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NUTRIENT BALANCE FROM AGRICULTURAL POLLUTION SOURCES ON SELECTED TRIBUTARIES TO THE ŠVIHOV RESERVOIR

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Abstract

Agriculture is the leading source of non-point sources of water pollution, especially in terms of the runoff process. Agricultural management promotes extensive water contamination, soil erosion and sedimentation in streams and reservoirs. The water reservoir Švihov on the Želivka river supplies drinking water to more than 1.5 million people. The catchment area of the water supply reservoir is intensively used for agriculture, more than 55% of the catchment area is arable land. Nutrients such as phosphorus and nitrates in the upper water-ways of tributaries are a huge problem. The aim of the research is to evaluate concentration trends and losses of nutrients (nitrates and phosphorus) at the chosen tributaries to the Švihov reservoir during 2018–2021. From the data on monthly concentrations and monthly discharges the monthly and annual losses of nitrates and phosphorus on each profile were calculated. The effect of discharges and concentrations on the magnitude of losses was investigated by correlation analysis. The influence of the forebay Trnávka dam on the magnitude of nutrient losses was also evaluated. The results show the importance of discharge magnitude on nutrient losses. The Trnávka forebay dam significantly reduces the transport of phosphorus from the Trnava catchment to the Švihov reservoir. In the catchment area of the reservoir it is recommended to implement nature-friendly and technical measures for water retention and accumulation in the landscape in order to reduce nutrient transport.

Keywords: phosphorus, nitrates, discharge, losses, agriculture, non-point sources, water retention

INTRODUCTION

Pollution of water sources can be divided into point, non-point – diffuse. Point pollution is continuous or recurrent, is not significantly influenced by meteorological factors and is linked to a narrowly defined area such as settlements, wastewater treatment plants, industrial plants, agricultural facilities, etc. Non-point pollution is difficult to monitor, irregular and dependent on meteorological, soil, morphological and vegetation characteristics. The decisive contribution of soluble reactive phosphorus in point sources is well documented by a study of wastewater treatment plants in the Kennet-England catchment (Neal *et al.*, 2005). The high representation of dissolved phosphorus beneath municipal wastewater treatment plants is documented by a number of studies (Millier and Hood, 2011; Krása *et al.*, 2013).

Intensive anthropogenic pressure such as high inputs of nutrients and pesticides severely threaten most European water bodies (Warner *et al.*, 2021; Kalinowska *et al.*, 2020). Agriculture is the leading source of non-point sources of water pollution (Ribaudo and Johansson, 2020), especially in terms of the runoff process (Ross *et al.*, 2022; Zajíček *et al.*, 2018). The characteristics and significance of the first-flush from agricultural areas have been studied by Obermanna *et al.* (2009). United States Geological Survey has found that high concentration of nitrogen in agricultural streams are correlated with nitrogen inputs form fertilizers and manure used on crops and form livestock waste (Ribaudo and Johansson, 2010).

Nitrogen and phosphorus are nutrients that significantly influence primary production (Elser *et al.*, 2007). It can be concluded that pollution of surface and groundwater by nitrogen comes mainly from area sources, while for phosphorus, point sources of pollution predominate. Fiala (2016) states that currently in the Czech Republic about 70% of active phosphorus comes from point sources (mainly wastewater), while for nitrogen it is only 20%.

Critical concentrations of total phosphorus from the perspective of eutrophication (10–20 $\mu g.l^{-1}$) tend to be lower than the soil phosphorus content required for successful growth of crops (200–300 $\mu g.l^{-1}$) (Kvítek *et al.,* 2017). On the contrary, its concentration, which is critical in terms of eutrophication, is usually an order of magnitude lower in the surface water (Fučík, Kaplická and Zajíček, 2009). The eutrophication continues to be a concerning global water quality problem (Ross, 2022). Phosphorus is commonly the limiting nutrient of biomass and algal growth in freshwater systems (Loague and Corwin, 2006).

Agriculture is considered a relatively large non-point P source, as continual applications of mineral fertilizer and manure can exceed P uptake by crops, leading to accumulation in soils that can be trans-ported to surface waters in runoff (Maccoux *et al.*, 2016; Robertson and Saad, 2011). The nature of P sources and mobilization from agricultural land entails significant losses during runoff events initiated by rainfall, snowmelt, or rain-on-snow that can account for most of the annual P budget (Long *et al.*, 2015). In particular, extreme runoff events have a significant impact on the transport of pollutants to surface waters. Ross (2022) for example states, as few as three events per year were found to be responsible for nearly half of total phosphorus (20–50%) and total dissolved phosphorus (14–44%) losses.

Although there is no single European regulation or directive focused on phosphorus, some European Member States are dealing with phosphorus losses from agricultural sources through national or regional legislation. The approach of countries or regions varies greatly: e.g. the width of the protection zone along watercourses (0.5–500 m) and the reduction of fertilization - from no phosphorus regulation to a strict maximum phosphorus dose (Amery and Schoumans, 2014).

Kronvang *et al.* (2005) indicated that approximately 80% of nitrate contamination of surface water is due to non-point sources of pollution. The risk of nitrate leaching is primarily reduced by reducing the fertilizer and changing the irrigation methods (Lazicki and Geisseler, 2017). Soil properties, organic material content in soil, type of cultivated crops, land use, hydrological (especially precipitation quantity, intensity, distribution during the year) and climatic characteristics also significantly affect nitrate leaching (Nemčić-Jurec and Jazbec, 2017; Kvítek *et al.*, 2009). The total amount of nitrogen that leaches from agricultural lands is estimated to be between 5% and 25% from the applied amount, even though some authors state higher coefficients, e.g. from 30% to 50% (Eugercios Silva *et al.*, 2017). The key factor determining the intake of nutrients by plants is also the availability of microelements and macroelements in soil, in particular the weight ratio between elements (Lawniczak *et al.*, 2016).

The need to reduce the negative impact of agriculture on water quality also follows from Council Directive 91/676/EEC (the Nitrate Directive) concerning the protection of waters against pollution by nitrates from agricultural sources. Methodology according to Klír and Kozlovská (2016) includes the principles of good agricultural practice for the protection of water against pollution by nitrates from agricultural sources.

The aim of the research is to evaluate concentration trends and losses of nutrients at the chosen tributaries to the Švihov reservoir in Czech Republic. In addition, to verify whether the concentration of the substance in the water or the value of the discharge has a greater influence on the magnitude of the losses of phosphorus and nitrates. Another objective is to evaluate the effect of the sedimentation Trnávka reservoir on nutrient transport. On the basis of the results, propose appropriate measures in the catchment area above the reservoir.

MATERIALS AND METHODS

Study Area

The water supply reservoir of Švihov on the Želivka river (hereinafter Želivka) was built between 1965–1975 and the catchment area of the dam is 1178 km^2 (Fig. 1). The main purpose of the system is to supply water to more than 1.5 million people. It is the largest water supply reservoir not only in the Czech Republic but also in Central Europe (Kvítek *et al.,* 2017).

The quality of water in the water supply reservoir, however, has been burdened by pollution from point and non-point sources for many years. The catchment area of the water supply reservoir is intensively used for agriculture (more than 55% of the catchment area of the Švihov river catchment is arable land) in the form of potato crops, winter rape, wheat, malt barley, silage corn, red clover, poppies, and grasses for seed (Oppeltová *et al.*, 2021). Agriculture promotes extensive soil erosion and subsequent sedimentation in streams and reservoirs (Liška *et al.*, 2016).

