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Anna-Kaisa Ronkanen

HYDROLOGIC AND HYDRAULIC PROCESSES IN NORTHERN TREATMENT PEATLANDS AND THE SIGNIFICANCE FOR PHOSPHORUS AND NITROGEN REMOVAL

FACULTY OF TECHNOLOGY,
DEPARTMENT OF PROCESS AND ENVIRONMENTAL ENGINEERING,
UNIVERSITY OF OULU

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ANNA-KAISA RONKANEN

HYDROLOGIC AND HYDRAULIC PROCESSES IN NORTHERN TREATMENT PEATLANDS AND THE SIGNIFICANCE FOR PHOSPHORUS AND NITROGEN REMOVAL

Academic dissertation to be presented with the assent of the Faculty of Technology of the University of Oulu for public defence in Raahensali (Auditorium L10), Linnanmaa, on 28 August 2009, at 12 noon

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Faculty of Technology, Department of Process and Environmental Engineering, University of Oulu, P.O.Box 4300, FI-90014 University of Oulu, Finland
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Abstract

The understanding of flow processes is a key to evaluating treatment efficiency in constructed wetlands. This work focuses on the effects of flow paths on phosphorus (P) and nitrogen (N)retention in four treatment wetlands constructed on pristine peatlands in Finland. Particular attention was paid to water residence time, effective flow area and effective flow depth. Both an artificial tracer test and a new method based on the analysis of stable oxygen and hydrogen isotope distributions were employed. Tracer tests were used to calibrate steady-state flow models created using a groundwater modelling MODFLOW code. Furthermore, concentrations of P, Al and Fe in the peat and concentration of N in the surface water were measured. Surface water tracer distributions showed overland flow to be the dominant flow process and it was divided into a preferential flow area and dead zones. Also, active channel formation was observed during the years of the study (2002–2005). The results indicate that the hydraulic performance might deteriorate drastically within a short period of time. The active flow areas in the peatlands comprised only about 40–48% in summer, meaning that large areas with potential for nutrient removal were left unused. Flow simulations showed that a more optimal length of the distribution ditch will create a larger effective flow area and possibly could prevent channel formation. The peat P concentration was 1.8±3.9 mg g^{-1}, and P was accumulated in the preferential flow area. The peat P concentration correlated positively with Al in the Ruka peatland treating wastewater. The results indicate that precipitation chemicals increase the P retention capacity of peatland substantially and maintain P retention at a stable level despite variable P loads. Furthermore, the results indicate that the accumulation of P to peat via adsorption and chemical precipitation is the major P removal process even after 10 years of loading. In Ruka, calculated N concentrations in surface water obtained with a first-order area model, together with regression analysis of the rate constant, were in good agreement with observed N concentrations. If a removal of 70% is to be achieved, the NH_4-N loading to the peatland should be below 0.10 mg m^2 d^{-1}.

Keywords: constructed wetland, hydraulic efficiency, nitrogen, peat, phosphorus, wastewater

To my loving family

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This research would have gone nowhere without challenging problems to solve, for which sincere thanks go to the peat industry and the Ruka and Mellanaava wastewater treatment plants. I am especially indebted to Petri Tähtinen (VAPO OY) and Esko Jumisko (Ruka wastewater treatment plant) for their helpfulness and co-operation. Further thanks go to Kati Martinmäki, Aino Kulmala and Hannu Marttila for carrying out part of the extensive field experiments and sampling.

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Oulu, March 2009 Anna-Kaisa Ronkanen

List of symbols and abbreviations

CW	Constructed wetland
PE	Peat extraction
WW	Wastewater
PFA	Preferential flow area
DL	Length of distribution ditch
BAT	Best available technique
GMWL	Global Meteoric Water Line
VSMOW	Vienna Standard Mean Ocean Water
W	Width of treatment peatland
L	Length of treatment peatland
C	Area of catchment
A	Area
A_{eff}	Effective area
K	Hydraulic conductivity
S	Specific yield
t	Time
t_p	Potential hydraulic residence time
t_d	Water residence time
t_s	Shortest residence time
m(t)	Amount of salt at time t
V	Water volume
V_m	Mobile water volume
s	Short-circuiting number
m_0	Injected amount of salt
v	Flow velocity
a	Cross-section area of flow in groundwater tube
C	Concentration
C_{in}	Concentration at inlet
C*	Background concentration
k	Rate constant
q	Hydraulic loading rate
y	Fraction of distance from inlet to outlet
Q	Volumetric flow rate
K	Hydraulic conductivity
S	Specific yield

pF-curve	Water retention curve
θ_{eff}	Effective porosity
h_{eff}	Effective flow depth (depth where water flow is fast)
δ	Enrichment of isotopes
R	Ratio of higher isotope mass to lower isotope mass

List of original publications

This thesis summarizes work reported in the following original publications, which are referred to in the text by their Roman numerals.

I Ronkanen A-K & Kløve B (2005) Hydraulic soil properties of peatlands treating municipal wastewater and peat harvesting runoff. Suo – Mires and Peat 56(2): 43–56.

II Ronkanen A-K & Kløve B (2007) Use of stabile isotopes and tracers to detect preferential flow pattern in a peatland treating municipal wastewater. Journal of Hydrology 347(3–4): 418–429.

III Ronkanen A-K & Kløve B (2008) Hydraulics and flow modelling of water treatment wetlands constructed on peatlands in Northern Finland. Water Research 42(14): 3826–3836.

IV Ronkanen A-K & Kløve B (2009) Long-term phosphorus and nitrogen removal processes and preferential flow paths in Northern constructed peatlands. Ecological Engineering 35(5): 843–855.

The author's contribution to publications I–IV: planned the work together with Bjørn Kløve, conducted the field surveys and data analysis, took responsibility for the modelling and wrote the papers. Bjørn Kløve critically commented on all the manuscripts.

Contents

1 Introduction

This thesis deals with treatment peatlands constructed on pristine peatlands, which are one type of constructed wetland (CW). Typically, treatment wetlands are classified as free surface water wetlands, subsurface wetlands (exhibiting both horizontal and vertical flow) and natural wetlands. All the peatlands studied in this work are natural wetlands. CW treatment systems are among the most widespread wastewater treatment systems in the world, being well represented even in cold regions in the North (Mæhlum 1998, Vymazal *et al.* 1998, Mander & Jenssen 2002). In general, wetlands can be described as land areas where soil is saturated during part or all of the year, so that they represent an interface between truly terrestrial ecosystems and aquatic systems. Constructed wetlands are designed and operated to mimic natural processes in wetland ecosystems with the objective of removing nutrients, suspended solids and bacteria from municipal and industrial wastewater, urban and agricultural runoff and acid mine drainage. Peatlands are ecosystems in which net primary production has exceeded decomposition over thousands of years with the result that organic matter has accumulated over time (Vitt 2006).

The abundant peatlands in the northern boreal region offer a good potential for effective water treatment at fairly low cost. A treatment wetland constructed on a pristine peatland represents the most common type of wetland for water treatment in Finland. The method has significantly improved water quality and reduced the nutrient load to aquatic systems (Ihme *et al.* 1991, Heikkinen *et al.* 1995b, Hallikainen 2003, Silvan *et al.* 2003).

1.1 History of peatlands as treatment wetlands

Peatlands are a characteristic part of the Boreal landscape. As much as one third of Finland’s area (8.9 million ha) is now classified as peatland (Hökkä *et al.* 2002). For centuries, the peatlands have contributed to human welfare, not least as a source of berries and as filtering systems for outflow waters from upland forest. With the beginning of large-scale drainage in the 1950s, however, much of the original peatland has been converted to agricultural use or ditched or drained in the interest of forestry, peat extraction and agriculture. At present, drained peatland constitutes 53% (4.7 million ha) and conserved peatland 12% (1.1 million ha) of the total area of peatland in Finland (Aapala 2001).

Indoor plumbing and sewerage became common in Finland in the early 1900s, creating an immediate need for wastewater treatment plants. The first of these plants were constructed in Helsinki and Lahti (Laakkonen 2001). By 1980, wastewater treatment plants were operational in all population centres in Finland. The construction of wastewater treatment plants is always costly, however, and small municipalities began to explore alternative methods. The first wastewater treatment peatland in Finland was constructed in the municipality of Kesälahti in 1957 (Surakka & Kämppi 1971), and by the early 1970s treatment peatlands were a common solution in municipalities where daily wastewater was not more than 500 m^3 d^{-1} (Lehtonen 1994). At first, the method involved infiltrating untreated wastewater into ditches on pristine peatlands. Sometimes peatland treatment was used after a pond treatment. Drainage ditches in the lower part of the treatment area were found to be essential. The method was cost-effective and it gave good results, especially for nitrogen (62%), bacteria (99%) and BOD_7 (biological oxygen demand, 80%) (Kämppi 1971a). Nevertheless, the first experiments showed that the high loads of solids clogged the peat in the long run, and the method was not therefore suitable in primary or secondary treatment where solids-loading was high (Lehtonen 1994, Munstermjelm 1972).

Peat has been an important part of Finnish energy management ever since the 1940s, but its use as a domestic energy source increased markedly after the energy crisis in the 1970s (Vasander 1996, Sopo 1998). As long ago as the early 1980s, it was well known that peat extraction or, as often called peat harvesting, increases the transport of suspended solids to receiving waters (Sallantaus 1984). The first solutions for reducing the negative effects of peat extraction were sedimentation ponds and various pipe structures at the extraction sites (Selin & Koskinen 1985). Later on, peak runoff control methods and constructed floodplains were developed to reduce suspended solids and nutrient leaching (Kløve 2000b). Since the late 1980s, pristine peatlands have been used to treat peat extraction runoff (Ihme *et al.* 1991, Heikkinen *et al.* 1995, Savolainen *et al.* 1996). By 2002, about 150 wetlands had been constructed by Vapo Oy Energy, the largest Finnish peat producer (Marja-Aho & Mander 2003). The Finnish authorities have now approved wetland treatment systems as the best available technique (BAT) to decrease the eutrophication of surface waters caused by runoff from peat extraction areas.

Current practical instructions for the construction of treatment wetlands on pristine peatlands are based on studies carried out in the early 1990s (e.g., Ihme 1994). The dimensioning parameters required for effective nutrient removal in treatment peatlands were considered more recently, e.g., by Heikkinen *et al.* (2002), Heikkinen *et al.* (2003) and Koskiaho & Puustinen (2005).

In 1994, a pilot project was started up in Ruka (Finland) with the aim of complementing the chemical treatment of municipal wastewater with treatment in a pristine peatland (Pirttijoki 1996, Hallikainen 2003). Peatlands have also recently been used for treating mining runoff (Räisänen *et al.* 2001, Sjöblom 2003). Some design and management guidelines were formulated during the pilot projects.

1.2 Retention processes in treatment peatlands

The foremost storages for nutrients are vegetation and surface peat. The contribution of vegetation to retention processes is indirect due to the annual life cycle of vegetation, at the end of which most of the stored nutrients are returned to the water (Kadlec & Knight 1996). From the viewpoint of water protection, however, the retention of nutrients in vegetation is important because the effects on eutrophication of the receiving water systems are more serve during the warm period of the year (Adamus & Stockwell 1983). Peat has four major roles in purifying wastewater. 1) It acts as a physical filter, with capacity depending on porosity and particle size. In general, the porosity of peat is high, 90–97% in pristine peatlands (Puustjärvi 1983). 2) It acts as a biological filter because its easily decomposing organic matter serves as a source of energy for micro-organisms, which create new biomass. Micro-organisms consume nitrogen and micronutrients such as phosphorus, and their growth is most efficient in warm seasons (Clymo 1983, Dickinson 1974). 3) The larger the outer surface of a solid the more efficiently it adsorbs particles on its surface. With a specific surface area of about 200 $m^2 g^{-1}$ (Puustjärvi 1983), peat is a highly effective surface-active material. 4) Peat has a high cation exchange capacity, or nutrient retention capacity, especially for NH_4^+ (Heikkinen *et al.* 1995). The roles of peat, vegetation and water in purification processes are summarized in Fig. 1.

