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# Nitrate Concentration in Leachate—Essential Information for Reducing Nitrogen Surplus and Groundwater Pollution from Agricultural Land in Slovakia

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**Abstract:** The aim of the study was to detect nitrate concentrations in leachate within agricultural land in three districts of Slovakia, namely Nitra, Nové Zámky and Dunajská Streda as well as in the DEEPWATER-CE pilot area. Using the average values of leachable nitrogen in the period 2015–2018 and the long-term amount of percolated water, the nitrate concentration values in leachate were detected. In most defined groundwater monitoring sites, the current nitrogen surplus and corresponding nitrate concentration in leachate create preconditions for the gradual reduction of groundwater nitrate pollution. However, in some groundwater monitoring places, especially in the Nitra district, the nitrate concentration in leachate exceeds 50 mg $L^{-1}$, which is completely unacceptable from the point of groundwater pollution. In detected hot-spots, it is necessary to reduce the nitrogen surplus up to 15 kg $ha^{-1}$ on average per year. In this sense, the nitrate concentration in leachate is an important indicator for the revision of existing measures in agriculture.

**Keywords:** Nitrates Directive; groundwater pollution; leachable nitrogen; nitrate concentration

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## 1. Introduction

Groundwater pollution by nitrates remains a persistent environmental problem requiring more attention. The importance of this topic is confirmed by many findings at both national and international levels [1–5]. Although considerable effort has been made to reduce nitrate concentration in water, especially since the enactment of the Nitrates Directive (91/676/EEC), the expected effect in groundwater has not been reached [2,6–8]. In addition, reaching the limit established by the Nitrates Directive can take decades in many locations owing to low rates of degradation or long lag times in the transport of water and solutes in the vadose and saturated zones [9–13].

Nevertheless, as indicated by the EU Biodiversity Strategy to 2030 and the Farm to Fork Strategy, the European Commission continues to promote further reduction of fertilizer application as well as the reduction of unproductive nutrient losses into the water and air. Therefore, the issue of reduction of above-limit nitrate concentration in groundwater remains highly pertinent from political, scientific and best-practice viewpoints.

Although the excessive load of nitrogen from agricultural practices is still considered a primary reason for water pollution by nitrates, current information on nitrogen surpluses and nitrate concentration in groundwater shows that there is not always a direct or unambiguous relationship between these two indicators [14–16]. Clearly, the nitrogen surplus, the qualitative risk of groundwater pollution by nitrogen [17–21] and the leaching rates of nitrogen into the waters [15,22–25] can serve as the basis for relevant hot-spot definition.

However, the consideration of hydrological or hydro-geochemical properties of a specific site [5,7,9,10,26,27] is essential in assessing the impact of leached nitrogen on overall nitrate concentration in groundwater and on the sufficiency or inadequacy of the measures taken. Consequently, the targeted addressing of the problem in hot-spots where nitrate concentration in seepage water exceed the Nitrates Directive limit is essential [1,28–31]. This is particularly important in aquifers, where the capacity to reduce nitrates is low or depleted and dilution represents the only mechanism for decreasing nitrate concentration in groundwater [26].

Until the whole country is included in the Nitrates Directive vulnerable zones, these could serve as priority areas for the implementation of more targeted and consistent measures. As is being documented by a significant number of publications [27,29–34], even within defined vulnerable zones, the efficiency of adopted measures is significantly influenced both by their allocation and the character of soil-climatic and hydrological conditions.

As was already mentioned, the diffuse pollution of groundwater by nitrates, in which agriculture plays a significant role, represents an issue to be addressed systematically. Any consolidation of existing measures or the adoption of new ones should be enforced on the basis of objective comprehensive information [5,9–13,35,36] and not only as a result of longing public expectations and force majeure occurrence [12]. Otherwise, the much-needed cooperation between the water management sector and agriculture remains suboptimal.

Therefore, the study, based on the examples of selected districts, aims to detect current nitrate concentration in leachate from utilized agricultural land, which provides immediate information to improve of efficiency of relevant measures in agriculture. The relatively simple procedure developed for this purpose consists of several consecutive steps: (1) the determination of nitrogen surplus within utilized agricultural land, (2) the determination of the amount of leachate, (3) the determination of leachable nitrogen and its conversion to nitrates, (4) the delineation of areas where nitrate concentration in leachate exceeds 40 mg $L^{-1}$, and (5) the quantification of nitrogen surplus to be reduced.

## 2. Materials and Methods

### *2.1. Delineation of the Evaluated Area*

In Slovakia, the Nitrates Directive vulnerable zones (VZs) represent the agricultural land in relevant municipal cadasters, and their list is revised every four years. With respect to the availability of input data for the nitrogen balance calculation, the local administrative units LAU-1 (districts) were applied.

Evaluation was focused on the two districts where groundwater pollution by nitrates from agricultural land is the most extensive and requires increased attention. These are the Nitra (NR) and Nové Zámky (NZ) districts, located in the western part of Slovakia (Figure 1). The choice was primarily based on the highest proportion of the groundwater monitoring sites with nitrate concentration equal to or over 50 mg $L^{-1}$ as well as the monitoring sites with elevated average nitrates concentration in range 40 to 49.99 mg $L^{-1}$ with an increasing trend in the period 2016–2019. The share of preselected monitoring sites with defined nitrate concentrations was 52.2% (NR) and 49.2% (NZ)—see Table 1.

Additionally, the district of Dunajská Streda (DS) was included, although the share of monitoring sites with nitrate concentrations equal to or over 40 mg $L^{-1}$ was more than five times lower (9.0%). The reason for its inclusion was that a large part of this district and its utilized agricultural land (UAL) belongs to the most important protected area of natural water accumulation (PANWA) in Slovakia—Žitný ostrov—see Figure 1. Therefore, the monitoring sites with nitrate concentrations 25–39.99 mg $L^{-1}$ with an increasing trend were also included (see Figure 2, Table 1). In this district, within the DEEPWATER-CE project, one of the pilot areas was selected in order to investigate possibilities of groundwater recharge (latter pilot area, PA)—see Figure 2. Therefore, this territory was separately evaluated.

