© Suoseura — Finnish Peatland Society
Helsinki 2005

ISSN 0039-5471
Suo 56(2): 43–56

Hydraulic soil properties of peatlands treating municipal wastewater and peat harvesting runoff

Anna-Kaisa Ronkanen & Bjørn Kløve

Anna-Kaisa Ronkanen & Bjørn Kløve, Water Resources and Environmental Engineering Laboratory, Department of Process and Environmental Engineering, P. O. Box 4300, FIN-90014 University of Oulu, Finland, e-mail: anna-kaisa.ronkanen@oulu.fi

Peat hydraulic conductivity (K), specific yield (S), degree of humification and shear strength were measured at two wetland treatment systems constructed on natural peatlands receiving different wastewater quality and loading in Northern Finland. Peat K was measured with a falling head piezometer test *in situ* and by taking soil cores in horizontal and vertical directions using Eijkelkamp cylinders. Peat S was obtained from pF-curves and drainage tests. The K *in situ* was $5.2 \times 10^{-7} - 2.9 \times 10^{-3}$ m s^{-1}, the horizontal K was $6.1 \times 10^{-6} - 3.8 \times 10^{-2}$ m s^{-1} and the vertical K was $4.2 \times 10^{-6} - 2.6 \times 10^{-2}$ m s^{-1}. The highest K value was usually found in the vertical direction. The estimated acrotelm layer with high K reached 40–60 cm at Kompsasuo wetland and 10–60 cm at Ruka wetland. There was an agreement between different measurement methods for S when pF values corresponding to relevant negative pressure were used. S varied from 0.023 to 0.23. After several years of wastewater loading, the peat hydraulic conductivity was still sufficient to maintain wastewater flow in the top 50 cm of the peatland.

Keywords: hydraulic conductivity; peat; specific yield; wastewater treatment; wetland

Introduction

In Finland, natural peatlands were used from 1957 to early 1980s to treat municipal wastewater by infiltrating the wastewater into ditches on peatlands (Surakka & Kämppi 1971, Lehtonen 1994). The first experiments showed that the high solid loads clogged the peat, and the method was therefore not suitable in primary or secondary treatment with high solid loading (Munsterhjelm 1972, Lehtonen 1994). However, since the late 1980s, peatlands have been used to treat waters with relatively low suspended solid content such as peat harvesting runoff and forest drainage runoff (e.g. Ihme et al. 1991, Heikkinen et al. 1994, Savolainen et al. 1996, Lyytikäinen et al. 2003). In 1994, a pilot project was started in Ruka (Finland) to complement chemically treated municipal wastewater by polishing the treated wastewater in peatland (Pirttijoki 1996, Hallikainen 2003). During the pilot projects, some design and management guidelines were formulated. However, the hydraulic properties such as peat hydraulic conductivity or specific yield had not been previously measured, and flow depths of wastewater in peatland remained uncertain. The active flow layer is important as it determined the total soil and water volume available for purification.

The soil physical properties of natural peatland are generally layered, with a top layer, acrotelm, consisting of living plants and rapidly decaying plant material and a lower layer, catotelm, where the plants have been humified to peat. In peatlands the hydraulic conductivity decreases with increasing humification and depth (Huikari 1959, Boelter 1969, Korpijaakko & Radforth 1972, Päivänen 1973). It is well documented that the hydraulic conductivity of catotelm is low at around 10^{-7}–10^{-9} m s^{-1} (Boelter 1965, Chason & Siegel 1986), whereas the hydraulic conductivity of acrotelm peat can be as high as 10^{-1} m s^{-1} (Burt et al. 1990 and Hobbs 1986). There is usually a large spatial variation in the hydraulic properties of peat and the hydraulic conductivity depends to a large degree on the pore-size distribution of the peat. Peats with high fiber content and low bulk density have the highest hydraulic conductivity (Boelter 1965). Also, the variation between mires can be high. Huikari (1959) found that the hydraulic conductivity was higher in the upper peat layer in bog fens than in pine mires, but the contrary was found in deeper peat layers (over 30 cm).

In addition to hydraulic conductivity, the subsurface flow in peat depends on peat water storage capacity. The effective porosity affects the subsurface flow velocity and water table fluctuations. In general, the water table movement in unconfined systems such as the acrotelm is modelled using the concept of soil specific yield, which is the relationship between the quantity of water that has been added to or removed from the soil and the subsequent change in the water table (Boelter 1965). Previous studies indicate that the specific yield decreases from around 0.8 to 0.1 as the peat changes from an undecomposed peat to a well-decomposed peat (Boelter 1965, Päivänen 1973).

Objectives of the study

The aim of this study was to determine the hydraulic properties of two peat-based wetland treatment systems which have been loaded with wastewater for several years. The hydraulic properties are a prerequisite for estimating water residence time and for modelling flow and transport of nutrients in the wetlands. In previous wetland studies, it has been suggested that the accumulation of organic matter could reduce the permeability and the life-time of the wetland (Sundblad 1988, McIntyre & Riha 1991, Tanner & Sukias 1995, Tanner et al. 1998, Mæhlum 1998). Another objective of this study was to determine the effective or main flow depth in which the wastewater flows in the peatland treatment systems. This is important as the purification processes occur mainly in the active flow layer.

Material and methods

Study Sites

The sites are located in northern Finland in the municipalities of Kuivaniemi (Kompsasuo, 65°45'N, 26°00'E) and Kuusamo (Ruka, 66°10'N, 29°7'E) (Fig. 1). The sites selected had similar peat properties, but received different types of wastewater. Kompsasuo wetland purifies drainage water from a peat harvesting area and Ruka wetland purifies municipal wastewater from a skiing resort after conventional chemical treatment. Both wetlands were originally minerotrophic mires with *Sphagnum* and *Carex* peat, varying from von Post humification scale (e.g. Puustjärvi 1970) of H1 to H5 in the upper 1 m layer (Table 1). The wetland areas receiving wastewater are 2.4 ha and 0.8 ha at Kompsasuo and Ruka, respectively. The sites have been loaded with wastewater since 1987 and 1995 for Kompsasuo and Ruka, respectively.

Wastewater is fed continuously to wetlands by distribution ditches in upper parts of the wetlands (Fig. 1). Both horizontal subsurface and surface flow occurs in both wetlands. At Ruka, the wetland is by-passed if the wastewater load exceeds 40 m^3 h^{-1}. A more detail description of Kompsasuo wetland is given in Ihme et al. (1991).

