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Analysis of Selected Water Quality Indicators from Runoff during Potato Cultivation after Natural Precipitation

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Abstract: When growing wide-row crops on sloped lands, there is significant surface runoff. In relation to the runoff process, potatoes are classified as a risk crop. This study aimed to grow potatoes in the Bohemian-Moravian Highlands, where the protection zone of the water supply reservoir of Švihov is also located. At selected experimental areas, water samples were taken after precipitation events when surface runoff and water erosion occurred. These samples were analysed (nitrates, total P, and selected pesticides used for potato growing) in an accredited laboratory. We located three different variants of nitrogen fertilisation in each experimental area. Precipitation and the amount of water from surface runoff after each higher precipitation event were also measured in the experimental areas. By knowing the acreage of each experimental area, the volume of surface runoff water and the concentration of nitrates, phosphorus, and pesticides, it was possible to calculate the balance of these substances. We also calculated the percentage of surface runoff. The results imply that a new potato cultivator in the technology of stone windrowing should be designed for weed control as part of a weed control system with reduced herbicide application requirements. Innovative agrotechnical processes reducing pollution of water sources by phosphorus and nitrates should also be enhanced. These are based on a precise application of mineral fertiliser into the root area of plants within the period of an intensive intake of nutrients.

Keywords: pesticides; residues; nitrates; phosphorus; water protection; water quality

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1. Introduction

Intensive agriculture significantly affects the quality of surface water and groundwater. Production practices used in agriculture can often lead to the leaking of many pollutants, including sediments, pathogens, pesticides, and salts, into water sources. [1]. Agriculture is an area source of water pollution, especially in terms of the runoff process [2]. Surface runoff is affected by the slope of land, the intensity and duration of precipitation, and the initial moisture in soil and vegetation cover [3]. According to analyses, more than 50% of agricultural land is endangered by water erosion in the Czech Republic and the degradation of the soil by erosion accelerated significantly over the last 30 years due to the intensification of agriculture [4]. During the runoff process, nitrates, phosphorus, and pesticides residues, as well as their metabolites, leak into surface water and shallow groundwaters. This is a global problem being addressed by scientists across the world [5,6].

Hydrological extremes are also increasingly causing water erosion. This can be avoided by implementing an appropriate system of water-management measures in the landscape [7]. In its August 2021 report, The Intergovernmental Panel on Climate Change points out the more frequent occurrence of hydrological extremes. The frequency, and particularly the intensity, of extreme drought as well as floods is changing. Over the last 24 years, the Czech Republic experienced approximately 19 sizeable hydrometeorological extremes. Drought occurred over eleven years and floods occurred across eight years [8]. In the Czech Republic, soil erosion is intensified by growing monocultures and large soil blocks, which are typical for countries in Central Europe (particularly Czechia, Slovakia, Poland, and Hungary) as a remnant of the intensive agriculture in the Soviet era of 1950–1990 [9]. Austria provides an example of agriculture based on small blocks of arable land and variability in crops [10], which decrease the risk of water erosion. A fundamental tool for the reduction of water erosion is anti-erosion measures divided into organisational, agrotechnical, and technical levels. The most effective protection against water erosion is a complex system composed of individual and mutually supplementing measures that have been properly selected for a given locality [11].

Nitrogen and phosphorus are nutrients that significantly influence primary production [12] and considerably contribute to the development of algae and cyanobacteria in freshwater and sea ecosystems. They have negative impacts on both biological variability and human health [13].

The total amount of nitrogen that leaches from agricultural lands depends on the type of crop, nitrogen dynamics in the soil, agricultural procedures, properties of the soil profile, presence of organic substances in the soil, total precipitation in the given year (wet or dry year), and the climate area. This amount 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% [14].

Surface waters are very sensitive to phosphorus leakage from agricultural sources. Phosphorus content, which is crucial for the successful growth of crops, is typically around 200–300 $\mu g\ L^{-1}$. On the contrary, its concentration, which is critical in terms of eutrophication, is usually an order of magnitude lower in the surface water. Types and amounts of phosphorus brought to surface waters from agricultural land are influenced by transport pathways and the phosphorus content in the soil. These processes are influenced by the hydrological conditions of the drainage area and methods of agricultural management, such as fertiliser doses and timings, types of crops being grown, the presence of drains, and more [15].

The presence of pesticide residues and their metabolites in surface water, groundwater, and drinking water has been discussed by number of studies. The contamination of water by these compounds, however, has been occurring over many years. In many cases, banned substances are found. Pesticide residues enter waterways from both point and area sources of pollution, while the area sources, i.e., runoff from agricultural land, have a significant impact on water contamination [16]. Older studies assumed that surface runoff was the main cause of pesticide transportation [17], however, the significance of a shallow surface runoff, which includes a drainage runoff, is currently being recognised, thanks to the improved options of monitoring. Its significance is substantial, especially in areas with a high ratio of drained agricultural land [18].

Considerable surface runoff occurs when wide-row crops grow on sloped land [19]. In relation to the runoff process, potatoes are a key risk crop not only in the Czech Republic but across the world. In the Czech Republic, potato production areas are often characterised by a hilly terrain, where considerable surface runoff occurs [20].

This issue is addressed by the research project, which aimed to grow potatoes in the Bohemian-Moravian Highlands, where the protection zone of the water supply reservoir of Švihov is also located. The management of drinking water source catchment areas should aim to increase retention and improve water quality.

The research aims to analyse runoff when growing potatoes in experimental areas, particularly in the catchment area of the Švihov reservoir.

2. Materials and Methods

2.1. Study Area

The water supply reservoir of Švihov was built on the Želivka river between 1965–1975 and the catchment area of the dam is 1178 km^2. In practice, this reservoir is known under the name water reservoir Želivka. The catchment area above the reservoir extends into three regions (Jihočeský, Středočeský, and Vysočina) and six counties. 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 [21]. The quality of water in the water supply reservoir, however, has been burdened by pollution from point and surface sources for many years. Nutrients such as phosphorus and nitrates in the upper waterways of tributaries are a huge problem, in addition to contamination by pesticides and their metabolites. The water supply reservoir has a specified protection zone and its extent and regime have been a long-discussed topic. However, the historic development of this problem is not the focus of the article. The catchment area of the water supply reservoir is intensively used for agriculture in the form of potato crops, winter rape, wheat, malt barley, silage corn, red clover, poppies, and grasses for seed. At selected experimental areas, water samples were taken after precipitation events, when surface runoff and water erosion occurred. By establishing the acreage of each experimental area, the volume of surface runoff water, and the concentration of nitrates, phosphorus, and pesticides, it was possible for us to calculate the balance of these substances, in addition to the percentage of surface runoff.

2.2. Methodology and Data

Field experiments took place in 2019 in the experimental plots of Valečov, Želiv I, and Senožaty I, and in 2020 in Valečov, Želiv II, and Senožaty II (Czech Republic) (Table 1). The Valečov plot is managed by the Potato Research Institute Havlíčkův Brod Ltd., the Senožaty I and Senožaty II plots are managed by the Agricultural Cooperative Senožaty, and plots Želiv I and Želiv II are managed by the Agricultural Cooperative Vysočina Želiv. All plots are in the Švihov water supply reservoir's catchment area. Only the experimental site of Valečov is outside the catchment area but it remains within its immediate proximity (Figure 1).

Table 1. Characteristics of individual experimental plots.

Locality	Area m^2	GPS Coordinates	Altitude m a.s.l.	Slope °
Valečov	9	49.6498083° N, 15.4978117° E	450	3.6
Želiv I	6.3	49.5252561° N, 15.2016386° E	452	3.8
Želiv II	10.8	49.5605167° N, 15.2979603° E	570	4.6
Senožaty I	10.8	49.5619189° N, 15.1896686° E	480	3.4
Senožaty II	6.3	49.5296164° N, 15.1607939° E	490	4.1

In the experimental plots, water samples were collected in collection containers after runoff events in the 2019 and 2020 growing seasons (Figure 2). These samples were subsequently analysed in an accredited laboratory at the Povodí Vltavy, State Enterprise (nitrates NO_3, total phosphorus P_{total}) and a laboratory at the University of Chemistry and Technology Prague (pesticide residues). Certified standards of pesticides were purchased from Dr. Ehrenstorfer HmbH (Augsburg, Germany), Honeywell Fluka or Honeywell Riedel-de Hean (both Seelze, Germany), Sigma-Aldrich (St. Louis, MO, USA). The purity of standards was in the range of 98–99%. The analysis of pesticide residues in water samples was performed using ISO 17025 accredited U-HPLC–(ESI+/−)–MS/MS metod [22]: Agilent Infinity 1290 LC system (Agilent Technologies, Santa Clara, CA, USA) with Agilent G6495C Triple Quadrupole system (Agilent Technologies). 100 µL of sample was separated on Acquity HSS T3 column (100 mm × 2.1 mm, 1.8 µm particle size, Waters), the components of mobile phase were methanol from Merck (Darmstadt, Germany), deionized water was produced using a Millipore Milli-Q system (Millipore, Bedford, MA, USA), LC-MS grade ammonium formate and formic acid (both from Sigma-Aldrich). For target analytes determination, external calibration was employed, to check possible matrix effects, standard addition approach was used too.

