BOREAL ENVIRONMENT RESEARCH 5: 81–94
Helsinki 28 March 2000

ISSN 1239-6095

# Retention of suspended solids and sediment bound nutrients from peat harvesting sites with peak runoff control, constructed floodplains and sedimentation ponds

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Kløve, B. 2000. Retention of suspended solids and sediment bound nutrients from peat harvesting sites with peak runoff control, constructed floodplains and sedimentation ponds. *Boreal Env. Res.* 5: 81–94. ISSN 1239-6095

Increased requirements for drainage water treatment has lead to the development of new methods for removing suspended solids and nutrients from peat mine drainage waters. Peak runoff control, constructed floodplains and sedimentation ponds were studied in the field at the Pohjansuo peat mine in Central Finland. Sediment and nutrient concentrations were observed during non-frost periods of 1995 and 1996 and during spring thaw in 1996. The results show that peak runoff control in particular is able to remove suspended sediment almost completely and particle-bound nutrients partially. The new method fulfils the requirement for a 65% reduction in suspended solids set by the authorities without affecting the peat harvest. The low cost of these new methods makes them available for most Finnish peat mines.

## Introduction

In Finland, peat is a major source of energy, especially for district heating. The environmental consequences of peat harvesting have recently received growing attention. It is well known that peat mining increases the transport of suspended solids (SS) to downstream receiving waters (e.g. Sallantaus 1983, Selin *et al*. 1994, Kløve 1997a) which causes enhanced eutrophication and decreased biodiversity (Selin *et al*. 1994). Part of the load has been reduced with sedimentation ponds and pipe structures that are required on all harvesting sites. However, national water authorities have proposed a reduction of 65% for suspended solids and 30% for nitrogen and phosphorus from the 1993 level until the year 2005.

Research into water treatment methods for reducing the negative effects of peat mining started in the 1980s when sedimentation basins and Bed Ditch Pipe (bdp) barriers were developed (Selin and Koskinen 1985). Despite the improved treatment that these basic methods offered, large SS and nutrient loads from peat mines still occur. Consequently, the peat mining company, Vapo Oy, started a research project — Aqua Peat, partly financed by the Sihti program — to develop more efficient ways of reducing SS transport and nutrient leaching (*see* Selin *et al.* 1994). A range of methods such as overland flow fields (Ihme 1994, Heikkinen and Ihme 1995), chemical precipitation (Selin *et al* 1994) and soil infiltration (Kemppainen *et al.* 1998) have been developed. However, the implementation of these methods has not been economically feasible for all mines (Selin *et al.* 1994). Furthermore, these methods can not always be applied because natural mires are required for overland flow fields and sandy eskers are required for soil infiltration. A serious deficiency with the improved methods is that they do not function well during large runoff events when most of the SS load occur.

A project was started in 1992 to develop efficient methods for removal of suspended solids. It was shown with modelling that peak runoff control could reduce peat mine SS transport by 95% (Kløve 1997b). Additionally, laboratory simulations in a hydraulic flume showed that the sediment peak is considerably reduced when the runoff peak is reduced (Kløve 1997c). Previously, similar techniques have been successfully applied in reducing SS transport in urban runoff (e.g. Amandes and Bedient 1980, Akan and Antoun 1994, Urbonas 1994). The SS transport is reduced as the peak runoff is stored until the solids have settled.

In order to apply runoff detention on peat mines a project was started in 1994 in the regime of Aqua Peat 2 and Sihti 2 programmes. Detention of runoff peaks had also previously been suggested as a good method for removing SS loads from peat mines (Sallantaus 1984), but the technology on how to do this was not known. A technical solution consisting of flow regulation with pipes was found in the early 1990s (Kløve 1994). The problem remaining was that more information was needed on hydrology and SS erosion from cutover peatland to apply the method efficiently. Recent studies on hydrology and SS transport from peat mines show that the main source of sediment during storms is erosion of previously settled material from the channel bed (Kløve 1998, Kløve and Bengtsson 1999). Therefore, the main purpose in peak runoff control is to prevented erosion of bed deposits. This is prevented by not allowing the flow velocity to increase above the threshold velocity for bed erosion.

Storm water detention structures allows diverting and controlling water flows. When water flows and water levels are controlled, techniques that were not previously possible can be applied. The use of constructed floodplains (artificial floodplains) in combination with peak runoff control was suggested in Kløve (1994). This type of methods is similar to vegetation strips and dry detention ponds that have previously been used to reduce non-point pollution effectively (*see* e.g. Oberts and Osgood 1991, Meyer *et al.* 1995). Studies in a laboratory (Kløve 1997d) and with a mathematical model (Kløve 1994, 1997b) showed that shallow constructed floodplains are an efficient way of settling small particles. The particles are better retained due to reduced turbulence when the water depth is decreased.

A field observation program was stated at Pohjansuo peat mine to test and develop the new techniques, peak runoff control and constructed floodplains, and to obtain more information on hydrology and pollution transport processes. Practical information was needed on using peak runoff control at different types of peat mines with different hydrological characteristics and on how ponding affects the moisture content of the surface peat. Further questions include: How should peak runoff control structures be built? How do they work during snowmelt? Does clogging of pipes occur and can it be prevented? Finally, are sedimentation ponds necessary when the runoff has already been controlled and the SS load has been reduced in the ditch network?

## Objectives

The main objective was to test and develop peak runoff control and constructed floodplains, in reducing suspended solids and nutrient leakage. The methods were tested on a newly drained area in Central Finland. Because newly drained areas are hydrologically different to old areas the aim was also to evaluate the effect of peak runoff detention on runoff values from old peat harvesting sites.

## Experimental set-up for water quality control structures at Pohjansuo peat mine

### Characteristics of the study areas

Peak runoff control, constructed floodplain, and sedimentation basin were tested at Pohjansuo peat mine. The hydrology of the mine has been studied in detail in a previous study (Kløve and Bengtsson 1999). Two years of observation showed that the daily quick flow is normally less than 10 mm even when the rainfall exceeds 30 mm. Usually following heavy rainfalls, rain-water infiltrates the soil, percolates down to the groundwater and is then slowly released. High runoff peaks exceeding 10 mm (115 $\mathrm{l\ s^{-1}\ km^{-2}}$) are observed during exceptional events such as rapid snowmelt or when the mine is flooded by water from the upland surrounding the peat mine.