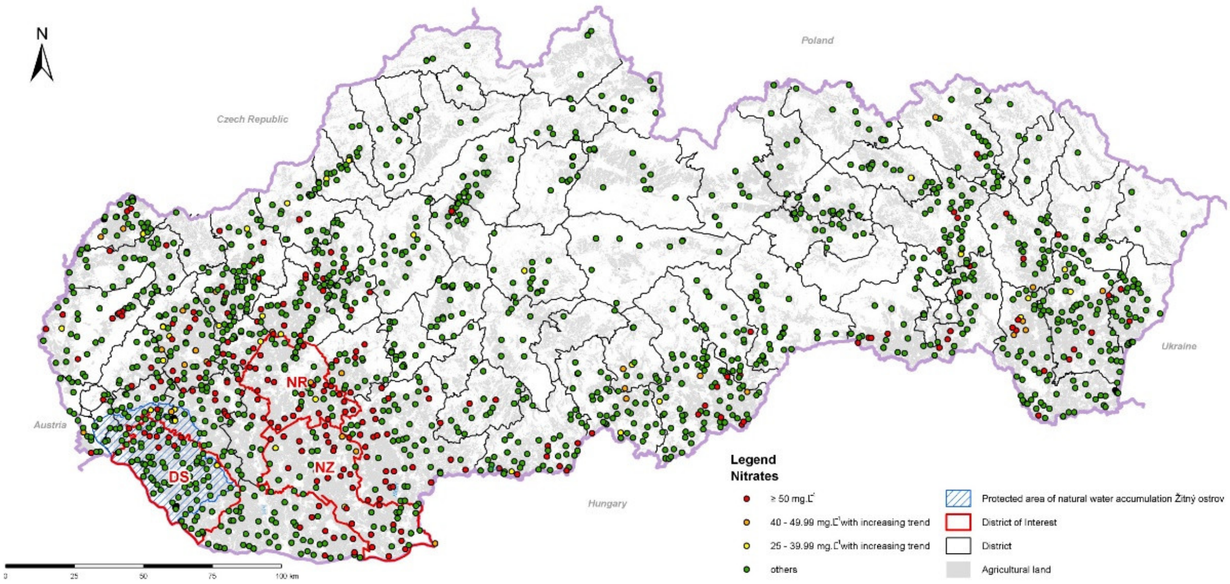


**Figure 1.** Spatial distribution of defined average nitrate concentrations in groundwater in 2016–2019 and allocation of selected districts.

**Table 1.** Relative share of groundwater monitoring sites (%) with defined nitrate concentrations (mg $L^{-1}$) of the total within UAL of selected districts and pilot area.

| District/Area | Relative Share of GW Monitoring Sites (%) | | |
|---|---|---|---|
| | **25–39.99 (mg $L^{-1}$) (Increasing Trend)** | **40–49.99 (mg $L^{-1}$) (Increasing Trend)** | **50 and More (mg $L^{-1}$)** |
| Nitra | 0.0 | 2.2 | 50.0 |
| Nové Zámky | 0.0 | 6.6 | 42.6 |
| Dunajská Streda | 0.8 | 0.8 | 8.2 |
| Pilot area | 0.0 | 0.0 | 0.0 |

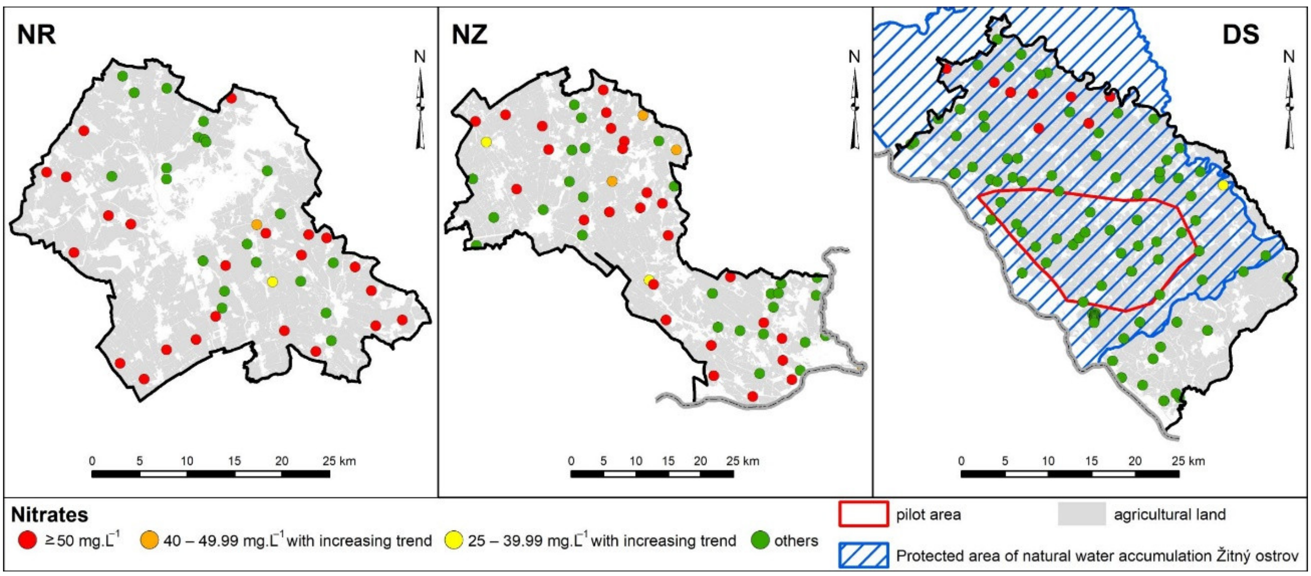


**Figure 2.** Spatial distribution of defined average nitrate concentrations in groundwater in 2016–2019 within selected districts and pilot area.

It should be recalled that the number of groundwater monitoring sites and the corresponding average values of nitrates in groundwater are based on the most recent data of the 2016–2019 period specified in the current report on the implementation of Council Directive 91/676/EEC in Slovakia [6].

Regarding agricultural land use, arable land, which includes kitchen gardens, is the clearly dominant type—over 97% of UAL. This modality is typical of intensively used agricultural areas in Slovakia while permanent cultures (orchards and vineyards) and permanent grasslands generally represent very small shares (see Table 2). The distribution of soil types classified by World Reference Base for Soil Resources—WRB (2015) is shown in Table 3.

