 DOI: 10.22616/rrd.25.2019.015

THE EFFICIENCY OF FOREST DRAINAGE SYSTEM SEDIMENTATION PONDS IN THE CONTEXT OF WATER QUALITY

Zane Kalvīte, **Zane Lībiete**, **Ivars Kļaviņš**
Latvian State Forest Research Institute 'Silava', Latvia
zane.kalvite@silava.lv

Abstract
The establishment, maintenance and renovation of forest drainage systems are carried out to ensure the development of high quality forest stands and to secure access to forest resources, but it also poses a risk of erosion and increased discharge of suspended solids and nutrients associated with it. The aim of the study was to analyse the efficiency of standard-sized sedimentation ponds built by JSC 'Latvia's State Forests' for sediment and nutrient retention during and after drainage network maintenance. To assess the efficiency of standard-sized sedimentation ponds six study sites were established and various chemical and physical parameters were measured for three years to evaluate water quality and to estimate runoff of plant nutrients and suspended solids. Sampling was carried out before and during drainage network maintenance and during two years following it.
Despite the fact that some effect in reducing suspended solid export from catchments was observed, the results revealed insufficient efficiency of the sedimentation ponds in retaining plant nutrients and eroded matter during and after the drainage network maintenance. Retention of N_{tot}, N-NO_3^-, P-PO_4^{3-}, N-NH_4^+ and DOC was ambiguous. It was concluded that other water protection structures should be considered or different parameters of sedimentation ponds should be used to improve the water quality exiting the drainage systems and entering waterbodies.
Key words: sedimentation pond; drainage system maintenance; nutrient export; total suspended solids.

Introduction

In the temperate and boreal regions around 15 million ha of paludified mineral soils and peatlands have been drained for forestry purposes, furthermore, about 10 million ha of them are located in countries of the Baltic Sea Region (Paavilainen & Päivänen, 1995).

Water availability is a major factor for site productivity (Gholz, Ewel, & Teskey, 1990). There is a strong relation between soil aeration, groundwater level and tree growth. High water level restricts seedling survival and tree growth. Subsequently, stands in such growth conditions have low productivity and are commonly understocked (Sarkkola, Hökkä, & Penttilä, 2004). Drainage of wetlands is one of the most effective measures in increasing the forest productivity. According to Sikström and Hökkä (2016), productivity of Scots pine after drainage network maintenance (DNM) increases by up to approx. 40 m^3 ha^{-1} during 20 years, on condition that nutrients are not limiting tree growth. An increase of productivity of fully stocked Scots pine stands as observed by Socha (2012) may increase up to 25%.

In Latvia, large-scale forest drainage activities were started in the second half of the 20th century. Nowadays there are more than 464,056 ha of drained area in state forests – the total length of the drainage network is 43,680 km. In Latvia, new ditches are currently only excavated within the existing drainage systems, but no new drainage systems are being built, primarily due to the reasons related to nature conservation. In Latvia, a large part of the forest drainage systems has already become ineffective due to deterioration and overgrowing of ditches and needs to be restored. Regular DNM should be carried out in order to ensure the efficiency of these systems. DNM involves cleaning of old ditches to their initial depth or digging supplementary ditches within the existing system, if necessary, or a combination of both methods. It is recommended to carry out DNM every 20-40 years to preserve appropriate growing conditions for the tree stands. Without drainage system restoring process, swamp formation processes may resume.

Despite the fact that DNM is needed to sustain the tree growth, it also poses a risk of erosion, as a result of which suspended particles, nutrients and heavy metals can enter the drainage systems and be further exported to water bodies. Organic material and suspended solids in drainage water are generally associated with nutrient losses from drained peatland forestry areas. As the sedimentation and eutrophication processes intensify, water quality may deteriorate; therefore, it is important to implement effective water protection structures and guidelines to improve the water management practices in forestry and water management.

The impact of ditch network maintenance on water quality is mainly described in Finnish scientific literature (Joensuu, 2002; Marttila & Kløve, 2010). There have been only a few studies on this topic in Latvia so far. The aim of this study was to analyse the efficiency of standard-sized sedimentation ponds built by JSC 'Latvia's State Forests' for sediment and nutrient retention during DNM.

