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# Slowing Down Quick Runoff—A New Approach for the Delineation and Assessment of Critical Points, Contributing Areas, and Proposals of Measures to Reduce Non-Point Water Pollution from Agricultural Land

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**Abstract:** Non-point sources of water pollution caused by agricultural crop production are a serious problem in Czechia, at present. This paper describes a new approach for the mutual delineation and assessment of different pollution sources where the critical points method is used to identify the origin of contamination and the source areas. The critical points, i.e., sites presenting the entry of quick surface and drainage runoff into waters, are classified into three (for surface pollution sources using a WaTEM/SEDEM model) or four (subsurface = drainage sources via the catchment-measures need index) categories, respectively. This enabled us to prioritize the most endangered areas at different scales, ranging from the third-order catchments to very small subcatchments, and to design the appropriate combination of control measures to mitigate surface and drainage water runoff, with these being the main drivers of associated pollution. This methodology was applied to a study conducted in the Czech Republic within the entire Vltava River basin, with a total area of 27,578 km$^2$, and utilized in depth to assess a 543 km$^2$ catchment of the Vlašimská Blanice River. When the effect of the designed surface runoff control measures system had been assessed for sediment transport through outlet profiles of the fourth-order catchments, the average reduction reached 43%. The total reduction in the subsurface transport of nitrogen within the fourth-order catchments was 24%. The approach and results are planned to be projected into river basin management plans for the Vltava River basin. Nevertheless, a thorough reassessment of current legislations and strategies is needed to enable the broader adoption of mitigation measures and sustainable management patterns within agricultural landscapes.

**Keywords:** catchment prioritization; critical point; drainage water management; non-point agricultural water pollution; surface runoff; water retention

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## 1. Introduction

Undoubtedly, non-point pollution sources related to agricultural land management substantially contribute to surface and subsurface water pollution in numerous countries practicing intensive farming, and profoundly hamper the obligations set by the EU Water Framework Directive (WFD) [1–3]. Non-point pollution sources consist of two types according to their origin: surface water and subsurface water. The main types of surface water pollution include soil erosion, sediment transport, and related chemicals bounded to sediment particles. Regarding subsurface water, the main type of pollution is related to land drainage systems [4–6]. Globally, the most significant pollutants present in surface and subsurface waters are pesticides [7,8], nitrates [9–11], phosphorus and suspended solids [12–14], and some micropollutants [15]. All these pollutants enter water bodies mainly in connection with rainfall–runoff events; in other words, runoff, and soil–water interactions and dynamics are the main drivers of pollutants transport from farmland to the surrounding waters [12,16–18]; therefore, water treatment options used to ensure clean water suitable for drinking purposes are more difficult and costly to achieve [19].

Although water conservation practices conducted in the Czech Republic are regulated at four different specific levels of protection [20–23], adhering to the requirements of the Water Framework Directive (WFD) 2000/60/ES [24], problems with water quality arising from non-point source water pollution are increasing, to date [3,16,17,25]. The WFD requires that the "good ecological and chemical status" of water bodies be achieved in all EU countries with respect to the cost–benefit standards of individually applied measures [25,26].

Numerous countries strive to improve their water quality, especially due to agricultural non-point source water pollution, with the use of various approaches depending on their climatic, economic, and agricultural conditions, and utilize the subsidy policy to encourage their farmers to adopt environmentally friendlier approaches to agricultural management [27–32]. The various aspects of the common agricultural policy (CAP) were analyzed by the authors of [32,33], who concluded that the approach was relatively rigid, and also stated that effective systems should consist of adaptive tools and measures addressing the specific spots, landscape, farmers, markets, and environmental problems of a given country. These studies concluded that it is necessary to respect the relations between farmers and nonfarmers, and the specific interests of individual groups and stakeholders [34].

Due to the limited budgets available for watershed management projects, effective, critical, catchment-site prioritization methods, and techniques for the placement of measures are required to achieve the maximal reduction in elevated runoff/pollutants with minimal costs [5,7,26]. Several approaches expressed in the literature address the prioritization of risky catchment sites for the adoption of various mitigation measures (mainly called nature-based solutions (NBSs), natural water retention measures (NWRMs), and natural infrastructures (NI)) according to the scale, available data, and the details of their design. However, not many studies offer procedures that enable the simultaneous assessment of both surface and drainage water pollution sources, nor propose appropriate measures that do not neglect the first or second type of rainfall–runoff process (and even the presence and topology of land drainage) or the associated water quality dynamics. In numerous cases, and especially in practice, runoff reduction interventions and water quality improvement measures are separately propounded or adopted solely for the selected individual measures [35–39]. Nevertheless, several complex approaches have been documented in the literature [40–44]. A comprehensive method utilized for identifying priority areas on a large scale, including agricultural drainage, was presented in a study conducted by [41], which assessed runoff and nitrate leaching processes using the SWAT model and GIS tools in risky areas, and accordingly positioned and evaluated seven types of structural measures in the study. On the other hand, the authors in [42] described a common lack of water quality benefits presented in the studies generally describing the principles and function of flood and runoff mitigation measures.

Several studies agreed that mitigation measures are the most effective method when designed and implemented as a mutually interconnected system of different measures in different landscapes within a watershed area [40–45]. At the same time, structural water retention measures provide an enhanced water storage capacity; therefore, they may generally be more effective for water quality improvements than agrotechnical measures [40–42]. Thus, the main aim of this study is to describe a method that is applicable to areas of varying scales and hydrological units to jointly address the attenuation of surface and subsurface runoff while considering the water quality.

More specifically, the objectives of this paper are the following:

- To present a new integrated and comprehensive approach for water quality conservation in relation to agricultural non-point pollution sources and rainfall–runoff processes within a catchment as a basis for the Watershed Management Plans for the Vltava River catchment.
- To assess and categorize hydrological units of various scales according to accelerated runoff, sediment, and nutrients transport.
- To introduce appropriate steps for the prioritization of the most threatened sites and methods for the design of structural measures within agrarian catchments.
- To document the effectiveness of designed systems of mitigation measures in a selected catchment.

## 2. Materials and Methods

### *2.1. Characteristics of the Area of Interest*

The Vltava River drains the 2nd-order catchment and forms the left-bank tributary of the Labe River (Figure 1). The total area of the catchment in the CZ is larger than 27,000 km$^2$, and it is divided into three main regional catchments, Berounka, Upper Vltava, Lower Vltava, and the entire area is managed by Povodí Vltavy, state enterprise (Table 1, Figure 1).