**Table 2.** Relative share of arable land, permanent grasslands and permanent cultures within UAL of selected districts/areas of Slovakia.

| District/Area | Utilized Agricultural Land (Thou. ha) | Relative Share (%) | | |
|---|---|---|---|---|
| | | Arable Land and Kitchen Gardens | Permanent Cultures | Permanent Grasslands |
| Nitra | 60.32 | 97.62 | 1.72 | 0.66 |
| Nové Zámky | 107.90 | 97.06 | 1.81 | 1.13 |
| Dunajská Streda | 75.04 | 98.58 | 0.72 | 0.70 |
| Pilot area | 16.69 | 98.70 | 0.32 | 0.98 |

**Table 3.** Relative share of soil types within UAL of selected districts/areas of Slovakia.

| Soil Type | District/Area | | | |
|---|---|---|---|---|
| | Nitra | Nové Zámky | Dunajská Streda | Pilot Area |
| Regosol | 27.33 | 10.13 | 0.03 | 0.05 |
| Fluvisol | 2.60 | 1.85 | 16.64 | 5.18 |
| Gleyic Fluvisol | 3.77 | 1.81 | 1.07 | 0.11 |
| Fluvic Gleyic Chernozem | 4.73 | 13.87 | 20.30 | 25.58 |
| Chernic Gleysol | 1.50 | 6.49 | 6.49 | 5.88 |
| Rendzic Skeletic Leptosol | 0.10 | 0.05 | | |
| Lithic Leptosol | 0.01 | | | |
| Haplic Chernozem | 6.13 | 26.52 | 53.96 | 59.70 |
| Luvic Phaeozem | 20.65 | 30.24 | | |
| Haplic Luvisol | 22.20 | 6.90 | | |
| Albic Luvisol | 2.61 | 0.69 | | |
| Stagnic Luvisol | 6.35 | 0.79 | | |
| Albi Stagnic Fragic Luvisol | 0.99 | 0.01 | | |
| Haplic Cambisol | 0.67 | 0.06 | | |
| Stagnic Cambisol | 0.11 | | | |
| Fragic Planosol | 0.07 | 0.02 | | |
| Gleysol | 0.09 | 0.02 | | |
| Histosol | | 0.11 | 1.40 | 3.51 |
| Haplic Solonchak | 0.02 | 0.36 | | |
| Anthrosol | 0.05 | 0.09 | 0.12 | |

### *2.2. Calculation of Nitrogen Balance and Nitrates Concentration in Leachate*

Nitrogen balance represents the first step of estimation of nitrogen losses to groundwater. Gross nitrogen balance on UAL was calculated by Eurostat & OECD methodology [37]. The main input data at district level were received from the National Statistical Office (number of farm animal categories, harvested area and crop yields, as well as acreage of utilized agricultural land) and Central Control and Testing Agricultural Institute (consumption of nitrogen fertilizers). Atmospheric nitrogen deposition was derived from EMEP data for the years 2015–2018 (available at: EMEP MSC-W HOME).

The amount of nitrogen leachable to groundwater was obtained by subtracting the gaseous nitrogen losses (during animal housing, manure storage and after its application on the land [38]), and gaseous N loses via the biological denitrification in the soil as described by Kunkel et al. [26] or originally by Kunkel and Wendland [39].

Amount of nitrogen losses via denitrification in soil rooting zone was calculated by following equation:

$$\frac{dN_s t_{soil}}{dt_{soil}} + D_{max} \cdot \frac{N_s t_{soil}}{k + N_s t_{soil}} = 0 \quad (1)$$

where $N_s t_{soil}$: remaining nitrogen surplus in soil after residence time $t_{soil}$; $t_{soil}$: residence time of percolation water in soil root zone (years); $D_{max}$: maximum annual denitrification rate in soil (kg N ha$^{-1}$ year$^{-1}$); $k$: Michaelis constant (kg N ha$^{-1}$ year$^{-1}$); and 0: displaceable nitrogen surplus in soil (kg N ha$^{-1}$).

Using the soil database operated by the National Agricultural and Food Centre—Soil Science and Conservation Research institute in Bratislava, the maximum annual denitrification rate was derived from grouping of soil types (see Table 3) to four out of five groups [40]. The rates 10, 20, 40 and 60 kg N ha$^{-1}$ year$^{-1}$, corresponding to very low, low, medium and good soil denitrification potential were corrected by residence time of percolation water through the soil, what is given by ratio of effective field capacity of the soil and leachate rate:

$$t_{soil} = \frac{FC_{eff}}{Q_p} \quad (2)$$

where $t_{soil}$: residence time of percolation in soil root zone (years); $FC_{eff}$: effective field capacity in the soil column (mm); and $Q_p$: the mean long-term leachate rate (mm year$^{-1}$).

The amount of the mean long-term average values of leachate rate was calculated as the difference between precipitation and evapotranspiration reduced by surface runoff by formula, described by Kunkel and Wendland [39]:

$$Q_p = P - ET_a - Q_o \quad (3)$$

where $Q_p$: the mean long-term leachate rate (mm year$^{-1}$); $P$: the long-term average of annual rainfall (mm year$^{-1}$); $ET_a$: real evapotranspiration calculated from the long-term annual rainfall and potential evapotranspiration (mm year$^{-1}$); and $Q_o$: surface runoff (mm year$^{-1}$).

The average long-term data on precipitation and potential evapotranspiration in the period 1986–2015 distinguishing between winter and summer half-year period were obtained from the Slovak Hydrometeorological Institute. This reference period was applied to eliminate inter-annual variability and the effect of individual dry or wet years, respectively [41].

The surface runoff was calculated according to formula, described by Kunkel and Wendland [39]:

$$Q_o = Q_p \cdot (P - 500)^{1.65} \quad (4)$$

where $Q_o$: surface runoff (mm year$^{-1}$); $Q_p$: the mean long-term leachate rate (mm year$^{-1}$); and $P$: the long-term average of annual rainfall (mm year$^{-1}$).