The removal efficiency of peatland has been described as first and foremost related to the degree of contact between the peat and the water to be purified (Heikkinen *et al.* 1995). Hence, any assessment of peat-based constructed wetland performance has to address the hydraulic characteristics of the system. Previous studies have mainly aimed at qualitative and semi-quantitative understanding of phosphorus removal and nitrification-denitrification processes and of the role of vegetation in nutrient retention (Ihme *et al.* 1991, Heikkinen *et al.* 1995, Silvan *et* *al*. 2004) while little attention has been paid to the hydraulic performance of treatment peatlands. My work focuses on the hydraulic performance.

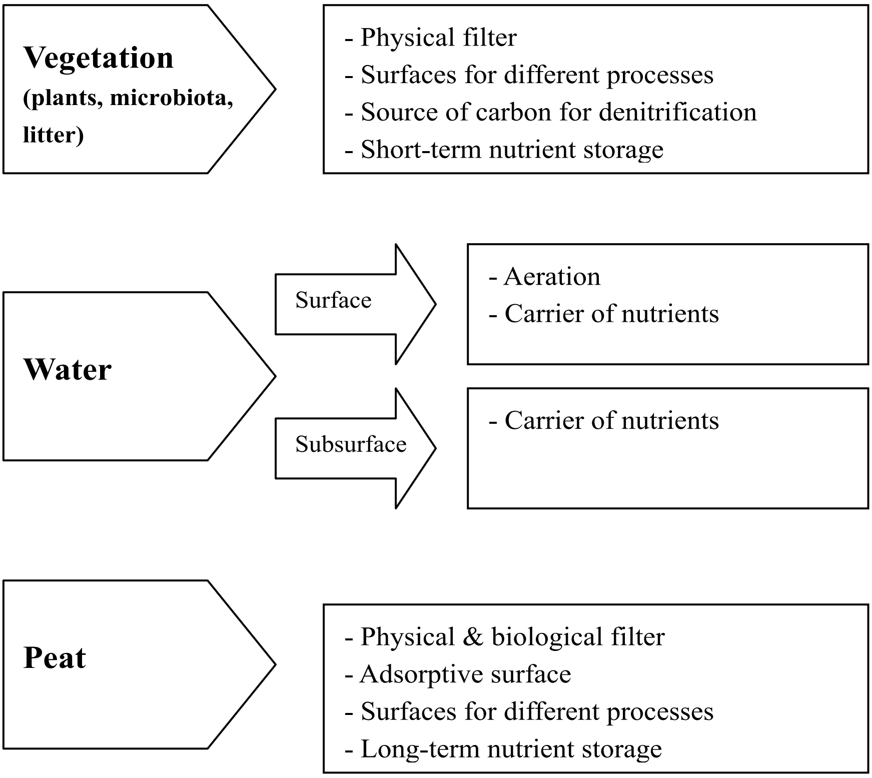

Fig. 1. The roles of water, vegetation and peat in the retention of phosphorus and nitrogen in treatment peatlands.

1.2.1 Phosphorus

Phosphorus (P) is a nutrient essential for plant growth and is a growth limiting nutrient in most boreal freshwater ecosystems and in some parts of the Baltic Sea (Pietiläinen & Räike 1999, Humborg *et al.* 2003). In treatment peatlands, phosphorus may be present in dissolved form or suspended in water, sorbed to the surface of peat particles, or contained in the structure of biomass and soil particles (Kadlec & Knight 1996). The removal of P in treatment wetlands is mediated by biological uptake of vegetation, by microbiological assimilation, and by (ad)sorption and precipitation. In (ad)sorption and precipitation P is trapped in porous media and reacts with minerals such as hydrous oxides of iron (Fe) and aluminium (Al) in acid soils, and with calcium (Ca) and magnesium (Mg) in alkaline soils (Richardson 1985, Kadlec & Knight 1996, Pant *et al*. 2001, Yang *et al.* 2001, Seo *et al*. 2005). Chemical sorption is considered to play an essential role in phosphorus retention in treatment wetlands over the long term, especially in wetlands treating municipal wastewater. Karjalainen *et al.* (2003) studied soil P adsorption capacity by measuring adsorption isotherms in batch tests for 20 different treatment wetlands, and concluded that P retention capacity was highest for wetlands treating municipal wastewater containing Fe and Al after chemical precipitation steps.

Although the sedimentation of particulate P is a major physical removal process in treatment wetlands in general (Uusi-Kämppä *et al.* 2000, Vymazal 2007), this is seldom the case in treatment peatlands because there the water table level scarcely rises above the peat surface. The physical P removal process is more like filtration through the peat and vegetation layer. Filtration occurs when the soil matrix is porous enough to allow water to flow through it (Vymazal 2002) and the vegetation is tall and dense enough (Deletic 2005). Through its accretion, peat functions a major long-term P sink in treatment peatlands, but this is true only if the production of biomass is high (Vymazal 2007). For the most part, the accumulation of organic matter in boreal peatlands is high because of the slow rate of decomposition of plant tissues (Moore & Basiliko 2006). This is the consequence of 1) the poor nutrient content and corresponding high refractory content of most peatland plants and of the underlying peat (Painter 1991, Verhoeven & Liefveld 1997); 2) the generally cool and frequently anoxic conditions in which the plant tissues decompose (Clymo 1965, Yavitt *et al.* 1997) and 3) the small microbial populations relative to soil organic carbon content (Moore & Basiliko 2006).

The sorption of soluble P is also regarded as an essential chemical P removal process in constructed wetlands. However, sorption has a finite capacity, up to saturation, and cannot contribute to long-term sustainable removal (Kadlec & Knight 1996, Pant & Reddy 2003). In treatment peatlands purifying peat extraction runoff, the phosphorus adsorption capacity of the peat has been estimated to be about 20 years (Heikkinen *et al.* 1995).

1.2.2 Nitrogen

Nitrogen (N) is of major concern in wastewater treatment because of its role in eutrophication. In some parts of the Baltic Sea, N is limiting for net primary production (Danielsson *et al.* 2008), and efficient N removal from wastewaters is essential. Some nitrogen compounds also have an effect on the oxygen content of receiving waters and are toxic to aquatic invertebrate and vertebrate species (Alonso & Camargo 2003, Chew *et al.* 2005, Alonso & Camargo 2006). Both organic and inorganic forms of N are present in wetlands. The most important of the inorganic forms are ammonia (NH_4), nitrite (NO_2^-) and nitrate (NO_3^-). Furthermore, N may be present in dissolved or particulate form in treatment peatlands.

The transformation and removal of N from wastewater involve numerous interrelated physical, chemical and biological processes including ammonification, nitrification-denitrification, adsorption, ion exchange, sedimentation, volatilization and biological uptake. These processes occur in water and on the surfaces of plants, plant debris and peat material. Nitrification-denitrification is considered the main process for N removal in most types of CWs (Kadlec & Knight 1996, Vymazal 2005, Vymazal 2007). In nitrification, ammonium is transformed into nitrite and nitrate by bacteria of the genera *Nitrosomonas* and *Nitrobacter*. The process proceeds only in the presence of oxygen, and typically the flux of dissolved oxygen limits the nitrification rate. Since oxygen transfer from atmospheric sources through water is a first-order process, the nitrification rate in wetland is also considered to be first-order (Kadlec & Knight 1996, Wörman & Kronnäs 2005). Nitrification is essential in wastewater treatment because most of the N load is in the form of NH_4 (Tanner *et al.* 2002, Karjalainen & Ronkanen 2005).

In denitrification, nitrate is reduced to nitrogen gas by facultative bacteria (*Bacillus*, *Enterobacter*, *Micrococcus*, *Pseudomonas* and *Spirillum*). The process requires anoxic conditions, but also has been observed in CWs where dissolved oxygen is present in surface water (Phipps & Crumpton 1994). This may be explained by the anoxic zones that are likely to be present in bacterial films (Kadlec & Knight 1996, Sirivedhin & Gray 2006, Wen *et al.* 2008). The supply of organic carbon that is required in denitrification (Kadlec & Knight 1996) is available in the abundant organic materials present in peatlands.

1.3 Hydrology and hydraulics of treatment peatlands

Hydrology is an essential factor in peat formation, plant growth and the surface patterns (variable hummocks, hollows and pools) of pristine peatlands. Peatlands are also classified according to their hydrology (Vitt 2006, Damman 1986). Hydrological characteristics of peatlands are usually presented assuming a two-layer model. Ingram (1978) summarized functional analyses of the layered structure of peatlands as follows: The upper layer, the active layer, 1) contains the oscillating water table; 2) possesses high hydraulic conductivity; 3) shows a variable water content; 4) is subjected to periodic air entry during the dewatering that follows lowering of the water table; 5) is rich in peat-forming aerobic bacteria and other organisms; and 6) has a live matrix of growing plant material. The lower layer, the inert layer, 1) is constantly saturated with water; 2) possesses a negligibly small hydraulic conductivity; 3) is not subject to air entry; 4) is devoid of peat-forming aerobic micro-organisms; and 5) is poor in microbes in general (Ingram 1978). This two-layer structure also exists in treatment peatlands. However, treatment peatlands are constructed so that the water table typically lies above the ground surface, decreasing the oscillation of the water level in the upper peat layer and increasing the area of surface water.

Water movement in peatlands is typically both lateral and vertical (e.g., Siegel & Glaser 1987, Waddington & Roulet 1997). Lateral water flow is greatest during a high water table because hydraulic conductivity is high in the upper peat layer (Verry *et al.* 1988). In treatment peatlands, the hydraulic gradient between the inlet and the outlet, and the slope, increase lateral water flow. Typically, the flow area of treatment peatlands comprises an active flow area (preferential flow area, PFA) and stagnant zones where water flow velocity is negligible as compared with the flow velocity in the preferential flow area. Most processes in wetlands are time dependent, and a fast preferential flow reduces nutrient retention and may result in saturation and loss of treatment efficiency (e.g., Bowmer 1987, Sanford *et al.* 1995, Dierberg *et al.* 2002). Knowledge of hydraulic performance is essential for modelling and design of treatment peatlands. One must know where the water flows and how long the flow pathways are. It is also important to understand the variations in flow velocities within the wetland. Information on wastewater distribution and flow enables a better prediction of the treatment efficiency and leads to a better optimization of the size and geometry of peatlands.

A basic design parameter for treatment wetlands is the potential or, as often called, the nominal hydraulic residence time of water (t_p) (e.g., Kadlec 1987, Shilton & Prasad 1996, Persson *et al.,* 1999, Farahbakhshazad 2000):

$$t_p = V/Q, \tag{1}$$

where t_p is the potential residence time (d), V the water volume of the wetland (m^3) and Q the mean volumetric flow rate of water through the wetland ($m^3\ d^{-1}$). The equation idealizes the wetland as a plug flow reactor. Porosity of the medium is taken into account in calculating the water volume of the peatland. Usually, t_p is smaller than the actually measured residence time due to zones in the wetlands that are not in the flow path. Especially in treatment peatlands, errors also arise due to the difficulty of determining the effective water volume (mobile water volume). That is, the peat is heterogeneous and the subsurface water volume requires a large sample network to be calculated accurately, and because the microtopography consists of alternating ridges and hollows, also the surface water volume cannot be estimated adequately from the water table elevation data. Moreover, the proportions of the subsurface and surface flows in the total water flow depend on hydraulic load, slope, effective porosity and hydraulic conductivity of the peat, and these parameters vary across a treatment peatland.

Tracer tests carried out in water samples by tracer addition and measurements of stable isotopes of hydrogen and oxygen are widely used in hydrological studies to measure flow processes and residence times (Sklash *et al.* 1976, Barnes & Allison 1988, Gibson *et al.* 1993, Rodríguez-Rodríguez *et al.* 2006). Because evaporation of surface water bodies (E) leads to enrichment of heavy isotopes ^2H and ^{18}O in the liquid phase, stagnant zones within the wetlands will have a high evaporation/inflow (E/Q) ratio and should be characterized by higher ^2H and ^{18}O contents than the inflow to the wetland. A properly designed survey of the stable isotope composition of water within a given wetland system provides important information in regard to spatial heterogeneity of the water in the system, and this information can be used to elucidate the structure of water flow, residence time and preferential flow. Stable isotopes are also useful when the residence times in wetland treatment systems are very long and artificial tracers cannot be added because of i) unsteady flow caused by a changing hydraulic load or weather, ii) density currents (Schmid *et al.* 2004) or iii) high costs or unreasonable time requirement.

