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Heini Postila

PEAT EXTRACTION RUNOFF WATER PURIFICATION IN TREATMENT WETLANDS CONSTRUCTED ON DRAINED PEATLANDS IN A COLD CLIMATE

UNIVERSITY OF OULU GRADUATE SCHOOL;
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FACULTY OF TECHNOLOGY

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Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in Auditorium GO101, Linnanmaa, on 17 June 2016, at 12 noon

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Abstract

Best available technology (BAT) should be used for peat extraction runoff purification. One currently used BAT technique is treatment wetland construction on pristine peatland, but under Finnish national strategies, new peat extraction areas should only be established on previously drained peatland and it can be challenging to find natural, intact peatland for treatment wetlands near these areas. This thesis evaluated the function and purification efficiency of treatment wetlands constructed on drained peatland and examined factors that could indicate their purification efficiency. The year-round removal efficiency of treatment wetlands established in drained or pristine peatland areas in a cold climate was also studied.

A first study examined the water flow processes in treatment wetlands constructed on drained peatland. In more than 50% of the 20 wetlands studied, the active flow depth was under 20 cm and water distribution was unequal.

A second study determined the purification efficiency of treatment wetlands constructed on drained peatland and examined factors indicating removal efficiency. The removal efficiency of suspended solids and inorganic nitrogen was good, but in some wetlands leaching of phosphorus and iron was observed, e.g. due to changes in peat properties, first after drainage and then after rewetting, altering e.g., oxygen conditions in the peat layer. The surface peat content of elements such as phosphorus, iron, aluminum, magnesium, manganese, and calcium can be used as a proxy to assess leaching of phosphorus.

A third study examined the year-round purification efficiency of treatment wetlands based on peat extraction load monitoring program values. Seasonal variation in the purification efficiency of constructed wetlands was observed for total nitrogen, ammonium-nitrogen, and chemical oxygen demand (COD_{Mn}).

Based on these results, it is possible to evaluate the suitability of different drained peatland areas for water purification purposes. Treatment wetlands were shown to generally purify runoff water during winter mainly as well as in other seasons, except for nitrogen and $COD_{Mn,}$ but there may be variations between wetlands.

Keywords: constructed wetlands, hydrology and hydraulics, overland-flow, peatland, phosphorus, winter

Postila, Heini, Turvetuotannon valumavesien puhdistaminen ojitetuille suoalueille perustetuilla kosteikolla pohjoisissa olosuhteissa.
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Tiivistelmä

Turvetuotannon valumavesien käsittelyssä tulee käyttää parasta saatavilla olevaa käyttökelpoista tekniikkaa, esimerkiksi luonnontilaisille suoalueille rakennettuja pintavalutuskenttiä. Valtakunnallisilla alueidenkäyttöstrategioilla turvetuotantoa ohjataan yhä enemmän jo aiemmin ojitetuille suoalueille. Näiden läheisyydestä ei välttämättä löydy sopivaa ojittamatonta suoaluetta pintavalutuskentän perustamista varten. Tämän tutkimuksen tavoitteena oli selvittää miten ojitetuille suoalueille rakennetut pintavalutuskentät (kosteikot) toimivat ja puhdistavat valumavesiä sekä mitkä tekijät voivat kuvata niiden toimivuutta. Työssä selvitettiin myös ojittamattomille ja ojitetuille suoalueille rakennettujen pintavalutuskenttien ympärivuotista toimivuutta.

Työn ensimmäisessä osassa tutkittiin veden virtausta ojitetulle suoalueille rakennetuilla pintavalutuskentillä. Yli puolella tutkituista pintavalutuskentistä oli havaittavissa, että veden virtauskerros turpeessa oli matala (alle 20 cm) ja vesi jakautui pintavalutuskentälle epätasaisesti.

Työn toisessa osassa selvitettiin ojitetuille suoalueille rakennettujen pintavalutuskenttien puhdistustehokkuutta ja sitä indikoivia tekijöitä. Ojitetut pintavalutuskentät puhdistivat hyvin kiintoainetta ja epäorgaanista typpeä, mutta joillakin kohteilla oli havaittavissa fosforin ja raudan huuhtoutumista, mikä johtunee osaltaan kuivatuksen aiheuttamista muutoksista turpeessa ja happiolosuhteiden muutoksista uudelleen vesittämisen jälkeen. Erityisesti fosforin huuhtoumista voitiin alustavasti arvioida pintaturpeen fosfori-, rauta-, alumiini-, magnesium-, mangaani- ja kalsiumpitoisuuksien perusteella.

Työn kolmannessa osassa määritettiin olemassa olevan vedenlaatuaineiston avulla pintavalutuskenttien ympärivuotista puhdistustehokkuutta. Selvää vuodenaikaisvaihtelua ei havaittu kokonaistyppeä, ammoniumtyppeä ja kemiallisen hapenkulutuksen (COD_{Mn})-arvoa lukuun ottamatta.

Työn tuloksia voidaan käyttää, kun arvioidaan etukäteen ojitettujen suoalueiden soveltuvuutta vedenpuhdistukseen. Kosteikot vaikuttivat pääasiassa typpeä ja COD_{Mn}-arvoa lukuun ottamatta olevan yhtä tehokkaita valumavesien puhdistajia myös talvella kuin muina vuodenaikoina, tosin kohteiden välillä oli vaihtelua.

Asiasanat: fosfori, hydrologia ja hydrauliikka, pintavalutus, suo, talvi, vesiensuojelukosteikko

To my sister’s children, Miika and Eveliina

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Oulu, June 2015 Heini Postila

List of symbols and abbreviations

Al	Aluminum
BAT	Best available techniques
BOD	Biological oxygen demand
C_{in}	Mean concentration in inflow
C_{out}	Mean concentration in outflow
Ca	Calcium
COD_{Mn}	Chemical oxygen demand
Fe	Iron
FINAS	Finnish Accreditation Service
ICP-OES	Inductively coupled plasma optical emission spectrometry
Inorganic N	NH_4-N and NO_{2+3}-N
K	Hydraulic conductivity
K.	Kainuu region
L.	Lapland region
Mg	Magnesium
Mn	Manganese
N	Nitrogen
N_{tot}	Total nitrogen
NH_4-N	Ammonium nitrogen
NO_{2+3}-N	Sum of nitrate and nitrite nitrogen
N.O.	North Ostrobothnia region
OFA	Overland flow area
P	Phosphorus
P_{tot}	Total phosphorus
PO_4-P	Phosphate phosphorus
PP	Pipe in peat layer
Q_{in}	Mean daily inflow discharge
Q_{out}	Mean daily outflow discharge
R	Water purification efficiency
sd	Standard deviation
SP	Pipe in mineral subsoil layer
SS	Suspended solids

TA/CA	Treatment wetland area as percentage of whole catchment area
Treatment wetland	Includes different kinds of treatment wetlands; in Finland OFAs and treatment wetlands constructed on previously drained peatland
W.F.	Western Finland region

List of original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:

I Postila H, Ronkanen A-K, Marttila H & Kløve B (2015) Hydrology and hydraulics of treatment wetlands constructed on drained peatlands. Ecological Engineering 75: 232–241.

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

III Postila H, Ronkanen A-K & Kløve B (2015) Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate. Ecological Engineering 85: 13–25.

The author's contribution to publications I–III:

I Designed the study together with Ronkanen and Kløve, and conducted the field work together with Ronkanen. Analyzed the results and wrote the paper together with the co-authors.

II Designed the study together with Saukkoriipi, Heikkinen, Karjalainen, and Kløve, conducted the field work together with Saukkoriipi, Karjalainen, and Kuoppala. Analyzed the results and wrote the paper together with the co-authors.

III Designed the study and conducted the data collection and field work. Analyzed the results and wrote the paper together with the co-authors.

Contents

1 Introduction

1.1 Treatment wetlands for water purification in a cold climate

Treatment wetlands are widely used throughout the world to purify water of nutrients, suspended solids (SS), and harmful elements from different types of point and diffuse sources, for example agriculture (Dunne *et al.* 2005) and municipal systems (Kadlec & Wallace 2009). Treatment wetlands are used in warm and mild climate regions (Kadlec & Wallace 2009), but also in cold climate regions (Mander & Jenssen 2002, 2003). A cold climate is challenging from the viewpoint of year-round efficient purification. Especially purification processes, which are driven by microbiological action, can become slower during winter due to the low temperature (Feng *et al.* 2012). However, the effect of temperature on water purification efficiency is not entirely clear: some studies have observed that nutrient and biological oxygen demand (BOD) purification efficiency decreases, at least partly, when the temperature is low (Kadlec *et al.* 2003), while others have concluded that there is no significant difference between seasons (Mæhlum & Stålnacke 1999).

In Finland, treatment wetland systems are commonly constructed on peatlands due to the abundance of this soil type (about one-third of the land area in Finland), and their suitability for purifying different types of wastewater. Peatland-based treatment wetlands are used to purify runoff from peat extraction areas (Heikkinen *et al.*1995a, 1995b, Ronkanen & Kløve 2009), in peatland forestry (Nieminen *et al.* 2005, Silvan *et al.* 2004), and also to polish municipal wastewater (Ronkanen & Kløve 2007) or mining effluents (Närhi *et al.* 2012, Palmer *et al.* 2015).

During winter, frost, ice cover, and snow accumulation change active flow areas and flow paths in constructed wetlands, which can be expected to affect their winter-time performance. For example, if water flows on top of an ice layer, this can induce preferential flow and low contact between runoff water and the peat medium. However, it can also result in longer residence time inside the medium/substratum due to the reduction in flow volume caused by frost (Ronkanen & Kløve 2007). A sufficiently long residence time and good contact between runoff water and medium/substratum are well-known design parameters in achieving good purification efficiency (Kadlec & Wallace 2009). The seasonal ground frost effect also affects runoff flow routes and water quality during the snowmelt period in spring (Eskelinen *et al.* 2016), because ground frost usually disappears after snowmelt (Eurola 1975).

Based on climate change scenarios, the future winter temperature is predicted to increase in Finland, which can shorten the length of winter and the snow accumulation period (Räisänen 2008, Vehviläinen & Lohvansuu 1991). The amount of precipitation is also projected to be higher in future (Räisänen 2008, Vehviläinen & Lohvansuu 1991), especially in the period November-April in northern Finland (Venäläinen *et al.* 2001). The increased temperature and precipitation during winter could together increase winter discharge (Vehviläinen & Lohvansuu 1991), which might decrease maximum flow in spring due to a smaller amount of accumulated snow. The climate changes for summer are predicted to be small, partly because increased evapotranspiration can compensate for increased precipitation. Therefore based on climate change scenarios, the importance of winter-time water purification will increase.

1.2 Peat extraction and treatment of runoff water from peat extraction areas in Finland

In Finland, the total area under peat extraction activities was about 74 500 ha in 2011 and peat was actively extracted from 65 000 ha (Ministry of the Environment 2013). This is less than 1% of the peatland area in Finland (Salo & Savolainen 2010). Nearly 25% of current peat extraction areas are located in the North Ostrobothnia region (Ministry of the Environment 2013). The extracted peat is mainly used for energy purposes (about 90%) and the remaining 10% as e.g., horticultural substrate, or litter peat. Peat extraction in an area typically lasts about 30 years. After that, it is possible to use the area for different purposes, such as forestry, agriculture, or wetland, depending on site properties and landowner choice (Salo & Savolainen 2010).

In the past, peat extraction runoff was treated by so-called basic level methods, such as sludge traps, peak runoff control, and sedimentation basins. Nowadays these basic level methods are not considered sufficient as the sole treatment step and subsequent treatment by so-called enhanced water purification methods, namely overland flow areas (OFAs) or chemical treatment, is required. The most widely used enhanced purification method today is OFAs in treatment wetlands established on undisturbed peatland (Heikkinen *et al.* 2002, Ihme 1994, Ronkanen & Kløve 2009). According to guidelines set by the Finnish Ministry of the Environment (2013), the wetland slope (recommendation 1%), wetland area relative to catchment area (recommendation >3.8%), average degree of humification of surface peat based on the von Post scale (recommendation H1–H3; Hobbs 1986), and average peat thickness (recommendation >0.5 m) are design parameters which should be determined in OFAs, because they can affect purification efficiency. OFAs are considered to be among the best available techniques (BAT) for treating runoff water from peat extraction areas (Heikkinen *et al.* 2009). However, for the protection of pristine mires, the current national areal planning strategy (Ministry of the Environment 2007) restricts the establishment of new peat extraction areas to previously drained sites, where e.g., peat properties may have changed compared with the pristine conditions. In other words, treatment wetlands have been constructed on drained peatland areas, without knowledge of their functionality or ability to retain harmful substances. The year-round use of treatment wetlands is also more common nowadays, again without general information on their functionality during winter. For new sites, specific environmental permits have been set for treatment wetland target purification efficiency, typically so that total nitrogen (N_{tot}), total phosphorus (P_{tot}), and SS reduction should be at least 20%, 50%, and 50% of the concentration, respectively.

1.3 Peatland drainage and its effects on water treatment by wetlands

Peatlands have been intensively drained in many countries, such as Finland, the Russian Federation, Great Britain, and Ireland (Holden *et al.* 2004), and high drainage pressure is still a reality in Eastern Europe and South East Asia (Hooijer *et al.* 2010). The main reasons for such drainage are for agriculture, forestry, and peat extraction (Paavilainen & Päivänen, 1995). Peatland use often changes with time due to many factors, such as changes in policy trends, national and local economies, and preferences. One consequence of this is that e.g., cultivated peatlands are later afforested (Vesterdal *et al.* 2002) or sites drained for forestry are later used for peat extraction.

Peatland drainage usually lowers the water table level (e.g., Holden *et al.* 2004, Könönen *et al.* 2015), leading to fast aerobic decomposition (Clymo 1984). Drainage and lower water table level alter peat properties (Burke 1978, Minkkinen 1999, Holden *et al.* 2004) such as degree of humification, hydraulic conductivity, water content, subsidence of peat, porosity, bulk density, and geochemical properties. For example, due to drainage, especially in the upper peat layer (the depth of the upper peat layer varies by up to 80 cm between studies), the porosity can be lower (Könönen et al. 2015) and bulk density higher (Könönen *et al.* 2015, Laiho *et al.* 1999, Minkkinen 1999). Elevated concentrations of P and N at oligo-ombrotrophic sites have been detected after drainage (Laiho *et al.* 1999, Sundström *et al.* 2000), but decreased concentrations have also been noted (Könönen *et al.* 2015). The potassium (K), calcium (Ca), and magnesium (Mg) concentration typically decrease after drainage (Könönen *et al.* 2015, Laiho *et al.* 1999, Sundström *et al.* 2000). Additionally, the vegetation on peatlands changes, e.g., more forest species have been observed after drainage (Laine *et al.* 1995). Moreover, the drainage ditches can function as clear preferential flow paths. Due to other changes, the hydrological properties, especially runoff amount during flow peak, may also be altered (Holden *et al.* 2004).

In Finland, there are large areas of unproductive forested peatland with no conservation value (Working Group on a National Strategy for Mires and Peatlands, 2011), which are nowadays often used for peat extraction (Fig. 1a and 1b). At these sites it is difficult to find pristine peatland on which to treat runoff in OFAs (Ihme 1994), and therefore treatment wetlands need to be constructed on drained peatland (Fig. 1b), which may cause some problems for the purification process (Nieminen *et al.* 2005). When treatment wetlands are constructed on drained peatlands, e.g., the treatment method for dealing with old ditches (blocked or not) (Fig. 1c) and the distribution system (Fig. 1d) must be selected.

When a treatment wetland is constructed on a drained area, the land use change resembles rewetting. After rewetting, the peat and the hydraulic properties of the area and the vegetation can change (Haapalehto *et al.* 2011). Pore water chemistry can also change and elevated concentrations of Ca, K, Mg, and sodium (Na) (Hribljan *et al.* 2014) and P (Niedermeier & Robinson 2009, Zak & Gelbrecht 2007) have been reported when the water table level is raised. However, the concentrations of minerals (Ca, K, Mg, manganese (Mn), and P) in wetland peat are reported to be at a similar level as in pristine peatlands 10 years after restoration (Haapalehto *et al.* 2011). Due to alterations in peat aerobic and anaerobic conditions, nutrients and geochemical elements may leach from the area. This has been observed in peatland rewetting areas (Kieckbusch & Schrautzer 2007, Koskinen *et al.* 2011, Vasander *et al.* 2003). Due to the presence of deep former ditches, the flow can interact with the underlying mineral soil (Fig. 1e). The old ditches can also function as preferential flow channels, which can decrease runoff water residence time and prevent even distribution (Fig. 1f), thus impairing purification efficiency. Different factors that should be taken into account when a treatment wetland is constructed on drained peatland are summarized in Figure 2. Due to obvious complexities in the biogeochemical processes of such systems, the influence of different factors should be clarified to evaluate whether treatment wetlands can be safely constructed on drained peatland. This was one major of this thesis work.

