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Hydraulic nutrient transport in a restored peatland buffer

Niko Silvan[1)3)]*, Tapani Sallantaus[2)], Harri Vasander[1)] and Jukka Laine[1)3)]

[1)] *Peatland Ecology Group, University of Helsinki, Department of Forest Ecology, P.O. Box 27, FI-00014 Helsinki University, Finland*
[2)] *Pirkanmaa Regional Environment Centre, FI-33300 Tampere, Finland*
[3)] *The Finnish Forest Research Institute, Parkano Research Centre, Kaironiementie 54, FI-39700 Parkano, Finland (*corresponding author's e-mail address: niko.silvan@helsinki.fi)*

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The aim of this study was to investigate the hydraulic transport of nitrate (NO_3^-) and phosphate (PO_4^{3-}) in a restored peatland buffer by quantifying the nitrate and phosphate input–output balance and nutrient transport in the buffer. The area of the buffer was ca. 0.5 ha, and it amounted to ca. 15%–25% of the water catchment area above. Nitrate and phosphate were added continuously during June–July in 1999, applying $Ca(NO_3)_2$ (110 kg Ca, 90 kg N ha^{-1}) and K_3PO_4 (38 kg K, 30 kg P ha^{-1}) water solution in the experimental area. Nutrient transport and retention in the buffer were monitored in the site in 1998–2001. Only ca. 0.5% of added nitrate and ca. 7% of added phosphate was leached through the buffer during the period 1999–2001. Especially added nitrate was retained in a relatively small area in the upper experimental area, ca. 0.2 ha, whereas added phosphate spread out to a much larger area. The results obtained indicate that the buffer is capable of removing effectively especially nitrate but also phosphate from throughflowing water, if the buffer area is large enough, and if the slope of the buffer is suitable.

Introduction

Forestry operations cause leaching of nutrients, especially nitrogen (N) and phosphorus (P), into water bodies located downstream from forestry operation areas. These forestry operations are cuttings (Hyvönen *et al*. 2000), ditch network maintenance in forested peatlands (Joensuu *et al*. 2002) and fertilizations (Nieminen 2000). Consequently, the detrimental effects, especially eutrophication caused by leached nutrients of forestry operations on water bodies have gained increasing interest in recent years (Ympäristöministeriö 1998). The most important detrimental effects caused by eutrophication are cyanobacteria bloomings and water quality deterioration for aquatic flora and fauna (Kauppila and Bäck 2001). In headwaters, concern regarding the survival of brown trout (*Salmo trutta* L.) has also been expressed (Laine 2001).

Boreal landscape is a mosaic in which upland forests, peatlands and water bodies form a moisture gradient, and the outflow water from upland forests was in most cases filtered naturally through pristine peatlands before large-scale drainage that began in the 1950s in Finland (Keltikangas *et al*. 1986). Drainage of peatlands has been very extensive in Finland: the present peatland drainage area represents 53% of the total peatland area in Finland, and in southern Finland the proportion of drained peatlands is as high as 75% (Hökkä *et al*. 2002). Since most peatlands have been drained, suitable buffer peatlands for interacting nutrient loads have to be created by restoring sections of peatlands drained for forestry (Sallantaus *et al*. 1998, 2003).

The prerequisite of a successful restoration of peatlands is to restore the original flow paths of waters and the water table levels by blocking and filling in the ditch network (Sallantaus *et al*. 2003). Some kind of treatment of the forest stand is usually also involved in the restoration of peatlands, depending largely on the original mire type of the restored site (Sallantaus *et al*. 2003). If the original mire has been open, complete harvesting is the obvious treatment, but in the case of peatlands which originally had a dense tree cover the whole tree stand is usually left intact during restoration (Sallantaus *et al*. 2003). This may be feasible from the biodiversity point of view, but not necessarily if the aim of the restoration of peatland is to create buffer for retaining nutrients from throughflowing water.

If the tree stand harvesting is complete during the restoration, the colonisation and growth of ground vegetation is much more rapid than in the situation of incomplete tree stand harvesting (Heikkilä and Lindholm 1997, Komulainen *et al*. 1998, 1999), especially if there are large amounts of nutrients present in the restored site (Silvan *et al*. 2004). Because the rapidly growing ground vegetation retains nutrients more efficiently than tree stand in peatlands (Finer and Nieminen 1997), the complete tree stand harvesting both enhances and increases the nutrient retention of restored peatland buffer. Furthermore, growing ground vegetation may also enhance the microbial growth in its rhizosphere (Liu *et al*. 2000, O'Donnell *et al*. 2001), and thus microbial nutrient retention in restored peatland buffers (Silvan *et al*. 2002, 2003).