1.4 Objectives of the study

The overall aim of this work was to clarify the effects of flow paths on phosphorus and nitrogen retention in treatment wetlands constructed on pristine peatlands in boreal conditions. The specific objectives were

- To determine the hydraulic properties of treatment peatlands and estimate the potential flow depth in treatment peatlands loaded during period of several years with municipal wastewater or peat extraction runoff (I, II).
- To determine the flow characteristics of treatment peatlands by using artificial tracers and by a new method based on the distribution of stable oxygen and hydrogen isotopes in surface water (II, III).
- To apply and develop methods allowing use of the readily available open source groundwater modelling MODFLOW code for modelling of wetland flow (III).
- To simulate the effect of the design of the inlet ditch on the hydraulic performance of treatment peatlands (III).
- To study the distribution of the peat phosphorus and surface water nitrogen concentrations from the viewpoint of flow paths and to find removal process parameters for phosphorus and nitrogen modelling in treatment peatlands (IV).

2 Description of the studied peatlands

The peatlands that were studied included two purifying runoff from peat extraction areas, and two that were polishing municipal wastewater. The first two were Kompsasuo (65º44'43' N, 25º57'80' E) and Puutiosuo (65º42' N, 26º03' E) and the latter were Ruka (66º10''10' N, 29º07''28' E) and Mellanaava (68º42' N, 27º40' E) (see Fig. 2). While the four sites had similar peat properties, they received different types of wastewater with various hydraulic loads.

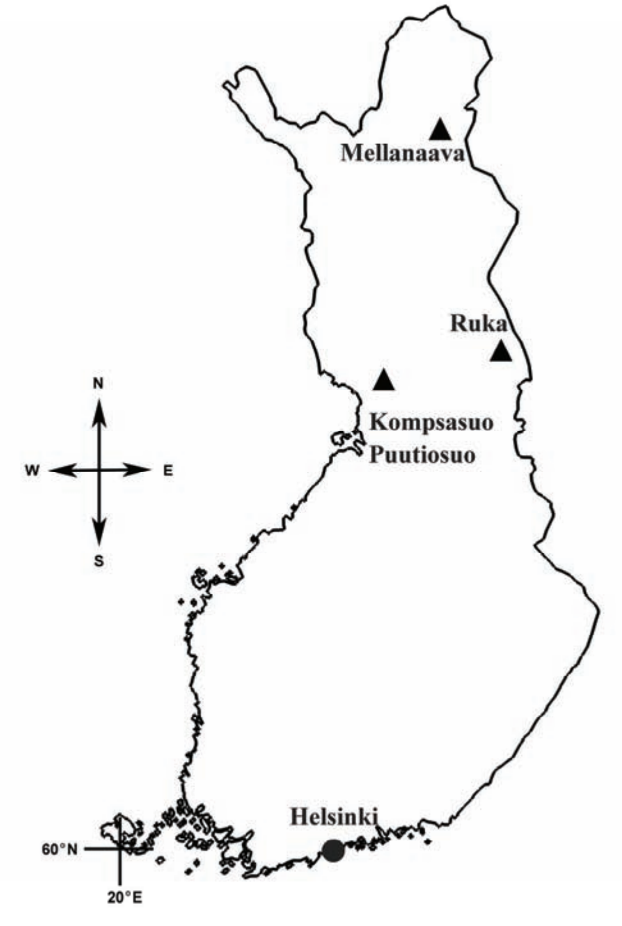

Fig. 2. Location of the four treatment peatlands studied in this work.

2.1 Kompsasuo

The Kompsasuo peatland is situated in the municipality of Kuivaniemi in the southern aapa mire zone in the mid-boreal region in Northern Finland. It currently purifies runoff from a peat extraction area (50 ha) after this has passed through a sedimentation basin (Fig. 3). The Kompsasuo area was ditched and dried for peat extraction in 1986–1989 and the wetland has been loaded since 1987. Present Finnish guidelines for the design of treatment peatlands for peat extraction runoff are based on studies in the Kompsasuo peatland, which have been ongoing since the treatment system was constructed (Ihme *et al.* 1991, Heikkinen *et al.* 1995, Heikkinen *et al.* 2002, Liikanen *et al.* 2006). The wetland area (slope 8‰) receiving runoff is 2.2 ha, which is 4% of the catchment area (56 ha). The water is fed to the wetland gravitationally via a distribution ditch (60 m) in the upper part of the wetland and it discharges via a Thomson V-notch weir to the river Hamarinjoki (Fig. 3). The water then flows along the river Kuivajoki to Bothnian Bay.

The wetland was originally a minerotrophic pine mire with *Sphagnum*, *Carex* and *Menyanthes* peat, varying on the von Post humification scale (e.g. Puustjärvi 1970) from H1 to H5 in the upper 1 m layer. Peat depth in the wetland is 1.9–3.1 m. The peat hydraulic conductivity varies from $5.2 \cdot 10^{-7}$ to $2.9 \cdot 10^{-3}$ m s^{-1}, and the peat porosity from 0.82 to 0.99 in the upper 1 m layer (I). During the years of the loading, the dominant vegetation has changed mainly due to a raised water table and more nutrient-rich conditions. The most dominant species in 1992 were *Sphagnum angustifolium, Sphagnum papillosum* and *Menyanthes trifoliate* (Huttunen *et al.* 1996), whereas in 2002 the dominant species were *Menyanthes trifoliate*, *Carex lasiocarpa* and *Potentilla palustris* (Kaasinen 2003).

In the frost-free period from May to October, the hydraulic load has averaged 17 mm d^{-1}, with as much as 54 mm d^{-1} recorded during peak runoff. The water table of the river Hamarinjoki usually rises during snow melt causing backwater in the outlet. Definitive data regarding the performance of the wetland cannot be collected during that time. During the frost-free period, the wetland removes an average of 25–64% of the total nitrogen load, 20–64% of the total phosphorus load and 21–64% of the suspended solids load. Studies on the Kompsasuo peatland are reported in publications I, III and IV.

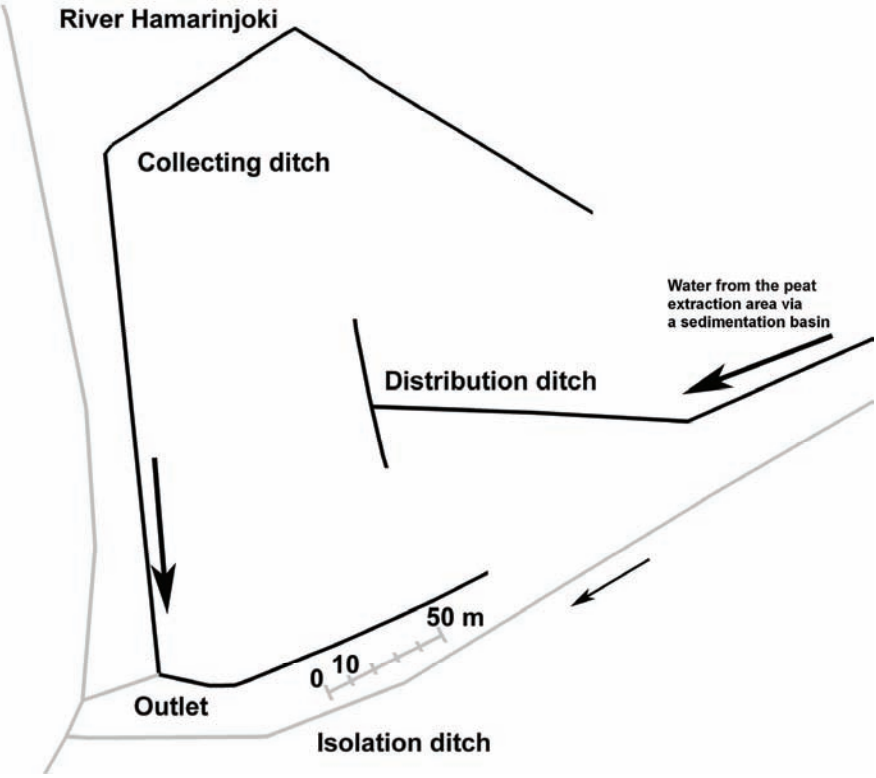

Fig. 3. Schematic image of the Kompsasuo treatment peatland.

2.2 Puutiosuo

Like Kompsasuo, the Puutiosuo wetland (6 ha, 6.7% of the catchment area) is situated in the municipality of Kuivaniemi in the southern aapa mire zone in the mid-boreal region. It purifies runoff from peat extraction areas (90 ha) after this has passed through a sedimentation basin, as well as runoff from Kompsasuo. The Puutiosuo area was ditched and dried for peat extraction in 1987–1991 and the wetland (slope 6‰) has been loaded since 1989. The operation pattern is identical with that of the Kompsasuo wetland (Fig. 4). The water from the wetland flows via a Thompson V-notch weir to the Säynäoja trench and onward, down the river Kivijoki, to lake Oijärvi where the water continues via the river Kuivajoki to Bothnian Bay.

The Puutiosuo wetland was originally an oligotrophic sedge fen with *Polytrichum-Sphagnum* peat, ranging in depth from 1.5 m to 5.0 m and being 3 m on average. In the upper 1 m peat layer the peat hydraulic conductivity varies from $2.7 \cdot 10^{-8}$ to $2 \cdot 10^{-3}$ m s^{-1} and porosity from 0.82 to 0.93.

In the frost-free period from May to October, the hydraulic load is on average 25 mm d^{-1}, but it may be as much as 300 mm d^{-1} during peak runoff. The wetland removed 32–60% of the total nitrogen load, 43–58% of the total phosphorus load and 30–66% of suspended solids during the frost-free periods in 1990–1996 (Heikkinen *et al.* 2002). The studies on the Puutiosuo peatland are reported in publications III and IV.

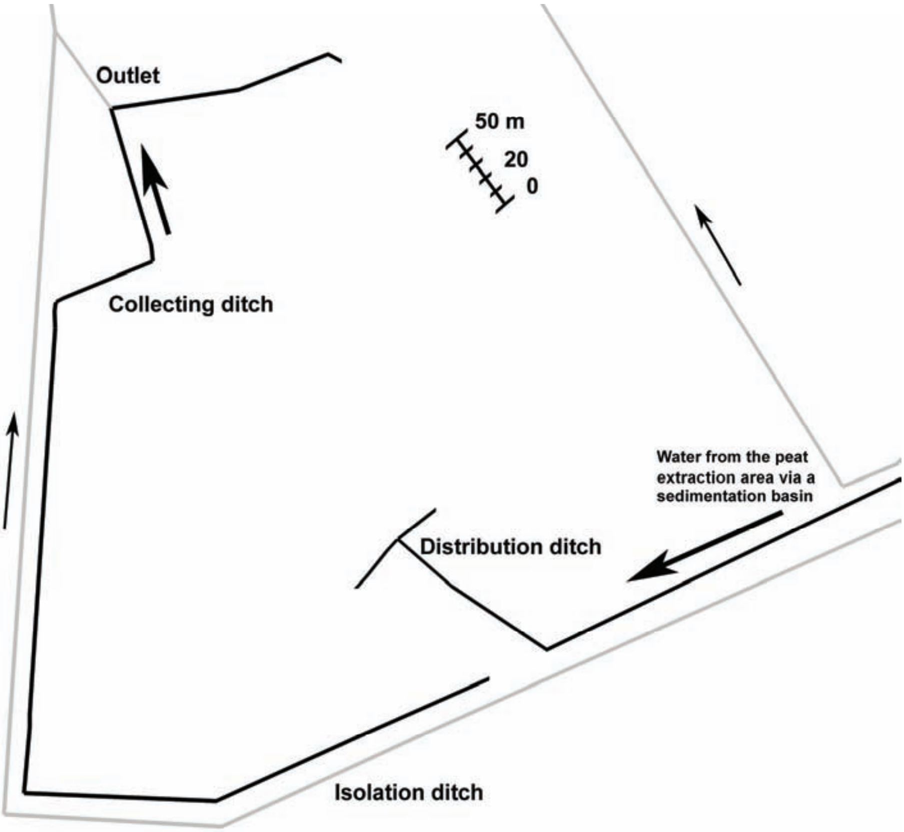

Fig. 4. Schematic image of the Puutiosuo treatment peatland.

2.3 Ruka

The Ruka wetland is located 286 m above sea level in the municipality of Kuusamo in the southern aapa mire zone in the mid-boreal region. Since 1995 the wetland has polished wastewater from the Ruka skiing resort after a conventional chemical activated sludge treatment step (Pirttijoki 1996) (Fig. 5). The precipitation chemicals are Fe and Al-based.