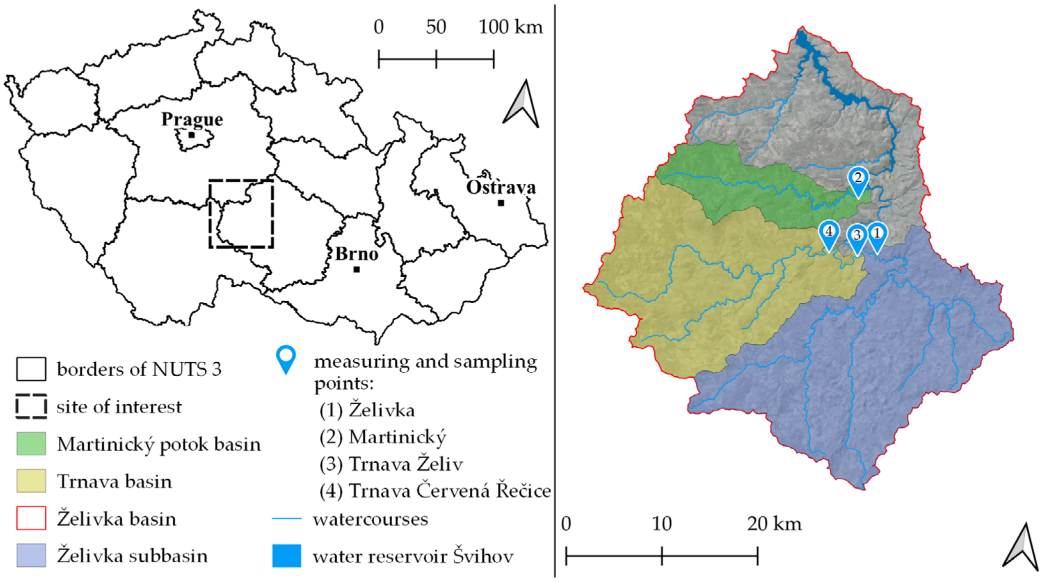
The most significant point sources of pollution are wastewater discharged into watercourses from waste water treatment plants or directly from sewerage systems. In the entire catchment area of the Švihov River on Želivka, wastewater treatment plants have been built over the years in all municipalities with a population equivalent of over 500 and some of them have already been gradually intensified. The new treatment plants and some of the older intensified ones have technology for increased biological elimination of nitrogen and phosphorus with the possibility of chemical precipitation of phosphorus (Liška *et al.*, 2016). For the largest industrial source of organic pollution in the catchment (CEREPA paper mill), an efficient mechanical treatment with biological aftertreatment stage and recirculation of process water has been built during the last years. Wastewater disposal in municipalities smaller than 500 population equivalent is faced with a lack of financial resources for the construction of sewage systems and treatment plants, and the proposed project solutions are therefore often adapted to the economic situation of the municipalities (Liška *et al.*, 2016).

The water supply reservoir has a specified protection zone and its extent and regime have been a long-discussed topic (Oppeltová *et al.*, 2021). However, the historic development of this problem is not the focus of the article.

The catchment area of the Švihov includes the following reservoirs: the Němčice reservoir on the Sedlice river, the Trnávka reservoir on the Trnava river and the Sedlice and Vřesník reservoirs on the Želivka river (Kvítek *et al.*, 2017).

A detailed analysis of the development of concentrations and losses of nutrients (phosphorus and nitrates) for the period 2018–2021 was carried out on three tributaries to the Švihov reservoir. These are the profiles Želivka river (hereafter Želivka), Martinický brook (hereafter Martinický) and Trnava – Želiv river (hereafter Trnava) (Fig. 1). The Trnava and Martinický are important left-side tributaries of the Želivka. The Želivka profile represents the water quality of several water bodies before the Trnava flows into the Želivka (i.e. the quality here is not affected by the inflow from the Trnava).

In order to express the influence of the Trnávka sedimentation reservoir on the phosphorus and nitrates balance, the discharges and concentrations at the Trnava - Červená Řečice profile on 8.8 river km were purchased and analysed, i.e. before the sedimentation reservoir.



1: *Area of interest, location of measuring and sampling profiles*

I: *Catchment characteristics and identification of water bodies*

Sampling profiles /parameters	Identification of water body	Catchment area	Agricultur land area	Arable land	Arable land from agricultural land	Average slope on arable land
Units		km²	km²	km²	%	%
Želivka	DLV_0330, 0340, 0350, 0360,0370	436.00	255.01	164.13	64.36	6.75
Martinický	DLV_0440	115.10	71.74	53.60	74.71	6.34
Trnava	DLV_0380, 0390, 0400	340.59	202.58	150.94	74.51	6.58

Source: Kvítek, 2017

The Trnava (Fig. 1) is the most important tributary to the Želivka in terms of catchment area, its length is 53.8 km and the shape of the catchment area is fan-shaped ($\alpha = 0.47$). The Trnávka reservoir was built here immediately before the confluence with the Želivka. There is a high proportion of arable land (Tab. I), the sampling profile Trnava Želiv is located at 0.6 river km (Kvítek *et al.* 2017).

The Martinický (Fig. 2) is 35.9 km long and the shape of the catchment is elongated ($\alpha = 0.24$). The catchment is characterised by low retention in reservoirs, with only a few ponds. At the same time, there is a high percentage of arable land, the sampling profile is located at 2.1 river km.

Sampling profile Želivka represents the water quality from several water bodies (Tab. I). In the upper part of Želivka catchment there is minimal retention, but there is a lower percentage of arable land. In the catchment of Bělá river there is also low water retention, but there are higher slopes of arable land. The Jankovský brook is one of the cleanest tributaries in the Švihov reservoir catchment.

Methodology and Data

Data on monthly concentrations of nitrates (NO^{3-}), phosphorus total (P_{total}) and orthophosphates ($P\text{-}PO_4^{III-}$) from the Želivka-Poříčí, Martinický, Trnava-Želiv (Trnava Ž.) and Trnava - Červená Řečice (Trnava Č. Ř.) sampling profiles (Fig. 1) for the period 2018–2021 were purchased from the Povodí Vltavy, state enterprise. Data on average monthly discharges at the monitored measuring profiles for the period 2018–2021 were purchased from the Czech Hydrometeorological Institute.

Data on average monthly temperature and monthly sum of precipitation 2018–2021 in the Hořice meteorological station were measured by Potato Research Institute Havlíčkův Brod, Ltd. (Tab. II, III).

In waters, are analysed mainly total phosphorus, orthophosphates and phosphorus bound in hydrolysable phosphates (polyphosphates and organophosphorus compounds). For all quality trend analyses and statistical evaluations, soluble reactive phosphorus ($P\text{-}PO_4^{III-}$), which primarily represents point sources of pollution, was subtracted from total phosphorus on all sampling profiles (Pitter, 2015). All results then represent a $P\text{-}PO_4^{III-}$ free value and are referred to as $P_{particulate}$ (P_p). According to Pitter (2015), the conversion of 1 mg PO_4^{III-} = 0.326 mg P was used. P_p concentrations show phosphorus values without the influence of point sources, only the influence of non-point sources i.e. mainly agriculture.

Sampling profile Želivka Poříčí is located at 50.6 river km, i.e. after the outfall of Trnava into Želivka. In order to assess the quality of water flowing through the Želivka without the influence of the Trnava tributary, the discharges and losses on the Želivka profile were subtracted from the discharges and losses on the Trnava Želiv profile. This resulted in values of individual parameters that represent the water quality of the water flowing through the Želivka (Fig. 1). In all results and analyses, the Želivka profile represents the values without the influence of the Trnava.

