Ditch network maintenance in peat dominated boreal forests – review and analysis of water quality management options

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Ditch network maintenance in boreal peatland forests – review and analysis of water quality management options

Abstract

The objective of this study was to evaluate the potential of different water management options to mitigate sediment and nutrient exports from ditch network maintenance (DNM) areas in boreal peatland forests. Available literature was reviewed, past data re-analyzed, effects of drainage intensity modeled and major research gaps identified. The results indicate that excess downstream loads may be difficult to prevent. Water protection structures constructed to capture eroded matter are either inefficient (sedimentation ponds) or difficult to apply (wetland buffers). It may be more efficient to decrease erosion, either by limiting peak water velocity (dam structures) or by adjusting ditch depth and spacing to enable satisfactory drainage without exposing the mineral soil below peat. Future research should be directed towards the effects of ditch breaks and adjusted ditch depth and spacing in managing water quality in DNM areas.

Keywords: drained peatlands; phosphorus; nitrogen; suspended solids; water quality

1. Introduction

Along with the recent shift to more bio-based economy the need for forest biomass is increasing. In the boreal regions, a significant proportion of this demand is covered by biomass harvest from forest sites, where the ground water level has been lowered by drainage. About 15 million ha of peatlands and paludified mineral soil sites have been drained for forestry purposes in the temperate and boreal regions and 10 million ha of them in the Baltic Sea Region (Paavilainen and Päivänen 1995). Drainage has been shown to significantly increase tree growth in both boreal peatlands and wet mineral soils (cf. Sikström and Hökkä 2016). In Finland, drained peatlands cover 25% of the forest land and their total annual stem volume increment is 25% (Päivänen & Hånell 2012) of the 104 Mm^3 of all forests (Finnish Statistical Yearbook of Forestry 2014). In Lithuania, stand growth has been reported to increase by 3.2-3.6 m^3 ha^{-1} year^{-1} after drainage (Ministry of Environment of the Republic of Lithuania 2003). In Sweden, the post-drainage volume increment of tree stands may exceed 10 m^3 ha^{-1} year^{-1} (Hånell 1988).

Currently, there is almost no first-time drainage of pristine peatlands carried out to increase tree production, but ditch network maintenance (DNM) and remedial drainage are done to sustain and improve the drainage conditions of forest soils. DNM can be done by clearing the old ditches (ditch cleaning) that have lost their water transportation capacity, e.g., because of occupation by wetland vegetation, or digging new ditches between the old ones (supplementary ditching), or as a combination of both. Remedial drainage is done to lower the ground water table level temporarily raised because of harvesting the water-consuming tree stand. The depth of ditches rarely exceeds 40-50 cm in remedial drainage, but the ditches excavated in DNM areas may reach deeper than one meter from the soil surface. Particularly in the shallow-peated areas, a significant proportion of the ditches may reach the mineral soil below peat (Joensuu et al. 1999). In the very thick-peated areas (peat depth > 1.5 m), only the collector ditches excavated somewhat deeper than the actual drainage ditches may expose any mineral soil below peat.

Despite that drainage operations can improve growth, a serious concern has been raised related to their impacts on water quality in receiving water bodies (Prévost et al. 1999, Holden et al. 2007, Ecke 2009, Ramchunder et al. 2009). Particularly, the increase in exports of suspended solids (SS) can be large (Joensuu et al. 1999, Marttila and Kløve 2010a, Nieminen et al. 2010). The ditches which reach the mineral soil below peat may be particularly large sources of SS (Joensuu et al. 1999, Holden et al. 2007). In Finland, DNM operations are estimated to increase SS export from forest land by over 50% compared to natural background loading, and cause about two-thirds of the forestry-induced phosphorus (P) export (Finér et al. 2010). DNM operations have also been shown to enhance the exports of dissolved inorganic nitrogen (N), particularly ammonium (Joensuu et al. 2002, Hynninen et al. 2011). In contrast, decreased exports of dissolved organic N and dissolved organic carbon (DOC) have been reported after DNM (Joensuu et al. 2002, Åström et al. 2004, Nieminen et al. 2010).

There are a large number of potential options to mitigate the SS and nutrient exports caused by DNM, but no general agreement on their efficiency. The main aim of this study was thus to evaluate the efficiency of different options to mitigate SS, N, and P exports from DNM areas and to define the major research gaps for improving water quality management related to DNM. To enable this, we identified three principal research objectives. First, we reviewed the available literature in order to compare the efficiency of different water quality management options to reduce the exports of SS, N, and P. The second objective was to elucidate, whether the excavation of deep ditches, which probably increases SS exports significantly more than shallow ditches, is necessary for maintaining satisfactory drainage conditions in DNM areas. For this, we used the hydrological model FEMMA (Koivusalo et al. 2008) to illustrate how varying ditch depth and spacing combinations affect the ground water level (GWL) under hydrologically contrasting conditions. Our hypothesis was that because peat decomposition increases and thus its hydraulic conductivity decreases over time since drainage, deep ditches become less important in maintaining good drainage conditions in old drainage area than in poorly decomposed peats in recently drained areas.

Sedimentation ponds are the most frequently used water protection structure in drained sites to mitigate the SS exports caused by DNM. Therefore, our third objective was to reanalyse the primary data by Joensuu et al. (1999) to improve the understanding behind the factors controlling the efficiency of the ponds to decrease SS exports. Our principal aim here was to elucidate how the pond volume and inflowing SS loading affect the retention efficiency.

2. Material and methods

2.1 Literature review

We carried out a literature review on published studies on the efficiency of different water management options used in conjunction with DNM and remedial drainage in the boreal forest region. The literature was searched by the scientists in the EU Baltic Sea Region Programme funded project Water Management in Baltic Forests (WAMBAF) (Piirainen et al. 2017). The water properties reviewed were suspended solids (SS) and total and dissolved species of nitrogen (N) and phosphorus (P). We did not include the studies related to the efficiency of natural and restored wetland buffers in retaining SS and nutrients in our literature search, as their performance was recently reviewed by Nieminen et al. (2015a). However, the factors related to the performance of wetland buffers, as well as the limitations in their use in operational forestry, are summarized briefly.

We found only eight studies that researched the efficiency of mitigation options other than wetland buffer areas in boreal peat dominated forests (Joensuu et al. 1999, Joensuu 2002, Liljaniemi et al. 2003, Nieminen 2003, Marttila and Kløve 2010b, Marttila et al. 2010, Hansen et al. 2013, Haahti et al. 2017). However, we found a number of studies related to the processes controlling SS, N, and P exports from drained sites. We also utilized the results of those studies in clarifying which water protection structures or management options could be efficient in managing water quality in DNM areas.