Because peat production effects peat hydraulic properties and runoff generation in many ways the effect of peak runoff control was simulated for harvesting sites having different peat properties than Pohjansuo. At harvesting sites, where production has started recently, such as Pohjansuo, runoff generation is different than from older mines where the hydraulic conductivity is usually lower and the groundwater tends to be closer to soil surface. At older sites less storage is available in the unsaturated zone and, therefore, high runoff values are possible. The mines used for testing the structure effect on peak flow comprise peat soils with variable conductivities, degrees of decomposition, shear strengths and ditch depths, all of which can directly or indirectly affect peak runoff. The hydraulic conductivity of the mines varies from $4.0 \times 10^{-8}$–$4.1 \times 10^{-6}$ $\mathrm{m\ s^{-1}}$ (Table 1). The high variation in the maximum peak runoff is partly due to the fact that some areas receive a considerable amount of water from upland areas. Two sets of soil characteristics are reported for the Haukkasuo mine as peat production was initiated separately in two areas; one in the 1980s and one in the 1990s. On the latter area the surface soil is still permeable and the hydraulic conductivity high.

### Peak runoff control

The effect of peak runoff control on water quality was studied in the field at the Pohjansuo peat mine using paired basin experiments as recommended by, for example, Clausen and Brooks (1983). The location of the runoff control structures are shown in Fig. 1. Areas 1 and 2 were compared during 1995 (May–October) prior to installation of control structures to establish whether there were any differences in SS transport between the areas. After this initial calibration period, the runoff control structure shown in Fig. 2a and b, was built on area 2. Its effect on water quality was studied by comparing loads from areas 1 and 2. The pipes in the structure were inclined opposite to flow direction to prevent transport of floating peat, which can easily clog pipes and deteriorate downstream water quality. A bdp barrier of type 1 (Klø-

**Table 1.** Characteristics of peat and hydraulics of different peat mines used to test the effect of peak runoff control.

| Mine | Location municipality | Area (ha) | Start of mining (year) | Ditch depth (cm) | Hydr. Cond. ($\mathrm{m\ s^{-1}}$) | Shear strength ($\mathrm{kN\ m^{-2}}$) | Degree humif. (von Post) | Runoff (non-frost) ($\mathrm{l\ s^{-1}\ km^{-2}}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Aver. | Min. | Max. |
| Haukkasuo | Anjalank. | 180 | 1990 | 130 | $2.5 \times 10^{-6}$ | 413 | 3 | | | |
| Haukkasuo | Anjalank. | | 1980 | 70 | $5.2 \times 10^{-8}$ | 265 | 5 | 12.9* | 0* | 97* |
| Huppions. | Juva | 149 | 1975 | 60 | $1.9 \times 10^{-7}$ | 307 | 6 | 12.8 | 0 | 188 |
| Lakeanr. | Juva | 30 | 1986 | 55 | $4.0 \times 10^{-8}$ | 228 | ** | 13.6 | 0 | 427 |
| Lappas. | Keitele | 24.4 | 1982 | 90 | $4.1 \times 10^{-6}$ | 360 | 5 | 16.9 | 0 | 149 |
| Ropolans. | Haukiv. | 41.3 | 1975 | 85 | $1.1 \times 10^{-7}$ | 302 | 4 | 10.8 | 0.15 | 392 |

*Runoff from Haukkasuo drained in the 1980s and 1990s
**Not measured

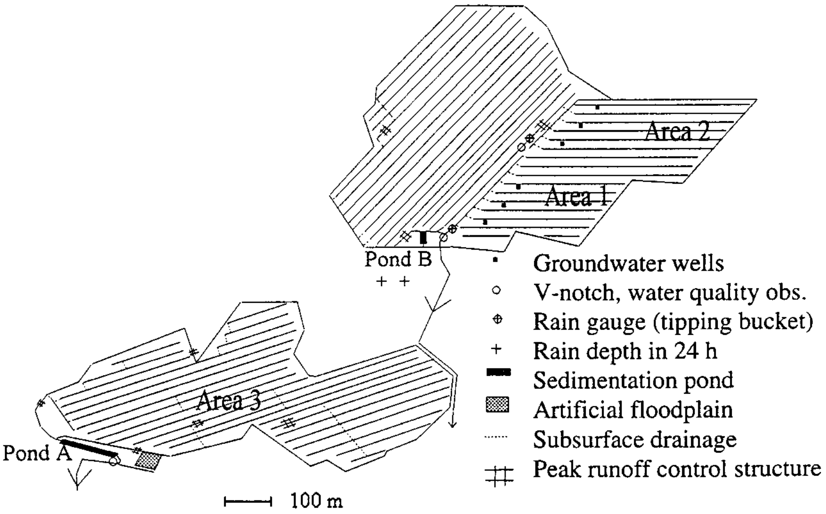

**Fig. 1**. Location of control structures and measurement points at Pohjansuo peat harvesting area.

ve 1997c) was placed in front of the pipes to prevent clogging. Area 3, which is much larger than the other two areas, was not used in this comparison as the runoff was already controlled at the time of the experiment initiation in 1995.

The runoff from control structure pipes can be calculated theoretically if the friction factor ($f$) and local losses in the pipe of known length ($L$) and diameter ($D$) are known. The relationship between the head difference upstream and downstream of the pipe ($h$) and the losses at entry ($K_{\text{in}}$), exit ($K_{\text{ex}}$) and in the pipe itself ($K_{\text{friction}} = fL/d$) can be expressed as:

$$h = \left(K_{\text{e}} + K_{\text{ex}} + K_{\text{friction}}\right)\left(\frac{v^2}{2g}\right) \tag{1}$$

which gives for a pipe of radius $r$

$$Q = \pi r^2 \sqrt{\frac{2gh}{\sum K}} \tag{2}$$

When the loss coefficients ($\Sigma K$) are known, the flow velocity in the pipe and the discharge ($Q$) can be easily obtained from Eq. 2. The sums of the friction factors ($K_{\text{in}} + K_{\text{ex}}$) in Eq. 1 for local losses were determined experimentally for pipes of 32, 50 and 75 mm in diameter (inner diameter 28, 45 and 70, respectively) and a value of approximately 2 was obtained. The experimental layout was similar to that in Kløve (1997c) for the hydraulic characteristics of bed ditch pipes. The wall friction was estimated from the Darcy-Weisbach equation (*see* e.g. Vennard and Street 1982) assuming a constant friction factor ($f$) of 0.02 — a value typical of smooth pipes according to Moody's diagram for Reynolds numbers between $10^4$ and $10^5$.

## Simulation of the effect of peak runoff control on runoff

The effect of Pohjansuo control structures on runoff from mines with the characteristics shown in Table 1 was estimated. The controlled outflow was calculated using reservoir routing (*see* e.g. Raudkivi 1979) under the assumption that observed hydrograph is the inflow into the ditch network.

