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Helsinki 2000

ISSN 0039-5471
Suo 51(3): 121–129

Effect of peat harvesting on peat hydraulic properties and runoff generation

Bjørn Kløve

Bjørn Kløve, Jordforsk, Norwegian Centre for Soil and Environmental Research, 1432 Ås, Norway (e-mail: bjorn.klove@jordforsk.no)

Peat hydraulic conductivity, shear strength, plant composition and runoff at seven peat harvesting sites in Central Finland were measured. A large variation in hydraulic conductivity (10^{-8}–10^{-6} m s^{-1}), peat shear strength (302–413 kPa), and peak runoff (97–898 l s^{-1} km^{-2}) was observed between different harvesting sites. The hydraulic conductivity showed a clear correlation with peat shear strength ($r = -0.89$), which has not been previously observed. The correlation between hydraulic conductivity and degree of humification was weak ($r = 0.60$). Soil lowering decreased the hydraulic conductivity and the peat shear strength. These reductions, with reduced drainage depths, increased peak flow and changed runoff generation patterns by increasing the possibility of Horton and saturation excess overland flow.

Keywords: runoff generation, hydrological pathways, drainage, peatlands, hydraulic conductivity, shear strength, soil loss, subsidence, peak runoff.

INTRODUCTION

Subsidence on cutover peatlands

Drained peatlands are used for agriculture, forestry and peat mining in several countries. Environmental problems related to drained peatlands include the release of climate gases (CO_2 and N_2O), erosion of suspended sediments and leaching of dissolved matter. This results in unwanted soil lowering, which can be 10–20 cm a^{-1} immediately after drainage, reducing to 2–5 cm a^{-1} after several years (Maslow et al. 1996). Eventually, all cutover peatlands will be lowered but the rate of soil lowering depends on the speed of soil degradation processes. The degradation processes are controlled by several factors including soil hydrology, which on peat soils, depends on several factors such as land management and climate. To help solve the environmental problems associated with drained peatlands, scientists must understand how land management effects peat properties and how peat properties effect hydrology.

Hydraulic properties of saturated peat

Undrained peatland consists of two different layers of organic material. A living and rapidly decaying plant layer (acrotelm) overlies a compact brown layer of partly decomposed peat (catotelm). The saturated hydraulic conductivity in the acrotelm is about 0.1 m s^{-1} (Burt et al. 1990, Hobbs 1986) and the hydraulic conductivity in catotelm ranges from 10^{-9} to 10^{-3} m s^{-1} (Burt et al 1990), a typical value being 10^{-7}–10^{-6} m s^{-1} (Clymo 1987). The specific yield (amount of water released per unit groundwater drawdown) in the top layer of acrotelm is about 0.5–0.8 (Boelter 1965), for partially decomposed peat 0.2–0.4 (Dooge 1975), and for the catotelm peat it ranges from 0.10 (Boelter 1965) to 0.26 (Kløve 1997).

The hydraulic properties of peat usually show a very large spatial variation. Generally, hydraulic conductivity decreases with depth as the degree of humification increases (Päivänen 1973). Observed differences between the hydraulic conductivities in the horizontal and vertical directions have not been consistent (Gillman 1994). In some cases, layers of less decomposed peat can be found beneath peat of low conductivity. The variation in the peat properties is attributed to plant composition, degree of humification, stratification of the peat and compaction. In some studies, the hydraulic conductivity increases with increasing fiber content and decreases with increasing humification and density (Boelter 1965).

Peatland hydrology and the effect of subsidence

The changes that occur to the peatland hydrology after drainage are not fully understood. Generally, drainage provides a pathway for water to exit the peatland even when water table is low increasing summer base flow (Price & Waddington 2000). In some cases the drainage can reduce the evaporation as the soils is dried resulting in increased annual runoff. The largest effect of drainage is the changes that occur in water pathways. Drainage increases subsurface flow through the catotelm and decrease overland flow or near surface storm flow that occurs in the acrotelm on undrained peatlands (Burt 1995). The analysis of individual rainfall-runoff events show that small runoff peaks are on drained peatland generated by rain on channels, whereas large runoff peaks are supplied by subsurface stormflow (David & Ledger 1988, Kløve & Bengtsson 1999). On cutover fens, extreme runoff peaks occur if the ditches surrounding the peatland flood into the fen (Kløve & Bengtsson 1999).

