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Ekológia (Bratislava) - Journal of the Institute of Landscape Ecology, Slovak Academy of Sciences Vol. 41, No. 3, p. 291–300, 2022

DOI:10.2478/eko-2022-0030

DEFINITION OF HOT-SPOTS TO REDUCE THE NITROGEN LOSSES FROM AGRICULTURAL LAND TO GROUNDWATER IN SLOVAKIA

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Received: 17.5.2022 / **Accepted:** 14.8.2022

Abstract

Bujnovský R., Koco Š.: Definition of hot-spots to reduce the nitrogen losses from agricultural land to groundwater in Slovakia. Ekológia (Bratislava), Vol. 41, No. 3, p. 291–300, 2022.

Agriculture is a significant contributor to nitrate pollution of groundwater which in many cases serves as a source of drinking water. Therefore, targeted reduction of nitrogen leaching losses is fully justified to address this issue. The aim of the study was to define the areas of utilized agricultural land (UAL) in Slovakia, where a nitrogen surplus needs to be reduced. Using the average values of leachable nitrogen in the period 2015-2018 and the long-term amount of percolated water, the nitrate concentration in leachate was calculated. To ensure that agricultural activities will contribute to the gradual reduction of nitrate concentration in groundwater, the nitrate concentration in leachate of 40 mg L^{-1} was chosen as the target value. This concentration was exceeded at 11.7% of the UAL area. The average indicative amount of nitrogen in industrial fertilizers that needs to be reduced to achieve a stricter nitrate concentration in the leachate in these hot-spots is 16 kg ha^{-1} with the proviso that in two districts this value exceeds 30 kg ha^{-1}.

Key words: Nitrates Directive, groundwater pollution, vulnerable zones, nitrogen surplus, nitrate concentration, leachate.

Introduction

Groundwater nitrate pollution, originating mainly from agriculture, remains continuing problem which requires enhanced attention. Its extent and importance is documented by a number of studies and documents (e.g. Andjelov et al., 2014; Cherry et al., 2008; Cibulka et al., 2020; European Commission, 2021; European Environment Agency, 2021; ICPDR, 2021b; Lawniczak et al., 2016; Musacchio et al., 2020; Sapek, 2005).
Although considerable efforts have been made since the adoption of the EU Nitrates Directive (91/676 / EEC) to reduce the nitrogen load on agricultural land and its subsequent losses to water, the current results of groundwater monitoring indicate only little progress (e.g. Cibulka et al., 2020; European Commission, 2021; Orellana-Macías et al., 2020; Van Grinsven et al., 2012; Wang et al., 2013).

In order to reduce nutrient losses (especially nitrogen), the European Commission supports further reductions of fertilizer consumption (European Commission 2020a,b) because reducing of N inputs is the primary way to reduce nitrate nitrogen leaching (Fan et al., 2010). However, the groundwater nitrate pollution can be caused not only by current agricultural practice but as well by past agricultural activities as a consequence of the low rate of nitrate degradation by denitrification or long lag times of water transport in vadose and saturated zones (Ascott et al., 2021; Højberg et al., 2017; Stuart et al., 2016; Vero et al., 2016; Wang et al., 2013).

Gross nitrogen balance has been used as the indicator of environmental pressure caused by agriculture practice and for further assessment of potential nitrogen loses to waters (Buczko, Kuchenbuch, 2010; Bujnovský et al., 2016; Cameira et al., 2019; Cherry et al., 2008; van Grinsven et al., 2012; Serra et al., 2019). Nitrate concentration in groundwater is an indicator used to define Nitrates Directive vulnerable zones. As confirmed by number of publications (e.g. Klages et al., 2020; Kuhr et al., 2013; Sieling, Kage, 2006), there is not an unambiguous relationship between these two indicators.

The definition of hot-spots is the initial precondition to ensure the efficiency of measures for nitrogen pollution reduction (Ackermann et al., 2016; Blicher-Mathiesen et al., 2014; Bujnovský et al., 2016; Cameira et al., 2021; Capri et al., 2009; Cherry et al., 2008; ICPDR, 2021a; Kuhr et al., 2013; Mititelu-Ionuș et al., 2019; Orellana-Macías et al., 2021; Pulighe et al., 2014). The Nitrates Directive vulnerable zones could serve as a proxy for the implementation of more targeted measures, however, as being documented by number of publications (e.g. De Vries et al, 2021; Kunkel et al., 2010; Mas-Pla et al., 2019; Wendland et al., 2020), even with vulnerable zones the efficiency of adopted measures is significantly influenced both by their allocation and the character of site specific conditions. For that

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reason, the targeted problem solving in hot-spot areas, defined with respect to nitrate concentration in the percolation water, is proposed (Andjelov et al., 2014; Bowles et al, 2018; De Vries et al., 2021; Kunkel et al., 2010).

