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Long-Term (2001–2020) Nutrient Transport from a Small Boreal Agricultural Watershed: Hydrological Control and Potential of Retention Ponds

Sari Uusheimo *, Tiina Tulonen, Jussi Huotari and Lauri Arvola

Lammi Biological Station, Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences, Helsinki University, FI-16900 Lammi, Finland; tiina.tulonen@helsinki.fi (T.T.); jussi.huotari@helsinki.fi (J.H.); lauri.arvola@helsinki.fi (L.A.)

* Correspondence: sari.uusheimo@iki.fi

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Abstract: Agriculture contributes significantly to phosphorus and nitrogen loading in southern Finland. Climate change with higher winter air temperatures and precipitation may also promote loading increase further. We analyzed long-term nutrient trends (2001–2020) based on year-round weekly water sampling and daily weather data from a boreal small agricultural watershed. In addition, nutrient retention was studied in a constructed sedimentation pond system for two years. We did not find any statistically significant trends in weather conditions (temperature, precipitation, discharge, snow depth) except for an increase in discharge in March. Increasing trends in annual concentrations were found for nitrate, phosphate, and total phosphorus and total nitrogen. In fact, phosphate concentration increased in every season and nitrate concentration in other seasons except in autumn. Total phosphorus and total nitrogen concentrations increased in winter as well and total phosphorus also in summer. Increasing annual loading trend was found for total phosphorus, phosphate, and nitrate. Increasing winter loading was found for nitrate and total nitrogen, but phosphate loading increased in winter, spring, and summer. In the pond system, annual retention of total nitrogen was 1.9–4.8% and that of phosphorus 4.3–6.9%. In addition, 25–40% of suspended solids was sedimented in the ponds. Our results suggest that even small ponds can be utilized to decrease nutrient and material transport, but their retention efficiency varies between years. We conclude that nutrient loading from small boreal agricultural catchments, especially in wintertime, has already increased and is likely to increase even further in the future due to climate change. Thus, the need for new management tools to reduce loading from boreal agricultural lands becomes even more acute.

Keywords: nutrients; agricultural watershed; loading; ponds; nitrate; phosphate

1. Introduction

Finland is among the few areas where agriculture has traditionally been carried out above the 60th parallel north. As climate change has already been most rapid in the North, Finnish agriculture is facing major challenges relating to rising air temperatures and losses of snow and freezing of ground in winter. As a result, erosion of soil may substantially increase, and higher nutrient loading from agricultural lands may be expected [1]. The importance of agriculture in nutrient loading is evident as 58% of phosphorus (P) and 51% of nitrogen (N) inputs to the Finnish waterways originate from agriculture [2]. Any increases in erosion and runoff will almost certainly enhance nutrient loading to inland waters, but specifically coastal waters, as the agricultural activities are most intensive in southern and western parts of Finland. Eutrophication is especially affecting the coastal waters of Finland and the entire Baltic Sea [3], but it is also deteriorating many inland lakes and rivers as well.

High availability of nutrients together with higher water temperatures may result in toxic algal blooms, which create health risks for recreational and agricultural use of water as well as fish farming.

According to climate predictions, precipitation will increase in Northern Europe [4,5]. Between 1847 and 2013, the annual mean temperature in Finland increased 0.14 °C per decade [6], which is more than the corresponding increase globally [7]. Typically in Finland, the highest discharge and nutrient loads have been detected during the spring melt or in autumn, but future scenarios state that periods of high discharge shift from spring towards winter months [8], a period when the warming has already been strongest [7]. As a result of increased winter air temperature and precipitation, snow depth has decreased in southern, western, and central parts of Finland [9]. Besides the increase in dissolved inorganic nutrients, mild and wet winters may also result in increased suspended sediment transport [1] and increased organic matter mineralization [10], which may further challenge the nutrient loss mitigation measures and regulations.

In Finland, the use of P and N fertilizers relative to field area was highest during late 1980s and early 1990s. To reduce agricultural nutrient loading, a fertilizer tax was set in 1992 until 1995, when Finland became part of the European Union (EU). Since the mid-1990s, water protection measures and agro-environmental subsidies, together with changes in agricultural cultivation practices, decreased the amounts of fertilizers consumed. However, the nutrient loss reductions have not reached the set targets [11]. As excessive amounts of N is harmful to people and nature, the EU adopted the Nitrates Directive (91/676/EEC) to reduce nitrate–nitrogen (NO_3-N) pollution. Although NO_3-N levels of surface and groundwaters are generally low in Finland in comparison to many other EU countries, increasing NO_3-N trends have been found in Finnish rivers and lakes, and very high NO_3-N concentration over 25 mg L^{-1} has been found in nine river sites [12].

Wetlands have been reported as efficient ecosystems in mitigating nutrient and sediment load from agricultural areas [13,14]. Besides, they can provide many other important ecosystem services such as biodiversity [15]. Wetland N removal is based on microbially driven denitrification and is temperature-dependent [16], which raises a question of its efficiency in cold climate [17,18]. N and P retention consists also of sedimentation and biomass accumulation, which is only partially permanent. Several studies suggest great variation in nutrient retention in wetlands between different seasons. Regardless of wetlands, during storm events in particular, nutrient leaching from agricultural fields may dramatically increase. In an agricultural stream with ponds, the combination of low temperature and high discharge can result in negative retention, while base flow and summertime often result in positive retention [19–22].

The trend in atmospheric N deposition at the Finnish Integrated Monitoring Catchment Area Valkea-Kotinen in Southern Finland, from 1988 to 2011, showed a decline [23], thus suggesting even stronger contribution of agricultural N today than some 20–30 years earlier. Despite the decreasing domestic atmospheric N loading, an increase was detected between 2002 and 2008, and the main source was suggested to be increased emission from abroad [23]. Another issue to be considered is the enrichment of N and P in soils [24,25]. It has been found that it may take a long time before any major water quality improvements can be detected in the recipient water bodies after decreasing fertilization of agricultural fields [24].