One of the difficulties in understanding the hydrology of drained peatlands is that peat properties change in time after drainage, due to (i) physical and biological changes in the peat, (ii) removal of top soil, and (iii) exposure of deeper underlying peat layers. The initial rapid subsidence by collapse of large pores is due to the decrease in buoyancy when the groundwater level is lowered (Hobbs 1986). The increased anaerobic decomposition results in CO_2 release and further compaction of the soil. Also, peat is compacted by the heavy machinery used in agriculture and peat harvesting. Erosion of suspended, dissolved and floating peat and peat cutting will eventually expose deeper peat layers to soil surface. The result of structural changes is, in theory, an increase in the portion of small pores. A decrease in large pores will result in a rapid decrease in saturated hydraulic conductivity as it is proportional to the pore radius in the power of two. A three-fold decrease has been noted on Canadian peat soils (Chow et al. 1992). Loss of effective pore space also reduces the specific yield from around 0.3–0.8 on undecomposed peat to close to 0.1 on well decomposed peat (Boelter 1965) resulting in a decrease in storage potential for water and an increased possibility of overland flow. Consequently, the water table dynamics, water storage and transmission properties and ultimately the runoff relation will be affected. Therefore, the objective of this study was to examine how hydraulic properties of cutover peatlands change when the soil is lowered and how these changes affect runoff generation.

MATERIAL AND METHODS

Study sites

Seven different types of peat harvesting sites in Central and Southern Finland were studied. Their locations are noted in Table 1. The sites were selected to include fields that had been cut for a different period of time. It was initially assumed that the exposure of deep peat layers would result in lower peat hydraulic conductivity and increased peak runoff. All the sites were managed by the peat harvesting company Vapo Oy. The peat was collected for energy production except at a part of Haukkasuo harvesting site where production started in 1990 and peat was harvested for horticulture (as milled peat).

All the peatlands had fen characteristics (except the horticultural part of Haukkasuo). Pohjansuo and Lakenarahka harvesting sites lay in a bedrock depression with steep upland slopes. Lappasuo, Ropolansuo and Huppionsuo were surrounded by a small portion of upland catchment that was relatively flat. Parts of Huppionsuo were clearly lower than the surrounding landscape and the surrounding ditches conveying the upland runoff were above the cutover area. Huppionsuo and Haukkasuo are relatively large peat mines with an area of approximately 149 and 189 ha, respectively (Table 1). Lakeanrahka, Lappasuo and Ropolansuo are small peat mines (24–30 ha). At Pohjansuo, runoff was monitored from several sub-catchments but only one was included in this paper as the hydrogeology is similar. The underlying mineral soil (clay) was exposed on Lappasuo; at other sites the ditches lay in the peat.

Hydrological measurements

Runoff was observed in 1995 and 1996 during the non-frost season (May–October). Runoff was monitored with a V-notch and a pressure probe. The continuous record was aggregated to daily runoff. At Pohjansuo, the hydrological monitoring also included two tipping-bucket rain gauges, two precipitation gauges measuring daily rainfall, two continuously monitored groundwater wells at peat water table, and several wells monitored biweekly. At Pohjansuo, the runoff generation was studied in detail using electrical conductivity as a tracer for separating the runoff hydrograph into different sources (see Kløve & Bengtsson 1999).

Peat properties and plant composition

Hydraulic conductivity and shear strength measurements were carried out at minimum three points at each peatland. The observation points were located at a minimum 40-meters apart to get a representative measurement for the whole area. Peat samples were taken from the infiltrometer bore hole and analysed at Vapo Oy by Veijo Klemetti for degree of humification and plant type using von Post classification (see e.g. Hobbs 1986).