2.2 FEMMA-model scenarios of ground water level

The available literature suggests that excavating deep ditches reaching the mineral soil below peat results in significantly larger SS exports than shallow ditches remaining in peat (Nieminen 2003, Joensuu et al. 1999). Therefore, we used the FEMMA (model for Forestry Environmental Management) hydrological process model (Koivusalo et al. 2008) to elucidate the importance of deep ditches in maintaining drainage conditions under hydrologically contrasting conditions. The FEMMA-model consists of sub-models for snow accumulation and melt, interception and transpiration in the overstory and understory vegetation layers, and soil- and ground water interactions, and runoff generation (Koivusalo et al. 2008). In the model, a drained peatland area is described as a hydrological response unit, which is a vertical one-dimensional soil column that resides between the drainage ditch and the midpoint between two parallel ditches or the catchment boundary. Canopy and snow sub-models are driven by daily standard meteorological input data and soil water movement and runoff generation processes are then simulated using potential transpiration and throughfall/snowmelt series available from the canopy and snow sub-models (Koivusalo et al. 2008).

The FEMMA model was applied to produce scenarios for the impacts of drainage on GWL using different combinations of ditch depth and spacing in peats of differing hydraulic conductivity. The simulations were calculated for open, treeless peatland sites, where the functioning of the ditch network has the greatest influence on site drainage conditions, i.e. drainage network may have minor contribution to site drainage conditions in mature stands, where water interception and transpiration by trees dominates the water balance (Sarkkola et al. 2010, 2012). The daily time series of air temperature, precipitation, relative humidity, wind speed, and downward short and log-wave radiation for southern (60°27N'; 24°57'E) and northern (64°43'N; 26°0'E) Finland during 2009, representing an average year with respect to air temperature and precipitation during a 30-year period (1981-2010), were the meteorological input data. We simulated two extremes to show the potential variation in GWL between different ditch depth and spacing combinations, i.e. the peat was either slightly decomposed (bulk density 0.06 g cm^{-3}) with high hydraulic conductivity (6.17 cm h^{-1}) or highly decomposed (bulk density 0.19 g cm^{-3}) with low hydraulic conductivity (0.16 cm h^{-1}). The ditch depth in the simulations was either 50 or 100 cm and the ditch spacing 20 or 40 m.

2.3 Re-analysis of sedimentation pond data

Sedimentation ponds excavated in the main outflow ditches are the most frequently used means to decrease SS transport to receiving water courses from drainage areas. Joensuu et al. (1999) presented a formula showing that, in addition to pond volume and maximum runoff, the concentration of SS entering the pond was the factor that explained most of the SS retention in the pond. To get a more thorough understanding of the impact of SS inflow loading and pond volume on the efficiency of ponds, we re-analysed the primary data by Joensuu et al. (1999) involving 37 ponds and calculated SS retentions for the first year after DNM as the difference between the SS entering (kg $year^{-1}$) and leaving (kg $year^{-1}$) the ponds. The SS loads in kg $year^{-1}$ were calculated by multiplying the mean monthly SS concentrations with the monthly runoff and summing up the monthly loads, e.g., Nieminen et al. (2010).

3. Water quality management in DNM areas

The best option to manage water quality in conjunction with DNM is to improve the guidelines for assessing the need for drainage. The sites where drainage does not improve forest growth involve the nutrient poor sites, where the availability of nutrients rather than drainage conditions limits the growth of trees. In Sweden, this area has been estimated to cover about 0.2 million ha, which corresponds to 20% of the area of drained peatlands (Hånell 2007). In Finland, where over 5 Mha of peatlands and paludified mineral soil sites have been drained for forestry, this area is also estimated to cover up to almost 20% (1 Mha) of the drained peatland area (Laiho et al. 2016). Also, mature stands, where water interception and transpiration dominate site water balance, may not be in need for drainage, even though the ditches had largely lost their drainage capacity (Sarkkola et al. 2010, 2012).

However, as soon as DNM is executed, the risk of increased exports of SS and nutrients to receiving water courses increases and efficient measures to mitigate water quality impacts are needed. In principle, there are three options, which can be executed either alone or concurrently, to manage water quality in the drained sites; 1) reduce SS and nutrient release from the drainage site by controlling drainage intensity, e.g., the depth and spacing of ditches, 2) reduce SS and adhered nutrient release by controlling the velocity and erosive force of drainage water, and 3) capture the SS and nutrients released after drainage before they enter the receiving water body.

3.1 Controlling drainage intensity

Controlling drainage intensity, i.e. the ditch depth and spacing, has received almost no attention in the drainage literature related to water quality management in DNM areas. However, it is well established that mineral soils, particularly silt and sand fractions, are vulnerable to erosion (Hjulström 1935), while the erodibility of peat soils is much lower and organic matter content in mineral soils increases their resistance against erosion (Carling et al. 1997). Due to its fibrous nature, peat has a relatively high shear strength even when highly decomposed (Eggelsmann et al. 1993) and thereby tangible resistant to erosion especially in the fibrous and mesofibreous layers (degree of humification <7 on the von Post scale, Tuukkanen et al. 2014). Accordingly, Joensuu et al. (1999) showed that the length of ditches reaching the mineral soil below peat was the factor that explained most of the variation in SS concentrations in discharge from DNM areas. Nieminen (2003) further showed that remedial drainage increased SS concentrations significantly from the catchment, where the ditches reached the mineral soil below peat, but not from the catchment, where the ditches remained in the peat layer. The results by Nieminen (unpublished data) similarly showed that SS exports were minor in the case where shallow remedial ditches were excavated in clear-cut peatland forest sites, but the existing deep drainage ditches were left intact. It can be judged from these studies that controlling ditch depth in such a way that the ditches do not reach the mineral soil underlying peat could be an effective means to manage water quality. The results from the areas treated with remedial drainage with a ditch spacing of 15-20 m indicate that this may be true (Nieminen 2003), even though the area covered by ditches is increased compared with DNM areas (ditch spacing generally 30-50 m). The narrower ditch spacing could decrease erosion also because the water flow velocity per ditch is likely reduced by having more ditches per unit area, although the flow peaks from the whole DNM area may increase (Ahti 1987).

Given that DNM with shallow ditches and narrow ditch spacing decreases SS exports, a question still arises whether that approach would enable similar drainage conditions as deep ditches with wider spacing. We used the hydrological process model FEMMA to elucidate the effect of variable ditch depth/spacing combinations on GWL in peat in treeless conditions (e.g., remedial ditching), where drainage network has the greatest contribution to site drainage conditions. Our simulations showed that deep ditches were important in maintaining low GWL in slightly decomposed peat, but 100 cm deep ditches with 40 m ditch spacing lowered average GWL between ditches less than 50 cm deep ditches with 20 m ditch spacing in highly decomposed peat (Fig. 1). The simulations similarly showed that very intensive drainage (ditch depth 100 cm/ditch spacing 20 m) would be needed to lower GWL clearly deeper than 30 cm in highly decomposed peat. Such very intensive drainage would likely induce large SS exports, which is questionable for its practical application.