The nitrogen concentration in leachate was calculated on the base of leachable nitrogen converted into nitrates and the amount of percolation water:

$$C_{NO_3^-} = \frac{443 \cdot N_s t_{soil}}{Q_p} \quad (5)$$

where $C_{NO_3^-}$: nitrate concentration in leachate (mg L$^{-1}$); 443: factor to convert nitrogen (mg L$^{-1}$) to nitrate (mg L$^{-1}$); $N_s t_{soil}$: nitrogen surplus after denitrification considered as leachable nitrogen (kg ha$^{-1}$); and $Q_p$: the mean long-term leachate rate (mm year$^{-1}$).

Figure 3 summarizes the above procedure.

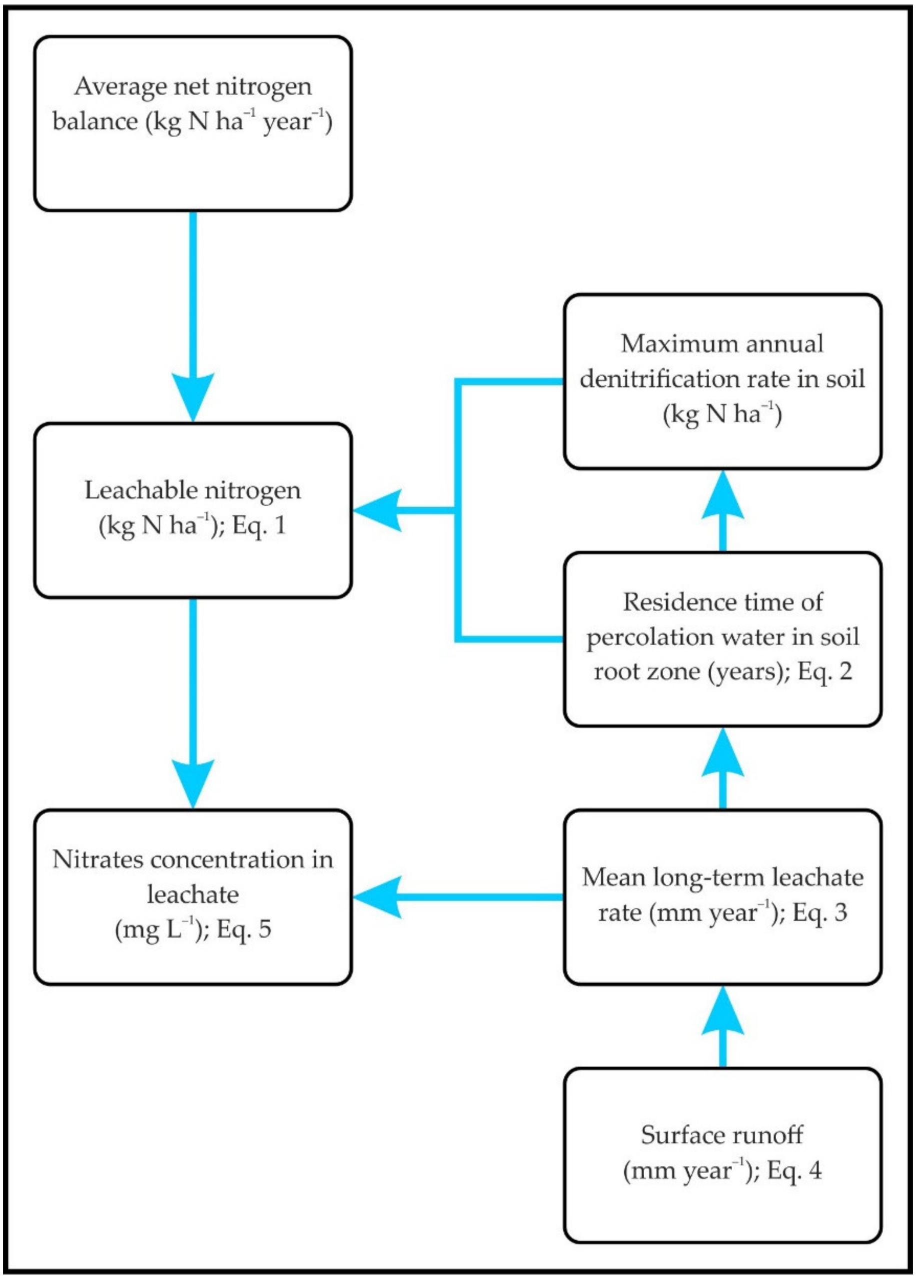


**Figure 3.** Summary flowchart for calculation of nitrate concentration in the leachate.

In line with the three-step concept "critical limits—critical loses—critical inputs" [31], the need to reduce the nitrogen excess was based on the backward recalculation of leachate nitrates above 40 mg L$^{-1}$ to nitrogen. This concentration, which is more stringent when compared to the value 50 mg L$^{-1}$ in leachate used by other authors [30,31,33,39], should contribute to a gradual decrease of nitrate concentration in groundwater.

## 3. Results

The average values of gross and net nitrogen balance on UAL in individual districts and the pilot area are illustrated at Table 4.

**Table 4.** Average values of nitrogen surplus on district/area level in period 2015–2018 (kg N ha$^{-1}$ of UAL).

| District/Area | Gross Balance | Net Balance |
|---|---|---|
| Nitra | 43.2 | 25.5 |
| Nové Zámky | 28.3 | 13.6 |
| Dunajská Streda | 44.2 | 23.5 |
| Pilot area | 44.7 | 21.5 |

While gross nitrogen surplus is just initial information on possible N losses into water, the net nitrogen surplus (according to Eurostat & OECD methodology [37] labelled as land budget) represents the indicator of potential N loses to groundwater. To classify the gross nitrogen balance, in Slovakia the indicative OECD limit value 50 kg ha$^{-1}$ was set as middle value of medium N surplus category (40.1–60.0 kg ha$^{-1}$). In the case of net nitrogen balance, the half values for individual categories could be provisionally used. In terms of this classification, the gross and net balance values as such (see Table 4) can be assessed quite favorably.

The calculation of leachable nitrogen is the next important step to determine nitrate concentration in leachate. The maximum annual denitrification rate in UAL is shown in Figure 4.