Materials and Methods

The efficiency of sedimentation ponds was studied in six catchments in Latvia's State forests. Two study sites were located in Northern Kurzeme forestry (BU1 – 'Būšnieki 1', BU2 – 'Būšnieki 2'), one study area – in Southern Kurzeme forestry (VA – 'Vaiļi')

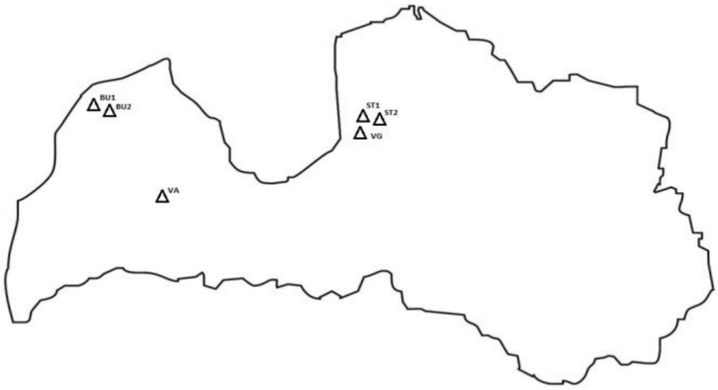

Figure 1. Location of the study sites in Latvia.

Table 1

General characteristics of the study sites

Study area	Coordinates (N; E)	Catchment area, ha	Dominant soil texture	Growing conditions, % of catchment area					Length of the sedimentation pond, m	Maintenance works finished
				Forests on dry mineral soils	Forests on wet mineral soils	Forests on wet peat soils	Forests on drained mineral soils	Forests on drained peat soils		
BU1	57.4354; 21.7011	76.1	Sandy loam	9			79	11	30 m	21.07.2012
BU2	57.43299; 21.70075	73.2	Sand	9			79	11	30 m	16.08.2012
VA	56.85576; 22.49577	448.2	Sand	5	7	5	80	2	50 m	15.09.2012
ST1	57.41015; 24.59164	272.1	Sand	18	1	1	9	70	50 m	11.05.2012
ST2	57.41046; 24.58986	92.6	Loam	37	9		21	33	50 m	10.04.2012
VG	57.29287; 24.55391	73.2	Sandy loam	52	30		17	1	30 m	01.06.2012

and three study areas – in Western Vidzeme forestry (ST1 – 'Stūrīši 1', ST2 – 'Stūrīši 2', VG – 'Vanagu gārša') (Figure 1). Catchment size of the study areas varied from 73.2 ha to 448.2 ha (Table 1). DNM was performed in the spring/summer of 2012.

Water quality sampling was carried out on the outlet ditch of each studied catchment where sedimentation pond was constructed. For reference, water samples were taken once before the maintenance works. After maintenance works were finished, water samples were taken twice a month until the end of October in 2012. In 2013 and 2014, water samples were taken twice a month in the study sites ST1, BU1 and VG, but in the study areas ST2, BU2 and VA – once a month from the beginning of May until the end of October. After the maintenance, water sampling was done in three points – at the inlet and outlet of the pond and in the pond itself. The samples were taken in 1.0 l polyethylene bottles directly from the ditches by carefully sinking the bottle below the water level.

In sites ST1, VG, BU1 simultaneously with water sampling, ditch profile (at water sampling locations) and stream velocity measurements were carried out to enable calculations of export of suspended solids and nutrients from the catchments.

To compare data statistically, the analysis of variance (*Anova*) in combination with *LSD* (*Least significant difference*) *post-hoc* test was conducted and standard errors were calculated. Different letters (a, ab, b) were used to indicate significant differences ($p \leq 0.05$) in the results. Sedimentation ponds were considered as effective if values significantly decreased ($p \leq 0.05$) after pond, comparing to the values before pond.

In Latvia, there are no threshold values to assess water quality in drainage systems, so results of the study are compared to Water Quality Standards for Priority Fish Waters by the Cabinet of Ministers of the Republic of Latvia.

Results and Discussion

Majority of published studies show that first-time drainage has a greater impact on runoff comparing to DNM (Åström, Aaltonen, & Koivusaari, 2001; Joensuu, Ahti, & Vuollekoski, 1999; Koivusalo *et al*., 2008), especially regarding the concentrations of suspended solids (Marttila & Kløve, 2010; Nieminen *et al*., 2010; Nieminen *et al*., 2017). At the same time, according to Ahti, Alasaarela & Ylitolonen (1995), Manninen (1995) and Manninen (1998), the effect on the concentration of suspended solids in the runoff of the initial ditching and DNM are similar.