Peat decomposition increases and its hydraulic conductivity decreases with years since drainage, therefore these results indicate that managing site drainage conditions in old peatland drainage areas with deep ditches has marginal effect on drainage condition. Executing drainage with shallower ditches and narrower spacing can result in similar drainage conditions and possibly decrease SS exports, although it is to be noted that significant lowering of GWL by drainage may no longer be possible in highly decomposed peat.

However, the economic and environmental outcomes of controlling drainage intensity by variable ditch depth and spacing combinations are still a clear research gap and should be the focus of future drainage studies. From the economic viewpoint, the two key questions for the narrow-spacing/shallow-ditches approach are whether excavating more ditches per unit area induces too high costs and whether the land area lost by the area covered by drainage ditches decreases the overall forest growth. It should also be noted that narrow ditch spacing may make forest harvesting more difficult. From the environmental viewpoint, it should be noted that environmentally feasible drainage becomes an increasingly important research subject with years since drainage because peat decomposition clearly increases its erodibility (Tuukkanen et al. 2014), as well as its subsidence, thus resulting in that the ditches in old drainage areas reach the mineral soil underlying peat more often than in recently drained areas with thicker peat layers.

Besides controlling ditch depth and spacing, one means to control drainage intensity could be to disturb the ditch bank vegetation as little as possible, thus not to impair its impact on bank stability (Wynn & Mostaghimi 2006), as well as to decrease the erosion of exposed soils in ditch banks by rain drops (Haahti et al. 2016). One means for that could be to develop such excavator´s scoops that only the bottoms of ditches are cleaned and the ditch banks remain largely intact. This novel approach has recently received attention in Sweden, but there are no data on its impact on SS and nutrient exports. However, intensive erosion of the mineral soils below the armouring rhizosphere in the ditch banks was qualitatively documented at one of the experimental sites (Froster 2016), possibly because the banks were clearly steeper than in conventional ditches.

3.2. Controlling flow velocity

After exposing bare peat or underlying mineral soil in DNM operations, the most disturbed surface soil layer is transported first followed by erosion of undisturbed soil layers, e.g. Stenberg et al. (2016). At this point, the water flow velocity and its temporal variation together with soil properties (soil type, mineral soil texture, peat thickness, degree of humification, whether the ditches reach mineral soil or not) determine the transported SS yield (Stenberg et al. 2015). The transport process is strongly related to temporal variation in local flow conditions and single storm flows or spring floods result in the largest transport rates (Stenberg et al. 2015). Thus, decreasing the velocity and erosive force of water by the peak runoff control (PRC) approach has been recognized as one of the means to decrease SS and adhered nutrient and metal exports (Marttila and Kløve 2010b, Marttila et al. 2010). Peak runoff control utilizes a dam and a set of control pipes to regulate runoff from the drainage area during high flows (Fig. 2). Besides peak runoff control dams, other types of dam structures are often mentioned in the operational guidelines for water quality management in DNM areas, but the empirical studies related to their performance are scarce.

Peak runoff control structures have been shown to efficiently diminish SS and particulate nutrient exports in peatland forestry conditions (Marttila and Klöve 2010b, Marttila et al. 2010). Proper functioning of PRC structures is based on correctly dimensioned pipes, which allow base flow through the dam (Fig. 2; lower pipe), but temporally store runoff water in the drainage network during high flow events. Under optimal conditions, the whole drainage network above the dam acts as a water retention area, thus efficiently decreasing water flow velocity and erosion during peak flows. The critical point in the functioning of PRC structures is the proper dimensioning of the control pipe according to local catchment and climatic properties, such as the catchment size, average slope, and regional precipitation patterns. While a too small pipe might cause long-term water damming in the upstream ditch network, potentially decreasing tree vitality and growth, a too large pipe may have minor effect on water flow during peak flows. Hökkä et al. (2011) showed that a properly dimensioned PRC structure had no negative effect on tree growth.

A sedimentation pond is generally excavated above the PRC structure to retain the sediments which are released despite of the PRC structure. A combined PRC/pond structure is reasonable in the sense that, while it is generally recommended to execute DNM only during dry periods, PRC is ineffective in retaining SS immediately after DNM, when flow rates are low and SS concentrations high (Haahti et al. 2017). For the efficiency of sedimentation ponds, however, low flow conditions with concurrent high SS concentrations are optimal (Joensuu et al. 1999, Haahti et al. 2017). To enhance the performance of PRC, another means could be to seal the lower pipe temporarily during the time of low flows during and after DNM (Haahti et al. 2017).

In previous studies, PRC structures were shown to decrease the exports of SS and particulate nutrients (Marttila and Klöve 2010b; Marttila et al. 2010), however, PRC structures had minor effects on the exports of dissolved nutrients. Thus, they cannot be used as the only water protection structure in sites, where the nutrient and carbon exports occur mostly in dissolved forms, such as in recently harvested peatland forests (Kaila et al. 2014, 2015, Nieminen et al. 2015b).

To our knowledge, the efficiencies of the dam structures without through-flow pipes, such as stone or earth made submerged and above-soil-level dams have received very scarce attention in the available scientific literature related to DNM. In Sweden, Hansen et al. (2013) studied the effects of DNM in ditches with and without above-soil-level dams at two sites, but found minor differences in SS, P, and N exports. Liljaniemi et al. (2003) similarly found that peat and stone made dams in ditches had minor effects on nutrient retention and recommended the use of extensive overland flow areas to improve water quality management in forested catchments. The problems with the dam structures are that their effective area for water retention above the dam is typically too small for any significant reduction in water flow velocity, as well as that there is no storage area for the retention of SS. Furthermore, dams can easily function as a source rather than a sink of SS, particularly if constructed on erosion sensitive soils. The modeling study by Haahti et al. (2017) indicated, however, that erosion-insensitive dams, which effectively pond the water above them, could have potential to significantly reduce SS exports.

3.3. Capturing released sediments and nutrients

To capture the SS released from DNM areas, a number of water quality management structures have been proposed. Sedimentation or silt traps are small pits (1-2 m^3) in the bottom of drainage ditches constructed for capturing the eroded solids (Haahti et al. 2017). Sedimentation ponds are significantly larger water protection structures (40-500 m^3) constructed in the main outlet ditch of the drainage area (Joensuu et al. 1999). Also non-ditched breaks in the ditches and leaving some of the ditches uncleaned in DNM areas are supposed to increase SS retention compared with that all ditches are cleaned completely. Another mechanism by which ditch breaks may decrease SS exports is decreased erosion, particularly when applied in the very erosion-sensitive stretches of ditch networks.