The diffuse pollution of groundwater by nitrates from agriculture represents an issue which should be solved systematically basis on the objective information and not as a result of longing public expectations or pressure of force majeure (Laurent, Ruelland, 2011; Musacchio et al., 2020; Vero et al., 2018; Wang et al., 2013). Therefore, the aim of the study was to define the areas of utilized agricultural land (UAL) in Slovakia, where a a nitrogen surplus needs to be reduced. Partial steps to achieve this goal were as follows: (1) determination of nitrogen surplus within utilized agricultural land, (2) determination of the amount of leachate, (3) determination of leachable nitrogen and its conversion into nitrate concentration, (4) determination of areas where the nitrate concentration in leachate exceeds 40 mg L^{-1}, and (5) quantification of nitrogen amount to be reduced.

Material and methods

Nitrogen balance represents the first step at the estimation of nitrogen loses to groundwater. Gross nitrogen balance (GNB) on utilized agricultural land (UAL), which is registered in Land Parcel Information System, was calculated by Eurostat & OECD methodology (Eurostat, 2013). The main input data at district level were received from National Statistical Office – number of farm animals by individual categories for calculation of nitrogen in the excreta of livestock, harvested area (serving as a base for nitrogen input via seeds and for calculation of biological symbiotic fixation by legume crops), area sown by specific crops (as a base for calculation of nitrogen input from seeds) and crop yields which corresponds with amount of nitrogen removed from agricultural land by harvested products, as well as acreage of utilized agricultural land which served as area for calculation of nitrogen input into soil by atmospheric deposition, and Central Control and Testing Agricultural Institute (consumption of nitrogen fertilizers – most important nitrogen input into agricultural land). Atmospheric nitrogen deposition has been derived from the data of European Monitoring and Evaluation Programme (EMEP) for the years 2015-2018. The amount of nitrogen leachable to groundwater was obtained by subtracting the gaseous nitrogen loses (during animal housing, manure storage and after its application on the land) (European Environmental Agency, 2016) from gross nitrogen balance (the values of net nitrogen balance – NNB – were obtained), and by subsequent subtracting of gaseous N loses via the biological denitrification in the soil as originally described by Kunkel and Wendland (2006).

When classifying the net nitrogen balance, the half of the indicative OECD limit value for gross nitrogen balance (50 kg ha^{-1}) could be provisionally used with a middle value of medium N net surplus category (20.1 – 30.0 kg ha^{-1}).

The amount of nitrogen loses via denitrification in soil rooting zone was calculated by the following equation described by Kunkel and Wendland (2006):

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

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 ha^{-1} $year^{-1}$ N), k: Michaelis constant (kg ha^{-1} $year^{-1}$ N), 0: displaceable nitrogen surplus in soil (kg ha^{-1} N).

Using the soil database operated by 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 to four out of five groups (Wienhaus et al., 2008). The nitrogen rates 10, 20, 40 and 60 kg ha^{-1} $year^{-1}$, corresponding to very low, low, medium and high annual soil denitrification potential were corrected by residence time of percolation water in the soil what is given by ratio of effective field capacity of the soil and leachate rate:

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

where t_{soil}: residence time of percolation water in the soil root zone (years), FC_{eff}: effective field water capacity (mm), 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 (2006):

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

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 $year^{-1}$), Q_o: surface runoff (mm $year^{-1}$).

To eliminate inter-annual variability and the effect of individual dry or wet years, the average long-term data on precipitation and potential evapotranspiration in period 1986-2015 distinguishing between winter and summer half-year period were obtained from Slovak Hydrometeorological Institute.

The surface runoff was calculated according to formula, described by Kunkel and Wendland (2006):

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

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

The nitrogen concentration in leachate was calculated on the basis of leachable nitrogen converted into nitrates and the amount of percolation water according to Kunkel and Wendland (2006):

$$C_{NO\bar{3}} = 443 \ N_s t_{soil} / Q_p \quad (5)$$

where $C_{NO\bar{3}}$: nitrate concentration in the leachate (mg L^{-1}), 443: nitrogen to nitrate converting factor, $N_s t_{soil}$: nitrogen surplus after denitrification considered as leachable nitrogen (kg ha^{-1} N), Q_p: the mean long-term leachate rate (mm $year^{-1}$).

The mentioned procedure for calculation of average nitrates concentration in leachate and the assignment of the relevant images is shown in Fig. 6.

In line with the three step concept "critical limits - critical loses - critical inputs" (de Vries et al., 2021), the need to reduce the nitrogen excess was based on the backward recalculation of leachate nitrates above 40 mg L^{-1} to nitrogen.

All spatial analyses and output maps were processed in the ArcGIS 10.4 software environment.

Results

The average values of net nitrogen balance on UAL of individual districts are shown in Figure 1. The highest average values exceeding 30 kg ha^{-1} have been detected on arable land of eleven districts of Slovakia (Malacky – MA, Pezinok – PK, Skalica – SI, Bánovce nad Bebravou – BN, Partizánske – PE, Prievidza – PD, Trenčín – TN, Zlaté Moravce – ZM, Rimavská Sobota – RS, Veľký Krtíš – VK, Michalovce – MI). At the national level, the share of nitrogen surplus over 30 kg.ha^{-1} was 12.4% of UAL. The net nitrogen balance with value below 20 kg ha^{-1}, which can be considered relatively safe in terms of groundwater nitrate pollution, has been detected at 58.6% of UAL.

Denitrification within the soil root zone can significantly contribute to reducing nitrogen losses by leaching. As can be seen from Figure 2, the soils with very low and low category of maximum annual denitrification rate (70.5% of UAL) predominate. On the contrary, the proportion of soils with high maximum annual denitrification potential represent less than 10% of the UAL area.