In frost-free period from June to October, the hydraulic load at Kompsasuo is on average 17 mm d^{-1}, but can reach up to 54 mm d^{-1} during peak runoff (Table 1). The wetland removes on annual average 25–64% of a total nitrogen load, 20–64% of a total phosphorus load and 21–64% of a suspended solids load in the frost-free period. At Ruka wetland, the hydraulic load is on

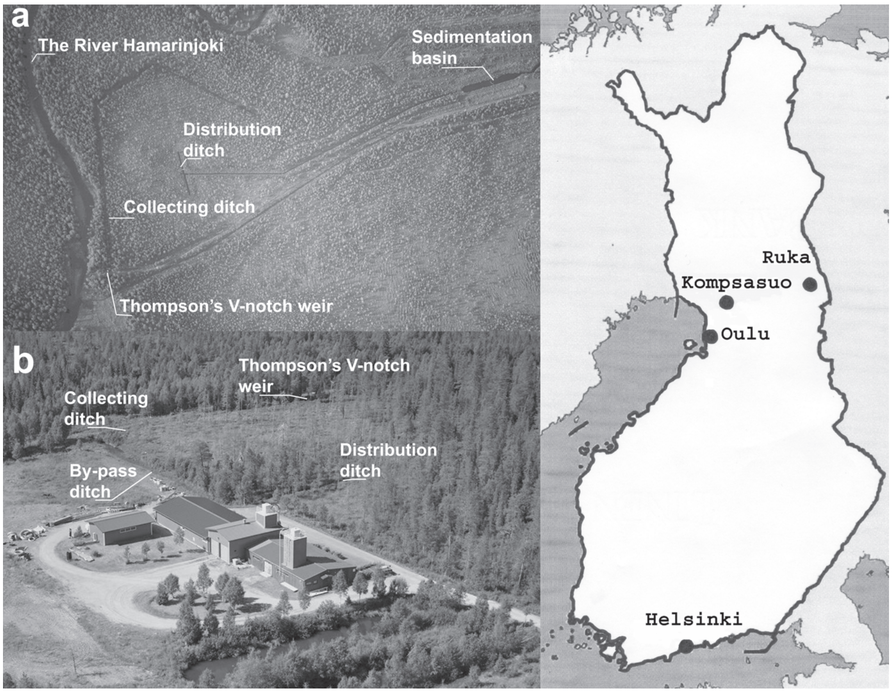


Fig. 1. Location of Kompsasuo (a) and Ruka (b) wetlands. (Photo: Suomen Ilmakuva Oy)

Kuva 1. Kompsasuon (a) ja Rukan (b) tutkimuskosteikkojen sijainti. (kuva: Suomen Ilmakuva Oy)

Table 1. Characteristics of the study sites on wetland (Kompsasuo and Ruka).

Taulukko 1. Kompsasuon ja Rukan tutkimuskosteikkojen ominaisuustietoja.

		Kompsasuo			Ruka		
Area (ha)		2.4			0.8		
Slope (‰)		8			8.5		
Design criterion		4.8% of drainage area			Max load 250 m^3/d		
Peat depth (m)		1.9–3.1			0.5–1.5		
Peat type[1]		SC and MenCS			CS		
Degree humif. (von Post)		H1–H5			H1–H6		
		Aver.	Min.	Max.	Aver.	Min.	Max
Discharge to the wetland	mm d^{-1}	17	2	54[2]	36	6	75
N	kg ha^{-1} d^{-1}	1	0.007	19[3]	21	1	79[4]
	mg l^{-1}	2	0.3	7	41	3	81
Total P	kg ha^{-1} d^{-1}	0.01	0.001	0.3	0.2	0.01	0.7
	mg l^{-1}	0.06	0.01	0.3	0.4	0.06	2
BOD_7	kg ha^{-1} d^{-1}	0.1	0.05	0.2	3	0.2	14
	mg l^{-1}	2	0.5	4	6	1	28
Susp. solids	kg ha^{-1} d^{-1}	1	0.04	35	6	0.3	25
	mg l^{-1}	6	1	104	3	2	34

[1] Men = *Menyanthes*, C = *Carex*, S = *Sphagnum*: [2] Frost–free period (from June to October): [3] total N: [4] Inorg.N

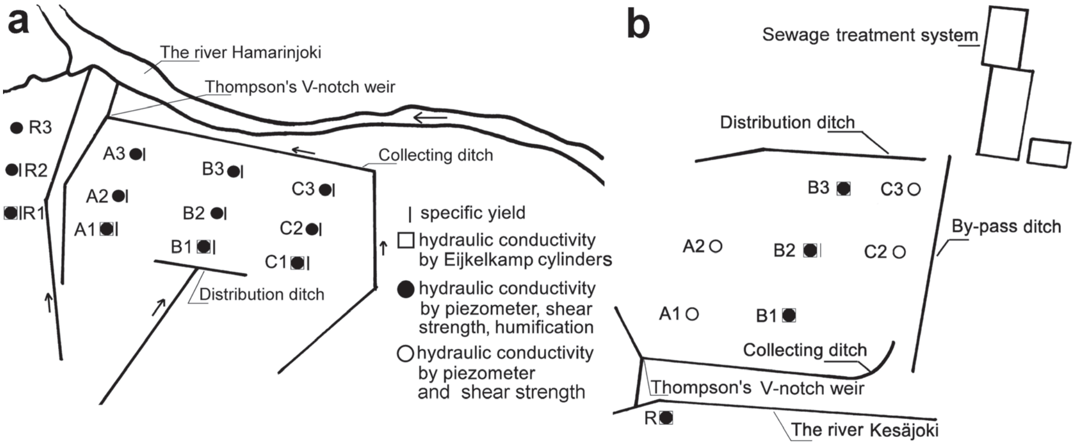


Fig. 2. Sampling points at a) Kompsasuo and b) Ruka wetlands and adjacent reference areas (R).

Kuva 2. Mittauspisteet a) Kompsasuolla ja b) Rukalla sekä niiden vertailualueilla (R).

average 36 mm d^{-1} reaching an annual maximum during winter ski holidays. The wetland reduces efficiently total phosphorus (69–93%), suspended solids (68–94%) and BOD (32–94%). The nitrogen load is mainly inorganic nitrogen and it is removed about 5–43% in the wetland.

Sampling points and soil sampling

Soil samples were taken in the treatment wetlands and for comparison from the adjacent natural peatland not affected by wastewater. At Kompsasuo, samples were taken from 9 sampling points in the wetland and from 3 sampling points in the reference area (Fig. 2a). At Ruka, 7 samples were taken in the wetland and one in the reference area (Fig. 2b). During sampling, the water table in both wetlands was at 0–5 cm below soil surface.

Intact peat cores were taken from 65–85 cm depths using a sharp edge auger (8 cm x 8 cm). For hydraulic conductivity measurements, 100 cm^2 cylinders (radius 2.5 cm) were pushed into the augered peat samples in the vertical and horizontal directions. No compression was observed. Furthermore, pF-rings (46.6, 51.3 or 54.0 cm^3) were taken from the augered peat for water retention measurements at Kompsasuo. At Ruka, undisturbed soil cylinders (8 cm in diameters) of 10, 20 and 30 cm height were taken for determination of soil water retention.

The shear strength was measured *in situ* with a hand vane tester (GeoNor), using 20 mm by 40 mm vane. At all sites, samples were also taken to determine the degree of peat decomposition (von Post), peat type and bulk density. Correlation analysis was used to test dependence of the hydraulic conductivity on other physical peat properties.

Specific yield and soil moisture retention

The specific yield (S) was determined by a simple drainage test and by calculation from soil water retention curves (pF-curves). The water retention curve for five different depths (4, 10, 30, 50 and 70 cm) was determined in a pressure cell for undisturbed fresh peat samples of Kompsasuo wetland. Wet peat samples were saturated and placed on a saturated ceramic plate. Peat water content was measured by weighing at eight pressure steps between pF 0 and 2.9. At the end of the experiment, peat samples were dried at 105°C for 24 h. In between measurement points, the volumetric water content was obtained by linear interpolation. S was calculated from water retention measurement for different assumed groundwater depths, i.e. negative pressure in peat.