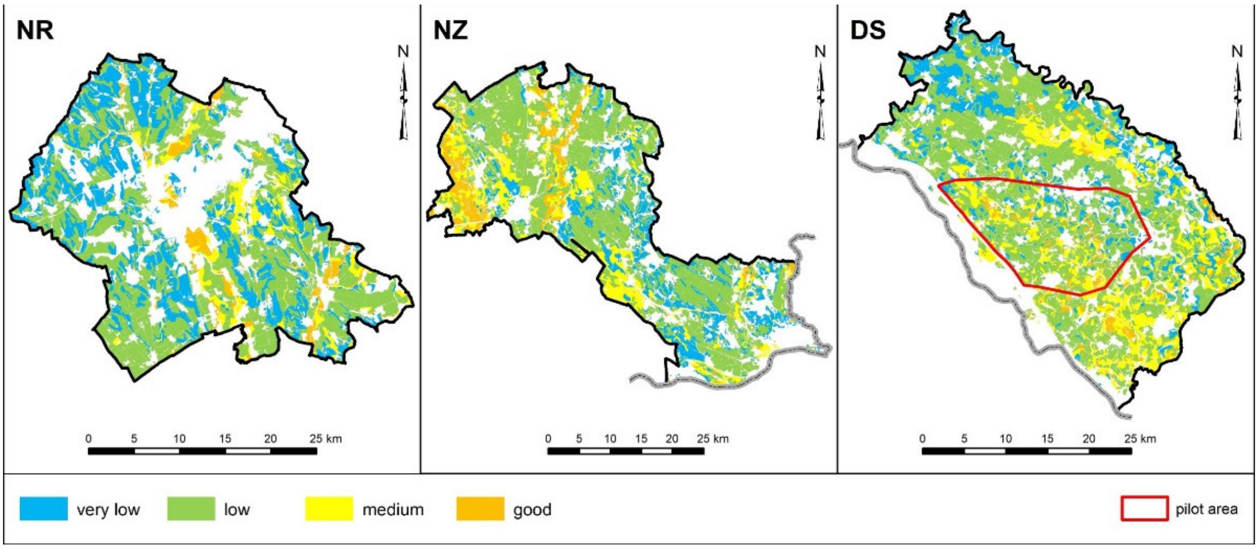


**Figure 4.** Maximum annual denitrification rate within UAL of selected districts.

As shown in Figure 4, UAL in selected districts shows mainly very low and low conditions for denitrification with shares over 75% (NZ = 75.5%, DS = 76.3%, and NR = 87.5%). In the pilot area, the conditions are almost equal to DS district (73.2%).

The detected share of UAL in selected districts with residence time of percolation water over one year (see Figure 5) is more than 75%. In the pilot area, it accounts for 75%. From the soil denitrification aspect, it can be assessed as favorable. It can no longer be claimed about the share of UAL with a residence time of percolation water up to 0.25 years, which is considerable especially in the district of Dunajská Streda (7.6%).

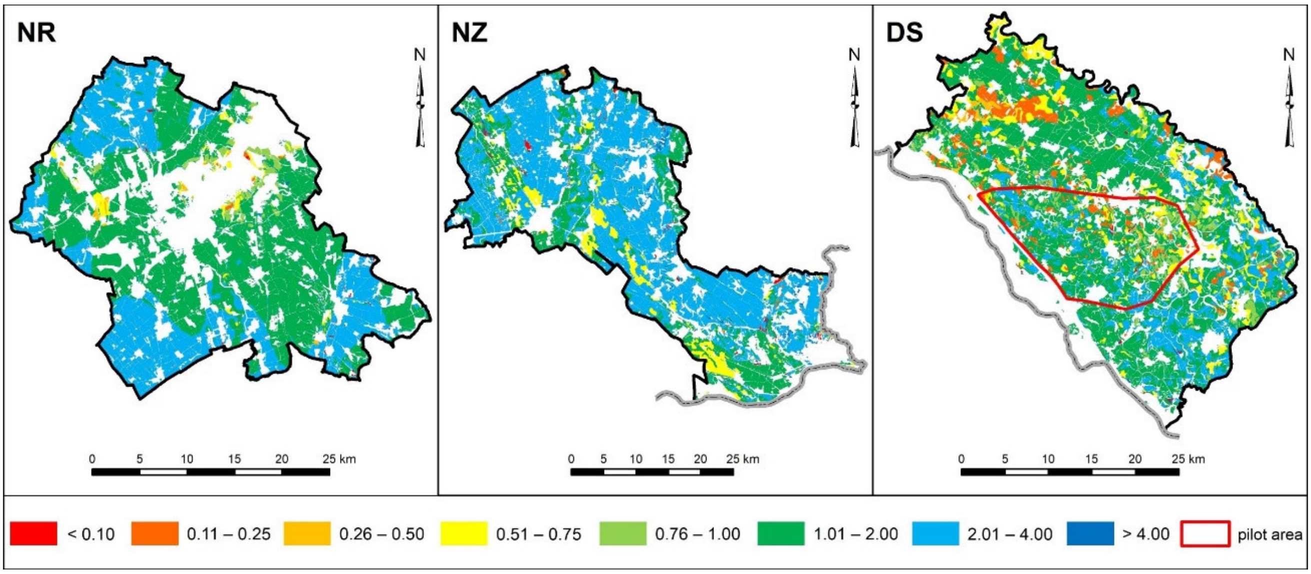


**Figure 5.** Residence times of percolation water in the agricultural soil (in years).

The amount of leachable nitrogen after losses via denitrification in the soil rooting zone is illustrated in Figure 6. As it can be seen, the lowest values are detected in district Dunajská Streda, followed by the Nové Zámky and Nitra districts. The share of UAL with displaceable nitrogen below 10 kg ha$^{-1}$ decreases in the order NZ (94.1%) > DS (80.5%) > NR (67.7%). In the pilot area, this share is little bit higher than in the whole DS district (85.3%).