The residence time of percolation water in the soil root zone (see Eq. 1) directly affects the proportion of real denitrification. The detected share of total UAL with a residence time of more than one year, which can be considered favourable in terms of denitrification, is 59.7%, as shown in Figure 3. These areas are mostly situated in climatically warm production areas in west, south and east part of Slovakia.

The mean long-term amount of percolation water (Fig. 4) directly affects the nitrate concentration in leachate. Although the amount of percolation water within the range of 100.1 to 300 mm dominates at the national level (62.2% of UAL), there is the large area where it does not exceed 200 mm (not shown). Areas with a leachate rate lower than 100 mm represent 31% of UAL. Alow amount of percolation water is often responsible for higher nitrate concentrations in leachate. In several districts (Dunajská Streda – DS, Galanta – GA, Hlohovec – HC, Trnava – TT, Komárno – KN, Nové zámky – NZ and Šaľa – SA) the areas with leachate rate below 100 mm exceed 50% of UAL.

Nitrate concentration in leachate is shown in Fig. 5a. The 8.1% share of UAL, where the nitrates concentration in percolation water exceeds 50 mg L^{-1}, has been detected. In such areas, the regulation of N inputs, surpluses or losses of N should be considered. The largest acreages (over 10,000 ha) were found in each of the following districts: Malacky (MA), Dunajská Streda (DS), Levice (LV), Nitra (NR) and Rimavská Sobota (RS).

Defined hot-spots for reducing the N-balance surpluses include the areas with the nitrate concentration in leachate exceeding 40 mg.L^{-1} which correspond of 11.7% UAL (see Fig. 5b).

The average nitrogen amount in industrial fertilizers that needs to be reduced to achieve a stricter nitrate concentration in the leachate in these areas is 16 kg ha^{-1} with the proviso that in two districts this value exceeds 30 kg ha^{-1}.

Discussion

Currently, the nitrogen surplus (namely gross nitrogen budget), which is used as the agri-environmental indicator expressing potential N loses to water, cannot provide any objective response to groundwater pollution by nitrates from agriculture (Klages et al., 2020). In this context, in Slovakia the national values of the gross nitrogen balance are lower than in the countries with more intensive agriculture (European Commission, 2022) and modelled nitrogen losses by leaching and runoff (de Vries et al. 2021) appear to be satisfactory. Nevertheless, the

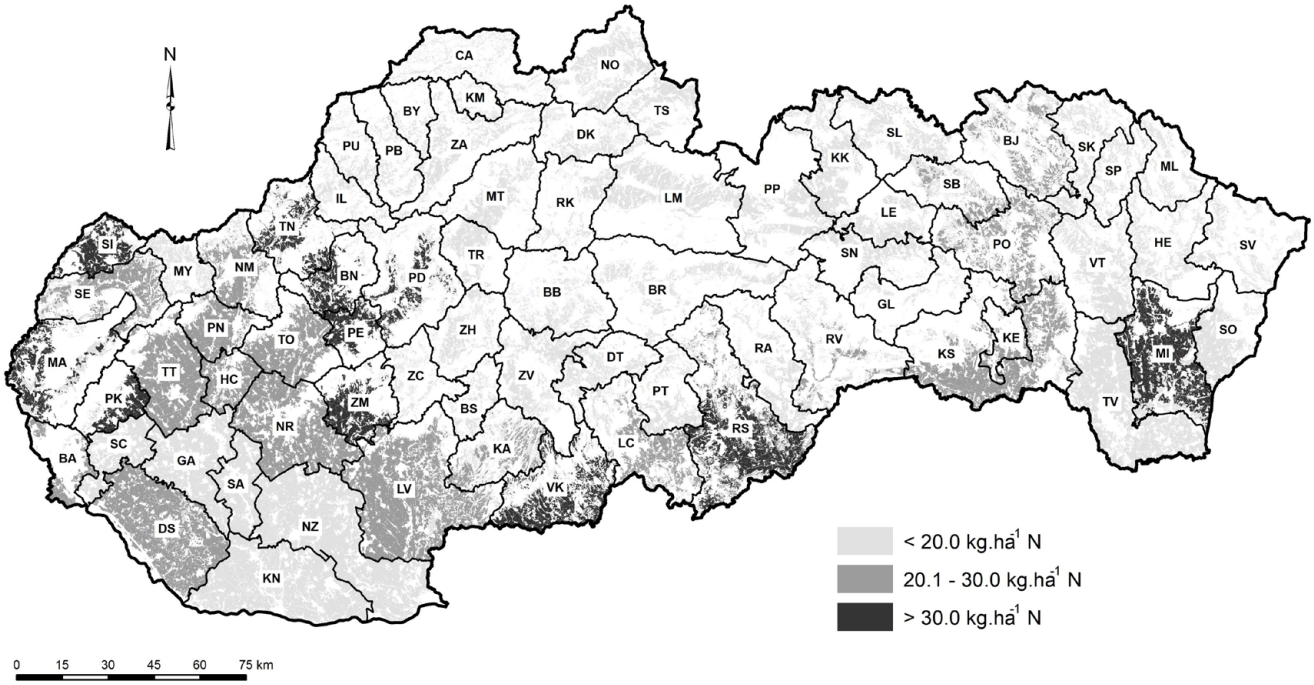


Fig. 1. Average values of net nitrogen surplus in period 2015-2018 (kg.ha^{-1} N).