II: *Sum of monthly precipitation and sum of year precipitation 2018–2021*

Yaer	2018	2019	2020	2021
Month	Monthly precipitatation	Monthly precipitatation	Monthly precipitatation	Monthly precipitatation
Unit	mm	mm	mm	mm
January	18.9	59.2	25.6	34.2
February	24.6	28.7	66.2	33.0
March	21.6	53.5	45.4	17.2
April	14.0	13.1	17.6	30.6
May	64.0	132.0	83.6	110.7
Juny	79.7	57.9	181.5	79.9
July	12.7	103.4	68.8	143.7
August	49.0	76.3	108.3	71.3
September	100.7	13.9	61.4	16.5
October	41.8	44.1	82.9	15.1
November	17.9	57.3	36.2	29.9
December	71.7	35.2	14.2	39.0
Sum	**516.6**	**674.6**	**791.7**	**621.1**

Source: Potato Research Institute Havlíčkův Brod, Ltd.

III: *Monthly and year average air temperature 2018–2021*

	2018	2019	2020	2021
Month	Monthly average air temperature	Monthly average air temperature	Monthly average air temperature	Monthly average air temperature
Unit	°C	°C	°C	°C
January	1.8	-1.5	0.8	-1.1
February	-3.1	1.8	4.2	-0.1
March	0.7	5.4	4.4	2.7
April	12.8	8.9	9.4	5.2
May	16.1	10.6	10.7	10.1
Juny	17.1	18.8	15.8	18.7
July	19.7	18.4	17.7	18.5
August	21.0	18.5	18.9	16.0
September	14.7	13.1	14.3	14.6
October	10.2	9.1	8.9	8.2
November	4.7	5.9	3.9	3.4
December	1.2	1.5	1.8	0.3
Average	**9.8**	**9.2**	**9.2**	**8.0**

Source: Potato Research Institute Havlíčkův Brod, Ltd.

The evolution of the concentrations of the monitored indicators was evaluated chronologically over the monitored period, the evolution was expressed by a linear trend line.

In addition, monthly average of nitrates and P_p concentrations were calculated for individual months for the period 2018–2021, where the trend was expressed as a polynomial trend line using Microsoft Excel.

Like the substance concentrations, the discharges were evaluated chronologically and average discharge for each month and year were calculated, including a polynomial trend line.

From the data on monthly concentration ($mg.l^{-1}$) and average monthly discharge ($m^3.s^{-1}$), the monthly losses (kg or metric ton) of each of the monitored substances on each profile (Želivka, Martinický and Trnava Želiv) was further calculated. The evolution of the losses of the monitored parameters was evaluated chronologically for the monitoring period 2018–2021, the evolution was expressed by a linear trend line.

Subsequently, monthly average of losses for each month for the period 2018–2021 was calculated and the losses trend was expressed as a polynomial trend line, again using Microsoft Excel.

The influence of the explanatory variables, i.e. discharge ($m^3.s^{-1}$) from the catchment and pollutant concentration ($mg.l^{-1}$) on the explanatory variable, i.e. pollutant losses from the catchment (kg or metric ton), was investigated using correlation analysis in Microsoft Excel.

In order to evaluate the influence of the forebay dam Trnávka on water quality and nutrient losses, the annual losses balance was also calculated for the Trnava Červená Řečice profile and the results were processed graphically. The difference in the balance between the profiles Trnava Červená Řečice and Trnava Želiv show the influence of forebay dam Trnávka.

Finally specific losses per hectare from arable land were calculated for all sampling profiles.

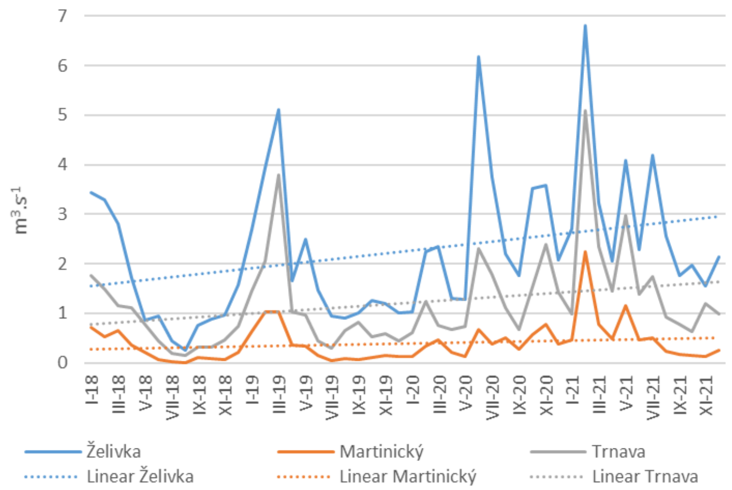
RESULTS

Discharge Trends

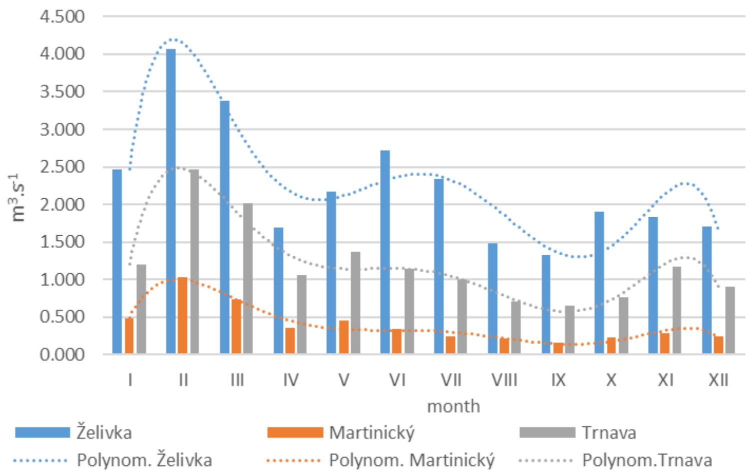
There is an increasing trend of discharge on all monitored profiles in the period 2018–2021, most significantly on the Želivka profile (Fig. 2). The highest discharge in the monitored period was measured on the Želivka profile. On all streams, the maximum discharges were in the winter months. The high discharge in 2020 and 2021 was also in the summer period, which was probably caused by heavy rainfall (Tab. II).

The four-year period of observation includes both hydrologically extreme years. In 2018 there were low precipitation and discharges and in 2020, 2021 significant precipitation and discharges occurred (Tab. II, IV). The lowest discharge during the entire study period was on the Martinický profile.

Monthly average of discharge and polynomal trend is similar on all profiles. As mentioned above, peak discharges were in February on all profiles, with further peaks in May/June and November/December (Fig. 3). The results for the period of record refute the assumptions of winters with insufficient rainfall and declining water supplies



2: *Chronological development of monthly discharge on monitored profiles during 2018–2021 with linear trend*



3: *Monthly average of discharge and polynomial trend on measuring profiles during the period 2018–2021*

IV: *Average annual discharges and annual specific discharges during 2018–2021*

	Želivka discharge	Želivka spec. disch.	Martinický discharge	Martinický spec. disch.	Trnava Č.Ř. discharge	Trnava Č.Ř. spec. disch.	Trnava Ž. discharge	Trnava Ž. spec. disch.
year	$m^3 s^{-1}$	$l.s^{-1}.km^{-2}$	$m^3 s^{-1}$	$l.s^{-1}.km^{-2}$	$m^3 s^{-1}$	$l.s^{-1}.km^{-2}$	$m^3 s^{-1}$	$l.s^{-1}.km^{-2}$
2018	1.495	3.429	0.251	2.181	0.738	2.324	0.744	2.184
2019	1.973	4.525	0.341	2.963	1.099	3.460	1.091	3.203
2020	2.609	5.984	0.405	3.519	1.262	3.974	1.271	3.732
2021	2.945	6.755	0.585	5.083	1.512	4.761	1.709	5.018

in the basin. On the contrary, three periods of abundant high discharge in February, June, and late November/early December are shown (Fig. 3). The lowest discharge is consistently at all profiles in September.