Overland flow areas or wetland buffers are created by simply conducting the discharge waters from drainage areas to pristine mires, or occasionally to paludified mineral soils (Nieminen et al. 2015a). However, because most peatlands and wetlands have already been drained, a common practice is to restore sections of drained peatlands by filling in or blocking the drainage ditches. Besides slowing down water flow and enabling sedimentation of soil particles and adhered nutrients, overland flow areas retain nutrients and metals through biological accumulation in wetland vegetation and chemical adsorption in their soils.

3.3.1. Sedimentation pits and ditch breaks

Operational guidelines for water quality protection in drained peatlands generally mention small sedimentation pits (1-2 m^3) and non-ditched breaks in the ditches as means to retain SS, but there is very limited data concerning their efficiency. Vuollekoski (unpublished data) sampled runoff waters from an about 20 m long uncleaned stretch in the main outlet ditch of a DNM area, but found no differences in SS concentrations between the samples collected above and below it. The modeling study by Haahti et al. (2017) indicated that sedimentation pits may even increase erosion by increasing flow velocity above them.

Negligible differences in SS concentration below and above uncleaned stretches of ditches suggest that ditch breaks in DNM areas could contribute to SS exports by decreasing the area covered by treated ditches rather than increasing SS retention in the uncleaned ditch area. Owing to that the velocity and erosive force of water are greater in the main collector ditches than the actual drainage ditches, leaving stretch/stretches of collector ditches uncleaned, whenever it is possible without risking site drainage conditions, could be a particularly efficient means of decreasing erosion. According to the modeling study by Haahti et al. (2017), well-targeted breaks have potential to decrease SS exports effectively and are the only sediment control structure in the ditch network than can have notable effect on bank erosion.

However, similarly to controlling ditch depth and spacing, further research is needed to assess the impacts of non-ditched breaks on SS and nutrient exports. Although Vuollekoski (unpublished) found no differences in SS concentrations below and above a ditch break, it may be that ditch breaks would sometimes be also efficient in capturing SS, particularly where the ditch break is long and filled with dense wetland vegetation (Haahti et al. 2017).

Compared to DNM in boreal conditions, non-ditched breaks have received much more attention in reducing SS exports in afforested upland peats in the UK, where steep slopes enable long breaks without raising water level and potentially impairing tree vitality and growth upstream from the break (Carling et al. 2001). Experiences from those sites indicate that non-ditched breaks can be highly effective in reducing SS exports.

3.3.2. Sedimentation ponds

Joensuu et al. (1999) studied the efficiency of 37 sedimentation ponds with the settling volumes ranging from 40 to 496 m^3 to retain SS from recently treated DNM areas. Their study showed highly variable retention efficiency from a decrease of 157 mg l^{-1} in SS concentrations below the ponds to an increase of 41 mg l^{-1}. The average decrease in the whole data set (including 37 ponds) was only 18.3%. Excluding the 17 ponds (46% of all ponds), which increased SS concentrations, still gave an average decrease of only 28.4%. The increases in SS concentrations were because of the erosion of the pond walls and bottoms, particularly because some of the ponds, contrary to current recommendations, were established in erosion-sensitive soils.

Our reanalysis of the pond data by Joensuu et al. (1999) indicated that there was minor retention when the SS input was less than about 10 000 kg year^{-1}, whereupon the SS retentions increased along with increasing SS loadings (Fig. 3). Recalculating the retention efficiencies by weighing the pond retentions by the SS inputs showed an average retention of 30.5% for the whole data set, and 38.1% when excluding the ponds which increased erosion, thus, about 10% higher retentions than when ignoring the variation in SS loadings (Joensuu et al. 1999). Similarly, after excluding the ponds that increased SS exports or received an annual loading of <10 000 kg year^{-1}, the remaining ponds indicated that there may be a positive correlation between pond size and retention efficiency (Fig. 4), although the number of ponds in the analysis was relatively small (n=12). The analysis also suggested that very large ponds (>400 m^{3}) might be needed to retain >50% of the SS loading.

Put together, the results suggest that the use of sedimentation ponds to mitigate SS exports is complicated as the efficiency of ponds is poor until the SS input loading increases to a high level and because relatively large ponds may be needed for efficiently retaining high SS inputs. A threshold SS input of 10 000 kg year^{-1} in the data by Joensuu et al. (1999) means that when DNM has increased sediment exports by over 10-times compared with the pre-DNM situation, sedimentation ponds are still ineffective in retaining SS. Some of the coarse-textured material transported in the bottom of ditches and plausibly effectively retained by ponds may not be fully represented in our calculation based on water samples from the ditches, but the increase in coarse-textured sediment transportation induced by DNM is minor compared with finer textured sediments (Joensuu et al. 1999). This is an obvious dilemma in the use of sedimentation ponds in DNM areas; they may be the most effective in retaining coarse-textured sediments, the erosion of which is not much increased by DNM. Very high water-flow velocities are needed for detaching large particles (Hjulström 1935).

An unanswered question still arises: Why did there appear to be a clear threshold in SS loading below which negligible retention occurred in sedimentation ponds? An obvious answer would be that the physical properties of transported sediment particles vary from site to site and dominate the retention processes. According to Stoke’s law, sedimentation velocity is determined by gravity, particle diameter, particle mass density and the density of water. Hence, the sedimentation velocity for different soil fractions varies tremendously. In a 1 m water column, the settling time for a sand particle is measured in seconds, while settling takes hours to weeks for fine silt and clay and small organic particles. The settling velocity of peat (particle size 0.5-16 mm, humification H5-H8) is of the same magnitude as fine silt (Kløve 1998). Therefore, the hydraulic retention time in sedimentation ponds must be very different for different particle fractions to allow settling. Thus, the sites with low SS release and retention may be dominated by the export of organic sediments with low settlement velocity, whereas the larger loadings and retentions are mineral soil particles with higher settlement velocity. Also, organic and finer particles typically do not settle down irrespective from each other, but collectively as more or less tightly adhered flocs or composites of particles (Marttila and Klöve 2015).