Nutrient loading from Finnish rivers to the Baltic Sea remains too high, and especially N concentrations have shown increasing trends in surface waters impacted by agriculture [26,27]. This study investigated the long-term nutrient trends in a small stream collecting waters from a small agricultural watershed in southern Finland. Boreal area having a large network of streams, canals, and ditches of small catchments is a potential site for high N retention [28]. Recently, a great number of small sedimentation ponds have been built in Finland to prevent loading from agricultural land. In this study, combining long-term weekly measured water chemistry with daily hydrological and meteorological data, we analyzed nutrient transport patterns relative to the hydrological and climatic conditions.

We have raised three key questions to be answered:

1. Has nutrient transport out of the watershed changed in the long run, and can it be explained by changes in weather and hydrological conditions?
2. Are there seasonal differences in nutrient transport relative to weather and hydrological conditions?
3. How do constructed retention ponds affect nutrient and suspended solids transport from a small agricultural watershed to the recipient lake?

2. Materials and Methods

2.1. Study Area and the Constructed Pond System

The studied stream, Koiransuolenoja, is in southern Finland in the watershed of Lake Pääjärvi. The size of the Koiransuolenoja catchment in the monitoring point K1 (61°04′97′′ N, 25°02′89′ E) is 6.8 km^2 (Figure 1). Most of the watershed is dominated by forestry (71%), but the stream is strongly influenced by agriculture with 24% of the catchment being cultivated fields. Koiransuolenoja has a high N content, consisting mainly of NO_3-N. Between 1995 and 2012, the mean Tot-N concentration in the stream was 2.5 ± 1.0 mg L^{-1}, and the mean annual precipitation 630 ± 81 mm [29]. Within the same time frame, the mean stream discharge (Q) in high season was 0.152 m^3 s^{-1} and in low season 0.020 m^3 s^{-1} [29]. Almost half of the catchment surface soil is easily erodible [30].

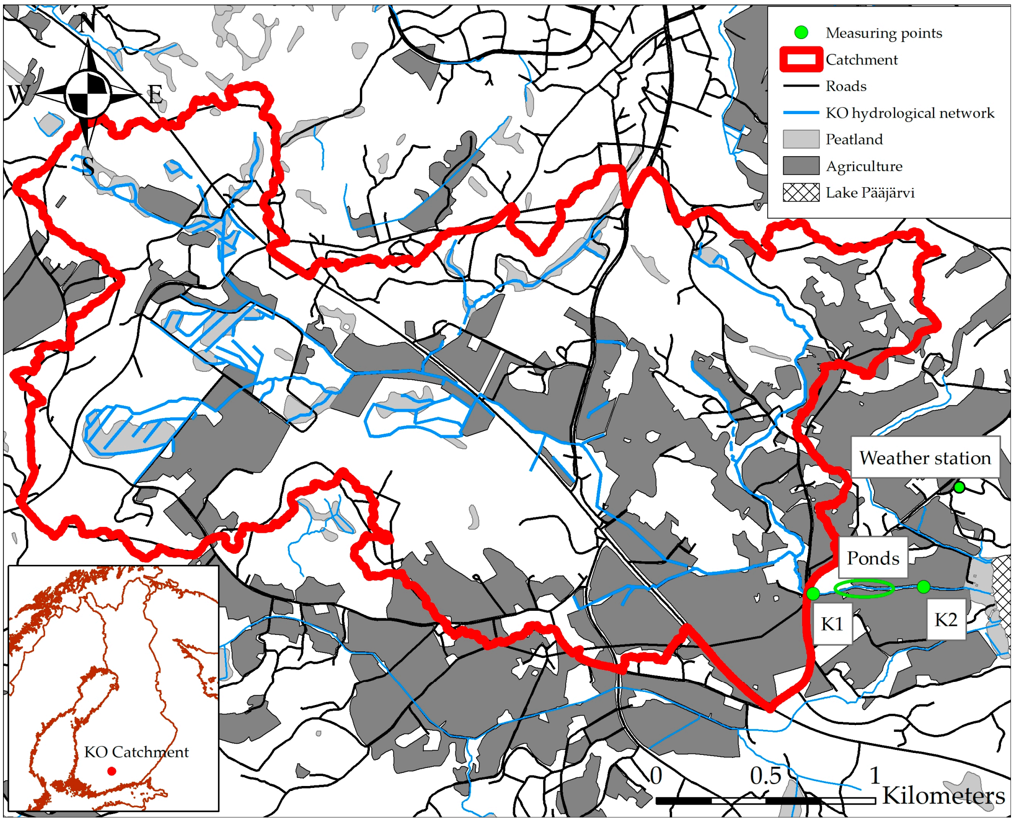

Figure 1. Koiransuolenoja watershed, land cover, and weather station (air temperature, precipitation, and snow depth), sampling sites K1 and K2, and the study ponds between them.

In March 2013, a set of 3 sedimentation ponds and bottom stone dams before and after them were constructed 450–700 m upstream from the lake inlet in the previously straightened Koiransuolenoja. The maximum depth of the ponds was 1.5–1.8 m. To investigate the efficiency of the pond system, water samples for nutrient and dissolved organic carbon (DOC) analyses were taken from two points from April 2013 to April 2015. Samples for suspended solids were taken once or twice a week from March to November in 2013 and 2014. The first sampling point was K1, about 127 m upstream from the first pond. The second sampling point was K2, located after the last pond and the bottom dam 510 m downstream from K1. The pond and stream surface area between the sampling points was 1247 m^2, representing 0.027% of the watershed size. The annual average theoretical hydraulic retention time between the sampling points during July 2014–June 2015 [18] was 5.5 h.