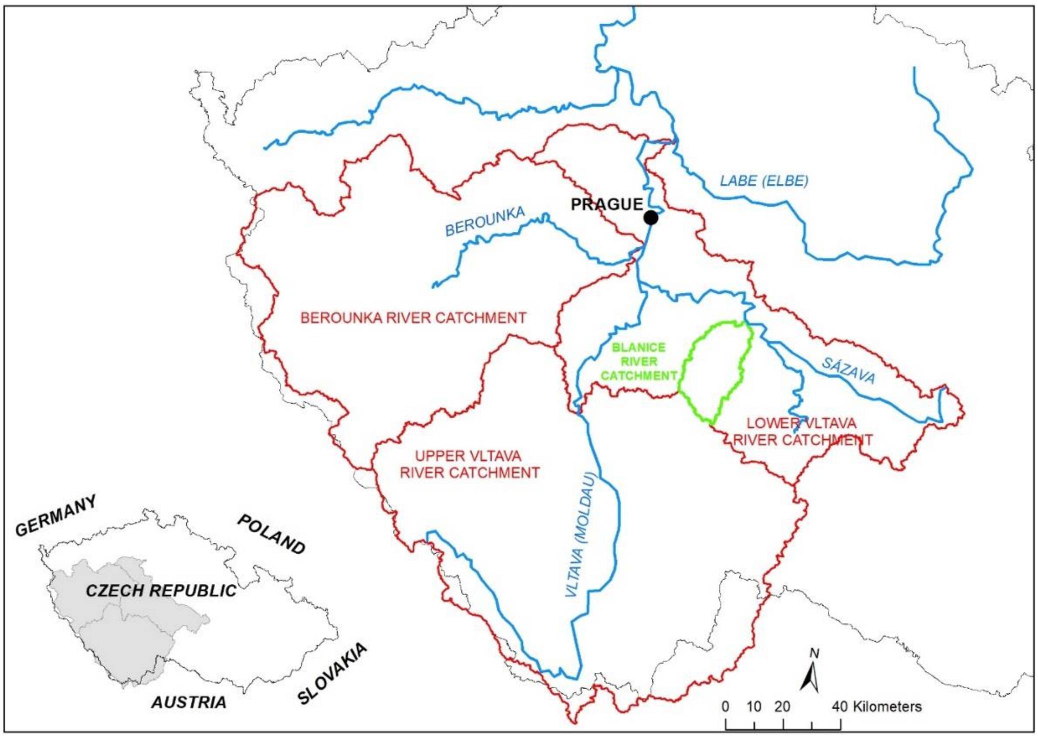


**Figure 1.** The Vltava River watershed with the pilot Blanice river catchment.

**Table 1.** Area of the main individual catchments.

| Subcatchment | Berounka | Lower Vltava | Upper Vltava | Total |
|---|---|---|---|---|
| Area (km$^2$) | 8816.3 | 7249.1 | 10,944.2 | 27,009.6 |

The geomorphic conditions of the area have a fundamental effect on surface runoff and erosion processes. The elevation of the majority of the area varies between 300 to 650 m above sea level. The landscape has morphologically heterogeneous highlands, mostly consisting of vertical arrangements up to 300 m high. Soil conditions crucially contribute to the division of water runoff into the categories of surface, subsurface, and baseflow, and this also determines the soil's susceptibility to erosion processes. The prevailing soil types in the area are cambisols (ca 60%) and pseudo-gleic/gleic (23%).

The size of forest areas is also a very important parameter related to rainfall–runoff conditions. Afforestation in the area of interest is slightly higher than the average value in the Czech Republic and is close to 34%. Smaller forest areas can be found in the intensively farmed northern, lowland area of the catchment (Lower Vltava), ca. 26.6%, while the mountainous areas located in the Upper Vltava and Berounka regions account for ca. 37%. The dominant forest types are coniferous (82%), with the main species being spruce.

Farming in the catchment area focuses on crop production. The crops mainly produced are cereals, but also include rapeseed and maize, which are used to produce oil. At the foothills of the mountains to the south and west of the area, meat-cattle pastures dominate, and in the eastern part of the catchment there is traditionally high potato production. The southern parts of the catchment are well known for their fishpond management and production systems [46].

### 2.2. Definition of the Critical Points

To accurately assess and categorize water non-point pollution sources, we employed the critical points method in the present study [47]. In contrast to the method described by [48], which delineates the critical points associated with the flood risk to settlements, the critical points method used in this study defines these points as being related to quick-surface and drainage runoff/pollution entry into water courses.

The phrase "critical point" is derived from HACCP (Hazard Analysis and Critical Control Point), which is generally used in several areas, ranging from food production [49], where there is a high risk of contamination to the food chain, to water resource conservation [50]. In this study, we defined "critical point" as the intersection of a potentially polluted surface or drainage runoffs with water courses. This definition enabled us to divide the hydrological network into ca. 300 m sections (on average), which was detailed enough to describe potential non-point pollution sources within a catchment and its entry into a water course. The critical points were marked as A (surface pollution sources (A1—water bodies, A2—fourth-order catchments, A3—nodes of ca. 300 water course sections) and B (subsurface (drainage) pollution sources (B1—water bodies, B2—fourth-order catchments, B3—subcatchments, B4—drainage groups). The critical points method was applied to the entire area of the Vltava River watershed and the associated subcatchments to determine the hydrological units at different scales as being affected by non-point pollution sources, their spatial distribution, extent of pollution, and to prioritize the most endangered areas according to the methodology [51].

### 2.3. Categorization of Critical Points Based on Surface Water Pollution Sources

Erosion and sediment transport processes occurring in agricultural (arable) land were modeled using a fully distributed, semi-empirical mathematical simulation model WaTEM/SEDEM [52]. The model is based on the USLE/RUSLE approach combined with the result of surface runoff sediment transport capacity. Soil loss, sediment transport, and erosion phosphorus (P) values were calculated using each single agricultural parcel in a hydrological network and downstream towards the outlet point = critical point. For each critical point, the total annual sediment and phosphorus transport figures were quantified based on the methodology [18,52]. WaTEM/SEDEM acknowledges three sections of the process. The first section presents the net erosion or deposition of sediment in each landscape cell (at a raster resolution of 10 m, in this study). The second section estimates the amount of sediment entering the river network from hillslopes and the flow of sediment through the river network. The third section calculates the amount of sediment trapped in reservoirs based on the user-defined trapping efficiency.

The model has been utilized (and calibrated) numerous times in the Czech Republic [12,53,54], with the parameters being tested and verified to suit the local conditions. The default parameters used in the study, based on the previously calibrated ones, are as follows: Ktc (low) = 35, Ktc (high) = 55, Ktc (limit) = 0.1; Ptef (cropland) = 0, Ptef (forest, pasture) = 75; parcel connectivity (cropland, forest, pasture) = 0, LS and nearing slope exponent [55], where Ktc represents the parameter of transport capacity, Ptef limits the non-arable-land areas, and parcel connectivity represents the border effect of neighboring parcels. A detailed description of the parameters has been published in [53,54].

The distributed R factor values at a 1 km grid resolution for the modeled area were derived by [56] using the Wischmeier methodology, based on processed pluviometric records obtained from the years 2005 to 2012 from 96 stations. Rainfall levels exceeding 12.5 mm and torrential rain levels exceeding 6 mm in 10 min were included in the analysis. The average value for the Czech Republic is 70.3 (MJ $ha^{-1}$ cm $h^{-1}$ $year^{-1}$); the mean value for the study area was 68.6 (MJ $ha^{-1}$ cm $h^{-1}$ $year^{-1}$).

The Land Parcel Identification System (LPIS; 1:10,000 scale) was used to overlay the ZABAGED land-use database. The territory was divided into basic characteristics (arable land, grassland, and forest), and the C factor corresponding to land cover was assigned by [57], based on the USDA handbook 537 [58]. The C factor for arable land was derived as an average value according to the logged crop rotation conducted in each territorial unit (76 districts) considering the altitude of the farmlands in the selected regions [59].