The specific yield of Ruka wetland was calculated from the results of a drainage test similar

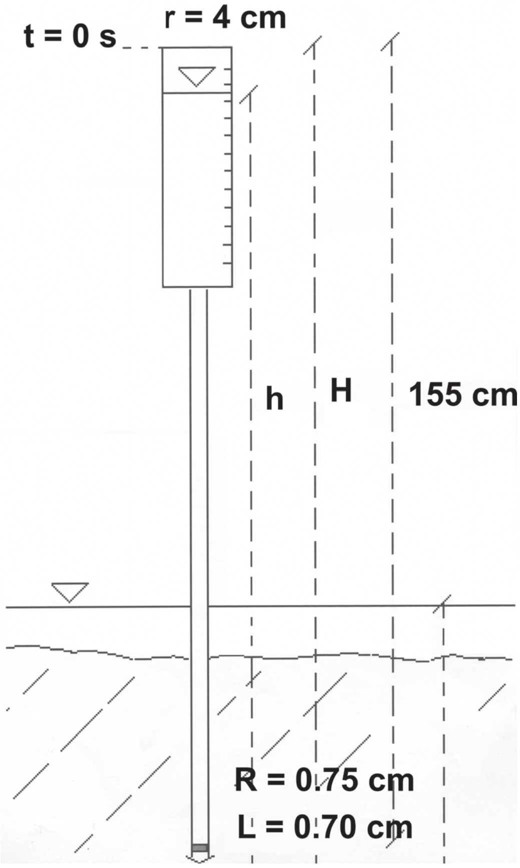


Fig. 3. Schematic of the direct-push piezometer: L = length of the perforated outlet; R = radius of the piezometer.

Kuva 3. Kaaviokuva mittauksissa käytetystä pietsometristä: L = purkuaukon pituus; R = pietsometrin säde.

to Tolman (1937). The drainage test was carried out using two 10 cm high, two 20 cm high and four 30 cm high intact peat cores that free drained on a wire tray for 13 days by gravity. The samples were weighed after 0, 5 and 13 days. Evaporation was eliminated by covering the samples and keeping the samples in a cool and dark room. The specific yield at corresponding pressure (10–30 cm) was calculated as the ratio of water released to original soil volume.

Hydraulic Conductivity

The saturated hydraulic conductivity was measured in two different ways: with a time-consuming laboratory method and a fast field method.

The peat K *in situ* was measured with a direct-push piezometer using the falling head method (Fig. 3). Due to head losses in the piezometer the methods allows for accurate K-measurements below 0.2 cm s^{-1}.

The rate of the outflow (q) at the piezometer tip at any time (t) is proportional to the hydraulic conductivity (K) of the soil and to the unrecovered head difference (H–h) (Hvorslev 1951), so that

$$q(t) = \pi r^2 \frac{\partial h}{\partial t} = FK(H - h) \qquad (1)$$

where r = radius of the piezometer reservoir; H = water level at the measuring point; h = water level in the reservoir; F = shape factor; t = time. Eq. (1) is rearranged in the following form

$$\frac{\partial h}{\partial t} + \frac{FK}{\pi r^2} h = \frac{FK}{\pi r^2} H \qquad (2)$$

which after integration, resolving the integration constant from the initial condition $h(0) = H_0$ and taking a natural logarithm yield

$$\ln\left(\frac{h - H}{H_0 - H}\right) = -\frac{FK}{\pi r^2} t \qquad (3)$$

Eq. (3) represents a straight line on a semi-logarithmical graph when the left-hand side is plotted against time. The slope of the line gives K when F is known. The calibration of the F factor was carried out with K measured in the laboratory (Eijkelkamp). Discharge of water (Q) through the porous media is defined by Darcy's law written in a one-dimensional form:

$$Q = K \frac{\partial H}{\partial x} A = qA \qquad (4)$$

where A = the cross-sectional area of flow layer (m^2), H = hydraulic head (m), x = distance in direction of flow (m) and q = specific discharge ($m\ s^{-1}$), then the flow velocity (v) is given by

$$v = \frac{q}{n} \qquad (5)$$

where n = the effective porosity. The average detention time of water (t_d) can be estimated by

$$t_d = \frac{V}{Q} \qquad (6)$$

where V = water volume in a wetland (m^3).

The detention time for each 10 cm layer was obtained using Darcy's law, and the respective average K value to estimate Q and porosity to obtain V. The detention times were scaled with mean detention time for the entire 70 cm peat layer (t*).

Results

Degree of humification

The degree of humification varied from H1 to H5 (depth 0–80 cm) in Kompsasuo wetland. Typically, the peat type was *Sphagnum-Carex* (H1–H5) in the upper peat layers (0–30 cm) and *Carex-Sphagnum* (H4–H5) at 30–80 cm. No change in the degree of humification was found compared to measurements carried out in 1992 (Ihme 1994). At Ruka the peat consisted of *Carex-Sphagnum* (H1–H5) in the upper part of the wetland (sampling points B3 and B2) and S*phagnum-Carex* (H1–H5) in the lower part of the wetland (sampling point B1). At one measuring point (B1), the degree of humification reached H6 already at the depth of 25–35 cm.

In general, the shear strength varied from 4 to 36 kPa at Kompsasuo and 8 to 41 kPa at Ruka wetland (Fig. 4) which is in agreement with Canadian observation of 1.5 kPa–38 kPa for amorphous or fine fibrous peat (Landva 1980), but somewhat lower than observed by Burke (1978). At Kompsasuo, the shear strength systematically decreases as far as 30 cm from the surface, supporting Kløve's (2000) observations, but then increased reaching generally the maximum value at a depth of 90–100 cm. At Ruka wetland, such a decrease was not observed even if maximum values generally occurred at a depth of 90–100 cm.

Specific yield

Specific yield (S) for both sites varied from 0.023 to 0.11 at suction 10 cm H_2O, from 0.045 to 0.14 at 20 cm H_2O and from 0.068 to 0.23 at 30 cm H_2O suction (Table 2 and 3). The lowest values were observed in the deepest peat layers and the highest values in the upper layers. All the peat samples contained more than 82% water by volume when saturated. During the measurements, the volume of the samples slightly decreased due to drying. S values after five days in the drainage test coincide with specific yield determined from pF-curves for layers at depths 4–10 cm. At deeper layers, S was some higher determined from the drainage test. Furthermore, S after 13 days was slightly higher at depths 4–10 cm and clearly higher at deeper layers than S determined from pF-curves.

Table 2. The peat specific yield determined from pF–curves for Kompsasuo wetland.
Taulukko 2. Kompsasuon pF–käyrästä määritetyt ominaisantoisuudet.