2.2. Long-Term Nutrient and DOC Sampling and Laboratory Analyses

Water samples for chemical analyses were collected manually from Koiransuolenoja stream monitoring point K1 (Figure 1) every week, year-round, from February 2001 until May 2020. The water temperature and flow rate were measured with a flowmeter (MiniAir2, Schiltknecht, Gossau, Switzerland) simultaneously with water level. The daily discharge was calculated from the curve based on the weekly measured flow rate and water level at site K1 during 2013–2015 and on regression model between Koiransuolenoja´s measurements and automatic discharge measurements from River Mustajoki (Finnish Environment Institute) situated in the same watershed area of Lake Pääjärvi. From water samples, dissolved organic carbon (DOC), NO_3-N (indicating the $NO_2^- + NO_3^-$), ammonium-nitrogen (NH_4-N), phosphate-phosphorus (PO_4-P), total N and P (Tot-N, Tot-P), and suspended solids were analyzed in the laboratory at Lammi Biological Station. Air temperature, precipitation, and snow depth data were obtained from the weather station of the Finnish Meteorological Institute (situated approximately 800 m northeast from the studied stream).

After sampling, water samples were kept dark and cold (+4 °C) and analyzed within 1–3 h from sampling. Total nutrients were analyzed from nonfiltered samples. Tot-N was analyzed according to SFS-EN ISO 11905-1. Tot-P and phosphate-phosphorus (PO_4-P) were analyzed following standard ISO/DIS 15681-2, except using persulfate digestion in the Tot-P analysis. For dissolved fractions, the samples were filtered with pre-rinsed (deionized water MQ; Millipore, Billerica, MA, USA) 0.45 μm filters (Millex-HA, Merck KGaA, Darmstadt, Germany). DOC was analyzed according to standard SFS-EN 1484 with a carbon analyzer (Ordior TOC-V, Shimadzu, Tokyo, Japan). NO_3-N was analyzed following SFS-EN ISO 13395 and NH_4-N analyzed according to standard SFS-EN ISO 11732 using the salicylate method. Nutrients were measured with a spectrophotometer (Gallery Plus, Thermo Fisher Scientific, Helsinki, Finland). Organic N (ON) and organic P (OP) were calculated by subtracting the concentrations of dissolved fractions from totals (i.e., ON = Tot-N-NO_3-N-NH_4-N and OP = Tot-P-PO_4-P). Concentrations of suspended solids were measured by filtering sample water through a Whatman GF/C fiberglass filter (Millipore, Billerica, MA, USA), and weighting and drying filters at 105 °C for 1 h. Finally, the concentrations and discharge rates were used to calculate rates of nutrient and material transport.

2.3. Data Analyses

We used non-parametric Mann–Kendall trend tests and Sen slope value (S) to analyze long-term (annual, seasonal, and monthly) weather conditions (air and stream water temperature, precipitation, discharge, snow depth), nutrient concentrations and nutrient loading from February 2001 to May 2020. The statistical significance limit (p-value) used was 0.05. Pearson correlation analysis was used to investigate the relationships between weather conditions and nutrient concentrations. In seasonal analysis, we divided the year into four seasons as follows: winter (December–February, XII–II), spring (March–May, III–V), summer (June–August, VI–VIII) and autumn (September–November, IX–XI). The nutrient and material retention of the pond system was calculated using loading rates between sampling points K1 and K2 for two years. The average annual retention was calculated for two periods (from mid-April 2013 to mid-April 2014 and similarly in 2014–2015) and separately for summer seasons in 2013 and 2014 (from mid-May to mid-September). The software used in the analysis was Microsoft Excel for Mac 16.37 with the XLSTAT package.

3. Results

3.1. Annual Weather Conditions and Fluctuation of Nutrient Delivery 2001–2019

During the 19 years study period, the average air temperature varied annually between 3.2 °C in 2010 and 6.0 °C in 2015 (sd ± 0.7). The highest annual precipitation was 816 mm measured in 2012 and the lowest 435 mm in 2018 (sd ± 112). The average stream discharge varied between 0.035 $m^3\ s^{-1}$ in 2003 and 0.064 $m^3\ s^{-1}$ in 2012. The snow depth (December–March) varied between the minimum of winter 2019–2020 (mean 2.5, max 9 cm) and the maximum of winter 2010–2011 (mean 42.9, max 62 cm). We did not find any trends in the annual weather conditions (Table 1). The air temperature became close to an increasing trend, however.

Table 1. Mann–Kendall trend test result for mean annual weather conditions, nutrient concentrations and nutrient loading 2001–2019. Statistically significant results (<0.05) in bold. Positive Sen slope indicates increasing values and negative slope indicates decreasing values.

Variable	*p*-Value	Sen´s Slope
Stream water temperature (°C)	0.783	−0.003
Air temperature (°C)	0.058	0.061
Stream discharge ($m^3\ s^{-1}$)	0.489	0.000
Precipitation (mm)	1.000	−0.233
Mean snow (cm)	0.456	−0.369
Max. snow (cm)	0.454	−0.563
Tot-N (µg L^{-1})	**0.008**	42.574
Tot-P (µg L^{-1})	**0.001**	1.030
NO_3-N (µg L^{-1})	**0.001**	53.458
NH_4-N (µg L^{-1})	0.298	2.124
PO_4-P (µg L^{-1})	**<0.0001**	0.712
DOC (µg L^{-1})	0.836	−0.013
Tot-N (kg $ha^{-1}\ a^{-1}$)	0.164	0.130
Tot-P (kg $ha^{-1}\ a^{-1}$)	**0.013**	0.002
NO_3-N (kg $ha^{-1}\ a^{-1}$)	**0.041**	0.129
NH_4-N (kg $ha^{-1}\ a^{-1}$)	0.238	0.006
PO_4-P (kg $ha^{-1}\ a^{-1}$)	**0.001**	0.002
DOC (kg C $ha^{-1}\ a^{-1}$)	0.836	0.068