In a study in Finland (Joensuu, 2002), a small decrease of total nitrogen concentrations was observed during the first years after ditch network maintenance; similar results were obtained in our study sites (Table 2; Table 3; Table 4; Table 5; Table 6; Table 7). On the contrary, earlier studies (Ahtiainen & Huttunen, 1999) ploughing and mounting to a mean level of 81.8 mg l–1 North Karelia Regional Environment Centre, P.O. Box 69, FIN-80101 Joensuu, University of Joensuu, Department of Biology, P.O. Box 111, FIN-80101 in 1986– 88, decreased to a level of 7.8 mg l–1 for 1989–91 and 4.5 mg l–1 for 1992–94. Total phosphorus concentration increased four-fold (142 µg l–1 reported that the total nitrogen concentrations increase after ditch maintenance.

$P\text{-}PO_4^{3-}$ concentrations in all research sites were generally low with small fluctuations over the years, except in site VA where relatively higher concentrations were observed during the first two years of sampling and during the third year before the sedimentation pond and in the pond itself.

In accordance with the Water Quality Standards for Priority Fish Waters (Cabinet of Ministers, 2002), the threshold value for total suspended solids is 25 mg L^{-1}. This value was exceeded in sites VG, ST1, ST2, BU2 in the first two sampling years. In site VA the concentrations of the suspended solids were high and exceeded the threshold value throughout all sampling period – although these results may have been influenced by prolonged renovation works that continued throughout all observation period.

In all sites $N\text{-}NO_3^-$ concentrations were higher in the renovation year and in the year after, but in general nitrate nitrogen values were low.

Overall, pH values in almost all sites fell within the interval of target values for Water Quality Standarts for Priority Fish waters – 6-9 (Cabinet of Ministers, 2002). In all study areas, pH values exceeded 6, except in the site VA in 2012. Comparing the pH values over the years, it has increased after DNM in all of the study sites, except in ST1 and VG. In the study by Joensuu (2002), the mean pH value increased by 0.6 immediately after renovation process, and it was still 0.3 units higher than during the pre-treatment period six years after DNM.

The reported decrease of DOC concentrations varied from 15% (Nieminen *et al*., 2010) to 30% (Hansen *et al*., 2013) during the first two years after DNM. In our study sites DOC concentrations have noticeably increased in the year subsequent to renovation, although in 2014 the concentrations declined again.

In contrast to the expected improvement in water quality by the construction of the sedimentation ponds, no statistically significant effect was detected in all research sites comparing observed water quality before and after the sedimentation ponds.

Comparing element concentrations over the years in site BU1, DOC concentrations in the year 2013 were significantly higher than in other sampling

Table 2

Mean element concentrations in sedimentation pond in forest drainage system 'BU1' on ditch N-23

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	25.19 ± 2.22	a	24.65 ± 3.17	25.49 ± 3.34	a
	2013	35.72 ± 3.67	b	35.85 ± 3.75	35.10 ± 3.82	b
	2014	20.24 ± 1.29	a	20.33 ± 1.26	20.81 ± 1.38	a
N_{tot} ± SE, mg L^{-1}	2012	2.06 ± 0.45	a	1.47 ± 0.35	2.47 ± 0.73	a
	2013	0.58 ± 0.04	b	0.57 ± 0.04	0.58 ± 0.05	b
	2014	0.47 ± 0.05	b	0.49 ± 0.05	0.49 ± 0.05	b
$N\text{-}NO_3^-$ ± SE, mg L^{-1}	2012	0.25 ± 0.03	a	0.27 ± 0.06	0.27 ± 0.04	a
	2013	0.13 ± 0.03	b	0.20 ± 0.05	0.18 ± 0.05	ab
	2014	0.08 ± 0.03	b	0.09 ± 0.03	0.09 ± 0.03	b
pH ± SE	2012	7.88 ± 0.08	ab	7.90 ± 0.12	7.88 ± 0.12	ab
	2013	7.84 ± 0.12	b	7.98 ± 0.09	7.99 ± 0.07	ab
	2014	8.09 ± 0.09	ab	8.13 ± 0.08	8.11 ± 0.08	a
$P\text{-}PO_4^{3-}$ ± SE, mg L^{-1}	2012	0.01 ± 0		0.01 ± 0	0.02 ± 0	
	2013	0.06 ± 0.05		0.01 ± 0	0.01 ± 0	
	2014	<0.01		<0.01	0.01 ± 0	
TSS ± SE, mg L^{-1}	2012	22.34 ± 6.98		20.68 ± 10.83	24.13 ± 11.70	
	2013	18.37 ± 4.57		19.76 ± 7.99	26.76 ± 8.83	
	2014	17.69 ± 7.20		6.61 ± 1.78	8.22 ± 2.14	

