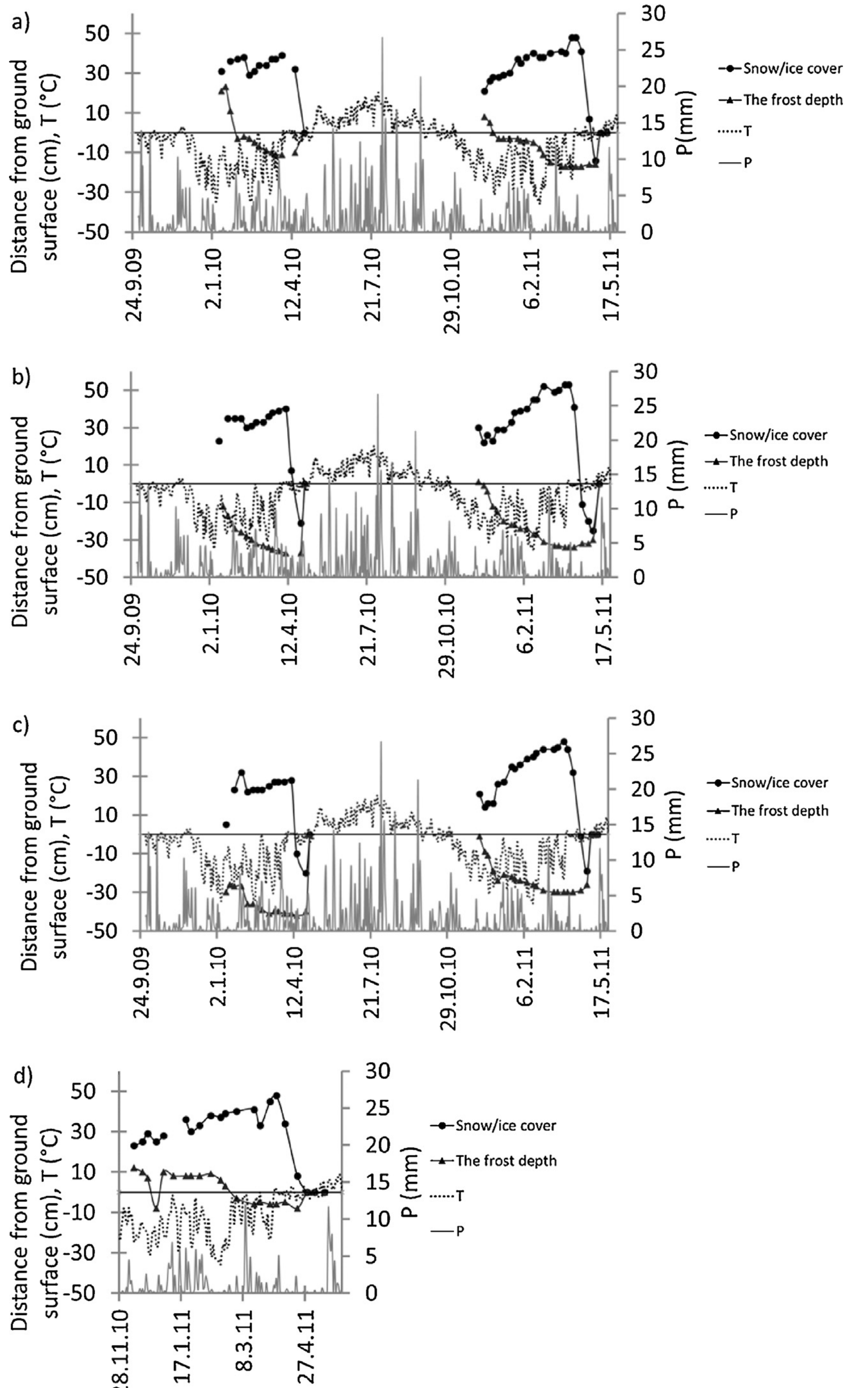

Fig. 7. Daily mean air temperature (T, °C), daily precipitation (P, mm), ground frost, and snow/ice cover in the four measuring pipes in the Pehkeensuo 1 wetland: (a) pipe 1, (b) pipe 2, (c) pipe 3, and (d) pipe 4. Mean daily temperature was −10.2 °C for the measuring period 1 October 2009–30 April 2010 and −10.6 °C for the period 1 October 2010–30 April 2011, while mean daily precipitation was 1.5 mm and 1.0 mm, respectively.

icing impacts on treatment systems (Table 1), the purification efficiency was not reduced significantly.