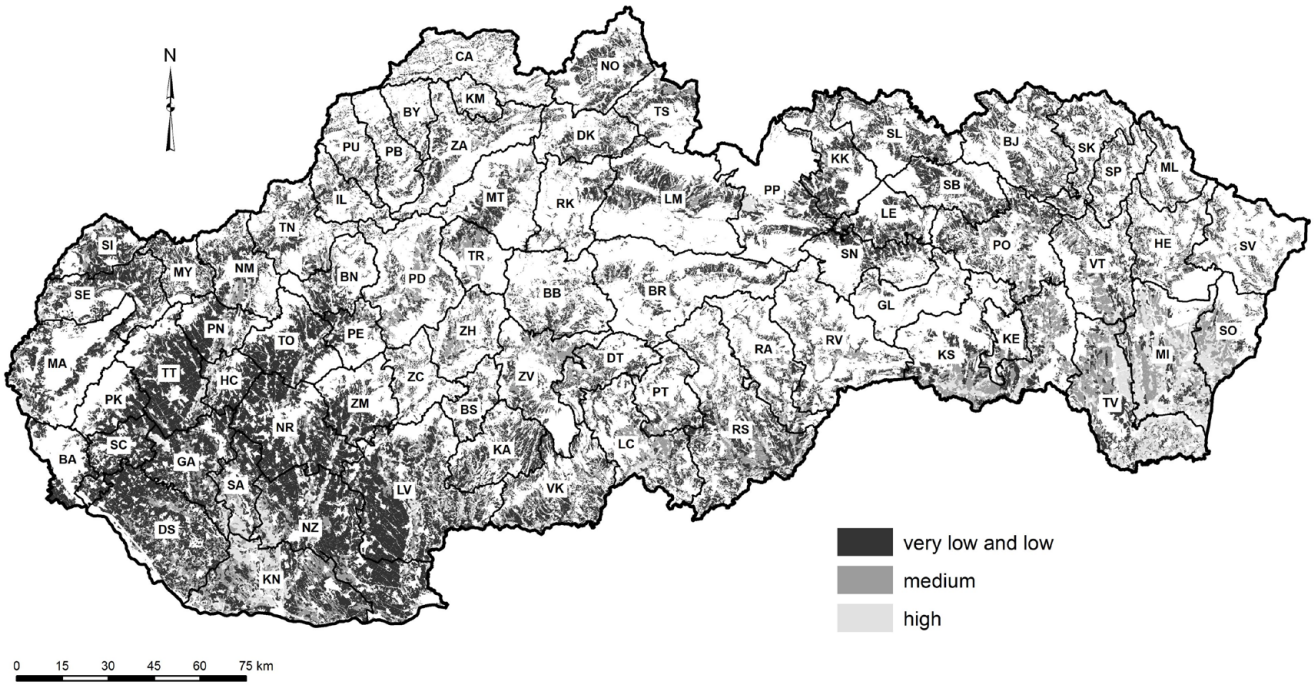


Fig. 2. Maximum annual denitrification rate.