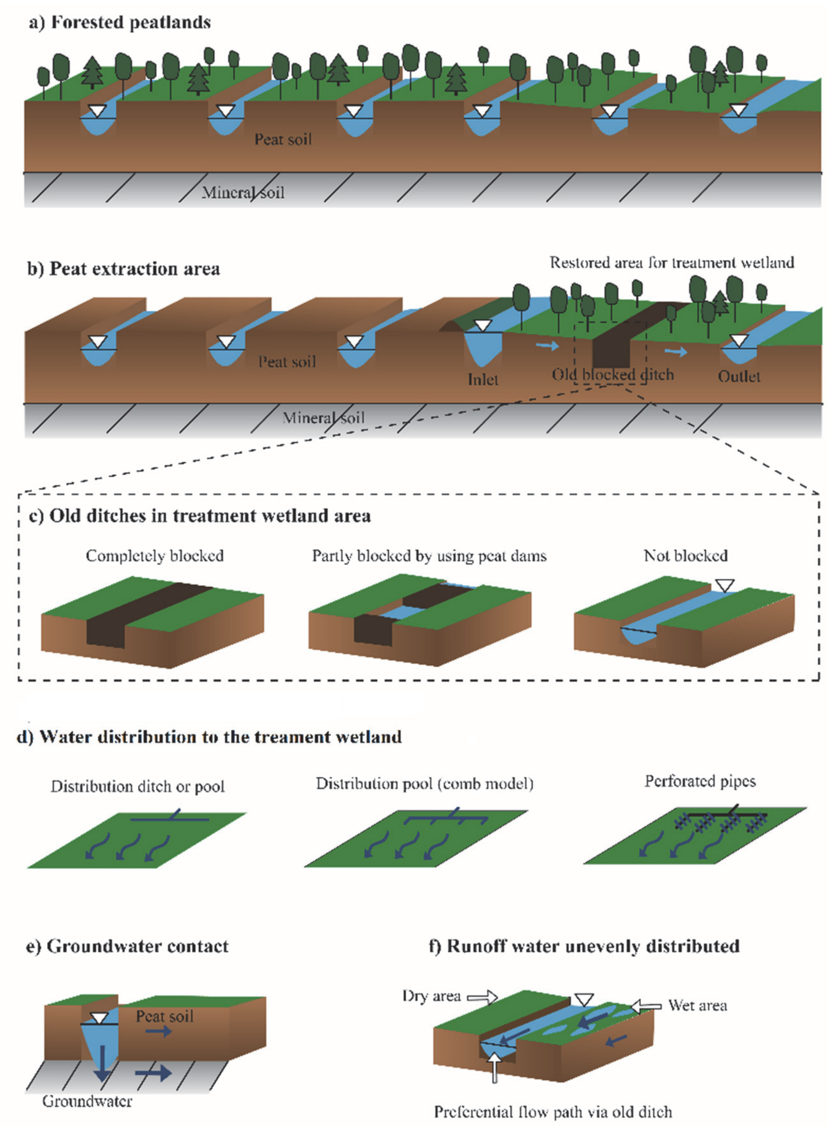

Fig. 1. a) Peatland drained for forestry and b) drained forestry site converted to peat extraction area (no vegetation, only peat cover). Part of the drained area is restored to treat runoff using different c) ditch blocking techniques and d) wetland inflow distribution systems. e) Hydraulic contact between wetland and groundwater results in water loss to the underlying aquifer and f) old ditches can result in short residence time, with poor contact between treated water and the peat filter (modified from Paper I).

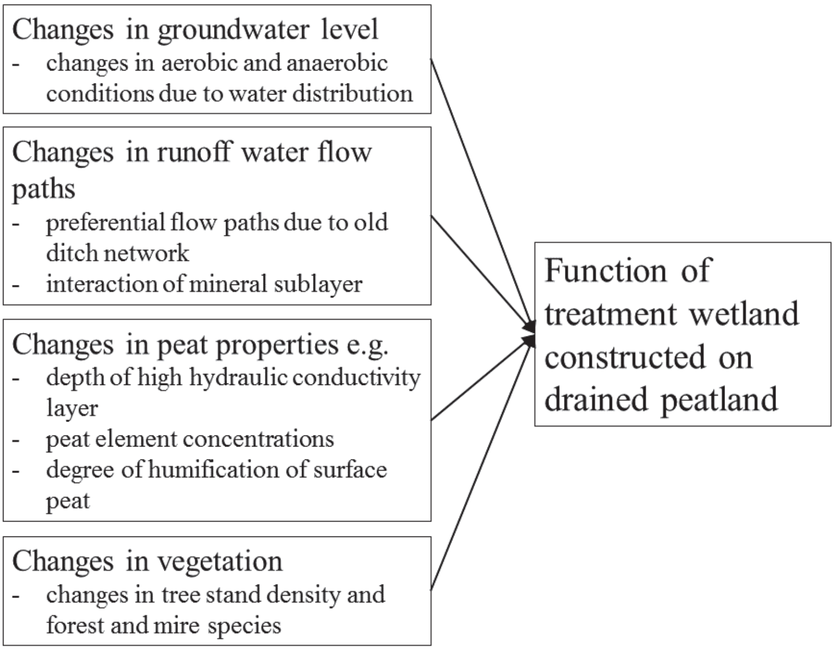

Fig. 2. Factors that should be taken into account when a treatment wetland is constructed on a drained peatland area.

1.4 Purification processes in treatment wetlands, especially P and N removal

Treatment wetlands should retain nutrients (P and N) and SS from peat extraction runoff. Several environmental and soil characteristics can affect treatment wetland purification efficiency. These characteristics include e.g., residence time (Wörman & Kronnäs 2005), soil properties (Kadlec & Knight 1996, Liikanen *et al.* 2004, Pant & Reddy 2003), climate (Kadlec 1999, Kuschk *et al.* 2003, Werker *et al.* 2002), redox dynamics (Niedermeier & Robinson 2007), biological factors such as microbes and plants (Henze *et al.* 2002, Huttunen *et al.* 1996), pH (Grybos *et al.* 2009, Kadlec & Knight 1996), and hydraulic load (Braskerud 2002, Heikkinen *et al.* 2002).

The P purification efficiency in OFAs or other types of treatment wetlands occurs via different biological, chemical, and physical processes (Kadlec & Wallace 2009). In OFAs, chemical adsorption by peat has been identified as the main process retaining phosphate phosphorus (PO_4-P) from peat extraction runoff (Heikkinen *et al.* 1994, 1995b). Sorption processes can occur e.g., with iron (Fe), aluminum (Al), and Ca (Richardson 1985, Seo *et al.* 2005). Precipitation can also occur where P can precipitate with Fe, Al, and Mn under acidic conditions and with Ca and Mg under near-neutral conditions (Reddy & DeLaune 2008). In treatment wetlands in general, P is known to be removed via sedimentation and filtration of particulate matter. Phosphorus can also be retained through uptake by microorganisms and plants. However, the role of plants as annual nutrient sinks is reported to be minor in wastewater wetlands (Richardson & Nichols 1985) and OFAs (Heikkinen *et al.* 1994, Huttunen *et al.* 1996). When the runoff includes Al and Fe, this can improve the peat long-term P retention capacity (Ronkanen *et al.* 2016). In treatment wetlands constructed on drained peatland, leaching of P can also occur, due to changes in the properties of the area (see section 1.3). For example due the reduction of Fe under anaerobic conditions, phosphate can be released (Reddy & DeLaune 2008).

The N purification efficiency also depends on different biological, chemical, and physical processes (Kadlec & Wallace 2009). Because biological processes (especially nitrification and denitrification) are usually considered most important in inorganic N (nitrite-N (NO_2-N), nitrate-N (NO_3-N) and ammonium-N (NH_4-N)) purification (Heikkinen *et al.* 1995a, Vymazal 2007), temperature has an important controlling effect on the removal efficiency (Feng *et al.* 2012). The NH_4-N purification effect can partly also occur by cation exchange, a process which can operate even in cold conditions (Wittgren & Mæhlum 1997). Water residence time in the treatment wetland affects NH_4-N removal (Hunter *et al.* 2001, Ghosh & Gopal 2010, Ronkanen & Kløve 2009). For example, previous studies show that the efficiency is better if the residence time is 6 days instead of 2 days (Hunter *et al.* 2001). Sedimentation and filtration can retain pollutants, especially particulate N and SS. Organic matter can be released due to peat decomposition in treatment wetlands constructed on peat soils. High porewater dissolved organic carbon (DOC) concentration was observed in one study when an extracted and drained bog was rewetted (Glatzel *et al.* 2003). The opposite has also been noted, with rewetting lowering DOC concentration (Frank *et al.* 2014). Overall, e.g., the water table level, which is coupled to redox status and moisture, can affect the DOC concentration and water table fluctuations between low and high have been observed to increase the DOC concentration (Hribljan *et al.* 2014). In general, if a treatment wetland is established on a previously drained area, the functioning of different purification processes can change, e.g., due to changes in peat properties or in hydrology arising from e.g., rapid flow via old ditches instead of flow in the peat matrix itself. Therefore it is important to study how treatment wetlands constructed on drained areas can retain nutrients and other harmful substances.

1.5 Aim of this thesis

While OFAs constructed on pristine peatland areas have been successfully used to treat peat extraction runoff water and are considered a BAT method by the Finnish authorities, the functioning of OFAs on drained peatlands (hereafter called "wetlands constructed on drained peatland") remains uncertain. Therefore, the overall aims of this thesis work were to: I) Evaluate how treatment wetlands constructed on drained peatland function hydraulically and hydrologically, II) determine how these wetlands purify runoff waters and which are the key factors affecting purification efficiency, and III) study how treatment wetlands constructed on drained and pristine peatland areas function in winter conditions. Specific objectives and hypotheses were:

1. To determine the hydraulic properties and hydrology of treatment wetlands constructed on drained peatland. The starting hypotheses were that: i) Hydraulic conductivity and active flow depth are lower in drained peatland used as a treatment wetland than in corresponding sites on pristine peatland used as a treatment wetland (OFA); ii) runoff water is distributed unevenly in wetlands on drained sites; and iii) in wetlands constructed on drained peatland, water residence time is shorter than in treatment wetlands on pristine peatland.
2. To determine the possibilities to purify peat extraction runoff using wetlands established on drained peatland areas and to identify characteristics of drained wetlands which can affect or indicate the P purification result. The starting hypothesis was that previous changes in peat physical properties by drainage, e.g., lowering the active flow depth or forest vegetation, can affect or indicate e.g., P retention possibilities in wetland.
3. To determine the seasonal purification efficiency of constructed wetlands treating peat extraction runoff in a cold climate and to understand key factors controlling purification efficiency and water flow paths in wetlands in winter. Winter flow paths have not been studied previously. The starting hypothesis was that there is seasonal variation in purification efficiency due to cold temperature and altered water flow paths due to ground frost and ice cover.

2 Materials and methods

The materials and methods used in the thesis work are summarized in this section. Full descriptions of all these can be found in Papers I–III.

2.1 Description of the wetlands studied

The wetlands studied (30 sites) were peatland-based (Fig. 3) and were designed to treat runoff from peat extraction areas. The wetlands were located mainly in North Ostrobothnia and Western Finland (Fig. 4). They were generally constructed on previously drained areas (Papers I, II), but year-round purification efficiency was also studied in seven wetlands constructed on pristine peatlands (Paper III) (Table 1). Wetland area varied from 1.6 to 23.5 ha and comprised between 1.8 and 8.9% of the total catchment area. The properties of wetlands are described in more detail in Papers I–III.

Mean annual precipitation in the study areas varies between 500 and 700 mm, mean annual temperature from 1 to 3 °C, and evaporation from 250 to 500 mm, with the lowest values in northern areas. Mean permanent snow cover duration in the North Ostrobothnia region is about 4.5–6 months and in Western Finland 3.5–4.5 months. In North Ostrobothnia, autumn and winter usually begin earlier and spring and summer later than in Western Finland due to the more northerly location. During winter there can be periods when the temperature is over 0 °C, especially at southern latitudes (Western Finland), which increases winter runoff.

Fig. 3. Examples of wetlands constructed on drained peatland in Finland. Left: Kapustaneva and (right) Äijönneva (photos by H. Postila).

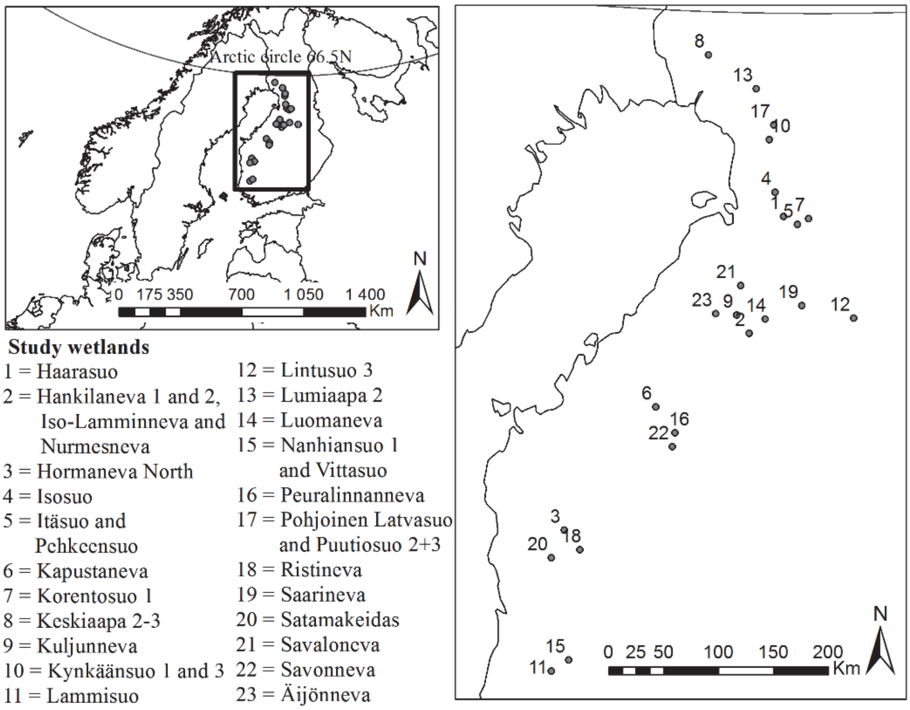

Fig. 4. Location of the 30 Finnish wetlands studied in this thesis.

Table 1. Name, location, year of establishment, previous land use, area (ha), and proportion (%) of total catchment area (TA/CA) of the 30 treatment wetlands studied in this thesis and the publication (Paper I, II, III) in which they were used.

Wetland	Region1	Wetland established	Previously drained area	Treatment wetland area (ha)	TA/CA (%)	I	II	III
Haarasuo	N.O.	1990	Yes	5	4.7	x		
Hankilaneva 1	N.O.	1992	Yes	8.9	8.9	x	x	
Hankilaneva 2	N.O.	1992	Yes	7.3	3.1	x	x	x
Hormaneva north	W.F.	2007	Yes	14.1	3.7			x
Iso-Lamminneva	N.O.	2010	Yes	1.6	4.1	x	x	
Isosuo	N.O.	1994	Yes	2.5	2.4-	x		
Itäsuo	N.O.	1995	Yes	12	6.3	x	x	
Kapustaneva	N.O.	2008	Yes	6.9	4.6	x	x	x
Keskiaapa 2-3	L.	1999	Yes	12.2	9.9	x		
Korentosuo 1	N.O.	2008	No	10.5	4.9			x
Kuljunneva	N.O.	2009	Yes	5.8	6.6	x	x	
Kynkäänsuo 1	N.O.	1996	Yes	3.9	3.5	x		
Kynkäänsuo 3	N.O.	2004	Yes	3.9	3.9	x		
Lammisuo	W.F.	2007	No	7.2	6.5			x
Lintusuo 3	K.	2002	Yes	1.7	4.1	x		
Lumiaapa 2	L.	1996	Yes	9.5	5.1	x	x	
Luomaneva	N.O.	1998	Yes	3.2	2.8	x	x	
Nanhiansuo 1	W.F.	2005	No	3.3	3.8			x
Nurmesneva	N.O.	1992	Yes	23.5	7.1	x		
Pehkeensuo 1	N.O.	1994	Yes	7.6	5.3	x		x
Peuralinnanneva	W.F.	2009	No	6.9	4.7			x
Pohjoinen Latvasuo	N.O.	1994	Yes	2.8	1.8	x	x	
Puutiosuo 2+3	N.O.	2001	No	6.2	6.3			x
Ristineva	W.F.	2006	No	8.9	3.7			x
Saarineva	N.O.	2009	Yes	6	4.4	x		
Satamakeidas	W.F.	1994	Yes	6.9	4.1			x
Savaloneva	N.O.	2005	Yes	6.1	7.4	x	x	x
Savonneva	W.F.	1999	No	2.7	2.5			x
Vittasuo	W.F.	2005	Yes	2.5	4.2			x
Äijönneva	N.O.	2009	Yes	5.8	5.6	x	x	

[1] N.O.= North Ostrobothnia region, L.= Lapland region, K.= Kainuu region, W.F.= Western Finland region.