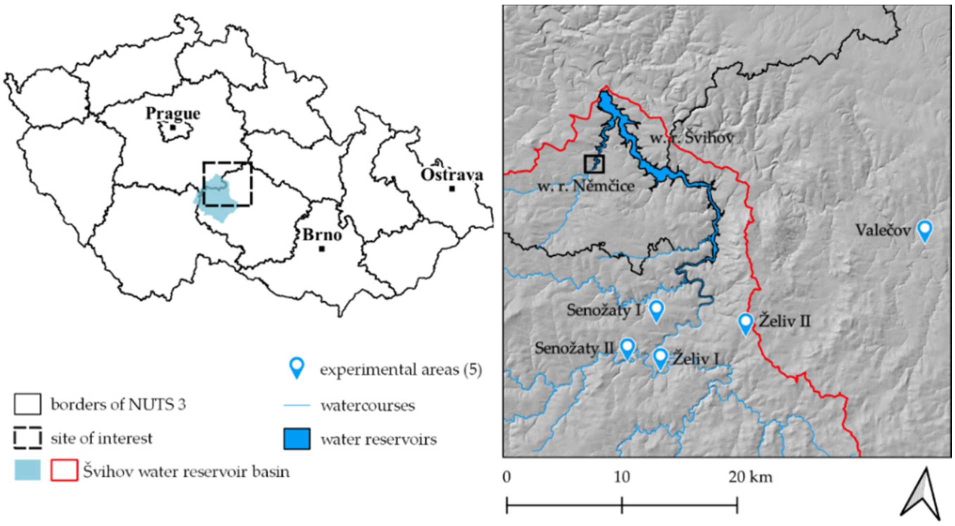


Figure 1. Area of interest, location of experimental plots.

Figure 2. Collectors and tanks placed at the bottom end of rows in experimental plots.

Seven pesticide residues were analysed in water samples: aclonifen, clomazone, flufenacet, flurochloridone, metribuzin, prosulfocarb, and bentazone. These pesticide residues were contained in agents for plant protection, which were tested within the project. Thanks to our cooperation with the subjects managing the experimental plots, we obtained information about specific applied pesticides and methods of fertilisation. As a result, it was possible to focus on specific substances during the analyses of pesticide residues.

The total precipitation (mm) and water volume (m^3) from the surface runoff were measured in experimental plots after every runoff event during vegetation periods. Based on this data, it is possible to determine the volumetric runoff coefficient (%).

By knowing the acreage of each experimental plot (m^2) (Table 1), the water volume from the surface runoff in the collectors (m^3), total precipitation (mm) and concentration of nitrates (NO_3), and the total amount of phosphorus (P_{total}) and pesticides (mg L^{-1}), we were able to calculate the balance of these substances (kg ha^{-1}). The balance assessment of nitrates (NO_3) and total phosphorus (P_{total}) was calculated from all runoff events during the vegetation periods of 2019 and 2020 (from all precipitation when the runoff occurred, i.e., when water from the surface runoff flowed into the collectors). The balance of selected pesticides was calculated only from runoff events, which were preceded by an application of a monitored protection medium for the potato crops; i.e., only runoff events were evaluated, during which the maximum concentration of monitored substances in the samples from the surface runoff were found.

The area of interest lies in the temperate climate zone of the Bohemian-Moravian Highlands. Individual experimental plots are located at an altitude of between 450 to 570 MSL (Table 1). The long-term average annual temperature is 7.0 °C and the long-term average annual precipitation amount is 652 mm. For the vegetation period from April to September, the long-term average temperature is 13.2 °C and the average precipitation level is 453 mm. The soil type is Gleyic Cambisol (CM according to FAO soil classification system) with a sandy loam structure [23]. The area of interest is located in the Moldanubian Zone and consists mostly of metamorphosed and igneous rock [21].

In 2019, there were three different nitrogen fertilisation variants used in each experimental plot:

- Base dose 120 kg N ha^{-1} before planting (variant 1)
- Base dose 120 kg N ha^{-1} before planting + 1 foliar application of 9% solution of urea, 400 L ha^{-1}—16.5 kg N ha^{-1} (variant 2)
- Base dose 120 kg N ha^{-1} before planting + 2 foliar applications of 9% solution of urea, 400 L ha^{-1}—16.5 kg N ha^{-1} (variant 3)

In 2020, five different variants of fertilisation were used in the Valečov plot and the PATENTKALI 400 kg ha^{-1} = K_2O 120 kg ha^{-1} + MgO 40 kg ha^{-1} was applied to the whole plot:

- Variant 1: 50 kg N ha^{-1} + 0 kg P_2O_5 ha^{-1}—application before planting
- Variant 2: 100 kg N ha^{-1} + 0 kg P_2O_5 ha^{-1}—application before planting
- Variant 3: 150 kg N ha^{-1} + 0 kg P_2O_5 ha^{-1}—application before planting
- Variant 4: 100 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}—application before planting
- Variant 5: 100 kg N ha^{-1} + 120 kg P_2O_5 ha^{-1}—application before planting

In the Želiv II and Senožaty II plots, only one variant of fertilisation was used in 2020: Želiv II:

- Variant 1: application of N 60 kg ha^{-1} + P_2O_5 40 kg ha^{-1} + K_2O 40 kg ha^{-1} before planting + ploughing in 38 t ha^{-1} of manure in autumn

Senožaty II:

- Variant 1: application of N 60 kg ha^{-1} + P_2O_5 53 kg ha^{-1} + K_2O 122 kg ha^{-1} before planting + P_2O_5 53 kg ha^{-1} in autumn + ploughing in 25 t ha^{-1} of manure in autumn

3. Results and Discussion

3.1. Runoff

Tables 2 and 3 show the volumetric runoff coefficient in % for individual plots and variants of fertilisation based on the measured total precipitation and volume of runoff. The highest value for each plot is highlighted in bold. The highest value of volumetric runoff coefficient (56.9%) for the whole monitored period was measured on 2 July 2019 in the Senožaty I plot. The lowest values were often under 1%.

Table 2. The runoff volume and variants of fertilisation in experimental plots in 2019. Individual fertilization variants are marked in colour (variant 1—black, variant 2—red, variant 3—blue).

Locality	Date	Variant	Volumetric Runoff Coefficient %	Runoff Volume (mm)	Precipitation Depth (mm)
VALEČOV	1 July 2019	1	36.9	15.28	41.4
VALEČOV	17 July 2019	1	7.4	1.72	23.3
VALEČOV	22 July 2019	1	0.4	0.04	10.4
VALEČOV	22 July 2019	2	0.2	0.02	10.4
VALEČOV	2 August 2019	2	0.5	0.02	4.6
VALEČOV	5 August 2019	1	16.9	2.39	14.1
VALEČOV	5 August 2019	3	28	3.94	14.1
VALEČOV	21 August 2019	3	15.2	3.17	20.8
VALEČOV	21 August 2019	2	15.2	3.17	20.8
VALEČOV	21 August 2019	1	4	0.83	20.8
ŽELIV I	19 June 2019	1	14.1	4.37	31
ŽELIV I	21 June 2019	1	22.8	12.54	55.1
ŽELIV I	2 July 2019	1	22.8	4.56	20
ŽELIV I	18 July 2019	1	0.4	0.11	30
ŽELIV I	23 July 2019	1	14.6	2.34	16
ŽELIV I	23 July 2019	2	4.7	0.75	16
ŽELIV I	31 July 2019	1	1	0.12	12.2
ŽELIV I	31 July 2019	2	0.4	0.05	12.2
ŽELIV I	6 August 2019	1	6.5	1.31	20
ŽELIV I	6 August 2019	3	2.6	0.52	20
ŽELIV I	6 August 2019	2	0.8	0.15	20
ŽELIV I	13 August 2019	3	0.4	0.16	44.6
ŽELIV I	13 August 2019	2	0.1	0.03	44.6
ŽELIV I	13 August 2019	1	0.01	0.02	44.6
ŽELIV I	21 August 2019	3	3.3	1.15	34.9
ŽELIV I	21 August 2019	2	0.2	0.08	34.9
ŽELIV I	21 August 2019	1	3.5	1.23	34.9
SENOŽATY I	19 June 2019	1	35.3	10.95	31
SENOŽATY I	21 June 2019	1	14.1	7.78	55.1
SENOŽATY I	2 July 2019	1	56.9	11.39	20
SENOŽATY I	18 July 2019	1	7.8	2.34	30
SENOŽATY I	23 July 2019	1	38.2	6.11	16
SENOŽATY I	23 July 2019	2	27	4.33	16
SENOŽATY I	31 July 2019	1	29.9	3.65	12.2
SENOŽATY I	31 July 2019	2	12.7	1.55	12.2

Table 3. The runoff volume and variants of fertilisation in experimental plots in 2020. Individual fertilization variants are marked in colour (variant 1—red, variant 2—blue, variant 3—purple, variant 4—green, variant 5—black).