Mean annual Tot-N loading was 6.6 kg (sd ± 2.1) N $ha^{-1}\ a^{-1}$ and Tot-P loading 0.093 (sd ± 0.037) kg P $ha^{-1}\ a^{-1}$. The maximum Tot-N load from the watershed was 11.1 kg $ha^{-1}\ a^{-1}$ in 2012 simultaneously with maximum discharge, and Tot-P load 0.210 kg $ha^{-1}\ a^{-1}$ in 2017. The minimum loading values 3.6 kg Tot-N $ha^{-1}\ a^{-1}$ and 0.058 kg Tot-P $ha^{-1}\ a^{-1}$ occurred during the same year in 2003 together with minimum discharge (and precipitation). Mean annual NO_3-N loading was 5.2 (sd ± 1.7) kg $ha^{-1}\ a^{-1}$, varying between 2.4 and 8.3 kg $ha^{-1}\ a^{-1}$ similarly during the same years as Tot-N. Mean NH_4-N loading was 0.26 (sd ± 0.11) kg $ha^{-1}\ a^{-1}$ and PO_4-P loading 0.028 (sd ± 0.028) kg $ha^{-1}\ a^{-1}$. The maximum NH_4-N load (0.53 kg $ha^{-1}\ a^{-1}$) was observed in 2017 as the maximum PO_4-P (0.096 kg $ha^{-1}\ a^{-1}$) and Tot-P load (0.21 kg $ha^{-1}\ a^{-1}$). The annual mean DOC transport from the watershed was 20.8 (sd ± 6.7) kg $ha^{-1}\ a^{-1}$, varying between 12.5 and 33.3 kg $ha^{-1}\ a^{-1}$.

Increasing trends were found for mean annual Tot-N-, Tot-P-, NO_3-N-, and PO_4-P-concentrations, but not for NH_4-N concentrations. Increasing loading trends were found for Tot-P, PO_4-P, and NO_3-N. No trend was found for DOC concentration or loading. However, the Sen slope value for DOC concentration was the only one having a negative value.

Pearson correlation analysis showed that mean annual precipitation correlated significantly with the concentration of Tot-N (r = 0.522, p = 0.022) and DOC (r = 0.744, p = 0.000), as well as with the loading of Tot-N (r = 0.718, p = 0.001), Tot-P (r = 0.584, p = 0.009), NH_4-N (r = 0.661, p = 0.002), NO_3-N (r = 0.608, p = 0.006), and DOC (r = 0.827, p < 0.0001).

3.2. Seasonal Trends in Weather, Nutrient Concentrations, and Loading

The average winter (months XII–II) air temperature was −5.1 °C (± 2.8), with a minimum of −10.6 °C in 2010 and a maximum of 0.0 °C in 2020 (Figure 2). During other seasons, the average air temperature in spring (III–V) was 3.9 °C, in summer (VI–VIII) 15.6 °C, and in autumn (IX–XI) 5.2 °C. The average stream discharge was highest in spring (0.07 $m^3 s^{-1}$) and lowest in summer (0.03 $m^3 s^{-1}$) (Figure 2), and the average stream water temperature was 0.9, 4.2, 13.6, and 6.3 °C for winter, spring, summer, and autumn, respectively (Table S1). The mean precipitation in summer (2.3 mm day^{-1}) was nearly twice the amount compared with spring (Table S1).

