Capacity of Riparian Buffer Zones to Reduce Sediment Concentrations in Discharge from Peatlands Drained for Forestry

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In 1995–2001, the efficiency of riparian buffer zone areas to reduce the concentrations of suspended solids in discharge from peatlands drained for forestry purposes was studied at 7 locations in south-central Finland. The two largest buffer zones reduced the concentrations of suspended solids by >70%. The efficiency of the three medium-sized buffer zones to reduce through-flow sediment concentrations was 50–60%, but no reduction occurred at the smallest two buffer areas. Thus, the capacity of buffer zones to reduce sediment concentrations was strongly related to their size. However, significant correlations were also found between reduction capacity and inflow water sediment concentrations, although the correlations at the two smallest buffer zones were low. The use of buffer zones in reducing sediment load from peatlands drained for forestry purposes is recommended, but relatively large areas for efficient removal capacity are needed.

Keywords ditching, erosion, peatlands, riparian buffer zones, suspended solids, water quality protection
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1 Introduction

About 15 million hectares of peatlands and paludified mineral soils have been drained for forestry in the boreal and temperate zones (Paavilainen and Päivänen 1995). Forestry drainage has been particularly intensive in Finland (>5 million hectares), where the share of drained peatlands forests from the total forestry area is almost 20%. Although drainage has transformed large areas of wetlands into productive forestry sites, it is on the other hand considered the most harmful forestry measure from the viewpoint of water quality protection (Joensuu 2002). The most pronounced change in water quality following drainage is the increase in the concentrations of suspended solids (SS). The highest pulses of SS are usually associated with the actual drainage work, i.e. the initial drainage of pristine peatlands and the maintenance of old ditch networks (Heikurainen et al. 1978, Joensuu et al. 1999). However, high loads can also occur after ditching operations due to the erosion of bare soil surfaces in the ditches (Heikurainen et al. 1978, Hynninen and Sepponen 1983). The increases in loads of SS due to ditching are high and last for a long time in areas where the ditches reach down into the mineral subsoil, but little erosion usually occurs from deep-peat areas where the ditches are entirely in the peat layer (Joensuu et al. 1999).

Enhanced SS transport can also occur from mineral soil forests. This is particularly true for clear-cut areas where heavy rainfalls erode soil material from skid trails and truck roads used for wood transporting (Rapp and Strömquist 1976, Larsson and Gretener 1982). Intensive soil preparation also increases the risk for sediment transport.

Sediment is a threat to all aspects of aquatic ecosystems and numerous adverse effects have been documented (Fairchild et al. 1987, Newcombe and MacDonald 1991). Sediment reduces primary production due to decreased light penetration and disruption of plant cells and respiratory surfaces. High sediment loads reduce numbers and diversity in populations of salmonid and other fish species and aquatic invertebrates. The role of sediment in the sorption, storage, transport, and release of contaminants is also important. Furthermore, sediment may be a significant source of nutrients that cause eutrophication and deterioration of water quality. In forestry as also in agriculture and different mining activities (metals, fertilizer minerals, horticultural and fuel peat etc.), all possible means should therefore be used to remove SS from discharge water before it reaches the recipient water ecosystem.

Sedimentation ponds of varying size and form are commonly used to retain SS from drained peatland forests and peat mining areas (Hannon and Coffey 1984, Ihme et al. 1991a, Wynne 1992, Joensuu et al. 1999, Kløve 2000). Ponds have been shown to efficiently remove coarse-textured mineral soil particles from discharge waters but their effect on fine-textured materials and peat particles may be negligible (Joensuu et al. 1999). The efficiency of ponds may also be poor due to the collapse of the pond walls. Furthermore, ponds are expensive to construct and need to be maintained and emptied regularly where the loads of SS from the upstream drainage areas or clear-cut sites are high.

The use of riparian wetlands for agricultural and household wastewater purification has long been a subject of active research (Hartland-Rowe and Wright 1975, Sloey et al. 1978, Tilton and Kadlec 1979, Nichols 1983, Dubuc et al. 1986, Moustafa 1999). More recently, purification of discharge waters from peat mining areas using riparian buffer zone concept has received attention (Ihme et al. 1991b, Heikkinen et al. 1995). Buffer zones have been considered an inexpensive and maintenance-free means of improving water quality also from peatlands drained for forestry purposes (Sallantaus et al. 1998, Silvan 2004), and suitable areas are presently being transformed into buffer wetlands in practical peatland forestry in Finland.