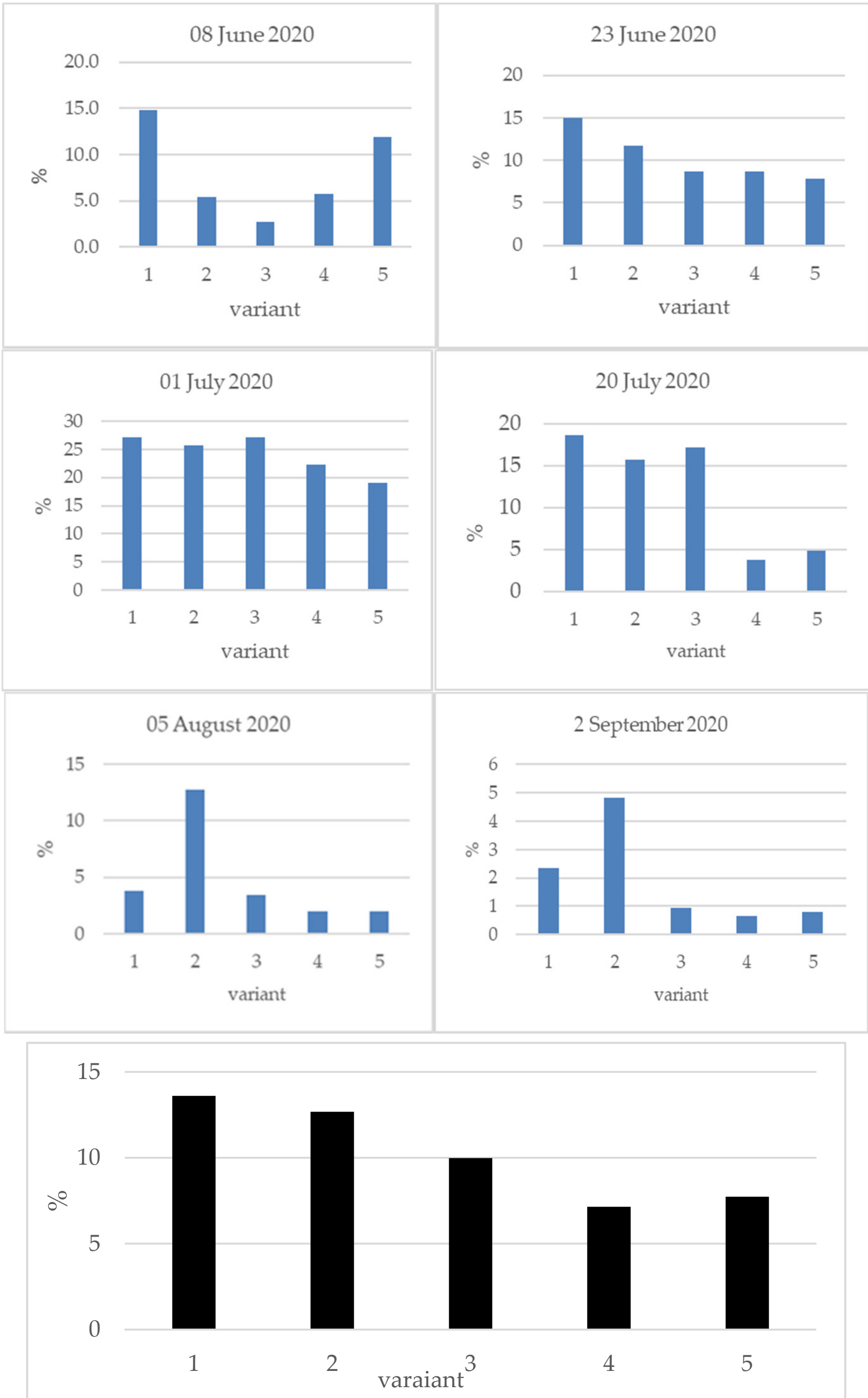
Locality	Date	Variant	Volumetric Runoff Coefficient %	Runoff Volume (mm)	Precipitation Depth (mm)
VALEČOV	8 June 2020	1	14.8	2.83	19.1
VALEČOV	8 June 2020	2	5.4	1.03	19.1
VALEČOV	8 June 2020	3	2.7	0.51	19.1
VALEČOV	8 June 2020	4	5.7	1.09	19.1
VALEČOV	8 June 2020	5	11.9	2.28	19.1
VALEČOV	23 June 2020	1	15	6.3	42.1
VALEČOV	23 June 2020	2	11.7	4.94	42.1

Table 3. *Cont.*

Locality	Date	Variant	Volumetric Runoff Coefficient %	Runoff Volume (mm)	Precipitation Depth (mm)
VALEČOV	23 June 2020	3	8.7	3.67	42.1
VALEČOV	23 June 2020	4	8.6	3.63	42.1
VALEČOV	23 June 2020	5	7.8	3.3	42.1
VALEČOV	1 July 2020	1	27.1	16.22	59.9
VALEČOV	1 July 2020	2	25.6	15.33	59.9
VALEČOV	1 July 2020	3	27.1	16.22	59.9
VALEČOV	1 July 2020	4	22.3	13.33	59.9
VALEČOV	1 July 2020	5	19.1	11.44	59.9
VALEČOV	20 July 2020	1	18.6	9.8	52.6
VALEČOV	20 July 2020	2	15.7	8.27	52.6
VALEČOV	20 July 2020	3	17.1	9	52.6
VALEČOV	20 July 2020	4	3.7	1.97	52.6
VALEČOV	20 July 2020	5	4.8	2.52	52.6
VALEČOV	5 August 2020	1	3.8	1.61	42.6
VALEČOV	5 August 2020	2	12.8	5.44	42.6
VALEČOV	5 August 2020	3	3.4	1.44	42.6
VALEČOV	5 August 2020	4	2	0.83	42.6
VALEČOV	5 August 2020	5	2	0.83	42.6
VALEČOV	2 September 2020	1	2.3	1.42	60.9
VALEČOV	2 September 2020	2	4.8	2.94	60.9
VALEČOV	2 September 2020	3	0.9	0.58	60.9
VALEČOV	2 September 2020	4	0.6	0.39	60.9
VALEČOV	2 September 2020	5	0.8	0.48	60.9
ŽELIV II	9 June 2020	0	1.46	0.66	44.9
ŽELIV II	23 June 2020	0	14.14	6.02	109.4
ŽELIV II	30 June 2020	0	5.5	8.61	60.9
ŽELIV II	15 July 2020	0	6.2	2.19	35.4
ŽELIV II	6 August 2020	0	0.59	0.37	62.9
ŽELIV II	3 September 2020	0	0.39	0.19	50
SENOŽATY II	9 June 2020	0	3.92	1.76	44.9
SENOŽATY II	23 June 2020	0	9.06	9.91	109.4
SENOŽATY II	30 June 2020	0	7.3	4.44	60.9
SENOŽATY II	6 August 2020	0	0.66	0.42	62.9
SENOŽATY II	18 August 2020	0	1.27	0.14	10.9

In the Želiv I and Senožaty I plots, a lower surface value of variants three and two was monitored in 2019, i.e., in plots where the urea was applied, foliar was applied. With these variants, the crops were in better condition, and it was higher, which has impact on the lower runoff (the reduction in the kinetic energy of the drops caused more water to drain down the leaves and stems to the plant roots). Upon foliar fertilisation, most of the nitrogen is absorbed by the leaves of plants and so it reduces the amount of nitrogen that leaks into the soil and water.

For the Valečov plot, the volumetric runoff coefficient for individual fertilisation variants in 2020 was illustrated graphically (Figure 3). For all fertilisation variants, the highest value was measured on 1 July 2020. The results show that crops with lower fertilisation (variants 1 and 2) have a higher average percentage of runoff coefficient (Figure 3), which is related to the better condition of more fertilised crops. Different mechanical methods of tilling potato crops have a significant influence on the volume of runoff.



(**a**)

(**b**)

Figure 3. Valečov—percentage of volumetric runoff: (**a**) coefficient for individual variants of fertilisation in 2020, (**b**) variant average of all runoff events in Valečov in 2020.

The results (Tables 2 and 3) show that the value of the runoff coefficient increases with the rainfall depths in most runoff events. However, the intensity of precipitation is also important.

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 [24].

Agronomic practices that reduce the environmental impact of potato production are in demand. Basin tillage is a potential option in which small dams are created in the furrows (row middles), resulting in basins that enhance infiltration, reduce runoff, minimise contaminant loads, and increase yields [25]. Basin tillage is a practice that increases the surface depression storage of a field, thereby conserving rainfall, reducing runoff, and increasing water availability to crops. It may not, however, be suitable for areas with a high probability for large runoff events, potentially causing ridge overtopping and accelerated erosion [26]. Field experiments performed in Canada demonstrated that the basin tillage had 78% and 75% less runoff than conventional tillage and row shaper tillage [25]. Sitting [24] also states that the application of micro-dams (basin tillage) reduced runoff water volume by 86% on average for potatoes. Small dams create barriers between furrows in order to encourage rainwater to infiltrate in the soil rather than to run off. The application of basin tillage is effective in reducing erosion and runoff significantly. The total loss of plant protection products to surface water is dramatically reduced and also strongly depends on the physic-chemical characteristics of the active ingredients. In addition, the technique tends to produce a higher yield of potato tubers as an effect of an optimised utilisation of the available rainwater and nutrients [27].