The aim of this study was to investigate the hydraulic transport of nitrate (NO_3^-) and phosphate (PO_4^{3-}) in a restored peatland buffer by quantifying the nitrate and phosphate input–output balance and nutrient transport in the buffer. Ihme *et al*. (1991) reported the retention of N, but the liberation of P, in the overland flow buffer areas in drained and shallow-peat areas for the purification of runoff water from peat harvesting areas. Also Kuusemets and Mander (2002) reported very high N retention in a shallow constructed storage lake in Estonia, but P retention was much lower. In addition, Sallantaus *et al*. (2003) reported leaching of phosphorus due to the restoration of peatlands drained for forestry. Thus, we postulated that the restored peatland buffer retains nitrate from throughflowing water quite effectively, but the retention efficiency of phosphate is much lower, and thus the leaching of phosphate may be remarkable. Also the peatland buffer area required for phosphate retention may be larger than that for nitrate retention.

Material and methods

Characteristics of the experimental site

Material was collected from a peatland site in central Finland (61°48´N, 24°17´E) that had been drained for forestry in the 1950s and restored in 1995 by rewetting the site and clear-cutting the forest stand (Komulainen *et al*. 1998, 1999). The original mire site type before forest drainage had been oligotrophic tall-sedge pine fen (for mire site type description *see* Laine and Vasander 1996) which is the most widespread mire site type in Finland (Keltikangas *et al*. 1986).

Part of the restored site was left as a control area (ca. 0.3 ha) with no NO_3^- or PO_4^{3-} addition (Fig. 1). The experimental area amounted to ca. 0.5 ha, which was ca. 15%–25% of the water catchment area above. The water catchment area was estimated by using the basic map and levelling measurements in the field. Water inflow into the restored site was conducted via two ditches, and water outflow via one outlet (Fig. 1). One of the ditches was used as the N and P feeder ditch discharging into the experimental areas while the other ditch was flowing into the control area (Fig. 1).

There was a height difference of 0.8 m in 70 m distance between the upper and lower parts of the experimental area (1.14% gradient) and the N and P increase in the lower area was received through hydrologic transport via the upper experimental area. The upper experimental area, which received high NO_3^- and PO_4^{3-} additions from the feeder ditch in 1999, had an area of approximately 0.2 ha (Fig. 1).

The lower experimental area which got a lower NO_3^- and PO_4^{3-} addition through the upper area was approximately 0.3 ha (Fig. 1). Boundaries of the areas were determined after N and P addition on the basis of the concentrations of NO_3^- and PO_4^{3-} in soil water.

The soil was rather humified *Carex* peat (H4–H6 according to the scale of von Post; Puustjärvi 1970), and the thickness of the peat layer was over 2 m (Jauhiainen *et al*. 2004). The total porosity of peat soil was approximately 88%, and the total carbon and nitrogen contents of soil were 519 ± 3.3 g kg^{-1} and 14.6 ± 0.09 g kg^{-1}, respectively. The pH of soil water varied between 4.0 and 4.5.