The average annual discharges and annual specific discharges have an increasing trend on all monitored profiles from 2018 to 2021 (Tab. IV). The highest annual discharge and annual specific discharge each year was on the Želivka profile, which has the highest slope on arable land in its catchment (Tab. I). From 2018 to 2020, the lowest annual specific discharge was on profile Martinicky, which has the lowest average slope on arable land. In the period 2018–2020, the annual discharge on the Trnava Červená Řečice and Trnava Želiv profiles was very similar (Tab. IV). However, in 2021 the annual discharge was higher on the Trnava Želiv profile, i.e. below the forebay dam Trnávka.

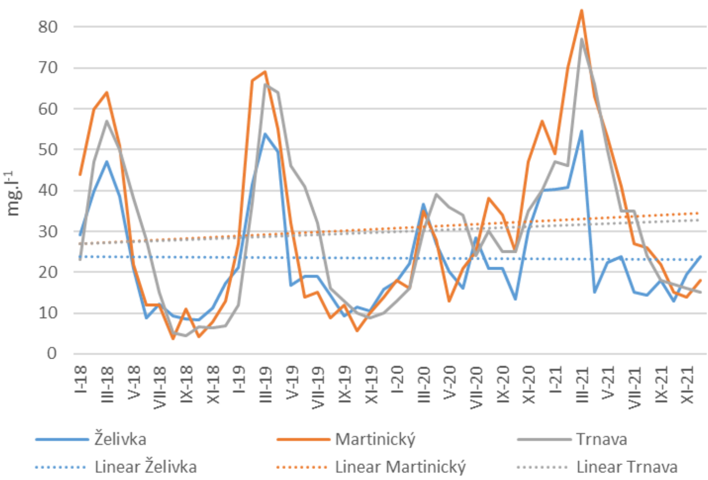
The reason for this was the increase in flows below the forebay dam due to the holding of boating competitions (May and September) and due to the increase in storage capacity for possible transformation of higher flows in the winter or spring (Povodí Vltavy, state enterprise, personal communication, September 2022).

Concentration Trends

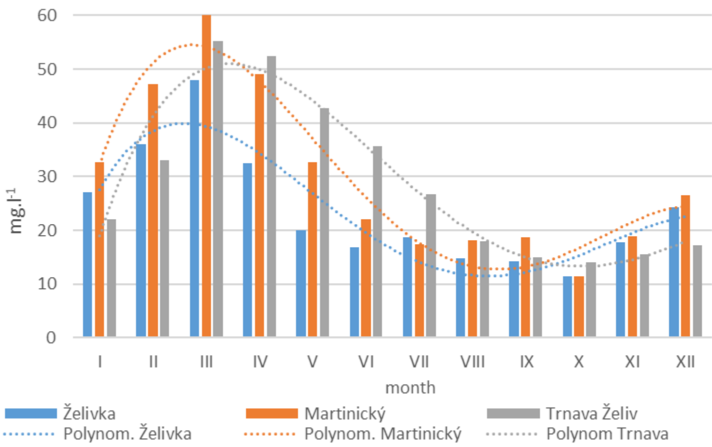
The results show a slightly increasing trend in nitrate concentration at all profiles for the period 2018–2021, with the Martinický and Trnava profiles showing a more pronounced increase than the Želivka profile (Fig. 4).

Maximum concentrations are monitored regularly in the spring period when nitrate is not consumed by vegetation (Johnson and Stets, 2020) and leached from the soil profile into surface waters (Fig. 4). The years 2018, 2019 and 2021 have a similar trend of concentrations, but in 2020 the maximum concentrations were significantly lower than the other years. According to information from Povodí Vltavy, state enterprise, in 2020, there was a high development of phytoplankton in all streams, which consumed nitrates. The strong correlation between nutrients and cyanobacteria biomass has been confirmed by a number of studies (Cremona *et al.*, 2018; Gil-Izquierdo *et al.*, 2021).

In March 2021, maximum nitrate concentrations were monitored on all profiles - on the Želivka profile they exceeded 50 mg.l^{-1}, on the Trnava profile 70 mg.l^{-1} and on the Martinický profile even 80 mg.l^{-1} (Fig. 4). On the Martinický and Trnava profiles, the maximum concentrations significantly exceeded the WHO drinking water limit (50 mg.l^{-1}). Želivka has about 10% lower concentrations, which are probably a consequence of the lower proportion of arable land in the catchment compared to Martinický and Trnava (Tab. I). Nitrate concentrations are lowest on all profiles in summer and autumn when they are consumed by vegetation.



4: *Chronological development of monthly nitrates concentration on monitored profiles during 2018–2021 with linear trend*

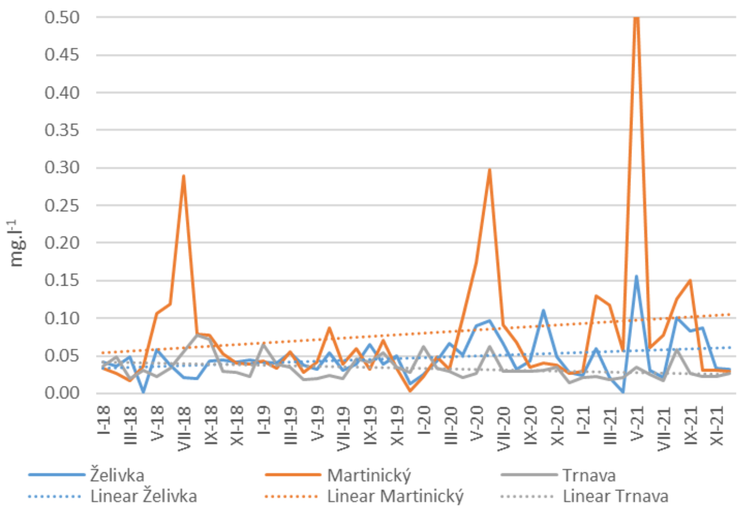


5: *Monthly average of nitrates concentration with polynomial trend on sampling profiles during the period 2018–2021*

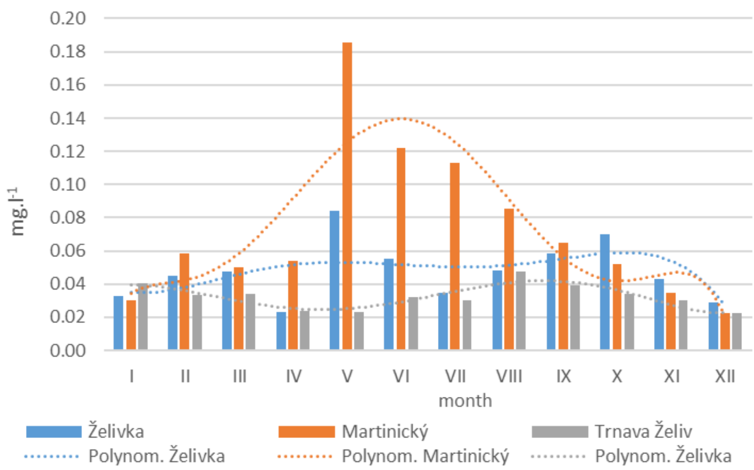
The monthly average of nitrate concentration in individual months and polynomial trend is identical for the Želivka and Martinický profiles, while it is slightly different for the Trnava profile (Fig. 5). The maximum nitrate concentrations tend to occur in the Želivka and Martinický profiles at the end of February and beginning of March, and in the Trnava profile at the end of April and beginning of May, which is probably due to the water retention time in the forebay of the Trnavka dam. The lowest concentrations on all profiles are in October, i.e. at the end of the growing season, when nitrates are consumed by vegetation.