Buffer wetlands in practical peatland forestry are usually created by simply conducting discharge waters from drained peatlands to pristine mires or, occasionally, also to paludified mineral soils. However, because most peatlands in Finland have been drained, buffer wetlands are very often created by restoring and rewetting sections of drained peatlands by filling in or blocking the main drainage ditches. Buffer area size may vary considerably but rarely exceeds 1.0–1.5 hectares. If only productive forestry land is available for the construction of the buffer small areas are preferred.

Although presently a relatively common water protection method in practical forestry, limited information is available on the efficiency of buffer zones to reduce sediment transport. In this study, the inflow and outflow waters were sampled at 7 buffer zone areas (BZAs) in peatland dominated catchments in south-central Finland with the aim to find out if BZAs significantly reduce the concentrations of SS in through-flow.

2 Material and Methods

The study was conducted at 7 locations in south-central Finland (between latitudes 60°N and 65°N). There was an old peatland drainage area at each location and a buffer zone area was designed downstream from the drainage site (Fig. 1, Table 1). The Asusuo, Hirsikangas, Kirvessuo, Murtsuo, and Sudenalho BZAs were constructed by filling in the main outlet ditch from the drainage area and conducting the water (via a distribution ditch at Hirsikangas, Murtsuo and Sudenalho) to an adjacent undisturbed and flat mire area. No active BZA construction operations were needed at Tulilahti and Kallioneva, where the outlet ditches from the drainage areas ended in undrained areas. The Tulilahti BZA was a paludified mineral soil forest while the other BZAs were peat soils. According to a careful levelling of the BZAs and the above watershed areas, the sizes of BZAs varied from 0.09 to 1.03 hectares, accounting for 0.05–4.88% of the area of watershed.

The ground vegetation at the Murtsuo and Kirvessuo BZAs had changed from the pristine phase due to drainage and they were classified as *Vaccinium myrtillus* type and Herb-rich type drained peatland forests, respectively (Heikurainen and Pakarinen 1982). The other 4 peat dominated BZAs were classified as pristine mires, since no changes from the undrained phase could be seen except next to the filled-in ditches. The depth of peat layer was >1 m at all 6 peatland dominated BZAs. There were only a few shallow patches of peat at the Tulilahti BZA, where the waters running from the upstream drainage area mostly

Table 1. Background information about the studied buffer zone areas.

	Asusuo	Murtsuo	Sudenalho	Kirvessuo	Tulilahti	Hirsikangas	Kallioneva
Location	60°26´N 23°38´E	61°01´N 28°19´E	60°44´N 22°14´E	61°14´N 25°16´E	63°01´N 26°59´E	64°04´N 26°40´E	62°16´N 23°48´E
Area, ha	0.20	0.16	0.09	0.12	0.09	1.01	1.03
Area, % of watershed area	0.23	0.15	0.05	0.09	0.18	1.12	4.88
Site description	Pristine mire	Drained peatland forest	Pristine mire	Drained peatland forest	Paludified mineral soil	Pristine mire	Pristine mire
Site type [a)]	Tall-sedge spruce swamp	*Vaccinium myrtillus* type	Herb-rich tall-sedge fen	Herb-rich type	*Vaccinium vitis-idaea* type	Low-sedge bog	Tall-sedge fen
Stand description	*Betula pubescens* dominated	*Betula pubescens* dominated	Open mire	Picea *abies* dominated	*Pinus sylvestris* dominated	Open mire	Open mire
Stand volume, $m^3 ha^{-1}$	80	80	0	100	30	0	0
Peat depth	>1 m	>1 m	>1 m	>1 m	<0.1 m	>1 m	>1 m

a) Site types for pristine mires and drained peatlands according to Heikurainen and Pakarinen (1982), for mineral soils according to Cajander (1926).