The LS factor was calculated using a laser-scan digital elevation model (DEM) with a spatial resolution of 10 m. The DEM was corrected for sinks. K-factor values were determined according to the national methodology [57], using the map database for valuated soil ecological units (VSEU; BPEJ in Czech, 1:5000 scale). In this study, the hydrological network was modeled as an oriented chart, where erosion sediments were moved downstream along the nodes of the network. Their total amount (annual load) was reduced according to the individual water reservoirs and then increased to account for the contribution to this effect by the arable land located within adjacent subcatchments. The total annual sediment load, sediment transport, and erosion phosphorus transport values were determined for each critical point for a given hydrological unit (A1 to A3). These units were then classified into 5 levels of risk (1—least risky; 5—riskiest).

### *2.4. Categorization of Critical Points Based on Drainage Water Pollution Sources*

Pollution sources caused by tile drainage were assessed and categorized in this study, based on a Catchment Measures Need Index (CAMNI), a methodology derived from studies [51,60]. The CAMNI approach combines soil properties and land use within various landscape zones to obtain the pollution leaching degree, along with the tile drainage extent occurring at a specific spatial unit (B1–4).

The CAMNI value, categorized into 5 risk classes, expresses the necessity of the design and the adoption of control measures to reduce the excess drainage runoff and associated water pollution. The classification of the CAMNI risk classes is presented in Table 2.

**Table 2.** Definition of risk assessment classes for the Catchment Measures Need Index.

| **Catchment Measures Need Index (CAMNI)** | **Classification:** | |
|---|---|---|
| | **Risk Class** | **Necessity of Measures** |
| 1 | Negligible risk | Very low |
| 2 | Low risk | Low |
| 3 | Moderate risk | Moderate |
| 4 | High risk | High |
| 5 | Extreme risk | Very high |

### *2.5. Selection of High-Priority Areas for Water Retention Measures*

To select the hydrological units with a high non-point source water pollution risk and thus in considerable need of water retention measures, a synthesis of A- (surface) and B (drainage)-type endangered areas was performed. For the A-type area, the criteria included high sediment and phosphorus inputs due to surface runoff and soil erosion (i.e., 4th and 5th risk classes); for the B-type area, the criteria included the 4th and 5th risk classes in the CAMNI index. In addition to the inclusion of the separate A- and B-type areas, the intersection of both pollution types was also provided.

### 2.6. Principles for the Design of Water Retention and Pollution Control Measures

The control measures designed in this study were proposed for risky subcatchments to slow down the quick runoff and to decrease the non-point agricultural pollution of both surface and drainage waters. Preference was given to the design of Natural Small Water Retention Measures, mainly technical and, to a lesser extent, land-use-change-measure types (namely grassing). The measures, their design, and placement were based on the catalogue of protective measures (Natural Small Water Retention Measures, NSWRM) [61], adjusted for the conditions in the Czech Republic and prepared within the study (unpublished). The catalogue included a total of 14 types of measures to reduce surface runoff rates and 15 measures to attenuate the drainage flow and related water pollution. Control measures were mostly designed as forming mutually related non-interfering effective combinations in the systems. The main anticipated effects of these systems were surface and drainage water retention and transformation, the support of water self-purification processes, and the retention of nutrients and sediment.

The three following key rules were formulated to fulfil the public's interests in terms of water quality and quantity [47], which were then applied during the NSWRM design and placement process:

1. Keep and retain water in the upper or central parts of the headwater catchments, e.g., by using technical retention measures or permanent buffer strips. Such technical measures must at least possess a passive system for outlet-water regulation, which promotes water retention, accumulation, and/or infiltration.
2. The subsequent measure concerns the transformation/capture of nutrients and particles in buffer strips, wetlands, small water reservoirs, etc. This is also applicable to drainage water management and measures.
3. Finally, where applicable, water should be stored for future use. This includes water reservoirs, ponds, polders, but also infiltration into soil and geological structures.

### 2.7. Effectiveness of the Proposed Measures

The effectiveness of the designed measures was evaluated in our study for the Vlašimská Blanice catchment (Radonice catchment outlet) with an area of 543 km$^2$. This catchment was selected due to its high-threat status caused by both surface and drainage pollution sources. An assessment of the effectiveness of the designed measures was conducted for the individual catchments of the 4th order, separately for surface and drainage pollution sources. The effects of the measures oriented towards the mitigation of surface pollution sources were assessed using the same mathematic tools and approaches as those employed for their identification and classification. An overview of the implemented measures for surface runoff and soil erosion control is presented in Table 3. Compared to the measures utilized for land drainage purposes, measures focusing on surface runoff and soil erosion were implemented in the watershed area and the effectiveness was evaluated at the catchment scale for the set of designed measures. For these reasons, no direct effectiveness of each single measure could be provided. The effectiveness was assessed according to two criteria:

Effectiveness 1—sediment/phosphorus transport.

Effectiveness 2—soil loss.

A detailed description of the approaches used for the assessment of the effectiveness of the surface water pollution measures incorporated in the experiment is presented in [18].

**Table 3.** An overview of control measures implemented in the sediment transport model to reduce non-point source water pollution (runoff and sediment transport).

| Control Measures Implemented in WaTEM/SEDEM Model |
|---|
| Wetland located at the outlet of the drainage system |
| Re-opening or elimination of drainage systems |
| Re-opening of main drainage structures (channels) |
| Hedges |
| Linear vegetation |
| Erosion control swale/ditch |
| Retention swale/ditch |
| Drainage canal |
| Field road with erosion control function |
| Dry pond |
| Erosion control reservoir/pit |
| Afforestation |
| Grassed waterways |
| Grassed buffer stripes |

The effectiveness of the control measures focusing on drainage water pollution was assessed as a reduced contribution of the drainage systems to nitrate–nitrogen (both concentration and flux) being the main pollutant for the 4th-order catchments in Czechia [11,62]. The effectiveness was assessed in two steps: the first step determined the contribution of drainage systems to the total pollution caused by nitrates under recent conditions, while the second step considered the potential effect of designed measures on reducing pollutant transport from the individual catchments.

The following parameters were used to determine the recent pollution: (a) total drained area within the assessed 4th-order catchments; (b) land-use of the drained land; (c) specific drainage runoff and nitrate concentration present in drainage runoff, based on the previous research and approaches [13,16,17,62–64].

The effectiveness of the measures related to land drainage was derived and applied in the study, based on the authors' knowledge as well as based on the results obtained from similar conditions described in the literature. An overview of the measures and effectiveness related to drainage flows and N-$NO_3^-$ concentrations applied in this study is presented in Table 4. For the purposes of this study, the average values presented in Table 4 were applied.

