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# High-resolution mapping to assess risk of groundwater pollution by nitrates from agricultural activities in Wielkopolska Province, Poland

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**Abstract:** The purpose of this research was to determine the groundwater intrinsic vulnerability to pollution of shallow groundwater in Wielkopolska Province, Poland and to assess the risk of pollution by nitrates. Wielkopolska is known as an area where the problem of water pollution by nitrates has existed for a long time due to intensive agriculture.

DRASTIC method and its optimized version as well as four other risk evaluation methods were selected to assess the risk pollution with nitrates. The results of either method did not correlate with nitrate concentrations recorded in the total of 1679 groundwater monitoring points. Therefore a new method of groundwater pollution risk assessment (NV-L) was proposed. The new method is based on optimized results of the DRASTIC system and the L parameter which considers not only land use types, but also the amount of nitrogen loading leached from soil as a result of fertilizer consumption, and from wet deposition. The final results of NV-L method showed that the largest part of the study area is covered by a very low class of pollution risk (30.6%). The high and very high classes occupy 11.6% of the area, mostly in the areas designated until 2012 as the Nitrate Vulnerable Zones. Validation of the results of all methods showed that the other methods than NV-L cannot be used as a basis for reliable assessment of the risk of groundwater pollution by nitrates, as they do not take into account the nitrogen load leached from the soil profile.

## Introduction

Taking care of the quality of groundwater as a key element of the environment and drinking water source is one of our primary responsibilities. In agricultural areas, one of the threats is potential pollution with nitrogen compounds. Vulnerability assessment methods are a definite tool supporting the fulfillment of this obligation.

The problem of groundwater hazard and pollution by nitrogen compounds is particularly often discussed in the literature from the end of the 1960s, when Margat (1968) defined vulnerability to pollution, to the present day (e.g. Stewart et al. 1968, Voutchkova et al. 2021).

Vrba and Zaporozec (1994) defined "intrinsic vulnerability" as an intrinsic property of a groundwater system and one that depends on the sensitivity of that system to human or natural impacts, whereas "specific vulnerability" was defined as the risk of pollution due to the potential impact of specific land uses and contaminants.

The DRASTIC (Aller et al. 1987) is one of the most common methods used internationally to evaluate the intrinsic vulnerability (e.g. Perrin et al. 2004). The most important assumptions made when assessing vulnerability with DRASTIC are that the contaminant is introduced at the ground surface, is flushed into the groundwater by precipitation and has the mobility of water (Aller et al. 1987). This model uses seven media parameters to estimate ntrinsic vulnerability: depth to water-table, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity. The DRASTIC approach adopted by the United States Environmental Protection Agency (EPA) is a frequently used tool for mapping vulnerabilities to pollution (Shirazi et al. 2012; Sarkar and Pal 2021). In the field of vulnerability, Polish experience refers to widely used DRASTIC method since the 1990s (Krogulec 2004). In addition to standard methods of its assessment in the context of describing the characteristics of the aquifer itself (Aller et al. 1987), a number of methods have been developed to take into account the specificity of groundwater hazard caused by nitrogen compounds, especially nitrates. Many modifications of the model have been done with omission or addition of layers such as, e.g., land use patterns to estimate contamination risk to pollutants. The most popular methods include: Composite DRASTIC – CD (Secunda et al. 1998), Nitrate Vulnerability – NV (Martinez-Bastida et al. 2010), DRASTIC-N (Voutchkova et al. 2021, Voudouris et al. 2018), DRASTIC-LU (Alam et al. 2014), agricultural DRASTIC (Saha and Alam 2014). The application of the analytical hierarchy process (AHP) to adjust the DRASTIC parameter weights to local settings has become prevalent (Yang et al. 2017). The methods involving risk assessment like composite Drastic CD and NV method were performed in Poland (Krogulec 2011). The work entitled "Vulnerability map of Poland" in the scale 1:500 000 (Duda et al. 2011) comprises an additional layer – a scenario map of nitrate pollution risk – computed assuming a constant value of nitrogen load from different types of land use and recharge values. This is the only method basing on nitrogen loads.

The present study has been carried out in Wielkopolska province, Poland. Within the boundaries of the research area, the problem of water pollution with nitrogen compounds has been present for a long time, which is directly related to the intensive agriculture, especially in its central and southern part, and the high consumption of nitrogen fertilizers in relation to other regions of Poland (Dragon 2013; Dragon and Górski 2015; Ławniczak et al. 2016). This does not mean that in other regions of Poland the problem of groundwater pollution with nitrates does not occur, on the contrary, it is also widely analyzed as an effect of agriculture presence – a common non-point source of pollution (Bojarczuk et al. 2019). This phenomenon may also cause that the implementation of the so-called small retention program will be difficult due to the significant contamination of surface waters causing potentially high eutrophication of the waters in future retention reservoirs (Wiatkowski et al. 2021).

From 2004, i.e., from Poland's accession to the European Union and the need to ratify, among others, the Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy and the Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources, Nitrate Vulnerable Zones (NVZ) were designated, from which nitrogen outflow from agricultural sources to surface waters should be limited. The legal basis was the regulations published in official journals of individual provinces by the Directors of Regional Water Management Authority in four-year cycles. Under them, by 2012, the corrective action programs covered 4,659 km$^2$, which is 15.6% of the study area (Regulation of the Director of Regional Water Management Authority, 2012). NVZ was determined by separating a fragment of the catchment area where high nitrogen concentrations were found in surface waters. A program of remedial measures was planned for the area designated in this way, mainly by recording all nitrogen sources used on the ground surface. Very often, unfortunately, monitoring activities were limited only to the control of the chemical status of surface waters, without properly designed and dedicated groundwater monitoring.