[2] Catchment area changed slightly between years.

2.2 Purification efficiency of wetlands

Summer time purification efficiency data were obtained from 26 treatment wetlands, and data available from 14 of these wetlands were used to analyze seasonal variability. To determine the purification efficiency of the treatment wetlands, the inflow and outflow concentrations of potential pollutants were calculated using data mainly obtained from peat extraction load monitoring programs. However, some extra analyses were commissioned at accredited laboratories in 2009 and 2010. The water samples were usually analyzed for SS, N_{tot}, P_{tot}, and chemical oxygen demand (COD_{Mn}) (Table 2). Additionally, e.g., NH_4-N, PO_4-P, and Fe were analyzed for some samples from different wetlands (Papers II, III). The sampling interval varied from once per week (typically in spring) to only one sample per season, but all sampling was calendar-based (e.g., every two weeks), without taking into account runoff quantity. The samples were taken on the same day from the wetland inflow and outflow.

Water purification efficiency (R) was determined by calculating the mean concentrations in inflow and outflow for each wetland, season, and year, using the equation 1 (Method 1):

$$R = (C_{in}-C_{out})/C_{in} * 100\% \tag{1}$$

where C_{in} is mean concentration (mg/L) in inflow and C_{out} mean concentration (mg/L) in outflow. From these mean purification results, total mean purification efficiency of each wetland was calculated. This was done using the mean concentrations of inflow and outflow in specific season and year instead of separate sampling results, because inflow and outflow samples were typically taken at nearly the same time on the same day, so these specific day concentrations did not describe the same water. The standard deviation for purification efficiencies and inflow concentrations, and minimum and maximum values, were also calculated based on seasons yearly mean results (Appendix 1 and 2).

Typically, only outflow from the treatment wetland was monitored, so the evaluation of purification efficiency was typically based on concentrations instead of mass balance. Inflow volumes were available for only four wetlands, and from these the load (Method 2, Eq. 2) and discharge-weighted (Method 3, Eq. 3) purification efficiency were calculated:

$$R_2 = \frac{\frac{\sum_{i=1}^{n} C_{in\,i} Q_{in\,i}}{n} - \frac{\sum_{i=1}^{n} C_{out\,i} Q_{out\,i}}{n}}{\frac{\sum_{i=1}^{n} C_{in\,i} Q_{in\,i}}{n}} * 100\% \qquad (2)$$

$$R_3 = \frac{\frac{\sum_{i=1}^{n} C_{in\,i} Q_{in\,i}}{\sum_{i=1}^{n} Q_{in\,i}} - \frac{\sum_{i=1}^{n} C_{out\,i} Q_{out\,i}}{\sum_{i=1}^{n} Q_{out\,i}}}{\frac{\sum_{i=1}^{n} C_{in\,i} Q_{in\,i}}{\sum_{i=1}^{n} Q_{in\,i}}} * 100\% \qquad (3)$$

where $C_{in\ i}$ is concentration (mg/L) in inflow in a sample, $Q_{in\ i}$ mean daily inflow discharge (L/d) from previous period (period starting from previous sampling day), $C_{out\ i}$ is concentration (mg/L) in outflow in the sample and $Q_{out\ i}$ mean daily outflow discharge (L/d) from previous period.

Treatment efficiencies were compared to the load from the peat extraction area. For this comparison, the load from the peat extraction area after the wetland treatment was calculated for 24 sites using outflow discharge, concentration, and catchment area. This calculation was done using data from the sampling days, when purification efficiency was also possible to calculate. The results (inflow, purification efficiency, and load) were then calculated based on the same data and were more comparable with each other. However, this can have caused differences in the total load for some specific wetlands and years compared with that stated in load monitoring reports.

2.3 Field measurements to study wetland properties

2.3.1 Hydraulic properties (Papers I, II)

The hydraulic properties of the 20 treatment wetlands constructed on drained peatland were determined (Table 1). These included e.g., hydraulic conductivity of the peat and water spatial distribution. The aim was to obtain information about e.g., active flow depth and active flow areas in the wetland. The hydraulic conductivity (*K*) of the peat was determined at 2–12 points in the 20 wetlands, between the old ditches. Each point included 1–7 different measuring depths, usually at 10- or 20-cm intervals depending on the research project and purpose for which they were analyzed. A direct-push piezometer using the falling head method (Ronkanen & Kløve 2005) was used for all hydraulic conductivity measurements (Papers I, II). Based on peat *K*, the studied wetlands were classified four groups: high *K* at all depths investigated (Group 1), *K* decreased at a depth of 20 cm (Group 2), *K* decreased at a depth of 50 cm (Group 3) and *K* decreased between 20–30 cm, but increased in the deeper layers (Group 4).

The water residence time was studied in four wetlands during early summer 2009 (Kapustaneva and Savaloneva) or 2010 (Luomaneva and Äijönneva) with tracer tests. Potassium iodide (KI) was used as the tracer, as described previously by e.g., Wörman & Kronnäs (2005) and Ronkanen & Kløve (2007). The KI was diluted and mixed in containers (350 or 75 L) before the solution was discharged into the wetland. In Kapustaneva and Savaloneva, the solution was added by gravity to the wetland inflow ditch and input time was 1.5 h and 6 h, respectively. The input time was long to avoid density-driven flows (Beinhorn *et al.* 2005, Müller *et al.* 2010). In Luomaneva and Äijönneva, the diluted KI was injected to the inlet pump well in 6 minutes with the pump in action, and then the water was mixed effectively by the pump. In Luomaneva, the pump worked for 2 hours (70 L/s) and in Äijönneva 15 minutes (100 L/s) per bout, as was usual. In Äijönneva only data from first four days were used because the pump malfunctioned on day four and this affected water flow to the wetland.

During tests at the outlet, one-hour aggregate samples were collected with automatic samplers. A sample comprising four subsamples were taken at 15-minute intervals. The iodide concentration in the water samples was analyzed in the laboratory using an iodine-selective electrode (Paper I). The tracer results were used to calculate the mean residence time (t_{mean}):

$$t_{mean} = \frac{\int_0^{\infty} t * c(t)dt}{\int_0^{\infty} c(t)dt} \tag{4}$$

where t is the time of sample (d) and c(t) the tracer concentration (mg/L) at time (t).

For most of the treatment wetlands studied, only outflow volume data were available, but for four wetlands (Kapustaneva, Luomaneva, Savaloneva, and Äijönneva) inflow data were also available from the frost-free period in 2009 and 2010. The inflow was measured from the inlet pumping pipe, using a Fluxus ultrasonic sensor, for all sites except Savaloneva. Savaloneva inflow and outflow from all sites were measured using a V-notch weir and water level loggers (measurement interval 15–30 min). Based on the measurements, typically approximately every two weeks, average daily inflow and outflow were calculated. This permitted investigation of e.g., possible runoff water infiltration into the groundwater system below due to the old ditches.

The spatial runoff water distribution (Paper I) in the wetlands was mainly determined from 20 wetlands by visual surveys in which the wetness of the wetland was mapped during summer, partly with the help of Global Positioning System (GPS). In Luomaneva and Äijönneva, the iodide concentration in wetland ditches (2–5 points per ditch) was also analyzed during the first 8 hours of the tracer experiment. The wetlands were classified into different areas from dry to wet, where dry meant that capillarity was not sufficient to raise the water to the peat surface, moist meant that the capillarity could raise the water to the peat surface but there was less than 5% free water surface area, and wet meant 5–90% free water surface.

Wetland groundwater levels were observed in four wetlands (Kapustaneva, Luomaneva, Savaloneva, and Äijönneva) by installing perforated groundwater pipes into the peat and into the mineral layer below the peat. Nine pipes were installed in Kapustaneva, 8 pipes in Luomaneva, 24 pipes in Savaloneva, and 9 pipes in Äijönneva, of which 3, 4, 7, and 3 pipes, respectively, were placed in the mineral layer. Water levels were logged hourly with sensors installed in 26 of the pipes during summer 2009 and in 16 during summer 2010. The water level was also determined by a manual groundwater level reader on visits to the wetlands (2–13 times per summer).

2.3.2 Peat properties and tree stands (Paper II)

Peat properties and tree stands were studied in 11 treatment wetlands constructed on drained peatland (Paper II), to determine whether and how they could indicate or affect the runoff water purification efficiency (Paper II). Peat samples were collected (2009–2011) from the peat surface (about 0–10 cm depth) at 4–11 points in each of the 11 study areas. In order to keep the results comparable, only the uppermost peat layer (0–10 cm) of all wetlands was analyzed, since the active flow depth of drained peatland can be low (Paper I) and the water flows mainly via surface peat. These samples were analyzed for degree of humification of surface peat (Hobbs 1986). The P, Fe, Al, Ca, Mg, and Mn concentrations were analyzed in a FINAS-accredited laboratory using ICP-OES method. The samples were first dried (40±5 °C) then (0.5 g) acidified with HNO_3 (9 mL) and HCl (3 mL) according to the EPA3051A standard. Based on the results, (Fe+Al+Mn)/P and (Ca+Mg)/P mass ratios were calculated and expressed in mg/kg dry matter (DM). The wetlands were divided into three different groups based on the mean (Fe+Al+Mn)/P mass ratio of surface peat and P content. Group 1 included wetlands with mean surface peat P content under 800 mg/kg DM. Group 2 had a high mass ratio (>45) and group 3 had a low mass ratio (⩽25), together with quite high P content (>1200 mg/kg). Estimation of tree stands in the wetlands was made visually.

2.4 Ground frost depth (Paper III)

In order to understand seasonal frost dynamics, ground frost pipes (Fig. 5) were installed in January 2010 in three of the wetlands studied and left in place for two winters. Two of these wetlands (Pehkeensuo 1 and Korentosuo 1) were located in North Ostrobothnia and one (Kapustaneva) in Western Finland (Fig. 4 and Table 1). Originally, three ground frost pipes were installed per wetland. However, in October 2010 one more ground frost pipe was installed near point 1 in Pehkeensuo 1 treatment wetland because water flow was noted close to the new point, whereas point 1 was frozen. The ground frost pipes (length 2.5 m) were made of transparent plastic tubes (Fig. 5), which were filled with methylene blue solution (Paper III). The solution color indicated presence of frost: uncolored with frost and blue when there was no frost. The pipes were installed so that there was about 1 m of pipe extending above the soil surface.

Fig. 5. Ground frost pipe installation in (left) the Pehkeensuo wetland and (right) ground frost pipe with protection tube in the Kapustaneva wetland (photos by H. Postila).

2.5 Statistical analysis used in assessment of the year-round function of treatment wetlands and OFA design guideline parameters

Different statistical tests were used to study factors and compare the treatment wetland removal efficiency and inflow concentration in different seasons. The factors evaluated were structural or design parameters for treatment wetlands in national guidelines set by the Finnish environmental authority, tree stand density, surface peat mean mineral content, peat hydraulic conductivity group, and the presence of icing problems. The analysis was performed using SPSS statistical software (IBM version 22). The test used was non-parametric. The limit for statistical significance was $p<0.01$ in every test. The analyses conducted were as follows:

- Using the Friedman test, which is suitable for related samples, differences in purification efficiency, inflow concentration, and load between different seasons were compared. In this test, every year, season, and wetland was included separately. In Paper III this was done using Kruskall-Wallis one-way analysis of variance, but later it was noticed that different seasons in same wetlands were not independent, and thus the Friedman test was used
- Using Kruskall-Wallis one-way analysis of variance, P purification efficiency between wetlands with different tree stand level, mean surface peat mineral concentration, and difference of high K layer ($K \approx 1*10^{-4}$ m/s or higher) between groups was evaluated.
- Using Spearman correlation, the effects on purification efficiency of structural and design parameters such as mean wetland length (m), treatment wetland area as a percentage of catchment area, slope of treatment wetland, mean degree of humification of surface peat (von Post, Hobbs 1986), and temperature and inflow concentration were studied. Mean season reduction 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 reduction efficiency of every wetland in different years was included in these tests. The difference in high K layer ($K \approx 1*10^{-4}$ m/s or higher) was also evaluated pair-wise between groups.

3 Results and discussion

3.1 Hydraulic properties and purification efficiency of treatment wetlands constructed on drained peatland (Papers I, II)

Wide variation was observed in hydraulic properties, peat properties, and tree stands for treatment wetlands constructed on drained peatland. This variation in wetland properties was also seen in differing purification efficiency. The main results found in Papers I–II are summarized in this section and full descriptions can be found in the original publications.

3.1.1 Hydraulic properties of the wetlands studied (Paper I)

To determine hydraulic properties in treatment wetlands constructed on drained peatlands and to compare these with pristine sites, 20 treatment wetlands were studied for hydraulic conductivity and water distribution to the wetland. Additionally, in four wetlands residence time, groundwater level, and inflow rate were studied. In more than 50% (12/20) of the wetlands constructed on drained peatland, the mean hydraulic conductivity (K) of the peat steeply decreased at below 20 cm depth (or even below 10 cm) (Group 2, Fig. 6), so the active flow depth was very low. In the topmost layer, K was on average $4*10^{-4}$ m/s and below that the mean K was slower than $1.3*10^{-5}$ m/s. In undrained treatment peatland, the high K layer has been measured to be about 50 cm (Ronkanen & Kløve 2005), which is clearly higher than observed in drained treatment wetlands in Paper I (minimum smaller than 10 cm). This decrease in the high K layer depth illustrates that treatment wetlands established on drained peatland may often have a small active flow depth in the peat layers. This indicates that there is probably less space for purification processes to take place, as contact between peat and purified water is one of the most essential factors for efficient purification results (Heikkinen *et al*. 1995b). Although the measured high K layer was generally lower than observed in pristine peatlands (Chason & Siegel 1986) and in OFAs (Ronkanen & Kløve 2005), the K values were similar to those found by Marttila and Kløve (2010) and Saarinen *et al.* (2013) in drained peatland forestry area. However, in five wetlands the K value was high at all depths investigated (down to 60–70 cm) (Group 1).

When the groups classified based on active flow depth (depth of peat high K layer) were evaluated statistically, there was a significant difference between groups 1 (high *K* at all investigated depths) and 2 (*K* decreased at the depth of 20 cm) (p=0.000), but not between other groups. Based on this, it is also possible to combine groups 1 and 3 and groups 2 and 4. When the statistical tests also included data from OFAs constructed on pristine peatlands (Ronkanen & Kløve 2005 and unpublished data from four other OFA sites), the results showed that group 1 was not significantly different from that of the OFA sites, but group 2 was clearly different (p=0.001). Based on that finding, in the majority of the treatment wetlands constructed on drained peatland examined in this thesis, peat drainage had clearly affected the hydraulic properties, although not in all wetlands. For more than 50% of cases, *K* and active flow depth were lower in drained peatland used as treatment wetland than at corresponding sites on pristine peatland used as treatment wetland (OFA), as hypothesized. However, for a few wetlands there was no support for this hypothesis.

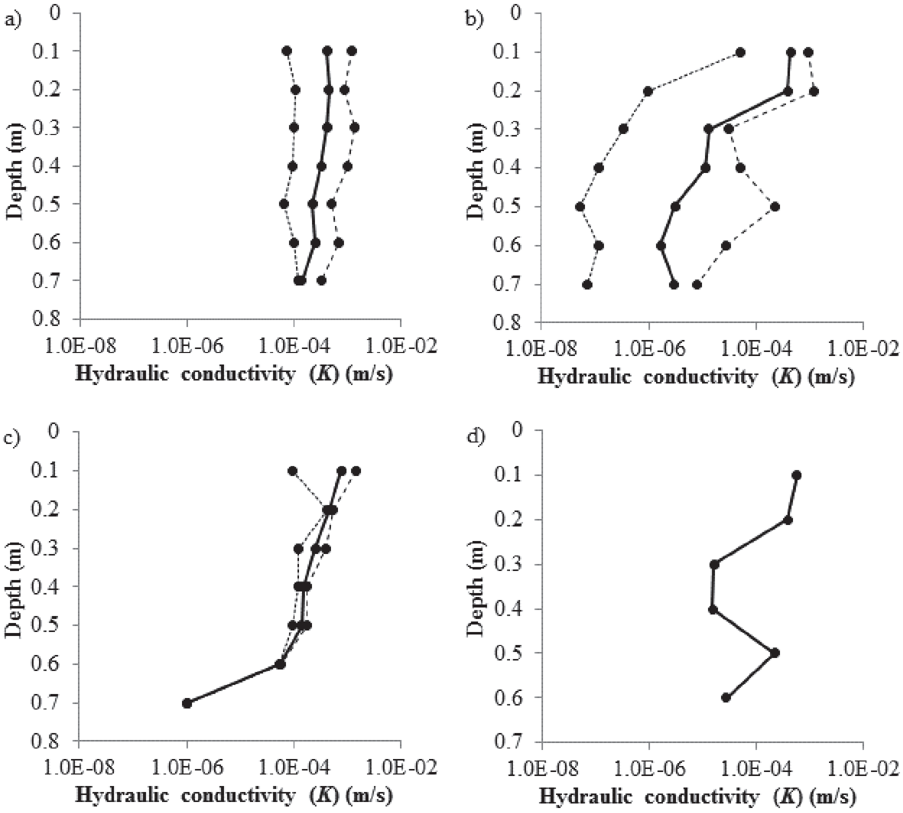

Fig. 6. Changes in mean hydraulic conductivity (*K*, m/s) with depth in the peat profile for different wetland groups and the variation within group (marked as dashed-line): (a) High *K* at all depths investigated (n=5) (Group 1), (b) *K* decreased at a depth of 20 cm (n=12) (Group 2), (c) *K* decreased at a depth of 50 cm (n=2) (Group 3) and *K* decreased between 20 cm and 30 cm, but increased in the deeper layers (n=1) (Group 4).