Table 3

Mean element concentrations in sedimentation pond in forest drainage system 'BU2' on ditch N-6

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	20.47 ± 2.00	a	18.90 ± 1.92	18.28 ± 1.86	a
	2013	39.97 ± 6.53	b	37.97 ± 6.43	36.34 ± 6.07	b
	2014	15.87 ± 1.53	a	16.38 ± 1.42	16.47 ± 1.27	a
N_{tot} ± SE, mg L^{-1}	2012	1.62 ± 0.23	a	1.51 ± 0.15	1.42 ± 0.32	a
	2013	0.57 ± 0.08	b	0.48 ± 0.04	0.46 ± 0.05	b
	2014	0.38 ± 0.05	b	0.36 ± 0.03	0.36 ± 0.02	b
N-NO_3^- ± SE, mg L^{-1}	2012	0.13 ± 0.05		0.20 ± 0.06	0.24 ± 0.07	
	2013	0.15 ± 0.03		0.24 ± 0.07	0.13 ± 0.06	
	2014	0.11 ± 0.06		0.12 ± 0.06	0.13 ± 0.06	
pH ± SE	2012	8.02 ± 0.10		8.04 ± 0.08	7.98 ± 0.06	
	2013	8.22 ± 0.06		8.19 ± 0.07	8.21 ± 0.06	
	2014	8.18 ± 0.17		8.18 ± 0.12	8.13 ± 0.12	
P-PO_4^{3-} ± SE, mg L^{-1}	2012	0.01 ± 0		<0.01	0.01 ± 0	
	2013	0.01 ± 0		0.01 ± 0	0.01 ± 0	
	2014	<0.01		<0.01	0.01 ± 0.01	
TSS ± SE, mg L^{-1}	2012	29.75 ± 9.17		9.10 ± 7.21	30.96 ± 14.18	
	2013	15.64 ± 4.33		9.25 ± 2.97	12.36 ± 5.41	
	2014	26.53 ± 7.37		3.15 ± 1.26	20.13 ± 16.14	

years, both before and after the sedimentation pond, while concentrations of N_{tot} in 2013 and 2014 were significantly lower than those in 2012 (Table 2).

In site BU1 concentrations of N-NO_3^- before pond were significantly higher in 2012 comparing to 2013 and 2014, however significant differences after pond were observed between two initial years of the study and 2014. Mean pH value, P-PO_4^{3-} and TSS concentrations did not differ significantly during the study years.

Comparing element concentrations in site BU2 over years, mean DOC concentrations in 2012 and 2014 were significantly lower than in 2013 both before and after the sedimentation pond. Mean N_{tot} concentrations in 2013 and 2014 were significantly lower than the respective values in 2012. The mean concentrations of other elements were not significantly different during sampling years, however mean DOC, N_{tot} and TSS concentrations generally had a tendency to decline, comparing before and after pond values (Table 3).

Table 4

Mean element concentrations in sedimentation pond in forest drainage system 'ST1' on ditch N-41

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	24.89 ± 1.05	a	24.15 ± 1.12	24.73 ± 1.11	a
	2013	36.91 ± 3.63	b	37.05 ± 3.65	37.25 ± 3.71	b
	2014	26.35 ± 1.38	a	25.18 ± 1.63	24.96 ± 1.80	a
N_{tot} ± SE, mg L^{-1}	2012	2.21 ± 0.30	a	2.07 ± 0.30	2.55 ± 0.52	a
	2013	1.25 ± 0.22	b	1.29 ± 0.23	1.28 ± 0.23	b
	2014	1.25 ± 0.21	b	1.26 ± 0.22	1.26 ± 0.22	b
N-NO_3^- ± SE, mg L^{-1}	2012	0.44 ± 0.12		0.54 ± 0.12	0.50 ± 0.12	
	2013	0.52 ± 0.24		0.54 ± 0.21	0.47 ± 0.19	
	2014	0.29 ± 0.11		0.30 ± 0.12	0.34 ± 0.12	
pH ± SE	2012	8.02 ± 0.07		8.02 ± 0.06	8.01 ± 0.06	
	2013	8.06 ± 0.11		8.06 ± 0.10	8.01 ± 0.09	
	2014	7.95 ± 0.09		7.99 ± 0.06	7.95 ± 0.07	
P-PO_4^{3-} ± SE, mg L^{-1}	2012	0.01 ± 0		0.01 ± 0	0.01 ± 0	
	2013	0.01 ± 0		0.01 ± 0	0.01 ± 0	
	2014	0.01 ± 0		0.01 ± 0	0.01 ± 0	
TSS ± SE, mg L^{-1}	2012	43.38 ± 18.84	a	24.38 ± 13.18	37.87 ± 17.25	a
	2013	7.83 ± 2.82	b	63.34 ± 54.94	20.43 ± 17.39	b
	2014	9.04 ± 4.53	b	4.97 ± 3.05	4.56 ± 2.50	b