The results of research in the Švihov reservoir catchment show that the dominant source of nitrate is agricultural (Kvítek, 2017). The majority of the Švihov reservoir catchment area is located in Nitrate vulnerable zones and therefore compliance with the principles and management practices set out in the Nitrate Directive is monitored. Even so, there is an increase in nitrate concentrations over the reporting period. These changes are likely to be due to the higher rainfall and its distribution in 2020–2021 (Tab. II) and hence increased leaching of applied nitrogen. The increase in nitrate concentrations and the exceedance of the 50 mg.l^{-1} limit (Fig. 4) is significant in terms of the water supply of the Švihov reservoir.

P_p concentrations show phosphorus values without the influence of point sources, only the influence of non-point sources i.e. mainly agriculture. The results show that the P_p concentration has an increasing trend over the period under study on all profiles (Fig. 6), most significantly on the Martinický profile. Clearly the highest P_p concentration for the period under study is on the Martinicky profile, where the maximum concentration in May 2021 was 0.554 mg.l^{-1}. Also in May 2018 and 2020, high concentrations of P_p were repeatedly measured on the Martinický profile



6: *Chronological development of P_p concentration on monitored profiles during 2018–2021 with linear trend*



7: *Monthly average of P_p concentration with polynomial trend on sampling profiles during the period 2018–2021*

(Fig. 6). On the other hand, the lowest values are mostly in Trnava profile, where the positive effect of the forebay dam Trnavaka is visible, where around 50% of P_p is captured (Tab. VII). The Želivka profile has higher dischages than the other profiles (Fig. 2), therefore pollution is more diluted here. However, also on the Želivka profile the influence of the forebay dams is visible. On the other hand, in the Martinický basin, water retention is minimal and P_p concentrations reach extremely high values (Fig. 6).

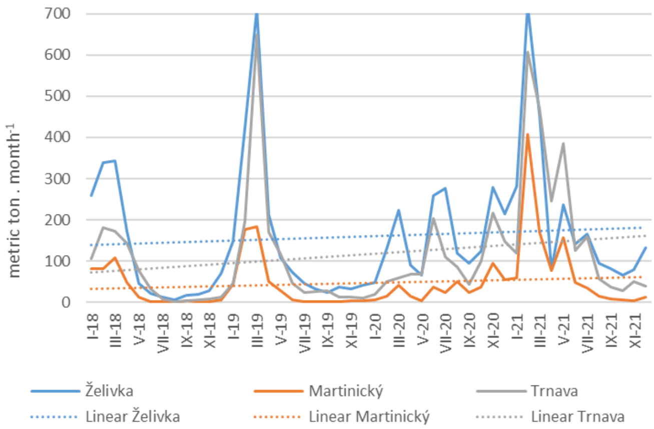
Monthly average of P_p concentration with polynomial trend in each month is different for each sampling profile (Fig. 7). The smallest month-to-month fluctuations are at Trnava profile, indicating a positive effect of the forebay Trnavka dam. On the contrary, the highest fluctuations are on profile Martinický, where the catchment is characterised by low retention in reservoirs and there is the highest proportion of arable land. On the Želivka and Martinický profiles the maximum P_p concentrations are in May, on the Trnava profile in August. The lowest concentrations on Želivka are in May, on Martinický and Trnava in December.

Losses Trends

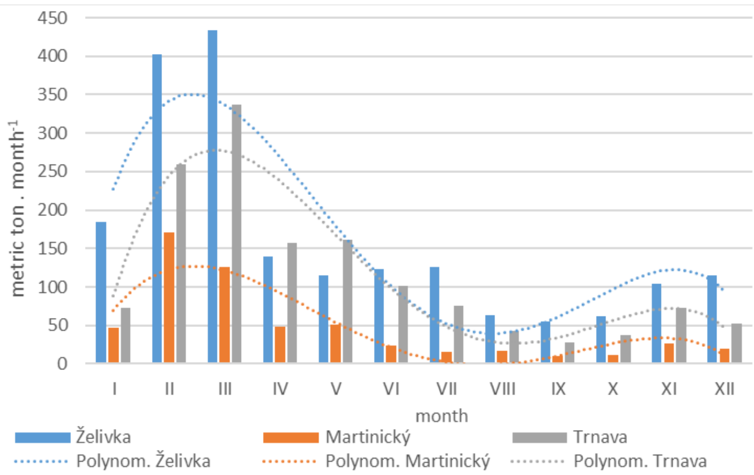
The trend in nitrate losses has a slightly increasing character on all profiles during the 2018–2021 study period (Fig. 8). This trend is consistent with the trend in discharge (Fig. 2).

The highest losses of nitrates were mostly on the Želivka profile. Maximum nitrate deposition was recorded on all profiles in February 2019 and 2021, when a combination of high discharges (Fig. 2) and concomitant high nitrate concentrations in winter months (Fig. 4) occurred. Compared to the other years, there are three fluctuations during the year (spring, summer, autumn) in 2020 (Fig. 8), with the highest loads correlating with discharge (Fig. 2). The minimum nitrate deposition in 2018, 2019, and 2021 are in the summer months, and these minima correlate with minimum concentrations (Fig. 4).

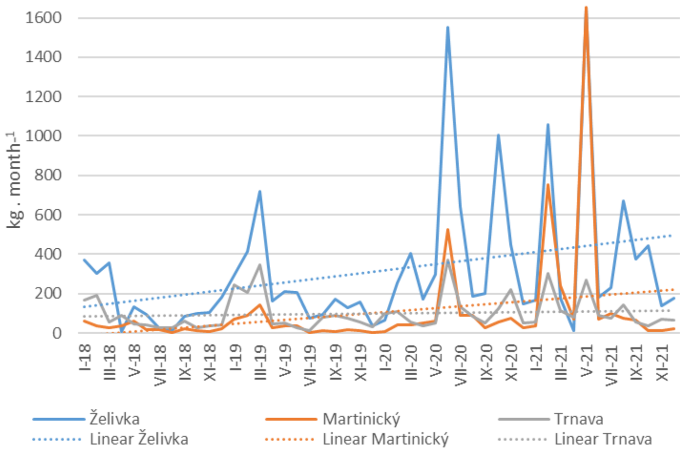
Monthly average of nitrates losses and polynomial trend is very similar on all profiles. On the Želivka and Trnava profiles the maximum nitrate losses are in March, on the Martinický profile in February (Fig. 9). This result reflects the water retention in the forebay dams on Želivka and Trnava. The lowest



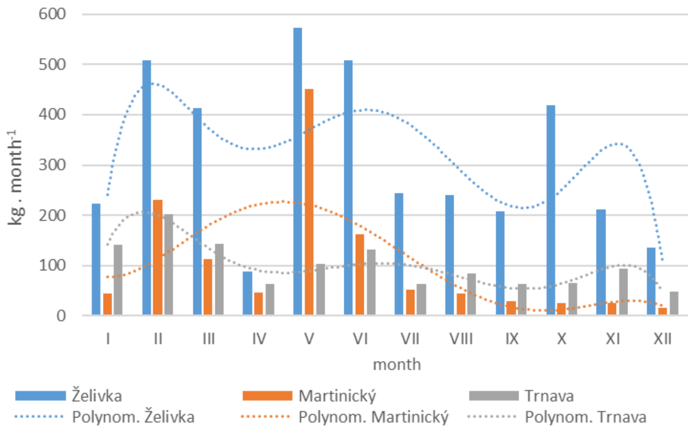
8: *Chronological development of nitrates losses on monitored profiles during 2018–2021 with linear trend*



9: *Monthly average of nitrates losses with polynomial trend on sampling profiles during the period 2018–2021*



10: *Chronological development of P_p losses on monitored profiles during 2018–2021 with linear trend*



11: *Monthly average of P_p losses with polynomial trend on sampling profiles during the period 2018–2021*

nitrate discharges are in September on all profiles monitored, which correlates with the minimum discharges (Fig. 3).