The lowest observed mean residence time in the wetland was 6 hours (in Luomaneva) and the highest was 12 days (in Kapustaneva). For the other two wetlands, the measured mean residence time was 2.5 days in Äijönneva and 4 days in Savaloneva. In the tracer response curves, at least two peaks were observed for Kapustaneva, Äijönneva, and Savaloneva (Fig. 7), indicating multiple flow paths. Such multiple peaks in treatment wetland have been observed by Ronkanen & Kløve (2007), and have also been observed for other types of wetlands (Wachniew *et al.* 2003). For Luomaneva, only one peak was observed (Fig. 7) and, taking into account the measured short residence time, this indicates that most of the water flowed along the old ditches at that site.

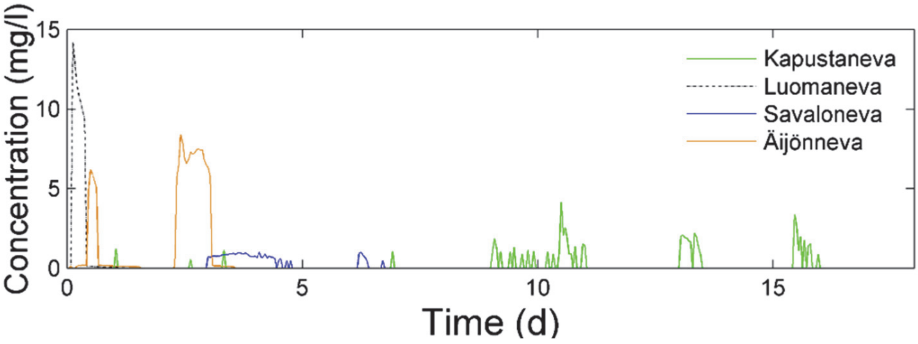

Fig. 7. Measured tracer response curves in Kapustaneva, Luomaneva, Savaloneva, and Äijönneva wetlands. Reprinted with permission from Elsevier B.V. (Paper I).

As the average flow velocity was calculated from tracer test results ($1.2*10^{-2}$ m/s) and compared with the measured peat *K* of the wetland ($1.2*10^{-4}$ m/s), it can be concluded that the water flowed mainly via rapid flow pathways in ditches or as overland flow in Luomaneva wetland. In Kapustaneva, Savaloneva, and Äijönneva, the mean flow velocity determined by the tracer tests was only 1.4- to 2.2-fold compared with the mean peat *K* value at 10 cm depth. This indicates that runoff water not only flowed in ditches or as overland flow, but also flowed through the upper layer of peat in these wetlands.

In previous studies, the residence time in Kompsasuo OFA was reported to vary from 6 to 11 days and that in the Ruka and Mellanaava OFAs was found to be about 1 day, as clear preferential flow paths were observed (Ronkanen & Kløve 2007, 2008) Thus, residence times in treatment wetlands established on drained peatlands can be quite similar to those in treatment wetlands constructed in pristine peatlands (Ronkanen & Kløve 2007, 2008) or faster.

Runoff water was not typically evenly distributed in the wetlands constructed on previously drained areas examined in this thesis and old ditches formed preferential flow paths, based on visual estimation and the tracer tests. There were dry areas (10–75%) without overland flow in more than half of the wetlands (Fig. 8). However, in some of the wetlands water was distributed quite evenly despite the ditches. In those wetlands, e.g., Hankilaneva 2, Lumiaapa 2, and Kynkäänsuo

1, the slope was small (⩽0.2%). Based on that finding, a small slope can prevent fast flow along ditches.

Based on inflow and outflow results for the four specifically studied wetlands, the water infiltrated into the groundwater system below in the Savaloneva treatment wetland (Fig. 9). This probably occurred via ditches that were cut down into the mineral subsoil (sand) layer. In Luomaneva, some bypass flow was also observed near the V-notch weir. In the two other wetlands (Äijönneva and Kapustaneva) with inflow data, infiltration or bypass flow was not so clearly visible, and evapotranspiration could explain most of the decrease in water volume. Complex surface water-groundwater interactions have been noted previously in pristine peatland areas (Fraser *et al.* 2001). However, in this thesis groundwater discharge was not observed based on outflow and inflow measurements. Groundwater inflow to the treatment wetlands is not likely as water was added to the treatment systems, resulting in many cases in a hydraulic gradient from the wetland to the groundwater. Furthermore, deep ditches, typically 1.5–1.8 m depth, surrounding the peat extraction site and treatment wetland area prevented groundwater flow to the wetland.

Based on the results obtained on the hydraulics of treatment wetlands constructed on previously drained peatland areas, it can be concluded that it is not only the changes in hydraulic conductivity of the peat layer which affect the hydraulics of the wetlands. Preferential flow via old ditches can be the most significant factor, at least in some wetland (e.g., Luomaneva). Water infiltration to the groundwater system below the wetland can also affect the water balance of some wetlands (e.g., Savaloneva). In some cases, small slope can prevent fast flow along the ditches (e.g., Hankilaneva 2, Lumiaapa 2, and Kynkäänsuo 1).

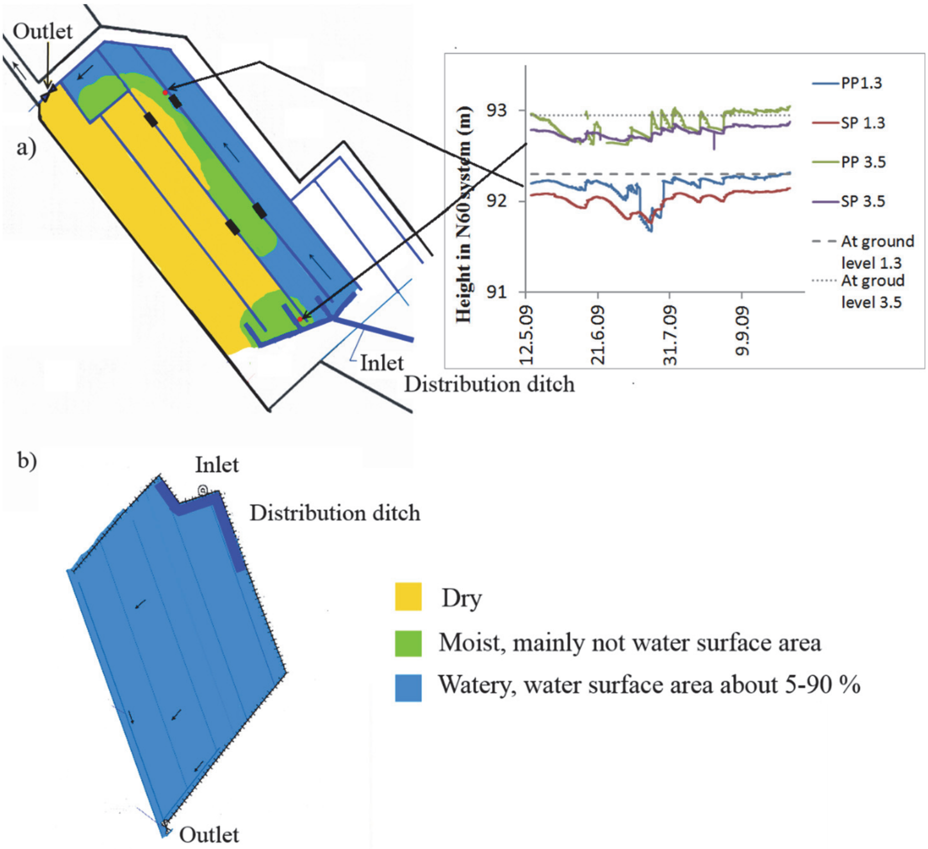

Fig. 8. Water distribution in (a) Savaloneva and (b) Hankilaneva 2 wetland. The Savaloneva diagram includes groundwater level information from two different points (PP = pipe in peat layer, SP = pipe in mineral subsoil layer) (modified from Paper I).

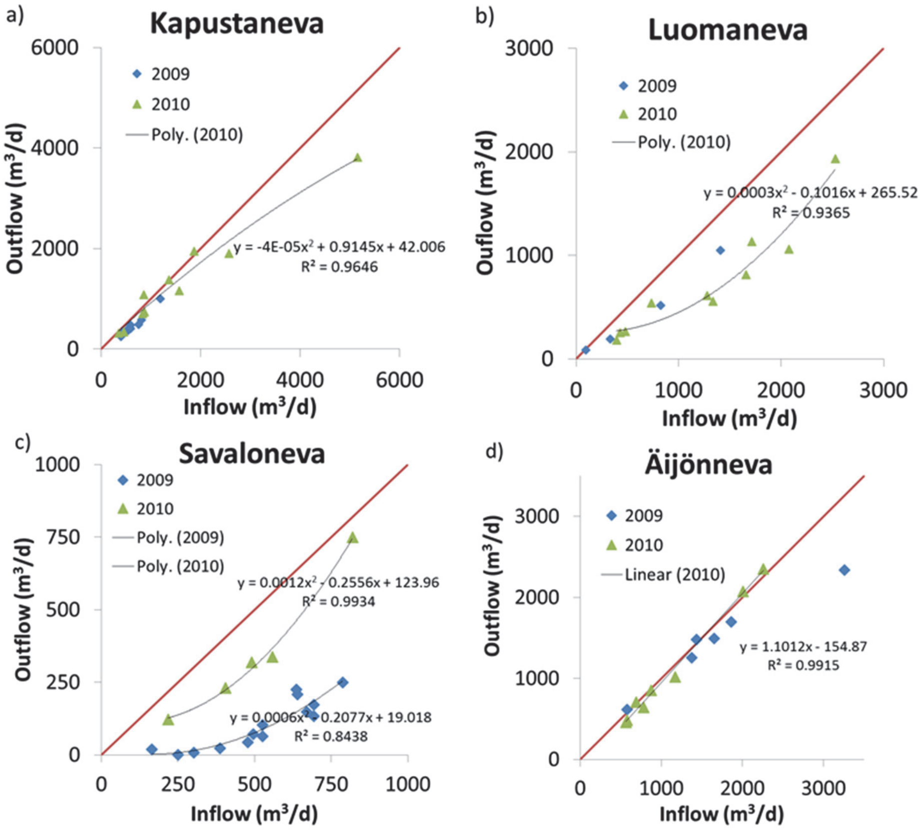

Fig. 9. Inflow and outflow in (a) Kapustaneva, (b) Luomaneva, (c) Savaloneva, and (d) Äijönneva wetlands during summer and autumn 2009 and 2010. Trend line only for 2010 except for Savaloneva, where it is also for 2009. Red solid line = outflow:inflow = 1:1. Reprinted with permission from Elsevier B.V. (Paper I).

Water table elevation varied spatially and temporally between and within the wetlands and was more uniform in wet areas than in dry or moist areas in Kapustaneva, Luomaneva, Savaloneva, and Äijönneva wetlands. The water table was always below the peat surface at many continuous measurement points (7/17). However, at two points in Kapustaneva and two points in Äijönneva, the water table was above the peat 88% of the time. At the remaining points, the water table was occasionally above the peat layer (16–79% of the time). At all points in Kapustaneva and at points in some other wetlands (total 7), water table was mainly deeper in the mineral layer than in peat, indicating a hydraulic gradient from the wetland to the groundwater. At some points in Luomaneva, Savaloneva, and Äijönneva (10), the water level in peat and in the subsoil mineral layer was similar for at least part of the time.

Overall, hydraulic conductivity and active flow depth were mainly lower in drained peatland used as a treatment wetland than in corresponding sites on pristine peatland used as a treatment wetland (OFA) ($p=0.001$), as hypothesized. However, in some wetlands there was no difference. As hypothesized, the runoff was mainly distributed unevenly in wetlands on the drained sites, except at sites where the slope was very small (<0.2%). Residence times in treatment wetlands established on drained peatlands can be quite similar to those in treatment wetlands constructed on pristine peatlands, contradicting the hypothesis, but partly also clearly shorter, as hypothesized.

3.1.2 Purification efficiency of treatment wetlands constructed on drained peatland (Paper II)

Summer time purification efficiency and characteristics indicating P retention capacity were determined for treatment wetlands constructed on drained peatlands (11 sites; Table 1). High variability in purification efficiency was observed between the wetlands (Table 2). Annual variations in purification efficiency were also observed (Paper II).

The wetlands retained inorganic N and mainly also N_{tot} (up to 66%) and SS (14–82%). The reduction of inorganic N and SS was nearly as good as in OFAs constructed on pristine peatlands, but the N_{tot} reduction was slightly lower than previously reported by Heikkinen *et al.* (2002) and Kløve *et al.* (2012).

The retention of P and Fe showed some scattering; at some sites the runoff water was quite well purified (P_{tot} reduction from 30% to 80%), while leaching of P and Fe occurred from some other wetlands. Previous studies (Heikkinen *et al.* 2002, Kløve *et al.* 2012) have reported 40–55% P_{tot} removal efficiencies in OFAs constructed in pristine areas. In many wetlands, some of the typical target purification efficiencies (N_{tot} 20%, P_{tot} 50%, and SS 50%) set by the environmental authorities for new wetlands were not achieved. This variation in treatment results was expected, as the wetland properties, hydraulic loading, and inflow concentration varied. This confirms what is generally known about treatment wetlands and stated e.g., in a review by Vymazal (2010), namely that the purification efficiencies in wetlands are variable and are approximately 30–60%

for N_{tot} and P_{tot} and 70–90% for SS in constructed wetlands for wastewater purification purposes.

The average COD_{Mn} values mostly increased within the wetlands, indicating leaching of organic matter. This is typical of treatment wetlands constructed on peatland, where humic substances are constantly released to runoff water by peat decomposition. This has also been observed in previous studies in riparian buffer zones established on peat soils and used to purify peatland forestry runoff (Nieminen *et al*. 2005). The DOC concentration increase can partly be mediated by Fe reduction (Knorr 2013). Leaching of organic carbon and P, as well as ammonium, has been related to redox conditions and better availability of decomposable organic matter in the upper peat horizon with high decomposition rate (Zak & Gelbrecht 2007).

Table 2. Monitoring years, purification efficiency (%), inflow concentration (mg/L) of total nitrogen (N_{tot}), total phosphorus (P_{tot}), chemical oxygen demand (COD_{Mn}), and suspended solids (SS), and number of samples (n) taken (at least in summer-time) for the 26 treatment wetlands studied in this thesis. Eleven of these wetlands were included in Paper II and 14 in Paper III. Paper I included same wetlands as Paper II and, in addition, reduction data were available and are presented here for four other wetlands included in Paper I.