4. Conclusions

Only the wetland purification efficiency for COD_{Mn} and NH_4-N differed significantly between seasons. The NH_4-N purification efficiency was highest during summer and lowest during winter, but NH_4-N removal also occurred in winter months. COD_{Mn} removal efficiency was lowest during summer and winter, when the COD_{Mn} concentration increased and organic matter leached from the treatment wetlands. No seasonal variation in purification efficiency was observed for nutrients (N_{tot}, P_{tot}, PO_4-P), particulate matter (SS), and iron (Fe).

Temperature affected NH_4-N purification efficiency mainly because nitrification is a temperature-dependent microbial purification process. Increased inflow concentration also increased removal efficiency except for N_{tot} and NH_4-N. Higher degree of humification of surface peat and previous drainage of the wetland area tended to be associated with decreased purification efficiency for P_{tot}, PO_4-P, and SS. Therefore, the peatlands in pristine state and with low humified surface peat are the best options for treatment wetlands if such areas are available.

Seasonal frost and ice altered water flow paths in the wetlands in winter. In conditions with sub-zero temperatures, water could still flow in deeper unfrozen peat layers. Moreover, in some areas of wetland there was also water flow in the surficial, partly frozen peat layers and on top of the peat. This shows that water purification in wetlands can continue to occur in winter conditions, under the snow and ice cover, even though the flow paths differ from those in summer. If runoff could be distributed more steadily using several pumps this might improve wintertime performance of treatment wetlands reducing icing and variable inflow rates. Overall, the winter-time purification processes, runoff flow paths and the effect of pumping regimes on treatment wetlands should be examined in more detail.

Acknowledgements

This study formed part of the project “Round-year treatment of runoff from peat production areas (TuKos)”, which was funded mainly by the European Regional Development Fund and the Centre for Economic Development, Transport and the Environment for North Ostrobothnia. Other funding bodies and partners in the project were: Vapo Oy, Turveruukki Oy, Kuopion energia Oy, Suomen turvetuottajat ry (Finland’s peat producers), Jyväskylän energia Oy, City of Oulu, Council of Oulu Region, and Regional Council of Central Finland. The Finnish Cultural Foundation, K.H Renlund Foundation, Maa- ja vesitekniikan tuki ry., Oulun läänin talousseuran maataloussäätiö, Emil Aaltosen säätiö and Sven Hallin Foundation also provided funding for the work. We thank all funders and also all those who helped in the field work and in data analysis, especially Sari Kantonen.

References

Eurola, S., 1975. Snow and ground frost conditions of some Finnish mire types. Ann. Bot. Fenn. 12, 1–16.

Department for Environment, Food and Rural Affairs, 2014. UK biodiversity indicators 2014.

Department of the Environment, 2014. Northern Ireland, Water Framework Directive, Statistics Report.

Feng, W., Yi, L., Yuxin, M., Xirui, W., Haizhen, Y., 2012. Characterization of nitrification and microbial community in a shallow moss constructed wetland at cold temperatures. Ecol. Eng. 42, 124–129.

Finnish Environment Institute, 2013. Watershed simulation and forecasting system (WSFS).

Finnish Environment Institute, 2014. Hydrological observation sites, the snow line measurement. Meta-information service, material identification data (in Finnish).

Finnish Meteorological Institute, 2015. 10 × 10 km grid interpolated daily precipitation and temperature averages 1.1.1961-31.12.2011 (Data collected 6.3.2015).

Heikkinen, K., Ihme, R., 1995. Retention of organic Fe-P-colloids from peat mining water in an overland flow wetland treatment system in northern Finland. Arch. Hydrobiol. 134, 547–560.

Heikkinen, K., Ihme, R., Lakso, E., 1995. Contribution of cation exchange property of overflow wetland peat to removal of NH + discharged from some Finnish peat mines. Appl. Geochem. 10, 207–214.