The results show that the P_p losses value has an increasing trend on all profiles during the period 2018–2021, most significantly on Želivka (Fig. 10). The highest peak was found on the Želivka profile in June 2020 and on the Martinický profile in May 2021, when a combination of high discharges (Fig. 2) and high P_p concentrations (Fig. 6) occurred. The losses in Trnava are significantly lower, showing the positive influence of the forebay dam. All profiles had higher P_p losses in hydrologically above-average years (Tab. II), thus again confirming the influence of discharge magnitude on losses. Maximum P_p losses (Fig. 10) are consistent with maximum discharges (Fig. 2). The highest discharge was found in May 2021 on the Martinický profile (Fig. 10), where the concentration was extremely high (Fig. 6) and the precipitations (Tab. II) and discharge (Fig. 2) were also higher. The lowest P_p losses during the study period were at all profiles in summer 2018, these values correlate with the minimum discharges (Fig. 2) and precipitation (Tab. II) for the period 2018–2021.

P_p monthly average losses are highly variable within months and between sampling profiles (Fig. 11). On the Želivka and Martinický profiles the maximum P_p loss was in May, on the Trnava profile in February. High loss in the winter months (Fig. 11) correlates with peak discharge in the same months (Fig. 3). The highest losses on the Želivka and Martinický profiles is in May, when the losses through the Martinický profile almost reaches the value of the losses in the Želivka profile. However, the discharges on the Želivka profile are approximately six times higher than the discharges on the Martinický profile (Tab. IV). The extremely high P_p losses values in May are due to the extreme concentrations in May 2018, 2020 and 2021 on the Martinický profile. The lowest discharges are on the Martinický and Trnava profiles in December, and on the Želivka profile in April.

The results of the correlation analysis (Tab. V) show that for nitrate, the correlations between losses and discharges and losses and concentrations are very similar on all profiles. The results confirm

V: *Correlation coefficients values: D = discharges; L = losses; C = concentrations*

Sampling profiles	Želivka		Martinický		Trnava	
Relationship between parameters	L x D	L x C	L x D	L x C	L x D	L x C
$P_{particulate}$	0.740	0.620	0.760	0.480	0.860	0.240
NO_3^-	0.890	0.820	0.983	0.864	0.897	0.845

the fact that both discharges and concentrations have a significant effect on nitrate transport, which has already been discussed above.

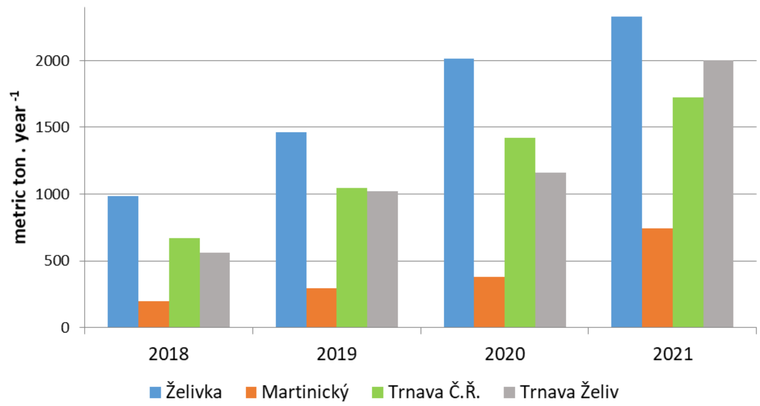
The results of the correlation analysis for P_p (Tab. V) show that discharge has a greater effect on losses than concentration. This is most pronounced on the Trnava profile, where the correlation coefficient is 0.86 between losses and discharge, and only 0.24 between losses and concentration. For the Želivka and Martinický profiles, this difference is not as pronounced; as mentioned above, on these profiles the discharge values were strongly influenced by extreme concentrations (Fig. 6), especially the Martinický profile.

The results show that nitrate annual losses were lowest on all profiles in the dry year 2018, but highest in 2021 (Fig. 12), when higher discharges (Fig. 2) and precipitation (Tab. II) occurred. These differences between 2018 and 2021 were approximately threefold, with total differences in the thousands of tons. In all years, the highest losses were on the Želivka profile (Fig. 12), which corresponds to the highest discharges (Tab. II). On the other hand, the lowest losses were every year on the Martinický profile, which again corresponds to the lowest discharges of all profiles monitored (Tab. IV).

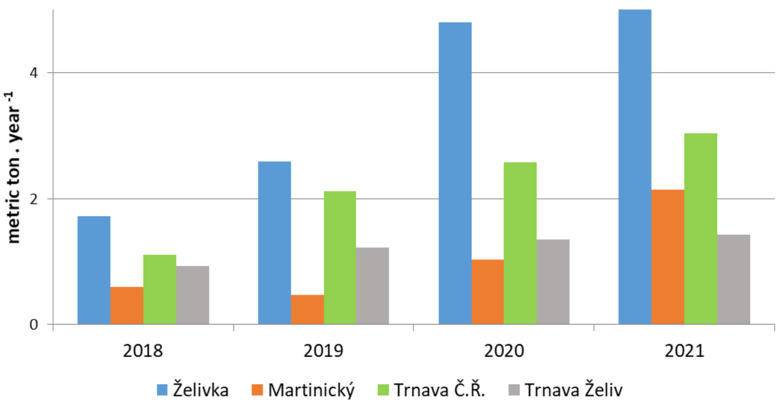
The highest nitrate losses over the whole period under study was on the Želivka profile, when 2326.6 metric ton of nitrate flowed through this profile in 2021. The lowest losses (200.6 metric ton) were on the Martinický profile in 2018 (Fig. 12).

In order to express the influence of the Trnávka forebay dam was the annual nitrate balance calculated for the Trnava Červená Řečice and Trnava Želiv profiles. The results show that the effect of the Trnávka forebay dam on nitrate transport was not demonstrated. This is because nitrate is dissolved in the water and flows out of the forebay dam, it is not bound in the sediment that is retained by the Trnávka forebay dam.

As with nitrate, results show (Fig. 13) that annual P_p balance was lower on all profiles in dry year 2018 (Tab. II, IV), and higher in hydrologically average



12: *Nitrates losses annual balance on sampling profiles during 2018–2021*



13: *P_p losses annual balance on sampling profiles during 2018–2021* or above average years (2020, 2021) (Fig. 13) when higher discharges (Fig. 2) and precipitation (Tab. II) occurred. These differences between 2018 and 2020, 2021 were up to threefold, with a total difference of about 3 metric ton on the Želivka profile, for example. The exception is the Trnava Želiv profile, i.e. behind the reservoir, where the differences between the dry year and the hydrologically above-average year were not as pronounced (Fig. 13) as on the other profiles, with only 0.5 metric ton difference between 2021 and 2018.

In all years, the highest P_p losses were on the Želivka profile (Fig. 13), which corresponds to the highest discharges (Tab. IV). On the contrary, the lowest P_p losses were in 2018–2020 on the Martinický profile, but in 2021 on the Trnava Želiv profile.

The highest loss of P_p for the whole period under study was on the Želivka profile, when 5.03 metric ton of P_p flowed through this profile in 2021. The lowest losses (0.47 metric ton) was on the Martinická profile in 2019 (Fig. 13).

For phosphorus, the positive influence of the forebay Trnávka dam is evident, as it captures high losses of P_p from the Trnava catchment (Fig. 13). Unlike nitrate, P_p is bound to the sediment that is retained in the reservoir. The influence of the forebay dam is more pronounced in years with higher discharges and precipitations (2020, 2021) than in the dry year 2018 (Tab. II, IV). From the average discharge above and below the forebay dam (Tab. IV), it can be seen that they are very similar, the P_p balance here is really influenced by the effect of capture in the forebay dam.