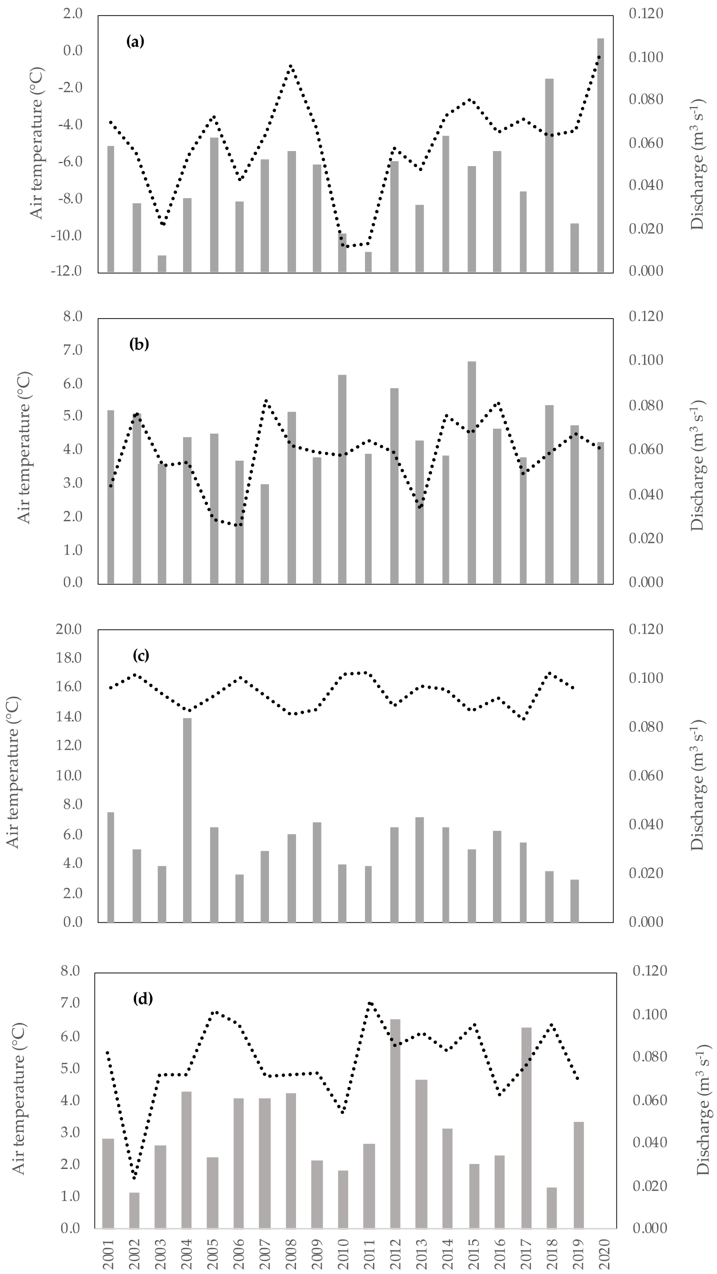

Figure 2. Average seasonal air temperature (dotted line) and Koiransuolenoja stream discharge (columns) for each year during (**a**) winter (2001–2020), (**b**) spring (2001–2020), (**c**) summer (2001–2019), and (**d**) autumn (2001–2019).

The highest Tot-N (3301 ± 615 µg L^{-1}), Tot-P (49.8 ± 14.3 µg L^{-1}), NH_4-N (166 ± 99 µg L^{-1}) and PO_4-P (13.7 ± 8.9 µg L^{-1}), ON (545 ± 242 µg L^{-1}) and OP (35.2 ± 8.4 µg L^{-1}) concentrations were measured in spring, whereas the highest NO_3-N concentrations were measured in winter (2614 ± 729 µg L^{-1}) and spring (2571 ± 580 µg L^{-1}) (Figure 3, Table S1). In contrast, DOC concentrations were highest in autumn and in spring, with averages of 9.6 and 9.5 mg L^{-1}, respectively (Figure 3, Table S1).

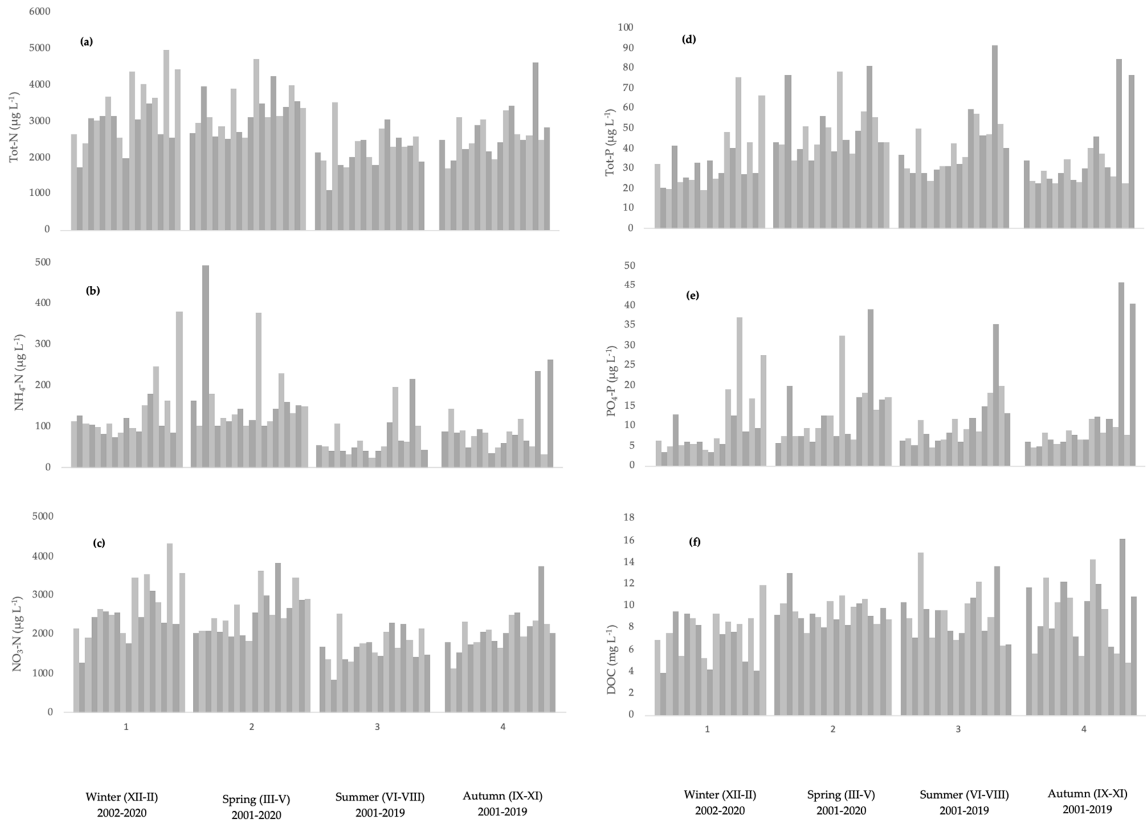

Figure 3. Average seasonal (**a**) Tot-N-, (**b**) NH_4-N-, (**c**) NO_3-N-, (**d**) Tot-P-, (**e**) PO_4-P-, (**f**) DOC-concentrations in the Koiransuolenoja stream between 2001 and 2020 (even years with light gray, odd years with dark gray). XII–II = December–February, III–V = March–May, VI–VIII = June–August, IX–XI = September–November.

We did not find statistically significant trends in the seasonal weather data including average air and stream water temperature, precipitation, and stream discharge 2001–2020. However, in monthly data, March discharge values increased significantly (S = 0.002, $p = 0.047$). The stream water temperature had an indicative value for decreasing trend without statistical significance in spring (S = −0.067, $p = 0.074$).