## Sedimentation ponds

Sedimentation and nutrient removal in two ponds, A and B (Fig. 1), were analysed by comparing concentrations in inflow and outflow water samples. Sedimentation pond A on area 3 was 8 m wide, 60 m long and 1.5 m deep. Pond B was slightly smaller. Pond B was only monitored during snowmelt in April 1996. Pond A was studied intensively during 1995 when water samples were taken at least once a week. When the rainfall exceeded 10 mm additional samples were taken for two consecutive days. The water was analysed

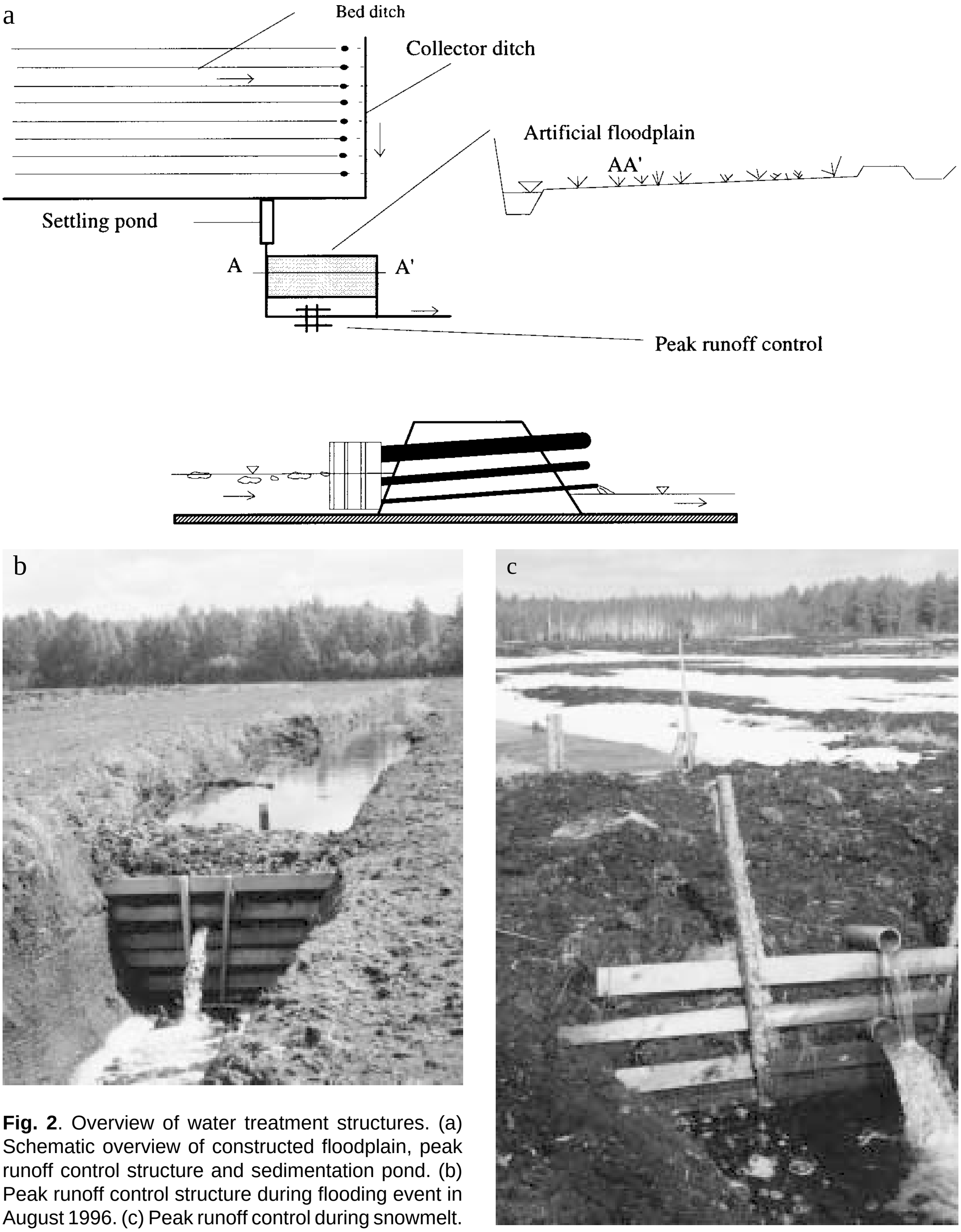

**Fig. 2**. Overview of water treatment structures. (a) Schematic overview of constructed floodplain, peak runoff control structure and sedimentation pond. (b) Peak runoff control structure during flooding event in August 1996. (c) Peak runoff control during snowmelt.

for SS, Ntot (not filtered) and Ptot (not filtered) and the reduction percentages for the basins were calculated as difference between the out- and inflowing mass of material using runoff values. During 1996, the measurement scheme was less vigorous and SS reduction in pond A was observed with sediment traps (*see* e.g. Braskerud, 1995). Cups of 20 cm height and 10 diameter were inserted 20 cm below the water surface at both the inlet and outlet. The cups were emptied once a month and the amount of deposited material measured. The difference in deposition was considered to be equal to the reduction of incoming SS.

### Constructed floodplain

A 30 m by 30 m floodplain was built during spring 1995. The basin floor was slightly above the water level in the adjacent ditch. The basin was inclined so that the outlet was approximately 30 cm higher than the inlet as shown in Fig. 2a. This was done to prevent erosion of settled material when the water levels decrease during hydrograph recession. The basin was built above the ditches in order to ensure rapid plant growth. Grass was planted immediately after the floodplain was built to improve retention of solids. Monitoring of SS was mainly based on sedimentation traps similar as those used in the sedimentation basin. Two traps were placed at inlet and two close to the outlet, these were emptied after each runoff event.

## Results and discussion

### Peak runoff control at test site Pohjansuo

Peak runoff control was studied by comparing runoff and SS transport from two adjacent, 6 ha areas at Pohjansuo harvesting area. During the calibration period of 1995, the runoff produced by rainfall events showed the same hydrologic characteristics for both areas, the SS transport was also about the same. The structures built on areas 2 and 3 worked well during 1995 and 1996 and reduced SS loads efficiently with the concentration always remaining below 20 mg $l^{-1}$ on area 2. During the extreme summer runoff peak in July 1996, the structure shown in Fig. 2b reduced the instantaneous runoff to 63 l $s^{-1}$ (compared with 174 l $s^{-1}$ observed on reference area 1) which completely prevented erosion of channel deposits (*see* Kløve 1997a). All the structures also worked well during snowmelt in 1996 (*see* e.g. Fig. 2c) and 1997. No problems have been reported in 1998 or in 1999. Clogging has not been observed, even in the smallest (4.5 cm diameter) pipe, indicating that the pipe inclination did indeed reduce the transport of floating peat that can clog pipes.