Table 5
Mean element concentrations in sedimentation pond in forest drainage system 'ST2' on ditch N-61

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	17.80 ± 1.11	a	17.93 ± 1.18	19.35 ± 1.04	a
	2013	35.00 ± 5.69	b	35.98 ± 6.01	35.59 ± 5.92	b
	2014	20.05 ± 1.69	a	20.24 ± 1.77	20.78 ± 2.08	a
N_{tot} ± SE, mg L^{-1}	2012	3.08 ± 0.57	a	2.79 ± 0.43	3.76 ± 0.65	a
	2013	1.33 ± 0.35	b	1.27 ± 0.35	1.27 ± 0.31	b
	2014	1.01 ± 0.22	b	1.06 ± 0.25	1.07 ± 0.24	b
N-NO_3^- ± SE, mg L^{-1}	2012	0.34 ± 0.10	a	0.29 ± 0.08	0.24 ± 0.06	ab
	2013	1.22 ± 0.58	b	1.29 ± 0.61	0.65 ± 0.35	ab
	2014	0.37 ± 0.14	b	0.37 ± 0.16	0.32 ± 0.17	b
pH ± SE	2012	7.92 ± 0.08		7.90 ± 0.07	7.88 ± 0.08	
	2013	7.78 ± 0.11		7.78 ± 0.10	7.75 ± 0.10	
	2014	8.01 ± 0.09		8.02 ± 0.09	8.00 ± 0.09	
P-PO_4^{3-} ± SE, mg L^{-1}	2012	0.01 ± 0	ab	0.01 ± 0	0.01 ± 0	a
	2013	0.01 ± 0	ab	0.01 ± 0	0.01 ± 0	ab
	2014	<0.01	b	<0.01	0.01 ± 0	b
TSS ± SE, mg L^{-1}	2012	43.12 ± 17.31	ab	19.09 ± 5.37	85.81 ± 40.50	a
	2013	4.93 ± 1.79	b	2.75 ± 1.36	6.43 ± 4.28	b
	2014	0.89 ± 0.40	b	1.07 ± 0.47	2.33 ± 1.20	b

Table 6
Mean element concentrations in sedimentation pond in forest drainage system 'VA' on ditch N-5

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	115.60 ± 16.73	a	112.80 ± 18.33	103.8 ± 14.12	ab
	2013	125.45 ± 18.04	a	113.24 ± 10.09	114.82 ± 10.46	a
	2014	91.05 ± 10.36	ab	70.16 ± 13.78	71.70 ± 12.33	b
N_{tot} ± SE, mg L^{-1}	2012	4.62 ± 0.89	a	4.72 ± 0.98	4.67 ± 1.37	a
	2013	2.60 ± 0.27	b	2.62 ± 0.22	2.75 ± 0.25	b
	2014	1.98 ± 0.33	b	1.61 ± 0.33	2.03 ± 0.31	b
N-NO_3^- ± SE, mg L^{-1}	2012	0.83 ± 0.49		<LOD	0.77 ± 0.15	
	2013	0.39 ± 0.06		0.27 ± 0.09	0.63 ± 0.28	
	2014	0.13 ± 0.11		0.18 ± 0.09	0.68 ± 0.47	
pH ± SE	2012	5.77 ± 0.32	ab	5.39 ± 0.39	5.69 ± 0.34	a
	2013	6.29 ± 0.27	ab	6.33 ± 0.24	6.16 ± 0.26	ab
	2014	6.18 ± 0.43	ab	6.74 ± 0.42	6.73 ± 0.41	b
P-PO_4^{3-} ± SE, mg L^{-1}	2012	0.31 ± 0.08	a	0.28 ± 0.03	0.25 ± 0.06	ab
	2013	0.18 ± 0.05	ab	0.23 ± 0.07	0.27 ± 0.10	a
	2014	0.14 ± 0.02	ab	0.11 ± 0.03	0.08 ± 0.02	b
TSS ± SE, mg L^{-1}	2012	887.64 ± 669.73	a	395.75 ± 241.23	702.64 ± 323.71	ab
	2013	38.67 ± 12.54	b	84.66 ± 41.58	95.63 ± 53.09	b
	2014	24.85 ± 8.16	b	26.67 ± 9.71	44.45 ± 21.57	b