Hydraulic conductivity was measured with a constant head infiltrometer developed by Dr. Korpijaakko at Geological Survey of Finland. A perforated steel pipe was pushed into the peat to a depth of 30 cm. The peat in the tube was removed with a soil drill. A constant head was provided by a Mariotte bottle. The hydraulic conductivity measurement was continued until a constant volume change in the Mariotte bottle was obtained (the principle is similar to the Guelph permeameter).

The soil shear strength was measured with a vane (80 mm by 160 mm). Torque reading was transformed to shear strength using a factor (5.3) obtained from Geological Survey of Finland. The test was carried out immediately adjacent to the infiltration measurement at 16 cm and 32 cm below the soil surface (at Haukkasuo and Pohjansuo

Table 1. Average peat characteristics and runoff (summers 1995 and 1996) at peat harvesting sites.

Site	Location in Finland	Area (ha)	Start of mining	Hydr. Cond. (m s^{-1})	Shear strength (kN m^{-2})	Degree humif. (v. Post)	Runoff (non-frost) (l s^{-1} km^{-2})		
							Aver.	Min.	Max.
Pohjansuo	Jämsänk.	6	1995	6.00×10^{-6}	370	4	16.2	3.47	898
Haukkasuo	Anjalank.	180	1990	2.50×10^{-6}	413	3			
Haukkasuo	Anjalank.		1980	5.20×10^{-8}	265	5	12.9*	0*	97*
Huppionsuo	Juva	149	1975	1.90×10^{-7}	307	6	12.8	0	188
Lakeanrahka	Juva	30	1986	4.00×10^{-8}	228	**	13.6	0	427
Lappasuo	Keitele	24.4	1982	4.10×10^{-6}	360	5	16.9	0	149
Ropolansuo	Haukiv.	41.3	1975	1.10×10^{-7}	302	4	10.8	0.15	392

*Runoff from Haukkasuo areas drained in the 80's and 90's
**Not measured

the shear strength was also measured from deeper layers). The average of these two depths was used to estimate the peat shear strength. The shear strength was determined by turning the vane until it ruptured. The maximum shear strength that could be measured was 420 kPa.

Analysis

The measured peat properties were related to hydraulic conductivity, and the hydraulic conductivity was related to peak runoff. Before relating hydraulic conductivity to runoff, two events, snowmelt runoff and flooding from upland, were removed from the runoff record. These events do not depend directly on soil characteristics but on snowmelt intensity and drainage procedures, clogging of drain pipes surrounding the mire, and the portion of upland/peatland area. The snowmelt effect was removed by including only June–November data.

RESULTS

Shear strength

The average peat shear strength ranged from 228 kPa at Lakeanrahka to 413 kPa at Haukkasuo (Table 1). The average for all sites was 322 kPa. The lowest value measured at a single point was 143 kPa and the highest 420 kPa. The true average values are somewhat higher as the maximum value that could be measured by the vane was 420 kPa. However, at all sites where 420 kPa was measured, lower values were also obtained, which suggest that the maximum is not much higher than 420 kPa. The observed shear strength was about one hundred times greater than Canadian amorphous or slightly fibrous peat (Landva 1980), indicating that roots and fibers provided the shear strength.

Shear strength decreased with depth, based on measurements on Haukkasuo and Pohjansuo, from around 420 kPa at the surface to 200–250 kPa at about 1 meter depth. At Haukkasuo horticultural peat area the shear strength at 1-meter depth was similar to deep layers at the adjacent lowered fuel peat area, which had different plant composition and greater humification. The shear strength decreased from about 400 to around 300 after 20 years of peat harvesting (Fig. 1) indicating that harvesting lowers the shear strength in the top peat layer. Theoretically, shear strength might decrease with depth in the unsaturated layer because moisture content increases, but this does not appear to be the case here. There was no significant decrease from 16 cm to 32 cm where the moisture content generally changes the most.