The need to address catchments as a whole in water management is not a new theme and it is relevant to the issue of soil erosion since the sources and route ways of sediment reaching watercourses need to be identified [28].

3.2. Phosphorus

The P_{total} sum in kg, which drained from the individual experimental plots (converted to 1 ha), is illustrated in Figure 4. The Želiv I and Želiv II plots show an extreme difference between 2019 and 2020. By far the highest amount of total phosphorus (1.9 kg ha^{-1}) drained in the Želiv I plot during the 2019 vegetation period. This balance was affected by two runoff events in June and July, when an extremely high percentage of runoff occurred (22.8%). During the runoff event in July 2019, very high concentrations of P (12 mg L^{-1}) were recorded, which affected the overall balance. The average concentration from all samples for the vegetation period was 4.59 mg L^{-1} (Figure 5). In the Želiv II plot, the percentage of runoff was between 0.39% and 14.14% in 2020 (Table 3), and the average concentration of P in the samples was 1.09 mg L^{-1} (Figure 5) for the vegetation period.

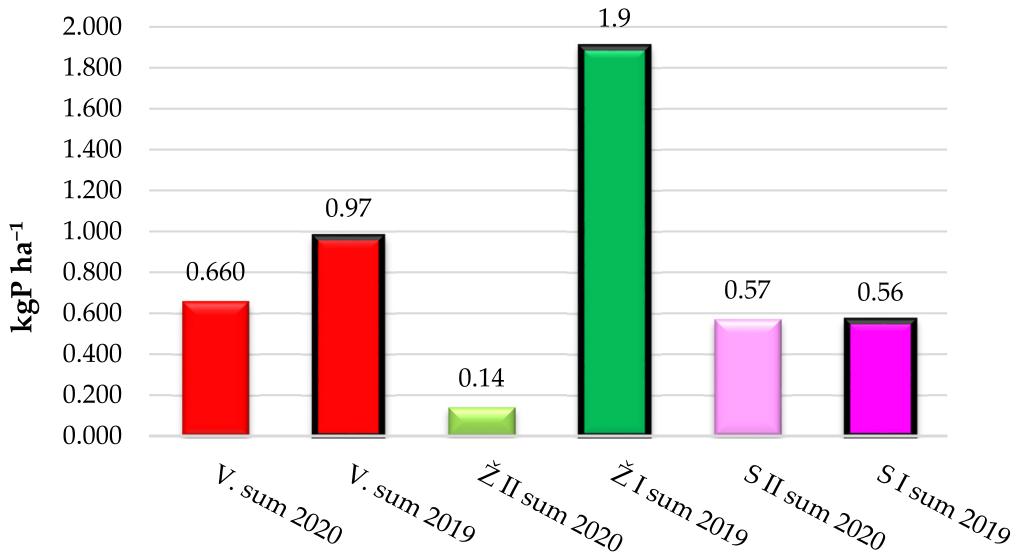


Figure 4. The P_{total} sum in kg, which drained from individual experimental plots (converted to 1 ha) during the vegetation period.

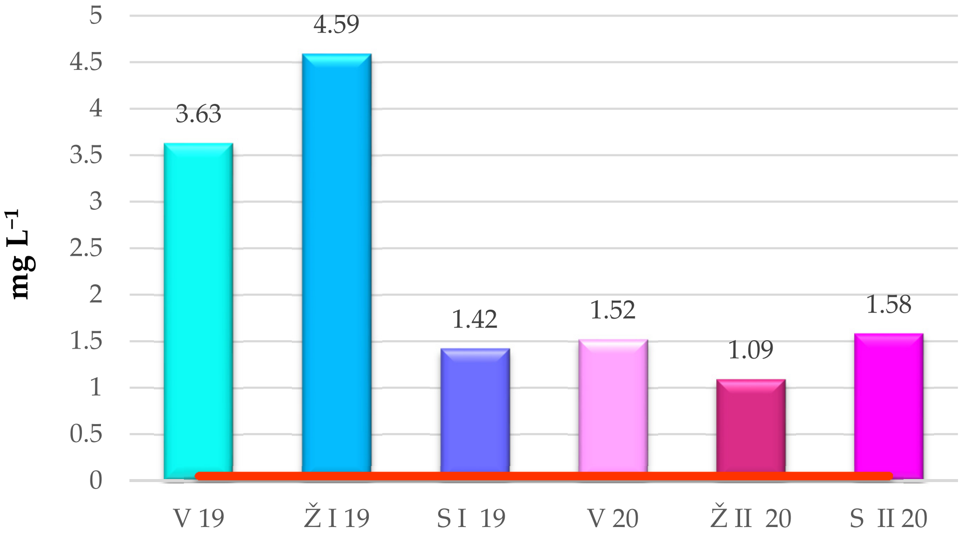


Figure 5. The average concentration of P_{total} from all samples for the vegetation period in individual localities with a limit of 0.05 mg L^{-1}, according to G.D. 401/2015 Coll.

In the Senožaty I plot, the average percentage of runoff for the vegetation period was 5.8% and the average concentration of P for the vegetation period in sample was 1.42 mg L^{-1} (Figure 5). In 2019, in the Senožaty II plot, it was 4.7% on average, and in 2020 the average concentration of P for the vegetation period in the sample was 1.58 mg L^{-1} (Figure 5). Thus, the balance of total phosphorus in the Senožaty I and Senožaty II plots is very similar (Figure 4).

As stated above, the Valečov plot is the only one with the experimental area that was the same in 2019 and 2020. Therefore, it is possible to compare the values in both years. It follows from the results that the average percentage of runoff for the vegetation period was 11.7% in 2019 and 10.2% in 2020. The average concentration of the P_{total} in samples for the vegetation period of 2019 was 3.63 mg L^{-1} (Figure 5) and only 1.52 mg L^{-1} (Figure 5) in 2020. That is why the overall balance for 2019 was higher than for 2020 (Figure 4).

If we compare the Želiv II and Senožaty II plots in 2020, we can see a significant difference in the P_{total} balance (Figure 4), which confirms the considerable influence of the fertilisation dose on the amount of drained phosphorus during the runoff. In the Želiv II, the dose of P_2O_5 was 40 kg ha^{-1}, but in the Senožaty II plot it was 106 kg ha^{-1}. In Valečov in 2020, the average dose of P_2O_5 from all fertilisation variants was 36 kg ha^{-1}, which is comparable to the Želiv II plot. However, the average runoff in the Valečov plot was 10.23% and in Želiv II it was only 4.71%. That is why the overall balance is higher in Valečov.

It follows from the P_{total} balance that the amount of phosphorus taken away during the runoff events differs for individual plots and years and can be significantly influenced by one specific runoff event. A similar study focusing on the calculation of nutrient loss during the surface runoff was performed under different climate and pedological conditions [29]. Values of the surface runoff were significantly higher, at around 27 L m^{-2}, but the P_{total} balance was lower at 0.2 kg ha^{-1} [29]. The reduction of phosphorus transported across sloped lands during the growing of potatoes can be also influenced by mechanical tillage. Gordon [25] states that the application of the basin tillage reduces the amount of phosphorus in the surface runoff by 15%. Ref. [29] states that the conservation tillage practice in potato cultivation, which included reducing tillage, green manure, and permanent soil cover, can reduce total P losses in runoff by 18%.

In connection with phosphorus leaching [30] highlight the importance N/P weight ratio content of manure that are applied to cropland. The manure needs to be managed with much more care in housing, storage, and spreading, in order to reduce N losses [31]. By doing so, higher N/P ratios can be achieved, and less P would be spread on fields, resulting in less P surplus, losses, and waste. Crops have differing N/P requirements—i.e., the N/P offtake weight ratios are 7.5 for potato [32].

The results of monitoring the total amount of phosphorus show that water with very high concentrations of phosphorus, which can negatively influence the quality of surface waters and enhance eutrophication, flows out the experimental plots during the runoff events. According to the Government Decree (G.D.) 401/2015 Coll. Ref. [33], the limit value of the total phosphorus amount for the surface water in the catchment area above water supply reservoirs is 0.05 mg L^{-1} and 0.15 mg L^{-1} for other surface waters. The results show that during some runoff events, water with P_{total} concentrations up to 100 times higher flows from the experimental plots.

Phosphorus in the catchment area of the Švihov reservoir comes from area sources. Kvítek [21] states that the main source of phosphorus in this area is municipal and industrial wastewater. However, the phosphorus lost from the agricultural lands during erosion is missing in the water-soil-plant system, where it represents one of the fundamental and limiting nutrients for successful agricultural production [21]. In the environment, phosphorus is an exhaustible source and its price on the world market is continually increasing as its sources are declining. For this reason, it is necessary to reduce the phosphorus transfer from agricultural lands during runoff events. The sustainable management of phosphorus and other nutrients is crucial for agriculture, food, industry, water, and the environment. The European Sustainable Phosphorus Platform brings together companies and stakeholders to address the phosphorus challenge and its opportunities.