In site ST1 observed mean DOC concentrations have similar tendencies as in previously described site – significantly higher values were observed in 2013, whereas N_{tot} and TSS concentrations were significantly higher in 2012. Although element concentration values before and after pond were not significantly different, generally declining tendencies of mean DOC and TSS concentrations were observed (Table 4).

In site ST2 results showed similar trends of mean DOC, N_{tot} and TSS concentrations as in site ST1 – significantly higher DOC values were observed in 2013, whereas N_{tot} and TSS concentrations were significantly higher in 2012. No declining trends of mean TSS concentrations were observed, comparing before and after pond values, while downward trends of N-NO_3^- concentrations were observed, although not

Table 7

Mean element concentrations in sedimentation pond in forest drainage system 'VG' on ditch N-52

Elements in water samples	Year	Before pond		In pond	After pond	
DOC ± SE, mg L^{-1}	2012	22.15 ± 1.33	a	20.38 ± 1.59	21.91 ± 1.71	a
	2013	42.17 ± 4.42	b	41.72 ± 4.19	42.01 ± 4.24	b
	2014	20.87 ± 1.38	a	20.73 ± 1.36	20.66 ± 1.25	a
N_{tot} ± SE, mg L^{-1}	2012	2.76 ± 0.62	a	2.71 ± 0.37	2.06 ± 0.31	a
	2013	0.83 ± 0.11	b	0.8 ± 0.09	0.79 ± 0.08	b
	2014	0.72 ± 0.10	b	0.71 ± 0.1	0.71 ± 0.10	b
N-NO_3^- ± SE, mg L^{-1}	2012	0.23 ± 0.03		0.2 ± 0.03	0.24 ± 0.04	
	2013	0.29 ± 0.11		0.21 ± 0.10	0.34 ± 0.15	
	2014	0.16 ± 0.05		0.15 ± 0.04	0.16 ± 0.05	
pH ± SE	2012	8.08 ± 0.10		8.09 ± 0.10	8.11 ± 0.09	
	2013	8.07 ± 0.08		8.06 ± 0.08	7.83 ± 0.16	
	2014	8.03 ± 0.11		8.04 ± 0.12	7.98 ± 0.18	
P-PO_4^{3-} ± SE, mg L^{-1}	2012	0.01 ± 0	ab	0.01 ± 0	0.01 ± 0.01	a
	2013	0.01 ± 0	ab	0.01 ± 0	0.01 ± 0	ab
	2014	<0.01	b	<0.01	<0.01	b
TSS ± SE, mg L^{-1}	2012	84.23 ± 49.13		373.18 ± 212.97	72.07 ± 51.47	
	2013	23.75 ± 16.66		40.82 ± 34.69	14.47 ± 8.17	
	2014	8.12 ± 3.49		9.76 ± 3.46	7.85 ± 4.87	

statistically significant (Table 5).

Mean DOC concentrations were not significantly different comparing the sampling years in site VA, except notably lower concentration after the pond in 2014. At the same time, there was a downward trend comparing values before and after the pond. N_{tot} and TSS concentrations were significantly higher in 2012. A downward trend of other element concentrations, comparing values before and after the pond, were not noticeable (Table 6).