The main goal of this paper was to determine the intrinsic vulnerability to pollution of shallow groundwater and assess the risk of pollution by nitrates in the whole area of Wielkopolska Province and at the same time this is the first study concerning regional approach to vulnerability by using DRASTIC method and its modifications. The risk assessment will allow, above of all, identifying all areas of the region (not only existing NVZ) where improperly conducted agricultural management may lead to the pollution of shallow groundwater and to the increase in nitrogen concentration discharged from the catchment by surface waters. To achieve the goal, it was necessary to collect information about the hydrogeological conditions affecting these issues, as well as to describe the land use structure along with the determination of the nitrogen load originated from the land surface. The evaluation of the intrinsic vulnerability performed with the use of selected methods was verified with the observed concentrations of nitrates. As the evaluation results did not correlate with the observed concentrations, a new evaluation method NV-L was proposed.

## Material and Methods

### *Study area*

Wielkopolska province is located in central-western Poland (Figure 1) and covers an area of 29,827 km$^2$. The terrain elevation varies from 27 m a.s.l. in the river valleys in the north-east to 273 m a.s.l. within the culmination of moraine hills in the south. An average, elevation ranges between 74 and 124 m a.s.l. The area is cut by the river valleys with a latitudinal arrangement. The largest is the Warta River – the main right-bank tributary of the Odra River, 808 km long. The area was shaped by the last glaciation that occurred in Poland. The landscape is dominated by young glacial uplands cut by a system of valleys, the largest of which is the modern Noteć valley consisting of lower Holocene terraces and higher terraces that are the remains of the Toruń-Eberswalde ice-marginal valley (Galon 1961).

Fresh waters in Wielkopolska Province are associated with Cenozoic sediments and overhead parts of the Mesozoic, they occur up to a maximum depth of 800 m, but most often up to 200–300 m. The hydrogeological structure of the system (Figure 2) is created by a very diverse system of permeable, poorly permeable and very poorly permeable layers of Quaternary, Neogene, Palaeogene, Cretaceous and Jurassic sediments, and aquifers often form of multi-level reservoirs (Dąbrowski et al. 2007).

The Quaternary aquifer occurs in almost the entire study area, except for the local lack of aquifers in the central and southern part of Wielkopolska Province. Usually they are multi-level structures (two- or three-level). Aquifers are represented by sands and gravels of alluvial or glacial origin. The thickness of the Quaternary aquifer is very variable, locally less than 1 m, sometimes exceeding 100 m. The uppermost aquifer usually is unconfined, except in the areas with local presence of poorly permeable sediments in the vadose zone. The aquifer is recharged directly by precipitation via infiltration in the case of subsurface aquifers and by seepage through poorly permeable layers from adjacent levels or through hydrogeological windows in the case of deeper aquifers. The drainage of the Quaternary aquifer occurs in river valleys. The renewable resource module varies in the range of 0.83–3.91 l/s·km$^2$ (Dąbrowski et al. 2007).

The Neogene-Paleogene aquifer is isolated with clay and silt-silty sediments of various thickness (average 20–60 m) (Figure 2). It creates the macrostructure of the subartesian water basin in which two aquifers are distinguished: Miocene and Oligocene (Dąbrowski et al. 2007). The Miocene aquifer is locally over 100 m thick and occurs at a depth of 20–190 m. The Oligocene aquifer is up to 80 m thick (most often 5–15 m), it occurs at a depth of 160–270 m. The renewable resource module depends on the degree of its isolation and depth of occurrence, the higher values are in the north-eastern part, it is variable within the range of 0.03–0.83 l/s·km$^2$ (Dąbrowski et al. 2007). The recharge of the Neogene-Palaeogene aquifers takes place by infiltration from the adjacent Quaternary layers, mostly through local hydrogeological windows. Locally, through tectonic faults, the reservoir is recharged ascendingly from the Mesozoic (Figure 2B). Regional drainage zones are located in the depressions of ice-marginal valleys and the main river valleys. The Miocene level, which is of economic importance, is also drained by numerous intakes and mine drainage. As a result of overexploitation, the piezometric pressure was reduced regionally in the eastern part (Dąbrowski et al. 2009, Szczepański and Straburzyńska-Janiszewska 2011).

The Cretaceous and Jurassic aquifers occur at a depth of 120–300 m (deeper in the north-eastern part of the research area, up to 600 m). The fracture and intergranular aquifer rocks are: marls, limestones, conglomerates and sandstones. In the south-eastern part of the region, the piezometric level in the Cretaceous sediments has changed as a result of coal mining dewatering (Dąbrowski et al. 2007, Jamorska 2015, Fiszer and Derkowska-Sitarz 2010).

### Land use

According to the Corine Land Cover 2018 (https://clc.gios.gov.pl), in the land use structure dominates non-irrigated arable land (CLC 211), which covers about 52% of the province. The second largest class is coniferous forests (CLC 311), covering approx. 18% of the area. The largest dense forest complexes occur in the north and are associated with the area of the Noteć Forest within the contemporary Noteć valley and the ice-marginal valleys (Figure 3). Other CLC classes with a fraction of more than 4% are: pastures (8%), mixed forests (5%) and discontinuous urban fabric (4%). The remaining classes usually occupy less than 1% of the area, including those classified as valuable in terms of nature and related to groundwater (CLC 322 and 333, area of 0.06%). The largest area concentrating artificial surfaces (CLC 1 at level 1) is the region's capital city – Poznań,