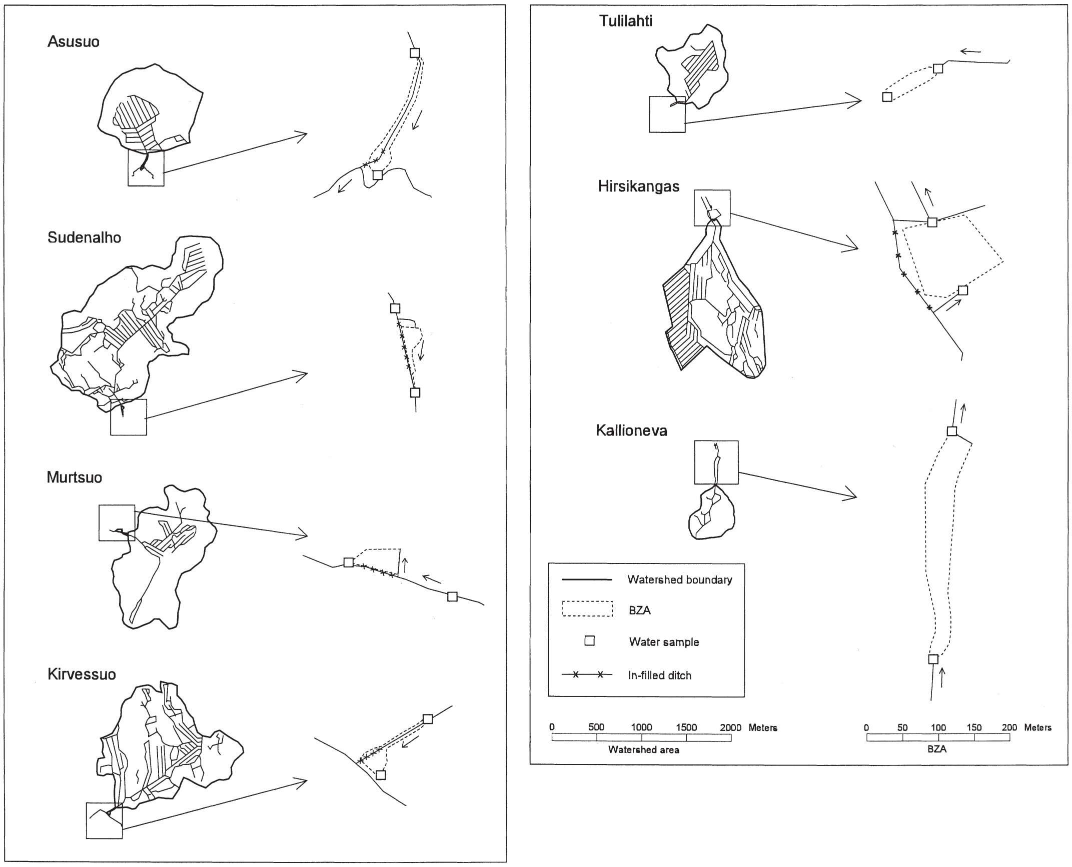

Fig. 1. The drainage areas and buffer zones (BZA) at Asusuo, Murtsuo, Kirvessuo, Tulilahti, Hirsikangas, Kallioneva, and Sudenalho.

flow in subsurface channels between big stones and bulk soil (silty till).

The Hirsikangas, Kallioneva and Sudenalho BZAs were open, treeless mires. The Asusuo and Murtsuo BZAs were both dominated by *B. pubescens* Ehrh. with an average volume of about 80 $m^3 ha^{-1}$. The Tulilahti BZA was dominated by *Pinus sylvestris* L. and had been cut in a seed tree position a few years before the start of the study. The Kirvessuo BZA was characterized by a few mature spruces (*Picea abies* Karst.), pines (*P. sylvestris*) and birches (*B. pubescens*) and an open area in the middle.

To increase the variation in the inflow of SS ditch network maintenance operations (ditch cleaning and/or complementary ditching) were performed at the drainage areas above each BZA (besides at Sudenalho). The maintenance operations were performed in 1996 at Murtsuo, 1997 at Asusuo and Tulilahti, 1998 at Kallioneva, and in 1999 at Hirsikangas and Sudenalho.