The wetland was originally a pine mire with *Sphagnum* and *Carex* peat. In the upper 1 m layer the hydraulic conductivity varies from 10^{-9} to $2.4 \cdot 10^{-3}$ m s^{-1} and the peat porosity from 0.88 to 0.94 (I). The dominant vegetation species in 2002 were *Carex rostrata*, *Carex lasiocarpa* and *Calamagrostis purpurea* (Karjalainen & Ronkanen 2005). Wastewater is continuously fed to the wetland (0.58 ha) by distribution ditches in the upper part of the wetland. The outlet ditch discharges through a Thompson V-notch weir to the river Kesäjoki. The left edge of the wetland is embanked to direct the wastewater to the collecting ditch. The dimensioning discharge to the wetland is 250 m^3 d^{-1}, and the wetland is by-passed if the inflow exceeds 600 m^3 d^{-1}. The hydraulic load has been, on average, 50 mm d^{-1} reaching an annual maximum (104 mm d^{-1}) during the height of the skiing season (March–April) and an annual minimum (8 mm d^{-1}) in August. The annual hydraulic load to the wetland increased from 18 m a^{-1} in 2000 to 29 m a^{-1} in 2005.

The Ruka wetland removed on average 80% of suspended solids, nearly 100% of PO_4-P, 86% of total P, 29% of NH_4-N and 63% of the BOD_7 load in the years 1995–2003 (Karjalainen & Ronkanen 2005). Concentrations are somewhat higher and removals somewhat lower in winter than in summer as a consequence of the lower temperatures and higher hydraulic load to the wetland in the winter months (Karjalainen & Ronkanen 2005). The studies on the Ruka peatland are reported in publications I, II and IV.

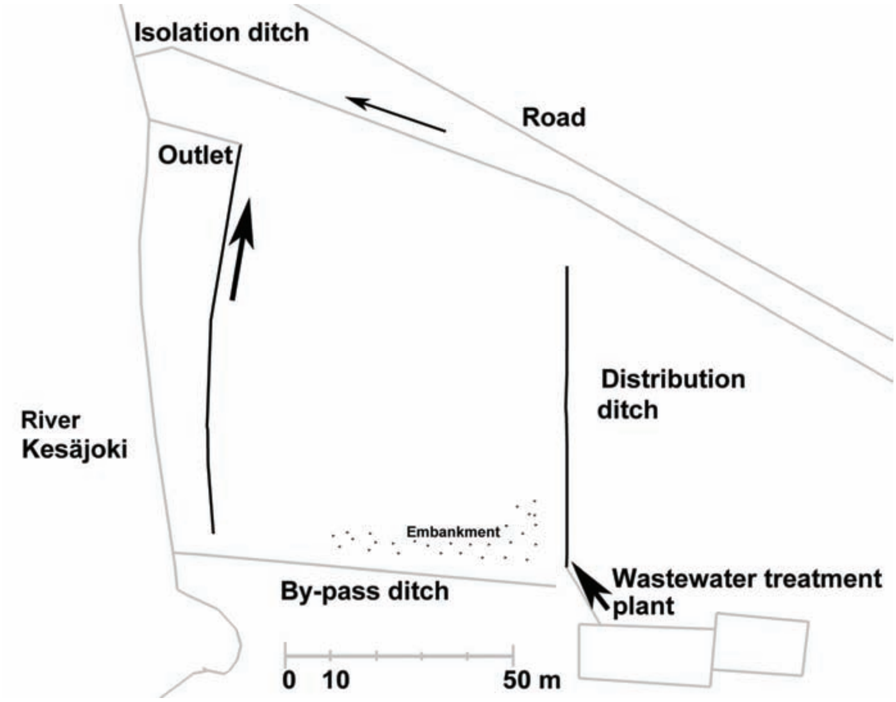

Fig. 5. Schematic image of the Ruka treatment peatland.

2.4 Mellanaava

The Mellanaava wetland in the municipality of Ivalo was constructed in 1994 to polish municipal wastewater coming from a conventional activated sludge treatment plant. The precipitation chemical was Fe-based until 2005 and after that Al-based. Besides Ruka, Mellanaava is the only wastewater treatment peatland in Northern Finland that has been used over five years. The water from the treatment plant flows through post-sedimentation basins (area 11 200 m^2; volume 16 800 m^3) where water residence time is 18 d on average before it is conducted to the wetland (Fig. 6). The wetland consists of two parallel sections (2.9 ha + 2.5 ha) that were operated on alternate months until 2004. Furthermore, before 2004 the wetland was by-passed from October to May. Only the left part of the wetland (Area 1, 2.9 ha) was studied in this work. The peat hydraulic conductivity varies from $2.7 \cdot 10^{-8}$ to $2 \cdot 10^{-3}$ m s^{-1} and porosity from 0.68 to 0.99 in the upper 1 m peat layer. After February 2005, the Mellanaava treatment plant was upgraded to include a biorotor treatment step. As the new biorotor treatment is more efficient than the previous chemical treatment, the concentrations of nutrients and solids in the inflow to the wetland have decreased, and so, too, the P and suspended solids retention values in the wetland. The frost-free season at Mellanaava is from June to September (Vadja & Venäläinen 2003), and frost may penetrate locally down to 30 cm. The results of the studies on the Mellanaava peatland are reported in publications III and IV.

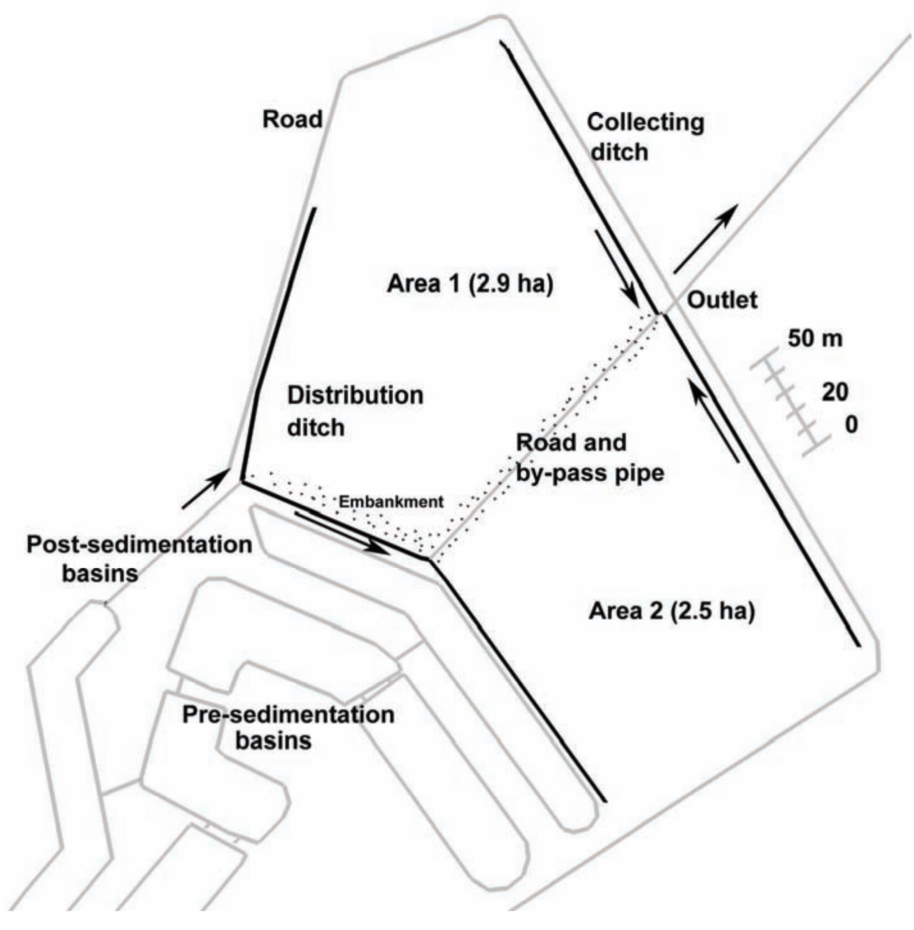

Fig. 6. Schematic image of the Mellanaava treatment peatland.

3 Material and methods

The material and methods are described only briefly in this section. Full descriptions can be found in publications I–IV.

3.1 Peat sampling and analysis (I, II, IV)

Peat samples were taken for laboratory measurements of hydraulic conductivity (K), porosity, bulk density, specific yield (S) and peat P, Al and Fe concentrations. Samples were taken in the treatment wetlands and, for comparison, from adjacent peatland not affected by wastewater (Table 1). Intact peat cores were taken from 65–85 cm depths with a sharp edged auger (8 cm × 8 cm) (Fig. 7). Samples for determination of K, porosity and specific yield from different depths were taken by pushing sharpened cylinders into the augered cores. The surface peat (depth 0–10 cm) was sampled by hand for measurements of oxalate-extractable P, Al and Fe after extraction by a modification of the method of Niskanen (1989) and for measurements of total P, Al and Fe after extraction with hydrochloric acid (HCl) (Andersen 1976).

Peat type and degree of peat decomposition were analysed at the Muhos Research Unit of METLA using von Post's humification scale (see Puustjärvi 1970). The organic matter content was calculated with the weight loss considered as the amount of organic matter in the sample. The dry weight and moisture content of the samples were determined by weighing and drying of samples at 105 ºC overnight. Since the sample volume was known, also bulk density and porosity were determined.

Table 1. Number and depth of sampling points (f × b) for the different analyses.

Analyses	Kompsasuo		Puutiosuo		Ruka		Mellanaava	
	wetland	ref. area	wetland	ref. area	wetland	ref. area	wetland	ref. area
Hydraulic conductivity	9 × 7	3 × 7	6 × 7	–	7 × 7	1 × 7	6 × 7	2 × 7
Porosity	9 × 7	3 × 7	6 × 3	3 × 3	7 × 7	1 × 7	6 × 3	2 × 3
Peat P, Al and Fe	20	3	20	3	20	–	19	1
Humification	9 × 7	3 × 7	–	–	9 × 7	3	–	–

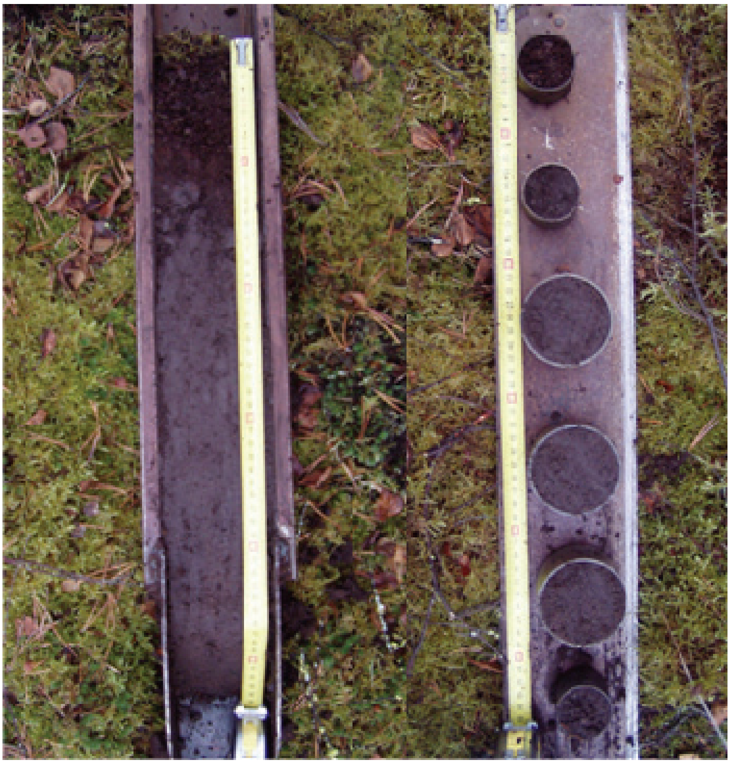

Fig. 7. Peat sampling (photo by A.-K. Ronkanen).