**Table 4.** Effectiveness of measures on land drainage as used in this study.

| Control Measures on Land Drainage | Reduction of Drainage Flow (%) | | | Reduction of N-$NO_3$ Concentration (%) | | |
|---|---|---|---|---|---|---|
| | Max. | Min. | Avg. | Max. | Min. | Avg. |
| Biofilter related to drainage system [65–68] | 25 | 10 | 15 | 80 | 40 | 60 |
| Controlled, spontaneous aging of drainage systems [69] | 100 | 75 | 87 | 90 | 25 | 50 |
| Local elimination of drainage [69] | 75 | 25 | 50 | 75 | 25 | 50 |
| Wetland located at the outlet of the drainage system [66,70,71] | 25 | 10 | 15 | 99 | 50 | 75 |
| Root-bed treatment system at the outlet of the drainage system [66,67,70,71] | 25 | 10 | 15 | 50 | 10 | 25 |
| Re-opening or elimination of drainage [69] | 100 | 50 | 75 | 50 | 1 | 25 |
| Re-opening of main drainage structures (channels) [69] | 100 | 50 | 75 | 50 | 1 | 25 |

**Table 4.** *Cont.*

| Control Measures on Land Drainage | Reduction of Drainage Flow (%) | | | Reduction of N-$NO_3$ Concentration (%) | | |
|---|---|---|---|---|---|---|
| | Max. | Min. | Avg. | Max. | Min. | Avg. |
| Total elimination of drainage [69] | 100 | 75 | 87 | 90 | 25 | 50 |
| Local transfer of drainage waters [69] | 75 | 25 | 50 | 75 | 25 | 50 |
| Subcatchment transfer of drainage waters [69] | 100 | 75 | 87 | 75 | 25 | 50 |
| Controlled drainage—main drains (ditches or large pipes) [66,72–74] | 50 | 20 | 35 | 75 | 25 | 50 |
| Controlled drainage—collective drains [66,72–74] | 75 | 25 | 50 | 75 | 25 | 50 |
| Decrease in drainage intensity—curtain [69] | 65 | 15 | 40 | 65 | 15 | 40 |
| Small pool connected to drainage [66,67] | 50 | 10 | 25 | 25 | 10 | 15 |
| Afforestation of drained agricultural land [69] | 100 | 75 | 87 | 99 | 75 | 90 |
| Infiltration drain [69] | 100 | 25 | 50 | 99 | 50 | 75 |

## 3. Results

### *3.1. Surface Pollution Sources*

In total, over 116,000 critical points of a detailed level (A3), 3000 critical points as outlets of the fourth-order catchments (A2), and 400 points of the third spatial category (outlets of water bodies according to the WFD) (A1) were identified and assessed within the whole Vltava River watershed. These hydrological units were analyzed for erosion sediment transport and erosion P input factors in a hydrographical network and correspondingly classified into five levels of risk (I—low risk; V—severe risk); see Figures 2 and 3. The individual colors represent the input of sediment/P into water courses, recalculated per unit area.