Sampling of inflow and outflow waters was started in the early summer of 1995 at the Murtsuo and Asusuo BZAs and in 1996 at Kirvessuo, Tulilahti and Sudenalho, and 1998 at Kallioneva and Hirsikangas. Water sampling continued until the end of 2000 at Sudenalho and Tulilahti, and until 2001 at the other BZAs. Sampling was usually started during snowmelt in spring and continued till the freezing of waters in late autumn. The sampling interval was twice a week during spring and weekly during other seasons. The inflow samples were taken either from the overflow of a V-notched weir (Asusuo, Murtsuo, Kallioneva) or directly from flowing water in the inlet ditch. Outflow water sampling also occurred at a V-notched weir (Kallioneva and Hirsikangas) or at a carefully selected sampling point, where sampling was possible from flowing water without stirring the deposited sediment. In the laboratory, the samples were first filtered through 1.0 µm fibreglass filters and the filters then dried (60 °C) and weighed for SS.

The total number of samples collected from the Asusuo BZA was 129 for both inflow and outflow water. The numbers of samples for the other areas were: Murtsuo; 213, Kirvessuo; 128, Sudenalho; 71, Tulilahti; 119, Hirsikangas; 81, and Kallioneva; 78. The mean concentrations of SS in inflow (SS_{in}) and outflow (SS_{out}) water at each BZA (Table 2) were calculated using all these samples. Reduction in SS concentrations at each BZA was calculated separately for each sampling occasion and mean reduction (Table 2) as the mean of all these reductions. Paired sample t-test was used to test if the differences in SS_{in} and SS_{out} at each BZA were statistically significant and simple Pearson correlation analysis to examine the dependence of SS reduction on SS_{in} concentrations.

3 Results

The concentrations of SS in discharge water were relatively low from all drainage areas before the ditch maintenance operations (see SS inflow concentrations in Fig. 2). The ditching operations increased the average leaching rates and the peak concentrations from the Asusuo, Murtsuo, Tulilahti, Kallioneva, and Hirsikangas drainage areas, but not from the Kirvessuo area.

The two largest BZAs (Hirsikangas and Kallioneva) removed SS efficiently from inflow waters (Fig. 2, Table 2). The mean SS_{in} concentration was 8.5 mg l^{-1} at the Hirsikangas BZA and 14.1 mg l^{-1} at Kallioneva, but the SS_{out} concentrations were only 2.5 mg l^{-1} at both areas. The mean reduction rate relative to SS_{in} was 71% at Hirsikangas and 82% at Kallioneva.

The Asusuo, Murtsuo, and Tulilahti BZAs were also relatively efficient in reducing SS concentrations. Although these three areas differed considerably from each other with respect to SS_{in} and SS_{out} concentrations and also SS reduction rates (in mg l^{-1}), the reduction rates relative to SS_{in} varied only little. The Asusuo and Tulilahti BZAs reduced SS concentrations by about 50% and the Murtsuo BZA by 60%.

Although no ditching operations were performed at Sudenalho, relatively high SS_{in} concentrations often occurred (Fig. 2). The reduction in SS concentrations at Sudenalho was not significant, however (Table 2). No reduction in through-flow SS concentrations occurred also at Kirvessuo.

The reduction in SS concentrations by BZAs appeared to be strongly related to their size. While the two largest BZAs (Hirsikangas and Kallioneva; 1.12 and 4.88% of watershed area, respectively) reduced through-flow SS concentra-

Table 2. Mean SS concentrations ± S.E. in water inflow (SS_{in}) and outflow (SS_{out}) and SS reduction (SS_{red}) at the studied BZAs. Significance of differences between SS_{in} and SS_{out} at each BZA according to t-test also are given.

	SS_{in}	SS_{out}	SS_{red}	p-value	n
	mg l^{-1}				
Asusuo	4.9 ± 6.7	2.5 ± 2.7	2.4 ± 0.8	0.005	129
Murtsuo	19.8 ± 17.8	8.1 ± 7.3	11.7 ± 1.6	<0.001	213
Kirvessuo	4.3 ± 2.7	4.8 ± 3.7	-0.5 ± 0.6	0.434	128
Sudenalho	7.0 ± 4.7	6.7 ± 4.6	0.3 ± 0.3	0.365	71
Tulilahti	11.5 ± 11.4	5.9 ± 5.6	5.6 ± 2.3	<0.001	119
Hirsikangas	8.5 ± 6.6	2.5 ± 2.4	6.1 ± 0.9	<0.001	81
Kallioneva	14.1 ± 14.4	2.5 ± 2.3	11.6 ± 3.2	<0.001	78