Hobbs, N.B., 1986. Mire morphology and the properties and behavior of some British and foreign peats. Q. J. Eng. Geol. Hydrogeol. 19, 7–80.

Ihme, R., 1994. Use of the overland flow wetland treatment system for the purification of runoff water from peat mining areas. VTT Publications 798 (in Finnish with English summary).

Kadlec, R.H., Axler, R., McCarthy, B., Henneck, J., 2003. Subsurface treatment wetlands in the cold climate of Minnesota. In: Mander, Ü., Jenssen, P.D. (Eds.), Constructed Wetlands for Wastewater Treatment in Cold Climates. WIT Press, Southampton, Boston, pp. 19–52.

Kadlec, R.H., Wallace, S.D., 2009. Treatment Wetlands, 2nd ed. CRC Press, Boca Raton, FL.

Kantonen, S., Master thesis 2011. Round-year wetland treatment of runoff from peat production areas. University of Oulu (in Finnish with English summary).

Korhonen, J., 2006. Ice conditions in lakes and rivers in Finland. The Finnish Environment 751 (in Finnish with English summary).

Kløve, B., Saukkoriipi, J., Tuukkanen, T., Heiderscheidt, E., Heikkinen, K., Marttila, H., Ihme, R., Depre, L., Karppinen, A., 2012. Pre-estimation of loading on water bodies from peat production and new pollution control methods (TuVeKu). The Finnish Environment 35/2012 (in Finnish with English summary).

Mander, Ü., Jenssen, P.D. (Eds.), 2002. Natural Wetlands for Wastewater Treatment in Cold Climates. WIT Press, Southampton, Boston.

Mander, Ü., Jenssen, P.D. (Eds.), 2003. Constructed Wetlands for Wastewater Treatment in Cold Climates. WIT Press, Southampton, Boston.

Mæhlum, T., Stålnacke, P., 1999. Removal efficiency of three cold-climate constructed wetlands treating domestic wastewater: effects of temperature, seasons, loading rates and input concentrations. Water Sci. Technol. 40 (3), 273–281.

OIVA database, 2015. Finnish Environment Institute, OIVA-environmental and spatial data service. Snow line results (Data collected 10.3.2015).

Postila, H., Saukkoriipi, J., Heikkinen, K., Karjalainen, S.M., Kuoppala, M., Marttila, H., Klöve, B., 2014. Can treatment wetlands be constructed on drained peatlands for efficient purification of peat extraction runoff? Geoderma 228–229, 33–43.

Putkuri, E., Lindholm, M., Peltonen, A., 2013. The state of the environment in Finland 2013. SYKE Publications 1 (in Finnish with English summary).

Ronkanen, A.-K., Kløve, B., 2005. Hydraulic soil properties of peatlands treating municipal wastewater and peat harvesting runoff. Suo 56, 43–56.

Syversen, N., 2005. Effect and design of buffer zones in the Nordic climate: the influence of width, amount of surface runoff, seasonal variation and vegetation type on retention efficiency for nutrient and particle runoff. Ecol. Eng. 24, 483–490.

Vehviläinen, B., Lohvansuu, J., 1991. The effects of climate change on discharges and snow cover in Finland. Hydrol. Sci. J. 36, 109–121.

Venäläinen, A., Tuomenvirta, H., Heikinheimo, M., Kellomäki, S., Peltola, H., Strandman, H., Väisänen, H., 2001. Impact of climate change on soil frost under snow cover in a forested landscape. Clim. Res. 17, 63–72.

Venäläinen, A., Tuomenvirta, H., Pirinen, P., Drebs, A., Reports No. 2005:5 2005. A basic Finnish climate data set 1961–2000 – Description and illustrations. Finnish Meteorological Institute.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Sci. Total Environ. 380, 48–65.

Wittgren, H.B., Mæhlum, T., 1997. Wastewater treatment wetlands in cold climates. Water Sci. Technol. 35, 45–53.

Züst, B., Schönborn, A., 2003. Constructed wetlands for wastewater treatment in cold climates: planted soil filter Schattweid–13 years’ experience. In: Mander, Ü., Jenssen, P.D. (Eds.), Constructed Wetlands for Wastewater Treatment in Cold Climates. WIT Press, Southampton, Boston, pp. 53–68.