Dimensioning theory for sedimentation ponds often assumes uniform flow field within the pond. Flow conditions are, however, often turbulent, which can strongly modify settling conditions and even lift deposited particles back to suspension. Thus, the further mechanism behind increasing retention with increasing SS loading may be that the ponds generally both retain and release SS, and only after sufficiently high SS loading, retention of SS clearly exceeds its release. To improve the functioning of the ponds, they should only be established in erosion-insensitive soils (e.g., thick undecomposed peats), but such are often missing in their targeted locations in the downstream parts of drained peatland catchments. Additionally, the ponds should be monitored for sediment filling and excavated when necessary. Depending on its volume and SS load, a pond may be filled within the first year after DNM (Joensuu et al. 1999). Furthermore, sedimentation ponds should be dimensioned sufficiently large to ensure proper conditions for the settling of SS particles of differing settling velocity.

3.3.3. Wetland buffers

Among the different water protection structures constructed to retain SS and nutrients in drainage areas, natural and restored wetland buffers may be the most efficient. Highly efficient SS retention has been reported particularly, where the SS inputs to buffer areas were large and the buffer size was at least 0.5-1.0% from the size of the upstream catchment area (Sallantaus et al. 1998, Nieminen et al. 2005a). In addition, efficient retention of dissolved nutrients has been shown in a number of papers (Silvan et al. 2005, Väänänen et al. 2008, Vikman et al. 2010), especially after transient high nutrient loadings. Along with the size and length of the buffer (Vikman et al. 2010), the rate of SS and nutrient input to wetland buffers is one of the key-factors explaining their efficiency. Significant reduction is not likely to occur from the inflow water with already low nutrient concentrations close to background levels of forested areas. It is therefore not surprising that poor retention efficiencies were reported when the performance of wetland buffers was assessed under such conditions (e.g., Nieminen et al. 2005b).

Despite that wetland buffers have proven to be the most efficient water protection structure, their use in operational forestry is very limited (Nieminen et al. 2015a). One major limitation in their use is that blocking or filling-in the ditches in a restored buffer area results in water table rising not only in the buffer area itself, but also in the upstream area. In a sloping land, the rewetted area above the buffer area may be just a few meters or tens of meters long, but in the very flat lowlands, the rewetted area may extend to several hundreds of meters from the buffer area. Thus, although the use of wetland buffers is currently recommended as the most efficient means of decreasing SS and nutrient exports in forested catchments, their use in operational forestry is restricted to sloping areas.

Furthermore, restoration of drained peatlands to be used as buffer areas may initially result in increased exports of nutrients and DOC (Vasander et al. 2003). In case where the initial nutrient and carbon exports caused by restoration are large, it may not be reasonable to restore a drained peatland for use as a buffer area, particularly if minor exports are expected from the upstream drainage area. This is particularly true for DOC, as drainage generally decreases DOC exports (Joensuu et al. 2002, Nieminen et al. 2010), but restoring a drained peatland can act as a high source of DOC (Postila et al. 2014, 2015, Koskinen et al. 2011, 2017). The results from the UK indicated that restoring of peatlands may also show an opposite pattern, with lower DOC concentrations than in unblocked ditches (Armstrong et al. 2010). However, there were still a number of blocked ditches where DOC was higher than in the unblocked ditches. Thus, it should be noted that, although restored wetland buffers in DNM areas would be efficient in reducing the exports of some elements, they may concurrently enhance the exports of the other elements, such as DOC.

4. Conclusions

We conclude that the focus of future research and operational peatland forestry should be on optimizing drainage in such a way that the groundwater level lowering is maximized without excavating deep ditches reaching the mineral soil underlying peat. The dams constructed with the aim to decrease flow velocity and erosive force of water may be efficient in decreasing SS and adhered nutrient exports, but the structures aiming at capturing the SS and nutrients released after drainage operations (sedimentation ponds/wetland buffers) may have limited practical applications. This is because they are either inefficient and need monitoring and proper management (sedimentation ponds), their use is limited to relatively rare topographic features (wetland buffers/sloping areas), or, while decreasing the exports of some elements, they increase the exports of other elements (restored wetland buffers/DOC). Thus, we conclude that future research should focus on decreasing the release of SS and nutrients rather than increasing their capture. In particular, tools for identifying erosion-sensitive locations in DNM areas and leaving them as ditch breaks, as well as controlling drainage intensity should be the focus of future research.

References

Ahti, E. 1987. Water balance of drained peatlands on the basis of watertable simulation during the snowless period. *Communicationes Instituti Forestalis Fenniae* 141. 64 pp.

Armstrong, A., J. Holden, P. Kay, B. Francis, M. Foulger, S. Gledhill, A. T. McDonald, and A. Walker 2010. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. *Journal of Hydrology* 381: 112-120. DOI:10.1016/j.jhydrol.2009.11.031

Åström, M., E.-K. Aaltonen, and J. Koivusaari 2004. Changes in leaching patterns of nitrogen and phosphorus after artificial drainage of a boreal forest - a paired catchment study in Lappajärvi, western Finland. *Boreal Environment Research* 10: 67-78.

Carling, P. A., M. S. Glaister, and T. P. Flintham 1997. The erodibility of upland soils and the design of preafforestation drainage networks in the United Kingdom. *Hydrological Processes* 11: 1963-1980.

Carling, P. A., B. J. Irvine, A. Hill, and M. Wood 2001. Reducing sediment inputs to Scottish streams: a review of the efficiency of soil conservation practices in upland forestry. *The Science of the Total Environment* 265: 209-227.

Ecke, F. 2009. Drainage ditching at the catchment scale affects water quality and macrophyte occurrence in Swedish lakes. *Freshwater Biology* 59: 119-126. DOI:10.1111/j.1365-2427.2008.02097.x.

Eggelsmann, R. A. L. Heathwaite, G. Grosse-Brauckmann, E. Kuster, W. Naucke, M. Schuch, and V. Schweickle 1993. Physical processes and properties of mires. In *Mires: Process,* *Exploatation and Conservation*, ed. A. L. Heathwaite, K. H. Gottlich, 171-262. Chichester UK: John Wiley.

Finnish Statistical Yearbook of Forestry 2014. Suomen virallinen tilasto: Maa-, metsä- ja kalatalous. 428 pp.

Finér, L., T. Mattsson, S. Joensuu, H. Koivusalo, A. Laurén, T. Makkonen, M. Nieminen, S. Tattari, et al. 2010. A method for calculating nitrogen, phosphorus and sediment load from forested catchments. *Suomen ympäristö* 10/2010. 33 pp. (in Finnish).

Froster, A. 2016. The fight about the ditch. *Hav & Vatten* no 4: 10-19. ISSN 2002-0252. https://issuu.com/havochvatten/docs/hav1604_e. (in Swedish).

Haahti, K., M. Nieminen, L. Finér, H. Marttila, T. Kokkonen, A. Leinonen, and H. Koivusalo 2017. Model-based evaluation of sediment control in a drained peatland forest after ditch network maintenance. Canadian Journal of Forest Research (accepted).