During snowmelt peak in 1996, runoff control reduced SS transport from 4 800 kg $km^{-2}$ to approximately 300 kg $km^{-2}$ with an almost 95% reduction (Table 2) in SS which is in agreement with modelled results (Kløve 1997b) and laboratory experiments (Kløve 1997c). This field study shows that extreme events can be controlled with the structures used and the SS load due to erosion of bed deposits will be completely prevented when the flow velocity is kept under the threshold for sediment movement. As erosion of channel bed deposits is the main reason for the SS load peak runoff control will almost completely remove the SS load.

Detention of runoff will probably also reduce the nutrient load. Reduced channel bed erosion

**Table 2.** Summary of SS and nutrient retention at the Pohjansuo mine with different water treatment alternatives.

| Treatment alternative at Pohjansuo | Removal of SS snowmelt 1996 (%) | Removal of SS Jun.–Nov. 1995 (%) | Removal of Ptot Jun.–Nov. 1995 (%) | Removal of Ntot Jun.–Nov. 1995 (%) | Removal of SS Jul.–Nov. 1996 (%) |
|---|---|---|---|---|---|
| Sedimentation pond | 0[1)] | 41[2)] | 14[2)] | 11[2)] | 68[3)] |
| Constructed floodplain | 79[1)] | | | | 76[3)] |
| Peak runoff control | 95[1)] | | | | 53–88[4)] |

[1)] Grab sample 20.4. 1999
[2)] From 35 grab samples
[3)] From deposition in traps
[4)] Daily grab sample from composite time integrated samples (every 30 minutes)

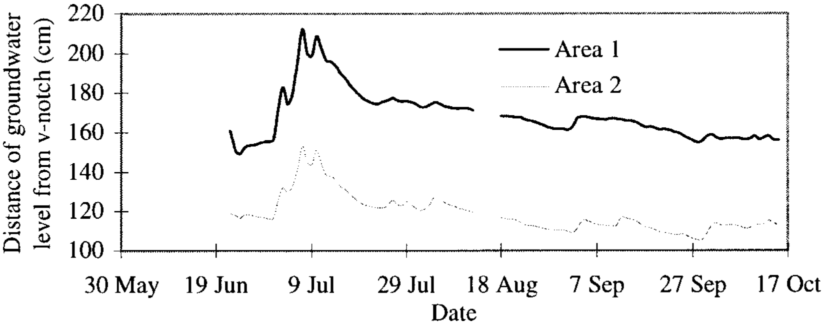

**Fig. 3**. Groundwater levels at Pohjansuo areas 1 (peak runoff control) and area 2 (no runoff control) during 1996.

can reduce phosphorus transport as the phosphorus is retained and stored in the channel during low flows (Svendsen and Kronvang 1993) and is carried with the peat sediments during channel bed erosion. An increased amount of inorganic nitrogen can be reduced through denitrification or transformed to less harmful organic nitrogen when the runoff is stored in the ditches. Data by Sallantaus (1983) imply that the reduction percentages of particulate phosphorus would be as high as the reduction of SS when the sediment load is reduced. When channel bed erosion is prevented, the 30% of phosphorus reduction required by the water authorities by the year 2005 could be achieved with peak runoff control. However, part of the phosphorus retained in the sediment might escape during late summer if the redox potential drops. Therefore, efficient removal of phosphorus requires ditch cleaning before the sediment adsorption capacity is reached. Preliminary results from peat fields in The Netherlands indicate that N and P removal is possible with sediment management (J. W. H. van der Kolk pers. comm.).

The peak runoff control structures will not affect the water-table movement and, therefore, will not effect the drying of the surface peat. During the summer flood in July 1996, the ponding did not affect peat mining as there was no difference between the groundwater level variations of area 1 and area 2 (Fig. 3). The time taken for groundwater table to return to pre-storm levels after a large rain-storm is much longer than the time interval that the storm-water is ponded and delayed in the ditches. Therefore peak runoff control structures do not affect peat harvesting if the ditch water levels are not considerably changed after installation of runoff control.

## Simulated effect of peak runoff control structure on runoff from peat harvesting sites in Central Finland

The effect of pipe structures on runoff detention at several peat harvesting sites in central Finland was calculated. Continuous runoff observations from the summer period were available from five different mines. At Haukkasuo peat harvesting site the peak runoff structure did not have a great effect on runoff. At this site, runoff intensities were low due to the large water storage capacity of the peat and no flooding from outside of the drainage area. However, high runoff will probably occur during rapid snowmelt events when peak runoff needs to be reduced. At Huppionsuo, a large and old mine of low hydraulic conductivity, the calculation show that a structure similar to that at Pohjansuo would have only slightly affected runoff during 1995 (Fig. 4). The two peaks occurring in late August would have been reduced from 167 and 90 l $s^{-1}$ to 110 l $s^{-1}$ and 50 l $s^{-1}$, respectively. The exceptionally high peak in July 1996 which delivered more than 100 mm in 10 days would have been delayed, but the peak values would have remained almost the same. Also at this site the largest effect of runoff control on peak runoff will probably be observed during rapid snowmelt events.

At the Lakeanrahka and Lappasuo mines, the observed runoff peaks are exceptionally high during both 1995 and 1996 — probably due to flooding from the uplands. Indeed, such flow was noted at Lakeanrahka harvesting site during the July 1996 event. The calculated effect of peak runoff control shows that at Lappasuo runoff detention would have reduced the peak from 30 to 5 l $s^{-1}$.