To compare the individual catchments with each other, nitrate specific losses and losses of P_p per hectare of arable land ($kg.year^{-1}.ha^{-1}$) were calculated (Tab. VI, VII). The results show that the magnitude of specific losses is significantly influenced by the value of discharge - in the dry year 2018, both nitrate specific losses and P_p losses are significantly lower than in 2020 and 2021 (Tab. VI, VII), when both precipitation (Tab. II) and discharge (Tab. IV) were higher.

VI: *Nitrates specific losses from arable land on sampling profiles in 2018–2021 [$kg.year^{-1}.ha^{-1}$]*

Sampling profile	2018	2019	2020	2021
Želivka	60,1	89.1	122.7	141.8
Martinický	37.4	55.0	70.8	138.3
Trnava Č.Ř.	44.5	69.3	94.3	114.3
Trnava Ž.	37.2	67.6	76.8	132.7

VII: *P_p specific losses from arable land on sampling profiles in 2018–2021 [$kg.year^{-1}.ha^{-1}$]*

Sampling profile	2018	2019	2020	2021
Želivka	0.105	0.158	0.292	0.307
Martinický	0.113	0.088	0.193	0.400
Trnava Č.Ř.	0.074	0.140	0.171	0.202
Trnava Ž.	0.062	0.081	0.089	0.094

The specific nitrate loss was highest in each year on the sampling profile Želivka (Tab. VI), where is the highest average slope on arable land (Tab. I) and specific discharge (Tab. IV). On the Trnava Červená Řečice profile the specific nitrate losses are slightly higher than on the Trnava Želiv profile. The exception is the year 2021, when the specific loss on the Trnava Želiv profile (i.e. below the forebay dam) is higher than the specific loss on the Trnava Červená Řečice profile (Tab. VI). This result clearly confirms the importance of the magnitude of discharge on the magnitude of losses.

In 2018–2020, the discharges above and below the Trnava forebay dam are the same (Tab. IV), but in 2021, the reservoir discharged slightly more water and there is a higher discharge below the reservoir (profile Trnava Želiv) than above the reservoir (profile Trnava Č.Ř) (Tab. IV). At the same time, in 2018–2020 the nitrate concentration was always higher above the reservoir, but in 2021 it was higher below the reservoir from March to August - i.e. on the Trnava Želiv profile.

The highest specific losses of P_p from arable land was in 2021 at Martinický profile (0.4 $kg.year^{-1}.ha^{-1}$). High specific P_p losses were also observed on the Želivka profile (Tab. VII). The lowest specific P_p losses were every year on the Trnava Želiv profile, i.e. behind forebay dam.

After comparing all four years, the results show that the lowest specific P_p losses were in the dry year 2018 (Tab. II, IV) among all the catchments, while the highest was in the hydrologically above-average year 2021. The exception is Martinický profile, where the specific P_p loss was lower in 2019 than in 2018. This is due to low P_p concentrations in 2018 (Fig. 6).

The values of specific P_p losses indicate the high importance of the Trnávka forebay dam in relation to the reduction of phosphorus pollution of the Švihov reservoir. This effect is most pronounced in years with high discharge and rainfall (Tab. II, IV), where in 2021 the forebay dam captured 53% of the P_p, whereas in the dry year 2018 it was only 14%.

DISCUSSION

The above results show that the magnitude of nutrient losses from the catchment is influenced not only by the concentration levels of the monitored substances, but especially by the discharge values and the existence of the sedimentation reservoir. At the same time, it can be shown that it is a combination of the influence of several factors: ploughing, slope, discharge, rainfall and crop representation. In the European and US risk assessment framework, surface runoff is used for the estimation of potential risks for the aquatic environment, i.e. for surface water bodies adjacent to agricultural fields (Sittig *et al.*, 2020).

Therefore, it is important to implement not only measures on arable land that directly reduce the total amount of nutrients applied (reducing fertiliser rates, not fertilising to stock, precision farming, crop rotation, inclusion of intercrops, etc.) (Hanrahan *et al.*, 2021; Iho and Laukkanen, 2012), but also measures that reduce surface and subsurface runoff. By increasing water retention, the residence time of water in the soil and rock environment will increase, thus nutrients can be captured and reduced, erosive runoff and discharge from the catchment can be reduced. In the Švihov reservoir catchment, it is recommended to increase water retention on agricultural land, reduce the volume and rate of runoff on arable land, thereby reducing erosion, increasing water quality through infiltration and eliminating eutrophication of surface waters, including the Švihov reservoir (Kvítek, 2017). Mamun *et al.* (2020), in relation to nutrient reduction in surface waters, highlights the high importance of reducing surface runoff in small sub-catchments. It is also considered that 80% of the pollution load can be captured by capturing 30% of the runoff volume, which is assumed to be due to first-flush of the storm event. Vejchar *et al.* (2019) state that changing agricultural technology for wide-row crops can reduce the surface runoff on sloping land. Also, crop rotation under organic farming significantly reduces nitrate leaching compared to conventional farming (Biernat *et al.*, 2020).

It should be stressed that measures to increase water retention are meant to be measures in the landscape, not just measures in watercourses. In the catchment area of the Švihov reservoir, it would be appropriate to combine nature-friendly and technical measures on arable land; the interconnection of these is very important. The nature-friendly measures include grassed infiltration areas, wetlands, afforestation, while the technical measures include detention swales and ditches, dry basins, ponds and reservoirs. The positive effect of grassed infiltration areas on improving water quality has been reported in a number of studies and researches not only in the Czech Republic (Zajíček *et al.*, 2013), as well as abroad (Ramler *et al.*, 2020; Glavan *et al.*, 2020). A vegetated buffer, barrier, or filter strip is a parcel of land that is designated to separate land used for agriculture from valued aquatic or terrestrial habitats. It exists partly with the intent to diffuse runoff and to impeded sediment, nutrients, pesticides, and other constituents from reaching off-site surface waters (Genea *et al.*, 2019). Parameters of vegetated buffer strips (width, slope) runoff intensity, soil composition, plant community can influence the efficacy of vegetated buffers in nutrient retention (Prosser *et al.*, 2020).

Targeted measures at specific problematic - critical sites in the Švihov reservoir catchment are very important (Kvítek, 2017) and furthermore Konečná *et al.* (2018) characterizes critical source areas as enclaves where elevated nutrient (nitrogen or phosphorus) concentrations in the soil intersect with high potential for formation or pathways of rapid surface or subsurface runoff and are considered dominant contributors to area sources of water pollution.

In order for the system of measures to work well, it is clear from the results that surface and groundwater quality can also be addressed to a large extent through water retention in the catchment, on agricultural land (Kvítek, 2017). This is where water flows away from, so it needs to be retained here as well. Martínková *et al.* (2018) states, that the agricultural land-use change influenced positively the discharge at the outlet of the catchment. The change of land-use represents the conversion of all catchment arable land, situated on coarse-textured, shallow and leaching-prone soils to grassland. This leads to 25% reduction of arable land.

The aim of retention and accumulation measures is to ensure that even under extreme hydrological conditions, surface water and groundwater flow out of agricultural catchments in good quality and in harmless quantities. The combined protection of water quantity and water quality, i.e. the application of the concepts of water retention and accumulation on agricultural land to agricultural practice, could then significantly reduce sediment loads on watercourses and reservoirs, significantly reduce soil water erosion, increase soil water accumulation and increase water accumulation in the catchment, partially address drought and flooding, and increase small groundwater sources, all at the same time (Kvítek, 2017).