Wetland and season	Monitoring years	N_{tot}			P_{tot}			COD_{Mn}			SS		
		%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n
Hankilaneva 1	2010	19	0.78	4	82	0.09	4	-2	16	3	75	16	4
Hankilanneva 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	-16	0.07	18	-78	25	18	64	15	18
Autumn	1992, 2007–2009	49	1.36	4	9	0.06	4	13	26	4	37	9	4
Winter	1991, 2007–2010	35	1.65	22	47	0.11	22	1	27	22	-9	48	22
Hormaneva North													
Spring	2008–2010	1	1.95	6	5	0.05	6	-6	34	6	20	6	6
Summer	2008–2009	12	2.81	22	14	0.14	22	-18	57	22	28	9	22
Autumn	2008–2009	3	3.56	7	-4	0.06	7	-7	51	7	-6	6	7
Winter	2009–2010	-5	2.89	10	10	0.11	10	-13	36	10	22	9	10
Iso-Lamminneva	2010, 2013	3	2.71	6	9	0.05	6	-86	36	6	25	16	6
Isosuo	1998–1999	21	1.52	18	20	0.05	18	-13	22	18	58	12	18
Itäsuo	1995	66	4.26	16	45	0.23	16	27	97	16	97	158	16
Kapustaneva													
Spring	2009–2010	11	2	7	20	0.05	7	-9	30	7	67	8	7

Wetland and season	Monitoring years	N_{tot}			P_{tot}			COD_{Mn}			SS		
		%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n
Summer	2008–2009	14	2.15	12	27	0.09	12	-28	55	12	68	10	12
Autumn	2008–2009	24	3.06	8	52	0.1	8	-4	61	8	81	20	8
Winter	2009–2010	3	2.84	9	26	0.1	9	-33	50	9	84	24	9
Keskiaapa 2-3	2001–2003	28	2.18	28	34	0.1	28	-11	20	28	58	50	28
Korentosuo 1													
Spring	2010, 2012–2013	45	1.42	8	49	0.04	8	10	19	8	85	9	8
Summer	2012–2013	52	2.15	18	54	0.09	18	-9	39	18	67	13	18
Autumn	2012–2013	53	2.33	3	57	0.09	3	1	31	3	86	25	3
Winter	2010, 2012–2013	18	1.77	11	34	0.09	11	-119	16	11	73	8	11
Kuljuneva[1]	2009	7	2.45	2	-98	0.04	2	-269	25	2	69	11	2
Kynkäänsuo 3	2004–2005	1	1.26	19	53	0.22	19	-132	16	19	76	9	19
Lammisuo													
Spring	2009–2010	14	4.15	6	30	0.09	6	3	38	6	48	12	6
Summer	2008–2009	13	5.02	13	34	0.12	13	10	53	13	57	29	13
Autumn	2008–2009	12	4.59	8	35	0.1	8	9	62	8	58	28	8
Winter	2009–2010	14	4.88	5	56	0.16	5	32	59	5	88	51	5
Lumiaapa 2	1998–2000, 2008–2009	41	3.55	36	34	0.05	36	-6	30	36	82	26	36
Luomaneva	1999, 2009–2010	25	1.87	17	-38	0.11	17	-23	38	17	51	22	17
Nanhiansuo													
Spring	2006–2010	36	2.49	14	55	0.2	14	4	62	14	72	61	14
Summer	2006–2009	17	2.01	46	34	0.26	46	2	103	46	51	33	46
Autumn	2006–2009	37	2.39	16	52	0.13	16	11	92	16	67	14	16
Winter	2006–2010	27	2.16	14	54	0.2	14	8	76	14	61	22	14
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	40	0.07	32	-7	31	32	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	1.8	18	60	0.09	18	18	25	18	91	56	18
Peuralinnanneva													
Spring	2010	31	1.93	4	60	0.11	4	-66	41	4	81	125	4
Autumn	2009	38	1.73	4	79	0.14	4	-27	46	4	93	134	4
Winter	2010	46	2.3	4	62	0.07	4	-58	49	4	88	25	4
Pohj. Latvasuo	1996–1997	25	1.11	8	33	0.06	8	-11	17	8	14	6	8
Puutiosuo 2-3													
Spring	2002–2005, 2007	26	1.13	10	51	0.05	10	2	15	10	67	5	10

Wetland and season	Monitoring years	N_{tot}			P_{tot}			COD_{Mn}			SS		
		%	mg/L	n	%	mg/L	n	%	mg/L	n	%	mg/L	n
Summer	2001–2004, 2007	53	2.01	35	71	0.09	35	-38	27	35	81	7	35
Autumn	2001,2003–2004, 2007	57	3.72	9	61	0.07	9	12	37	9	82	31	9
Winter	2002, 2004–2005, 2007–08	41	2.19	20	65	0.09	20	-45	16	20	71	4	20
Ristineva													
Spring	2007–2009	47	0.96	4	60	0.03	4	11	32	4	85	8	4
Summer	2007–2009	43	1.38	31	66	0.07	31	9	54	31	91	18	31
Autumn	2007–2009	33	1.73	12	61	0.04	12	2	51	12	72	6	12
Winter	2007–2008	25	1.48	4	73	0.05	4	-10	44	4	92	15	4
Satamakeidas													
Spring	2002–2010	21	1.14	30	31	0.08	30	0	14	30	69	19	30
Summer	2001–2009	5	1.07	90	21	0.11	90	-37	19	88	46	10	90
Autumn	2001–2009	13	1.55	36	13	0.09	36	-31	19	36	38	9	36
Winter	2002–2010	-15	1.18	39	-8	0.1	39	-85	11	39	27	12	39
Saarineva	2012	16	2.92	4	6	0.07	4	-3	49	4	45	17	4
Savaloneva													
Spring	2009	-70	1.69	3	-193	0.03	3	-79	25	3	-500	3	3
Summer	2009	-40	2.9	10	-206	0.06	10	-43	53	10	-109	21	10
Autumn	2009	-1	3.03	3	-132	0.05	3	-38	41	3	-15	9	3
Winter	2009	-80	2.2	6	-197	0.04	6	-158	33	6	-249	4	6
Savonneva													
Spring	2002–2004	24	1.64	10	24	0.05	10	1	29	10	62	7	10
Summer	2001–2004	34	2.81	32	28	0.13	32	2	72	32	40	16	32
Autumn	2001, 2003	24	4.54	9	22	0.12	9	11	89	9	62	38	9
Winter	2002–2004	16	2.28	11	-64	0.05	11	-20	33	11	39	9	11
Vittasuo													
Spring	2005–2009	20	1.82	14	21	0.08	14	5	40	14	28	32	14
Summer	2005–2009	25	2.28	47	16	0.09	48	4	68	48	14	17	48
Autumn	2005–2009	32	2.61	20	55	0.08	20	8	77	20	62	10	20
Winter	2006–2010	23	2.13	16	47	0.08	16	5	59	16	62	22	16
Äijönneva	2009–2010	-17	2.39	14	-156	0.97	14	-139	42	14	49	14	14

[1] Summer+autumn.

The inflow water quality varied markedly between wetlands and years, and affected the water purification efficiency, but on average it was at the same level as measured in previous studies (Tuukkanen *et al.* 2012). If the inflow concentration was very low, it is obvious that the wetland purification efficiency cannot be very high. This was noted for e.g., Hankilanneva 1 in 2010, when N_{tot} inflow concentration was 780 µg/L (reduction 19%) and also in Iso-Lamminneva in 2013, when P_{tot} inflow concentration was 51 µg/L (reduction 25%). Although the reduction was not very high or at the level required by the environmental authorities, the runoff water was purified and the outflow concentration was quite low, which can be seen an overall aim of water treatment in wetlands. Reduction percentage is clearly not always a good measure of performance if inflow concentration is low, and outflow concentration should also be considered as an additional measure of treatment performance.

The loading during summer season from the wetlands varied markedly (Table 3). It was low e.g. in Itäsuo, Kapustaneva, and Savaloneva, where e.g., the average P load was 0.2–0.5 g/ha d and N load 5–7 g/ha d. The highest P and N loads were 10 or 20 times higher than the average values. For example in Itäsuo, the purification efficiencies were good (Table 2) and the loads were low (Table 3), but for example at Vittasuo or Kapustaneva the summer P loads were quite low but the P purification efficiencies were not so good. The observed low load from Savaloneva is partly due to infiltration to the groundwater system. Some of the calculated loads can be overestimates due to uncertainties in discharge measurements by V-notch weirs, since flooding occurred and the water level in ditches after the weir was very high and determined the water level in the weir.

Table 3. Monitoring years and load of total nitrogen (N_{tot}), total phosphorus (P_{tot}), chemical oxygen demand (COD_{Mn}), and suspended solids (SS), calculated based on the outflow concentration and discharge data. The data include only the same sampling times used in Table 2, when water quality data were available for both inflow and outflow. For that reason, the load values below partly differ from peat extraction load monitoring program values. If the season is not given, the value is for summer. At the end of the table, summer mean, standard deviation (sd), minimum (min), and maximum (max) for all treatment wetlands constructed on drained peatlands are shown.

Wetland and seasons	Monitoring years	Load (g/ha d)			
		N_{tot}	P_{tot}	COD_{Mn}	SS
Hankilanneva 2					
Spring	2007,2009, 2010	300	12.3	5709	2563
Summer	2007–2009	9	0.5	284	73
Autumn	2007–2009	8	0.6	248	56
Winter	2007–2010	41	1.0	614	209
Hormaneva North					
Spring	2008–2010	26	0.6	480	61
Summer	2008–2009	13	0.5	338	28
Autumn	2008–2009	70	1.2	1031	182
Winter	2009–2010	21	0.7	297	59
Iso-Lamminneva	2010, 2013	46	0.8	1109	213

Wetland and seasons	Monitoring years	Load (g/ha d)			
		N_{tot}	P_{tot}	COD_{Mn}	SS
Isosuo	1998–1999	82	2.1	1792	260
Itäsuo	1995	5	0.5	233	12
Kapustaneva					
Spring	2009–2010	62	1.4	1155	104
Summer	2008–2009	7	0.2	276	12
Autumn	2008–2009	31	0.6	769	40
Winter	2009–2010	18	0.4	421	18
Keskiaapa 2-3	2001–2003	15	0.5	191	28
Korentosuo					
Spring	2010, 2012–2013	24	0.6	444	37
Summer	2012–2013	11	0.4	414	46
Autumn	2012–2013	11	0.4	282	27
Winter	2010, 2012–2013	11	0.3	214	14
Kuljuneva1	2009	51	1.9	2021	74
Kynkäänsuo 3	2005	6	0.5	207	14
Lammisuo					
Spring	2009–2010	120	2.1	1170	233
Summer	2008–2009	27	0.5	301	92
Autumn	2008–2009	138	2.6	2463	420
Winter	2009–2010	80	1.3	708	138
Lumiaapa 2	1998–2000, 2008–2009	25	0.3	288	27
Luomaneva	1999, 2009–2010	5	0.4	170	31
Nanhiansuo					
Spring	2006–2010	26	1.4	1098	220
Summer	2006–2009	9	0.8	576	73
Autumn	2006–2009	29	1.1	1530	76
Winter	2006–2010	26	1.3	1091	134
Pehkeensuo 1					
Spring	1997, 2008–2010	35	1.0	559	178
Summer	1997, 2005–2009	7	0.3	238	35
Autumn	1997, 2005–2009	12	0.4	309	51
Winter	2008–2010	9	0.3	152	34
Peuralinnanneva					
Spring	2010	26	0.9	1358	458
Autumn	2009	6	0.2	330	53
Winter	2010	3	0.1	159	8
Puutiosuo 2-3					
Spring	2002, 2004, 2007	53	1.6	992	65
Summer	2002–2005, 2007	4	0.1	161	9
Autumn	2001,2003–2004, 2007	19	0.2	256	9
Winter	2002,2007–2008	19	0.2	258	30

Wetland and seasons	Monitoring years	Load (g/ha d)			
		N_{tot}	P_{tot}	COD_{Mn}	SS
Ristineva					
Spring	2007–2009	4	0.1	237	9
Summer	2007–2009	4	0.1	255	12
Autumn	2007–2009	19	0.2	809	36
Winter	2008	31	0.3	1207	7
Saarineva	2012	83	2	1630	247
Satamakeidas					
Spring	2005–2010	34	1.8	437	206
Summer	2005–2009	11	0.9	290	44
Autumn	2005–2009	36	1.9	711	166
Winter	2005–2010	36	2.3	724	110
Savaloneva	2009	5	0.2	90	49
Savonneva					
Spring	2002–2004	30	0.9	669	46
Summer	2001–2004	7	0.2	258	18
Autumn	2001, 2003	47	1.1	1065	178
Winter	2002–2004	8	0.3	151	22
Vittasuo					
Spring	2006–2009	41	1.2	1193	256
Summer	2005–2009	11	0.3	513	45
Autumn	2005–2009	32	0.6	1250	76
Winter	2006–2010	38	1.0	1227	345
Äijönneva	2009–2010	29	1.9	834	85
Summer mean		24	0.8	618	75
Summer sd		26	0.7	628	82
Summer min		5	0.2	90	12
Summer max		82	2.1	2021	260

[1] Summer+autumn

Water sampling was carried out according to peat extraction monitoring guidelines and the sampling interval was calendar-based. In other studies of SS and particulate-associated matter there was some bias in the flux evaluation (Horowitz *et al.* 2015, Walling *et al.* 1992) and it would have been more accurate to use hydrology-based sampling (Horowitz *et al.* 2015). Calendar-based sampling together with extra peak flow samples could be a good alternative to get more reliable results for peat extraction areas (Heitto 2014). Based on Eskelinen *et al.* (manuscript), a weekly sampling interval gives about 20% better estimates of load than normal two-weekly sampling. However, the results of this study based on concentration data (Method 1) are comparable with the values in peat extraction monitoring reports required by the environmental authorities.

In four wetlands, it was possible to calculate summer time purification efficiency based on load-based (Method 2) and discharge-weighted sampling (Method 3). Based on the results, the load-based purification efficiencies were higher than the concentration-based values (Table 4). The use of concentration-based purification efficiency values can give weaker results due to infiltration, as the outflow water volume can be lower than the inflow volume. Evaporation can also affect the calculation, especially during the summer. Furthermore, the purification efficiencies calculated based on discharge-weighted concentration values (Method 3) were sometimes smaller and sometimes higher than those based on concentration values calculated by Method 1.

Table 4. Purification efficiency calculated by three different methods. Meth.1=based on concentration, Meth.2=based on load, and Meth.3=based on discharge-weighted concentration.

	N_{tot} (%)			P_{tot} (%)			COD_{Mn} (%)			SS (%)		
	Meth.1	Meth.2	Meth.3	Meth.1	Meth.2	Meth.3	Meth.1	Meth.2	Meth.3	Meth.1	Meth.2	Meth.3
Kapustaneva	25	43	27	37	55	-265	-29	1	32	56	73	26
Luomaneva	34	60	37	11	49	20	16	48	17	69	84	75
Savaloneva	-33	63	-5	-202	3	-171	-48	56	-10	-123	38	-40
Äijönneva	-17	13	-4	-156	-156	-213	-139	-105	-149	49	39	26

3.1.3 Wetland characteristics indicating P retention capacity (Paper II)

Leaching of P has typically been observed after rewetting of drained peatlands (Kieckbusch & Schrautzer 2007, Kjaergaard *et al.* 2012, Koskinen *et al.* 2011, Meissner *et al.* 2008, Nieminen *et al.* 2005). Leaching of P occurred in some of the wetlands studied in Paper II, at least during the first years after the wetland was constructed. A high water table can be a risk in anoxic conditions and the main mechanism for P leaching has been stated to be anoxic conditions causing release of Fe-bound P (Fe^{3+} reducing to soluble Fe^{2+}) (e.g., Niedermeier & Robinson 2009). This can partly explain the results in this thesis, because in Äijönneva (leaching occurred) the water table was typically at least partly above the ground surface at all study points, giving anoxic conditions. In Kapustaneva (no leaching) the water table at some study points was above the ground surface most of the time, but there was also points at which the water table was under the surface.

Leaching of P was observed e.g., in Luomaneva, Savaloneva, and Äijönneva wetlands, which had dense tree stands (Fig. 10, Paper II) and low *K* below 10–20 cm depth (Fig. 11, Paper II), indicating clear changes in hydrological conditions after drainage. On the other hand, Kapustaneva, Itäsuo, Lumiaapa 2, and Pohjoinen Latvasuo wetlands, which had at least partly sparse tree stands (Fig. 10, Paper II) and mainly high *K* to 50 cm depth except for Kapustaneva (Fig. 11, Paper II), all retained P_{tot} even in the first or second year after construction. The properties of those wetlands indicate that they were constructed on poorly drained areas where drainage operations had only had a minor influence on peat properties. Furthermore, these results indicate that it is possible, at least on a rough level, to evaluate the risk of P leaching from proposed treatment wetlands on the basis of tree stands in the peatland area, because changes in the species composition of drained peatland areas reflect changes in abiotic factors. Thus the findings in this thesis indicate that the best performing treatment wetlands for peat extraction runoff water purification, especially in terms of P, appear to be those that have similar characteristics to pristine peatland and especially no trees or only a sparse tree stand (see Fig. 10).