Tendencies of mean DOC and N_{tot} concentrations in site VG were similar to previously described sites (BU1, BU2, ST1, ST2) with DOC concentration significantly higher in 2013 and N_{tot} significantly

Table 8

Output of biogenic elements from BU1, ST1, VG catchment areas throughout the observation period, kg ha^{-1} per year

Elements	Year	BU1		ST1		VG	
		Before pond	After pond	Before pond	After pond	Before pond	After pond
N_{tot}	2012	1.14	1.05	0.16	0.24	0.08	0.07
	2013	1.37	1.27	0.20	0.29	0.10	0.08
	2014	1.34	1.29	0.27	0.32	0.10	0.90
TSS	2012	43.78	8.71	2.12	4.50	5.04	8.73
	2013	34.58	6.88	1.67	3.56	3.98	6.89
	2014	35.98	5.74	1.78	3.18	3.87	7.20
DOC	2012	23.77	<0.01	2.34	2.67	0.78	0.87
	2013	19.49	<0.01	1.92	2.19	0.64	0.71
	2014	21.18	<0.01	1.72	1.15	0.61	0.69
N-NO_3^-	2012	0.20	0.10	0.04	0.05	0.01	0.01
	2013	0.22	0.11	0.05	0.05	0.01	0.02
	2014	0.22	0.13	0.04	0.04	0.01	0.01
P-PO_4^{3-}	2012	0.02	0.01	<0.01	<0.01	<0.01	<0.01
	2013	0.02	0.01	<0.01	<0.01	<0.01	<0.01
	2014	0.01	0.01	<0.01	<0.01	<0.01	<0.01
N-NH_4^+	2012	0.05	0.05	0.01	0.01	<0.01	<0.01
	2013	0.05	0.06	0.01	0.01	<0.01	<0.01
	2014	0.05	0.05	0.01	0.01	<0.01	<0.01

higher in 2012. A downward trend comparing the TSS concentrations before and after pond was observed, although not statistically significant (Table 7).

Our results on the leaching of biogenic elements are comparable with the data from the Finnish scientific literature (Joensuu, 2002). In most cases the output of biogenic elements in Latvia are lower than in Finland, which can be explained by different soil composition – none of our research sites are located on deep peat soils.

Nieminen *et al*. (2017) synthesized the information on the DNM impact on water quality and runoff from different studies. Most of the reviewed studies showed significantly decreased DOC runoff after DNM. Comparing runoff data over the years in our study sites, DOC export has also decreased, however in site VG the efficiency of DOC retention in the sedimentation pond was lower than in the other sites (Table 8).

In the site BU1 the runoff values of most elements were lower after the pond, while the element values in sites ST1 and VG after the sedimentation pond were similar or, in some cases, even higher than before it. The efficiency of sediment and nutrient retention in BU1 site was higher than in sites ST1 and VG. Differences between sites can be explained by different conditions in catchment areas, and a very low amount of runoff during the sampling period, as in some months runoff close to 0 was observed.

A study by Joensuu (2002) observed that during summer (the low flow period), phosphorus concentrations were the highest. Although the role of a sedimentation pond is to detain and collect the flow of nutrients and suspended particles, in a study by Kløve (2000) it is mentioned that if the size of soil particles is large and water flow is small in the sedimentation pond, most elements will be detained, but small particles such as fine silt and clay possibly will not sediment in all cases.

Conclusions

1. Mean concentrations of suspended solids and biogenic elements gradually decrease over the years after the drainage system maintenance. The efficiency of sedimentation ponds is higher in reducing the concentration of suspended particles than in reducing the concentration of nutrients.
2. Sedimentation ponds have not achieved the expected efficiency to reduce the leaching of SS and biogenic elements. The use of other water protection structures such as peak flow control dams, surface runoff areas or different parameters of sedimentation ponds should be considered depending on the size and conditions in the catchment area.

Acknowledgements

The study was carried out within the frames of Latvian State Forest Research Institute 'Silava' and JSC 'Latvia's State Forests' collaboration research programme.