	Specific yield								
	10 cm H_2O			20 cm H_2O			30 cm H_2O		
Depth (cm)	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
4	0.045	0.053	0.066	0.089	0.107	0.13	0.13	0.16	0.2
10	0.027	0.043	0.061	0.053	0.086	0.12	0.08	0.13	0.18
30	0.025	0.033	0.043	0.051	0.066	0.086	0.076	0.099	0.13
50	0.026	0.028	0.03	0.052	0.056	0.059	0.078	0.084	0.089
70	0.023	0.03	0.034	0.045	0.061	0.068	0.068	0.091	0.1

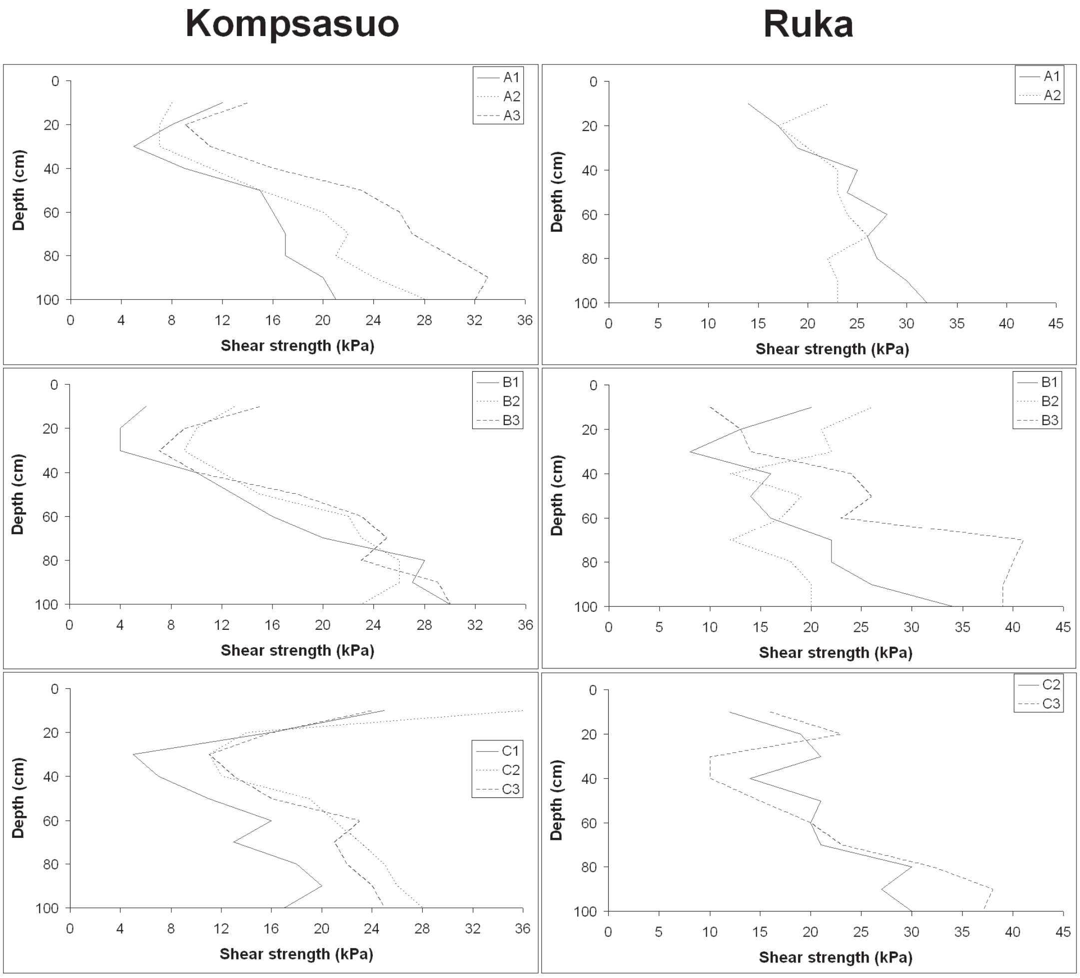


Fig. 4. Shear strength in Kompsasuo and Ruka wetlands at the depths 0–100 cm below the peat surface.

Kuva 4. Kompsasuolla ja Rukalla mitatut leikkauslujuudet turpeen syvyyksillä 0–100 cm.

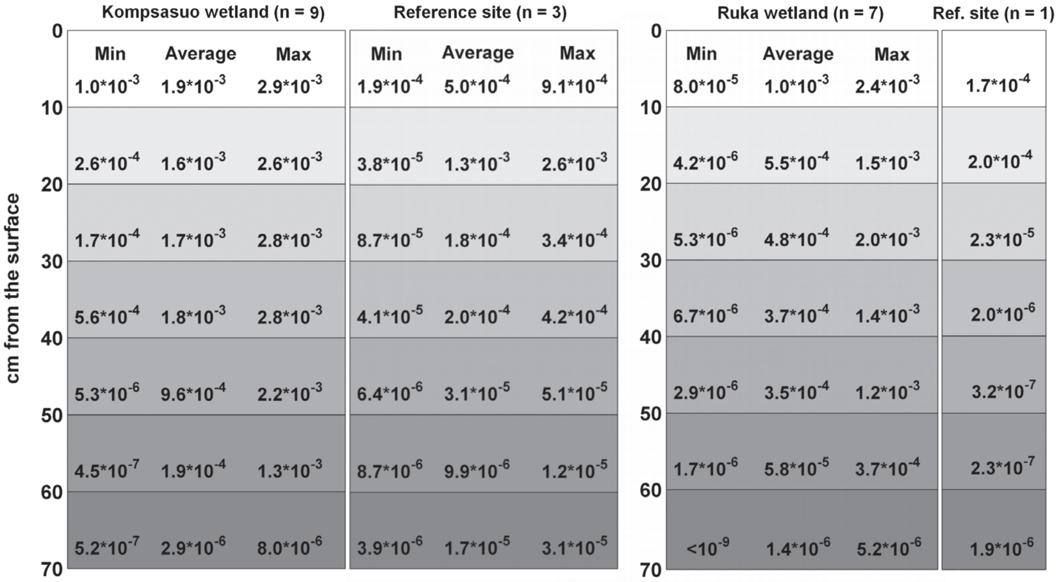
Table 3. The peat specific yield determined by the drainage test for two drainage durations on samples from Ruka wetland.

Taulukko 3. Rukan valutuskokeessa määritetyt ominaisantoisuudet kahdella eri valutusajalla.

	—— Specific yield ——	
Pressure (cm H_2O)	5 d	13 d
10	0.066	0.11
20	0.11	0.14
30	0.16	0.23

Hydraulic conductivity

At Kompsasuo wetland, the average *in situ* K was almost constant ($1.0 \times 10^{-3} - 1.9 \times 10^{-3}$ m s^{-1}) for 0–50 cm depths (Fig. 5). At depths below 50 cm, a rapid decrease from 1.0×10^{-3} cm s^{-1} to 2.9×10^{-6} m s^{-1} was observed. In the top layer (0–10 cm), K varied between 1.0×10^{-3} and 2.9×10^{-3} m s^{-1} whereas at a depth of 30–40 cm the K ranged from 5.6×10^{-4} to 2.8×10^{-3} m s^{-1}. The measurements indicate an increasing variation of K with



Kompsasuo wetland (n = 9)			Reference site (n = 3)		
Min	Average	Max	Min	Average	Max
$1.0*10^{-3}$	$1.9*10^{-3}$	$2.9*10^{-3}$	$1.9*10^{-4}$	$5.0*10^{-4}$	$9.1*10^{-4}$
$2.6*10^{-4}$	$1.6*10^{-3}$	$2.6*10^{-3}$	$3.8*10^{-5}$	$1.3*10^{-3}$	$2.6*10^{-3}$
$1.7*10^{-4}$	$1.7*10^{-3}$	$2.8*10^{-3}$	$8.7*10^{-5}$	$1.8*10^{-4}$	$3.4*10^{-4}$
$5.6*10^{-4}$	$1.8*10^{-3}$	$2.8*10^{-3}$	$4.1*10^{-5}$	$2.0*10^{-4}$	$4.2*10^{-4}$
$5.3*10^{-6}$	$9.6*10^{-4}$	$2.2*10^{-3}$	$6.4*10^{-6}$	$3.1*10^{-5}$	$5.1*10^{-5}$
$4.5*10^{-7}$	$1.9*10^{-4}$	$1.3*10^{-3}$	$8.7*10^{-6}$	$9.9*10^{-6}$	$1.2*10^{-5}$
$5.2*10^{-7}$	$2.9*10^{-6}$	$8.0*10^{-6}$	$3.9*10^{-6}$	$1.7*10^{-5}$	$3.1*10^{-5}$