Haahti, K., H. Marttila, L. Warsta, T. Kokkonen, L. Finér, and H. Koivusalo 2016. Modeling sediment transport after ditch network maintenance of a forested peatland. *Water Resources Research* 52: 9001–9019. DOI:10.1002/2016WR019442.

Hånell, B. 1988. Postdrainage forest productivity of peatlands in Sweden. *Canadian Journal of Forest Research* 18: 1443-1456.

Hånell, B. 2007. Data based on the National Swedish Forest Inventory and presented by Björn Hånell at a conference 14 November 2007 at the Royal Swedish Academy of Agriculture and Forestry, KSLA.

Hansen, K., V. Kronnäs, T. Zetterberg, M. Zetterberg, F. Moldan, P. Petterson, and J. Munthe. 2013. The effects of ditch cleaning on runoff, water chemistry and botany fauna in forest ecosystems. Rapport. IVL Svenska Miljöinstitutet AB. 108 pp. (in Swedish).

Hjulstrom, F. 1935. Studies of morphological activity of rivers as illustrated by the river Fyris. *Bulletin of the Geological Institute University of Uppsala*, 25: 221-527.

Hökkä, H., H. Hyttinen, H. Marttila, J. Jämsen, and B. Klöve 2011. The effect of the PRC method on volume growth of tree stands in ditch maintenance areas. *Silva Fennica* 45(3): 331-339.

Holden, J., M. Gascoign, and N. R. Bosanko 2007. Erosion and natural revegetation associated with surface land drains in upland peatlands. *Earth Surface Processes and Landforms* 32: 1547-1557. DOI:10.1002/esp.1476.

Hynninen, A., S. Sarkkola, A. Laurén, H. Koivusalo, and M. Nieminen 2011. Capacity of riparian buffer areas to reduce ammonium export originating from ditch network maintenance areas in peatlands drained for forestry. *Boreal Environment Research* 16: 430-444.

Joensuu, S., E. Ahti, and M. Vuollekoski 1999. The effects of peatland forest ditch maintenance on suspended solids in runoff. *Boreal Environment Research* 4: 343-355.

Joensuu, S., E. Ahti, and M. Vuollekoski 2002. Effects of ditch network maintenance on the chemistry of run-off water from peatland forests. *Scandinavian Journal of Forest Research* 17: 238-247.

Kaila, A., A. Laurén, S. Sarkkola, H. Koivusalo, L. Ukonmaanaho, L. Xiao, Z. Asam, C. O´Driscoll, et al. 2015. The effect of clear-felling and harvest residue removal on nitrogen and phosphorus export from drained Norway spruce mires in southern Finland. *Boreal Environment Research* 20: 693-706.

Kaila, A., S. Sarkkola, A. Laurén, L. Ukonmaanaho, H. Koivusalo, L. Xiao, C. O'Driscoll, Z. Asam, et al. 2014. Phosphorus export from drained Scots pine mires after clear-felling and bioenergy harvesting. *Forest Ecology and Management* 325: 99-107. DOI:10.1016/j.foreco.2014.03.025

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

Koivusalo, H., E. Ahti, A. Laurén, T. Kokkonen, T. Karvonen, R. Nevalainen, and L. Finér 2008. Impacts of ditch cleaning on hydrological processes in a drained peatland forest. *Hydrology and Earth System Science* 12: 1211-1227. DOI:10.5194/hess-12-1211-2008

Koskinen, M., T. Sallantaus, and H. Vasander 2011. Post-restoration development of organic carbon and nutrient leaching from two ecohydrologically different peatland sites. *Ecological Engineering* 37: 1008-1016. DOI:10.1016/j.ecoleng.2010.06.036

Koskinen, M., T. Tahvanainen, S. Sarkkola, M. W. Menberu, A. Laurén, T. Sallantaus, H. Marttila, A-K. Ronkanen et al. 2017. Restoration of fertile peatlands poses a risk for high exports of dissolved organic carbon, nitrogen, and phosphorus. *The Science of the Total Environment* 586: 858–869. DOI:10.1016/j.scitotenv.2017.02.065

Laiho, R., S. Tuominen, S. Kojola, T. Penttilä, M. Saarinen, A. Ihalainen 2016. Forestry-drained peatlands of low productivity in Finland. *Metsätieteen aikakauskirja* 2/2016: 73–93. (In Finnish).

Liljaniemi, P., K-M. Vuori, T. Tossavainen, J. Kotanen, M. Haapanen, A. Lepistö, and K. Kenttämies 2003. Effectiveness of constructed overland flow areas in decreasing diffuse pollution from forest drainages. *Environmental Management* 32: 602-613. DOI:10.1007/s00267-003-2927-4.

Marttila, H., and B. Kløve 2010a. Dynamics of erosion and suspended sediment transport from drained peatland forestry. *Journal of Hydrology* 388: 414-425. DOI:10.1016/j.jhydrol.2010.05.026

Marttila, H., and B. Kløve 2010b. Managing runoff, water quality and erosion in peatland forestry by peak runoff control. *Ecological engineering* 36(7): 900-911. DOI:10.1016/j.ecoleng.2010.04.002

Marttila, H., and B. Kløve 2015. Spatial and temporal variation in particle size and particulate organic matter content in suspended particulate matter from peatland-dominated catchments in Finland. *Hydrological Processes* 29: 1069–1079. DOI:10.1002/hyp.10221

Marttila, H., K-M. Vuori, H. Hökkä, J. Jämsen, and B. Kløve, B. 2010. Framework for designing and applying peak runoff control structures for peatland forestry conditions. *Forest Ecology and Management* 260(8): 1262-1273. DOI:10.1016/j.foreco.2010.06.032

Ministry of Environment of the Republic of Lithuania Department of Forest. 2003. The chronicle of Lithuanian forests XX century. *Vilnius*: 2003: 631.

Nieminen, M. 2003. Effects of clear-cutting and site preparation on water quality from a drained Scots pine mire in southern Finland. *Boreal Environment Research* 8: 53-59.

Nieminen, M., E. Ahti, H. Nousiainen, S. Joensuu, and M. Vuollekoski 2005a. Capacity of riparian buffer zones to reduce sediment concentrations in discharge from peatlands drained for forestry. *Silva Fennica* 39: 331-339.

Nieminen, M., E. Ahti, H. Nousiainen, S. Joensuu, and M. Vuollekoski 2005b. Does the use of riparian buffer zones in forest drainage sites to reduce the transport of solids simultaneously increase the export of solutes? *Boreal Environment Research* 10: 191-201.