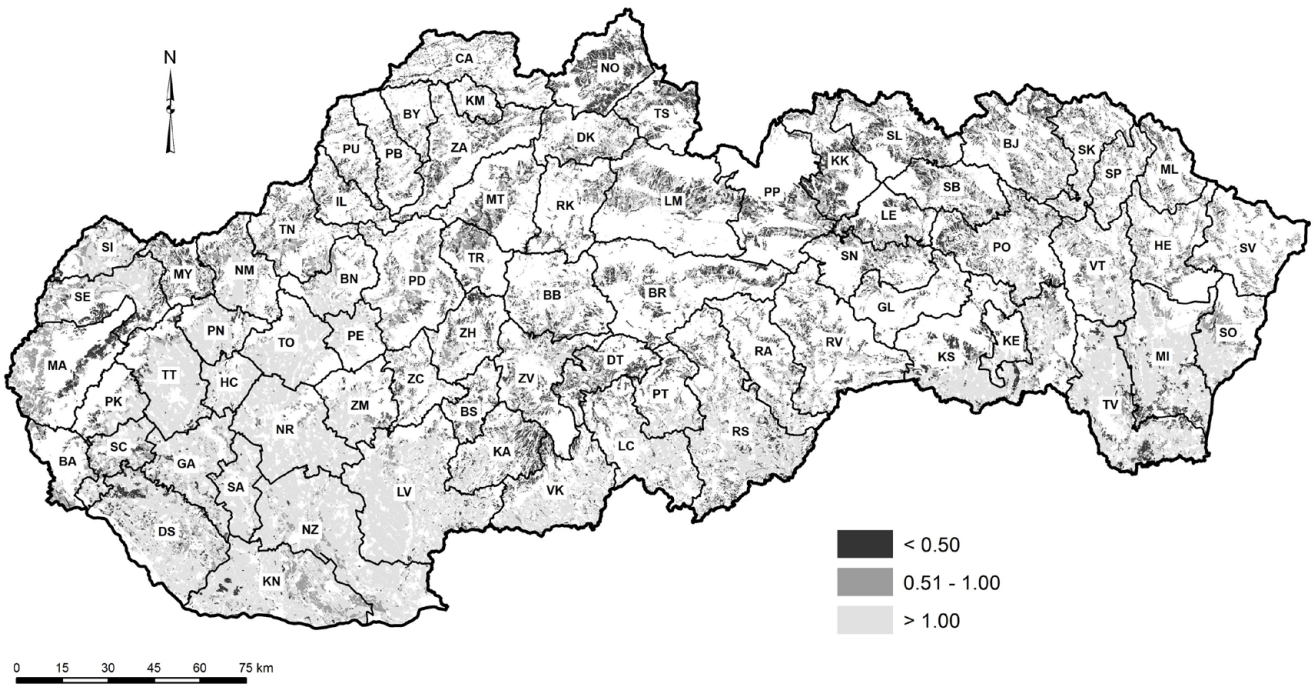


Fig. 3. Residence times of percolation water in the soil root zone (years).

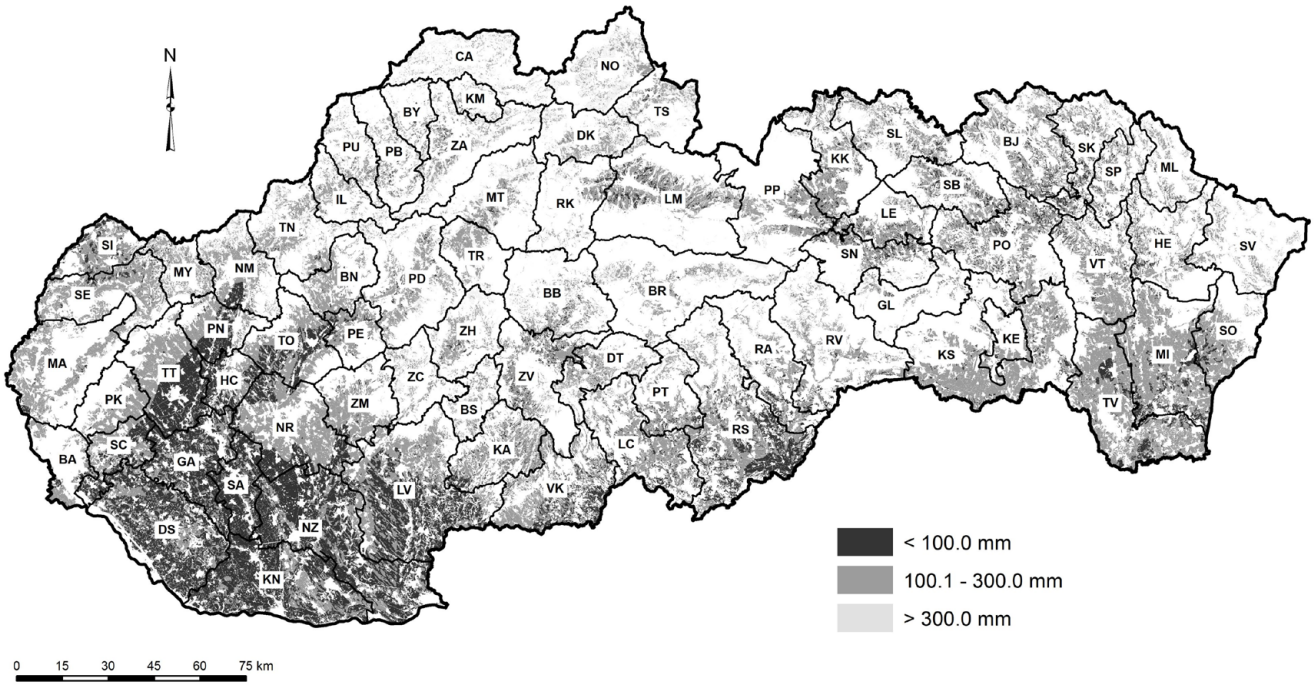


Fig. 4. Calculated amount of percolation water.

high levels of nitrate concentration detected in many groundwater monitoring sites (Cibulka et al., 2020) indicate that more effective solutions should be applied to solve this problem.

Although the net nitrogen balance compared to the gross N surplus mentioned above is more objective indicator of nitrogen loses to groundwater, the use of modelled nitrate concentrations in leachate are more suitable in predicting the efficiency of adopted measures or as a basis for their revision (Kuhr et al., 2013; Kühling et al., 2021; Kunkel et al., 2017). Fundamental problem is the fact, that even the identical N balance surplus or the same leachable nitrogen rates may lead to different nitrate concentration in leachate as a consequence of different denitrification rates and infiltration (Kuhr et al., 2013).

As shown in Fig. 1, the values of net nitrogen surplus over 20 kg ha^{-1}, may lead to excessive nitrate pollution of groundwater in areas where maximum annual soil denitrification rate (see Fig. 2) and residence times of percolation water in soil root zone (Fig. 3), affected by leachate rate (Fig. 4) are low.