Ruka wetland (n = 7)			Ref. site (n = 1)
Min	Average	Max	
$8.0*10^{-5}$	$1.0*10^{-3}$	$2.4*10^{-3}$	$1.7*10^{-4}$
$4.2*10^{-6}$	$5.5*10^{-4}$	$1.5*10^{-3}$	$2.0*10^{-4}$
$5.3*10^{-6}$	$4.8*10^{-4}$	$2.0*10^{-3}$	$2.3*10^{-5}$
$6.7*10^{-6}$	$3.7*10^{-4}$	$1.4*10^{-3}$	$2.0*10^{-6}$
$2.9*10^{-6}$	$3.5*10^{-4}$	$1.2*10^{-3}$	$3.2*10^{-7}$
$1.7*10^{-6}$	$5.8*10^{-5}$	$3.7*10^{-4}$	$2.3*10^{-7}$
$<10^{-9}$	$1.4*10^{-6}$	$5.2*10^{-6}$	$1.9*10^{-6}$

Fig. 5. The *in situ* K (m s^{-1}) in Kompsasuo and Ruka wetlands at depths 0–70 cm below soil surface, n = number of measuring points.

Kuva 5. Kompsasuon ja Rukan kosteikkojen in situ K (cm s^{-1}) eri syvyyksillä, n = mittauspisteiden lukumäärä.

depth. At Ruka wetland, the average *in situ* K was nearly one order of magnitude smaller for depths of 10–40 cm than at Kompsasuo wetland (Fig. 5). The variation in K was high for all layers and the variation did not increase with depth. In the top layer, K ranged from 8.0×10^{-5} to 2.4×10^{-3} m s^{-1}. The mean value remained almost constant for depths 10–50 cm. Below 50 cm a rapid decrease was observed.

In the reference areas, the *in situ* K was generally lower than in the treatment wetlands, varying from 3.9×10^{-6} to 9.1×10^{-4} m s^{-1} and from 2.3×10^{-7} to 2.0×10^{-4} m s^{-1}, for Kompsasuo and Ruka, respectively. The highest K values were observed at depths of 10–20 cm and the lowest values were observed at depths of 60–70 cm. Generally, in these layers the average K was the same order of magnitude as in the treatment wetlands, but at all other depths, the K was one or two orders of magnitude lower in the reference sites than in treatment wetlands. However, in Ruka wetland at depths 0–30 cm (sampling points B3 and B2), the minimum values were one or two orders of magnitude smaller than in the reference site.

The horizontal hydraulic conductivity (K_h) measured with Eijkelkamp cylinders varied from 1.8×10^{-5} to 1.3×10^{-2} m s^{-1} for Kompsasuo and from 6.1×10^{-6} to 3.8×10^{-2} m s^{-1} for Ruka (Tables 4 and 5). The vertical hydraulic conductivities (K_v) were slightly greater, ranging from 4.2×10^{-6} to 1.9×10^{-2} m s^{-1} for Kompsasuo and from 3.1×10^{-5} to 3.2×10^{-2} m s^{-1} for Ruka.

At Kompsasuo, the highest correlation of K (*in situ*) was found with shear strength and depth (Table 6). As the shear strength values are not corrected for rod resistance, the values are only be used to evaluate the variation in K. The correlation with the specific yield was 0.37. The peat bulk density and the degree of humification did not correlate significantly with K. In Ruka, the best correlation was observed between K and the degree of humification (–0.54) (Table 6). The correlation coefficient was –0.67 and –0.40, for depth and shear strength, respectively. In all data, the highest correlation was founded between shear strength and K.

The vertical variation of K, porosity and the hydraulic gradient in the wastewater flow direction was used to estimate the flow velocities of

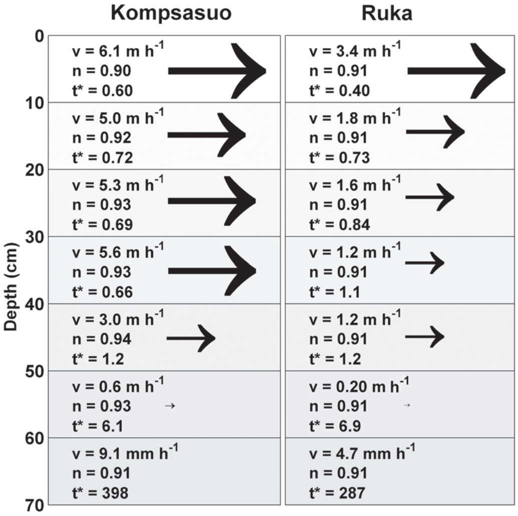


Fig. 6. The average flow profile for Kompsasuo and Ruka wetlands. Sizes of arrows indicate the relative discharge at each depth. v = flow velocity, n = porosity and t* = scaled mean detention time

Kuva 6. Keskimääräinen virtausprofiili Kompsasuolla ja Rukalla. Nuolen koko kuvaa suhteellista virtaamaa eri syvyyksillä, v = virtausnopeus, n = huokoisuus ja t = skaalattu keskimääräinen viipymä*

wastewater (Eq. 5) in different peat layers. The results show that the wastewater flows mainly at depths of 0–40 cm in Kompsasuo and at depths of 0–30 cm in Ruka treatment wetland (Fig. 6). In both wetlands, the water detention time of the peat profile is dominated by layers 0–50 cm (t* = 0.40–1.2) (Fig. 6).

Discussion

Shear strength

The increase of shear strength at depth is mainly caused by increased resistance of the vane rod. Because the resistance of the vane rod was not taken into account, the deeper peat shear strength is probably overestimated. However, the measured values can be used to compare peat structure between measurement points. The shear measurements do not indicate a clear change in peat properties with wastewater application. 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 as the solid load and nutrient load is highest close to the inlet. At Kompsasuo, slightly lower shear values were measured close to the inlet ditch but at Ruka the results do not indicate any changes in shear values between locations. At Kompsasuo, the high shear strength in the top layer of C measuring line probably results from the high root density of shoots as observed by Kaasinen (2003).

Specific yield

Originally, the specific yield was determined by drying saturated material by gravity and calculating the yield from the volume of drained water per unit of saturated bulk volume (Tolman 1937, Boelter 1965); but the drainage time has not been reported in previous studies. Boelter (1965) has determined specific yield to be 0.15 for herbaceous, moderately decomposed peat and 0.10 for well-decomposed peat by using water-retention values obtained with 10 cm high undisturbed core samples. Corresponding values for moderately decomposed peat at Ruka was 0.07 after 5 day draining and 0.11 after 13 day draining. Similar increase of S with time has also been found in sandy soils (Dos Santos Junior & Youngs 1969).

The results indicate that the drainage time should be considered when specific yield is used in peatlands to estimate changes in the water table. Partly for that reason the S-term of peat will be overestimated in transient flow simulation if the pF-curve (that describes steady state situation at certain negative pressure) is used.