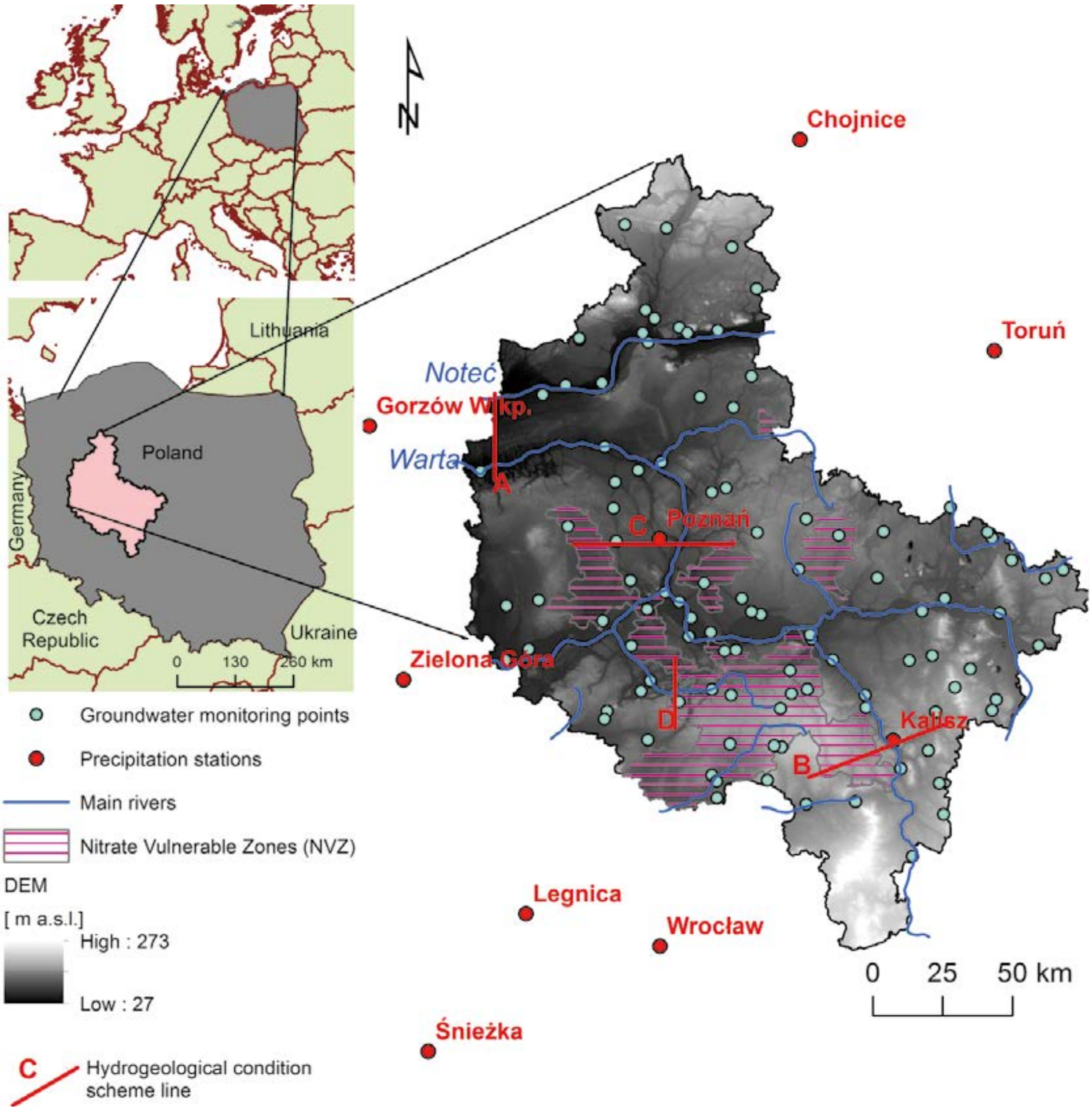


**Fig. 1.** Study area location (DEM source: www.gugik.gov.pl; monitoring point source: gios.gov.pl; Nitrate Vulnerable Zone location: Journal of Laws 2012)

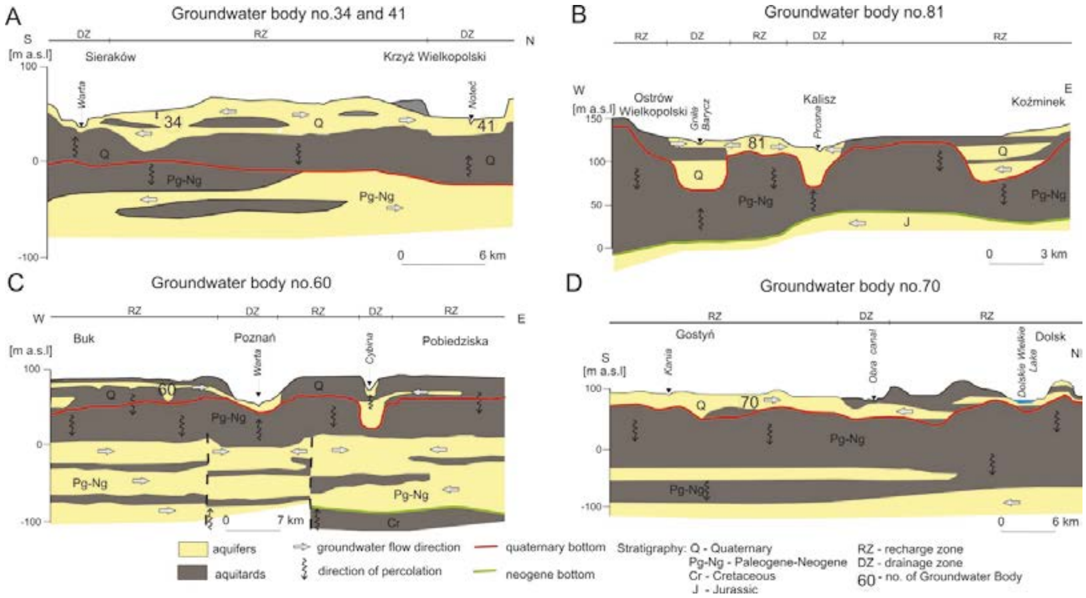


**Fig. 2.** Hydrogeological condition schemes (www.pgi.gov.pl, modified)

where urban fabric, airport, industrial or commercial units and road and rail networks and associated land occur (Figure 3).

### *Nitrogen loadings and concentrations*

Two possible sources of nitrogen origin were considered in the study area, which may migrate from the surface to shallow groundwater: from the wet deposition and from consumption of fertilizers.