3.2 Hydraulic properties of peat (I)

3.2.1 Hydraulic conductivity and shear strength

The saturated hydraulic conductivity of peat (K) *in situ* was measured with a direct-push piezometer, using the falling head method, at depth 0–1 m and intervals of 10 cm (Fig. 8). Owing hydraulic head losses in the piezometer, the method provides K measurements accurate to 0.2 cm s^{-1}. In the Kompsasuo and Ruka wetlands, saturated hydraulic conductivity was also measured with Eijkelkamp cylinders (volume 100 cm^2, radius 2.5 cm) in the laboratory of Bioforsk (Norwegian Institute for Agricultural and Environmental Research) in 2002. Both vertical and horizontal hydraulic conductivities were measured in the laboratory. The results of the laboratory measurements were used to find a suitable shape factor for the piezometric method.

Shear strength describes physical properties of soil: soil bulk density, degree of humification, water content and organic-matter content (Landva 1980, Kløve 2000a, Burke 1978, Davies 1982, Ekwue 1990). To study spatial differences in peat properties within the Kompsasuo and Ruka treatment peatlands, peat shear strength was measured *in situ* with a hand vane tester (GeoNor), using a 20 mm by 40 mm vane. If the wastewater application caused changes in the peat, differences in shear strength between values close to the inlet and values close to the outlet would be expected since the suspended solid and nutrient loads are highest close to the inlet. The measurements were carried out beside the K measuring points at depth of 0–1 m and at intervals of 10 cm.

3.2.2 Specific yield and soil moisture retention

In the Ruka wetland, the specific yield (S) was determined by a simple drainage test similar to that of Tolman (1973). The test was carried out for two 10-cm-high, two 20-cm-high and four 30-cm-high intact peat cores that had been allowed to free drain by gravity on a wire tray for 13 days. The specific yield at corresponding pressure (10–30 cm) was calculated as the ratio of water released to the original soil volume.

In the Kompsasuo wetland, S was determined by calculations from soil water retention curves (pF-curves) at five different depths (4, 10, 30, 50 and 70 cm) in a pressure cell. S was calculated from the water retention measurements for different assumed groundwater depths, i.e., negative pressure in peat.

Fig. 8. Measuring hydraulic conductivity with a piezometer (photo by A.-K. Ronkanen).

3.3 Tracer experiments (II, III)

In this work, flow processes of the peatlands were studied with different tracers. Tracer experiments were carried out with artificial tracers (KBr, KI, NaCl) and measuring the stable isotopes ratio of surface water ($^{18}O/^{16}O$, $^{2}H/^{1}H$) in studied peatlands.

3.3.1 Artificial tracers

Water residence time distributions

Water residence time distributions were determined (not at Puutiosuo) by tracer test using potassium bromide (KBr) in 2001 and 2002 and potassium iodide (KI) in 2005. Table 2 describes the tests. Tracers were dissolved in wastewater and introduced to the distribution ditch during 30 to 60 min depending on the inflow rate and avoiding density stratification in the distribution ditch. Water samples were taken more frequently at the beginning of the tests, and the sampling interval was increased depending on the inflow rate. In the Kompsasuo and Ruka wetlands, also an automatic sampler (ISCO) was used to take six samples every 10 to 40 minutes. The six samples were then pooled into one sample. In addition, surface water samples were taken to detect spatial variation and spreading of the tracer. The bromide concentrations were determined by ion chromatography at the North Ostrobothnia Regional Environment Centre. The iodide concentration was determined in filtered water samples (filter diameter 45 μm) by using an ion selective electrode (Orion Thermo Ionplus 9653BN). The electrode was calibrated with water from the wetland.

Table 2. Determination of water residence time distributions in the Kompsasuo, Mellanaava and Ruka peatlands.

Wetland/	Kompsasuo		Ruka		Mellanaava	
Year	Tracer (kg)	Number of surface water samples	Tracer (kg)	Number of surface water samples	Tracer (kg)	Number of surface water samples
2001	KB (20)	–	–	–	–	–
2002	KB (15)	6 × 11	KBr(10)	–	–	–
2005	KI (3)	5 × 6	KI(2)	2 × 23	KI(4)	3 × 17

The mean residence time of the wetlands (t_d) was calculated by first moment analysis from the tracer responsive curve (Kadlec & Knight 1996). Different tests and wetlands were compared by normalizing the tracer response curves according to Werner & Kadlec (1996) using the mobile water volume (V_m) as the system volume. A short-circuiting number (s) was calculated using the ratio $s = t_{16}/t_{50}$, where t_{16} is the residence time at which 16% of the tracer is recovered and t_{50} the residence time at which 50% of the tracer is recovered (Ta & Brignal 1998).The effective porosity θ_{eff} of the wetlands was calculated as

$$\theta_{eff} = V/(h_{eff} \cdot A_{eff}), \qquad (2)$$

where A_{eff} is the effective flow area determined from the isotope measurements (m^2), h_{eff} is the mean peat depth (m) of fast water flows obtained in an infiltration test (where the infiltration resistance equals the resistance in the infiltration device) and V_m is the mobile water volume (m^3) determined by tracer test ($V_m = Q \cdot t_d$, where Q is the mean outflow rate, $m^3\,d^{-1}$).

Velocity of subsurface flow

The subsurface flow component was determined in the Ruka wetland in a salt experiment where sodium chloride (NaCl) was used. A small amount (about 20 ml) of NaCl solution (concentration 150 mg l^{-1}) was rapidly poured into groundwater tubes and mixed well. The electrical conductivity and water temperature were measured automatically with probes and recorded with a data logger (Campbell Scientific CR10X) at two depths (10 cm and 40 cm) at 10 min intervals. The assumptions for the experiment were

- the flow velocity in a groundwater tube is equal to the flow velocity in the peat layer
- the inflow to the groundwater tube is equal to the outflow from the groundwater tube (steady-state condition)
- the flow is laminar, and density current does not occur
- the vertical flow is negligible relative to the horizontal flow in the groundwater tube
- diffusion and dispersion are insignificant compared with advection
- transpiration and precipitation do not disturb the experiment
- the injection of NaCl does not change the water volume in the groundwater tube

If the in- and outflows are constant and equal, the concentration as a function of time can be expressed as

$$c(t) = \frac{m(t)}{V} = \frac{m_0}{V} e^{-\frac{va}{V}t}, \tag{3}$$

where m(t) is the amount of the salt at time t (g), V the water volume (m^3), m_0 the injected amount of the salt (g), v the flow velocity (m h^{-1}) and a the cross-section area of flow (m^2). A calibration line for the salt concentration and the electrical conductivity was determined in water from the wetland by adding a known amount of salt to the wastewater and measuring the increase in electrical conductivity. The initial electrical conductivity was subtracted at each measuring point. The flow velocity was calculated by fitting Eq. 3 to the concentration data.

3.3.2 Stable isotopes

The stable isotope ratio $^{18}O/^{16}O$ was measured in the surface water of all studied peatlands at 14–20 sampling points. Measurements at the Puutiosuo and Mellanaava wetlands were done in 2004, and those at the Kompsasuo and Ruka wetlands in 2002, 2004 and 2005. The ratio $^{2}H/^{1}H$ was measured only in the Kompsasuo and Ruka wetlands, in the year 2002. Also, samples from different depths (0–85 cm in the Kompsasuo wetland and at 20 and 40 cm in the Ruka wetland) were taken with an auger sampler and squeezed by hand. Sampling was done in 2002. The ratios $^{2}H/^{1}H$ and $^{18}O/^{16}O$ were determined at the University of Mining and Metallurgy, in Kracow (Poland), in 2002. The ratio $^{18}O/^{16}O$ was determined by mass spectrometry in the Dating Laboratory, Finnish Museum of Natural History, in Helsinki (Finland), in 2004 and 2005.

The values of the isotope ratios are reported using δ-notation (‰) and correspond to the international VSMOW standard (Vienna Standard Mean Ocean Water) according to the relation

$$\delta = 1000 \frac{R_{\mathrm{sample}} - R_{\mathrm{standard}}}{R_{\mathrm{standard}}}, \qquad (4)$$

where R represents the ratio of the higher to the lower mass isotopes and δ the enrichment ($\delta > 0$) or depletion ($\delta < 0$) of the rare isotope ^{18}O (^{2}H) with respect to ^{16}O (^{1}H).

3.4 Modelling (III, IV)

3.4.1 Flow modelling

A readily available groundwater model MODFLOW (McDonald and Harbaugh 1988) was used with the Groundwater Modelling System interface GMS 6.0 (GMS 6.0 2007) to simulate the steady-state flow paths derived from the isotope distributions. Peatland treatment systems like those described here can be considered as wetlands separated from regional flow fields. This assumption is valid due to the 1) high hydraulic loads, 2) significant hydraulic heads between inlet and outlet, 3) surrounding ditches and embankments preventing water flow from outside and 4) high water levels above the ground surface. Three-dimensional active model domains were defined with a series of drain cells, no-flow cells, and specific flow cells along the model boundaries.

Models of the Kompsasuo and Puutiosuo wetlands comprised two regular mesh layers of constant saturated thickness, while Mellanaava was modelled with a single layer of constant saturated thickness. Model topographies (the top of the first layer) were imported from elevation data derived from topographic maps of wetlands based on surface levelling measurements. The elevation of the second model layer coincides with peat layer thickness, where the measured hydraulic conductivity (K) was 10- or 100-fold higher than the hydraulic conductivity in the layer below. K was considered isotropic and heterogeneous. Model layers were divided into zones with different K values. The Preconditioned Conjugate Gradient 2 (PCG2) solver package was used in all simulations.

Models for the wetlands were calibrated in a steady-state form on the basis of their inflow and water level at observations points as measured on the isotope sampling dates. The GMS parameter estimation procedure was used to find correct K values in the high surface flow and suitable drain conductance values in the Modflow “Drain Package”. A sensitivity analysis suggested that the models are sensitive to the K values of high flow areas, and these K values were accordingly confirmed by tracer tests in the Kompsasuo and Mellanaava wetlands. Simulated water levels were within ± 0.1 m of the observed levels. MODPATH and MT3DMS codes (Pollock 1994, Zheng & Wang 1998) in conjunction with MODFLOW were used for particle tracking simulation. Only the advection package was included in the MT3DMS simulations.

3.4.2 N and P process modelling

A first-order area model was used to find process parameters for N and P removal in the Kompsasuo and Ruka peatlands. The residual concentration for the first-order homogeneous batch reaction is given by Kadlec & Knight (1996) as

$$C = \left(C_{in} - C^*\right) e^{-\frac{k}{q}y} + C^*, \tag{5}$$

where C is the concentration at distance y, C_{in} the concentration at inlet (g m^{-3}), C* the background concentration (g m^{-3}), k the rate constant (m d^{-1}), q the hydraulic loading rate (m d^{-1}) and y the distance from the inlet as a fraction of the distance from inlet to outlet. The background concentration is assumed to be zero, as is commonly done (Kadlec & Knight 1996). The surface water NH_4-N and $NO_{2/3}$-N concentrations were measured in the Kompsasuo and Ruka wetlands in 2002 (Karjalainen & Ronkanen 2005) and 2004, and the surface water NH_4-N, $NO_{2/3}$-N and total P concentrations in the Ruka wetland in 1995 and 1996 (Pirttijoki 1996). The influence of hydraulic loading, P and N loading, water residence time and the age of the wetland on the k value was evaluated through regression analysis using SPPS 16.0.1 (SPSS Inc. 2007).

4 Results and discussion

4.1 Flow characteristics of treatment peatlands (I, II, III)

Wide variation in inflow rate was characteristic of the peatlands Kompsasuo and Puutiosuo purifying peat extraction runoff (Table 3). Usually, the highest flow occurred during snow melt in spring, and inflow could drop almost to zero in dry seasons, in which case the water table would stay within the peat layer. In the peatlands Ruka and Mellanaava polishing wastewater, the inflow rate was less variable and the water table height was usually above the peat surface.

The four wetlands were similar in their peat hydraulic conductivity and porosity. Typically, hydraulic conductivity was greater than the initial resistance of the piezometer in surface layers (0–30 cm) and drastically decreased at depth 50 cm. In the Ruka wetland, however, the hydraulic conductivity was nearly 100-fold slower, even in the surface peat (0–10 cm), in the preferential flow area than in other areas. In general, measured hydraulic conductivities were in agreement with previous values reported for pristine peatlands in Finland (Päivänen 1973).