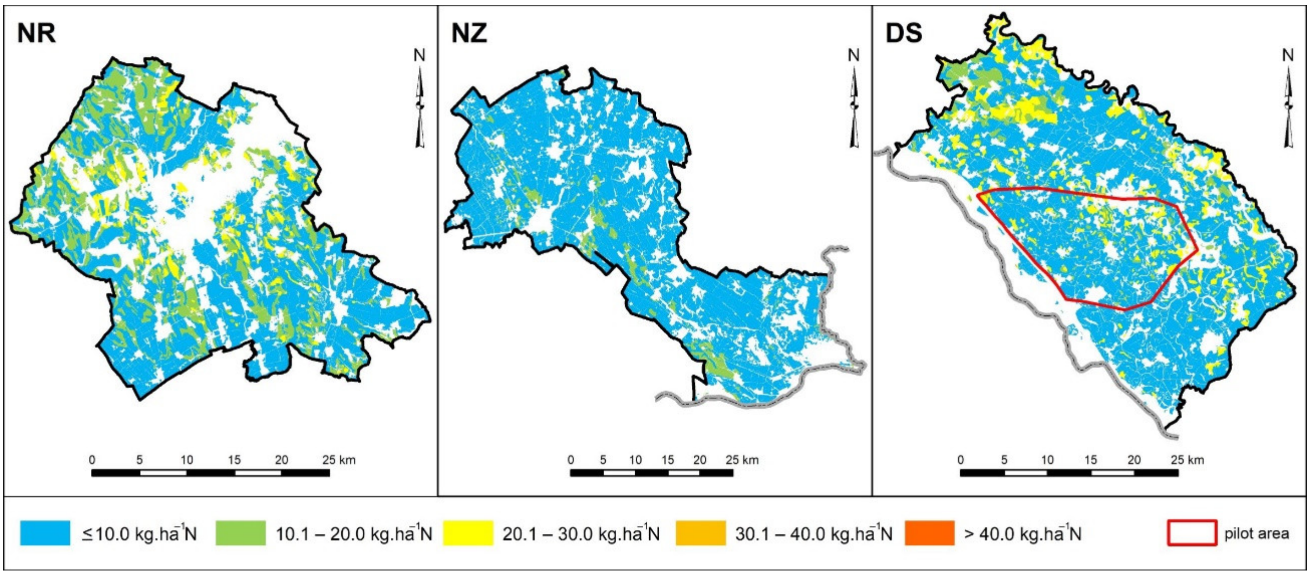


**Figure 6.** The amount of leachable nitrogen within UAL of selected districts.

The amount of percolation water within UAL of selected districts (see Figure 7) corresponds to typical annual values up to 200 mm, which occur at precipitation totals around 600 mm in areas with warm climate.

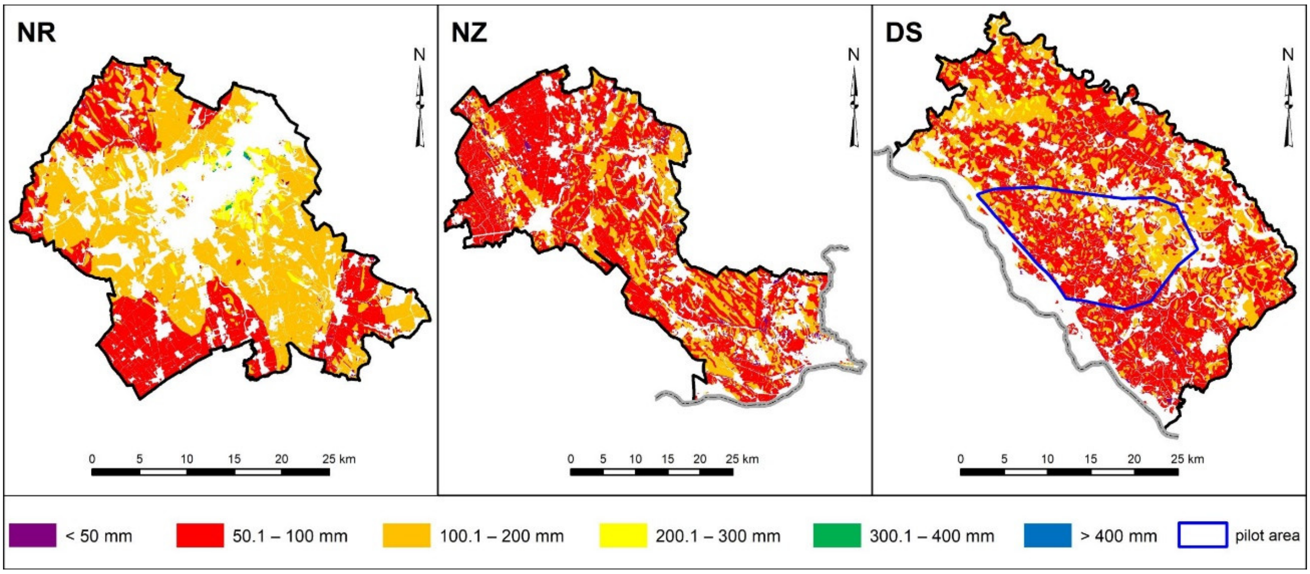


**Figure 7.** Calculated average amount of percolation water.

The mean long-term nitrate concentrations in leachate show some differences (Figure 8). The share of UAL where nitrate concentrations are $\geq$40 mg L$^{-1}$ decreases in the order NR (25.9%) > DS (12.2%) > NZ (2.5%). In the pilot area, it is slightly higher than in the DS district (13.3%). In corresponding areas, a targeted reduction in the nitrogen balance surplus should be considered in order to ensure a gradual decrease of nitrate concentration in groundwater or to secure the current good status where detected.