Generally, the specific yields determined from pF-curves has been calculated at pF 2 which corresponds to a matric suction of 100 cm H_2O or a drainage depth of 1 m. At pF 2, the specific yield at Kompsasuo wetland varied from 0.21 to 0.48 which is typical for moderately decomposed peat in Finland (Päivänen 1973). These values are similar to Canadian measurements by Price (1992) who measured variations of specific yields from 0.1 to 0.5 with depth for *Sphagnum* in lysimeters.

The value of specific yield depends on the pressure differences used in calculation. It is obvious that using values determined at pF 2, specific yields obtained are too high for calculating water table fluctuation in peatlands where the water table fluctuations occur near the ground surface and at higher water content than at pF 2. Results in Table 2 show that different S values should be applied depending on the groundwater fluctuation (pressure drop) if the water table movement is simulated using specific yield. For small water table fluctuations, such as a 10 cm fluctuation, the specific yield is around 0.02–0.07, whereas at higher water table fluctuations (30 cm) the specific yield is about 0.07–0.2. The results indicate a somewhat lower S value for peat than has been previously estimated.

Hydraulic conductivity

The results of K (*in situ*) measurements indicate that the catotelm starts at a depth of 40–60 cm for Kompsasuo and at 10–60 cm for Ruka. Observed *in situ* catotelm K values ($5 \times 10^{-7} - 10^{-4}$ m s^{-1}) are in agreement with previous Finnish observations of $10^{-8} - 10^{-4}$ m s^{-1} (Päivänen 1973, Kløve 2000). The *in situ* hydraulic conductivity for the acrotelm ($10^{-4} - 3 \times 10^{-3}$ m s^{-1}) is somewhat higher than 10^{-3} m s^{-1} previously observed by Chason & Siegel (1986), but somewhat lower than observed by Burt et al. (1990) and Hobbs (1986) (0.1 m s^{-1}).

The difference of K between treatment wetlands and reference sites is partly due to water table lowering as a consequence of ditching of treatment wetlands affecting also the reference sites. Ditching accelerates settling and decomposition in peat which reduces peat porosity. At the reference site, the structural change in peat could be faster than in the constructed wetland as the wetland is kept wet with high wastewater loading. The higher K in the treatment wetland could also be caused by increased erosion in peat caused by increased hydraulic loading. Internal erosion in peat and formation of underground channels has been noted on blanket peat, a peat type that forms in areas with high precipitation. These conditions could be comparable to conditions with high hydraulic loading; however, this needs more studies. Anikwe & Nwobodo (2002) have observed long-term (20 years) municipal waste disposal to increase hydraulic conductivity of soil (consisting of sand, silt and clay) in Nigeria. They concluded that it was due to erosion of the soil.

Chason & Siegel (1986) have reported that

Table 4. Hydraulic conductivities for Kompsasuo wetland, K_h = horizontal hydraulic conductivity, K_v = vertical hydraulic conductivity and K = the hydraulic conductivity *in situ*.

Taulukko 4. Hydraulinen johtavuus Kompsasuolla K_h = horisontaalinen hydraulinen johtavuus, K_v = vertikaalinen hydraulinen johtavuus ja K = in situ hydraulinen johtavuus.

	Depth	K_h (m s^{-1})	K_v (m s^{-1})	K (m s^{-1})	log(K_h/K_v)
A1	5 cm	4.2×10^{-3}	1.8×10^{-2}	-	–0.6
	20 cm	3.6×10^{-5}	1.6×10^{-3}	1.0×10^{-3}	–1.6
	40 cm	8.8×10^{-4}	4.2×10^{-6}	2.0×10^{-3}	2.3
B1	5 cm	1.3×10^{-2}	9.2×10^{-3}	-	0.2
	20 cm	8.7×10^{-4}	9.4×10^{-3}	2.6×10^{-3}	–1
	40 cm	1.1×10^{-3}	-	2.8×10^{-3}	-
C1	5 cm	1.2×10^{-3}	1.6×10^{-2}	-	–1.1
	20 cm	5.6×10^{-4}	1.5×10^{-2}	1.6×10^{-3}	–1.4
	40 cm	1.8×10^{-5}	1.9×10^{-2}	1.8×10^{-3}	–3
R1	5 cm	4.7×10^{-5}	8.3×10^{-4}	-	–1.2
	20 cm	8.1×10^{-6}	2.5×10^{-6}	2.6×10^{-3}	0.5
	40 cm	1.7×10^{-6}	4.4×10^{-5}	4.2×10^{-4}	–1.4
Mean		1.8×10^{-3}	8.1×10^{-3}	1.9×10^{-3}	
Standard deviation		0.004	0.008	0.8×10^{-3}	
Range		1.3×10^{-2}	1.9×10^{-2}	2.4×10^{-3}	

K_h was generally one or two orders of magnitude greater than K_v for partially decomposed peat in a spring fen-raised bog complex in the Lost River Peatland. Also others have found K_h to be greater than K_v (Korpijaakko & Radforth 1972, Beckwith et al. 2003). However, in this study K_v was greater than K_h in 65% of samples and smaller only in 26% of samples. Furthermore K_v was nearly equal to K_h in 9% of the samples.

In general, K_v was one or two orders of magnitude greater than K_h, The anisotropy factor $\log(K_h/K_v)$, as according to Chason and Siegel (1986), deviate from zero more than 0.5 nearly for all samples indicating that the peat structure orientation could be predominantly vertical and the peat body is anisotropic at depths of 0–40 cm. Chason & Siegel (1986) have explained that vertical orientation of living stems of *Sphagnum* creates vertical water passageways between the stems, whereas pronounced stratification and horizontal planar passageways are formed when the plants died and fall over.

In Ruka wetland, the horizontal K was the highest being similar to vertical K in the measuring point closest to the wastewater discharge area (B3 in Fig. 2b). This was also observed in Kompsasuo. If the horizontal direction is dominant which often is the case in peat soils, this observation indicates some erosion rather than some clogging be caused by high hydraulic loading which is the highest near the inlet section. However, differences between K_h and K_v for a given depth partly reflect small-scale heterogeneity within the wetland as K_h and K_v were measured from separate but adjacent soil cores.

In Kompsasuo, the measured *in situ* K values were similar to the corresponding laboratory values, whereas for Ruka the *in situ* K was one order of magnitude lower than the laboratory values. For the entire K-dataset, *in situ* K was lower than the laboratory values in six samples, between the horizontal and vertical hydraulic conductivities in six samples and greater than values in the laboratory in three samples (Tables 4 and 5). A larger variation was observed in the laboratory values (standard deviation = 0.004–0.01) than for the *in situ* measurements (standard deviation = 0.0008–0.001) (Tables 4 and 5). Boelter (1965) and Päivänen (1973) have previously reported laboratory hydraulic conductivities to be greater than hydraulic conductivities in the *in situ* method. Probable reasons for differences are: i) the peat sample for the laboratory method represents a very small part of the peat column, ii) there

Table 5. Hydraulic conductivities for Ruka wetland, K_h = horizontal hydraulic conductivity, K_v = vertical hydraulic conductivity and K = the hydraulic conductivity *in situ*.

Taulukko 5. Hydraulinen johtavuus Rukalla K_h = horisontaalinen hydraulinen johtavuus, K_v = vertikaalinen hydraulinen johtavuus ja K = in situ hydraulinen johtavuus.