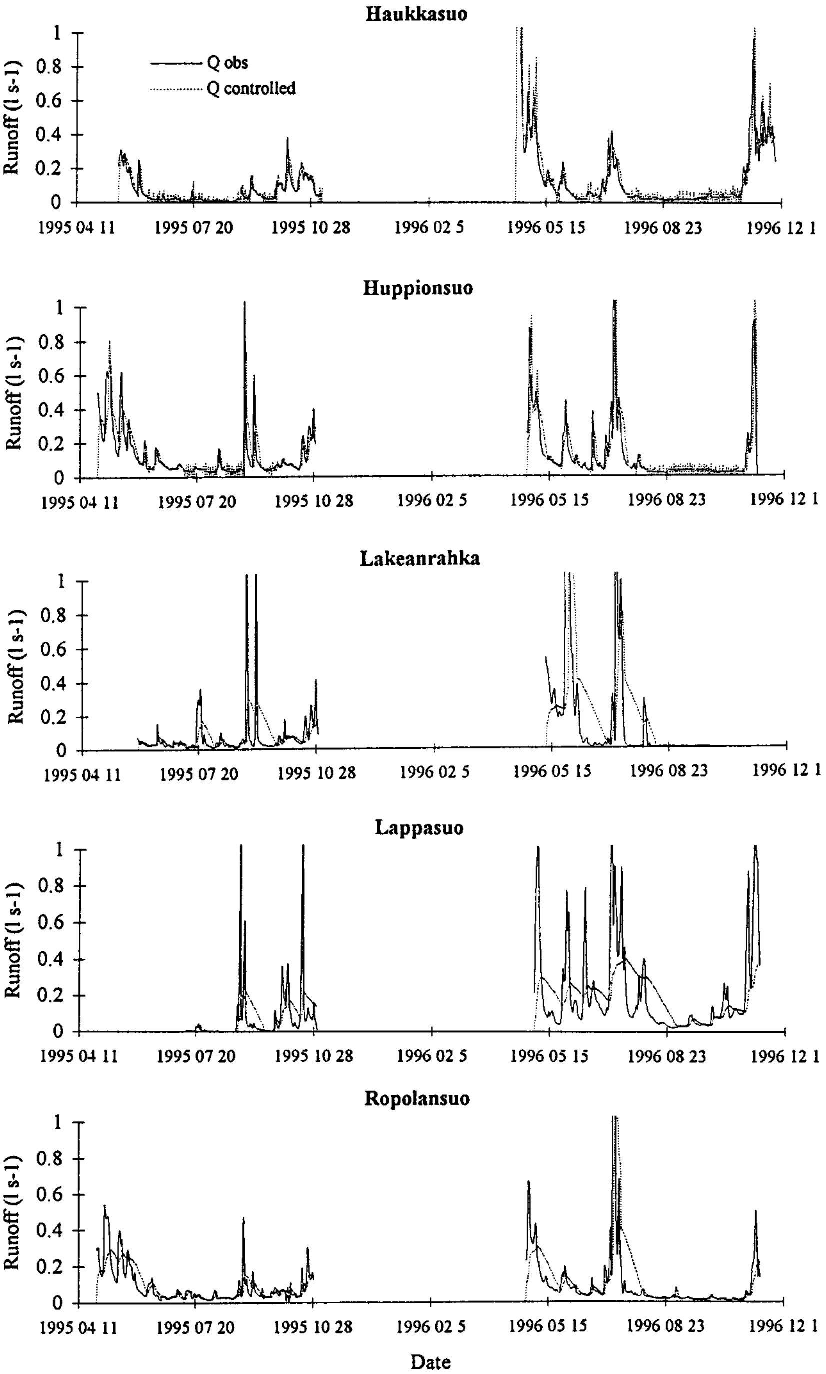

**Fig. 4**. Runoff from peat mines observed during 1995 and 1996 with no peak runoff control and with peak runoff control structures designed to detain 60 mm runoff for 3–5 days.

For the large event in July 1996 the peak would have been reduced from 36 to 8 l s$^{-1}$. Similarly, at Lakeanrahka the peaks would have been reduced from 63 to 9 l s$^{-1}$ for 1995 and from 80 to 24 l s$^{-1}$ in 1996. In May 1996 the peak would have been reduced from 128 to 37 l s$^{-1}$.

At Ropolansuo, all the calculated peaks are lower than the observed peaks in 1995 and a smoother hydrograph would have ensued with control. Only during the July 1996 event can a clear delay be observed as the runoff is considerably reduced. On all mines, the calculated outflow hydrograph quickly returned to the same shape as the uncontrolled hydrograph after the peak.

## Design principles for peak runoff control structures

Peak runoff is reduced by storing the storm-water in ditches and basins during extreme runoff events. The ponding of water in the ditch may negatively affect peat mining operations. For instance, elevated water levels in the ditches could increase the water-table and soil moisture at soil surface; the deposition of mineral soil transported by floodwater from the ditch bed could lower the quality of the peat as fuel. Previous studies show that the runoff generated by large rainfalls during the non-frost season is controlled on new peat mines such as Pohjansuo and Haukkasuo by the hydraulic conductivity of the peat. At older mines where the surface is less permeable, for instance, Lakeanrahka, Ropolansuo and Lappasuo, the ponding of storm-water does not generally continue for a long time, but after the July 1996 event, the storm peak was considerably prolonged. After the storm, the water levels in the ditches remained at above normal values (max. 30 cm) for a maximum of two weeks. It is not likely that this would greatly affect peat mining as peat, roads and so on, usually need several days after a large storm to dry-out before peat harvesting re-commence. During 1995, 1996 and 1997, peat production was normal at Pohjansuo and no hindrance to peat harvesting was noted. During snowmelt, flooding depends on the melt rate, but the delay in runoff in this season is not so important as peat is not harvested. It follows from the above discussion that the structures used at Pohjansuo can safely be used on different peat mines to control runoff without negatively affecting peat production.

Peak runoff control structures for a peat mine can be designed using the pipe flow equation (Eq. 2) and hydrological data as inputs. When the flow to the ditches is known, a structure that detains the inflow peak by the desired amount can be built. On newly drained areas, the drain volume is large enough to store an effective rainfall of 60 mm, which is much larger than generally expected during the non-frost season. Due to lack of hydrological data at Pohjansuo when the structures were built in spring 1995, the size of the pipes were selected to ensure that the structure would detain 60 mm of instantaneous effective rainfall for not more than 3–5 days. The maximum length of detention was selected so that the peat harvesting would not be reduced. Detention should be greatest at the beginning of storms when the erosion and sediment concentrations are highest. Therefore, the lowest pipes have the smallest diameters. Flooding is prevented by having larger pipes at higher levels as seen in Fig. 2a. The outflow from structures used at Pohjansuo for different water levels can be seen in Fig. 5. Usually several structures must be built in order to achieve ponding over the whole mine area and efficient use of the entire ditch volume. At Pohjansuo, the selected area behind a structure varied from 2–20 ha. Locating the control structure so that all areas available for storm water storage, such as fire protection basins and collector ditches, are used is important. The location in connection to these dams also prevents clogging as these dams usually have less floating peat than the bed ditches.