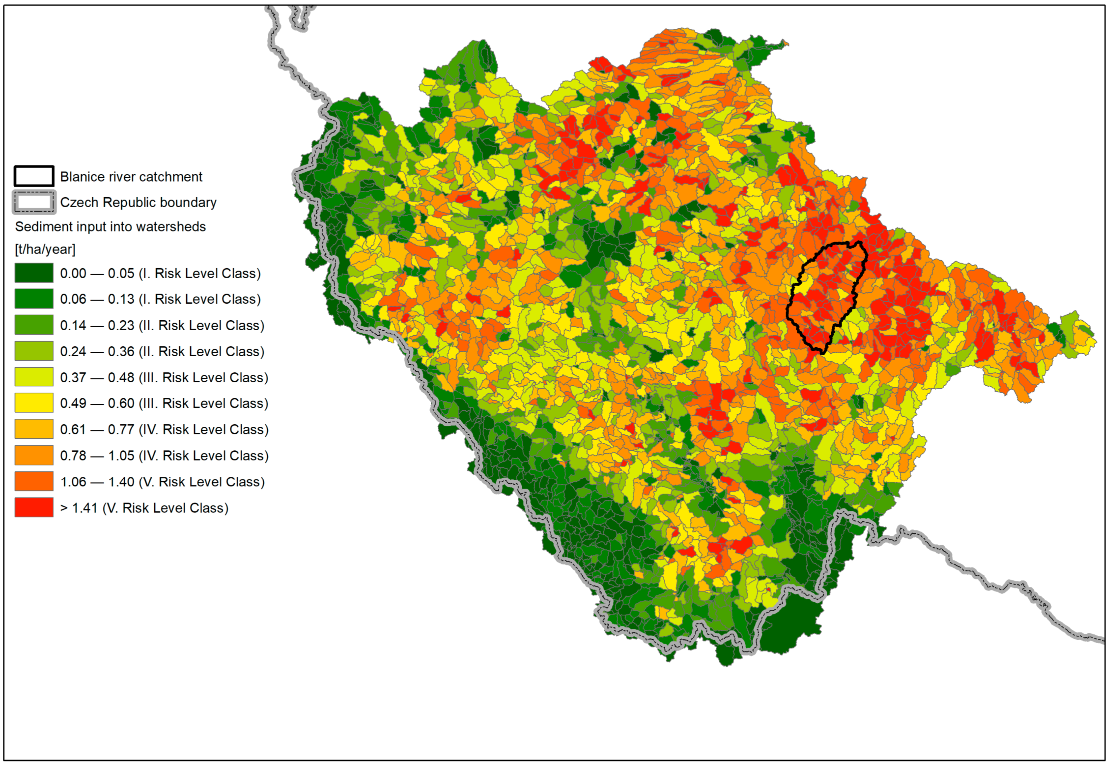


**Figure 2.** Sediment input into fourth-order catchments for the entire Vltava watershed area.

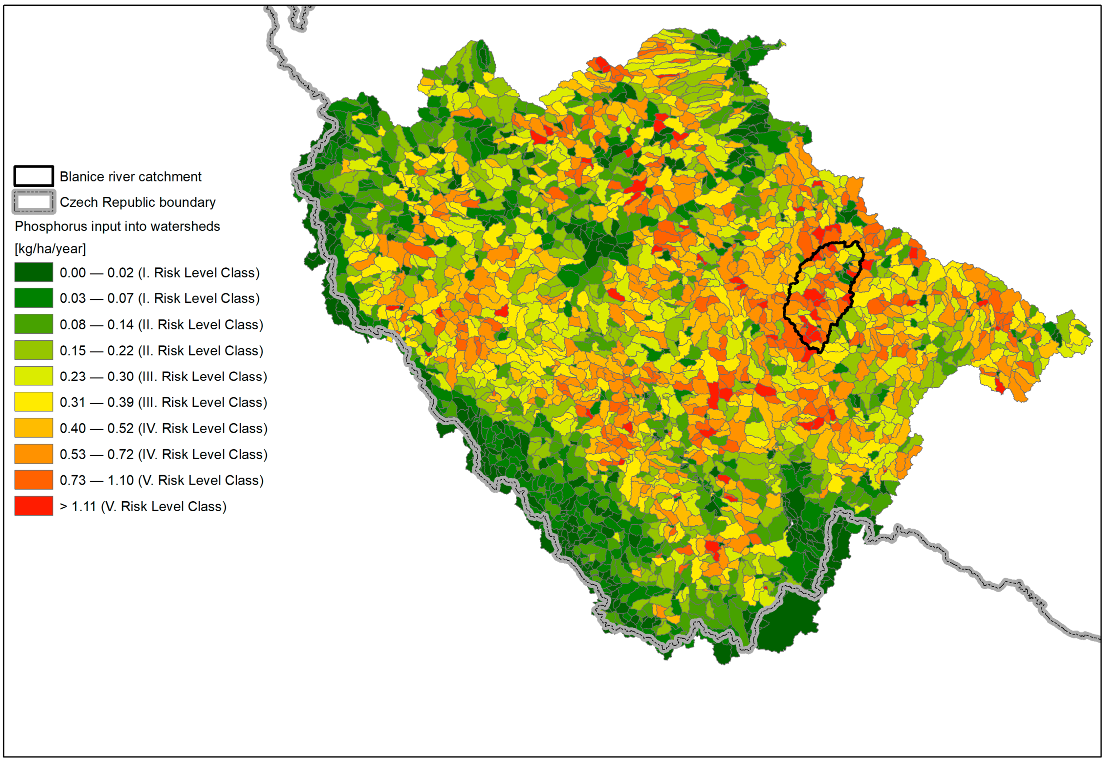


**Figure 3.** Erosion phosphorus input into fourth-order catchments for the entire Vltava watershed area.

These pictures provide a good overview of the effect of agricultural land-use together with the geomorphology concerning erosion intensity and eroded material input into water courses. Altogether, 1432 fourth-order catchments, mostly with a higher elevation, and less arable land, presented a significantly lower amount of transported eroded material (mostly risk level 1, transport into watercourse at catchment scale lower than 0.13 t·ha$^{-1}$·year$^{-1}$) and also negligible erosion P entering the water bodies. Contrastingly, for 445 fourth-order catchments with risk levels 4 and 5, more than 0.6 t·ha$^{-1}$·year$^{-1}$ (in extreme conditions, this can even be over 1.4 t·ha$^{-1}$·year$^{-1}$) is transported into the streams polluting river net system and water bodies. The pictures also show that the magnitude of erosion P input into water courses depends on the erosion intensity and also on the P concentrations in agricultural soils. Therefore, the catchments that are assessed as being at greatest risk by P transport are not identical to those exhibiting sediment transport (1465 fourth-order catchments with lowest-risk catchments less than 0.07 kg·ha$^{-1}$·year$^{-1}$; 448 fourth-order catchments with highest-risk levels 4 and 5 over 0.4 kg·ha$^{-1}$·year$^{-1}$ or over 1 kg·ha$^{-1}$·year$^{-1}$, respectively.

### *3.2. Drainage Pollution Sources—Critical Points and Their Categorization*

For all hydrological units with critical points, the CAMNI values were determined and then converted into risk levels within the entire Vltava River watershed area. From a total 138 assessed water bodies, according to CAMNI, 19 were classified as risk level 5 (extremely high need of control measures), while 25 were categorized as risk level 4 (high need of control measures). On the other hand, for 26 water bodies, the need for control measures was assessed as being either very low or low. Concerning the fourth-order catchments, 279 were classified as category 5. In greater detail, a total of 12,819 subcatchments in the 3rdcritical points category were identified, of which 2008 were classified as CAMNI category 5—where a proposal for control measures is highly desirable; see Figure 4.

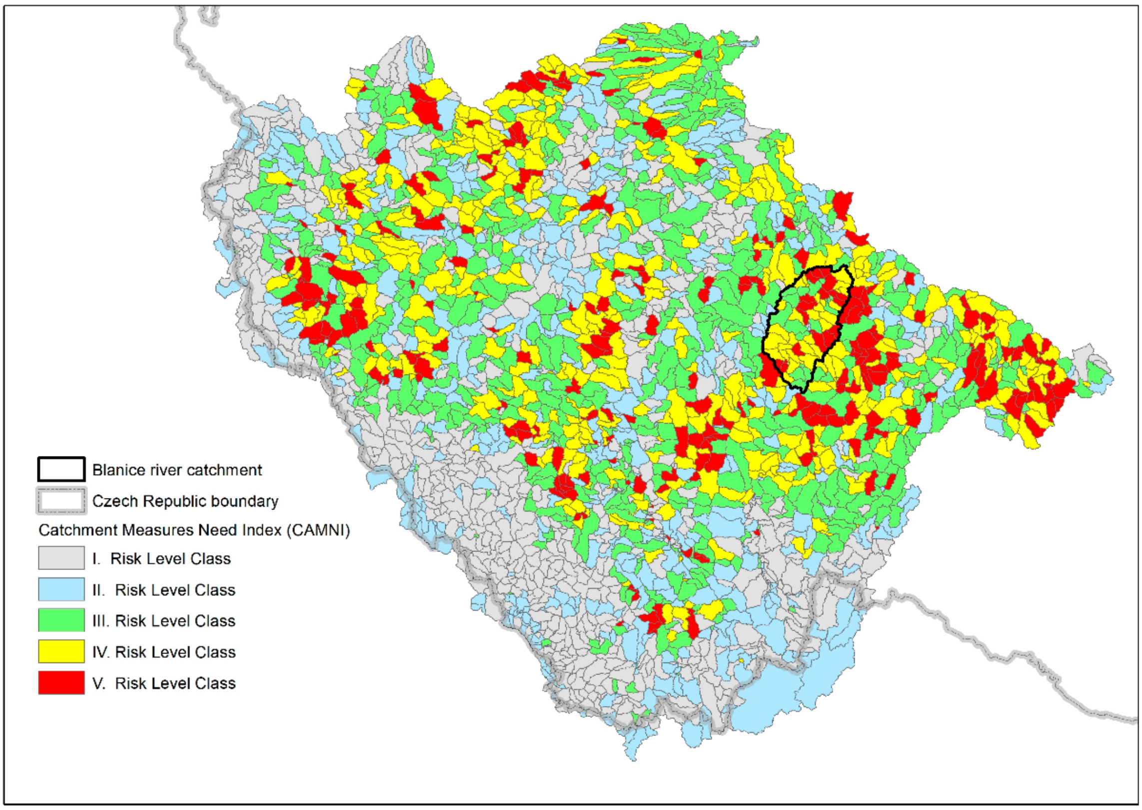


**Figure 4.** CAMNI classification of fourth-order catchments for the entire Vltava watershed area.

The above-mentioned CAMNI classification at the fourth-order catchments level was compared and calibrated against a long-term water quality monitoring program provided by the Research Institute for Soil and Water Conservation [16,63,75] and a satisfactory accordance was determined. The measured N-$NO_3$ concentrations in the drainage waters, weighted by discharge (flow-weighted concentrations; Cfw) increased in line with the increasing risk level, as determined by CAMNI. Average Cfw N-$NO_3$ 9.6 mg·$L^{-1}$ was determined for CAMNI category one, while in the case of CAMNI 3, Cfw N-$NO_3$ was 13.1 mg·$L^{-1}$, and for CAMNI 5, Cfw N-$NO_3$ accounted for 17.8 mg·$L^{-1}$. To correctly interpret the CAMNI categorization of individual fourth-order catchments, the recalculation of drainage contribution to a particular spatial unit of assessed subcatchment was necessary. In this study, the average specific drainage runoff of 0.1 L·$s^{-1}$·$ha^{-1}$ was applied for drainage hydrology and evaluating the drainage-related measures, as reported by [16,76,77]. For the catchments classified as category CAMNI 5, this contribution was determined as 2290 kg N-$NO_3$·$year^{-1}$·$km^{-2}$, while for the CAMNI 3 catchments, it was 1241 kg N-$NO_3$·$year^{-1}$·$km^{-2}$, and for CAMNI 1, it was 796 kg N-$NO_3$·$year^{-1}$·$km^{-2}$.

### *3.3. Effectiveness Assessment of the Designed Control Measures*

The effectiveness of the designed measures was assessed for seventy-one fourth-order catchments that comprise the Vlašimská Blanice river watershed. In total, thirty-one of them were classified in categories 4 to 5, according to the surface pollution sources, and fifty of them were assessed as risky (CAMNI categories four and five) according to drainage pollution. The proposal for mitigation measures was only applied to the selected risky catchments due to the specifications of the related project of the Vltava River Management Authority.