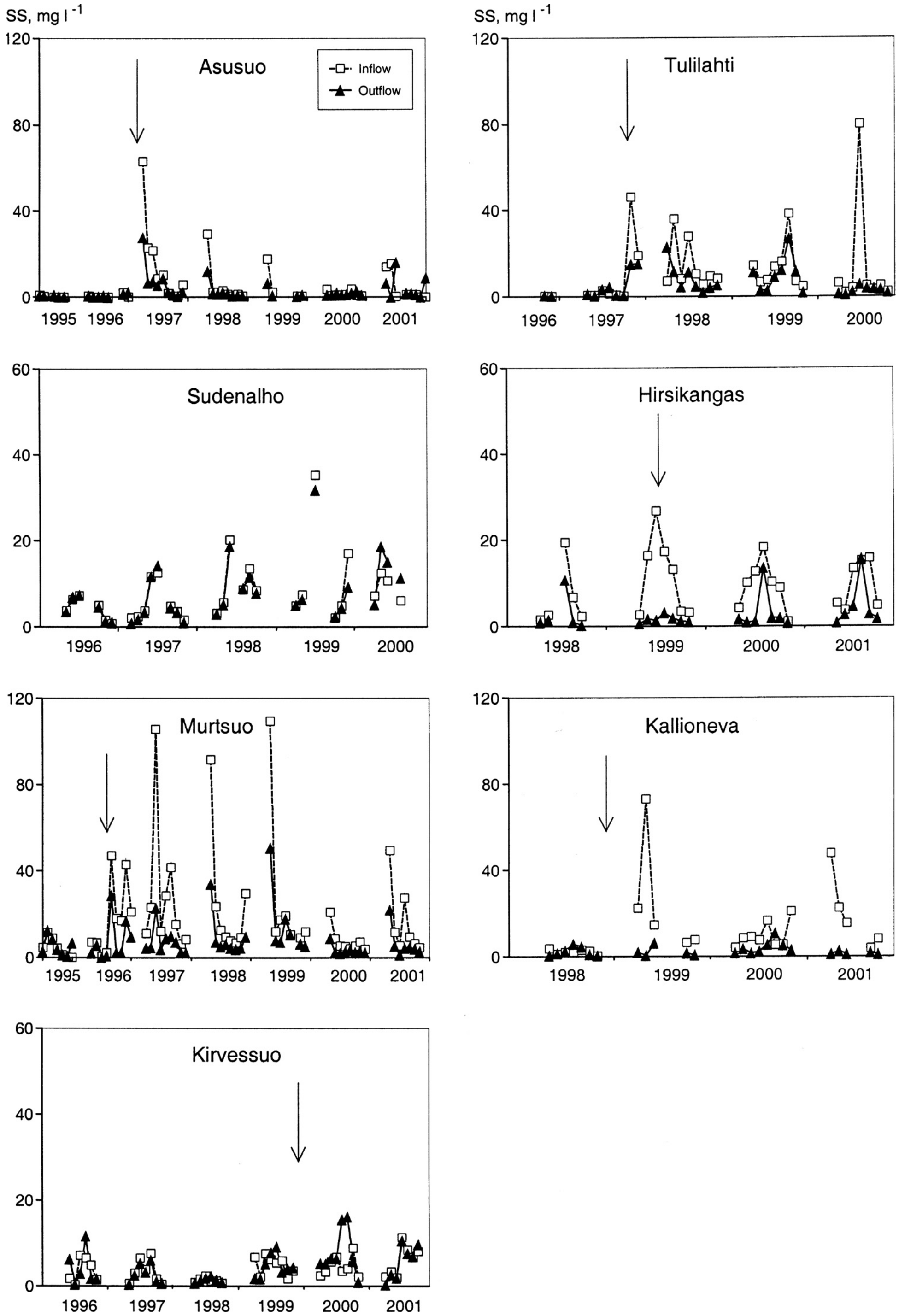

Fig. 2. Mean monthly SS concentrations in water inflow and outflow at the studied BZAs. Time of ditch network maintenance at the upstream drainage area is indicated by an arrow. No ditching operations were performed at Sudenalho.

Table 3. Correlation coefficients between the reductions of SS by BZAs and SS_{in} concentrations. For the number of samples, see Table 2.