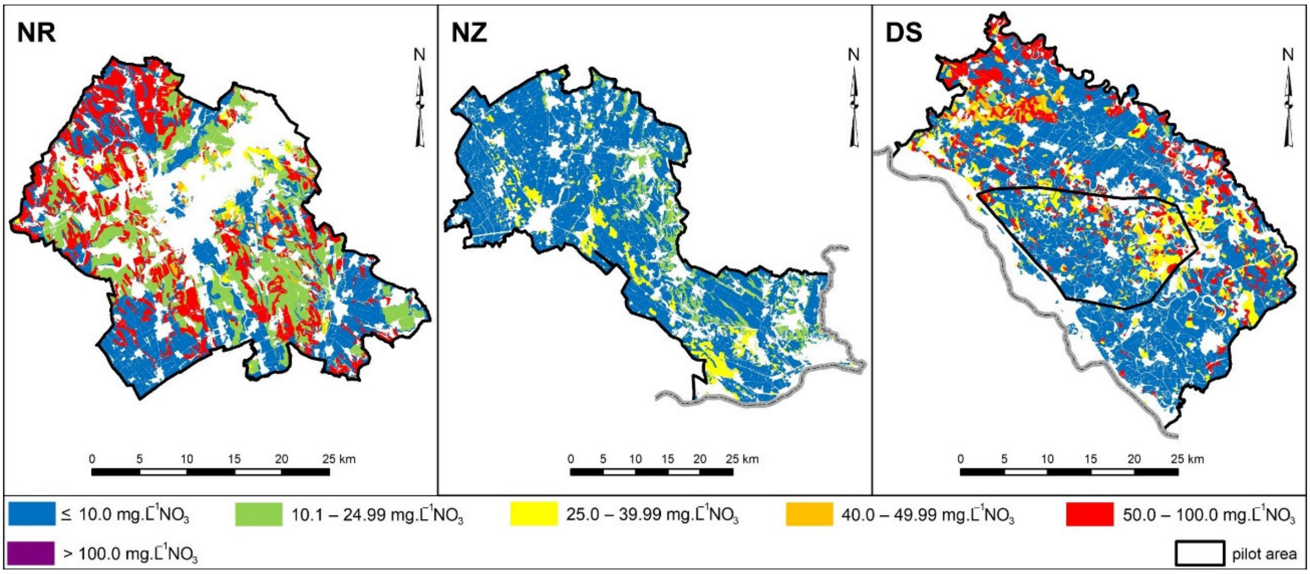


**Figure 8.** Mean annual nitrates concentration in leachate.

Finally, the comparison of nitrate concentration in leachate with their values in groundwater monitoring sites are shown in Table 5. The average nitrate concentration in leachate might contribute to the gradual decrease of concentration of nitrates in most groundwater monitoring sites. However, in some groundwater monitoring sites, especially in the Nitra district, the nitrates concentration in leachate goes beyond 50 mg L$^{-1}$ what is completely unacceptable from the point of groundwater pollution. Currently, the concentration range of nitrates in groundwater monitoring sites within the pilot area are out of the pre-defined range.

**Table 5.** Number of groundwater monitoring sites corresponding to combinations of average annual nitrate concentration in seepage water and groundwater.

| District | Nitrates Concentration (mg $L^{-1}$) | | | |
|---|---|---|---|---|
| | Percolation Water | Groundwater | | |
| | | 25–39.99 | 40–49.99 | ≥50 |
| Nitra | <25 | 1 | 1 | 14 |
| | 25–39.99 | - | - | 1 |
| | 40–49.99 | - | - | - |
| | ≥50 | - | - | 8 |
| Nové Zámky | <25 | 2 | 3 | 24 |
| | 25–39.99 | - | 1 | 2 |
| | 40–49.99 | - | - | - |
| | ≥50 | - | - | - |
| Dunajská Streda | <25 | - | 1 | 8 |
| | 25–39.99 | - | - | - |
| | 40–49.99 | - | - | 1 |
| | ≥50 | 1 | - | 1 |

The need to reduce the balance surplus of nitrogen to subsequently ensure the average nitrates concentration in seepage water at 40 mg $L^{-1}$ is illustrated in Table 6.

**Table 6.** The acreage of UAL which has to reduce the nitrogen surplus to ensure an average nitrate concentration in percolation water of 40 mg $L^{-1}$.

| District/Area | N Surplus (kg $ha^{-1}$) | UAL Acreage (ha) |
|---|---|---|
| Nitra | 0.1–5.0 | 1148 |
| | 5.1–10.0 | 17,234 |
| | 10.1–15.0 | 251 |
| Nové Zámky | 0.1–5.0 | 4 |
| | 5.1–10.0 | 0 |
| | 10.1–15.0 | 0 |
| Dunajská Streda | 0.1–5.0 | 2587 |
| | 5.1–10.0 | 10,387 |
| | 10.1–15.0 | 0 |
| Pilot area | 0.1–5.0 | 1389 |
| | 5.1–10.0 | 737 |
| | 10.1–15.0 | |

As Table 6 shows, the average reduction in annual N surplus to ensure a nitrate concentration of 40 mg $L^{-1}$ in leachate does not exceed 15 kg N $ha^{-1}$ in detected hot-spot areas which are shown in Figure 8. The largest share of UAL acreage in hot-spot areas falls within the reduction of nitrogen surplus only up to 10 kg N $ha^{-1}$, especially for the districts of Nitra and Dunajská Streda. On the other hand, no need to reduce the nitrogen surplus in the Nové Zámky district is anticipated at present. The situation in the pilot area is more favorable compared to the Dunajská Streda district. In the corresponding hot-spot area, where it is necessary to reduce the excess of nitrogen, the category 0.1 to 5 kg N $ha^{-1}$ prevails.

## 4. Discussion

Water monitoring is an essential tool to address the current status of groundwater pollution and to identify how far it is from reaching the desired environmental level [42], but on its own it cannot to be used to predict the further development of water quality and the effect of the measures adopted in agriculture [43–45]. Likewise, the combination of water monitoring results with general information on recent land use patterns, fertilizer consumption, livestock density, etc. does not significantly improve comprehension in this regard, although it may seem beneficial when no information is available.

The modelled nitrate concentration in leachate serves as a predictive approximation of the adopted measures efficiency and as the base for their possible reassessment [15,44,46], while the spatial information concerning the net nitrogen balance represents the starting point for that. Moreover, as indicated by several authors [15,44], identical N balance surpluses or even leachable nitrogen may lead to completely different nitrate concentration in leachate as a consequence of different denitrification rates and infiltration. As a result, the values of nitrogen balance cannot provide any objective response to groundwater nitrate pollution from agriculture in the current period even when surveyed at the level of individual plots, nor can they serve for monitoring the efficiency of mitigation measures as stated by Klages et al. [14].

Although in Slovakia the values of the gross nitrogen balance at country level are clearly lower than in the countries with more intensive agriculture, and modelled nitrogen losses by leaching and runoff [24,25,31] indicate a quite good situation, unsatisfactory high levels of nitrate concentration in groundwater [6] compel us to address this issue in relevant areas as effectively as possible.