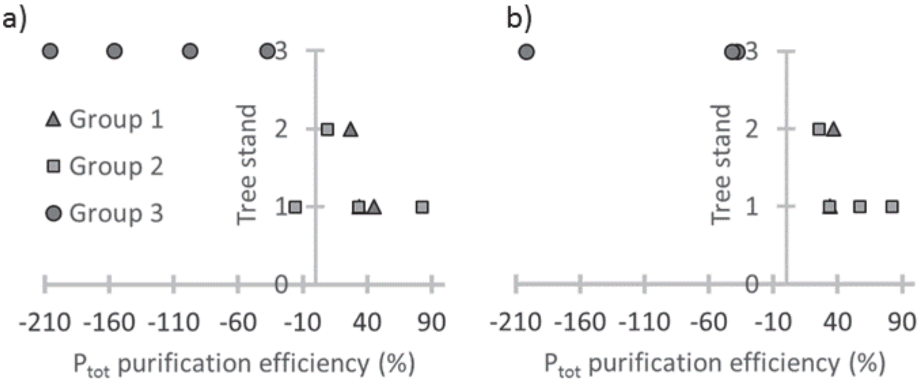

Fig. 10. a) P_{tot} purification efficiency (%) during summer time including also the year when the wetland was established, b) P_{tot} purification efficiency (%) during summer time without the year when the wetland was established compared with tree stand level (Level 1 = Sparse/no trees, Level 2 = Sparse/dense, Level 3 = Dense). The data were divided into three group based on mineral content of surface peat (Group 1 = P<800 mg/kg DM, Group 2 = (Fe+Al+Mn)/P mass ratio >45, Group 3 = (Fe+Al+Mn)/P mass ratio ≤25 and P>1200 mg/kg DM).

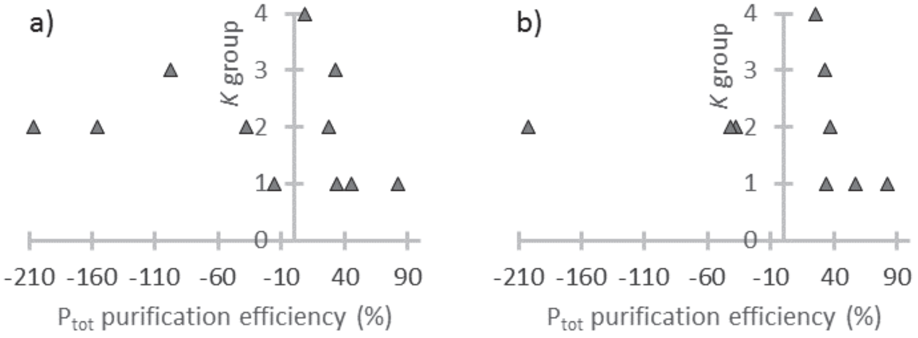

Fig. 11. a) P_{tot} purification efficiency (%) during summer time, including the year when the wetland was established, b) P_{tot} purification efficiency (%) during summer time without the year when the wetland was established compared with hydraulic conductivity, *K*, group (Group 1 = High *K* at all depths investigated, Group 2 = *K* decreased at a depth of 20 cm, Group 3 = *K* decreased at a depth of 50 cm and Group 4 = *K* decreased between 20 cm and 30 cm, but increased in the deeper layers).

The (Fe+Al+Mn)/P mass ratio in surface peat was identified as being a possible tool to predict the suitability of a drained peatland area for water purification purposes under typical acid conditions. This is because increased Fe and Al content in particular can increase P adsorption (Dunne *et al.* 2005, Wang *et al.* 2009, Yoo *et al.* 2006). Alkaline or near-neutral conditions, e.g., presence of Ca, can also affect P adsorption (Reddy & Delaune 2008, Wang *et al.* 2009, Yoo *et al.* 2006) The results (see the wetland specific mean surface peat content from Appendix 3) obtained for the wetlands studied here indicated that P leaching occurred mainly when surface peat had an average low (Fe+Al+Mn)/P mass ratio (⩽25) and quite a high P content (>1200 mg/kg DM) (Group 3 in Fig. 10), i.e., Luomaneva, Savaloneva, Äijönneva, and Kuljunneva wetlands (Paper II). An average high (Fe+Al+Mn)/P mass ratio (>45) (Group 2 in Fig. 10 and Fig. 12) seemed to indicate good or at least moderate P purification efficiency if the wetland had been established and rewetted less recently, e.g., Hankilaneva 1, Hankilaneva 2, and Pohjoinen Latvasuo. However, in these wetlands the variation between sampling points was high (Fig. 13) and peat Al and Fe content were probably partly increased due Al and Fe concentration in peat extraction runoff during the years. Despite quite low (Fe+Al+Mn)/P mass ratio (<25), when the average P content was also low (<800 mg/kg DM) (Group 1 in Fig. 10 and Fig.12), the purification efficiency of P was quite good at Kapustaneva, Itäsuo, and Lumiaapa 2. This was perhaps due to the small amount of P in the peat at these sites. There was some statistical difference in the purification efficiency between groups ($p=0.027$). Observations from wetlands are in agreement with Zak *et al.* (2010), who also observed that molar ratios of Fe:P or Al:P of peat correlate negatively with P release in rewetted fens (i.e., the higher the ratio, the smaller the release of P). Based on Forsmann & Kjaergaard (2014), soil bicarbonate-dithionite (BD) extractable Fe_{BD}:P_{BD} molar ratio above 10 may indicate low risk of P release. However, at Savaloneva total Fe:P molar ratio of peat based on EPA3051A standard was 14 and P was leached. Based on the results in this thesis, a peat Fe:P molar ratio (determined based on EPA3051A standard) above 17 shows no risk of P leaching, except possibly in the first year.

Itäsuo and Lumiaapa 2 had also high (Ca+Mg)/P mass ratio and runoff water from Lumiaapa 2 was quite neutral ($pH \approx 7$) (Paper II). In those cases the Ca probably provided P adsorption capacity, thus explaining the higher P purification efficiency. However, more data for different treatment wetlands and different regions of Finland are needed in order to allow final conclusions to be drawn on the impact of (Fe+Al+Mn)/P mass ratio and perhaps (Ca+Mg)/P mass ratio on P purification in treatment wetlands. Extra data collected later strengthened the finding that if the average surface peat P content is low, the area can retain P at least in a wetland which had been established and rewetted for some years earlier (Karppinen & Postila 2015). At six wetlands, soil samples were also taken from deeper layers (20–30 cm), but because in many wetlands the high hydraulic conductivity layer was shallow and runoff water contact with deeper layers was weak, these data were not included in the evaluation. Both P content and (Fe+Al+Mn)/P mass ratio were on average usually smaller in the 20–30 cm layer compared with the surface layer.

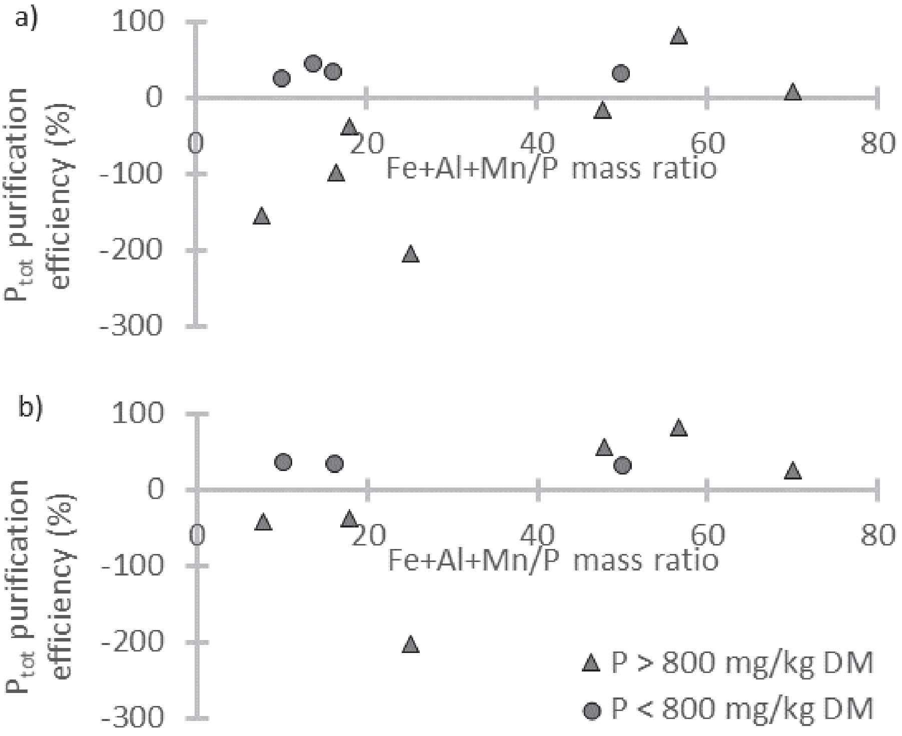

Fig. 12. **a) P_{tot} purification efficiency (%) during summer time including in the year when the wetland was established, b) P_{tot} purification efficiency (%) during summer time without the year when the wetland was established compared with Fe+Al+Mn/P mass ratio. The data were divided into two groups, with P>800 mg/kg DM and P<800 mg/kg DM.**

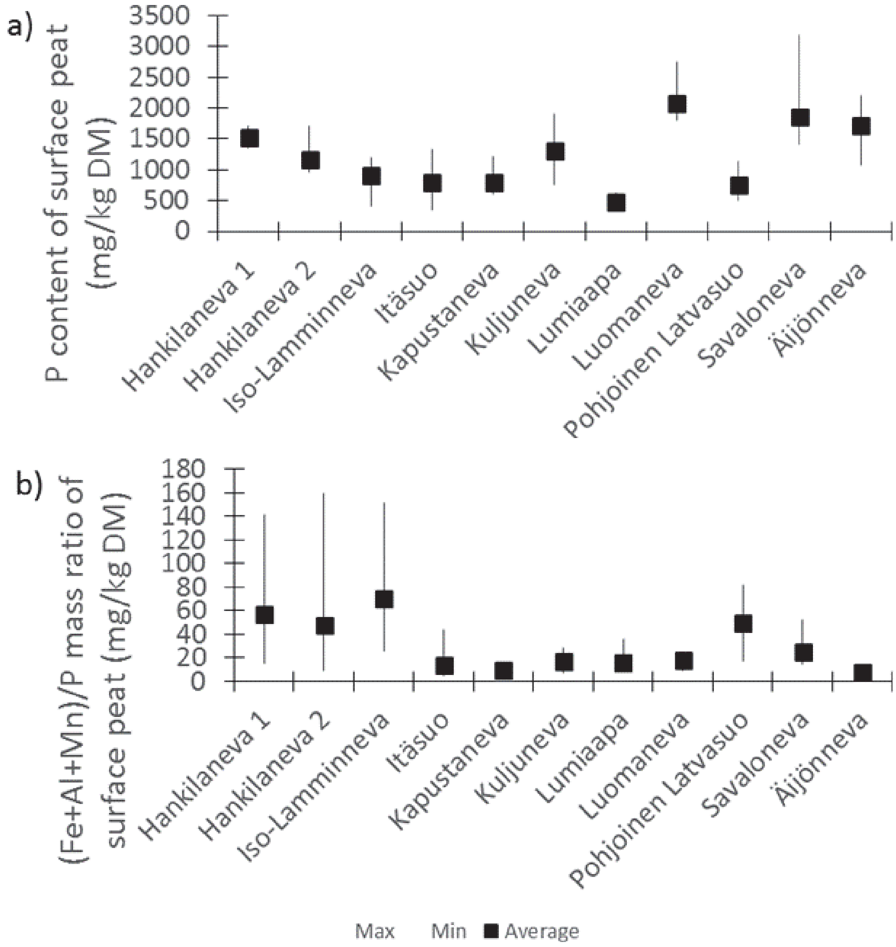

Fig. 13. a) P content (mg/kg DM) and b) (Fe+Al+Mn)/P mass ratio in surface peat samples from different wetlands.

The characteristics of the previously drained sites were compared against OFA design values issued by Ministry of the Environment (2013). OFA design criteria such as slope, degree of humification of surface peat, and treatment wetland area as a proportion of total catchment area (TA/CA ratio) varied between the wetlands constructed on drained peatlands. However, these design criteria did not have a significant impact on purification efficiency for treatment wetlands constructed on drained peatlands. For example, the purification efficiency was around average, although the TA/CA ratio was lower than the recommended >3.8%. In addition, the average degree of humification of surface peat in drained peatlands was usually above the recommended H1–H3. Thus based on OFA guidelines and parameters, it is not possible to select suitable drained peatland areas for treatment wetland purposes. However, a minimum 0.5 m peat depth in the wetland is a good guideline for drained wetlands, preventing flow to mineral soil.

The results confirm the hypothesis that when drainage has altered peat physical properties, e.g., there is lower active flow depth or forest vegetation/more trees, they can affect or indicate P retention possibilities in wetlands.

3.1.4 Evaluating the suitability of drained peatland for water purification purposes (Paper II)

Based on results from 11 treatment wetlands constructed on drained peatland areas, a conceptual decision tree (Fig. 14) was drawn up to help in designing and establishing treatment wetlands on drained peatland areas and taking into account different factors (see also Figs. 10 and 12) which may influence the purification efficiency for runoff water (especially as regards P). Based on the tree, it is possible to make a preliminary evaluation of the potential suitability of a drained peatland for runoff treatment purposes in peat extraction areas if pristine peatland is not available. The design parameters used for OFAs (treatment wetland constructed basically on pristine area) are not included in the conceptual decision tree, as OFAs have well-established criteria that do not correlate with the purification efficiencies of drained areas. The decision tree has four steps:

- **First,** check if there is suitable pristine peatland area available. If there is, it should be selected, because typically in these areas purification efficiency is better (Heikkinen *et al.* 2002, Kløve *et al.* 2012). If not, continue with this conceptual decision tree.
- **Second,** evaluate whether there is contact with the mineral subsoil layer. If ditches in the drained peatland are cut into the mineral soil and the K value of the mineral soil is high, there is a risk that some of the runoff water could be lost to the local groundwater system in the mineral soil when the area is used for establishing a treatment wetland. As the groundwater impacts are not known, it is good to avoid these situations.
- **Third,** evaluate the density of the tree stand. Areas with dense tree stands should be avoided because, based on results in this thesis, these areas leach P (Fig. 10). Based on Kruskall-Wallis one-way analysis of variance, there was

some difference (p=0.023) in P purification efficiency between wetlands with different tree stand levels (1 = Sparse/no trees, 2 = Sparse/dense, Level 3 = Dense) wetlands.

- **Fourth,** collect surface peat samples and analyze them for P and for the most important metals affecting P retention (Al, Fe, Mn, Ca, Mg) because, based on results in this thesis, the mineral content of P and at least (Fe+Al+Mn)/P mass ratio seem to indicate P leaching (Figs. 10 and 12; see also section 3.1.3). About one sample per wetland hectare and at least four samples from the wetland area are recommended to calculate the mean value.

By using this decision tree model, it is possible to establish a treatment wetland with a high possibility of good purification efficiency, especially in terms of P retention. However, this model cannot guarantee a certain level of removal efficiency, because this depends on various local, hydrological, and geochemical factors. More data are also recommended to further refine and validate the decision tree.

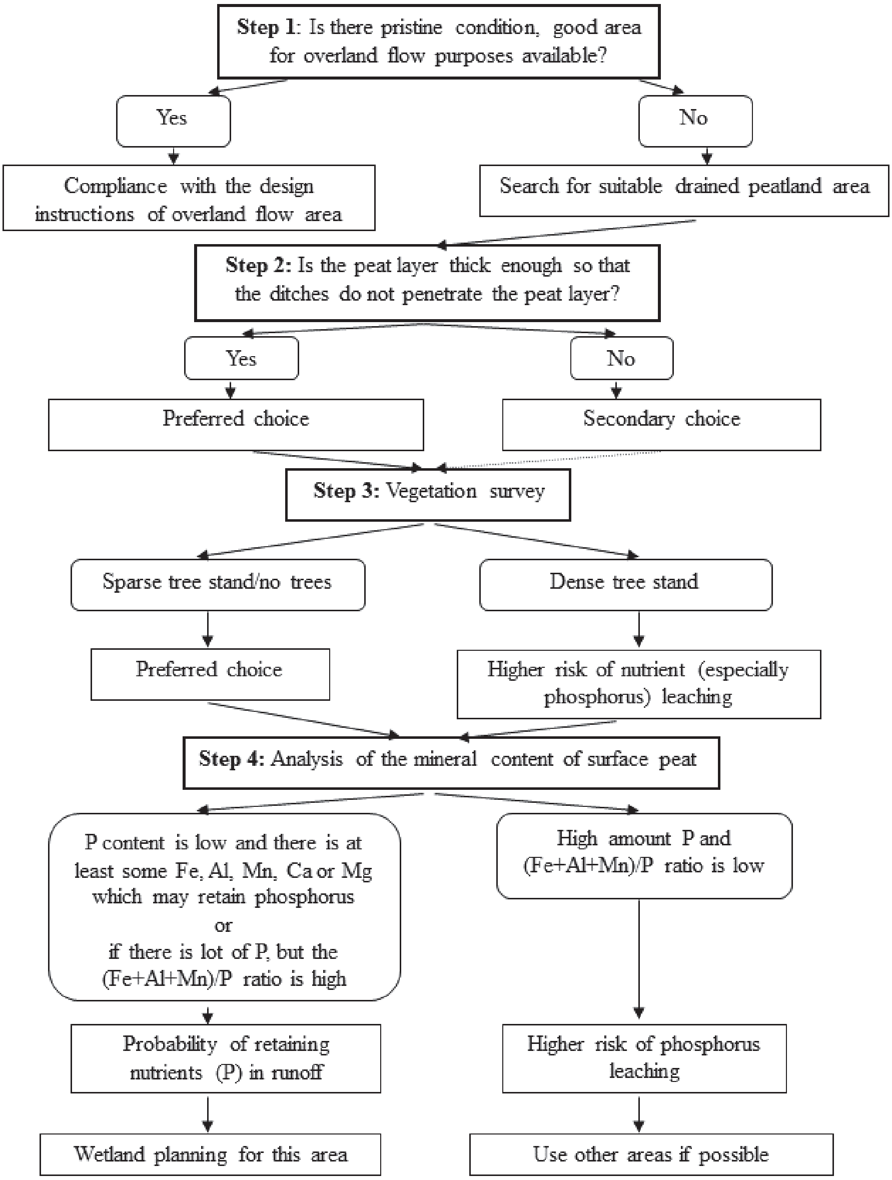

Fig. 14. Decision tree analysis for evaluating the suitability of previously drained peatland areas for use as treatment wetlands (modified from Paper II).