#### 3.3.1. Surface Water Pollution Sources

When the effect of the designed soil erosion control measures system was assessed in the study for sediment transport through outlet profiles of the individual fourth-order catchments, the average reduction value was 43%. The minimum effect was 0% (in one case) and the maximum effect was 84%. The effect of designed soil erosion control measures on sediment transport through outlet points of the evaluated catchments is presented in Figure 5.

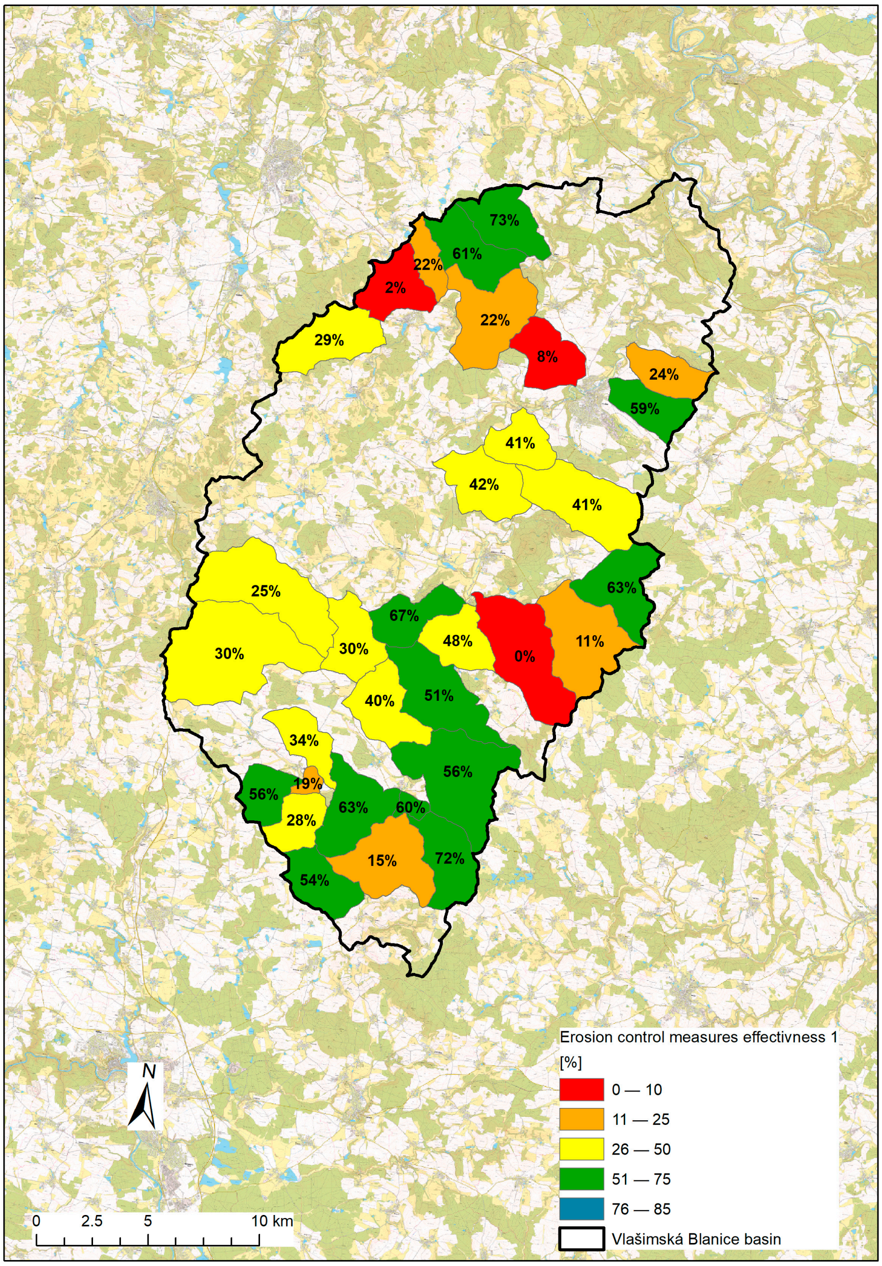


**Figure 5.** Assessment of erosion control measures of effectiveness 1 in terms of sediment transport.

If the effect was assessed in terms of the reduction in sediments transported into water courses within the assessed catchments, the average value was 36%. The minimum reduction that was observed accounted for 0% (for one subcatchment); the maximum effect was 69%.

The effect of designed soil erosion control measures on reducing the soil loss from agricultural land within the individual catchments was 16% on average. The minimum soil loss reduction of 0% was identified within two catchments, while the maximum reduction was 34%. The effect of designed soil erosion control measures on the soil loss from the individual catchments is presented in Figure 6.