3.3. Nitrates

The nitrate (NO_3) concentration for individual fertilisation variants for the Valečov samples from 2019 fluctuate greatly (from 4.9 mg L^{-1} to 84 mg L^{-1}). The average concentration for the vegetation period from all fertilisation variants is 26.8 mg L^{-1} (Table 4) in Valečov. The concentration of nitrates ranges from 4.3 mg L^{-1} to 35 mg L^{-1} in Senožaty I (the average for the vegetation period is 21.1 mg L^{-1}). In the Želiv I plot, it also fluctuates greatly from 5.6 mg L^{-1} to 99 mg L^{-1} (NO_3 average for the vegetation period is 36.7 mg L^{-1}) (Table 4). The hypothesis that upon a higher dose of nitrogen during fertilisation, a higher concentration of nitrates in water samples collected from the runoff occurs, was not confirmed.

Table 4. Average nitrate (NO_3) concentrations, runoff coefficient, and sum of precipitation in individual plots.

Locality	NO_3 Average Concentration mg L^{-1}	Runoff Coefficient %	Sum of Precipitation mm
V 19	26.8	11.7	206
S I 19	21.1	27.8	164
Ž I 19	36.7	5.8	263
V 20	31.7	10.23	297.2
S II 20	20.36	4.7	289
Ž II20	8	4.4	363.5

The concentration of nitrates (NO_3) in the Valečov samples for individual variants of nitrogen fertilisation (V1–V5) also fluctuated greatly in 2020 (from 4.4 mg L^{-1} to 92 mg L^{-1}) (Figure 6). High concentrations were recorded in early June, i.e., at the beginning of the monitored period, and by the end of the month they were significantly lower, dropping below 10 mg L^{-1} during summer. Its concentrations then began to increase again up to values of around 40 mg L^{-1} in August (Figure 6). On the other hand, concentrations of nitrates in the Želiv II plot were significantly lower. They ranged from 3.2 mg L^{-1} to 19 mg L^{-1} throughout the monitored period. In the Senožaty II plot, they were up to 10 mg L^{-1} in June and increased to 19 mg L^{-1} in August (Figure 6).

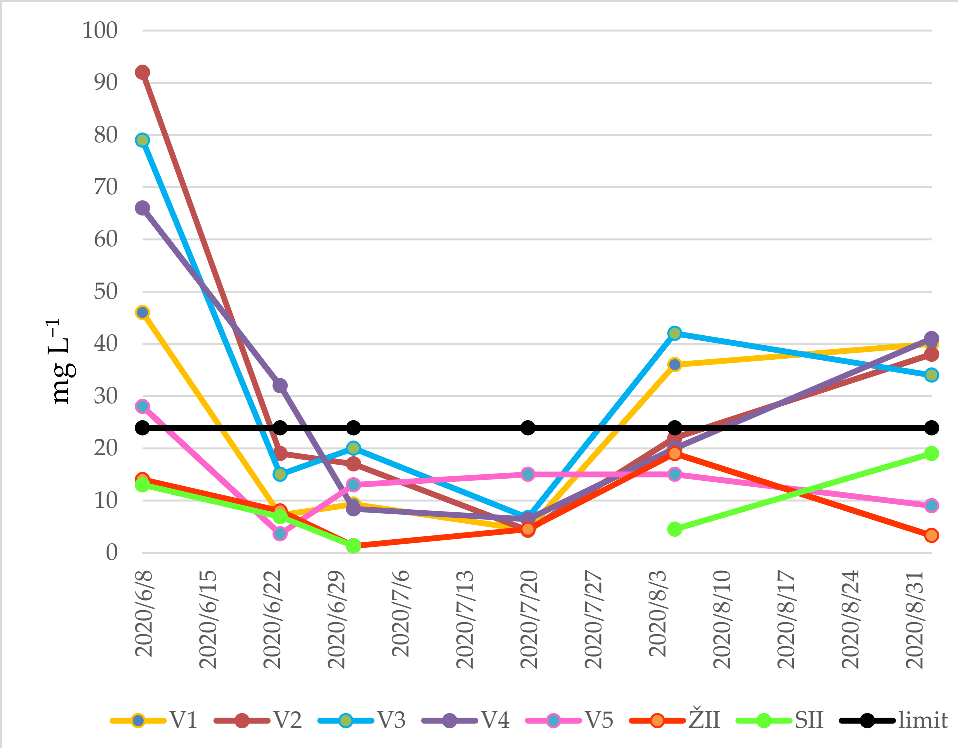


Figure 6. Nitrate (NO_3) concentration for individual fertilisation variants (V1–V5) in Valečov, Želiv II and Senožaty II samples in 2020. A limit 23.9 mg L^{-1} NO_3 (corresponding value 5.4 mg L^{-1} N-NO_3) according to G.D. 401/2015 Coll is marked.

The average concentration of nitrates (NO_3) across all samples (i.e., from all variants) in Valečov was 31.7 mg L^{-1} for the vegetation period of 2020 (Table 4). The average concentration of all samples in Želiv II was 8 mg L^{-1} in the Senožaty II plot it was 20.36 mg L^{-1} (Table 4).

As well as for phosphorus, the overall balance of individual plots was calculated for nitrates for 2019 and 2020. The level of nitrates (NO_3) in kg, which drained from individual experimental plots (converted to 1 ha), is illustrated in Figure 7. The highest level of nitrates for a vegetation period was located in the Senožaty I plot at 11.14 kg ha^{-1} (Figure 7). This balance was influenced by high average values of runoff during the vegetation period (27.8%) (Table 4). These results show a significant influence of vegetation on the surface runoff. In the Želiv I plot, vegetation was dense with high sprouts, whereas in the Senožaty I plot, where the crop was infested with Leptinotarsa decemlineata, potato sprouts were very low and sparse.

On the contrary, the lowest nitrate masses, which were drained within the monitored period, were recorded in the Senožaty II and Želiv II plots in 2020 (Figure 7), while the average percentage of runoff was only 4.7% and 4.4% respectively (Table 4). In Valečov, the nitrate (NO_3) balance for all variants of fertilisation was higher in 2020 than in the plots of Želiv II and Senožaty II (Figure 7). This may have been influenced by the Dali variety found in Valečov, which generally has a smaller stature and lower ground coverage than varieties in the Želiv II and Senožaty II plots.

Gordon [25] states that upon the application of the basin tillage, the amount of nitrates in the surface runoff is reduced by 45%. Drought also greatly affects the concentration of nitrates in the soil, as in a dry season, plants are not able to use the nitrates and they concentrate in the soil as a result. These nitrates are leached from the soil during the first rain after a dry season [34]. The irrigation can have a similar effect [35]. The tied riding method and similar soil treatments in potato cultivation can reduce water runoff and decrease phosphorus and nitrate losses from production areas [36,37].

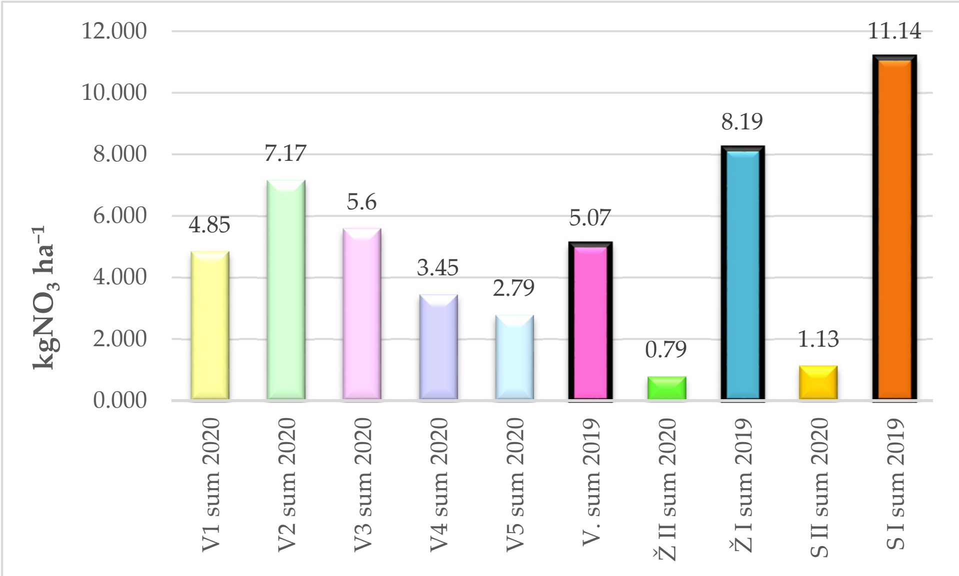


Figure 7. The sum of nitrates in kg, which drained from individual experimental plots (converted to 1 ha) during the vegetation period.

As all experimental plots are located in vulnerable areas, it is important to comply with all measures of the Nitrate Directive to reduce the contamination of agriculture by nitrates. In connection with nitrogen losses, it is advisable to carry out nitrogen concentration test in the soil before planting [38]. Many studies emphasize the importance of cover crops, green manures, and catch crops in potato growing. A reduction from 133 to 6 kg N ha^{-1} (−95%) in nitrate leaching was shown in a potato crop grown on soil previously cultivated with grain legume, while a reduction in nitrate leaching from 213 to 17 kg N ha^{-1} (−92%) was recorded when potato cultivation was cultivated after green manure [39].