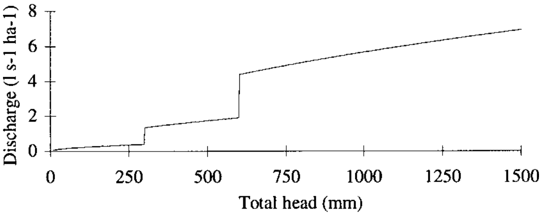

**Fig. 5**. Discharge as a function of hydraulic head (*h*) for the structure used at Pohjansuo peat harvesting area.

The main criteria and difficulty in structure dimensioning is the selection of effective rainfall. The design storm is the size of the event when the main pollution load occurs, which generally equates to snowmelt runoff or extreme summer rains. Where information is lacking, the value of 60 mm, as used on Pohjansuo, could be used. Studies at Pohjansuo (Kløve and Bengtsson 1999) showed that runoff intensities of 60 mm $d^{-1}$ occur only during extreme events such as rapid snowmelt or flooding by external water. Peat erosion and sediment transport occur mainly during these events when the gener-

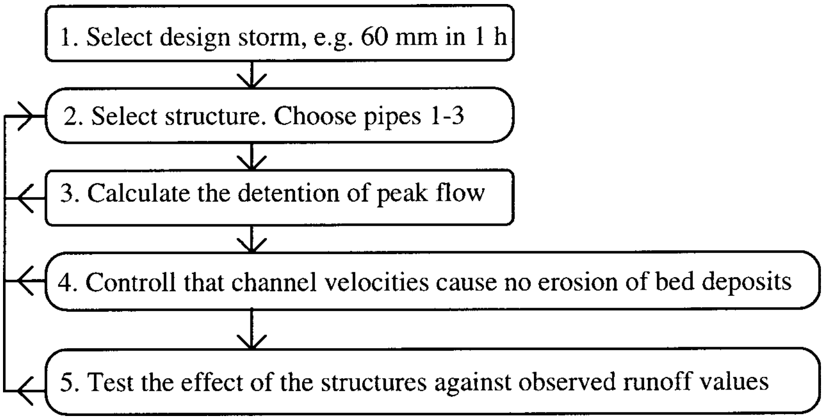

**Fig. 6.** Principles for peak runoff control structure selection.

ated flow is sufficient to remove the SS.

In theory, peak runoff control structures can be designed with the five step procedure presented as a flow diagram in Fig. 6. The size of the pipes in the structure are obtained when the mine area, design storm and the detention time are known. The detention time can be set to 3–5 days as at Pohjansuo. No information is available on when scouring of the bed occurs, so step 4 has to be omitted. If the critical flow velocity for bed sediment erosion were available, the detention time could be adjusted in such a way that no erosion occurs. Using the Pohjansuo dimensioning principles, the maximum flow velocities in the collector ditches when the ditches are full will be approximately 2.4 cm $s^{-1}$ and the velocities in the bed ditches will be below 1 cm $s^{-1}$. Such velocities are insufficient to erode channel deposits, therefore the SS load will almost completely disappear. It is reasonable to assume that if the bed ditch material is fairly similar at different mines as has been noted (Kløve 1998), the dimensioning principle used at Pohjansuo would also prevent channel bed erosion at these other mines and step 4 may be omitted.

If runoff data are available, the effect of a possible structure can be approximated in the final step. The runoff from a mine can be calculated when the inflow to the ditches, the channel size and the hydraulic characteristics of the structure are known. The effect of peak runoff control can be calculated assuming that the observed hydrograph is inflow. The outflow can be obtained using, for example, reservoir routing (e.g. Raudkivi 1979).

## Sedimentation ponds

During the non-frost period in 1995, 41% of the SS load removed in the pond (Table 2). This is in agreement with observations made in previous studies on areas where runoff was not controlled (Selin and Koskinen 1985, Ihme *et al.* 1991). The higher amount of removal (68%) observed during 1996 could possibly be attributed to the differences in observation techniques (sedimentation cups used in 1996). It can be seen from the inflow and outflow series of SS (Fig. 7) that removal is greatest when the concentration is high and that nothing is removed when the incoming concentration is low. This confirms laboratory observations (Kløve 1997d), that is, when the particle size is small (assumed for low concentrations) the sedimentation basin does not reduce SS loads; conversely, when the concentration is high (and particles are large), the reduction is high if the hydraulic load is not too high. Because high concentrations of SS were occasionally observed during low flows, the sedimentation ponds are also necessary when peak runoff is reduced. On old mining areas where the detention storage is small, the basin should be placed before the peak runoff control structure. If a vegetation pond or wetland is used as part of the structure, it should be placed after the sedimentation and runoff control structure. This will prevent clogging of the vegetation filter.

During spring thaw in 1996, slight erosion of sediments was observed in both ponds A and B. The suspended solids concentration increased from 6 at inlet to 6.9 mg $l^{-1}$ at outlet in pond A and

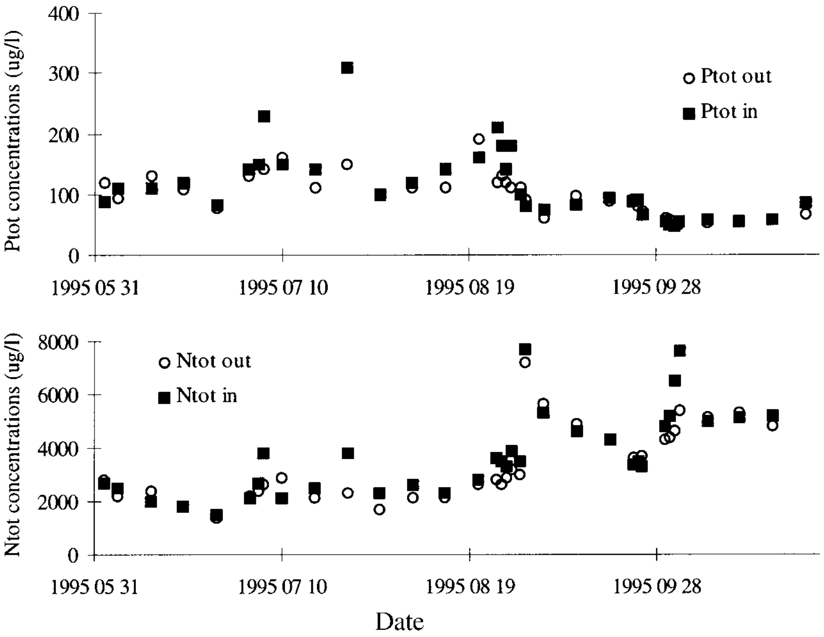

**Fig. 7**. Inflow and outflow concentrations of suspended sediment (SS), total particulate phosphorus (P) and nitrogen (N) in sedimentation basin A at Pohjansuo.

from 1.5 to 6.6 mg $l^{-1}$ in pond B. The material deposited during summer and winter low flows was eroded during high flows due to increase of bed shear stress above the critical values for particle movement. SS transport from sedimentation ponds during high snowmelt induced runoff is a well recognised problem (e.g. Selin and Koskinen 1985). This study shows that some erosion also occurs when the runoff peak is controlled with structures that have been dimensioned to detain 60 mm effective rain for 3–5 days. However, the measured SS concentrations are low and the erosion is small. A way of preventing sediment erosion from ponds is to convey the flood water around the pond (Selin and Koskinen 1985). This can easily be done with peak runoff control structures such as those shown in Fig. 2. A structure can be built at the sedimentation pond outlet that detains runoff during snowmelt more than the structures in the ditch network. This would cause the water to rise immediately upstream of the sedimentation pond. The excess water could be conveyed through a separate ditch around the pond or through a constructed floodplain.