### *Nitrogen loadings*

Research on the precipitation chemistry in 25 rainfall stations in Poland, carried out in the years 2000–2020, made it possible to determine the average annual nitrogen load from the wet deposition (www.gios.powietrze.gov.pl). The load was recalculated from the concentrations taking into account the sum of atmospheric precipitation. The obtained spatial distribution for the studied area shows considerable variability, the highest average annual nitrogen load occurs in the central part of the province (15.7 kg N/ha·year), lower in the northern and southern parts, where it reaches minimum values of approx. 8.6 kg N/ha·year (Figure 4A).

The average annual nitrogen load was also determined by calculating the consumption of mineral and organic fertilizers. These data are recorded at the level of municipalities (NUTS 5 = LAU: Local Administrative Units, https://ec.europa.eu/), while the data on the consumption of organic fertilizers were converted from the annual production and concentration of the pure component (nitrogen) from livestock farming, the number of which was also recorded at the level of municipalities (www.stat.gov.pl). On the basis of the data from the Regulation of the Council of Ministers (2020), the value of 52.24 kg N/1pc/year was set to convert the production into pure N component. The results of the calculations were related to the area of agricultural land. The consumption of mineral and organic fertilizers per pure N component ranged from 9.13 to 497.7 kg N/ha·year. The highest consumption of fertilizers occured in municipalities located in the central and southern part. The lowest values were recorded in the north-western part (Figure 4B).

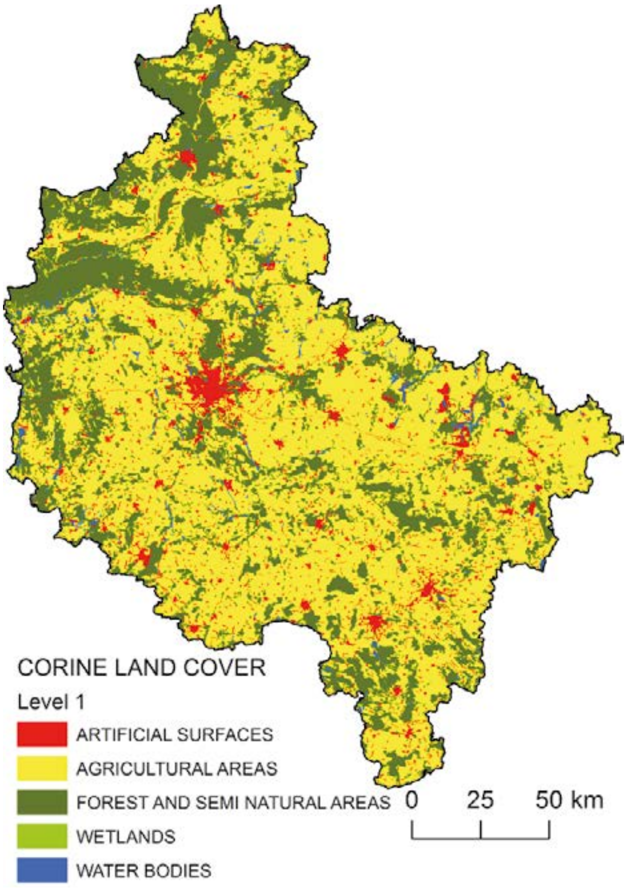


**Fig. 3.** Land use structure from Corine Land Cover 2018 at level 1 (https://clc.gios.gov.pl)

The interpretation of annual changes in the years 2000–2020 (Figure 5) allowed calculating the average nitrogen load from all sources to define groundwater pollution risk. There was a considerable increase in mineral fertilizer consumption in years 2005–2007, later it can be assumed that the consumption was constant. In the last two years the annual consumption (72 kg N/ha·year) was similar to average (77 kg N/ha·year). In the last 20 years there was a slight increase in organic fertilizers' input from 21 to 31 kg N/ha·year. In the precipitation there was differences in annual nitrogen loadings from 9 to 17 kg N/ha·year with no trend of changes.

### *Nitrate concentrations*

In the area of Wielkopolska Province there are monitoring points for the chemistry of shallow groundwater, operating as part of the state monitoring network Monitoring Data Base – MONBADA (www.gios.gov.pl). For the analysis of the spatial distribution of nitrate concentrations, 110 monitoring points were selected, in which groundwater table is unconfined or occurs under a poorly permeable deposits less than 5 m thick. Groundwater table of the uppermost aquifer was located at a depth of 0 to 43.5 m, with an average of 7.5 m. Monitoring is being performed on annual or semi-annual basis, depending on the current chemical conditions of a given groundwater body.