Winter concentration of Tot-N increased during the study period, but during spring and autumn the increase was not statistically significant (Table 2). Tot-P concentration showed an increasing trend during winter and summer. NO_3-N concentrations increased in winter, spring, and autumn, but PO_4-P concentration increased during every season. NH_4-N concentration did not show any trend. From organic fractions, only OP had an increasing trend in summer.

Winter Tot-N loading increased, and the elevation of Tot-P and NH_4-N loading was close to statistical significance (Table 2). NO_3-N loading had an increasing trend in winter, but springtime loading was only close to statistical significance. PO_4-P loading increased during winter, spring, and summer. Wintertime increase in OP loading was evident, but no trend was found in DOC loading.

Most nutrient fractions were positively correlated with air temperature, precipitation, and discharge (Table S2). During spring, only discharge was positively correlated with NO_3-N ($r = 0.474$, $p = 0.035$). Summertime nutrient concentrations and organic fractions were negatively correlated with air temperature, but only ON and DOC showed statistical significance ($r = -0.458$, $p = 0.048$, $r = -0.535$, $p = 0.018$, respectively). Increased summertime precipitation and discharge indicated mainly positive relationships with nutrients. In autumn, air temperature did not show any strong correlations with nutrients. However, increased autumn precipitation and stream discharge had a clear elevating effect on nutrient levels in Koiransuolenoja (Table S2).

Table 2. Mann–Kendall trend test results for Tot-N-, Tot-P-, NO_3-N-, NH_4-N-, PO_4-P-, ON-, OP-, and DOC concentrations and loadings in Koiransuolenoja during each season 2001–2020. Statistically significant *p*-values (<0.05) written in bold.

Season	Concentration	*p*-Value	Sen's Slope	Loading	*p*-Value	Sen's Slope
Winter	Tot-N (μg L^{-1})	**0.034**	75.889	(kg day^{-1})	**0.049**	0.724
Spring		0.055	43.370		0.288	0.207
Summer		0.186	29.148		0.783	−0.032
Autumn		0.058	46.397		0.534	0.246
Winter	Tot-P (μg L^{-1})	**0.013**	1.098	(kg day^{-1})	0.058	0.010
Spring		0.319	0.426		0.586	0.003
Summer		**0.002**	1.231		0.332	0.003
Autumn		0.093	0.650		0.298	0.004
Winter	NO_3-N (μg L^{-1})	**0.034**	72.238	(kg day^{-1})	**0.041**	0.646
Spring		**0.007**	52.495		0.055	0.312
Summer		0.211	23.436		0.945	−0.026
Autumn		**0.005**	47.508		0.447	0.229
Winter	NH_4-N (μg L^{-1})	0.298	2.427	(kg day^{-1})	0.058	0.037
Spring		0.501	1.040		0.924	0.003
Summer		0.172	1.757		0.534	0.003
Autumn		0.836	−0.341		0.730	0.008
Winter	PO_4-P (μg L^{-1})	**0.008**	0.442	(kg day^{-1})	**0.016**	0.003
Spring		**0.010**	0.607		**0.040**	0.003
Summer		**0.000**	0.621		**0.034**	0.002
Autumn		**0.001**	0.440		0.068	0.002
Winter	ON (μg L^{-1})	0.679	−3.476	(kg day^{-1})	0.489	0.051
Spring		0.319	−7.112		0.677	−0.021
Summer		0.945	−0.993		0.581	−0.012
Autumn		0.401	−12.183		0.890	−0.010
Winter	OP (μg L^{-1})	0.093	0.498	(kg day^{-1})	**0.049**	0.006
Spring		0.631	−0.123		0.974	0.000
Summer		**0.013**	0.731		0.581	0.001
Autumn		0.363	0.400		0.447	0.002
Winter	DOC (mg L^{-1})	0.783	0.053	(kg day^{-1})	0.332	1.154
Spring		0.773	−0.020		0.924	−0.081
Summer		0.575	−0.052		0.489	−0.320
Autumn		0.783	−0.075		1.000	0.208

3.3. Nutrient Retention of the Pond System

The two-year monitoring period showed clearly that precipitation peaks on a regular basis were followed by high water flow rates in Koiransuolenoja, with exceptions during the snow melt in spring (Figure 4). Water residence time in the pond system varied from hours to a few days. In the first year after construction of the pond system, mean annual water temperature and discharge were higher than in the second year, which resulted in higher delivery of total nutrients, suspended solids, NO_3-N, and PO_4-P (Tables 3 and 4). The difference between the years was not as clear with ammonium load. During the first year, on average 4.8% of Tot-N load and 4.3% of Tot-P load stayed in the pond system. The next year, Tot-N retention was only 1.9%, but Tot-P retention increased, being on average 6.9%. Mean loss of suspended solids was 74 kg day^{-1} in 2013 with almost 40% of material sedimented in the pond system (in 2014, 33 kg day^{-1} and 25%, respectively). On a yearly basis, NO_3-N retention was low (−0.1 and 1.0%), but retention of NH_4-N was significantly higher (13.7 and 22.0%). Retention of PO_4-P was 15.8% in the first year, but dropped to slightly negative during the second year.