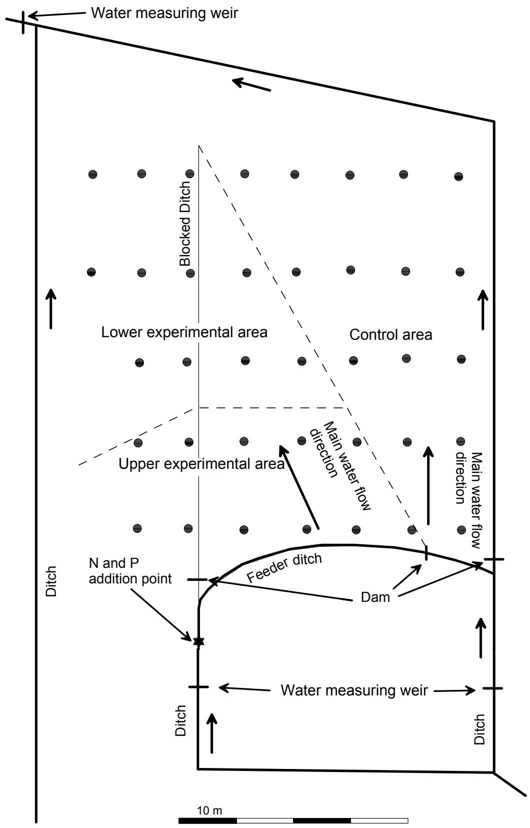

Fig. 1. Schematic map of the site, showing the N and P addition point, feeder ditch, and main water flow directions. Filled circles are water sampling wells.

Experimental design

The experiment was carried out by using the calibration period-reference area method, with 1998 as the calibration year. In 1999, NO_3^- and PO_4^{3-} were added continuously during June–July, applying $Ca(NO_3)_2$ (110 kg Ca, 90 kg N ha^{-1}) and K_3PO_4 (38 kg K, 30 kg P ha^{-1}) water solution into the experimental area through the feeder ditch. The addition was scaled so that the N and P increase was approximately 100 times higher than the natural level, mimicking the release of N and P after NP fertilization or N and P liberation in connection with forestry operations (N and P from decomposing logging residues, especially from needles) in the drainage area or in the upland forest catchment above (Kenttämies 1981, Hyvönen *et al*. 2000, Nieminen 2003).

Analysis of hydraulic nutrient transport

The hydraulic load and nutrient transport were monitored in the site in 1998–2001. Hydraulic load rates were measured with triangular Thompson's (90°) measuring weirs equipped with limnographs (graphic water level recorder) allowing continuous measurements. Natural nutrient inputs were determined by multiplying nutrient concentrations in inflowing water (μg l^{-1}) before the nutrient addition in 1999 by hydraulic load (l y^{-1}) for both experimental areas and the control area separately. Input–output balance was determined by subtracting output nutrient amounts from input nutrient amounts. Water samples were taken monthly above and below the restored buffer for inflow and outflow water. NO_3^- and PO_4^{3-} were analysed from the water samples with SFS 3030 and SFS 3025 FIA analysers in the Environmental Centre of Pirkanmaa, respectively, and K and Ca with ARL 3580 ICP analyser in the Finnish Forest Research Institute.

For determining the dynamics of inner spatial variation in NO_3-N, PO_4-P, K and Ca concentrations in soil water within the buffer, water samples were taken from 37 systematically situated water sampling sites. At each site, a pipe well (diameter 20 mm, PVC) was inserted in surface peat in 1997. The pipe wells were densely perforated (with 3 mm holes) for an 8-cm stretch that was located below the water-table level. Water

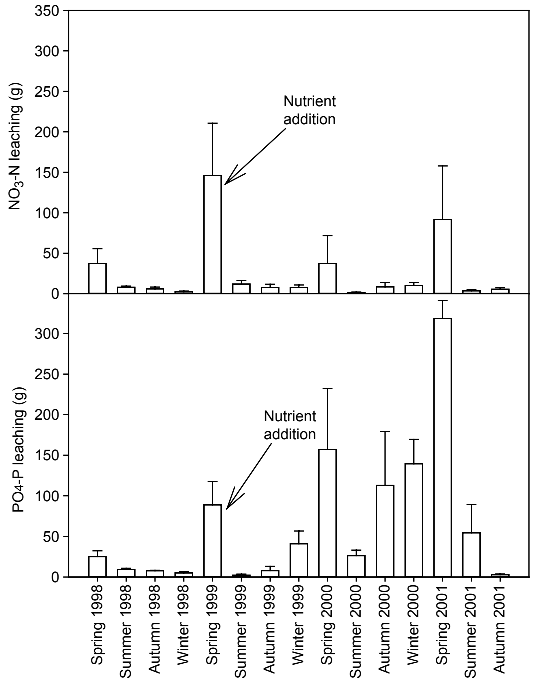

Fig. 2. NO_3-N and PO_4-P leaching (g) during three-month periods in 1998–2001.