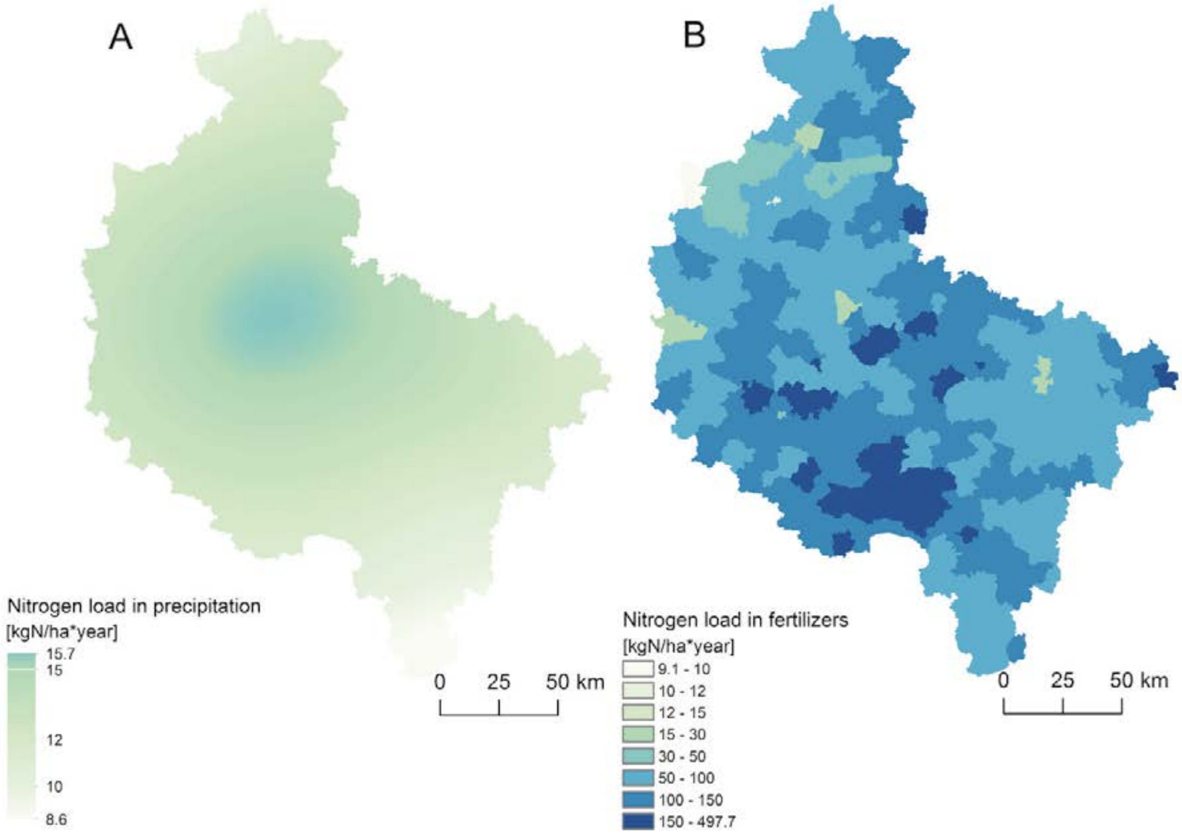


**Fig. 4.** Spatial distribution of average nitrogen load in the years 2000–2020:
A – in precipitation (data interpolated from 25 precipitation stations, www.gios.powietrze.gov.pl);
B – in fertilizers (data calculated for each of 226 municipalities (communes), www.stat.gov.pl)

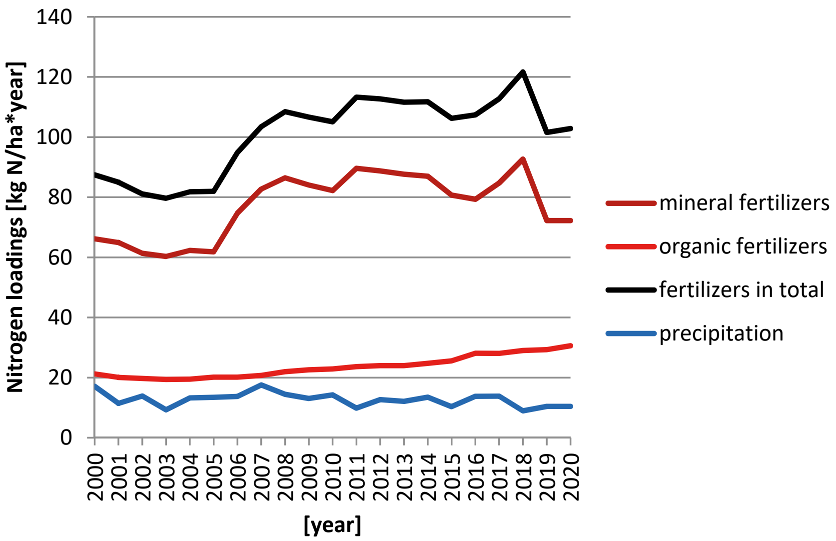


**Fig. 5.** Changes of annual nitrogen load in the years 2000–2020

In the set of 110 points, there were 33 points for which the observation sequence was longer than 10 years (Figure 6). For all points the average nitrate concentrations for the observation period ranged from 0.01 to 213.2 mg/l $NO_3^-$. Supplementary data were the concentrations of nitrates in groundwater sampled once in 2007, 2009 or 2012, as part of the work on the Hydrogeological Map of Poland in the scale 1:50 000, Uppermost Aquifer, Vulnerability and Quality, which covered 50% of the study area. Therefore, the analysis has included 1569 points, for which nitrate concentrations ranged from 0.01 to 708 mg/l $NO_3^-$, with an average value of 46.7 mg/l $NO_3^-$ and the depths of the groundwater table ranged from 0 (spring) to 37 m, on average 3.7 m (www.geoportal.pgi.gov.pl).

Most of the nitrate observation points were within the agricultural areas – 960 (56%), then urban fabric – 335 (20%), forests – 221 (13%), pastures – 128 (8%), industrial or commercial units – 31 (2%), inland marshes and peat bogs – 4 (0.2%).

### *Assessment of intrinsic vulnerability*

To assess natural vulnerability, DRASTIC method (Aller et al. 1987) was used, which assumes that the final susceptibility index *V* is the sum of the products of ranges and weights of seven basic parameters describing the natural properties of the environment of groundwater occurrence, according to the equation (1):

$$V = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where: *r* – range, *w* – weight, parameter's names are described in Table 1.

The ranks for individual parameters have been assigned arbitrarily, so the description of the variability of each element is complete and adapted to the specificity of the area. For all parameters and for the output data, high-resolution space discretization was applied to a block size of 300×300 m.