Hydraulic conductivity

The average hydraulic conductivity for all sites varied from 4.0×10^{-8} m s^{-1} to 6.0×10^{-6} m s^{-1} (Table 1). This range is typical for Finnish peat in general (Päivänen 1973) and *Sphagnum* peat with H3–H10 decomposition. Hydraulic conductivity varied considerably between sites, with low values at Haukkasuo (5.2×10^{-8} m s^{-1}) and Lakeanrahka (4×10^{-8} m s^{-1}) and high conductivities at Pohjansuo and Lappasuo (about 10^{-6} m s^{-1}). Generally, the standard deviation within a site was similar to the measured conductivity. In other words, sites with high conductivity exhibited high standard deviation and sites with low conductivity had low standard deviation.

Soil lowering (subsidence and soil removal by peat harvesting) reduced hydraulic conductivity. The hydraulic conductivity was higher at new production areas than at areas where peat had been produced for 20 years (Fig. 1). The effect of peat removal was clearly seen at Haukkasuo where conductivity was high (2.5×10^{-6} m s^{-1}) at the area which had been mined for 6 years and low (5.2×10^{-8} m s^{-1}) where peat production had continued for 16 years. When different peat properties are correlated to hydraulic conductivity it can be seen that the soil shear strength best explains variations in soil surface hydraulic conductivity ($r^2 = -0.80$). The hydraulic conductivity can only partly be explained by the degree of humification ($r^2 = 0.36$). Previously, the degree of humification has been the parameter most often related to variations in hydraulic conductivity. The degree of