Although in certain conditions the groundwater environment enables some decrease of nitrates concentration (e.g. Højberg et al., 2017; Knoll et al., 2020a), the capacity of this mechanism is exhaustible (Knoll, et al., 2020b; Kunkel et al., 2017). Therefore, the dilution of groundwater with less polluted percolation water often remains the most available way to reduce an excessive nitrate concentration in groundwater (Mas-Pla, Menció, 2019). It is clear that in the areas with a low amount of seepage water, the mentioned dilution factor cannot be applied in such sense. On the other hand, lower rates of leachate, which are typical for eastern European countries (Kumar et al., 2020), can promote the process of soil denitrification due to longer residence time of percolation water in the soil.

It is obvious that certain decrease of crop cultivation intensity accompanied by reduction of nitrogen surplus and thus also the amount of leachable nitrogen represent the basic precondition for decreasing of the groundwater nitrate concentration (e.g. Ackermann et al., 2016; Andjelov et al., 2014; European Commission, 2020b; Hansen et al, 2017; Kuhr et al., 2013; Kühling et al., 2021).

The stringently set the leaching concentration limit 40 mg L^{-1} compared to other studies (e.g. Andjelov et al., 2014; Kuhr et al., 2013; deVries et al., 2021) can be considered as effective way to achieve the necessary effectiveness of current/future measures taken in the agriculture. This value was used as base for backward calculation of nitrogen surplus. Unlike some authors (e.g. Ackermann et al., 2016; Wendland et al., 2020; Wolters et al., 2021), multiannual average values instead single year nitrogen balance were applied as these values may be subject to significant inter-annual variability. By analogy, the average annual nitrogen reduction requirement in the hot-spots of this study does not exceed 35 kg ha^{-1}, due to year-on-year variability. This may occur in some years and thus approach the data of other authors (e.g. Kunkel et al., 2010; Andjelov et al., 2014; de Vries et al., 2021).

The reduction of nitrogen surplus should be considered particularly in areas where nitrate concentration in groundwater was detected over 50 mg L^{-1} or is over 39.99 mg L^{-1} with increasing trend. Some authors (e.g. Kuhr et al., 2013; Wolters et al., 2021) rely on the limits set by the Directive 2006/118/EC on the protection of groundwater against pollution and deterioration such as nitrate concentration in groundwater over 50 mg L^{-1} or over 37.5 mg L^{-1} with increasing trend. In some foreign studies (e.g. Wendland et al., 2020; Wolters et al., 2021) the spatial nitrate concentrations in leachate can be compared only with the point values of nitrates in groundwater at monitoring sites, although there is an attempt to extrapolate the nitrate concentration values from monitoring sites into the area val-

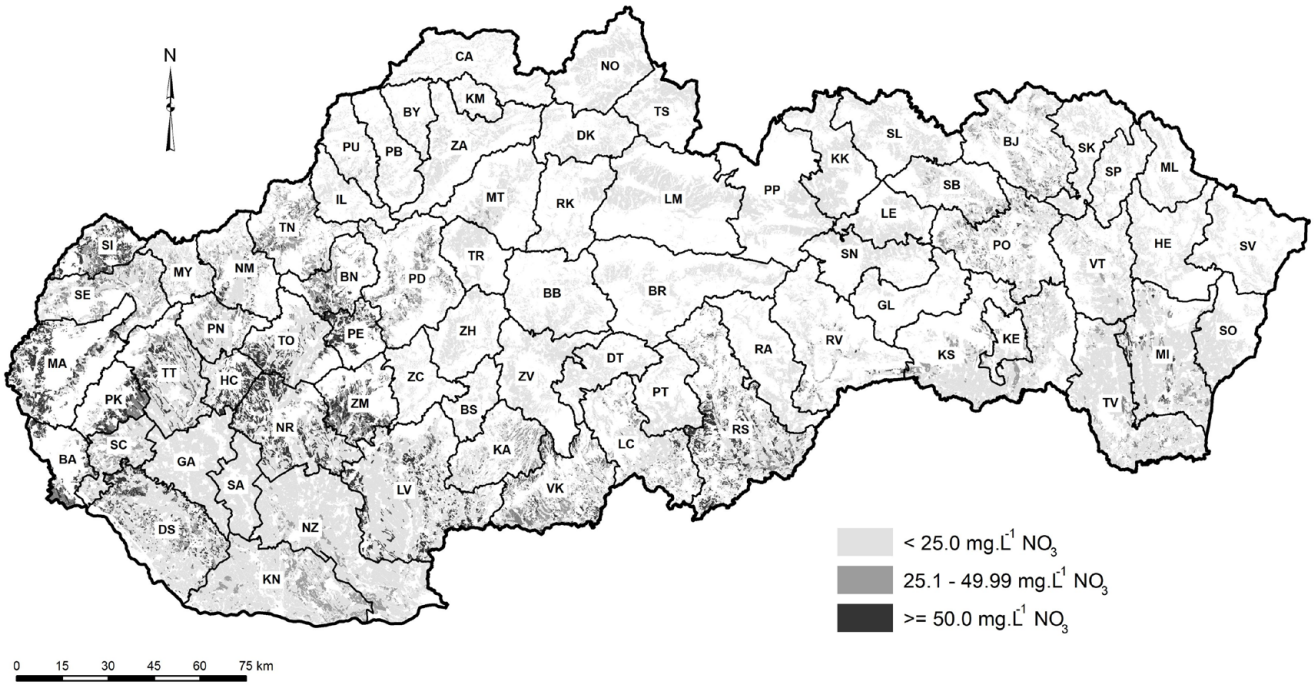


Fig. 5a. Mean annual nitrates concentration in the leachate.