Good agricultural practice principles include avoiding the application of manure and fertiliser prior to anticipated heavy or prolonged rainfall. Adherence to these principles can significantly reduce 'incidental losses', save finances, and improve the water quality [40]. The management in agricultural practice should be based on the prediction of spatial variability of soil properties that allow to ensure proper application of N fertilizers, resulting in the reduction of possible N losses [30]. Kvítek [21] states that nitrate concentrations in several watercourses in the Švihov reservoir catchment area exceed the emission limits according to the G.D. 401/2015 Coll. and the limit requirements for good ecological status according to the Water Framework Directive. It also states that in the Švihov catchment area, agriculture is the long-term dominant source of nitrates and point sources are only of marginal importance.

3.4. Pesticides

In water samples, in which the application of individual agents for the plant protection was indicated, respective pesticide residues were found in concentration up to tens of µg L^{-1}, usually depending on the time elapsed since the treatment. However, clomazone, flufenacet, flurochloridone, metribuzin, and prosulfocarb were also found in almost all water samples in which the treatment of a respective agent was not indicated, in concentration levels up to hundredths of µg L^{-1} (metribuzin and flufenacet even tenths of µg L^{-1}). These findings can be explained, for example, by the fact that the pesticides persisted in the environment before the project experiments began (control samples were not taken). It can also be caused by secondary contamination from the application technology used. The highest concentrations (Table 5) were recorded during the runoff events preceded by the application of protective agents.

Table 5. Maximum pesticide concentrations found in the first flush after application for the period 2019–2020.

Active Substance	Max Concentration µg L^{-1}	Locality	Date
aclonifen	19.731	Želiv I	21 June 2019
clomazone	73.5	Želiv II	9 June 2020
flufenacet	41.794	Valečov	14 June 2019
flurochloridone	28.126	Senožaty I	21 June 2019
metribuzin	103.32	Valečov	14 June 2019
prosulfocarb	65.002	Valečov	14 June 2019
rimsulfuron	22.3	Senožaty II	23 June 2020
bentazone	471	Senožaty II	23 June 2020

The used active substance of aclonifen is subjected to the Environmental Quality Standards (EQS) for surface water bodies for substances listed in the Annex II of the Directive of EP and Council (priority substances and other specific pollutants—see the Government Decree 401/2015 Coll as amended) [33]. According to the G.D. 401/2015 Coll, the highest permissible concentration of aclonifen is 0.12 µg L^{-1}. Findings in the water samples from runoff after the application were almost 20 µg L^{-1} (Table 5). The results of the assessment show that 1.86 g of aclonifen flowed from one hectare during this runoff event. In 2020, the concentration of aclonifen was below the 1 µg L^{-1} value in all plots, while the highest concentration (0.74 µg L^{-1}) was recorded in the Želiv II plot.

Bentazone is also subjected to the Environmental Quality Standards for specific pollutants of surface water bodies and values of pollution for water bodies used for water supply purposes according to the Government Decree 401/2015 Coll. Here, the average permissible annual concentration is 4.5 µg L^{-1}. We do not state the annual average in our results but the maximum measured concentration (Table 5) exceeded 100 µg L^{-1} in all monitored plots in all years, with the maximum was measured in Senožaty (471 µg L^{-1}).

A balance was calculated and graphically illustrated for bentazone, clomazone, metribuzin, flurochloridone and flufenacet after every first precipitation when the runoff occurred after the application of a specific active substance for individual plots. Figures 8–12 demonstrate the amount of monitored active substances in mg, which flew from individual experimental plots (converted to 1 ha) after the application of a specific active substance. Therefore, the presented numbers are not the total sum for the whole vegetation period. They only represent samples with the highest concentrations of monitored pesticide residues (i.e., after the first precipitation after application when the runoff occurred). The application of a specific active substance and precipitation were different at each experimental plot. Therefore, it is not possible to compare them. Rather, it is an illustration of how much of these substances were washed away during the first precipitation following application.

The highest bentazone balance (almost 47 g ha^{-1}) for a vegetation period was measured in the Senožaty II plot in 2020, where the maximum concentration was also recorded at 471 µg L^{-1} (Table 5). Bentazone has a relatively high water solubility and therefore a potential high mobility in soil thus contaminating groundwater [41]. In humans, it causes vomiting, diarrhoea, dyspnoea, tremors, and weakness, or generates eye irritation [42]. According to a World Health Organization (WHO) report [43], the health-based value, which is protective of health effects from lifetime exposure to bentazone, is 0.5 ppm.

The highest balance of clomazone was recorded in Valečov in 2019, when it reached almost 2000 mg ha^{-1} in a vegetation period (Figure 9). In 2020, the maximum balance for a vegetation period was recorded in the Želiv II plot (Figure 9). The findings of clomazone cause harm not only in drinking water sources but also in fish gills and livers [44].

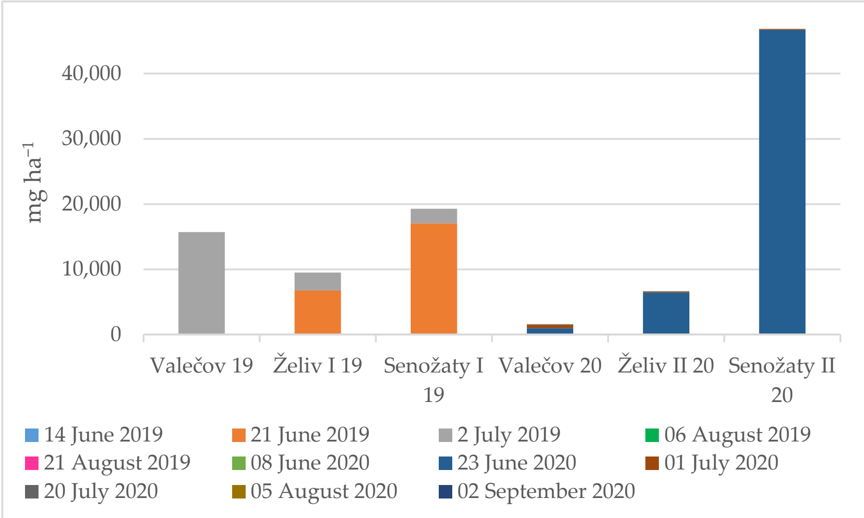


Figure 8. Bentazone balance in 2019 and 2020 after every first runoff after application.

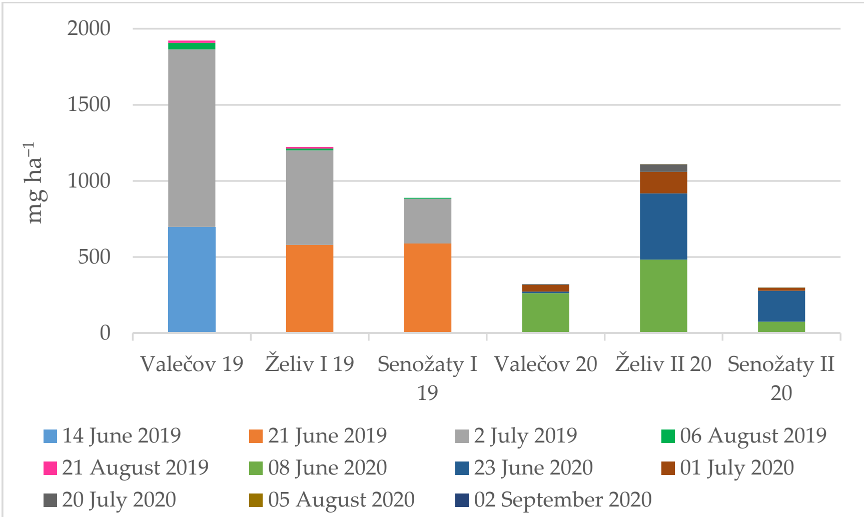


Figure 9. Clomazone balance in 2019 and 2020 after every first runoff after application.

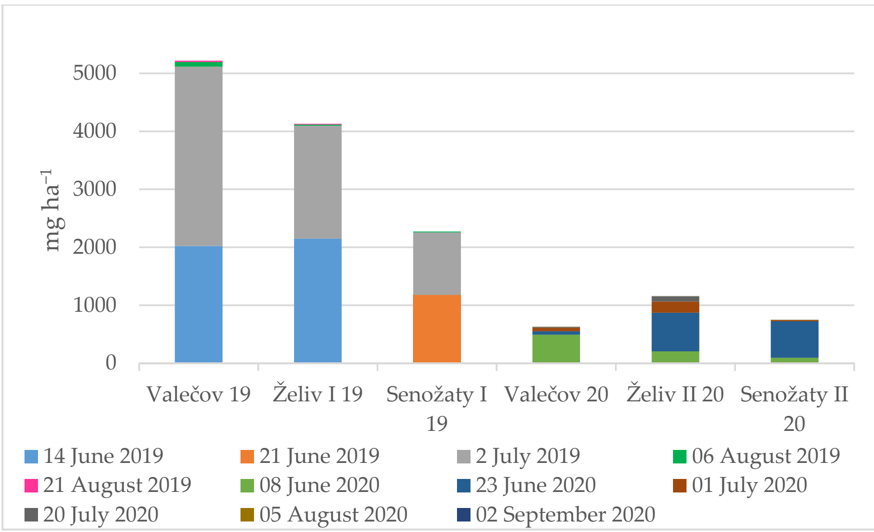


Figure 10. Metribuzin balance in 2019 and 2020 after every first runoff after application.