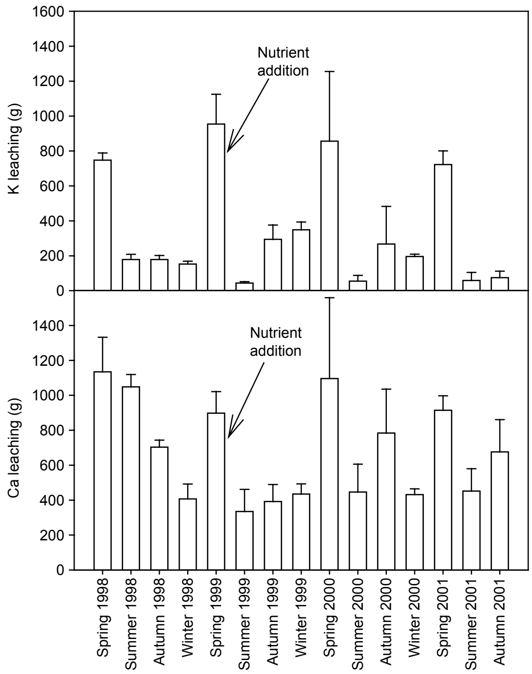

Fig. 3. K and Ca leaching (g) during three-month periods in 1998–2001.

samples were taken monthly during the growing seasons 1998, 1999 and 2000, and analysed as above.

The differences in NO_3-N, PO_4-P, K and Ca leaching amounts between the years 1998–2001 were analysed with one-way ANOVA. The NO_3-N, PO_4-P, K and Ca leaching amounts were used as dependent variables and the study year as an independent variable. Analyses were performed using the SYSTAT for Windows statistical tool package (SYSTAT 1999). The nutrient transport rates were calculated multiplying the hydraulic load rates with the nutrient concentrations in water and integrating the values over the study period.

Results

The monthly average water inflow was 0.05–0.7 l s^{-1} in the experimental area and 0.05–0.5 l s^{-1} in the control area in 1998–2001. The water inflow was greatest during the spring flood season and lowest in winter.

Natural NO_3-N input into the experimental area was 8–43 g per year and natural PO_4-P input 4–9 g per year. Corresponding natural NO_3-N and PO_4-P inputs in the control area were 18–67 g per year and 15–31 g per year. The natural N and P input in the experimental area was minimal as compared with the N (45 kg) and P (15 kg) addition in the growing season 1999. Despite the high nutrient pulse in 1999, the leached amounts of nutrients in outflow water in 1999–2001 were relatively low (Figs. 2 and 3), except for PO_4^{3-} (Fig. 2), leaching of which was significantly higher after the nutrient addition than in the control year 1998 ($F = 6.68$, $P < 0.01$). Instead, leaching of NO_3^-, K and Ca was not significantly higher after the nutrient addition. A small increase in NO_3^- leaching was observed only just after the nutrient addition in 1999, but the PO_4^{3-} leaching increased during the period 1999–2001 (Fig. 2). A very small increase was also observed in both K and Ca leaching in spring 2000, one year after nutrient addition (Fig. 3).

The added NO_3^- was mainly retained in the upper experimental area of ca. 0.2 ha (Fig. 4), whereas added PO_4^{3-}, K and Ca spread out in a much larger area, over 0.5 ha (Figs. 4 and 5).