References

1. Ahti, E., Alasaarela, E., & Ylitolonen, A. (1995). *Kunnostusojituksen vaikutus suon hydrologiaan ja valumavesien ainepitoisuuksiin*. (*Drainage system renovation impact on marsh hydrology and runoff water content*). In: Saukkonen S., & Kenttämies, K. (eds.), *Metsätalouden vesistövaikutukset ja niiden torjunta*. METVE projektin loppuraportti (pp. 157–168). Suomen ympäristö 2. Suomen ympäristökeskus. (in Finnish)
2. Ahti, E., Joensuu, S., & Vuollekoski, M. (1999). *Kunnostusojituksen vaikutus metsä ojitusalueiden valumaveden kemiallisiin ominaisuuksiin*. (*Impact of drainage system renovation on the chemical propreties of runoff water in drained forest areas*). In: Ahti, E., Granlund, H., and Puranen, E. (eds.) *Metsätalouden ympäristökuormitus* (pp. 79–90). Metsäntutkimuslaitoksen tiedonantoja. (in Finnish)
3. Ahtiainen, M., & Huttunen, P. (1999). Long-term effects of forestry managements on water quality and loading in brooks. *Boreal Environment Research*, 4(2), 101–114. DOI: 101-114, ISSN 1239-6095.
4. Åström, M., Aaltonen, E.K., & Koivusaari, J. (2001). Impact of Ditching in a small forested catchment on concentrations of suspended material, organic carbon, hydrogen ions and metals in stream water. *Aquatic Geochemistry*. DOI: 10.1023/A:1011337225681.
5. Cabinet of Ministers. (2002). *Regulation No. 118. Regulations Regarding the Quality of Surface Waters and Groundwaters*. Riga: Latvijas Vēstnesis.
6. Gholz, H.L., Ewel, K.C., & Teskey, R.O. (1990). Water and forest productivity. *Forest Ecology and Management*. DOI: 10.1016/0378-1127(90)90122-R.
7. Hansen, K., Kronnäs, V., Zetterberg, T., Zetterberg, M., Moldan, F., Petterson, P., & Munthe, J. (2013). *The effects of ditch cleaning on runoff, water chemistry and botany fauna in forest ecosystems*. Report. IVL Svenska Miljöinstitutet: Sweden.
8. Joensuu, S., Ahti, E., & Vuollekoski, M. (1999). The effects of peatland forest ditch maintenance on suspended solids in runoff. *Boreal Environment Research*, 4(4), 343–355.

9. Joensuu, S. (2002). *Effects of ditch network maintenance and sedimentation ponds on export loads of suspended solids and nutrients from peatland forests.* Academic dissertation, University of Helsinki, Helsinki, Finland.
10. 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 Environment Research*.
11. Koivusalo, H., Ahti, E., Laurén, A., Kokkonen, T., Karvonen, T., Nevalainen, R., & Finér, L. (2008). Impacts of ditch cleaning on hydrological processes in a drained peatland forest. *Hydrology and Earth System Sciences*. DOI: 10.5194/hess-12-1211-2008.
12. Manninen, P. (1995). *Kunnostusojituksen vesiensuojelu tutkimus; veden laadun kuormituksen ja biologian muutokset kahden ensimmäisen ojituksen jälkeisenvuoden aikana* (*Drainage system renovation research; changes in water quality and biology during the first two years after the renovation*). In: Saukkonen, S. Kenttämies, K. (eds.). *Metsätalouden vesistöhaitat ja niiden torjunta*., METVE projektin loppuraportti (pp. 169–181). Suomen ympäristö 2. Suomen ympäristökeskus. (in Finnish)
13. Manninen, P. (1998). Effects of forestry ditch cleaning and supplementary ditching on water quality. *Boreal Environment Research*.
14. Marttila, H., & Kløve, B. (2010). Managing runoff, water quality and erosion in peatland forestry by peak runoff control. *Ecological Engineering*. DOI: 10.1016/j.ecoleng.2010.04.002.
15. Nieminen, M., Ahti, E., Koivusalo, H., Mattsson, T., Sarkkola, S., & Laurén, A. (2010). Export of suspended solids and dissolved elements from peatland areas after ditch network maintenance in south-central Finland. *Silva Fennica*. DOI: 10.14214/sf.161.
16. Nieminen, M., Palviainen, M., Sarkkola, S., Laurén, A., Marttila, H., & Finér, L. (2017). A synthesis of the impacts of ditch network maintenance on the quantity and quality of runoff from drained boreal peatland forests. *Ambio*, pp. 1–12. DOI: 10.1007/s13280-017-0966-y.
17. Paavilainen, E., & Päivänen, J. (1995). *Peatland forestry: ecology and principles*. *Peatland Forestry Ecology and Principles*. DOI: 10.1017/CBO9781107415324.004.
18. Sarkkola, S., Hökkä, H., & Penttilä, T. (2004). Natural development of stand structure in peatland Scots pine following drainage: Results based on long-term monitoring of permanent sample plots. In *Silva Fennica*.
19. Sikström, U., & Hökkä, H. (2016). Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance. *Silva Fennica*. DOI: 10.14214/sf.1416.
20. Socha, J. (2012). Long-term effect of wetland drainage on the productivity of Scots pine stands in Poland. *Forest Ecology and Management*. DOI: 10.1016/j.foreco.2012.02.032.