Settling of SS in sedimentation pond reduces the nutrient load. It can clearly be seen from Fig. 7 that the removal of Ptot (unfiltered) mainly occurs because SS is removed, which agrees with previous studies (e.g. Oberts and Osgood 1991). On average, 14% of P and 11% of N are removed. During the event in late July 1995, the inflow Ptot concentration exceeded 300 µg $l^{-1}$, almost 50% of the total P in the water was removed. The reduction of P and N is in agreement with results by Braskerud (1995) who observed 30–40% retention of P and 10% retention of N in sedimentation ponds on agricultural areas in Norway.

## Constructed floodplains

During 1995, the runoff was never high enough for the ditch water level to rise above the outlet structure of the constructed floodplain, so observations of SS removal could not be made. The first flood that was large enough to rise the ditch water level so that flow occurred to the field was observed during snowmelt peak on 20 April 1996 (Fig. 8b). The melt water flooded the ice and snow layer of the floodplain and the SS concentration in melt water was reduced from 120 mg $l^{-1}$ to below 7 mg $l^{-1}$. During the series of large rainfalls in late June and early July 1996, flow occurred on the floodplain (Fig. 8d) and removal of SS as much as 76% was registered with the sedimentation cup method. The floodplain retention of SS was higher than in the sedimentation basin which confirms previous laboratory studies where high retention

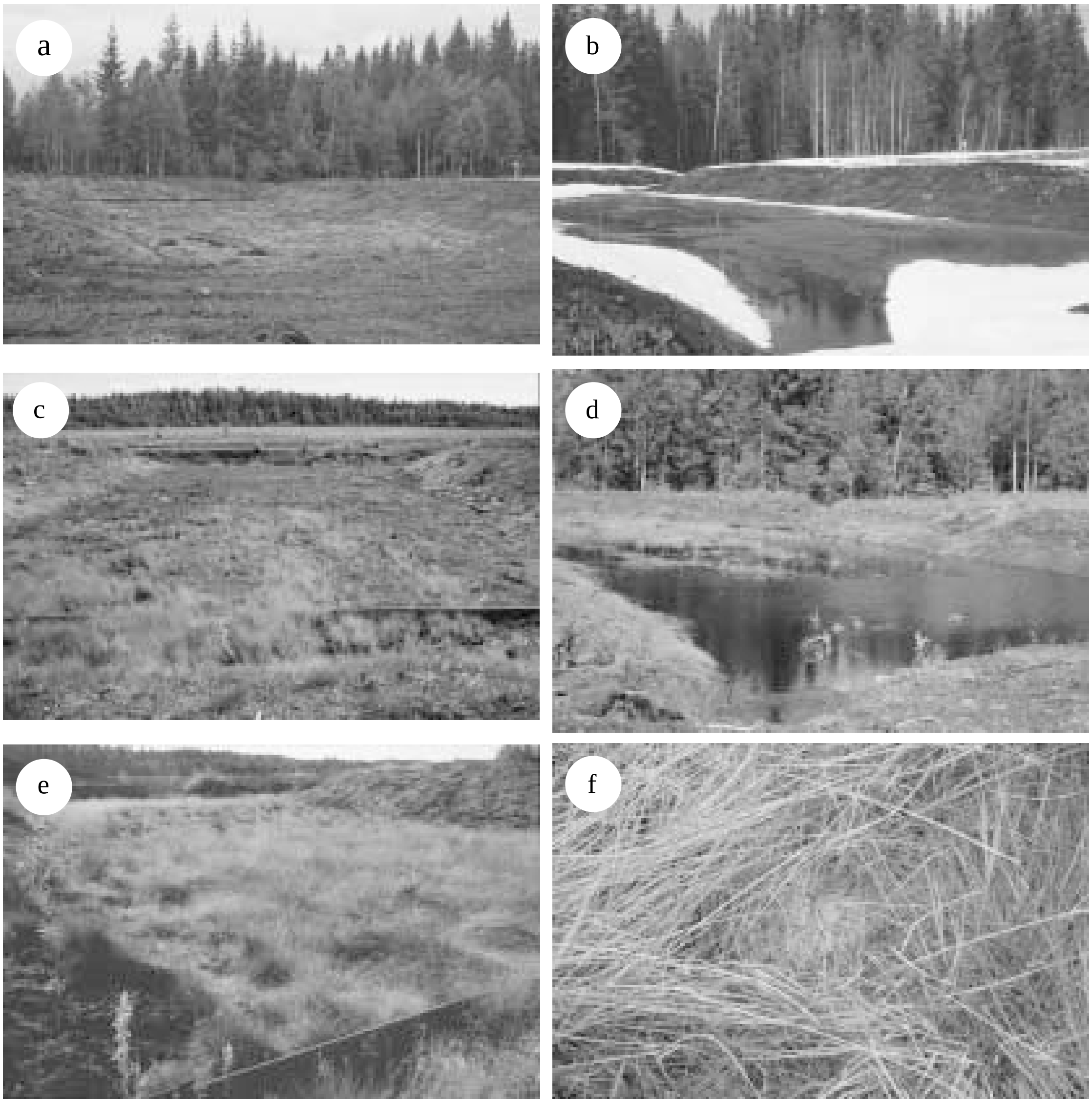

**Fig. 8**. The constructed floodplain at Pohjansuo. — a: After construction in 1995; — b: Flooding during snowmelt in 1996; — c: Vegetation cover in 1996 (Photo: Marja-aho); — d: Flooding during the summer peak runoff in 1996; — e: Vegetation cover in 1997 (Photo: Marja-aho); — f: *Sphagnum* development under *Eriophorum vaginatum* in 1998.

was observed in shallow ponds (Kløve 1997d). The high retention can partly be due to overestimation of SS retention with the sedimentation cup method which has not been previously tested for this purpose. Further studies are necessary to develop and test this method.