Kvítek (2017) states that the following principles should be followed to increase retention in the catchment while improving water quality:

The runoff process should capture water on agricultural lands, preferably in their upper or middle portions of the sub-catchment where soils are permeable and the water table is at a greater depth. Linear engineering features (e.g. detention ditches, detention swales) with strips of permanent grassland are suitable for this purpose. Here, water infiltration and sedimentation of suspended solids must occur. These technical measures significantly reduce soil erosion and at the same time must have at least a passive runoff control system and a system of artificial infiltration of water into the hydrogeological structure so that water and sediment are not rapidly discharged into watercourses, ponds and reservoirs after capture. Bol *et al.* (2018) states that the headwater catchments are the right places to be to manage, monitor and reduce diffuse phosphorus emissions.

A follow-up measure must be the transformation and utilisation of nutrients and trapped substances in grassland, in the soil profile, in wetlands, in small water reservoirs, etc. This also applies to the requirements for the discharge and regulation of runoff from drainage systems (Kvítek, 2017). Martínez -Fernandez (2013) states that the use of wetlands for nutrient retention would reduce the amount of nutrients from diffuse sources by 40%. A study in Spain shows that the restoration and use of wetlands for nutrient retention is not only very effective, but that every 100 Euros invested contributes to the retention of 16.2 kg of nitrogen and 5.7 kg of phosphorus.

The water can then be stored for further use. Related to this is the issue of water reservoirs, ponds, water infiltration into the hydrogeological structure, various forms of irrigation, or other use of water by pumping it to the upper parts of the sub-catchments, where water can infiltrate under suitable conditions into the hydrogeological structure - artificial infiltration.

The results show that the construction of large sedimentation reservoirs just above the outfall of major tributaries to the reservoir is a very effective measure. The Trnávka forebay dam can reduce phosphorus pollution by up to 50% and protect the reservoir from pollution. Its importance increases in hydrologically above average years. These reservoir has a positive impact on the quality of surface water, as they largely capture sediment from the catchment area and prevent it from settling in the Švihov reservoir. Similar results have been reported by a number of international studies. Jossette (1999) states that the retention (or elimination) and export of nitrogen and phosphorus in three major reservoirs (France) represented about 40% of the incoming flux of nitrate and 60% of phosphate. The retention was lower for total phosphorus than for phosphate. On the other hand, managing retained sediment is problematic and financially difficult. Therefore, preventive measures to reduce surface runoff and losses in the catchment are very important.

A clear loss or retention of nitrogen and phosphorus was observed in the reservoirs and represented about 40% of the incoming flux of nitrate and 60% of phosphate. In particular, dam reservoirs sequester nutrient elements and, hence, reduce downstream transfer of nutrients to floodplains, lakes, wetlands, and coastal marine environments (Maavara *et al.*, 2015).

An important prerequisite for the implementation of measures to increase water retention and accumulation in the agricultural landscape is to increase the interest of agricultural entities in this issue and, above all, to motivate them, while at the same time changing the state subsidy policy. It would therefore be necessary to establish permanent surcharges for the non-productive functions of agriculture. It is important that the financial resources from the Common Agricultural Policy directed to the landscape water retention programme should be channelled directly to agricultural operators. These entities would be investors in nature-friendly and technical measures on agricultural land. In the public interest, farmers would be paid by the state or the EU to fulfil these non-productive functions of water, soil and landscape. Retention and storage measures are costly to implement, but they are socially advantageous when the society-wide effects and non-productive functions of agriculture are taken into account. Staccione *et al.* (2021) report that the investment costs of building retention basins in agricultural landscapes in Italy are justified and balanced by the ecosystem services and non-productive functions gained. Holden *et al.* (2017) states that the decisions involving agriculture and water need to be made based on a long-term perspective; with appreciation of the time (timescale of decades) it takes for policies to have sustained impact.

A questionnaire survey among farmers in the Czech Republic in 2015 confirmed the assumption that the awareness of the representatives of farming entities about the environmental impacts of agriculture is somewhat decreasing with the increase in the area of land blocks. This is related, among other things, to the continuing fact that large blocks of agricultural land in the Czech Republic, with monocultures of some crops, are essential for the generation of surface runoff, the effects of water erosion and the input of nutrients and pesticides into water (Fučík *et al.*, 2016). Experiences from Central and Northern Europe and the USA show that it is beneficial to take into account farmers' attitudes and practical knowledge in the setting of catchment or conservation landscape management (Heinz, 2008; Kalcic *et al.*, 2014). On the other hand, it also appears that it is necessary to deepen the awareness of our farmers about the non-productive functions and management options in the landscape, especially in terms of optimizing its water and nutrient regime (Fučík *et al.*, 2016).

Retention and accumulation measures significantly improve water quality, reduce soil erosion, reduce the risk of localised flooding, shorten agronomic and hydrological drought periods, raise the water table, increase soil water retention, increase water storage in the catchment, vegetation has a cooling effect, increase airborne CO_2 uptake and increase the vigour of shrubs and trees.

CONCLUSION

The main results of this article can be summarized in the following points:

- There is an increasing trend of discharge and annual specific discharge on all monitored profiles in the period 2018–2021, most significantly on the Želivka profile. The lowest discharge during the entire study period was on the Martinický profile. Peak discharges were in February on all profiles, with further peaks in May/June and November/December.
- The results show a slightly increasing trend in nitrate concentration at all profiles. Nitrate concentrations are lowest on all profiles in summer and autumn when they are consumed by vegetation. The increase in nitrate concentrations and the exceedance of the 50 $mg.l^{-1}$ limit is significant in terms of the water supply of the Švihov reservoir.
- The trend of monthly nitrate losses has a slightly increasing character on all profiles. This trend is consistent with the monthly trend in discharge. Maximum nitrate losses are in winter, the lowest in September.
- Correlation analysis show that for nitrate, the correlations between losses and discharges and losses and concentrations are very similar on all profiles. The results confirm the fact that both discharges and concentrations have a significant effect on nitrate transport.
- P_p concentration has an increasing trend on all profiles, most significantly on the Martinický profile.
- P_p monthly losses value has an increasing trend on all profiles, most significantly on Želivka. Maximum P_p losses and specific losses are influenced by the value of discharge. Also correlation analysis results for P_p show that discharge has a greater effect on losses than concentration. This is most pronounced on the Trnava profile, where the correlation coefficient is 0.86 between losses and discharge, and only 0.24 between losses and concentration.
- The values of specific P_p losses indicate the high importance of the Trnávka forebay dam in relation to the reduction of phosphorus pollution of the Švihov reservoir. This effect is most pronounced in years with high discharge and rainfall, where in 2021 the forebay dam captured 53% of the P_p, whereas in the dry year 2018 it was only 14%. Unlike nitrate, P_p is bound to the sediment that is retained in the reservoir. On the other hand, in the Martinický catchment, water retention is minimal and P_p concentrations and specific losses reach extremely high values.
- The results show that nitrate and P_p annual losses were lowest on all profiles in the dry year 2018, but highest in 2021, when higher discharges and precipitation occurred.
- This work evaluates the trends of discharges, concentrations and losses of nutrients in a four-year period. During this period, there were both extremes, years with significant precipitation on one side, as well as a year with low precipitation and discharge on the other side. Hydrologically extremes have a significant influence on the results. The four-year period is not about long-term trends, but rather evaluates the current state of hydrological extreme years.
- Due to increased water retention and accumulation in the catchment area of the Švihov reservoir, it would be appropriate to combine nature-friendly and technical measures on arable land. The aim of retention and accumulation measures is to ensure that even under extreme hydrological conditions, surface water discharge from agricultural catchments in good quality and in harmless quantities.

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