	Depth	K_h (m s^{-1})	K_v (m s^{-1})	K (m s^{-1})	$\log(K_h/K_v)$
B3	5 cm	2.3×10^{-2}	1.2×10^{-2}	–	0.3
	20 cm	2.3×10^{-2}	2.1×10^{-2}	4.2×10^{-6}	0
	40 cm	5.8×10^{-5}	5.3×10^{-5}	2.9×10^{-6}	0
B2	5 cm	7.9×10^{-4}	2.6×10^{-2}	–	–1.5
	20 cm	2.9×10^{-4}	1.7×10^{-2}	3.1×10^{-5}	–1.8
	40 cm	6.1×10^{-6}	3.1×10^{-5}	1.7×10^{-5}	–0.7
B1	5 cm	7.2×10^{-3}	2.2×10^{-2}	–	–0.5
	20 cm	3.8×10^{-2}	1.3×10^{-2}	1.8×10^{-4}	0.5
	40 cm	2.5×10^{-5}	3.2×10^{-2}	6.7×10^{-6}	–3.1
R	5 cm	6.7×10^{-3}	4.2×10^{-3}	–	0.2
	20 cm	1.5×10^{-5}	4.0×10^{-4}	2.0×10^{-4}	–1.4
	40 cm	7.9×10^{-4}	4.2×10^{-3}	2.0×10^{-6}	–0.7
Mean		8.3×10^{-3}	1.3×10^{-2}	5.5×10^{-5}	
Standard deviation		0.01	0.01	0.8×10^{-4}	
Range		3.8×10^{-2}	3.2×10^{-2}	2.0×10^{-4}	

could be leakage along the interface between the core and the inside wall of the sampling cylinder during the measurements, especially with peat materials having very low hydraulic conductivity and iii) taking peat samples with the cylinders and transferring them from the field to the laboratory is difficult without breaking the peat structure. Also, gas bubble formation during storage has been found to change the hydraulic conductivity of the peat (Beckwith & Baird, 2001), but then the laboratory values would be somewhat lower than measured in the field.

The study sites are relatively similar in their degree of humification, peat type and shear strength, so it could be assumed that variation of hydraulic conductivities are also similar. However, *in situ* K for the measurement point closest to wastewater discharge points (B3 and B2 in Fig. 2) for depths of 10–40 cm in Ruka wetland, were two or three orders of magnitude lower than hydraulic conductivities for other points at equal depths. Furthermore, the lowest values in the top layer were in the observed main flow path of wastewater in Ruka. The results of hydraulic conductivity measurements might indicate some clogging in the main wastewater flow path in Ruka wetland. The average suspended matter loading-rate at Ruka was higher (5.6 kg ha^{-1} d^{-1}) than at Kompsasuo (1.2 kg ha^{-1} d^{-1}) which could be the reason why the results seem not to support clogging of peat at Kompsasuo.

The calculations indicate that the effective flow depth, where purification occurs in these peatlands, can be estimated to be around 50 cm. Hydraulic conductivities of these layers varied from 10^{-3} to 10^{-4} m s^{-1}. The effective flow depth observed in this study is higher than the 0.20 m previously estimated by Ihme (1994) indicating that a larger peat volume can be used for purification.

At the depth of 50–60 cm purification processes could be achievable in the point of flow condition but below 60 cm the water flow is slow and in the same range as the diffusion rate. Hoag & Price (1995) have found diffusion to be an important transport mechanism as the hydraulic conductivity of the peat was 10^{-7}–10^{-6} m s^{-1}. Similar values can be found at depths of 20–70 cm in Ruka and at depths of 50–70 cm in Kompsasuo, but generally below 60 cm in both wetlands.

Conclusions

The hydraulic conductivity for acrotelm varied from 3×10^{-3} to 10^{-4} m s^{-1} and for catotelm from 5×10^{-7} to 10^{-4} m s^{-1}. Generally, the vertical conductivity was higher than the horizontal conductivity. The laboratory method seemed to overestimate the hydraulic conductivity compared to the *in situ* measurement.

The specific yield varied from 0.023 to 0.23, depending of the negative pressure used in calculating S values. The S value depended on time, and higher S values were obtained with long drainage times indicating that this should be accounted for if the S terms are used to explain variation in water table fluctuations. There was an agreement between the drainage test and the pF-curve method determining the specific yield.

The study indicates that fairly high hydraulic conductivity is maintained in the peatlands despite several years of wastewater loading. The

Table 6. Correlations of the hydraulic conductivity between other physical properties, n = number of samples.

Taulukko 6. Hydraulisen johtavuuden korrelaatio turpeen muiden fysikaalisten ominaisuuksien kanssa, n = näytteiden lukumäärä.

	Shear strength	n	Depth	n	Humif.	n	Bulk density	n	Specific yield	n
Ruka	–0.40**	51	–0.67**	52	–0.54**	25	-	-	-	-
Kompsasuo	–0.67**	78	–0.70**	79	–0.16	76	0.23	25	0.37*	25
All data	–0.59**	129	–0.67**	131	–0.31**	101	0.23	25	0.37*	25

** significant at the 0.01 level and * at the 0.05 level effective flow depth for both sites was estimated at approximately 50 cm, which is deeper than previously estimated.

Acnowledgements

The material of this study has been gathered and analysed in the Department of Biophysics in the University of Oulu. The authors would like to acknowledge the financial support of this project from the European Commission (PRIMROSE contract number EVK1-CT-2000-00065), Academy of Finland, North Ostrobothnia Regional Environment Centre (NOREC), VAPO Oy, Energy and Water Cooperative of Kuusamo (EVO) and the city of Kuusamo. The manuscript was reviewed by Jan Vymazal and Niko Silvan.

References

Anikwe, M. & Nwobodo, K. 2002. Long-term effect of municipal waste disposal on soil properties and productivity of site used for urban agriculture in Abakaliki, Nigeria. Bioresource Technology 83: 241–250.

Beckwith, C.W. & Baird, A.J. 2001. Effect of biogenic gas bubbles on water flow in poorly decomposed blanket peat. Water Resources Research 37: 551–558.

Beckwith, C.W., Baird, A.J. & Heatwaite. A.L. 2003. Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. I: laboratory measurements. Hydrological Processes 17: 89–101.

Boelter, D.H. 1965. Hydraulic conductivity of peat. Soil Science 100: 227–231.

Boelter, D.H. 1969. Physical properties of peat as a related to degree of decomposition. Division S-6 – Soil and Water Management and Conservation, pp. 606–609.

Burke, W. 1978. Long-term Effects of Drainage and Land Use on Some Physical Properties of Blanket Peat. Irish Journal of Agricultural Research 17: 315–322.

Burt, T.B., Heathwaite, A.L. & Labadz, J.L. 1990. Runoff production in peat covered catchments. In: M.G. Andersson and T.P. Burt (eds), Process studies in hillslope hydrology, John Wiley, pp. 463–499.

Chason, D.B. & Siegel, D.I. 1986. Hydraulic conductivity and related physical properties of peat, Lost River Peatland, Northern Minnesota. Soil Science 142: 91–99.

Dos Santos Junior, A.G. & Youngs, E.G. 1969. A Study of the specific yield in land-drainage situation. Journal of Hydrology 8: 59–81.