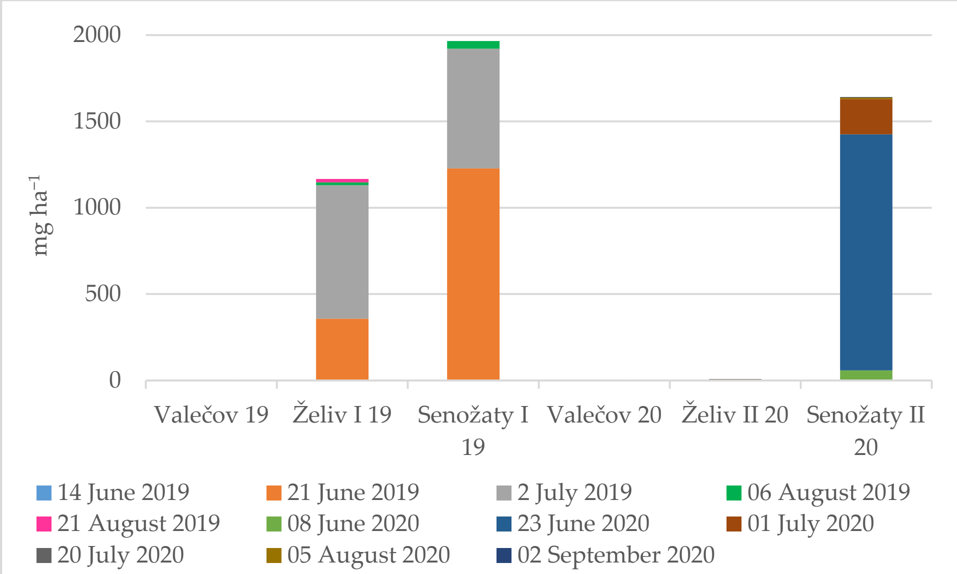


Figure 11. Flurochloridone balance in 2019 and 2020 after every first runoff after application.

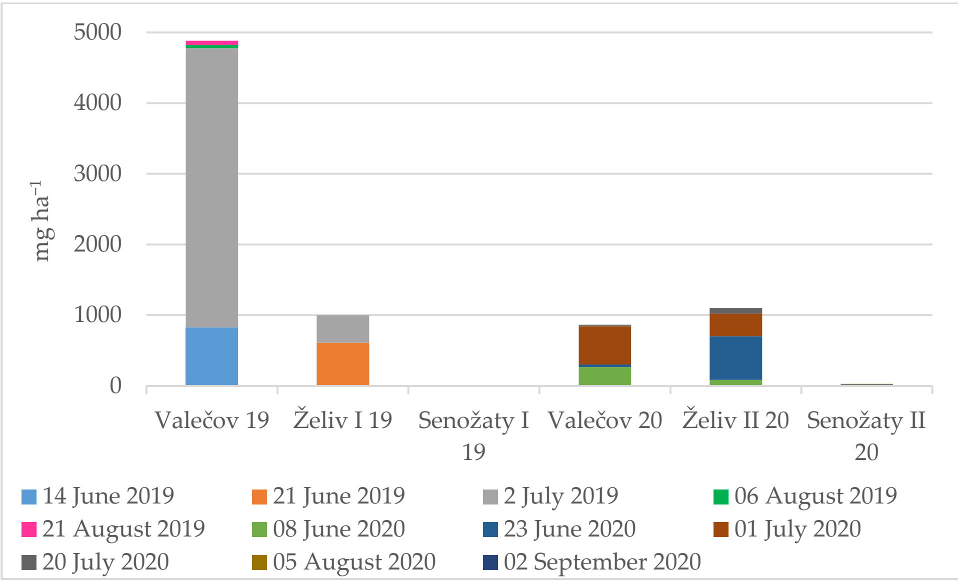


Figure 12. Flufenacet balance in 2019 and 2020 after every first runoff after application.

For the active substance metribuzin, a significantly lower balance was found in 2020 at all monitored sites than in 2019. The maximum balance was recorded in Valečov in 2019 (Figure 10). Jeanne [45] states that metribuzin and its metabolites, desamino-diketo-metribuzin (DADK) and diketo-metribuzin (DK), may contaminate not only surface water but also groundwater. The past application of metribuzin at the site had contaminated the groundwater with both DK and DADK, which were detected in 99% and 48%, respectively, of the groundwater samples analysed. The findings of metribuzin in the groundwaters intended for irrigation and sources of drinking water are stated in [46]. We also highlight the significant increase of metribuzin concentrations (around 47 µg L^{-1}) during the first runoff event after its application on the potato crops in [47].

The flurochloridone balance was very different for individual localities (Figure 11). In Valečov in 2019 and 2020 and Želiv II in 2020, almost no contamination was detected in the samples. On the contrary, in the Želiv I and Senožaty I plots in 2019 and Senožaty II in 2020, very high concentrations were found (Figure 11). Flurochloridone was not applied in Valečov in 2019, nor in 2020. It was applied in other sites in 2019, in 2020, and also in the past. Thanks to its relatively low mobility in soil, it is the best herbicide agent for application in the protection zones of water sources.

The appropriate amount and concentration of flurochloridone should be applied to potato crops due to the residues in potato leaves, roots, tubers, and in the soil, and to ensure the European maximum residue limit recommendation (0.1 mg kg^{-1}) is not exceeded [48].

In the Senožaty I and Senožaty II plots, flufenacet was not applied on potatoes neither in 2019, nor in 2020. That is why very low concentrations in the runoff samples were found as well as a low overall balance, where only residues from earlier applications were found. The highest concentration (Table 5) and the balance (Figure 12) was found in the Valečov plot in 2019. Residues of flufenacet may pose a threat to aquatic plants. The amount of flufenacet applied should be controlled, and the flufenacet emission concentration of agricultural sewage should be less than 20 μg L^{-1} [49]. The maximum concentration of 41.794 μg L^{-1} of flufenacet in analysed samples was found in Valečov in 2019, meaning the recommended limit was exceeded twice.

The contamination of surface waters and groundwaters by pesticides occurs not only during the surface runoff but also through drainage systems, which present a considerable risk. Controlled drainage with subsurface irrigation treatment increased surface runoff, which transported more herbicides from free drainage and controlled drainage treatments [50].

There are no drainage systems directly in the experimental plots of Valečov, Senožaty I, Senožaty II, Želiv I and Želiv II. However, in the Švihov WR basin, 149.5 km^2 was drained in the period 1930–1994, which represents 12.7% of the catchment area. Drainages are located mainly in the north-western and south-western parts of the catchment area [21]. For two years, the final specific profiles of two drainages with different land use were monitored on two experimental sub-basins in the Švihov WR catchment area. The first sub-basin was almost entirely grassed, with pesticides last applied seven years ago. In the second sub-basin there is arable land and normal farming takes place there. In the samples from regular sampling, i.e., at the time of relatively low flows and the predominant base and slope runoff, mainly metabolites of pesticides were detected in the drainage water. On the contrary, during runoff events, a wider spectrum of pesticides appears in both drainage and surface runoff than in the period of normal flows. The presence of parent substances, which were almost non-detectable under normal conditions and whose concentrations can be quite high during a runoff event, is particularly significant [51]. This is also confirmed by the above results from flushes from our experimental plots. The condition for leaching of the parent substance is that the runoff event occurs shortly after their application. Kvítek [21] states that the most important factors for the risk assessment of surface water pollution by water from drainage systems in 4th order river basins in the Švihov WR basin are the share of soil plowing and the share of drainage areas.

Povodí Vltavy, State Enterprise, carries out long-term monitoring of water quality in the Švihov WR basin. For the needs of the project, data of selected surface water quality indicators near experimental plots were purchased. Their evaluation is not part of this article, but it can be stated that applied pesticides on potato stands are also detected in surface waters. E.g. metribuzin concentrations in most of the analysed surface water samples in the period 2019 and 2020 were below the limit of quantification, i.e., 10 ng L^{-1}, but in the spring months concentrations of up to 86 ng L^{-1} were detected on some monitored profiles. High concentrations of bentazone (up to 196 ng L^{-1}) and clomazone (160 ng L^{-1}) were also found on the Lučický stream (in the catchment area of which is the Valečov experimental plot).

Due their effects on human health and the environment, laws and regulations restrict the use of herbicides in many countries, especially in developed countries where the water quality law is well defined [52]. According to [53], the European Union legislation that defines the maximum concentration of pesticides in drinking water is the most stringent in the world.

For these reasons, drinking water must be treated to remove contaminants before distribution to the population. We observed many pesticide residues that were resistant to conventional water treatment methods. These compounds remained stable throughout all the steps in the process, with few exceptions. Therefore, tertiary treatments in drinking water treatment plants are vital. Among several advanced treatment techniques for pesticide residues removal, the adsorption process presents high efficiency and a high adsorption capacity for a wide range of pesticides. This, therefore, may be a process with great potential [52]. Raw water from Švihov WR is treated in the Želivka water treatment plant. In 2021, an extensive technological modernization was completed here, consisting of adsorption by granular activated carbon. Thanks to this technology, microplastics, pharmaceuticals, and also pesticides are removed from the water.