In the Ruka peatland, the mean water residence time measured by tracer tests was 1.1 d in high flow conditions (March 2002) and 0.82 d during low flow in August 2005. As discussed in paper I, these values are somewhat smaller than might be supposed from the peat hydraulic conductivity measurements. The mean water residence time was 6.0–11 d and 1 d in the Kompsasuo and Mellanaava peatlands, respectively. Water residence time less than 1 d is generally considered too short for meaningful nitrogen removal in wastewater treatment wetlands (Kadlec & Knight 1996).

Table 3. Flow characteristics of the studied peatlands.

Property	Kompsasuo	Puutiosuo	Ruka	Mellanaava
Discharge (m^3 d^{-1})				
MQ	690	1500	250	870
MHQ	9600	9900	540	1000
MNQ	100	440	160	670
Mean hydraulic load (mm d^{-1})	31	25	43	16
Peat K (m s^{-1})	$4.5 \cdot 10^{-7}$–10^{-3}	$2.3 \cdot 10^{-8}$–10^{-3}	$< 10^{-9}$–10^{-3}	$< 10^{-7}$–10^{-3}
Peat porosity	0.82–0.99	0.82–0.93	0.80–0.94	0.68–0.99
Mean t_d (d)	6.0–11	–	0.12–1.6	1.0
Effective porosity	0.92–0.99	–	0.68	0.75
Short-circuiting number s	0.31–0.53	–	0.17–0.64	0.60
A_{eff} (%)	40–99	48	30–40	42

MQ mean discharge; MHQ mean maximum discharge; MNQ mean minimum discharge; K hydraulic conductivity at the depth 0–100 cm; t_d water residence time measured in tracer tests; A_{eff} effective flow area

4.1.1 Isotope measurements to determine the effective flow area (II, III, IV)

In surface waters of the studied peatlands, the $^{18}\delta$ values measured relative to the VSMOW standard, varied from −14.45‰ to −10.04‰ with standard deviations of 0.17‰ to 0.74‰ as summarized in Table 5. The accuracy of the measurements was within ± 0.1‰ and the repeatability was 0.1‰ and 0.15‰ in 2004 and 2005, respectively. Because standard deviations of the data were greater than the accuracy of the measurements, the observed variation in $^{18}\delta$ values must have been due to fractionation processes in the surface waters. Furthermore, the Kruskal-Wallis test for $^{18}\delta$ distributions in the Ruka peatland showed the distributions measured in different field campaigns to be similar (II). The results confirmed that $^{18}\delta$ values can reliably be used to study surface flow processes in treatment peatlands.

The lowest $^{18}\delta$ value was always measured in inflows. The minimum values were −12.1 to −12.2‰, −11.2‰, −14.5 to −14.1‰ and −13.4 to −12.9‰ in the Kompsasuo, Puutiosuo, Ruka and Mellanaava wetlands, respectively. Differences between the several years of the study were due to weather conditions. As discussed in paper II, the lower the value of $^{18}\delta$ the less the evaporation in proportion to the precipitation. For the most part, the $^{18}\delta$ distributions distinguished two parts in the peatlands: a preferential flow area where $^{18}\delta$ was close to the inflow value and a stagnant area where it clearly deviated (Fig. 9). The more positive the $^{18}\delta$ value relative to the inflow the higher is the evaporation effect, indicating a slower surface flow velocity. These two flow areas were also observed in the nitrogen distributions of the surface waters (Fig. 9). Especially in the Ruka wetland, where the water residence time was too short to oxidize a high NH_4-N load, the nitrogen concentrations were high in the preferential flow area. The measurable enrichment of $^{18}\delta$ was reached in 1 to 16 days depending on the wetland and the sampling date. In other words, in some cases even one day without precipitation is sufficient to cause an observable deviation in $^{18}\delta$ values.

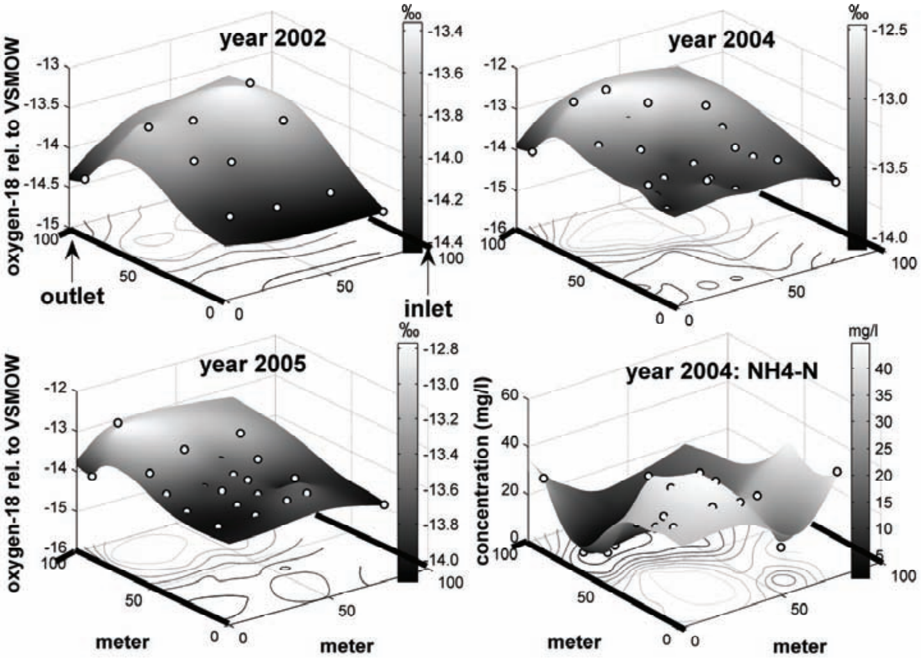

Fig. 9. Measured $^{18}\delta$ distributions in years 2002, 2004 and 2005, and nitrogen distribution in year 2004 in the Ruka wetland. Circles indicate sampling points.

During the summers of 2002–2005, the preferential flow areas were 40%–48% of the total wetland areas. However, the preferential flow area was clearly greater in high flow situations; for example, it reached 90% in the tracer test in the Kompsasuo peatland during snow melt in May 2002.

Table 4. Statistical summary of $^{18}\delta$ distributions in surface water in the studied peatlands.

Wetland	Year	N	Min	Max	Range	Mean	SD
Kompsasuo	2002	17	−12.09	−11.45	0.64	−11.86	0.16
	2005	25	−12.24	−11.45	0.79	−11.88	0.17
Puutiosuo	2004	22	−11.17	−10.04	1.13	−10.54	0.34
Ruka	2002	11	−14.45	−13.34	1.11	−13.93	0.38
	2004	22	−14.06	−12.45	1.61	−13.40	0.47
	2005	22	−14.13	−12.69	1.44	13.69	0.35
Mellanaava	2004	22	−12.93	−10.79	2.14	−11.97	0.47
	2005	13	−13.66	−11.32	2.33	12.92	0.74

N number of the samples; SD standard deviation

Both $^{18}\delta$ and $^{2}\delta$ varied with flow depth, being most negative at the lowest measuring depth (40 cm) in the Ruka peatland and at about 30 cm in the Kompsasuo peatland. Only a slight decrease in the $^{18}\delta$ value from the surface water to a depth of 30 cm was observed in the Mellanaava wetland. The mean decline in $^{18}\delta$ in Mellanaava was 0.36‰, whereas it was greater in the Ruka and Kompsasuo peatlands (0.45‰ and 1.7‰, respectively). In general, the most negative δ values fit within the range of values reported for regional groundwater (Kortelainen & Karhu 2004). In the case of the Mellanaava wetland, however, the $^{18}\delta$ value of the local groundwater was observed to be below −15.0‰ (Korteleinen & Karhu 2004) deviating by 1.3–2.1‰ from the values measured in this study. The results indicate that the flow depth of the Mellanaava wetland is 30 cm at minimum. The origin of the water in the Ruka and Kompsasuo wetlands could not be deduced from the $^{18}\delta$ measurements. In the Ruka wetland, both $^{18/2}\delta$ of the inflow and $^{18/2}\delta$ of the lowest measuring depth were in the range of the values for groundwater, whereas in the Kompsasuo wetland the $^{18}\delta$ and $^{2}\delta$ values found at the lowest measuring depth (85 cm) were equal to the values in the surface water. However, the results show that the isotopic concentration varies considerably in the uppermost peat layer because fractionation processes, especially evaporation and freezing, occur mainly in the top peat layer. In other words, the active flow depth mainly coincides with the top 0–40 cm.

In the Ruka peatland the relation between the $^{2}\delta$ and $^{18}\delta$ values did not adhere to the Global Meteoric Water Line (GMWL), nor did values correlate with each other. The opposite was true in the Kompsasuo peatland. There, the linear relation $^{2}\delta = 6.00^{18}\delta + 19.27$ deviated somewhat from the local water line for Finland

($^{2}\delta = 8.51^{18}\delta + 16.27$) determined by Kortelainen & Karhu (2004), indicating that evaporation has a significant influence on the isotopic composition of the water. The lack of correlation indicates that surface flow processes dominate (Barnes & Allison 1984).

4.1.2 Surface and subsurface flow structures (II, III)

The water residence time distributions determined by the tracer tests showed multi-peaks for all the peatlands. Tracer responsive curves showed two peaks in the Ruka peatland and several peaks in the Kompsasuo and Mellanaava peatlands. The peaks indicate the existence of two or more flow paths in each of the peatlands. Furthermore, each peatland was clearly divided into a preferential flow area and an area outside it. This division was not only indicated by the surface water tracer concentrations but also by the measured $^{18}\delta$ isotope distributions.

In both the Kompsasuo and Ruka peatlands, the surface water structure changed during the years 2002–2005. The short-circuiting number s increased from 0.17 to 0.64 in the Ruka peatland and from 0.31 to 0.53 in the Kompsasuo peatland, confirming that channel formation had increased. The increase was also visibly observed during field work, particularly in the Ruka peatland. Moreover, the water residence time decreased in the Ruka peatland despite the lower hydraulic loading. In 2005, the preferential channel was measured at less than 16 m, which is 27% of the wetland width.

In the Ruka peatland, subsurface flow as measured in the salt experiment ranged from $5.6 \cdot 10^{-5}$ m s^{-2} to $3.5 \cdot 10^{-7}$ at depth 10 cm and from $2.9 \cdot 10^{-6}$ to $1.1 \cdot 10^{-7}$ at depth 40 cm. Unlike the surface flow, the subsurface flow was not clearly divided into two flow areas. At 10 cm depth, the slowest velocity was in the preferential flow area near the inlet ditch, but at 40 cm depth the slowest value was observed at the extreme measuring points located outside the preferential flow area. At 10 cm depth the fastest velocity was in the preferential flow and at 40 cm depth the fastest velocity was outside of this area. As was concluded in paper I, the results show that the topography of the wetland and the vegetation play a larger role than peat hydraulic conductivity in creating surface flow distribution in a wetland.

According to the measured subsurface flow velocities, in the Ruka peatland a tracer peak would have taken about 61 d to flow through the peat layer 0–10 cm and nearly 900 d to flow through the peat layer 30–40 cm. As the duration of the tracer test was much shorter (11 and 22 d), only the surface flow component was measured in tracer tests. Because mass recovery in the tests was 87–90%, the subsurface flow must be a minor flow process in the peatland. This could also be the situation in the other peatlands since their peat hydraulic conductivities and hydraulic gradients were similar to the values observed at Ruka. However, vertical exchange between surface flow and peat pore water may occur, as observed by Rutherford & Nguyen (2004). Indeed, such exchange was suggested by the measurements in the Kompsasuo and Mellanaava peatlands where tracers were locally detected in peat layers 0–50 cm as well.

4.2 Phosphorus (IV)

In the treatment peatlands purifying peat extraction runoff (PE, Kompsasuo and Puutiosuo), the phosphorus load ranged from 0.72 to 5.6 mg m^{-2} d^{-1}, being on average 1.8 mg m^{-2} d^{-1} at Kompsasuo and 1.5 mg m^{-2} d^{-1} at Puutiosuo. In the wastewater treatment peatlands (WW, Ruka and Mellanaava) the incoming P load was higher, varying from 8.6 to 26 mg m^{-2} d^{-1}. Typically, the highest load to both WW peatlands occurred in March when ski resorts were busiest. Despite the highly variable P load, the annual total P removal has been high (80–95%) and stable in the Ruka wetland. Moreover, the P removal has continued high after eight years of intensive loading. Mean P removal in the Kompsasuo peatland, was 53%, which is similar to that measured in the Puutiosuo peatland (52%). Typically, the P removal was lowest during snow melt in spring and most efficient in summer. In general, the Mellanaava wetland was the most ineffective treatment peatland in P removal: mean P removal was only 12%.