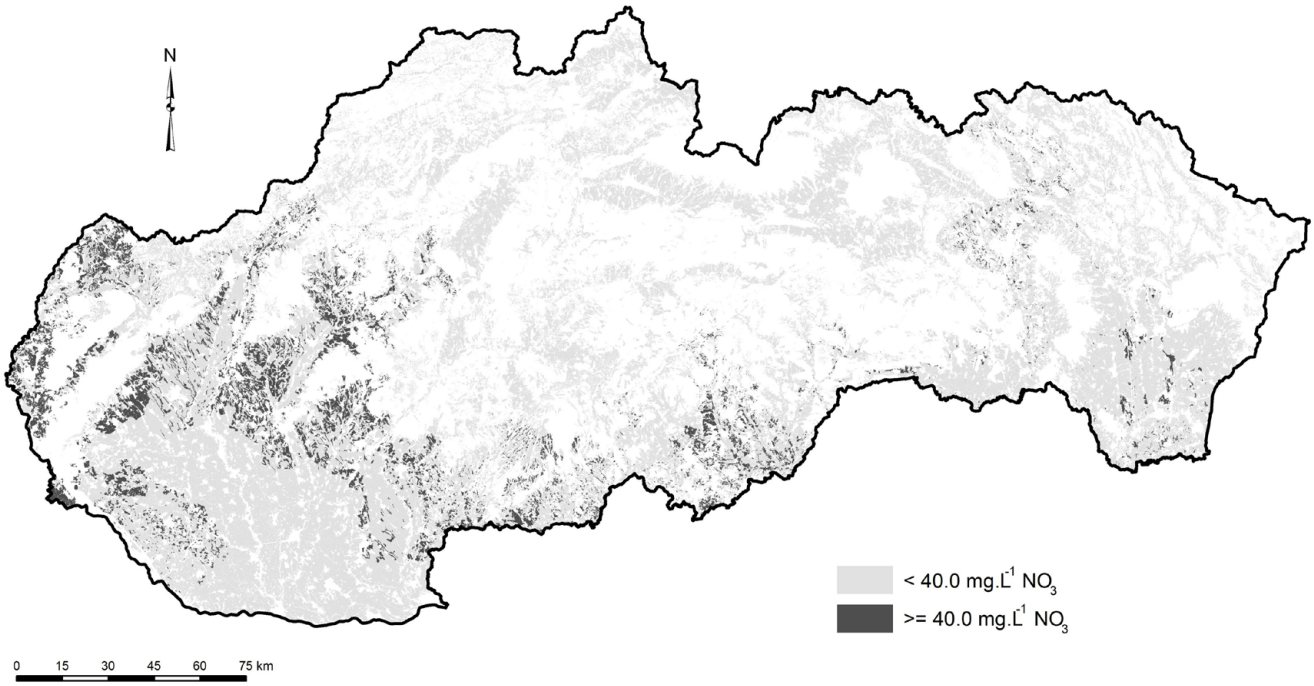


Fig. 5b. Hot-spot areas with mean annual nitrates concentration in the leachate over 40 mg L^{-1}.