Cultivating plants, mechanical, and chemical methods are combined judiciously to retrieve the best results while optimising the cost of potato production [54]. Effective pest management requires monitoring the resistance of pests and developing a well-programmed pesticide treatment to simultaneously reduce the insecticide and herbicide selection pressure and environmental pollution [55].

Kvítek [21] states that the water quality of the Švihov reservoir is affected by the main water course (Želivka), where a great volume of water with pesticide residues flows into the reservoir during the vegetation period. In the winter season, the inflow water has a lower concentration of pesticide residues than the water in the reservoir and thus dilutes the pollution in the tank itself.

The presence of pesticide residues is a problem not only in surface water and groundwater but also in drinking water. Moulisová [56] stated that in the Czech Republic since 2017, occurrence of pesticide residues is considered in case of drinking water as issue of priority concern, while in the past time, attention was mainly paid to nitrates levels. In 2017, the Czech National Institute of Health initiated monitoring program focused on pesticide residues and their metabolites in drinking water. Representative samples of drinking water from more than 170 water supplies in all regions, from surface, mixed, and ground sources were collected for analysis. The results show that approx. 75% of monitored water supplies is contaminated by pesticide residues. Findings of the pesticide residues are more or less stable; short-term peaks after the application of agents for the plant protection are not reflected in the monitoring of drinking water. Pesticide residues and/or their metabolites, the use of which were banned over ten years ago (e.g., alachlor in 2008 and atrazine in 2004), are also still recorded, indicating the persistence of these substances and the presence of local old loads. Only one quarter of the analysed water supplies (42 water supplies) did not show the presence of these substances in the samples collected [56]. This begs the question, why? One explanation is the water supply was not contaminated at all, or the monitored substances were eliminated by the technology at the water treatment plant.

The results of monitoring the water supply sources, which were established by the CHMI, show that pesticides were found in 72% of sources, while 50% of sources show overlimit concentrations. Overlimit concentrations for the pesticide sum were recorded in 30% of sources [57].

As shown in the above results and in line with other published studies, the contamination of surface water and groundwater by nutrients and pesticide residues is a global problem. On this account, agricultural management needs to be altered to eliminate the input of nitrogen, phosphorus, and other pesticides, especially in the river basins above water supply reservoirs. Thus, a long-term cooperation between water managers and farmers is crucial.

It is also important to increase farmers' awareness of non-production functions and the possibilities of management in the landscape, especially in terms of water and nutrient regimes. However, owner relationships are crucial for the willingness of farmers to accept protective measures on their agricultural soil. A large share of rented soil or a non-stable market environment complicates these activities. Grants related to the creation and management of soil-protection and water-protection measurements in the landscape should partly work as a support of a public interest in the form of a public service. They should be stable and claimable against properly set management conditions and representatives of small and medium-sized agricultural enterprises should also participate in their preparations [58]. It is important that financial resources from the Common Agricultural Policy are directed to the water retention programme and the creation of biological and technological measures and their maintenance are directed at the investor, which is the farmer. Just like every village or city takes care of its roads, parks, lands, lighting, and waste collection, every farmer should not only ensure agricultural production but he/she should take care of all non-production functions of agriculture, including activities related to the water retention of the landscape. He/she should also be paid for it [59].

International studies also point out that there is no solution available that is suitable for everyone, and every economical tool in water management has its own pros and cons. Moreover, economical tools cannot be universal. All specifics of a given field related to regulation and/or technological measures need to be considered. The involvement of all participants in the process is important in ensuring that political objectives and tools are a result of a consensual agreement [60]. The correct timing of the application is also very important. Only a small proportion of the pesticides applied to crops actually reaches their target. The rest enters into the environment, contaminating air, water, and soil, and often persists over long time periods [61].

Farmers working in the catchment area above the Švihov water supply reservoir are aware of long-term problems with the water quality and they have engaged in a three-year pilot project termed the Support of Measures to Reduce the Impacts of the Agricultural Primary Production in the Protective Zone of the Švihov na Želivce Water Supply Reservoir. The project is supported by the Ministry of Agriculture and 16 agricultural subjects are involved (12,640 ha of arable land), which are active in the catchment area of the water supply reservoir. The river basin administrator, state enterprise of Povodí Vltavy, and other professional institutions are also involved in the project. The objective of the project is to reduce the application of agents for the plant protection in the agricultural lands in the protective zone of the Švihov water supply reservoir within a certain order of the comprehensive catchment area, where intensive agriculture leads to the increased presence of pesticide residues and their metabolites in the water supply reservoir. The objective of the project is to maintain or improve the water quality in the catchment area of the water supply reservoir, so the water quality in the reservoir does not deteriorate and agricultural management is maintained. Important features of the project are voluntariness and positive motivation, not sanctions. The principle of the project is to limit the application of the agents for the plant protection in the protective zone of the water supply reservoir and acquire financial compensation. After 24 h of using the preparation for plant protection, farmers are obliged to report information to a special application. Controlling other agrotechnical measures (organic fertilisation, crop rotation, percentage of present crops) in the plots signed into the project is also important. A great contribution to this project is the active involvement of farmers and their cooperation with water managers and other professional institutions. It will be possible to apply the results of the project to other water supply reservoirs within the Czech Republic; however, an individual approach to each reservoir and its catchment area is crucial [62].

As stated above, the Potato Research Institute Havlíčkův Brod, Ltd., Agricultural Cooperative Senožaty and Agricultural Cooperative Vysočina Želiv are also active in the catchment area of the Švihov reservoir (but not in the protective zone of the water source). Within the project, they cooperate with the water managers and try to design new methods for growing potatoes that reduce pesticide inputs. A new potato cultivator in the technology of stone windrowing for the regulation of weeds is being designed as part of the system of weed regulation with reduced requirements of herbicide application. Alternative ways of regulating weeds and using biological agents for plant protection are also being tested in the experimental plots. Innovative agrotechnological methods reducing the pollution of water sources by phosphorus and nitrates are also being designed. They are based on a precise application of mineral fertilisers to the root zone of plants at the beginning of an intensive intake of nutrients. It is critical that they use procedures to reduce the surface runoff of water in sloped lands and the washing away of soil. For this purpose, innovative mechanisation tools for modifying the shape of beds, hollows, and furrow dikes were designed and verified (Figure 13). The Varior 500 cultivator was also developed (Figure 14). This machine effectively increases the soaking of water into the profile of beds through disturbance of the soil crust at the beginning of the potato growing season. It simultaneously transports some of the mineral fertiliser into the root zone of plants. One of the results of the project is a complex methodology for growing potatoes, meeting the requirements for farming in the catchment areas of drinking water supplies.

Figure 13. Hollows and furrow dikes created by the bed modulator located on the planter.

Figure 14. The potato cultivator Varior 500—disturbance of the soil crusts related to the application of fertilisers in the beds.

4. Conclusions

The results of the runoff evaluation show the following. In plots where the urea was foliar applied, a lower surface value of variants three and two was monitored. With these variants, the crops were in better condition, and it was higher, which has impact on the lower runoff (the reduction in the kinetic energy of the drops caused more water to drain down the leaves and stems to the plant roots). Upon foliar fertilisation, most of the nitrogen is absorbed by the leaves of plants and so it reduces the amount of nitrogen that leaks into the soil and water.

The results of Valečov in 2020 show that crops with lower fertilisation (variants 1 and 2) have a higher average percentage of runoff coefficient, which is related to the better condition of more fertilised crops. Different mechanical methods of tilling potato crops have a significant influence on the volume of runoff.

The results of P_{total} evaluation confirm the considerable influence of the fertilisation dose on the amount of drained phosphorus during the runoff (a higher fertilisation dose of P_2O_5 cause a higher value of the phosphorus balance). The results of monitoring the total amount of phosphorus show that water with very high concentrations of phosphorus, which can negatively influence the quality of surface waters and enhance eutrophication, flows out the experimental plots during the runoff events.

The hypothesis that upon a higher dose of nitrogen during fertilisation, a higher concentration of nitrates in water samples collected from the runoff occurs, was not confirmed. These results show a significant influence of vegetation condition on the surface runoff and thus also on the nitrate balance. In experimental plots, where the vegetation was dense with high sprouts, the nitrate balance was lower than in experimental plots, where the crop was infested with Leptinotarsa decemlineata and the potato sprouts were very low and sparse. The influence of potato variety on the nitrate balance was also demonstrated. The Dali variety with a smaller stature and lower ground coverage had a worse nitrate balance.

The highest concentrations of individual agents for the plant protection were recorded during the runoff events preceded by the application of protective agents. Concentrations of aclonifen and bentazone in some samples after the application of agents for the plant protection exceeded the limits according to the G.D. 401/2015 Coll.

The results show that potato growers must prevent surface runoff, which is also associated with surface water contamination. It is convenient to cultivate the varieties with dense vegetation and high sprouts. Special mechanical methods of tilling potato crops have a significant influence on the volume of runoff and nitrate contamination of waters. The application of the basin tillage can reduce the amount of nitrates in the surface runoff. We recommend to the Potato Research Institute Havlíčkův Brod, Ltd. to evaluate the effect of Varior 500 machine on reducing the surface runoff.

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