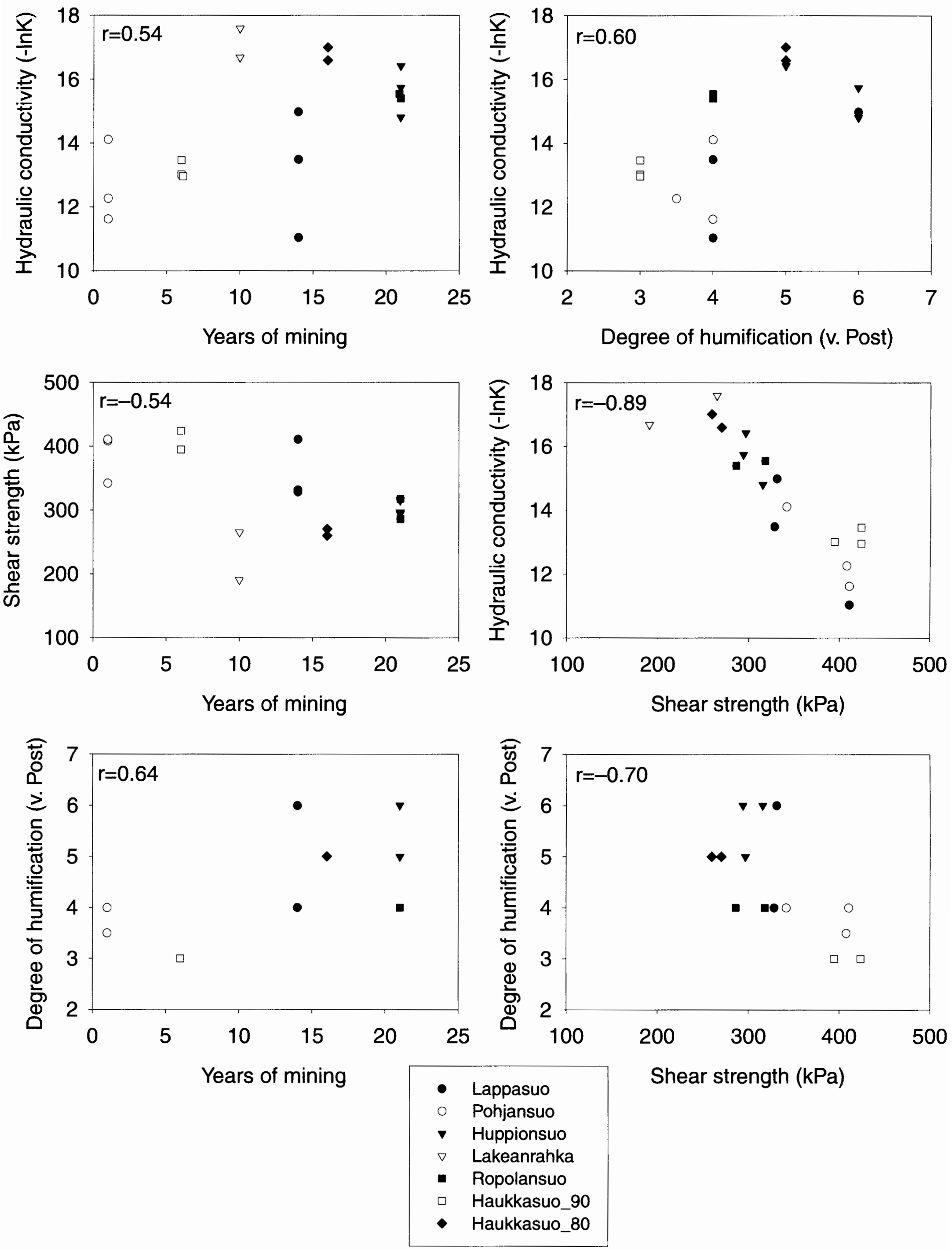

Fig. 1. Relationship between hydraulic conductivity (–lnK), years of mining, degree of humification (von Post) and vane shear strength at different harvesting sites.

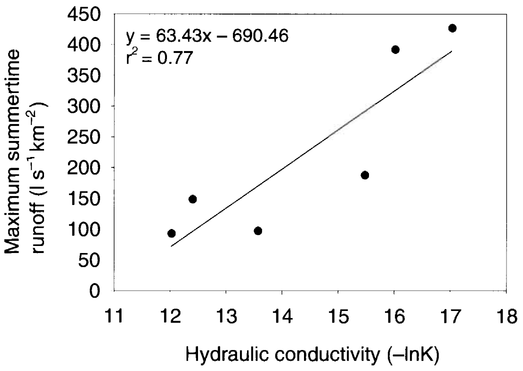

Fig. 2. The dependence of summertime maximum runoff on soil hydraulic conductivity.

humification explains part of the variation in shear strength ($r^2 = 0.48$, $r = -0.70$). This is in agreement with observations by Al-Khafaji & Andersland (1981) on a texture prepared from kaolin and pulp fibres. Neither shear strength nor hydraulic conductivity related to the dominant plant species that the peat consisted of. Peat containing *Eriophorum* or *Carex* did not have higher shear strength than *Sphagnum* peat and it was not seen that these plants alone reinforced the peat as suggested by Landva & Pheeney (1980).

Variation in stream runoff

The average runoff for the observation period (May–October) varied from 11 l s^{-1} km^{-2} to 17 l s^{-1} km^{-2} (Table 1). Generally, the runoff was characterised by low base flow and rapid variation in peak runoff. The highest peak runoff was at a 6 ha sub-catchment of Pohjansuo where the maximum runoff approached 900 l s^{-1} km^{-2}. Based on measurements from adjacent Pohjansuo areas with no flooding, it can be seen that the maximum runoff at the measurement site was primarily caused by flooding from the upland. Similar flooding was observed at Huppionsuo and Lakeanrahka during the maximum peak rainfall in August, 1996. When flooding is not included, the maximum daily runoff from a newly drained Finnish peatland is around 90 l s^{-1} km^{-2} during the non-frost season (Kløve & Bengtsson 1999). When flooding occurs the peak flow depends on the size of the upland and on the portion of the floodwater which enters the harvesting site.