The high P removal of the Ruka WW peatland was partly due to high incoming concentrations. The mean P concentration in the peat was 5.3 mg g^{-1}± 3.9 and as much as 14 mg g^{-1} in the preferential flow area (Table 6). Also, the highest concentration of Al, Fe and oxalate-extractable P, Al and Fe in peat was observed in the Ruka wetland. In the PE wetlands, the mean peat P concentration was 1.0 mg g^{-1} in the Kompsasuo wetland and 0.74 mg g^{-1} in the Puutiosuo wetland. These concentrations are somewhat greater than those previously reported in Finland: 0.39–1.8 mg g^{-1} for cultivated mineral soils, 0.41–2.0 mg g^{-1} for cultivated peatlands (Kaila 1963) and 1.3–4.6 mg g^{-1} for treatment peatland purifying untreated municipal wastewater after 13 years of loading (Kämppi 1971b). The indexes for the degree of soil saturation with phosphorus (DSSP) were very low in all the wetlands, which mean that potential for P release from the peat to water was low. The results of this study indicate that Al- and Fe-based precipitation chemicals substantially increase the P retention capacity of peatlands. Other factors to the effective P removal especially in Ruka could be the high P loading as observed in several studies (e.g. Tanner *et al.* 1995, Lu *et al.* 2009). For example, Al injection could be used to further improve P-removal in wetlands suffering from low P retention.

ANOVA analysis showed that P was not accumulated in the preferential flow area (PFA) in the PE wetlands. In the Kompsasuo PE wetland, the average peat P concentration was 1.1 mg g^{-1} in the PFA and 0.99 mg g^{-1} outside this area. The highest P concentration (1.5 mg g^{-1}) was measured in the upper part of the wetland but outside of the PFA. In contrast, a clear difference between inside and outside the PFA was observed in the WW wetlands ($p < 0.001$)). In the Ruka wetland, the mean peat P concentrations were 8.3 mg g^{-1} and 3.7 mg g^{-1} in the PFA and the area outside, respectively. The corresponding values in the Mellanaava wetland were 0.86 and 0.40 mg g^{-1}.

Table 5. Total P, Al and Fe concentrations in the peat and the inflow (mean value ± standard deviation) of the studied peatlands in 2004. The inflow concentrations are mean values from frost-free periods for the Kompsasuo and Puutiosuo peatlands and annual mean values for the Ruka and Mellanaava peatlands.

	Kompsasuo	Puutiosuo	Ruka	Mellanaava
Peat P	1.0 ± 0.27	0.74 ± 0.18	5.3 ± 3.9	0.50 ± 0.31
(mg g^{-1})	n = 22	n = 26	n = 20	n = 18
Peat Al	2.8 ± 2.0	4.6 ± 4.2	43 ± 52	0.79 ± 0.58
(mg g^{-1})	n = 22	n = 26	n = 20	n = 18
Peat Fe	14 ± 3.6	24 ± 22	34 ± 28	4.3 ± 2.3
(mg g^{-1})	n = 22	n = 26	n = 20	n = 18
P_{in}				
(mg l^{-1})	0.058 ± 0.032	0.058 ± 0.019	0.44 ± 0.28	0.26 ± 0.25
(kg ha^{-1} a^{-1})	6.6	5.3	70	15
%	53	52	83	12
N_{in}				
(mg l^{-1})	2.5 ± 1.3	1.8 ± 0.82	46 ± 19	56 ± 22
(kg ha^{-1} a^{-1})	285	170	7300	3300
%	52	46	19	18
Al_{in}				
(mg l^{-1})	0.24*	0.13*	2.4	0.28*
(kg ha^{-1} a^{-1})	28	12	430	16
Fe_{in}				
(mg l^{-1})	2.6 ± 1.3	4.2 ± 1.7	0.50 ± 0.64	1.9*
(kg ha^{-1} a^{-1})	290	380	87	110

* indicative values due to lack of data; n number of samples

In the Ruka wetland, in both the PFA and the slow flow area the P accumulation decreased exponentially with distance from the inlet. The accumulation was at least effective in the PFA. The peat P_{tot} concentration was measured to be 0.3–3.4 mg g^{-1} (mean 1.3 mg g^{-1}) in 2002 (Karjalainen & Ronkanen 2005), this means that about 4 mg P g^{-1} had accumulated in the peat during two years (Mean value in 2004 was 5.3 mg g^{-1}; see Table 6). Calculating enrichment in the PFA (depth 10 cm) as kilograms (II), the peat P_{tot} concentration is seem to have increased by about 86 kg in two years. The P_{tot} retention based on the inlet/outlet data during two years was about 92 kg, which means that about 93% of the removed P had accumulated in the peat.

In the Kompsasuo wetland, P was accumulated into the lower part of the wetland in the PFA. Laiho *et al.* (1999) have reported that peat P_{tot} concentration is 0.70 ± 0.10 mg g^{-1} at depth 5 cm and 0.95 ± 0.15 mg g^{-1} at depth 15 cm in undrained meso-oligotrophic peatlands in Finland. In present study, the peat P_{tot} range was 0.8–1.4 mg g^{-1}, and 1.0 mg g^{-1} on average, in the PFA at depth 0–10 cm, which means that the concentration had not substantially increased since the construction of the peatland. However, the total P retention has averaged 53% in summer (from May to August). The reason why no increase in accumulation was observed may be the low loading rate. The P load to Kompsasuo has been one tenth that to the Ruka wetland. However, temporary P releases cannot be excluded for two reasons: First, only the Fe concentration correlated statistically with the P concentration indicating that, under anaerobic conditions, P can be leached because Fe becomes soluble (Patrick *et al.* 1973, Patrick & Khalid 1974). This was supported by the P accumulation far from the inlet ditch since anaerobic conditions in the peat layer would more easily be created near the inlet ditch where the water table usually lies on top of the peat and the BOD loading is the greatest.

In 1995, Pirttijoki (1996) measured the surface water total P concentration twice for three measuring lines within the Ruka wetland. In the present study, P removal rate constants for the wetland were found by fitting a first-order reaction model to Pirttijoki's data. The k values averaged 0.9 d^{-1} and 1.5 m d^{-1} when the P loadings were 0.040 mg m^{-2} d^{-1} and 0.032 mg m^{-2} d^{-1}, respectively. The mean first-order area reaction rate for P removal was 1.2 m d^{-1}, which is considerably higher than the values of about 0.055 m d^{-1} estimated by Kadlec (2000) and 0.59 m d^{-1} estimated by Braskerud (2002) for constructed wetlands with free water surface. The results indicate that the accumulation of P to peat via adsorption and chemical precipitation is still the most important phosphorus removal process in treatment peatlands after 10 years of loading. The results also show long-term phosphorus accumulation in the WW peatlands.

Overall, peat Al, Fe and P analyses showed that the in-coming loading affects P retention to peat. The Fe loading was high in the PE wetlands, and also the peat Fe concentration correlated positively with the peat P. The correlation increased linearly as the log-transformed Fe concentration of the inflow increased ($y = 0.278x + 0.199$, $R^2 = 0.99$). Al loading was almost 40 times higher in the Ruka wetland than in the other wetlands, and it also clearly correlated with peat P ($r = 0.77$, $p < 0.01$). The data also show that the higher the P loading, the higher was the peat P concentration.

4.3 Nitrogen (II, III, IV)

The NH_4-N load to the WW peatlands, Ruka and Mellanaava, varied from 0.069 to 9.1 g m^{-2} d^{-1}, whereas it was clearly lower (0.003–650 mg m^{-2} d^{-1}) to the PE peatlands (Kompsasuo and Puutiosuo). The NH_4-N load was about 70% and 40% of the total N load to the WW peatlands and PE peatlands, respectively. In the PE peatlands the NH_4 removal was 52–97% during frost-free periods, whereas in the WW peatlands, it was 2–80%. The annual removal in the WW wetlands was only 3–40%. The lower removal values in the WW peatlands are partly explained by the higher loading and shorter water residence times (II, III). The NH_4-N removal (Red_{NH4}) decreased exponentially as the NH_4-N load (NH4) increased ($Red_{NH4}=0.758e^{1.08NH4}$, $R^2 = 0.68$). In the Ruka peatland, moreover, there was an exponential decrease in N removal with the age of the peatland. This might have been due to increased channel formation (II).

According to ANOVA analysis, the concentrations of NH_4+NO_{2+3}-N in the surface water of the Ruka peatland were higher inside the PFA than outside the PFA ($p = 0.03$). The same trend was evident in the concentration distributions (see figures in publication IV). Measured concentrations were highest in the PFA and they remained high throughout the area. The first-order area model for nitrogen (NH_4+NO_{2+3}-N) removal gave 0.083, 0.27, 0.085 and 0.048 m d^{-1} as the mean rate constant values (k) in 1995, 1996, 2002 and 2004, respectively. Regression analysis shown a linear relationship between k and discharge (Q) ($k = -0.0003Q + 0.15$, $R^2 = 0.91$). These results, and the measured inflow concentrations, were used to estimate outflow NH_4+NO_{2+3} concentrations by the first-order area model for the Ruka wetland in 1996 and 2000–2002. Figure 10 shows good agreement between the observed and calculated concentrations. Also some other factors appear to be influencing the k values, however, especially for high outflow concentrations where only weak agreement was observed between the fitted and observed values.

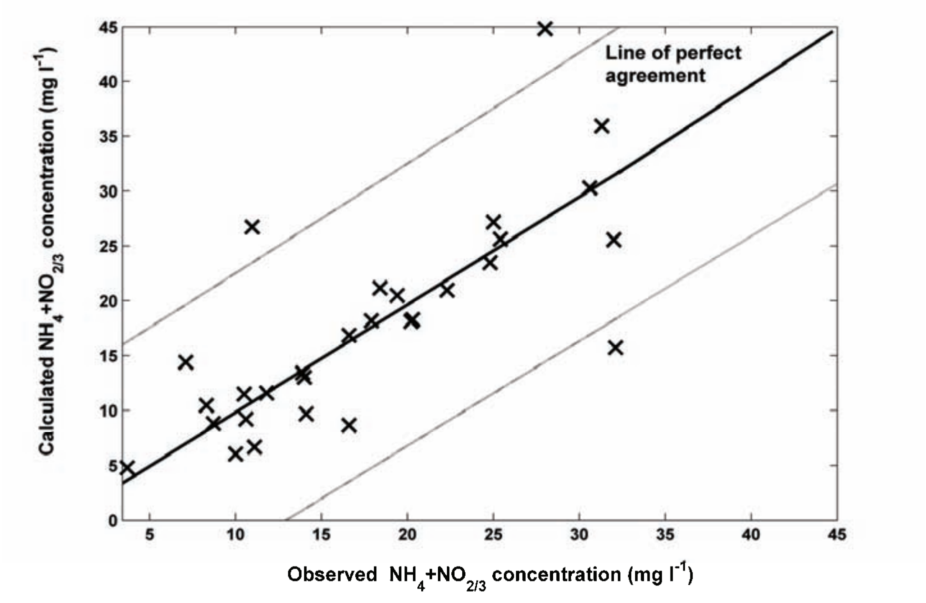

Fig. 10. Calculated versus observed NH_4+$NO_{2/3}$ concentrations (mg l^{-1}) in the Ruka wetland in 1996 and 2000–2002. The confidence level 95% is indicated with grey lines.

In general, water residence time influences the NH_4 removal rate in treatment wetlands. In the Kompsasuo wetland, mean concentrations of NH_4+NO_{2+3}-N in the surface water were not different in the PFA and the area outside. Concentrations were clearly higher in the PFA near the inlet ditch, but decreased, close to values outside the area in the downstream in the PFA. The NH_4-N removal efficiency has been good too, ranging from 57 to 97% during summer. This means that the water retention time is long enough to oxidize NH_4 even in the PFA. The mean k value for NH_4+NO_{2+3}-N removal was 0.011 m d^{-1} for data from 2004 and 0.21 m d^{-1} for data from 2002. The values are not substantially higher than those in the Ruka peatland where the nitrogen removal has been poor. Because the mean nitrogen load to the Kompsasuo peatland is only about 4% of that to Ruka, the determined k values are certainly sufficient for the removal of nitrogen from the runoff water.