The grass planted in the beginning of the experiment died quickly. However, more suitable mire vegetation spread from the adjacent ditches and rapidly covered the area as seen in photos taken in 1995–1997 (Fig. 8). The plant composition changed in time. The wetland vegetation grew most quickly near the outlet where the soil surface was dryer than close to the inlet where the soil was wet and plant development took a long time. In 1998, the first mosses were observed on the field (Fig. 8f). Because the vegetation improves the settling in the basin by capturing particles, floodplains should be built in such a way that the ditch bed at the inlet is also about 15 cm above the channel water level. The vegetation will not have a great effect on flow velocities as the outlet structure, not the channel roughness, controls the flow. In the outlet channel after the floodplain, some erosion occurred during high runoff events. The outlet channel should be made strong enough to withstand high runoff. The risk for anoxia and leaching of phosphorous and iron is probably very small as the field is only flooded during peak runoff events that last for 3–5 days. Also the large surface area and shallow pond depth favours oxygen diffusion from air to water and the risk for resuspension is probably smaller than in deep ponds.

## Conclusions

The new drainage water treatment methods, peak runoff control and constructed floodplain, worked well during observations periods in 1995–1997. There was no clogging in pipes controlling runoff, and the structures worked well during snowmelt events. The peak runoff was considerably reduced, which in turn reduced the annual SS load by 95%. The constructed floodplains decreased the SS load by 76%–79% during peak runoff. Sedimentation ponds removed 41%–68% of SS, 11% of the total nitrogen and 14% of the total phosphorus.

The observations carried out at the Pohjansuo harvesting site confirm previous studies and point to almost complete removal of SS with peak runoff control. Runoff simulations at different harvesting sites show that structures similar to Pohjansuo reduce runoff peaks. Groundwater elevation measurements confirm that peak runoff control structures will not affect the drying of the surface peat and peat harvesting. The sedimentation pond's high removal efficiency shows that they are necessary even when the SS is reduced with peak runoff control. The goals for SS reduction by year 2005 can be obtained using the new treatment methods presented in this study. Also phosphorus and nitrogen loads will probably be reduced through sorption to ditch sediment and increased denitrification, however, more information is needed before reduction percentages can be presented.

*Acknowledgements*: This study was financed by Vapo Oy, the Sihti 2 program and the Academy of Finland. It was part of a larger research program called Aqua Peat aiming at reducing environmental impacts of peat mining. The paper was prepared at Lund university, Department of Water Resources Engineering, and at Jordforsk, Norwegian Centre for Soil and Environmental Research. Valuable comments were given by Prof. Lars Bengtsson, Dr. Pirkko Selin, M.Sc. Jari Marja-aho, M.Sc. Olli Madekivi, and M.Sc. Lauri Ijäs.

## References

Amandes C.B. & Bedient P.B. 1980. Storm-water detention in developing watersheds. *J. Env. Eng. Division* 106: 403–419.

Akan O.A. & Antoun E.N. 1994. Runoff detention for flood volume or erosion control. *Journal of Irrigation and Drainage Engineering* 120:168–178.

Braskerud B.C. 1995. *Tilbakeholdelse av jord, fosfor og nitrogen I fangedammer, resultater-metoder-representativitet*. Jordforsk, Rapport nr. 9/95, 53 pp.

Clausen J.C. & Brooks K.N. 1983. Quality of runoff from Minnesota peatlands: I. a characterization. *Water Res. Bulletin* 19: 763–767.

Ihme R. 1994. *Use of the overland flow wetland treatment system for the purification of runoff water from peat mining*. Ph.D. thesis, VTT publications 798. 140 pp.

Heikkinen K. & Ihme R. 1995. Retention of organic Fe-P-colloids from peat mining water in an overland flow wetland treatment system in northern Finland. *Archiv für Hydrobiologie* 134: 547–560.

Kemppainen S., Lippo H. Hiljanen, R. & Selin, P. 1998. *Haihdutus ja maaperäimeytys turvetuotannon vesienkäsittelyssä*. Metla reports 687: 98 p.

Kløve B. 1994. *Control of sediment transport due to erosion from peat mines*. Licentiate's Thesis, Helsinki University of Technology, Department of Civil Engineering and Surveying, Laboratory of Water Resources Engineering, 149 pp. [In Finnish with English abstract].

Kløve B. 1997a. Leaching of nitrogen, phosphorous and organic matter from a plough-drained peatland in Central Finland. In: Kløve, B. 1997. *Environmental impact of peat mining, development of storm-water treatment methods*. Ph.D. Thesis, Lund Univ., 159 pp.

Kløve B. 1997b. Control of sediment transport from peat mines. *Boreal Env. Res.* 2: 199–207.

Kløve B. 1997c. Comparison and development of ditch structures (bed pipe barriers) in reducing suspended solids concentrations in waters flowing from peat mining sites, *Boreal Env. Res.* 2: 275–286.

Kløve B. 1997d. Settling of peat in sedimentation ponds. *J. Environ. Sci. Health,* part A 32: 1507–1523.

Kløve B. 1998. Erosion and sediment delivery from peat mines. *Soil & Tillage Research* 45: 199–216.

Kløve B. & Bengtsson L. 1999. Runoff generation in a plough-drained cutover fen in Central Finland. *J. Hy-*

*drology* 218: 157–168.

Meyer L.D., Dabney S.M. & Harmon W.C. 1995. Sediment-trapping effectiveness of stiff-grass hedges. *Transac. ASAE* 28: 809–815.

Oberts G.L. & Osgood R.A. 1991. Water-quality effectiveness of a detention/wetland treatment system and its effect on an urban lake. *Environmental Management* 15: 131–138.

Raudkivi A.J. 1979. *Hydrology, an advanced introduction to hydrological processes and modelling*. Pergamon press. 479 pp.

Sallantaus T. 1983. *The load to watercourses from peat mining*. M.Sc. thesis, University of Helsinki, Department of Limnology. 122 pp. [In Finnish with English summary.]

Sallantaus T. 1984. Quality of runoff water from Finnish peat mining areas. *Aqua Fennica* 14: 223–233.

Selin P., Marja-aho J. & Madekivi O. 1994. *Aqua Peat 95, new methods for purifying the run-offs of peat production areas*. Ministry of Trade and Industry, Reviews B182: 195 pp. [In Finnish with English abstract.]

Selin P. & Koskinen K. 1985. *Laskeutusaltaiden vaikutus turvetuotantoalueiden vesistökuormitukseen.* National Boards of Waters, Report 262: 112 pp.

Svendsen L. M. & Kronvang B. 1993. Retention of nitrogen and phosphorus in a Danish lowland river system: implications for the export from the watershed. *Hydrobiologia* 251: 123–135.

Urbonas B. 1994. Assessment of storm-water BMPs and their technology. *Water Sci. Tech.* 29: 347–353.

Vennard J.K. & Street R.L. 1982. *Elementary fluid mechanics*. 6 ed. John Wiley & Sons, 685 pp.

Received 15 January 1999, accepted 18 November 1999