Hallikainen, S. 2003. Kosteikkokäsittely Rukan ja Kempeleen jälkikäsittelykentillä: puhdistustehon vaihtelu ja kehitys (Summary: Wetland treatment in wastewater plants of Ruka and Lakeus: Changes in reduction rates and development of efficiency). M.Sc. Thesis (Tech.), University of Oulu, 99 pp.

Heikkinen, K., Ihme, R. & Lakso, E. 1994. Ravinteiden, orgaanisten aineiden ja raudan pidättymiseen johtavat prosessit pintavalutuskentällä (Summary: Processes contributing to the retention of nutrients, organic matter and iron in an overland flow wetland treatment system). Publications of the Water and Environment A193, National Board of Water and Environment, Helsinki, Finland, 80 pp.

Hoag, R.S. & Price, J.S. 1995. A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog. Journal of Hydrology 172: 171–184.

Hobbs, N.B. 1986. Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly Journal of Engineering Geology 19: 7–80.

Huikari, O. 1959. Kenttämittaustuloksia turpeiden vedenläpäisevyydestä (Referat: Feldmessungsergebnisse über die wasserdurchlässigkeit von torfen). Communicationes Instituti Forestalis Fenniae 51:1–26 pp.

Hvorslev, M.J. 1951. Time lag and soil permeability in ground-water observations. Waterways Experiment Station, Corps of Engineers, Bulletin no 36, 50 pp.

Ihme, R. 1994. Pintavalutus turvetuotantoalueiden valumavesien puhdistuksessa (Summary: The use of overland flow for the purification of runoff water from peat mining areas). Ph.D.Thesis, University of Oulu, 140 pp.

Ihme, R., Heikkinen, K. & Lakso, E. 1991. Pintavalutus turvetuotantoalueiden valumavesien puhdistuksessa (Summary: The use of overland flow for the purification of runoff water from peat production areas). Publications of the water and environment research institute, National Board of Waters and Environment, Helsinki, Finland A75, 181 pp.

Kaasinen, E. 2003. Kompsasuon pintavalutuskentän kasvillisuusmuutoksista, M.Sc. Thesis, University of Oulu, 42 pp.

Kløve, B. 2000. Effect of peat harvesting on peat hydraulics properties and runoff generation. Suo 51: 121–129.

Korpijaakko, M & Radforth, N.W. 1972. Studies on the hydraulic conductivity of peat. The Proceedings of the International Peat Congress, Volume III, pp. 323–334.

Landva, A.O. 1980. Vane testing in peat. Canadian Geotechnical Journal 17: 2–19.

Lehtonen, J. 1994. Jäteveden kehitys Suomessa pitkällä aikavälillä (Summary: Long-term development of waste water treatment in Finland). Tampere University of Technology, Institute of Water and Environmental Engineering No. B 58 100 pp.

Lyytikäinen, V., Vuori, K-M. & Kotanen, J. 2003. Kunnostusojitusten suojavyöhykkeiden toimivuus – Kuohattijärven pintavalutuskenttien tutkimukset vuosina 1998–2001 (Summary: Functioning of the buffer zones in forest drainage sites – results of the overland flow area studies in the Kuohattijärvi catchment in 1998–2001), Regional Environmental Publications 315, North Karelia Regional Environment Centre, Joensuu, 62 pp.

McIntyre, B.D. & Riha, S.J. 1991. Hydraulic conductivity and nitrogen removal in artificial wetland system. Journal of Environmental Quality 20: 259–263.

Munsterhjelm, K. 1972. Jäteveden suoimeyttämöiden toiminnasta eri vuodenaikoina ja sen tehostamiseta (Summary: On the efficiency of peat infiltration of sewage during various seasons and on its improvement). National Board of Waters, Finland, Report 38, 114 pp.

Mæhlum, T. 1998. Cold-climate constructed wetland: Aerobic pre-treatment and horizontal subsurface flow wetlands for domestic sewage and landfill leachate Purification. Doctoral Thesis, Agricultural University of Norway, 180 pp.

Pirttijoki, J. 1996. Pintavalutus Kuusamon Rukan jätevesien jälkikäsittelymenetelmänä (Summary: Treatment of wastewater from Ruka in Kuusamo by using overland flow method). M. Sc. Thesis (Tech), University of Oulu, 85 pp.

Price, J.S. 1992. Blanket bog in Newfounland. Part 2. Hydrological processes. Journal of Hydrology 135: 103–119.

Puustjärvi, V. 1970. Degree of decomposition. Peat & Plant News 4: 48–52.

Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta Forestalia Fennica 129: 1–70.

Savolainen, M., Kaasinen, A., Heikkinen, K., Ihme, R., Kämä, T. & Alasaarela, E. 1996. Turvetuotannon vesiensuojeluvaihtoehtojen tapauskohtainen vertailu, Suomen ympäristö 35. 116 pp.

Sundblad, K. 1988. Recycling of waster nutrients in a wetland filter. Linköping Studies in Arts and Science No. 27.

Surakka, S. & Kämppi, A. 1971. Jätevesien suoimeytyksestä. Suo 22: 51–57.

Tanner, C.C. & Sukias, J.P. 1995. Accumulation of organic solids in gravel-bed constructed wetlands. Water Science and Technology 32: 229–239.

Tanner, C.C., Sukias, J.P. & Upsdell, M.P. 1998. Organic matter accumulation during maturation of gravel-bed constructed wetlands treating farm dairy wastewater. Water Research 32: 3046–3054.

Tolman, C.F. 1937. Ground water. McGraw-Hill Book Company, Inc., New York and London, 593 pp.

Tiivistelmä: Turpeen hydrauliset ominaisuudet kunnallisten jätevesien ja turvetuotantoalueen valumavesien puhdistukseen rakennetuissa kosteikkopuhdistamoissa

Tässä tutkimuksessa mitattiin turpeen hydraulista johtavuutta (K), ominaisantoisuutta (S), maatuneisuusastetta ja leikkauslujuutta kahdella luonnontilaiselle suolle rakennetulla jätevesien kosteikkopuhdistamolla Pohjois-Suomessa. Kosteikot ovat erilaiset puhdistettavan veden laadun ja määrän suhteen. K mitattiin muuttuvapaineisella pietsometrillä kentällä sekä Eijkelkampin sylintereillä laboratoriossa (sekä horisontaalinen että vertikaalinen K). Turpeen ominaisantoisuus määritettiin pF-käyrästä sekä valutuskokeella. K *in situ* oli $5.2 \times 10^{-7} - 2.9 \times 10^{-3}$ m s^{-1}, horisontaalinen K $6.1 \times 10^{-6} - 3.8 \times 10^{-2}$ m s^{-1} ja vertikaalinen K $4.2 \times 10^{-6} - 2.6 \times 10^{-2}$ m s^{-1}. Vertikaalinen K oli tavallisesti suurempi kuin horisontaalinen K. Arvioitu virtauskerroksen paksuus oli 40–60 cm Kompsasuolla ja 10–60 cm Rukalla. Eri ominaisantoisuuden (S) mittausmenetelmien välillä oli hyvä yhteensopivuus. Ominaisantoisuus vaihteli välillä 0.023–0.23. Usean vuoden kuormituksesta huolimatta tutkimuskosteikkojen hydraulinen johtavuus oli riittävän korkea mahdollistamaan jäteveden virtauksen noin 50 cm syvyisessä kerroksessa.

Received 30.9.2004, Accepted 4.2.2005