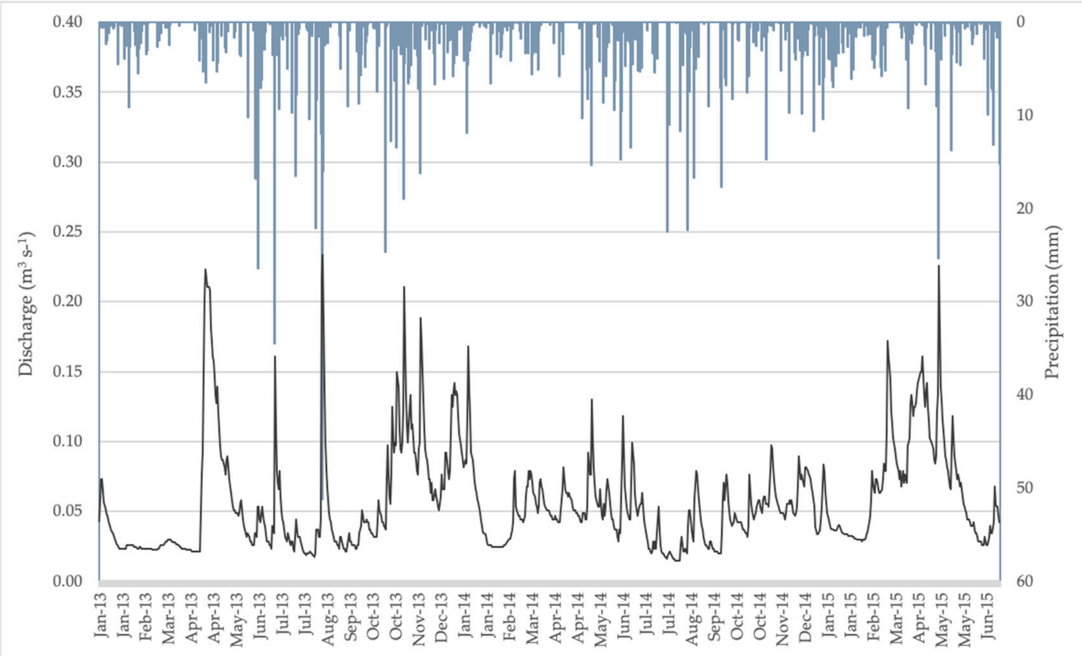

Figure 4. Koiransuolenoja stream discharge (black line) and precipitation (columns, light grey) from January 2013 to June 2015.

Table 3. Mean total (March–November) and summer (May–September) stream water temperature, discharge, nutrient load, and retention in the Koiransuolenoja sedimentation pond system.

Variable	Unit	1. Year	2. Year	Summer 2013	Summer 2014
Water temperature	°C	7.9	5.6	13.4	13.6
Stream discharge	$m^3\ s^{-1}$	0.073	0.063	0.033	0.041
Tot-N	$g\ ha^{-1}\ day^{-1}$	41.4	31.2	13.5	13.7
	retention %	4.8	1.9	8.6	4.6
NO_3-N	$g\ ha^{-1}\ day^{-1}$	34.3	26.6	10.2	9.2
	retention %	−0.1	1.8	6.3	8.2
NH_4-N	$g\ ha^{-1}\ day^{-1}$	1.4	1.3	0.7	1.2
	retention %	13.7	22.0	14.1	26.4
Tot-P	$g\ h^{-1}\ day^{-1}$	0.77	0.42	0.34	0.46
	retention %	4.3	6.9	3.9	4.2
PO_4-P	$g\ ha^{-1}\ day^{-1}$	0.20	0.11	0.07	0.06
	retention %	15.8	−0.1	18.1	−2.4

Table 4. Mean total and summer (May–September) loading and retention of suspended solids in the Koiransuolenoja stream sedimentation pond system in 2013 and 2014.

Variable	2013		2014	
	Year	Summer	Year	Summer
Load $kg\ ha^{-1}\ day^{-1}$	0.33	0.15	0.17	0.24
Retention $kg\ day^{-1}$	74	48	33	28
Retention %	39	40	25	19

In consecutive summers, water temperatures were equal, but discharge was slightly higher during the second summer. Tot-N transport was lower in summer than on a yearly basis and retention was higher. Summer retention of dissolved N compounds was clearly higher than the annual mean value (Figure 5). In summer, the loss of NO_3-N was 6–8%, but leakage of nitrate from the pond system was obvious in the cold season. Transport of suspended solids was 0.15 kg day^{-1} ha^{-1} in

2013 and 0.24 kg day^{-1} ha^{-1} in 2014. Retention of suspended material decreased from 40% to 19% in consecutive summers.

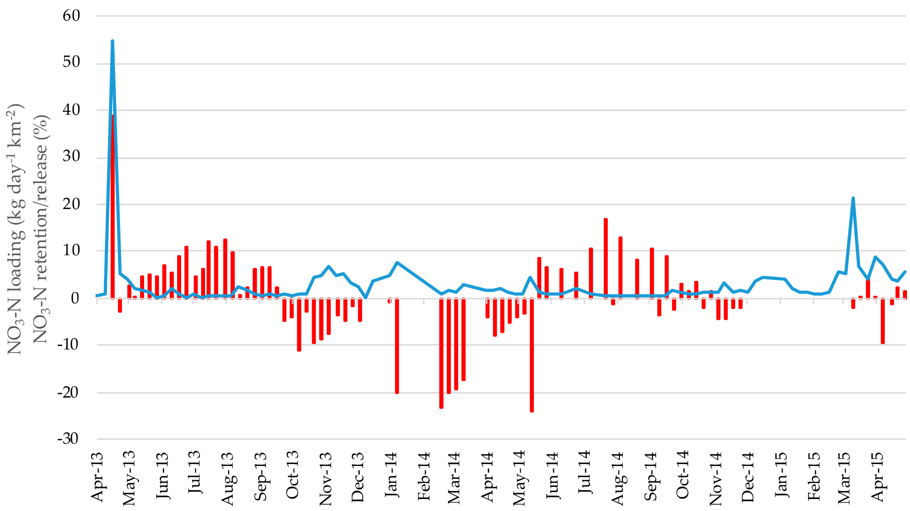

Figure 5. NO_3-N loading (blue line) from the Koiransuolenoja stream watershed, as well as NO_3-N retention (positive) or release (negative) (red columns) in the constructed pond system from April 2013 to April 2015.