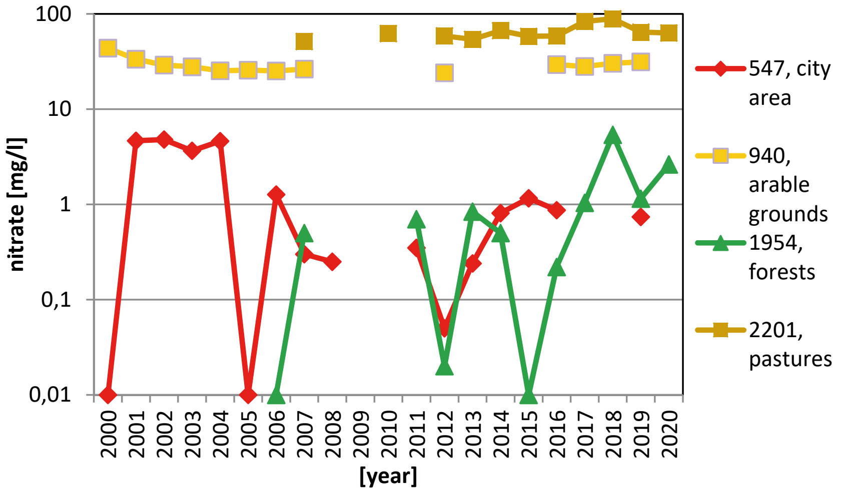


**Fig. 6.** Courses of nitrate concentrations in four shallow aquifers in period of 2000–2020 in selected monitoring points, with numbers of the points and type of spatial development according to www.gios.gov.pl

**Table 1.** Parameter classes with range and weight

| **Parameter** | | **Parameter classes** | **weight** | **range** | **% area** |
|---|---|---|---|---|---|
| **D** | Groundwater depth [m] | >100.0 | 5 | 1 | **<0.1** |
| | | 50.0–100.0 | | 2 | **0.3** |
| | | 30.0–50.0 | | 3 | **2.0** |
| | | 20.0–30.0 | | 4 | **4.3** |
| | | 15.0–20.0 | | 5 | **5.3** |
| | | 10.0–15,0 | | 6 | **11.0** |
| | | 5.0–10.0 | | 7 | **22.7** |
| | | 2.0–5,0 | | 8 | **26.2** |
| | | 1.0–2,0 | | 9 | **11.6** |
| | | 0.0–1.0 | | 10 | **16.7** |
| **R** | Recharge [mm/year] | <50 | 4 | 1 | **31.0** |
| | | 50–70 | | 2 | **0.7** |
| | | 70–90 | | 3 | **10.9** |
| | | 90–110 | | 4 | **9.1** |
| | | 110–130 | | 5 | **25.5** |
| | | 130–150 | | 6 | **19.2** |
| | | 150–170 | | 7 | **3.6** |
| | | 170–190 | | 8 | **0.0** |
| | | 190–210 | | 9 | **0.0** |
| | | >210 | | 10 | **0.0** |

| | | | | | |
|---|---|---|---|---|---|
| **A** | Aquifer lithology | Sands in loams and silts | 3 | 1 | **0.7** |
| | | Sands in till and sanded till | | 2 | **45.4** |
| | | Mudstones, sandstones, gypsum, rock salts and anhydrites | | 3 | **<0.1** |
| | | Sands, gravels, river bogs, peat and silt | | 4 | **19.7** |
| | | River sands, gravel and silt, sand and silt | | 5 | **0.7** |
| | | Conglomerates, sandstones, siltstones, limestones, dolomites | | 6 | **<0.1** |
| | | Heaps and embankments | | 7 | **0.3** |
| | | Gravel, sand, boulders and tils of moraines | | 8 | **4.1** |
| | | Aeolian sands | | 9 | **3.4** |
| | | Fluvioglacial sands and gravels, sands and gravels of moraines, gravel and sands | | 10 | **25.6** |
| **S** | Soil type | D – Stagnic Phaeozems | 2 | 1 | **2.9** |
| | | T – Histosols and Murshic Histosols | | 2 | **0.4** |
| | | E – Fluvic Histosols | | 3 | **3.6** |
| | | F – Fluvisols | | 4 | **6.7** |
| | | B – Cambisols | | 6 | **0.5** |
| | | Be and Bd – Eutric and Dystric Cambisols | | 7 | **31.9** |
| | | A – Podzols and Entic Podzols | | 9 | **53.5** |
| | | No soil cover | | 10 | **0.5** |
| **T** | Terrain slope [%] | >9 | 1 | 1 | **0.1** |
| | | 8–9 | | 2 | **0.1** |
| | | 7–8 | | 3 | **0.2** |
| | | 6–7 | | 4 | **0.3** |
| | | 5–6 | | 5 | **0.7** |
| | | 4–5 | | 6 | **1.5** |
| | | 3–4 | | 7 | **3.3** |
| | | 2–3 | | 8 | **7.4** |
| | | 1–2 | | 9 | **21.1** |
| | | 0–1 | | 10 | **65.5** |
| **I** | Impact of vadose zone | Clays, silts | 5 | 1 | **<0.1** |
| | | Clays, silts and sands, tills, | | 2 | **30.9** |
| | | Sandy tills, clays and deluvial sands, clays, sands and, gravels of moraine | | 3 | **0.8** |
| | | Chalk, gyttie, | | 4 | **0.1** |
| | | Boggy peat, peat | | 5 | **6.9** |
| | | Sands and silts, clay sands, humus sands | | 6 | **10.8** |
| | | Heaps and embankments | | 7 | **2.3** |
| | | Deluvial sands, gravels and clays, sands, gravels and silts | | 7 | **6.3** |
| | | Fluvioglacial sands, river and lake sands | | 8 | **5.1** |
| | | Aeolian sands | | 9 | |
| | | Fluvioglacial sands and gravels, sands and gravels of moraines, gravel and sands | | 10 | **36.9** |
| **C** | Hydraulic conductivity [m/d] | <2 | 3 | 1 | **<0.1** |
| | | 2–4 | | 2 | **46.2** |
| | | 4–8 | | 3 | **16.0** |
| | | 8–12 | | 4 | **8.7** |
| | | 12–16 | | 5 | **3.4** |
| | | 16–20 | | 6 | **25.6** |
| | | 20–30 | | 7 | **0.0** |
| | | 30–50 | | 8 | **0.0** |
| | | 50–100 | | 9 | **0.0** |
| | | >100 | | 10 | **0.0** |