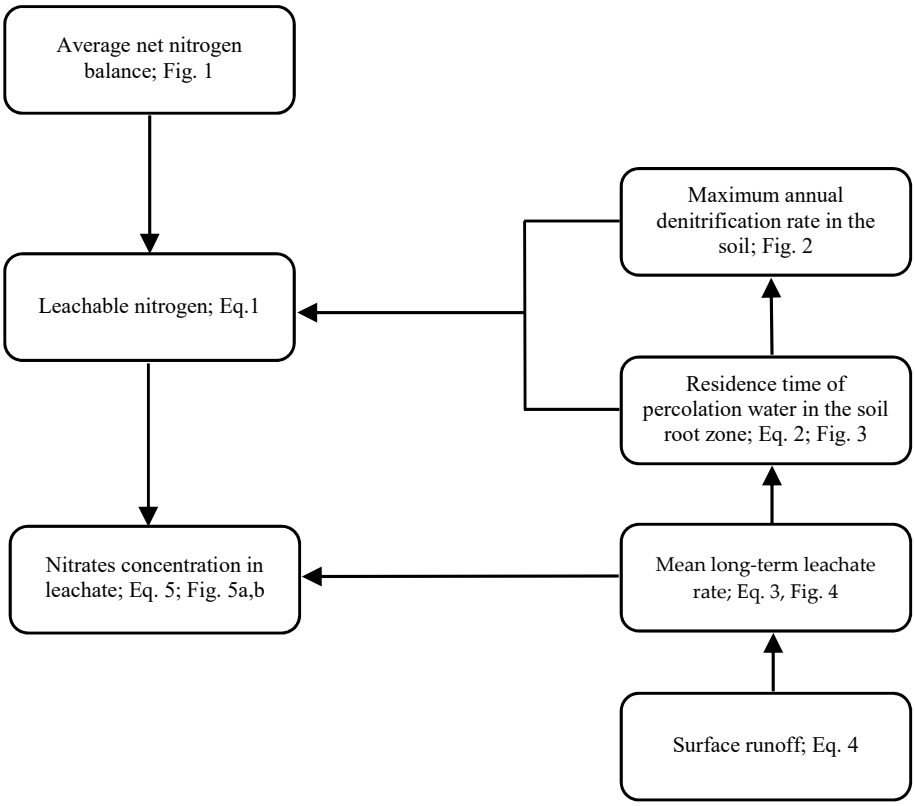


Fig. 6. Flowchart for calculation of average nitrates concentration in leachate and corresponding pictures.

ues (e.g. Stuart et al., 2016). As indicated by Knoll et al. (2019), the accuracy of spatial prediction of nitrate concentration in groundwater depends on the availability and quality of spatial environmental data that serve as predictors. When defining the spatial variability of nitrates in groundwater in high resolution, it is necessary to take into account the relatively low density of monitoring sampling points, which also applies for Slovakia case. As reported by Heldstab et al. (2020), local nitrate concentrations in groundwater may differ from regionalized values.

Reduction of the nitrogen fertilizers consumption and consequent reduction of nitrogen loss by leaching can also be achieved by switching from conventional to organic farming (e.g. Biernat et al., 2020; European Commission, 2020b). Because organic farming in Slovakia is dominated by permanent grasslands, it can be assumed that a certain increase in organic agriculture will not significantly reduce overall nitrogen fertilizer consumption. Therefore, in order for organic farming to significantly contribute to reduction of nitrogen losses by leaching, the focus must be aimed to hot-spots located mainly on arable land. Only then this measure may become more result-based.

Nitrogen capture by winter crops or catch crops in hot-spot areas for reducing agricultural N-balance surpluses (Bowles et al., 2018; De Notaris et al., 2018; Hansen et al., 2017; Hérivaux et al., 2013; Kühling et al., 2021) can be considered as a suitable complementary action to the reduction of nitrogen inputs, because in Central Europe the nitrogen leaching usually takes place during the autumn-spring period (Buczko, Kuchenbuch, 2010; Haberle et al., 2009; Stark, Richards, 2008). Klages et al. (2022) consider the compulsory cultivation of winter catch crops where necessary and appropriate. In addition, the summer drought or inter-annual weather/drought variability also affects the cultivation of winter catch crops in warm lowland areas (Bowles et al., 2018; Kühling et al., 2022; Texeira et al., 2016). In Slovakia, the drought occurrence during vegetation period significantly contributes to higher values of nitrogen surplus especially in lowlands (Bujnovský, Koco, 2019).

The information provided in this study aims to improve the existing of Nitrates Directive vulnerable zones revision as well to serve as a base for the assessment of the adequacy of the measures taken. At the same time, it is important to keep in mind that all relevant information is influenced by the accuracy/scale of the input data as pointed also by Wolters et al. (2021). Currently, the disaggregation of nitrogen balance values at districts (LAU-1) level according to the type of agricultural land and intensity represents the most suitable approach. Refinement of the calculation and scan of the nitrogen balance from the district level to the level of municipalities or even farms make sense, provided that sufficient quality/correct input data from farms are ensured.

Although the nitrate concentration in leachate is one of the most critical indicators to detect hot-spots where nitrogen surplus should be reduced, the time lag corresponding to the thickness of unsaturated zone or depth of groundwater (>20 m) and historical accumulation of nitrogen in unsaturated zone should also be taken into account at revision of agricultural

measures (Wang et al., 2013; Ascott et al., 2017; Kühling et al., 2021). For this reason, the stable or even rising trend of nitrate concentration in groundwater, which is also mentioned in the latest Slovak report on the implementation of the Nitrates Directive (Cibulka et al., 2020), does not unnecessarily mean that current agricultural practices need to be further tightened. When applied for unjustified cases, this may lead to conflicting exchange of views between the environment and agricultural sectors, or at least to disproportional rise of costs due to application of unnecessary more stringent measures.

Conclusion

Agriculture significantly contribute to nitrate pollution of groundwater. Although the measures taken under the Nitrates Directive have been in force in Slovakia for almost 20 years, the expected impact on reduction of nitrate concentrations in groundwater has not yet been very apparent. In order to gradually decrease the concentration of nitrates in groundwater, it is necessary to reduce their concentration in leachate.

Defined hot-spots within UAL for reducing the N-balance surpluses include the areas with the nitrate concentration in leachate exceeding 40 $mg.L^{-1}$. Reduction of nitrogen loses can be achieved by reduction of nitrogen inputs and subsequently its balance surplus, as well as by reduction of its losses by growing winter catch crops. The share of UAL where the N surplus balance needs to be reduced is 11.7%. The average nitrogen amount in industrial fertilizers that needs to be reduced to achieve a stricter nitrate concentration in the leachate in these hot-spots is 16 kg ha^{-1} with the proviso that in two districts this value exceeds 30 kg ha^{-1}.

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