When the upland runoff was excluded from the runoff record, there was a clear correlation ($r = 0.88$) between maximum runoff and peat hydraulic conductivity (K) (Fig 2.) The increase in peak flow occurs due to changes in runoff generation. At Pohjansuo (high K), overland flow did not occur even during the severe event in late August 1996; however, at Ropolansuo (low K) the fields were covered with water during heavy rain and sheet and rill flow occurred (Fig. 3). At Ropolansuo the hydraulic conductivity was low (0.4 mm h^{-1}), similar to typical rainfall intensities occurring in Finland. Also at Huppionsuo, Lakeanrahka and the old part of Haukkasuo the conductivities were low (0.2–0.7 mm h^{-1}), which could form Horton overland flow. At other sites (Pohjansuo, Lappasuo and Haukkasuo 1990), the conductivity varied from 9 to 22 mm h^{-1}, which is too high for Horton overland flow for Finnish conditions.

Overland flow generally occurs if the soil is saturated and drain ditches are not adequate. At Pohjansuo and Haukkasuo the ditch depths are about 120 cm and the groundwater level is usually about 60 cm from soil surface, which provides about 60–90 mm water storage with a 0.1–0.15 storage coefficient The storage was adequate for most rainfall events, indicating that overland flow would not occur on deeply drained sites with high conductivity. At sites with shallow ditches, overland flow due to saturation excess is likely as groundwater flow velocity will be too low to prevent peat saturation during rainfall. For example, at Lappasuo where the surface layer was about 1 m above ditches, the maximum gradient was roughly 1/10. With a 0.5 m thickness of the conveying layer, the Darcy flow velocity would be about 0.18 mm h^{-1}. Thus, overland flow can occur.

DISCUSSION

The results show that variations in peat shear strength explains variations in peat hydraulic conductivity. The good correlation between shear strength and conductivity probably relates to the peat's fiber content, as suggested by Landva (1980) and Al-Khafaji & Andersland (1981).

Fig. 3. Drainage and soil surface on two cutover peatlands of different hydraulic properties. (a) Soil surface and ditch depth on a newly drained fields (Pohjansuo) where overland flow is not observed and (b) ponding of water on soil surface and generation of overland flow due to low hydraulic conductivity and shallow drainage at an old peat harvesting site (Ropolansuo).

Fibers and roots require a considerable force before breaking. The good correlation between vane shear measurement and conductivity is of practical importance because shear strength is easier to measure than degree of humification.

Traditionally, variations in hydraulic conductivity are explained by the degree of humification, which varies with depth. Although conductivity decreases with depth in forested soils (Päivänen 1973), this is not necessary the case at peat harvesting sites (Melantie 1988). The explanation could be that, generally, forested soils studies are conducted in the acrotelm and uppermost catotelm layer, which are important for tree roots. In this layer (<60 cm) the change in peat structure and degree of humification is rapid, and the effect of depth on hydraulic conductivity is easily noticed. In deeper peat layers the humification is slower due to less oxygen and temperature and substrate limitations (Farrish & Grigal 1988). Moreover, in deep peat layers variation in hydraulic conductivity is more related to plant composition or macroporosity from roots and fibers than to the degree of humification alone.

Decrease in soil depth, drainage depth and hydraulic conductivity potentially change hydrological pathways by increasing overland flow and decreasing subsurface stormflow. This is seen as larger runoff peaks when the hydraulic conductivity is reduced. Peat harvesting reduces drainage depth and the hydraulic gradient. As the hydraulic conductivity is also reduced, groundwater velocity in the saturated peat layer will greatly diminish. For example, using the conductivity and gradient values for Haukkasuo, the Darcy velocity values are about 2 000 times lower at the area drained in the 1980's than the area drained in the 1990's. With reduced conductivity the water table will be higher in the peat field and the storage capacity in the unsaturated zone will be reduced. Water storage capacity will be reduced as the pore space is decreased, so the capacity to store rainwater will be much smaller as the soil is lowered. For example, a decrease in the unsaturated zone thickness from 0.5 m to 0.1 m and a decrease in specific yield from values typical for moderately decomposed peat (0.20) to well decomposed peat (0.10) will reduce the water storage capacity in the top soil layer from 100 mm to 10 mm at field capacity. The implications for runoff are that less water can be stored in the peat, overland flow is quickly produced and the runoff peaks will increase.