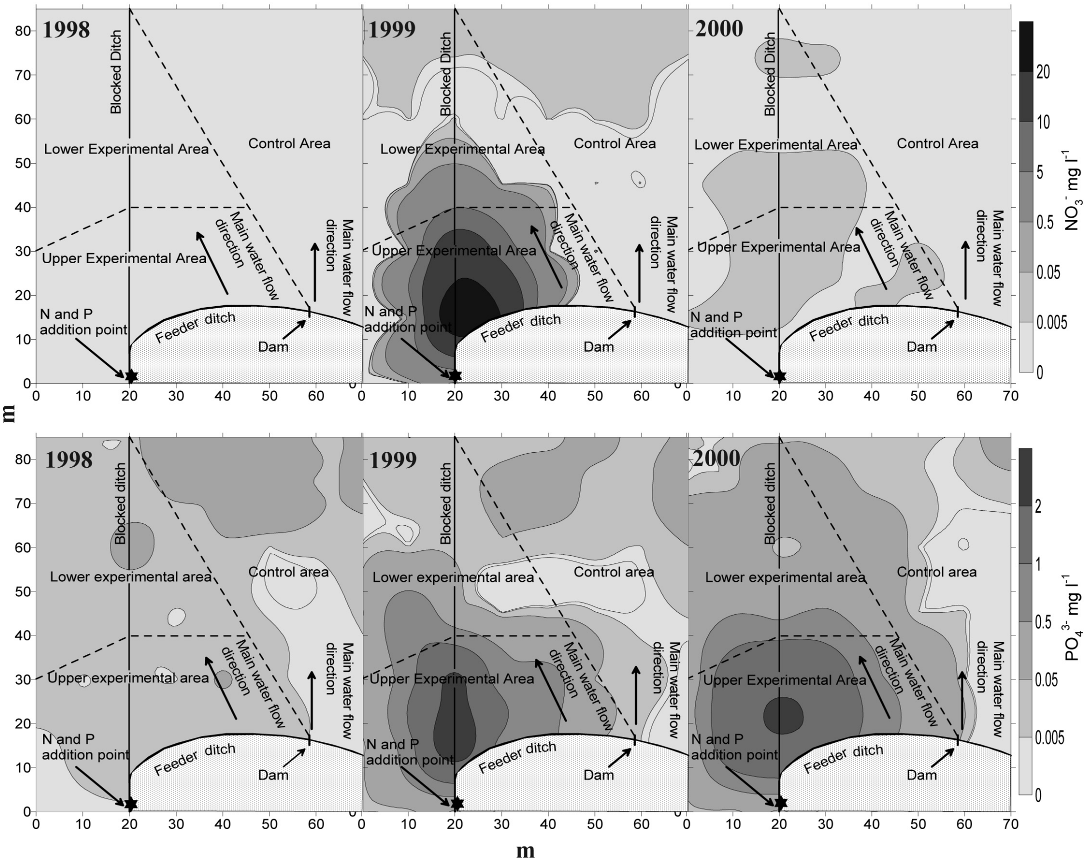

Fig. 4. Spatial variation in NO_3-N and PO_4-P concentrations (mg l^{-1}) in soil water in the restored peatland buffer during 1998–2000. The average NO_3-N and PO_4-P concentration values for the summer of each year were calculated from water samples taken 3–4 times during the period.

Discussion

Despite the high nutrient pulse, only ca. 0.5% of added nitrate and only ca. 7% of added phosphate was leached through the buffer during the period 1999–2001. However, the concentration of phosphate increased gradually in outflow water during this period (Fig. 2). Thus, it is possible that phosphate leaching from the area will increase in the future, although during the period 1999–2001 it was much lower than the leaching from restored peatlands reported in e.g. Sallantaus *et al*. (2003). The magnitude and duration of possible phosphate leaching depends largely on the duration of phosphate retention in vegetation, microbial biomass and peat matrix. Also our former studies (Silvan *et al*. 2003, 2004, Silvan 2004) showed that the phosphate leaching from the study site slightly increased during the second year after the nitrate and phosphate addition. However, our study lasted only three years, and thus a more long-term study is needed to investigate the magnitude and duration of phosphate leaching in the future.

The results of this study support partly our postulate, which stated that restored peatland buffer retains quite effectively nitrate from throughflowing water and the retention efficiency of phosphate is much lower. Further, the added nitrate was mainly retained in the upper experimental area, which suggests that the buffer area required for effective retention of nitrate may be much smaller than that required for the retention of phosphate. However, high rates of leaching of phosphate were not observed in spite of quite high phosphate addition in 1999.