Asusuo	0.97***
Murtsuo	0.91***
Sudenalho	0.27*
Kallioneva	0.99***
Kirvessuo	0.26**
Tulilahti	0.97***
Hirsikangas	0.77***

Significance level: * $p<0.05$, ** $p<0.01$, *** $p<0.001$

tion by >70% and the three medium-sized BZAs (Asusuo, Murtsuo and Tulilahti; 0.15–0.23% of watershed area) by 50–60%, no SS reduction occurred at the two smallest areas (Sudenalho and Kirvessuo; <0.10% of watershed area). However, the reduction in SS concentration by BZAs was also strongly related to SS_{in} concentrations (Table 3). The correlations between SS reduction and SS_{in} were relatively low at the two smallest areas, however.

4 Discussion

This study indicated that the reduction in discharge SS concentrations by BZAs is strongly and positively related to their size. Under conditions where discharge waters from large areas drain through significantly smaller areas as in the case of BZAs, the reduction in SS is likely governed by how much the water flow is slowed down in the area to allow the suspended particles to efficiently settle down among ground vegetation and surface soil. The strong influence of BZA size on SS removal is therefore not unexpected.

The reductions in through-flow SS concentrations by BZAs were also related to SS_{in} concentrations, but less strongly at Kirvessuo and Sudenalho than the other 5 areas. Low correlations between SS reduction and SS_{in} at Kirvessuo and Sudenalho are most probably because water flow did not slow down due to their very small size and no settling of SS occurred in response to either low or high SS_{in} concentrations. However, it should be noted that, regardless of the size of BZA, the correlations between SS reduction and SS_{in} may be poor if the concentrations of SS_{in} are very low. Thus, the relatively poor correlation at the Kirvessuo BZA may not only be due to its small size but also because of low SS_{in} concentrations (Table 2, Fig. 2).

The efficiency of BZAs to reduce SS transport may also be related to the type and weight of SS material, i.e. light peat particles are probably less effectively retained than high-density mineral soil particles (Joensuu et al. 1999). Sampling of sediment transport in the present study occurred from flowing surface water and some of the larger particles rolling in the bottom of water channels may have been excluded. These larger particles likely represent the sediment fraction that is most efficiently retained by BZAs and the results may therefore somewhat underestimate the capacity of BZAs to reduce the overall sediment transport.

In addition to their size, coverage of ground vegetation, magnitude of slope and type of surface soil may be important BZA characteristics influencing SS reduction. However, as flat areas with full vegetation cover and peat as the surface soil material are generally chosen as to be used as buffer areas, the effect of the other site characteristics will remain low compared with the high influence of BZA size.

The Vanneskorpi BZA in the study by Sallantaus et al. (1998) decreased through-flow SS concentrations by about 97%, which is higher than the maximum removal (82%) in the present study. The very high removal rate at Vanneskorpi is due to very high SS inflow rate (101 $mg\,l^{-1}$), relatively large BZA area (2% of watershed area), and also because heavy mineral soil particles were most probably the main source of SS. The cause for drastically increased transport of mineral soil particles in the area was that the main outlet ditch from the drainage area had been dug in a coarse-textured mineral soil. Lyytikäinen et al. (2003) found an average SS removal efficiency of only 15% at 13 BZAs in north-east Finland, but their BZAs were very small and SS inflow rates considerably low (0–20 $mg\,l^{-1}$, average 1.2 $mg\,l^{-1}$).

Although BZAs are an efficient water protection method concerning the removal of SS, a negative impact may be involved that they increase the outflow of soluble phosphorus (Vasander et al. 2002). This may be particularly true if a drained peatland site is restored and rewetted and used as a BZA, because the phosphorus accumulated in peat iron complexes during drained state is released in anoxic conditions. It is, however, still unclear whether this increased P leaching from BZAs is a common problem. It is also unclear if BZAs act as a sink or source for other soluble pollutants. It should be noted that, although enhanced leaching of soluble pollutants would occur during BZA construction operations and a few years after, BZAs may turn into pollutant-accumulating systems in the long-term (Liljaniemi et al. 2003). Thus, future research should be focused on the long-term monitoring of soluble pollutants in discharge from different types of BZAs.

Sedimentation ponds are commonly used to decrease SS transport from drained peatland forests, but their efficiency is often poor (Joensuu 2002). Based on the results of the present study, the use of BZAs for decreasing sediment transport is more recommendable. However, achieving high reduction in SS concentrations, relatively large BZAs are needed.

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