3.2 Winter flow paths and purification efficiency of constructed wetlands treating runoff from peat extraction areas in a cold climate (Paper III)

In a cold climate, the runoff water flow paths can change in winter due to ice cover and frost formation. This can partly affect runoff water purification efficiency, by changing conditions e.g., for filtration, but a clear effect on the purification efficiency was not observed in this thesis (Paper III).

3.2.1 Runoff water flow paths during seasonal frost (Paper III)

Runoff water flow paths during seasonal frost were studied in three wetlands. Seasonal maximum frost depth varied between 0 and 42 cm, with a mean maximum depth of 20 cm in the three treatment wetlands studied (Kapustaneva, Korentosuo 1, and Pehkeensuo 1). The seasonal mean maximum ground frost depth in peatlands has not been much studied in the literature. A study in Northern Ostrobothnia in the 1970s of pristine mires observed frost depths of around 0.3 m (Eurola 1975). For a region with a cold climate in Japan, a frost depth of 0.39 m was observed (Iyobe & Haraguchi 2005). The high water content in peat typically prevents deep frost penetration, but results in a solid ice cover. All three wetlands studied in Paper III were mainly frozen, with no apparent water flow. In two of the wetlands some surface flow was observed at the beginning of winter (Fig. 15, Paper III). The seasonal frost layer was deeper in northern treatment wetlands due to the lower snow cover at these sites in 2010 and in the beginning of winter 2011, and perhaps partly also due to slightly colder winter periods (mean temperature 1 October 2009-30 April 2010 and 1 October 2010-30 April 2011 at southern and northern sites was -9.4 and -10.5 °C, respectively).

Based on Paper III, in cold climate conditions different flow paths can occur in treatment wetlands where runoff water is pumped to the wetland. Water can flow through preferential flow paths that are unfrozen throughout the winter (Fig. 16). Some flow can also occur in the peat below the frost layer if the high hydraulic conductivity peat layer (acrotelm) is deeper than the frost layer. At some study sites, bulge ice formed on the wetland surface, probably as water flow was partly prevented by frost within the treatment wetland. Different amounts of inflow, pumping equality, and wetland properties can result in differences in runoff water flow paths.

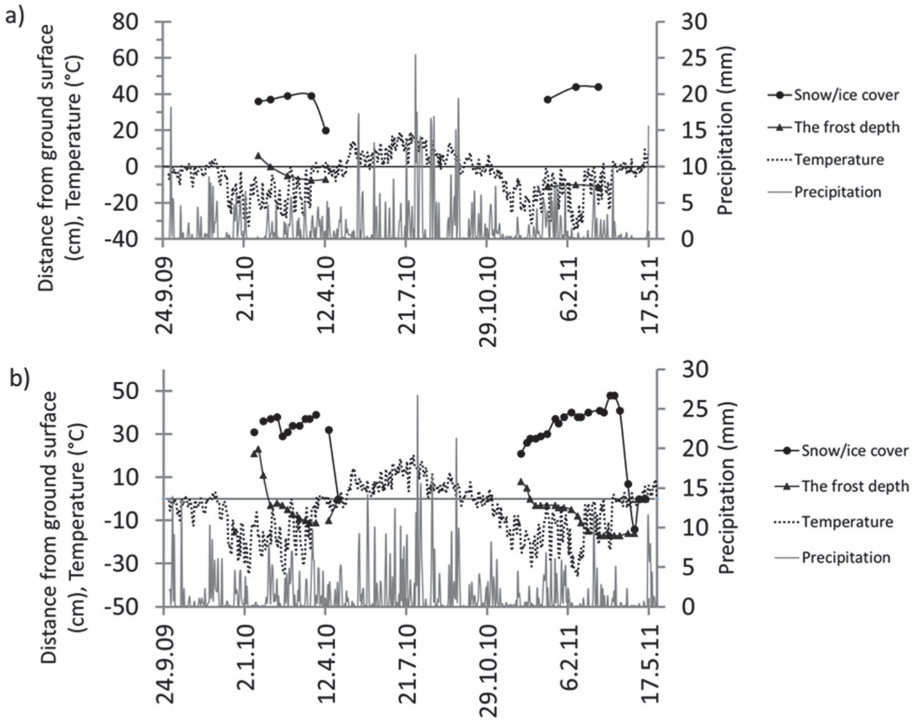

Fig. 15. Daily mean air temperature (°C), daily precipitation (mm), ground frost depth (m), and thickness of the snow/ice cover (m) a) in measuring pipe 1 in Kapustaneva wetland and b) measuring pipe 1 in Pehkeensuo 1 wetland (modified from Paper III).

Fig. 16. (Left) Bulge ice and water flow on top of the ice layer in Korentosuo wetland and (right) preferential flow path in Kapustaneva wetland both in January 2010 (photos by H. Postila).

3.2.2 Winter purification efficiency of constructed wetlands in a cold climate (Paper III)

To determine the seasonal purification efficiency of constructed wetlands treating peat extraction runoff in a cold climate, 14 wetlands were studied. There was a clear seasonal variation in purification efficiency for N_{tot} (p=0.000), NH_4-N (p=0.000), and COD_{Mn} (p=0.003) in the 14 treatment wetland datasets studied (Table 2). N_{tot} purification efficiency was lower in winter time than during other seasons. The NH_4-N purification efficiency was correlated with temperature (NH_4-N and T, r_s=0.42, p=0.000) and was typically highest during summer and lowest during winter, indicating temperature-dependent microbial processes as the controlling purification process. Generally the optimum temperature range for nitrification by bacteria has been found to be >20 ºC (Kadlec & Knight 1996) and a temperature below 15 ºC can clearly slow down this process (Reddy & Patrick 1984). However, during winter NH_4-N was removed, which could partly be related to cation exchange (Heikkinen *et al.* 1995a, Wittgren & Mæhlum 1997). Additionally, the nitrifying microbial community can be partly adapted to regional and seasonal climate (Feng *et al.* 2012, Wittgren & Mæhlum 1997), and thus some removal via nitrification can also occur in winter.

The COD_{Mn} removal efficiency was typically negative in summer and winter. In spring and autumn, the purification efficiency was on average positive. Springtime humic substances leaching prevention can be caused by overland flow on the frozen treatment wetland. In the other words, leaching of humic substances typically occurs in treatment wetlands constructed on peatland owing to peat decomposition. Seasonal variation in purification efficiency was not observed for the other water quality parameters (P_{tot}, PO_4-P, Fe, and SS). This could indicate that their removal is controlled by non-temperature-dependent physical (e.g., filtration) and only slightly temperature-dependent chemical (e.g., sorption) processes. This also means that there are sufficient possibilities for these processes to occur in treatment wetlands, despite ice and ground frost formation. This is supported by other studies on other types of constructed wetlands and buffer zones, where no seasonal variation in P_{tot} and PO_4-P has been observed (e.g., Syversen 2005, Züst & Schönborn 2003). A seasonal fluctuation in inflow water quality was observed for all pollutants except SS, e.g., COD_{Mn} concentrations were high during summer time. Koehler *et al.* (2009) observed the same trend in DOC concentrations.

In general, the removal efficiency (P_{tot}, PO_4-P, COD_{Mn}, Fe, and SS) was correlated with the inflow concentration, with higher inflow concentrations resulting in better purification efficiency. The load was highest during spring in the North Ostrobothnia region, but in Western Finland it was high also in autumn and winter (Table 3, Paper III).

Some properties of treatment wetlands, such as degree of humification of the surface peat, were found to influence some water quality parameters and purification efficiency in comparisons mainly between wetlands, but the differences not so detectable between seasons. In general, the factors that may decrease P_{tot} and SS purification efficiency were: 1) lower inflow concentration, 2) higher average degree of humification of the surface peat, and 3) wetland construction on drained peatland. The observed impacts of ice formation on treatment systems did not reduce their removal efficiency significantly, based on statistical evaluation. However, because prior drainage appears to affect the year-round purification efficiency of treatment wetlands, in future the suitability of drained areas should be evaluated as described in section 3.1.4.

The starting hypothesis was that there is seasonal variation in purification efficiency due to cold temperature. The results partly support the hypothesis, because there was clear seasonal variation in purification efficiency due to cold temperature, but only in some parameters (N_{tot} ($p=0.000$) and NH_4-N ($p=0.000$)). As hypothesized, water flow paths were altered due to ground frost and ice cover.

4 Conclusions

According to the results presented in this thesis, the hydraulic properties and hydrology of treatment wetlands were at least partly altered due to previous drainage. Moreover, the purification efficiency of treatment wetlands constructed on drained peatland varied; at some sites it was as good as in OFAs on pristine peat, but some malfunction, e.g., P leaching, also occurred. It was shown that peatland tree stands and peat properties can be used as indicators of possible P leaching. The N_{tot}, NH_4-N, and COD_{Mn} purification efficiency varied seasonally and, based on ground frost data, different flow paths can occur during winter.

The hydraulic properties of treatment wetlands constructed on drained peatland differed from those of wetlands constructed on pristine peatland. More than 50% of the 20 treatment wetlands on drained peatland studied here had a shallower (only 10–20 cm) active flow depth layer with high hydraulic conductivity, K. However, K was high at all depths investigated (down to 60–70 cm) in 25% of the drained wetlands studied. Preferential flow and unequal distribution of runoff water appeared to increase if existing drainage ditches were not blocked. The residence time can also sometimes be shorter than in pristine wetlands, but the variability was high and similar residence times to those in pristine peatland were observed.

Based on the results, treatment wetlands constructed on drained peatland areas can be used to remove nutrients and SS from runoff water originating from peat extraction sites. However, there were marked variations in purification efficiency between wetlands, and some sites even released P and Fe. Leaching of P in particular was observed immediately after rewetting and wetland construction on some wetlands, but after the initial P losses, the P retention capacity can recovered. Elevated COD_{Mn} values in runoff water flowing through the wetlands were observed for pre-drained and pristine sites. Sometimes the inflow concentration was low, which should also be taken into consideration when evaluating wetland functionality, along with reduction (%) capacity.

These results indicate that drainage may alter the properties of a peatland, e.g., peat hydraulic conductivity, active runoff layer in the peat profile, and vegetation such as tree stands growing in the area. The best performing treatment wetlands for purification of peat extraction runoff appeared to be those on drained peatland sites that have similar characteristics (e.g., mire vegetation without a dense tree stand) to wetlands constructed on pristine peatlands. It appeared possible to predict P retention in particular from surface peat P content and (Fe+Al+Mn)/P mass ratio. The possibilities for good treatment efficiency appeared to be best when

(Fe+Al+Mn)/P mass ratio was high (> 45) or P content low and at least some Fe, Al, Mn, Ca, and Mg was present in the surface peat.

Based on the results, a conceptual decision tree was designed for wetland performance evaluation. This decision tree can be used as a guide for the construction of treatment wetlands on drained areas that have higher possibilities for good purification efficiency. However, in the future, it would be useful to collect new data from other wetlands and refine and validate this decision support tree based on a larger dataset. This conceptual tree does not consider dimensioning properties of OFAs (constructed basically on pristine or at least undisturbed area) e.g., treatment wetland size relative to catchment area, because in this thesis it was not observed that they clearly affected the purification efficiency.

Seasonal frost and ice changed winter flow paths in the wetlands. In winter, water can flow in the deeper unfrozen peat layers. In some parts of the wetland water can flow through preferential flow paths that are unfrozen throughout the winter. Due to complexities in winter processes and variation between winters in different regions of Finland, this needs more attention in future studies.

When wetland purification efficiency was compared between seasons, only N_{tot}, NH_4-N, and COD_{Mn}, purification efficiency varied significantly between different seasons. The N_{tot} purification efficiency was lower during winter than in the other seasons. The NH_4-N purification efficiency was highest in summer and lowest in winter, but NH_4-N purification occurred even in winter. Temperature influenced NH_4-N removal, mainly because nitrification-denitrification is a temperature-dependent microbial purification process. The COD_{Mn} removal efficiency was on average negative during summer and winter, reflecting organic matter leaching from the treatment wetlands. No seasonal variation in removal efficiency was noted for phosphorus (P_{tot}, PO_4-P), particulate matter (SS), or iron (Fe), indicating that their purification efficiency occurred mainly e.g., by physical processes, which are not temperature-dependent. The data used were from different years and the number of study years varied between wetlands, which can partly have affected the evaluation, but is not likely to affect the main results.

Based on the results, some of the treatment wetlands built on drained peatland can be safely used for runoff water treatment, with quite similar purification efficiency as in overland flow areas on pristine peatland. A preliminary assessment of suitable areas can be made using the decision tree developed here. This decision tree was developed based on data from 11 treatment wetlands, mainly only in the North Ostrobothnia region, so for refining and validation of the tree more data should be collected from other treatment wetlands and from different regions. In some drained areas with marked changes due to drainage, some losses of nutrients, especially P and Fe, can be expected, at least in the first year after construction. Methods to prevent this possible negative load (P) should be developed, because in the future only drained peatland areas may be available for treatment wetland construction. Effective water purification year-round is becoming increasingly important with a climate warming scenario. This thesis showed that treatment wetlands can be used effectively for water purification purposes in cold climates, even though the flow paths may differ from those in summer due to ice and snow cover. In future studies, winter-time purification processes and runoff flow routes should be examined in more detail, because in this thesis only a few data were available for winter season. The effect of possible future changes in ground frost duration and depth also needs more research. However, precise pre-evaluation of treatment wetland purification efficiency is always challenging, because it depends on various local, hydrological, and geochemical factors.

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Appendix 1

Monitoring year and total nitrogen (N_{tot}), total phosphorus (P_{tot}), chemical oxygen demand (COD_{Mn}), and suspended solids (SS) mean (ẋ) purification efficiency (%) and the standard deviation (sd), minimum (min), and maximum (max) of purification efficiency (%) between different years. Only 20 treatment wetlands for which there were data at least from 2 years are included (n= number of sampling years (a)).