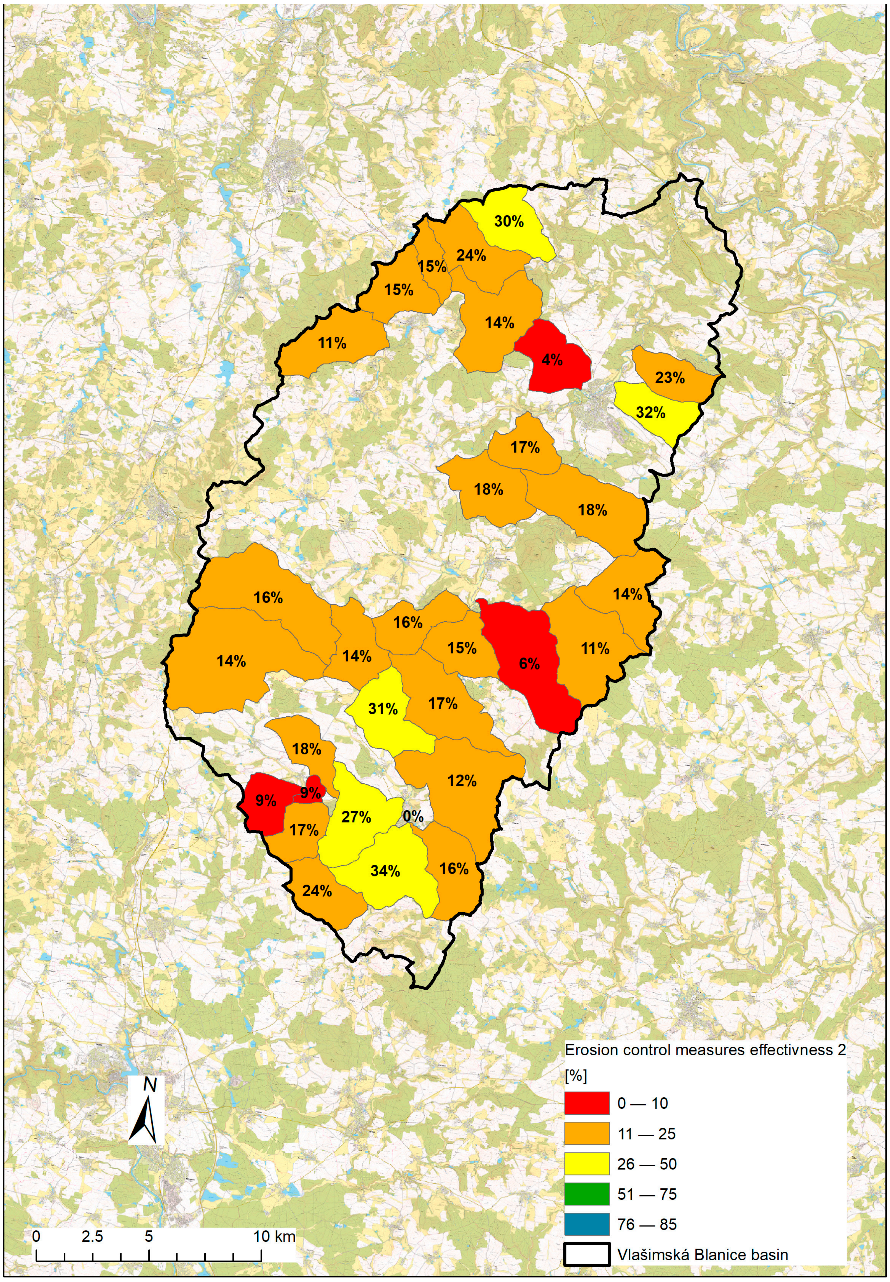


**Figure 6.** Assessment of erosion control measures of effectiveness 2 in terms of the soil loss from agricultural land.

### 3.3.2. Drainage Pollution Sources

The measures focused on the abatement of drainage water pollution concentrated in 26 fourth-order catchments. In total, 496 control measures were designed to reduce N-$NO_3$ transport by drainage systems, which affected 38% of the drained area within the entire Vlašimská Blanice watershed. These measures mainly concerned diverting or controlling drainage runoff, the opening of drains, the design of pools, wetlands, and biofilters.

To estimate the effectiveness of the proposed interventions on land drainage, the first step was to quantify the recent contribution of the drainage systems to the total N-$NO_3$ load in the individual fourth-order catchments. The total N-$NO_3$ load in the fourth-order catchments varied between a value close to 0 (catchments without drainage systems) and 20.1 tons of N-$NO_3$ per year. The mean value of N-$NO_3$ transport from individual catchments was 5.8 t·year$^{-1}$. Based on this assumption, the total contribution of drainage systems in the entire Vlašimská Blanice watershed area to the nitrate–nitrogen load was estimated as 411.4 t·year$^{-1}$. The transported amounts related to individual CAMNI risk levels are presented in Table 5, including specific N-$NO_3$ transport per 1 km$^2$ of a catchment, which was estimated as 708 kg·year$^{-1}$·km$^{-2}$.

**Table 5.** Nitrate loads the fourth-order Blanice river catchments according to CAMNI risk classes.

| Risk Class—CAMNI | 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|
| Number of catchments (n) | 2 | 2 | 17 | 31 | 19 | 71 |
| Mean transport of N-$NO_3$ (kg·year$^{-1}$) | 20 | 274 | 4567 | 6127 | 7540 | 5795 |
| Mean specific transport of N-$NO_3$ (kg·year$^{-1}$·km$^{-2}$) | 24 | 207 | 414 | 767 | 998 | 708 |

The subsequent step was to determine the effectiveness of designed control measures in the individual fourth-order catchments. One up to thirty-five measures were designed per single catchment, and the affected area varied from 6 to 92% with an average value of 38% drained areas within the catchments. The reduction in the N-$NO_3$ flux caused by the designed control measures applied to the catchments varied between 3 to 85%, with a mean value of 25%. The results of the nitrate–nitrogen reduction for the fourth-order individual catchments are presented in Figure 7. Generally, the larger the area affected by the drainage systems within a given subcatchment, the greater the nitrate transport reduction rate. In some cases, the measures designed to primarily reduce surface pollution masked this trend—especially for grass strips and grassed waterways. The total reduction rate of the subsurface transport of nitrogen within the entire Vlašimská Blanice catchment was assessed as 24%. When recalculated to absolute values, it represented a reduction rate of 55.1 t·year$^{-1}$ of N-$NO_3$.