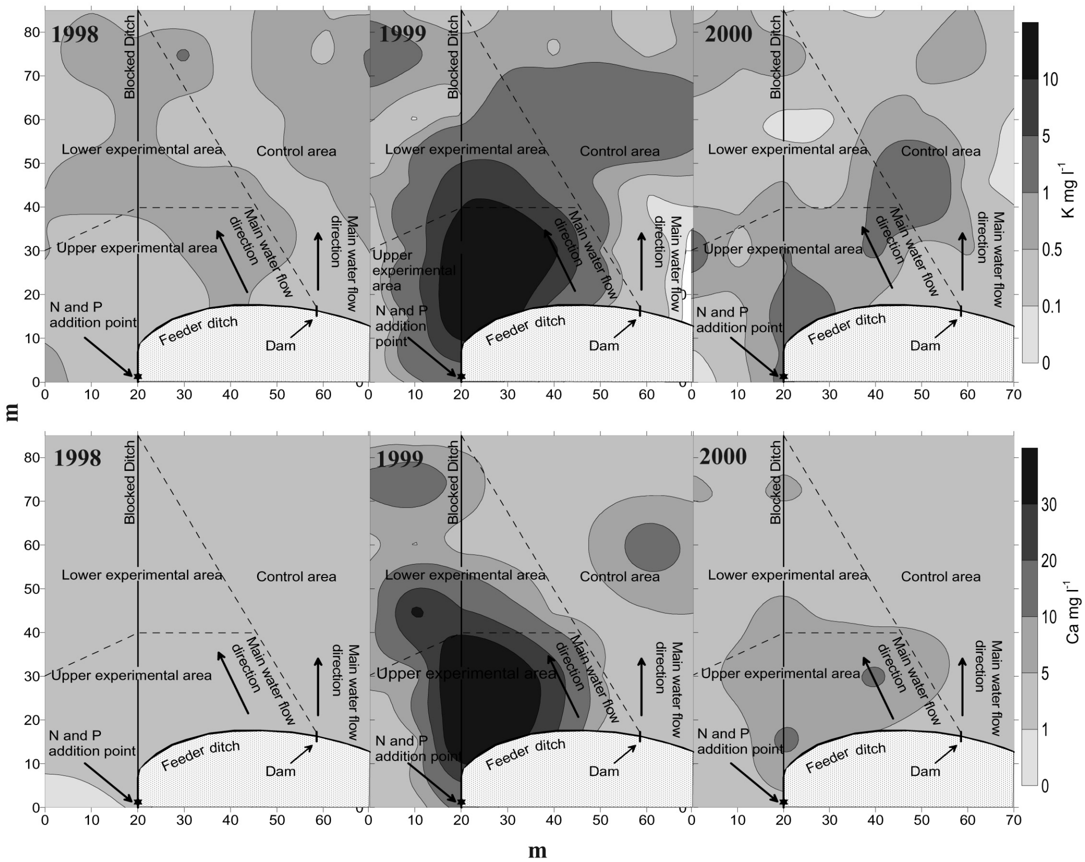

Fig. 5. Spatial variation in K and Ca concentrations (mg l^{-1}) in the restored peatland buffer during 1998–2000. The average K and Ca concentration values for the summer of each year were calculated from water samples taken 3–4 times during the period.

The restored peatland buffer was quite large (ca. 15%–25% of the catchment area) in relation to its estimated water catchment area, and thus if the buffer had been smaller, the retention efficiency might also have been weaker. The results of our former studies (Silvan *et al*. 2002, 2003, 2004) showed that ca. 15% of the added nitrate was removed in a gaseous form and ca. 15% and 70% were retained in the microbial biomass and in the vegetation during the first year after addition, respectively. For the added phosphate the retention percentages were ca. 25%, 25% and 43% in the microbial biomass, vegetation and peat matrix, respectively.

The major harmful hydrological effect of restoration of peatlands earlier drained for forestry seems to be the leaching of phosphorus (Sallantaus 1999, Sallantaus *et al*. 2003). However, it is still unclear how common this problem is, and whether it can be reduced. One answer to this question may be the complete or partial harvesting of existing tree stand, also in the originally densely wooded nutrient rich peatlands to ensure rapid colonisation and growth of nutrient retaining ground vegetation (Silvan *et al*. 2004). The harvesting of tree stand is important at least if the purpose of peatland restoration is water protection, because the leaching of phosphorus seems to be higher the denser is the remaining tree stand in the restoration area. In addition, negative effects in water bodies may also strongly affect the public attitudes towards peatland restoration in general.

The national water protection programme aims at decreasing the nutrient loads from forested areas until 2005 by 50% from the level of 1993. Thus, in the future, the control of the detrimental effects of forestry operations on water bodies will become increasingly important. The results from this study showed that the aim could be achieved by using sufficiently large restored peatland buffers in decreasing the leaching of N and P into adjacent water bodies. The results obtained indicate that the buffer is capable to remove effectively especially nitrate but also phosphate from throughflowing water, if the buffer area is large enough, and if the slope of the buffer is suitable. Thus, potentially each drainage area should include a restored buffer part through which outflowing water both from the drainage area and from the surrounding upland forest catchment would be filtered.

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