Nieminen, M., E. Ahti, H. Koivusalo, T. Mattsson, S. Sarkkola, and A. Laurén 2010. Export of suspended solids and dissolved elements from peatland areas after ditch network maintenance in south-central Finland. *Silva Fennica* 44: 39-49.

Nieminen, M., A. Kaila, M. Koskinen, S. Sarkkola, H. Fritze, E-S. Tuittila, H. Nousiainen, H. Koivusalo, A. Laurén, H. Ilvesniemi, et al. 2015a. Natural and Restored Wetland Buffers in Reducing Sediment and Nutrient Export from Forested Catchment: Finnish Experiences. In: *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape*, ed. Jan Vymazal, 57-72. Springer, Switzerland.

Nieminen, M., M. Koskinen, S. Sarkkola, A. Laurén, A. Kaila, O. Kiikkilä, T. M. Nieminen, and L. Ukonmaanaho 2015b. Dissolved organic carbon export from harvested peatland forests with differing site characteristics. *Water Air and Soil Pollution* 226: 181. DOI:10.1007/s11270-015-2444-0

Paavilainen E., and J. Päivänen 1995. Peatland forestry. Ecology and Principles. Springer-Verlag. Berlin.

Päivänen, J., and B. Hånell 2012. Peatland Ecology and Forestry – a Sound Approach. *University of Helsinki, Department of Forest Sciences Publications* 3. 267 pp.

Piirainen, S., L. Finér, E. Andersson, K. Armolaitis, O. Belova, D. Čiuldiené, M. Futter, W. Gil, Z. Glazko, T. Hiltunen, et al. 2017. Forest drainage and water protection in the Baltic Sea Region countries – current knowledge, methods and needs for development. 44 p.

Postila, H., J. Saukkoriipi, K. Heikkinen, S. M. Karjalainen, H. Marttila, and B. Kløve 2014. Can treatment wetlands be constructed on drained peatlands for efficient purification of peat extraction runoff? *Geoderma* 228-229: 33-43. DOI:10.1016/j.geoderma.2013.12.008

Postila, H., A.-K. Ronkanen, and B. Kløve 2015. Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate. *Ecological Engineering* 85: 13-25. DOI:10.1016/j.ecoleng.2015.09.066

Prévost, M., A. P. Plamondon, and P. Belleau 1999. Effects of drainage of a forested peatland on water quality and quantity. *Journal of Hydrology* 214: 130-143. DOI:10.1016/S0022-1694(98)00281-9.

Ramchunder, S. J., L. E. Brown, and J. Holden 2009. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress in Physical Geography* 33: 49-79. DOI:10.1177/0309133309105245

Sallantaus, T., H. Vasander, and J. Laine 1998. Prevention of detrimental impacts of forestry operations on water bodies using buffer zones created from drained peatlands. *Suo* 49: 125-133. (in Finnish).

Sarkkola, S., H. Hökkä, H. Koivusalo, M. Nieminen, E. Ahti, J. Päivänen, and J. Laine 2010. Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands. *Canadian Journal of Forest Research* 40: 1485-1496. DOI:10.1139/X10-084

Sarkkola, S., H. Hökkä, E. Ahti, M. Nieminen, and H. Koivusalo 2012. Depth of water table prior to ditch network maintenance is a key factor for tree growth response. *Scandinavian Journal of Forest Research 27.* 10 pp. DOI:10.1080/02827581.2012.689004

Sikström, U., and H. Hökkä 2016. Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance. *Silva Fennica* 50. 29 pp. DOI:10.14214/sf.1416

Silvan, N., T. Sallataus, H. Vasander, and J. Laine 2005. Hydraulic nutrient transport in a restored peatland buffer. *Boreal Environment Research* 10: 203-210.

Stenberg, L., T. Tuukkanen, L. Finér, H. Marttila, S. Piirainen, B. Kløve, and H. Koivusalo 2015. Ditch erosion processes and sediment transport in a drained peatland forest. *Ecological Engineering* 75: 421-433. DOI:10.1016/j.ecoleng.2014.11.046

Stenberg, L., T. Tuukkanen, L. Finér, H. Marttila, S. Piirainen, B. Kløve, and H. Koivusalo 2016. Evaluation of erosion and surface roughness in peatland forest ditches using pin meter measurements and terrestrial laser scanning. *Earth Surface Processes and Landforms* 41: 1299–1311. DOI:10.1002/esp.3897

Tuukkanen, T., B. Kløve, and H. Marttila 2014. Effect of soil properties on peat erosion and suspended sediment delivery in drained peatlands. *Water Resources Research* 50: 3523-3535. DOI:10.1002/2013WR015206

Tuukkanen, T., L. Stenberg, L. Finér, H. Marttila, S. Piirainen, H. Koivusalo, and B. Kløve 2016. Erosion mechanisms and sediment sources in a peatland forest after ditch cleaning. *Earth Surface Processes and Landforms* 41: 1841-1853. DOI:10.1002/esp.3951

Väänänen, R., M. Nieminen, M. Vuollekoski, H. Nousiainen, T. Sallantaus, E-S. Tuittila, and H. Ilvesniemi, H. 2008. Retention of phosphorus in peatland buffer zones at six forested catchments in southern Finland. *Silva Fennica* 42: 211-231.

Vasander, H., E-S. Tuittila, E. Lode, L. Lundin, M. Ilomets, T. Sallantaus, R. Heikkilä, M-L. Pitkänen, et al. 2003. Status and restoration of peatlands in northern Europe. *Wetland Ecology and Management* 11: 51-63. DOI:10.1023/A:1022061622602

Vikman, A., S. Sarkkola, H. Koivusalo, T. Sallantaus, J. Laine, N. Silvan, H. Nousiainen, and M. Nieminen 2010. Nitrogen retention by peatland buffer areas at six forested catchments in southern and central Finland. *Hydrobiologia* 641(1): 171-183. DOI:10.1007/s10750-009-0079-0.