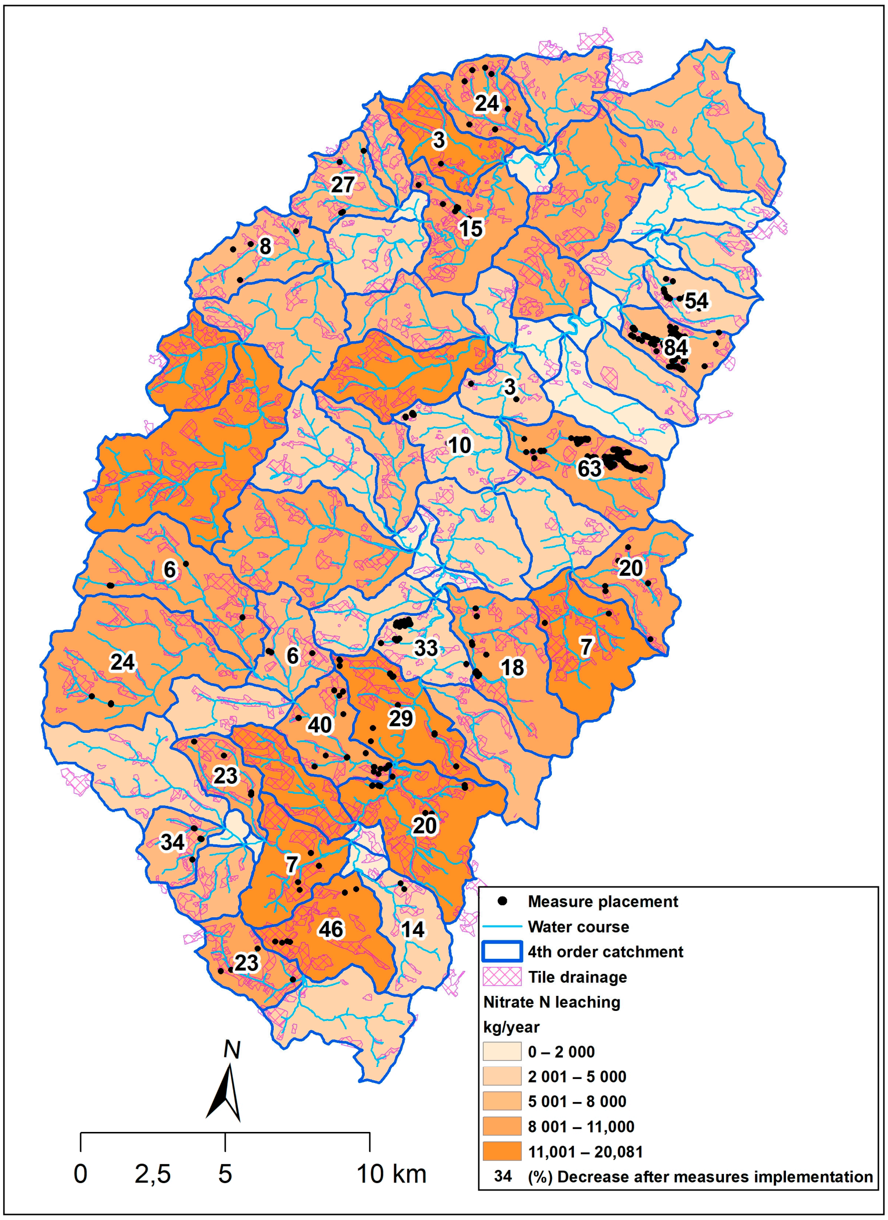


**Figure 7.** Reduction (%) in N-$NO_3$ transport via drainage runoff after adopting the control measures.

## 4. Discussion

The results of the analysis showed the extensive threat to the pilot catchment both by surface and subsurface non-point water pollution sources. The applied technique worked with both types of pollution and, moreover, it enabled us to assess the catchments (and smaller hydrological units) with an insufficient catchment water retention capacity, where both types of quick runoff and associated pollution occurred. The correct spatial targeting of the appropriate measures is necessary in terms of achieving successful implementation of programs to improve the ecological status of the agricultural landscape [78]. Recently, many studies focused on approaches for the delineation of risky areas and demonstration of methods for prioritization nature-close interventions on agricultural land to mitigate quick runoff and non-point water pollution sources at various scales [40–45]. The advantage of these methods is the applicability of a uniform methodology for identifying vulnerable areas with different spatial scales. The method presented in this study can be used to identify vulnerable water bodies, the most vulnerable fourth-order catchments that comprise them, and the sub-basins in the most vulnerable catchments where it is more necessary to propose such measures. The correct identification of vulnerable sites was confirmed, in terms of surface runoff by a mathematical model, and in terms of subsurface runoff and water pollution by water quality monitoring, not only for this site of interest, but also elsewhere [60,75]. The list of proposed measures implemented in this paper is longer than that presented in similar studies [40–45]; nevertheless, the principles used to determine their precise location remain analogous. However, for studies conducted in the future, it is a priority to automate these principles as an easily applicable GIS tool.

The effectiveness of the measures proposed in this study was shown to be relatively high in catchments where an optimum number of NSWRMs was designed using a hydrologically continuous system [60]. Moreover, these systems of measures allow the quick runoff and the associated pollution to be managed in the headwaters of vulnerable catchments, positively affecting both water quality and quantity in their outlets [42].

There were some limitations to our study that were related to the influence of individual measures as well as of the measures systems on different runoff components and processes (overland flow, baseflow, infiltration, evaporation), as well as on water quality dynamics for various hydrological scenarios. This fact is due to a certain lack of longer time monitoring data from implemented NSWRM, and especially of the mutually interconnected systems of several measures. The data shortage has been expressed by several authors in their studies, and, moreover, the demand for such complex data and information has also been extensively expressed [41,44,66,78–80].

A general agreement exists across the mentioned studies concerning the need for increasing the catchment water and nutrient retention capacity, as the periodicity and magnitude of extreme hydrological events tend to escalate due to climate change. The annual rainfall sum in central Europe in recent years has remained at approximately the same level; however, the temporal distribution, number of events, and intensity has changed during the last 15 years [81]. The profound dry periods experienced in recent years has shown that precipitation cannot be the only origin to maintain water resources under the conditions prevailing in the Czech Republic. Moreover, drought is most likely responsible for the decreased catchment retention capacity for nutrients, especially in homogeneous, low diverse catchments [82]. Overall, the considerable extent and intensity of both forms of non-point source water pollution is related to recent climate change as well as intensive farming practices, which pose new challenges in terms of food provision, soil conservation, and integrated catchment management [33,83].

To increase the proportion of rainwater storage available in agricultural areas and to improve water quality, revised legislations and incentives need to be implemented for the 2024+ period to eliminate the barriers of NSWRM adoption [28,84]. Furthermore, to date, the water retention control measures (or NSWRMs) targeted to agricultural land were designed with a precipitation periodicity of only N = 10–20. Such dimensioning or an adoption of soft agrotechnical measures merely, as applied within Good Agricultural and Environmental Conditions (GAECs) or in the land consolidation process in the past, is not sufficient to address the sustainable soil and water conservation practices considering the climate change conditions and anticipated agriculture demands [28,32,47,85–87]. Nevertheless, the agricultural policy and setting of the associated standards defined by governments have a crucial effect on water quality [88–90]. The permissive GAEC setting applied in Czechia in the past can be explained mainly by socio-economic factors [46,91,92]. During the period of 1990–2004 (from the Velvet revolution to the accession to the EU), farmers in the Czech Republic were not able to compete in the market. Therefore, the GAEC control measures focusing on water quality and retention were designed in a way that did not harm the farmers on an economic basis. Economic forces and the orientation towards the agricultural economy turned the farmers' interests to stable and profitable products (small grains and rapeseed oil) and intensive maize production, which was related to the considerable governmental support of biogas stations. In 2017, these three crops were produced on 74.06% of the total arable land in the Czech Republic [93]. Soil conservation crop rotation became very limited due to the economic orientation towards these three main crops. Due to the reduction in fodder crops on arable land and the decline in livestock production (within the EU market), the supply of organic matter decreased across the whole of Europe.

It is clear that the most effective control measures to improve landscape retention capacity and water quality include permanent grassing and technical water management control measures on agricultural land [27,28,40–46,57,61,66]. These measures, essential to be present in the landscape, are being prepared as "non-economically productive investments" and "eco-schemes," and farmers should be able to use them soon as nature-close measures within the available state-supported programs [47,84,92]. It is essential to properly implement them either in land consolidation practices or to substitute and improve the effectiveness of GAEC's, which are well-organized and -supported; however, they do not work well in the case of average-to-high rainfall–runoff events or longer dry periods. The readily available methods for the prioritization of hydrological units with a considerable need for the adoption of structural water retention measures as well as advanced techniques for NSWRM designs and placements [40–45] and this study support their inclusion in watershed management plans. However, to successfully introduce these steps and to employ a complex approach require a comprehensive, whole-basin survey, including SWOT and cost–benefits analyses, as well as the appropriate engagement of different stakeholders, ranging from regional policy makers and municipalities to farmers and landowners [94–96].

## 5. Conclusions

This study presented a novel approach applied by the largest water management authority in the Czech Republic, Vltava River Basin Management Authority, state enterprise, to attain the WFD standards and requirements and to respond to climate change. The method presented in this study identified the critical points related to water courses and surfaces, where the delivery of soil erosion products and pollution from tile drainage was assessed using GIS-related models and techniques, as well as newly derived empirical relationships based on natural catchment, geomorphological, and agricultural characteristics. The critical points were hierarchically defined within four categories based on hydrologically related contribution areas and their connectivity. This network spanned from a small subcatchment (tens of hectares) area to the water body level (hundreds of square km). The results of this study are available for the River Basin Management Plans for the Vltava River watershed area, where, in accordance with the WFD, the sheets of control measures type A, i.e., focusing on land parcel scale, are required. All the above-mentioned facts can crucially affect the practical implementation of catchment management approaches within the Czech landscape after the year 2023. Given the general agreement among scientists, governments, and stakeholders concerning the control of diffuse agricultural pollution sources, the clear necessity of agricultural landscape transformations and careful land-use planning exists to fulfill the WFD requirements in the Czech Republic.

The designed control measures are multifunctional in many cases, which were not entirely addressed in this study. They might promote the cooling effect of vegetation, support carbon sequestration by vegetation, decrease agronomic drought, and support the biological diversity of agricultural landscapes. At the same time, many of the NSWRMs, when properly designed, could initiate water accumulation below surfaces, ensure well-balanced discharges in small streams, and support water self-sufficiency within small catchments where no water reservoirs are planned or were constructed. The approach presented in this study presents a possible direction for the future research towards adopting and fulfilling the WFD requirements in the Czech Republic and central Europe and towards adapting the landscape to climate change and related societal challenges.

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