The primary step for decreasing nitrates concentration in groundwater below 50 mg $L^{-1}$ directly corresponds with the reduction of the amount of potentially leachable nitrogen in the soil and thus net nitrogen balance [1,15,44,46]. Even though, under certain conditions, the groundwater environment enables a further decrease of nitrates concentration [47], the capacity of this mechanism is exhaustible [46], it being associated with negative side-effects such as the release of arsenic, nickel and rising sulphate concentration. For that reason, groundwater dilution by less polluted leachate and regulation of nitrogen surplus remains the most accessible way to reduce the above-limit values of nitrates in groundwater as also stated by Mas-Pla and Menció [32].

Recharge rates significantly influence both the concentration of nitrates in leachate and the rate of groundwater concentration change. This is especially relevant in NR, NZ and DS because the annual amount of leachate is often less than 100 mm (see Figure 6), and thus the dilution effect is limited. On the contrary, as stated by Kumar et al. [48], lower rates of leachate, which are typical for eastern European countries, can promote the process of soil denitrification due to longer residence time of percolation water in the soil.

The definition of hot-spot regions with nitrate concentration in groundwater over 50 mg $L^{-1}$ or over 37.5 mg $L^{-1}$ with increasing trend is the primary base for deriving maximum acceptable nitrogen balance surplus [15,41]. In this case the second limit value is derived from the Directive 2006/118/EC on the protection of groundwater against pollution and deterioration (Article 5, Annex IV). A similar approach was also used in this study with the proviso that Nitrates Directive limits were applied (nitrate concentration over 50 mg $L^{-1}$, nitrate concentration over 39.99 mg $L^{-1}$ with increasing trend and nitrate concentration over 25 mg $L^{-1}$ with increasing trend) (see Figure 2). Currently, the concentration limit 40 mg $NO_3$ $L^{-1}$ in leachate in selected districts can be considered an acceptable result from the agricultural practice. As can be seen from the Table 5, in most cases nitrate concentration in leachate contributes to gradual dilution in groundwater, especially within the range over 50 mg $L^{-1}$. However, in some groundwater monitoring sites, mainly in Nitra district, indicate that the nitrate concentration in leachate requires the review of the measures to reduce leachable nitrogen. Defined hot-spot areas (see Figure 8) should effectively serve as a basis in this regard.

In comparison to foreign studies [1,15,31], the average rates to reduce nitrogen surplus to ensure nitrate concentration of 40 mg $L^{-1}$ in leachate are lower. But it should be recalled that in these studies single year nitrogen balance was applied instead of the multiannual average [22,33,41,46], thus the final results may be subject to significant inter-annual variability, which Kühling et al. [44] have also noticed. In any case, the lower limit of nitrates concentration in leachate (40 mg $L^{-1}$) can be considered as a certain guarantee for achieving the necessary effectiveness of measures in agriculture.

It is clear that certain decreases of N input in fertilizers or the reduction of intensity of crop cultivation [22,26,43], formulated in the EU Biodiversity Strategy to 2030 and the Farm to Fork Strategy, as well as nitrogen capture by winter crops or catch crops in hot-spot areas [15,17,22,26,28,43], can help to reduce groundwater nitrate pollution. As for Slovak conditions, the higher nitrogen surplus is recorded in the lowlands as the consequence of cultivation of cash crops and the summer droughts [29]. The drought in the growing season affects not only the nitrogen surplus as Bowles et al. indicate [28], but also the cultivation of winter catch-crops in warm lowland areas, which also applies to the NR, NZ and DS districts. The problem is to reach the stand completeness of winter intercrops, which are sown in summer, also confirmed by Kühling et al. [44]. The expansion of winter crops, in turn, faces the problem of dominant share of winter wheat stands which have lower capacity to uptake nitrogen in autumn compared to rapeseed or rye.

The information presented here significantly improves existing descriptive and qualitative approaches both in the review of vulnerable areas as well as in the assessment of the adequacy of existing measures. It is also possible to partially supplement the monitoring network with other sites that better reflect diffuse groundwater pollution. Even though the precautionary principle is being applied in Slovakia to classify agricultural land into vulnerable areas, information on nitrate concentration in leachate can contribute to a better-informed application of the precautionary principle in the study area.

However, it should be taken into consideration that all relevant information is influenced by the accuracy/scale of the input data [41] rather than the grid in which the results are displayed. Although the soil maps and data in Slovakia are in very good scale (1:10,000), this does not apply for relevant climatic data and the input and outputs for nitrogen balance calculation being calculated on districts (LAU-1) level.

Currently, the disaggregation of nitrogen balance numbers according to the type of agricultural land and intensity represents the most suitable approach to deal with the situation. Therefore, the values of gross and net nitrogen balance in specific districts were redistributed according to the type of agricultural land (especially arable land, permanent grassland and permanent cultures such as orchards and vineyards) and the intensity of their use, which can be derived from some measures of the second pillar of the current Rural development program (e.g., ecological agriculture). In accordance with Kunkel and Wendland [39] and Knoll et al. [47], who indicate the necessity to take into account the type of agricultural land in the area of interest, the highest balance surpluses of nitrogen occur on intensively used arable land contrary to the lowest N surpluses on permanent grasslands, which in Slovakia are often used extensively. Direct calculation of nitrogen balance at LAU-2 or municipal cadasters level or even at field level can bring improvement provided that it covers all UAL and sufficient quality/correct data from farmers are ensured.

Although nitrate concentration in leachate is a terminative indicator to detect hot-spots, as stated in several works [11,12], the time lag which also corresponds to the thickness of unsaturated zone or depth of groundwater should be also taken into account at revision of agricultural measures.

## 5. Conclusions

Nitrate concentration in leachate within the agricultural land represent an important indicator for determining the current hot-spot areas in terms of groundwater nitrate pollution. In most cases nitrate concentration in leachate contributes to gradual dilution in groundwater, especially in the range over 50 mg $L^{-1}$. The target value of this indicator, 40 mg $NO_3$ $L^{-1}$, can serve as the baseline for revision of the measures taken by farmers in selected districts of Slovakia. In the identified hot-spots, the average reduction of average annual N surplus to ensure a nitrate concentration of 40 mg $L^{-1}$ in leachate does not exceed 15 kg $ha^{-1}$.

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