Wetland and season	Monitoring years	N_{tot} (%)				P_{tot}(%)				COD_{Mn} (%)				SS (%)				(a)
		ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	
Hankilanneva 2																		
Spring	2007.2009. 2010	27	1	26	28	36	8	27	40	5	31	-31	24	60	6	54	65	3
Summer	1992, 2007-2009	18	18	-10	28	-16	122	-199	47	-78	114	-248	-9	64	11	53	79	4
Autumn	1992,2007-2009	49	17	33	66	9	80	-83	57	13	24	-15	29	37	55	-26	72	3
Winter	1991, 2007-2010	35	15	12	47	47	47	-34	87	1	48	-60	67	-9	164	-299	98	5
Hormaneva North																		
Spring	2008-2010	1	4	-3	4	5	5	0	11	-6	6	-13	-2	20	28	-8	47	3
Summer	2008-2009	12	1	11	12	14	9	8	21	-18	15	-29	-8	28	16	16	39	2
Autumn	2008-2009	3	2	2	4	-4	9	-11	2	-7	7	-12	-3	-6	33	-30	17	2
Winter	2009-2010	-5	13	-15	4	10	6	6	14	-13	9	-20	-6	22	30	1	43	2
Iso-Lamminneva	2010, 2013	3	56	-37	42	9	22	-6	25	-86	100	-156	-15	25	54	-13	63	2
Isosuo	1998-1999	21	10	14	28	20	3	18	22	-13	18	-26	0	58	13	49	67	2
Kapustaneva																		
Spring	2009-2010	11	6	7	16	20	17	8	32	-9	18	-22	4	67	2	66	69	2
Summer	2008-2009	14	20	0	28	27	15	17	38	-28	1	-29	-27	68	11	61	76	2
Autumn	2008-2009	24	14	14	34	52	5	49	55	-4	16	-16	7	81	10	73	88	2
Winter	2009-2010	3	4	0	6	26	13	17	35	-33	20	-47	-19	84	11	76	92	2
Keskiaapa 2-3	2001-2003	28	12	3	25	34	47	-20	65	-11	26	-41	7	58	40	17	98	3
Korentosuo																		
Spring	2010, 2012-2013	45	10	37	56	49	2	47	51	10	18	-7	29	85	10	75	94	3
Summer	2012-2013	52	8	46	58	54	16	42	65	-9	2	-10	-8	67	19	54	81	2
Autumn	2012-2013	53	11	45	61	57	5	53	60	1	8	-5	7	86	8	80	91	2
Winter	2010, 2012-2013	18	16	5	36	34	34	-4	62	-119	129	-265	-19	73	13	59	84	3
Kynkäänsuo 3	2004-2005	1	29	-19	22	53	25	36	71	-132	31	-154	-110	76	10	69	83	2
Lammisuo																		
Spring	2009-2010	14	4	11	17	30	10	23	37	3	3	1	5	48	14	38	58	2
Summer	2008-2009	13	0	12	13	34	14	24	44	10	14	0	20	57	47	24	90	2
Autumn	2008-2009	12	5	9	16	35	19	21	48	9	8	4	15	58	29	37	79	2
Winter	2009-2010	14	10	7	22	56	11	49	64	32	4	29	34	88	5	84	91	2
Lumiaapa 2	1998-2000. 2008-2009	41	22	17	71	34	23	9	57	-6	27	-35	24	82	10	74	96	5
Luomaneva	1999, 2009-2010	25	16	6	36	-38	87	-138	24	-23	69	-102	22	51	31	16	75	3
Nanhiansuo																		
Spring	2006-2010	36	12	23	51	55	15	40	77	4	18	-18	27	72	15	54	94	5
Summer	2006-2009	17	14	2	31	34	18	18	51	2	6	-4	7	51	38	-5	78	4
Autumn	2006-2009	37	9	30	49	52	7	44	61	11	4	4	14	67	2	64	69	4

Wetland and season	Monitoring years	N_{tot} (%)				P_{tot}(%)				COD_{Mn} (%)				SS (%)				(a)
		ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	
Winter	2006-2010	27	14	13	48	54	17	25	67	8	9	-5	15	61	33	26	100	5
Pehkeensuo 1																		
Spring	1997, 2008-2010	28	7	18	33	46	25	24	72	17	15	3	38	71	24	48	96	4
Summer	1997, 2005-2009	27	16	11	52	40	24	-1	60	-7	33	-51	41	71	13	50	81	5
Autumn	1997, 2005-2009	48	37	0	94	32	49	-54	68	20	30	-24	51	46	91	-117	95	5
Winter	1997-1998, 2008-2010	40	10	29	50	60	12	40	71	18	26	-18	50	91	3	89	94	5
Pohjoinen Latvasuo	1996-1997	25	7	20	29	33	5	29	36	-11	6	-15	-7	14	2	13	15	2
Puutiosuo 2-3																		
Spring	2002-2005, 2007	26	17	3	45	51	24	20	83	2	9	-7	15	67	17	44	91	5
Summer	2001-2004, 2007	53	12	41	66	71	9	61	82	-38	10	-52	-24	81	8	70	93	5
Autumn	2001,2003-2004, 2007	57	29	19	88	61	28	22	91	12	44	-31	70	82	17	64	100	4
Winter	2002.2004-2005.2007-2008	41	15	21	62	65	10	54	82	-45	47	-87	8	71	21	38	91	5
Ristineva																		
Spring	2007-2009	47	14	31	56	60	13	50	75	11	12	3	24	85	7	77	90	3
Summer	2007-2009	43	14	30	57	66	12	52	74	9	4	5	11	91	1	90	92	3
Autumn	2007-2009	33	6	29	40	61	6	54	67	2	11	-6	15	72	12	60	84	3
Winter	2007-2008	25	5	21	29	73	1	72	74	-10	24	-26	7	92	4	89	94	2
Satamakeidas																		
Spring	2002-2010	21	8	8	35	31	15	9	58	0	11	-14	15	69	11	53	87	9
Summer	2001-2009	5	18	-24	29	21	41	-61	57	-37	43	-127	12	46	18	26	71	9
Autumn	2001-2009	13	13	-4	41	13	26	-36	40	-31	22	-65	1	38	27	-12	72	9
Winter	2002-2010	-15	28	-59	26	-8	53	-104	45	-85	59	-169	-2	27	69	-145	81	9
Savonneva																		
Spring	2002-2004	24	6	20	31	24	21	4	46	1	10	-9	12	62	27	31	79	4
Summer	2001-2004	34	12	20	47	28	24	10	63	2	11	-13	11	40	33	13	88	3
Autumn	2001. 2003	24	14	14	34	22	39	-6	49	11	12	3	19	62	27	43	81	2
Winter	2002-2004	16	24	-12	32	-64	21	-88	-52	-20	15	-32	-3	39	29	17	72	3
Vittasu**o**																		
Spring	2005-2009	20	13	2	36	21	40	-45	62	5	6	-2	14	28	57	-65	87	5
Summer	2005-2009	25	15	7	42	16	19	-12	35	4	7	-6	9	14	43	-58	55	5
Autumn	2005-2009	32	12	18	50	55	17	28	74	8	2	6	11	62	9	53	73	5
Winter	2006-2010	23	14	14	47	47	10	36	62	5	6	2	15	62	33	10	97	5
Äijönneva	2009-2010	-17	39	-45	11	-156	160	-269	-42	-139	124	-226	-51	49	7	44	54	2

Appendix 2

Monitoring year and total nitrogen (N_{tot}), total phosphorus (P_{tot}), chemical oxygen demand (COD_{Mn}), and suspended solids (SS) mean (ẋ) inflow concentration (mg/L) and the standard deviation (sd), minimum (min), and maximum (max) of inflow concentration (mg/L) between different years. Only 20 treatment wetlands for which there were data at least from 2 years are included (n= number of sampling years (a)).

Wetland and season	Monitoring years	N_{tot} (mg/L)				P_{tot} (mg/L)				COD_{Mn} (mg/L)				SS (mg/L)				(a)
		ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	
Hankilanneva 2																		
Spring	2007.2009. 2010	1.14	0.42	0.81	1.66	0.07	0.01	0.06	0.09	20	1.6	18	21	20	9.8	10	29	3
Summer	1992, 2007–2009	1.24	0.34	0.97	1.73	0.07	0.01	0.07	0.08	25	8.0	18	36	15	1.3	14	16	4
Autumn	1992,2007–2009	1.36	0.48	1.13	1.99	0.06	0.03	0.04	0.09	26	18.9	13	49	9	4.2	5	13	3
Winter	1991, 2007–2010	1.65	0.79	0.84	2.91	0.11	0.08	0.06	0.26	27	11.6	18	41	48	74.0	10	182	5
Hormaneva North																		
Spring	2008–2010	1.95	0.58	1.50	2.60	0.05	0.01	0.04	0.05	34	9.7	26	45	6	2.2	3	7	3
Summer	2008–2009	2.81	0.78	2.26	3.36	0.14	0.02	0.13	0.15	57	9.4	51	64	9	0.9	8	9	2
Autumn	2008–2009	3.56	0.03	3.53	3.58	0.06	0.00	0.06	0.07	51	12.3	41	58	6	2.0	5	8	2
Winter	2009–2010	2.89	0.13	2.80	2.98	0.11	0.02	0.10	0.12	36	2.0	35	37	9	5.2	6	13	2
Iso-Lamminneva	2010, 2013	2.71	0.35	2.46	2.95	0.05	0.00	0.05	0.05	36	4.5	33	39	16	2.9	14	18	2
Isosuo	1998–1999	1.52	0.94	0.85	2.18	0.05	0.00	0.05	0.05	22	11.1	14	30	12	2.8	10	14	2
Kapustaneva																		
Spring	2009–2010	2.00	0.66	1.47	2.40	0.05	0.01	0.04	0.06	30	3.9	27	32	8	0.4	8	9	2
Summer	2008–2009	2.15	0.55	2.02	2.80	0.09	0.01	0.08	0.09	55	11.3	52	68	10	0.2	10	10	2
Autumn	2008–2009	3.06	0.34	2.83	3.30	0.10	0.02	0.08	0.11	61	28.8	40	81	20	15.9	9	31	2
Winter	2009–2010	2.84	0.71	2.40	3.40	0.10	0.02	0.08	0.11	50	0.6	50	51	24	17.0	13	38	2
Keskiaapa 2-3	2001–2003	2.18	0.39	1.34	2.13	0.10	0.04	0.06	0.14	20	4.4	16	24	50	75.6	5	138	3
Korentosuo																		
Spring	2010, 2012–2013	1.42	0.52	0.72	1.76	0.04	0.01	0.03	0.04	19	8.7	11	27	9	9.6	6	23	3
Summer	2012–2013	2.15	0.13	2.05	2.24	0.09	0.00	0.08	0.09	39	2.3	37	40	13	0.3	13	13	2
Autumn	2012–2013	2.33	0.25	2.10	2.45	0.09	0.00	0.09	0.09	31	9.9	22	36	25	21.6	15	45	2
Winter	2010, 2012–2013	1.77	0.09	1.70	1.87	0.09	0.01	0.08	0.10	16	0.9	15	17	8	1.0	7	9	3
Kynkäänsuo 3	2004–2005	1.26	0.02	1.24	1.27	0.22	0.04	0.19	0.25	16	3.6	13	18	9	2.1	8	11	2
Lammisuo																		
Spring	2009–2010	4.15	0.07	4.10	4.20	0.09	0.00	0.09	0.09	38	4.9	35	42	12	1.9	11	13	2
Summer	2008–2009	5.02	0.93	3.90	5.22	0.12	0.03	0.11	0.16	53	17.0	49	73	29	26.3	23	60	2
Autumn	2008–2009	4.59	1.18	3.75	5.43	0.10	0.03	0.08	0.12	62	16.6	51	74	28	21.1	13	43	2
Winter	2009–2010	4.88	0.57	4.40	5.20	0.16	0.04	0.14	0.20	59	3.9	56	61	51	11.7	42	58	2
Lumiaapa 2	1998–2000. 2008–2009	3.55	1.53	2.09	5.93	0.05	0.02	0.03	0.08	30	15.4	19	57	26	33.6	12	89	5
Luomaneva	1999, 2009–2010	1.87	0.14	1.71	1.99	0.11	0.01	0.10	0.13	38	6.6	31	44	22	3.7	18	25	3
Nanhiansuo																		
Spring	2006–2010	2.49	0.31	2.15	2.93	0.20	0.03	0.15	0.23	62	16.5	47	87	61	26.8	33	103	5
Summer	2006–2009	2.01	0.20	1.74	2.23	0.26	0.06	0.18	0.31	103	8.7	91	111	33	13.0	22	50	4
Autumn	2006–2009	2.39	0.23	2.15	2.70	0.13	0.03	0.10	0.16	92	6.0	84	97	14	6.3	8	20	4
Winter	2006–2010	2.16	0.69	1.94	3.30	0.20	0.32	0.15	0.87	76	26.1	63	130	22	18.9	7	55	5
Pehkeensuo 1																		
Spring	1997, 2008–2010	1.31	0.22	0.96	1.49	0.06	0.03	0.03	0.08	18	5.8	11	24	44	33.5	5	82	4
Summer	1997, 2005–2009	1.26	0.20	1.04	1.54	0.07	0.02	0.06	0.10	31	9.2	25	47	18	7.7	11	32	5
Autumn	1997, 2005–2009	2.22	0.25	1.84	2.50	0.07	0.04	0.04	0.13	38	4.1	32	41	32	47.9	6	120	5
Winter	1997–1998, 2008–2010	1.80	0.51	1.17	2.31	0.09	0.03	0.04	0.10	25	7.7	18	35	56	27.1	5	79	5

Wetland and season	Monitoring years	N_{tot} (mg/L)				P_{tot} (mg/L)				COD_{Mn} (mg/L)				SS (mg/L)				(a)
		ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	ẋ	sd	min	max	
Pohjoinen Latvasuo	1996–1997	1.11	0.02	1.10	1.13	0.06	0.00	0.06	0.06	17	2.2	15	19	6	1.0	5	7	2
Puutiosuo 2-3																		
Spring	2002–2005, 2007	1.13	0.26	0.74	1.35	0.05	0.03	0.03	0.09	15	1.0	14	17	5	5.1	1	13	5
Summer	2001–2004, 2007	2.01	0.34	1.70	2.42	0.09	0.02	0.07	0.13	27	3.1	22	31	7	1.8	5	9	5
Autumn	2001,2003–2004, 2007	3.72	2.61	2.75	8.30	0.07	0.09	0.04	0.23	37	41.7	21	110	31	122.9	3	250	4
Winter	2002.2004–2005.2007–2008	2.19	0.56	1.90	3.30	0.09	0.03	0.05	0.12	16	10.2	12	37	4	1.5	2	6	5
Ristineva																		
Spring	2007–2009	0.96	0.03	0.94	1.00	0.03	0.01	0.03	0.04	32	4.5	28	37	8	2.3	5	9	3
Summer	2007–2009	1.38	0.26	1.17	1.66	0.07	0.01	0.06	0.08	54	3.8	51	58	18	2.8	15	20	3
Autumn	2007–2009	1.73	0.14	1.58	1.85	0.04	0.00	0.03	0.04	51	6.6	43	56	6	1.2	5	8	3
Winter	2007–2008	1.48	0.07	1.40	1.50	0.05	0.01	0.04	0.06	44	9.0	34	47	15	9.9	4	18	2
Satamakeidas																		
Spring	2002–2010	1.14	0.16	0.83	1.33	0.08	0.02	0.05	0.12	14	1.9	11	18	19	12.7	6	43	9
Summer	2001–2009	1.07	0.14	0.86	1.38	0.11	0.02	0.07	0.13	19	5.7	12	28	10	4.6	6	21	9
Autumn	2001–2009	1.55	0.32	1.18	2.33	0.09	0.02	0.05	0.13	19	7.7	9	34	9	6.8	5	26	9
Winter	2002–2010	1.18	0.27	0.80	1.60	0.10	0.03	0.05	0.15	11	3.6	6	19	12	11.0	3	35	9
Savonneva																		
Spring	2002–2004	1.64	0.11	1.53	1.73	0.05	0.01	0.04	0.05	29	4.5	26	34	7	3.6	3	10	4
Summer	2001–2004	2.81	0.19	2.56	3.01	0.13	0.03	0.08	0.15	72	9.4	58	80	16	7.6	8	26	3
Autumn	2001. 2003	4.54	0.42	4.28	4.88	0.12	0.04	0.08	0.15	89	8.8	82	94	38	29.3	15	57	2
Winter	2002–2004	2.28	0.39	1.70	2.45	0.05	0.01	0.05	0.06	33	3.1	30	36	9	4.8	4	12	3
Vittasu**O**																		
Spring	2005–2009	1.82	0.24	1.57	2.07	0.08	0.02	0.05	0.11	40	9.4	27	53	32	23.2	13	71	5
Summer	2005–2009	2.28	0.61	1.45	2.98	0.09	0.04	0.07	0.16	68	24.5	26	84	17	16.1	8	49	5
Autumn	2005–2009	2.61	0.61	2.13	3.63	0.08	0.03	0.06	0.13	77	6.2	71	85	10	3.3	7	15	5
Winter	2006–2010	2.13	0.92	1.72	4.00	0.08	0.02	0.06	0.11	59	18.6	48	87	22	12.8	11	43	5
Äijönneva	2009–2010	14.00	0.37	2.13	2.65	2.39	0.04	0.07	0.13	97	7.7	37	47	42	3.9	11	17	2

Appendix 3

Mean surface peat content (mg/kg DM), pH, and number of samples (n) from studied wetlands.

Wetland	Al	Ca	Fe	Mg	Mn	P	pH	n
Hankilaneva 1	11185	6368	72613	1220	336	1509	4.7	8
Hankilaneva 2	6649	6477	58854	2430	602	1166	4.4	7
Iso-Lamminneva	9607	4087	55657	1301	462	914	4.0	7
Itäsuo	2812	10342	8761	2992	259	796	4.6	9
Kapustaneva	1292	6655	5995	1442	164	782	3.7	6
Kuljunneva	5106	4198	13015	900	213	1294	3.8	8
Lumiaapa 2	1761	6888	5761	1359	63	465	4.8	8
Luomaneva	6088	8520	31275	2560	650	2075	4.6	4
Pohjoinen Latvasuo	11875	7400	23588	4494	311	751	4.6	8
Savaloneva	1541	2077	47182	376	96	1861	3.7	11
Äijönneva	2959	3980	9926	1170	97	1714	3.7	8

Original publications

I Postila H, Ronkanen A-K, Marttila H & Kløve B (2015) Hydrology and hydraulics of treatment wetlands constructed on drained peatlands. Ecological Engineering 75: 232–241.

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

III Postila H, Ronkanen A-K & Kløve B (2015) Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate. Ecological Engineering 85:13–25.

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