4.4 Dimensioning of the treatment peatland

Traditionally, one of the key factors in dimensioning Finnish treatment peatlands purifying peat extraction runoff has been the ratio of length (L) of the peatland to the width (W). Optimally, the L/W ratio should be 0.5–1 (Ihme 1994). Less attention has been paid to the dimensioning of distribution ditches. In this study, the design of the distribution ditch was studied by carrying out MT3DMS simulations of the Kompsasuo wetland (L/W = 0.5) with different lengths of the distribution ditch (DL). Simulations showed that elongating the ditch relative to the width of the wetland improved the effective flow area. Also, the shortest water residence time (t_s) increased. The dependence was found to be logarithmic with r-square value 0.99 (DL/W ratio = $0.698 \cdot \ln(t_s) - 0.966$). Furthermore, a greater DL/W ratio in the simulation decreased the proportion of the PFA in the flow process. The implication of the simulation of wetland design described here is that hydraulic performance varies significantly with the DL/W ratio. As concluded in paper III, the results show that, even if the proper location for the distribution ditch is unambiguous, longer ditch length will create a larger effective flow area. It is also possible that a more optimal length of the distribution ditch could prevent channel formation and the formation of dead zones.

Another important design factor for treatment peatlands purifying peat extraction runoff has been the ratio of the area of a constructed wetland to the area of its catchment (W/C) (Savolainen *et al.* 1996). Several studies suggest that this ratio is the single most important design factor (Kovacic *et al.* 2000, Uusi-Kämppä *et al.* 2000, Koskiaho & Puustinen, 2005). In practice, what it means is that removals depend on loadings. Thus, Koskiaho & Puustinen (2005) report a linear regression $y = 6.95x + 0.08$ ($R^2 = 0.77$) between N removal and the W/C ratio and a linear regression $y = 6.54x + 0.01$ ($R^2 = 0.75$) between P removal and the W/C ratio. Removals of 70% in N and P would be achieved with W/C ratios of 0.10 and 0.11, respectively. The W/C ratio is 0.04 and P removal 53% for the Kompsasuo peatland. The removal in the Ruka peatland is clearly higher (83%) despite the high loading. In contrast to this, the findings of the present study show that P removal depends more on the removal processes within the peatland than on the P loading (or the W/C ratio).

Finland has set limits on nitrogen value for municipal wastewater treatment: the outflow concentration should be below 10–15 mg l^{-1} depending on population equivalent, and the annual mean total N removal should be at least 70% (Ministry of the Environment 1994). The results of the present study show that the NH_4

loading to the peatland should be below 0.10 mg m^2 d^{-1} in order to achieve a removal of 70%. In the Ruka wetland, this means that the mean inflow rate should be below 25 m^3 d^{-1} (4 mm d^{-1}), which is 15% of the present annual mean flow rate. Furthermore, the mean N loading to the Ruka wetland is 42 mg l^{-1} and the flow rate 190 m^3 d^{-1}, and the k value is therefore about 0.094 m d^{-1}, meaning that the water retention time should be 2.5 d in order to achieve an outflow concentration of 10 mg l^{-1}. The present mean water retention time is just somewhat more than 1 d since the PFA is 40% of the total wetland area. If the PFA was equal to the total wetland area, the water retention time would be 2.2 d assuming effective porosity 0.7 and flow depth 0.1 m. The calculation shows that an effective distribution of water flow needs to be provided in designing treatment peatlands.

A successful model application requires a good understanding of local stratigraphy and hydrogeology. According to the present study, six boreholes (1–3 ha^{-1}) down to the impermeable layer (at 1 m in this study) are a minimum for collecting data on peat properties such as porosity and K values. The demanding part of the MODFLOW application for treatment peatlands is how to simulate the surface flow. In this study, K values for the uppermost layers were calibrated by tracer tests. The calibration is critical because models are sensitive to the K value. As dry cells must be prevented, the uppermost layers in the model include both the overland water flow and the shallow water flow within the peat. The calibrated K values do not describe peat hydraulic conductivity physically but rather they are the sum of overland flow and shallow flow. A major question is how the K values in the uppermost model change with the hydraulic loading. This relationship will be resolved in future studies. It might be possible to use Saint Venant's equation for surface flow (Restrepo *et al.* 1998, Bauer *et al.* 2006), but still some parameters, like the roughness coefficient, remain physically non-specific. Also, the width of channels and the surface level of the water in channels are difficult to specify due to the complex surface structure of peatlands. A summary of the proposed modelling procedure is given in Fig. 11.

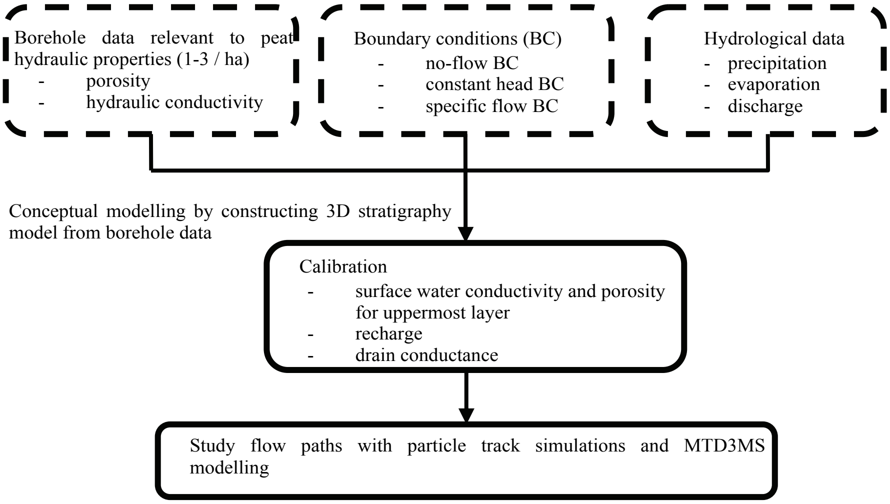

Fig. 11. Schematic presentation of modelling of treatment peatlands in MODFLOW.

5 Conclusions and directions for future studies

Determinations of preferential flow area and flow depth are essential in designing treatment peatlands. The potential flow depth, as determined by hydraulic conductivity measurements could be as much as 50 cm in treatment peatlands. In the Ruka peatland, the subsurface water flow velocity, averaged only $1.5 \cdot 10^{-5}$ m s^{-1} already at 10 cm depth, which means that the subsurface flow had only a minor role in the purification processes.

Both artificial tracer and surface water $^{18}\delta$ distributions showed that overland flow was the dominant flow process. In all four peatlands studied, the surface flow was divided into an active, preferential flow area and dead zones. Especially in the Ruka peatland, the water volume through the preferential flow area increased during the years of the study, indicating the existence of active channel formation processes. The observed exponential decrease in N removal with age of the peatland also pointed to accelerated channel formation. These results show that, without maintenance, the hydraulic performance of peatlands can deteriorate drastically within a short period of time. Not only is purification efficiency reduced, but also the life-time of the peatlands may be shortened. Channel formation, the development of preferential flow areas and erosion in the vegetation and surface peat layer are all poorly known and need to be clarified in future studies.

The active flow areas in the peatlands generally comprised about 40–48% in summer meaning that large areas with potential for nutrient removal were not being used. This is an important finding since most of the nutrient load of peat extraction occurs during summer. Practical recommendations arising from this study, which might prevent or reduce short-circuiting and dead zones in treatment peatlands are the following: (1) the ratio of inlet ditch length to peatland width should be more than 0.45, (2) the height of the water table in the inlet ditch should be just above the peat surface and (3) the inlet ditch should not slope along the wetland surface inclination.

The surface water $^{18}\delta$ distributions in the peatlands confirmed the usefulness of isotopes in evaluating water flow structures in cold climate peatlands. Isotopes can be used to evaluate the active flow width and flow depth. Depending on weather conditions, as little as one day without precipitation was sufficient to obtain isotope enrichment required for meaningful measurements. Also, variations in water temperature were found to define the most active flow area in the wetland.

The measured residence times were an order of magnitude shorter than the potential residence time. This study suggests for treatment peatlands, that the potential residence time formula should be modified to include effective flow depth, area and porosity θ_{eff} as $V = \theta_{eff}A_{eff}h_{eff}$. The effective area ($A_{eff}$) can be evaluated by isotope measurements and effective flow depth h_{eff} by infiltration tests (0.1–0.5 m). Here, the effective porosity θ_{eff} was determined to be 0.68–0.99.

Flow models created with the MODFLOW code accurately simulated the hydraulic head across wetlands: the correlation coefficient was 0.95–0.99. Similarities between the flow models and the $^{18}\delta$ distributions suggest the possibility of using the MODFLOW code for the design of peatland treatment systems. Some guidelines for modelling treatment peatlands were proposed.

The peat P_{tot} concentrations ranged from 0.097 to 14 mg g^{-1} being 1.8 ± 3.9 mg g^{-1} on average, and P was accumulated in the PFA. Although P_{tot} concentrations were locally high, the index of potential soil P release from peat to water was very low in all the studied peatlands indicating that the peat was not saturated with phosphorus. The P_{tot} in the wastewater peatlands correlated positively with the peat Al_{tot} concentration indicating that Fe- and Al-based precipitation chemicals increase the P retention capacity of peatland substantially and maintain P retention at a stable level despite varying P loads.

In the Ruka wastewater treatment peatland, the mean first-order area reaction rate for P_{tot} removal was 1.2 m d^{-1}, which is considerably higher than previously observed. This result indicates that the accumulation of P_{tot} to peat via adsorption and chemical precipitation is still the most important phosphorus removal process in wastewater treatment peatlands after 10 years of loading. It also indicates long-term phosphorus accumulation in peatlands receiving municipal wastewater. Furthermore, the study showed that P_{tot} retention in treatment peatlands depends more on the removal process than on P_{tot} loadings.

Calculated nitrogen concentrations in surface water obtained with the first-order area model, together with regression analysis of the rate constant, were in good agreement with observed nitrogen concentrations. The regression analyses showed that k values for N removal depend on N loading and flow rate to the wetland. To achieve a removal of 70%, the NH_4-N loading to the peatland should be below 0.10 mg m^2 d^{-1}.

Constructed wetlands and treatment peatlands have been under intensive study throughout the world including in cold climates. The performance of purification processes in winter conditions is not yet fully understood, however. The hydraulics of treatment peatlands during winter months needs to be clarified. How does frost affect flow paths? Does the effective flow area change during snow cover? Climate change promises to raise annual mean temperatures and, in the North, increase precipitation especially in winter months. The effects on the depth of snow cover, frost penetration and runoff formation will pose tough challenges for purification processes in treatment peatlands. Finally, the importance of winter runoff in total runoff will increase in peatlands treating peat extraction runoff.

Construction of wetland treatment systems on pristine peatlands will probable not be possible in the future as a government decision-in-principle has targeted pristine peatlands for conservation (Ministry of the Environment 2007). Treatment peatlands for purifying point source and diffuse pollutants will have to be constructed in other areas not necessarily optimal for nutrient removal. The results of this study indicate that Al originating in precipitation chemicals used in wastewater treatment substantially increases the P retention capacity of peatland and maintains P retention. Thus, Al injection could offer a way to improve P removal in wetlands suffering from low P retention. Further studies are needed, however. We need to know, for example, how much Al is needed and how particular hydrological and chemical conditions affect P and Al retentions.

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Original publications

This thesis summarizes work reported in the following original publications, which are referred to in the text by their Roman numerals.

I Ronkanen A-K & Kløve B (2005) Hydraulic soil properties of peatlands treating municipal wastewater and peat harvesting runoff. Suo – Mires and Peat 56(2): 43–56.

II Ronkanen A-K & Kløve B (2007) Use of stabile isotopes and tracers to detect preferential flow pattern in a peatland treating municipal wastewater. Journal of Hydrology 347(3–4): 418–429.

III Ronkanen A-K & Kløve B (2008) Hydraulics and flow modelling of water treatment wetlands constructed on peatlands in Northern Finland. Water Research 42(14): 3826–3836.

IV Ronkanen A-K & Kløve B (2009) Long-term phosphorus and nitrogen removal processes and preferential flow paths in Northern constructed peatlands. Ecological Engineering 35(5): 843–855.

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