CONCLUSIONS

The study showed a high correlation between hydraulic conductivity and shear strength ($r = -0.89$), indicating that the field vane shear test is a good indicator for the soil hydraulic conductivity and the change of hydrology in time. The degree of humification only slightly explained the variations in hydraulic conductivity ($r^2=0.36$), and plant composition had no measurable effect.

The study shows that peat harvesting and subsidence can over time decrease hydraulic conductivity and increase runoff. When the upper soil layer is removed, peat of lower hydraulic conductivity is exposed. Combined with reduced drainage depth, this results in a reduced storage capacity for rainwater and reduced groundwater flow velocity. The accumulated effect is increased potential for Horton or saturation excess overland flow which increase peak runoff. The effect of peat subsidence and harvesting on hydrology could be tested with simple tests as the vane shear test and the site geometry.

ACKNOWLEDGEMENTS

The study was financed by Vapo Oy, Finnish Academy, Sihti 2 and Jordforsk The measurement equipment were borrowed from Dr. Martti Korpijaakko at Finnish Geological Survey. The peat characteristics were analysed by Mr. Veijo Klemetti at Vapo Oy. Prof. Jonathan S. Price gave valuable comments to the manuscript.

REFERENCES

Al-Khafaji, A. W. N. & Andersland, O. B. 1981. Compressibility and strength of decomposing fibre-clay soils. Geotechniques 31: 497–508.

Branfireun, B. A. & Roulet, N. T. 1998. The baseflow and storm flow hydrograph of precambrian shield headwater peatland. Hydrological processes 12: 57–72.

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

Burt, T. B. 1995. The role of wetlands in runoff generation from headwater catchments. In: J. Hughes & L. Heathwaite (eds), Hydrology and hydrochemistry of British wetlands, John Wiley, pp. 21–38.

Burt, T.B., Heathwaite, A. L. and 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.

Chow, T. L. Rees, H. W. Ghanem, I. & Cormier, R. 1992. Compactability of cultivated spghagnum peat material and its influence on hydrologic characteristics. Soil Science 153: 300–306.

Clymo, R. S. 1987. The ecology of peatlands. Science Progress Oxf. 71: 593–614.

David, J. S. & Ledger, D. C. 1988. Runoff generation in a plough-drained peat bog in Southern Scotland. Journal of Hydrology 99: 187–199.

Dooge, J. 1975. The water balance of bogs and fens (review report). In: Hydrology of Marshridden Areas. The Unesco Press, IAHS, 233–272.

Eyzerman, N. I. 1993. Physical Properties and Drainage Standards of Forest Soils. Eurasian Soil Science 25: 104–110.

Farrish, K. W. & Grigal, D. F. 1988. Decomposition in a ombotrophic bog and a minerotrophic fen in Minnesota. Soil Science 145: 353–358.

Gillman, K. 1994. Hydrology and wetland conservation. Institute of hydrology, Wallingford, UK. Wiley. 101 pp.

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.

Kløve, B. & Bengtsson, L. 1999. Runoff generation in a plough-drained cutover fen in Central Finland. Journal of Hydrology 288: 157–168.

Kløve, B. 1997. Environmental Impact of Peat Mining. PhD thesis, Lund. Univ. 159 pp.

Landva, A. O. 1980. Vane testing in peat. Canadian Geotechnical Journal 17: 1–19.

Landva, A. O. & Pheeney, P. E. 1980. Peat fabric and structure. Canadian Geotechnical Journal 17: 416–435.

Maslow, B. S. Kolganov, A. V. & Kreshtapova, V. N. 1996. Peat soils and their change under amelioration. Rossel'khozizdat, Moscow. 147 pp.

Melantie, E. 1988. Turvetuotannon vaikutus saraturpeiden vedenläpäisevyyteen. MSc thesis, Joensuun yliopisto, Metsätieteellinen tiedekunta. 54 pp. [in Finnish]

Price, J. S. & Waddington, J. M. 2000. Advances in Canadian wetland hydrology and biogeochemistry. Hydrological Processes 14: 1 579–1 589.

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

Received 29.12.1999, accepted 15.5.2000