Wynn, T., and S. Mostaghimi 2006. The effects of vegetation and soil type on streambank erosion, southwestern Virginia, USA. *Journal of the American Water Recources Association*. pp. 69-82. DOI:10.1111/j.1752-1688.2006.tb03824.x

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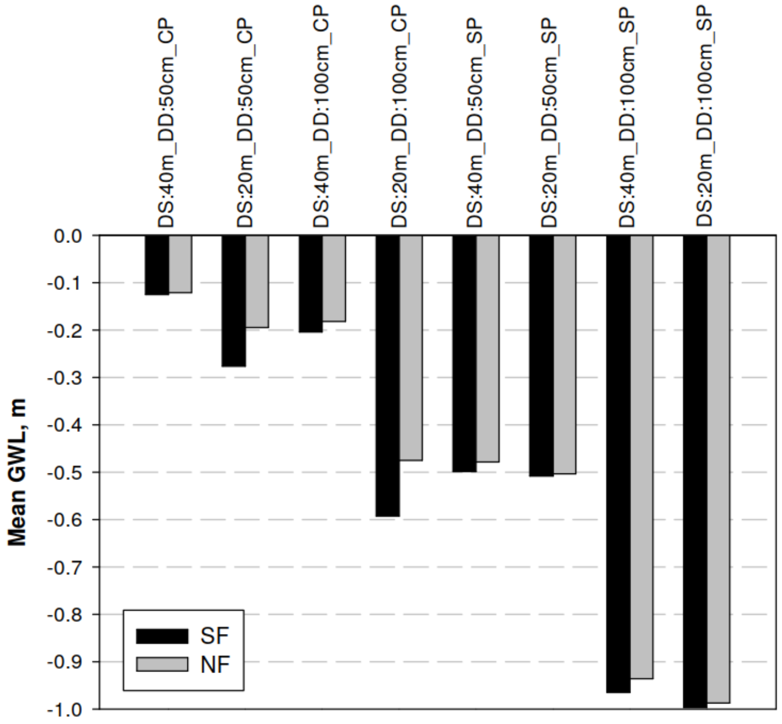

Fig. 1. Mean ground water levels (GWL) during growing season (May-September) in drained Carex (CP) and Sphagnum (SP) peat dominated peatland areas in southern (SF) and northern Finland (NF) as simulated by the FEMMA-model (Koivusalo et al. 2008). The weather input data is as during 2009 in southern (60°27N'; 24°57'E) and northern (64°43N'; 26°0'E) Finland. Ditch depths (DD) are 0.5 and 1.0 m, and ditch spacings (DS) 20 m and 40 m. The bulk density and hydraulic conductivity of SP are 0.060 g cm^{-3} and 6.17 cm h^{-1}, respectively, and 0.190 g cm^{-3} and 0.16 cm h^{-1} in CP.

Fig. 2. Peak runoff control dam. Photo: Hannu Hökkä.

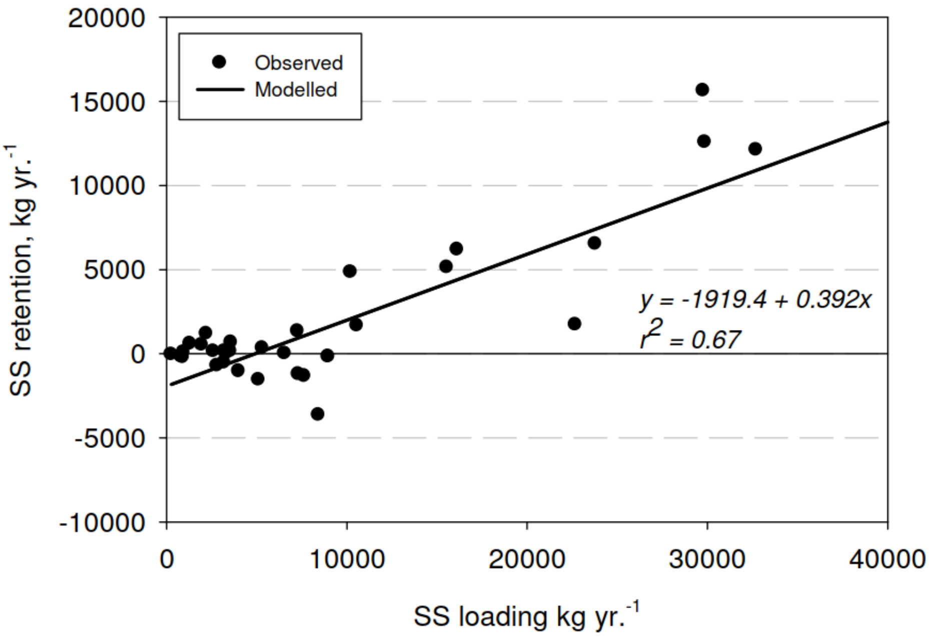

Fig. 3. Relationship between SS retention (kg year^{-1}) and SS loading (kg year^{-1}) during the first year after DNM in the sedimentation pond data (n=37) by Joensuu et al. (1999). For the calculation of SS retention and loading, see text.

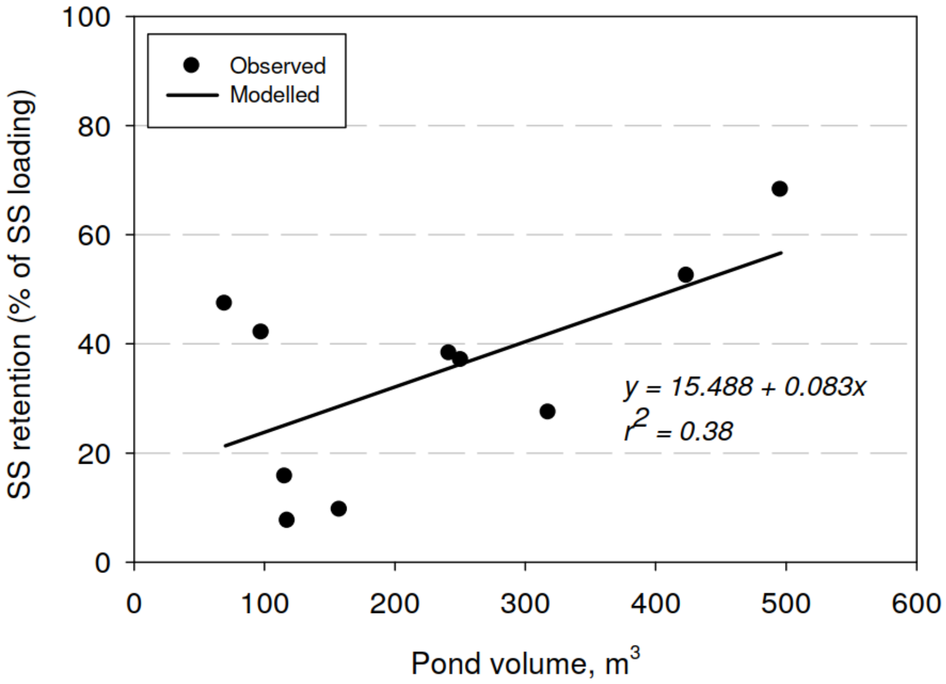

Fig. 4. Relationship between SS retention (% of SS loading into the pond) and pond volume (m^3) during the first year after DNM in the sedimentation pond data by Joensuu et al. (1999), when the ponds with increased SS export or SS loads less than 10 000 kg $year^{-1}$ were excluded. For the calculation of SS retention and loading, see text.