### ***Characteristics of DRASTIC parameters***

#### *Depth to Groundwater*

The depth to the groundwater table of the uppermost aquifer was determined on the basis of the materials contained in the serial Hydrogeological Map of Poland in the scale of 1:50 000, Uppermost Aquifer, Hydrodynamics and Occurrence (implemented in years 2007–2012, www.geoportal.pgi.gov.pl), which covered 87% of the study area. Groundwater contour maps of aquifer related to the mean annual hydrodynamic state were used to prepare a raster map, which was subtracted from the Digital Elevation Model (DEM) raster. As a result of the performed calculations, a groundwater table depth map was obtained with values in the range from 0 (presence of surface waters) to 123.6 m, with an average value of 6.7 m and standard deviation 8.0 m. A special feature of the area is the shallow occurrence of groundwater in the river valleys and deep occurrence within the uplands. The groundwater table is deepest in the eastern part, in the area of dewatering of opencast mines. In the southern part, on the glacial uplands, the depths do not exceed 40 m, in the northern part, on the edge of the Noteć River valley they reach up to 60 m. The class with the rank of 8, where the depth is in the range of 2–5 m, covers 26% of the area, 23% is the class 7 with the depth in the range of 5–10 m, 16.7% is the highest class (10) with the depth to the groundwater table between 0 and 1 m (Figure 7).

### *Net Recharge*

The infiltration recharge was estimated by the indicator method, which required assigning the infiltration index to the lithological type of subsurface deposits. The calculations were based on the average annual rainfall for the years 2000–2020 from rainfall stations throughout Poland (www.powietrze.gios.gov.pl). The value of the average annual rainfall for the study area is increasing to the north from 486 to 634 mm. The infiltration index changed from 0.05 for Pliocene clays and stagnant silts, to 0.25 for fluvioglacial and glacial sands and gravels.

The variability of the infiltration recharge ranged from 33 to 158 mm/year with an average value of 92 mm/year ± standard deviation 43 mm/year. The values obtained by this method are considered to be the least precise, hence they were compared with the groundwater runoff determined for the Warta River catchments for the years 1971–2010. The average for whole area was estimated as 113 mm/year (Wrzesiński and Perz, 2016; https://poznan.wody.gov.pl/). The highest values were found in the catchments artificially fed by waters from the drainage systems of opencast mines (158–205 mm/year), much lower in the western part of the Warta catchment (120 mm/year), which correspond with values 92 and 110 mm/year respectively obtained from indicator method. The lowest average value 85 mm/year was calculated for catchments directly belonged to the Odra basin in the southern east. Class no. 1 covers 31% of the area with infiltration below 50 mm/year, class no. 5 is 25% with a recharge in the range 110–130 mm/year, class no. 6 is 19% of the area with a values between 130–150 mm/year. The lowest values occur in the central part of the area within the limits of the glacial uplands cut by river valleys (Figure 7).

### *Aquifer Media*

The lithology of the aquifers was determined on the basis of the Geological Map of Poland in the scale of 1:500 000 (www.pgi.gov.pl). Class no. 2, sands in tills and sanded tills, has the biggest area occurrence (45%), followed by class 10, which includes fluvioglacial and moraine sands and gravels (25.5%). The third class is class no. 4 – sands, gravels, silts of river genesis as well as peats (19.6%) (Figure 7).

### *Soil Media*

The basis for the development of the layer was the Map of soil types on a scale of 1:500 000 (updated 2005–2010, www.iung.pl), detailed by the Geological Map of Poland in the scale 1:50 000 (www.geoportal.pgi.gov.pl). Soil types have been ranked according to their insulating abilities: lower rankings generally indicate higher resistance to pollutant migration from the ground surface, the lowest where there is no soil cover at all. Class no. 9, Podzols and Entic Podzols, covers 53% of the area. The second class is Eutric and Dystric Cambisols, which constitute 32%, and the third is class no. 4 – Fluvisols, occupying 6.6% (Figure 7).

### *Topography*

Pixels of size 100×100 m, taken from the DEM resources of GUGiK (Head Office of Geodesy and Cartography, www.gugik.gov.pl), were transformed into a slope map expressed in % through the ArcGIS Slope tool. It has occurred that flat areas with a slope of up to 1% are dominating, as the class 10 covers 65% of the study area. The next classes with higher slopes are class no. 9, slopes 1–2% (21% of the area) and class no. 8, 2–3% of the slope (7% of the area). Higher values, up to a maximum slope of 13%, include the area of dunes and erosive edges of river valleys, especially of the Noteć River from the north (Figure 7).

### *Impact of Vadose Zone*

To determine the lithology of the vadose zone, the data from 108 sheets of the Geological Map of Poland in the scale 1:50 000 (www.geoportal.pgi.gov.pl) were used. The input data have been generalized and grouped according to the dominant lithology and genetic type. Class no. 10, fluvioglacial, frontal moraine sands and gravels, as well as gravels and sands, cover 36% of the area. Poorly permeable grounds created by clays, silt and sands, and tills, are in class no. 2 (30%), and sands and silts, clay sands, and humus sands are in class no. 6 (11%), (Figure 7).

### *Hydraulic Conductivity*

The data on the aquifer conductivity was obtained from the CBDH points (Central Hydrogeological Data Bank), own hydrodynamic model studies (unpublished) and research done during the documentation of the GZWP (Major Groundwater Reservoirs, www.pgi.gov.pl). The results were related to the geological divisions on the Map of Poland in the scale 1:50 000. The averaged values for individual groups varied from 1.1 m/d for sands, silts, clays and lake gyttas, clays, silts and stagnant sands to 16.5 m/d for fluvioglacial sands and gravels. The largest area is occupied by class no. 2 with a conductivity of 2–4 m/d (46%), successively class no. 6 in the range of 16–20 m/d (25%) and class no. 3 in the range of 4–8 m/d (16%) (Figure 7).

### *DRASTIC optimization by Parameter Sensitivity Analysis*

In order to reduce the subjectivity associated with assigning weights to DRASTIC parameters, a sensitivity analysis was performed (Napolitano and Fabbri 1996, Al-Adamat et al. 2003, Babiker et al. 2005). Single parameter sensitivity analysis is used to evaluate the impact of each factor on the overall vulnerability index by deriving an effective weight as stated in equation (2):

$$W = \frac{P_r \cdot P_w}{V} 100 \tag{2}$$

where: $W$ – parameter's effective weight [%]; $P_r$ – parameter's range; $P_w$ – parameter's weight ; $V$ – vulnerability index.