4. Discussion

Despite only 20 years of data, we found a statistically significant increasing trend in discharge during March and transport of nutrients in the study area. Pearson correlation analysis revealed that especially wintertime nutrient and DOC concentrations were sensitive to changes in weather. According to the analysis, the increased NO_3-N and PO_4-P loading during winters can be explained by changes in precipitation, discharge, and daily temperature. The results confirmed that mean annual precipitation and discharge are important factors contributing nutrient concentrations and delivery into recipient waters. Should winter and spring temperatures rise as predicted in the northern latitudes, it would mean increased nutrient loading and the need for even more efficient water protection measures in agricultural watersheds.

It should be kept in mind that water quality of a small stream can be very sensitive to rain and storm events compared with larger rivers [31,32]. Generally, in small streams, even short-term storm events can propagate an increase in discharge and a consequent increase in loading. Therefore, a middling increase in discharge may cause a rather dramatic increase in loading, if the nutrient concentrations remain at high level. Moreover, mild winters with unpredictable liquid rain events can cause rapid and high variability in the wintertime water quality and discharge. Recently, new sensor-based continuous monitoring methods have been found to be even more beneficial and more reliable in loading assessment when compared with sporadic water sampling [33].

Agricultural practices have not changed during the study period, though they vary annually to some extent depending on cultivation history, situation on the market, and weather conditions. In our study, the annual mean Tot-N and Tot-P loads were similar or lower compared with other long-term data from small agricultural watersheds in Finland [34,35]. The increasing PO_4-P concentration and loading in every season found in our data was a surprise. P fertilization in Finnish fields peaked in the 1980s, and it was estimated that the P content of the plough layer of fields had been doubled in the 1900s [36]. The increase of wintertime organic P and PO_4-P loading may refer to wetter soil with less oxygen, which would add P solubility into pore water from soil particles [37]. The question is, are we still measuring the legacy P from the 1980s, or are the soil processes changing due to higher winter temperatures, liquid rain, and wetter unfrozen soil, or perhaps both? In the case of increased soil organic matter mineralization, NH_4-N concentration would have likely also increased, which, however, was not found in this study; neither did we find any sign of elevated transport of dissolved organic compounds, which have been reported in several studies [38–40]. The issue of upward trend in long-term nutrient loading does need further investigation.

In recent decades, constructed wetlands and sedimentation ponds have been applied to remove excess nutrients and suspended solids from agricultural runoffs. Their nutrient removal efficiency has been highly variable [14,41–43], depending on the wetland surface area relative to the watershed area, as well as residence time of the water, which is dependent on the volume of the wetland relative to the runoff. In this study, the area of the sedimentation pond system was very small compared to most of the studied wetlands, but still our intensive data revealed clear retention of nutrients, especially in summertime, despite the leakage of nitrate in autumn and in winter when low temperatures slowed down the denitrification rate of sediment microbes [18]. Our results of P indicate that even a minor restoring effort of agricultural stream could decrease, at least periodically, P loading to recipient aquatic ecosystems. The sedimentation pond removed a substantial amount of suspended material, which is important, especially in the long-term, as agricultural catchments are sensitive to erosion and shallow shore areas will be filled up.

If major hydrological changes take place in the future with a higher proportion of annual runoff in winter, it will be challenging to the efficiency of constructed wetlands in the North, especially to remove N. The existing knowledge and the size recommendations (0.5–2% of the watershed area) for efficient wetlands for Finnish latitudes have been available [44], but their implementation in practice has been challenging [45]. In addition, weather-driven control in discharge and nutrient loss from arable fields has been recognized [30,46], thus the need for better economic support and construction policy for larger wetlands arises even more under the warming climate. In our study, the pond area corresponded only to 0.027% of the watershed area and removed a high percentage of particulate matter from the inflow to the lake. This is contradictory to the recommendations, and in this way the finding is novel. In addition, given the ownerships of Finnish agricultural land with their predominantly small and medium-sized fields, it may be unrealistic to assume that the farmers are willing to build larger sedimentation ponds and wetlands to reduce loading from agricultural fields, at least without sufficient economic compensation. Nevertheless, sedimentation ponds and smaller wetlands can provide ecosystem services under future climatic conditions and need to be included in the important management methods in reducing loading from boreal agricultural lands.

To fill the large data gap concerning the response of boreal and arctic environments to climate change, it has been emphasized to use frequent sampling conducted also during the periods after the plant senescence and before snowmelt [47]. Based on our frequent, year-round water sampling, nutrient transport has changed in the long run, as increasing trends in annual concentrations in the stream water were found for nitrate, phosphate, total phosphorus, and total nitrogen. No changes in annual air temperature or precipitation were found; however, we detected an increase in monthly discharge in March during the study period 2001–2020. Annually, nutrient loading has indeed increased for total phosphorus, phosphate, and nitrate. Seasonally, winter was the time we found elevated nutrient loading for most of the nutrient fractions, which suggests that wintertime nutrient loading from agricultural areas in Finland is increasing. Traditionally, wintertime nutrient loading has been low due to freezing of soil. Now, increasing wintertime loading might have unknown effects on the conditions in the receiving boreal waterbodies. For example, we do not know if P is sedimented before the spring bloom, or if the higher availability of NO_3-N will result in increased emissions of greenhouse gas nitrous oxide N_2O under cold conditions. Finally, we recommend the construction of smaller ponds and wetlands as well, as they decrease loading into recipient waters with their individual potential. We need to harness all the available retention potential into use to protect the shallow Finnish waters.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/10/2731/s1. Table S1: Seasonal minimum, maximum, mean, and standard deviation in air and stream water temperature, precipitation, discharge, and nutrient concentrations 2001–2020, Table S2: Pearson correlation matrix for weather and nutrient concentrations during each season in the Koiransuolenoja stream 2001–2020.

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