It helps to understand the influence of individual input parameters on the model's output by estimating the change in output map with each change in the input, so the procedure can be called as optimization of the DRASTIC results based on changed weights of the parameters.

### *Groundwater pollution risk map*

Four independent methods were used to assess the risk of contamination of groundwater with nitrates, which differ in the number of parameters and/or their weights: CD (Secunda et al. 1998), also known as land use DRASTIC, NV (Martinez-Bastida et al. 2010), agricultural DRASTIC, hereinafter as an abbreviation A-DRASTIC (Saha and Alam 2014), AHP land use DRASTIC, hereinafter AHP-DRASTIC (Sarkar and Pal 2021), (Table 2).

The CD method proposed by Secunda et al. (1998) consists in adding an additional parameter defined as the impact of land use *L*, the original weight of which was equal to 5. The range of the *L* parameter depends on the strength of anthropogenic pressure on groundwater, which can be equated with the risk of nitrates in groundwater.

The mostly modified method in relation to the DRASTIC is the NV method (Martinez-Bastida et al. 2010), which assumes that the relevant types of the land use are characterized by protective abilities in relation to groundwater pollution with nitrates. Hence, the vulnerability index should be lowered in the case of land use types with protective properties. The final DRASTIC index was multiplied by the *LU* parameter (type of land use), which takes values from 0.1 to 1 (Table 3).

The agricultural DRASTIC method (hereinafter as an abbreviation A-DRASTIC) assumes maintaining the same parameters as in the original method, but the weights of individual parameters have been changed and adjusted to the specificity of agricultural pollution (Saha and Alam 2014).

The AHP land use DRASTIC (hereinafter AHP-DRASTIC) method is in practice the CD method, however the weights of 8 parameters have been modified using the analytical hierarchy process (AHP) (Sarkar and Pal 2021).

### *The new NV-L method*

The existing risk assessment procedures did not take into account the nitrogen load supplied to groundwater. Therefore, it was decided to use a new method, which in its assumptions takes into account not only the land use type as in the NV method, but also the amount of nitrogen load leached from the soil profile. The previously calculated optimized DRASTIC

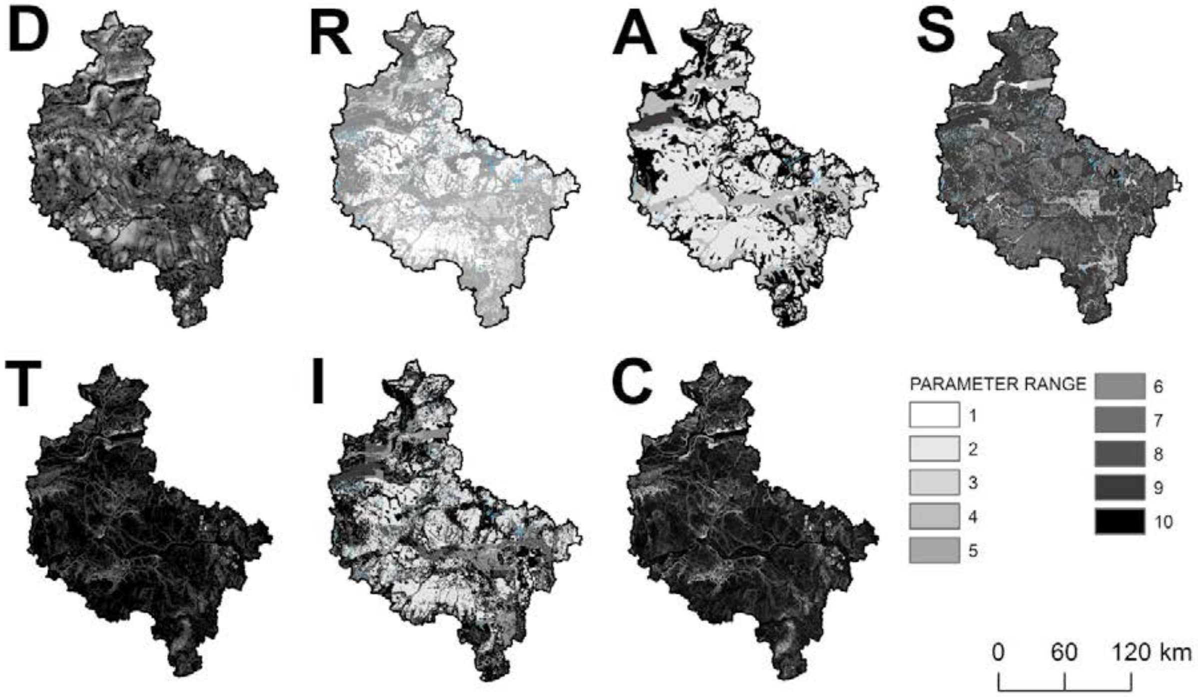


**Fig. 7.** Ranges of DRASTIC parameters

**Table 2.** Parameters and their weights used in groundwater pollution risk methods

| Parameter | A-DRASTIC | CD | NV | AHP-DRASTIC |
|---|---|---|---|---|
| **D** | 5 | 5 | 7.48 | 7.36 |
| **R** | 4 | 4 | 2.22 | 4.60 |
| **A** | 3 | 3 | 2.31 | 1.38 |
| **S** | 5 | 2 | 2.63 | 1.61 |
| **T** | 3 | 1 | 1.68 | 1.61 |
| **I** | 4 | 5 | 5.02 | 2.30 |
| **C** | 2 | 3 | 1.66 | 1.38 |
| **LU** | – | 5 | (0.1÷1) | 2.76 |
| **weight sum:** | 26 | 28 | 2.3–23 | 23 |

with the weights given in Table 4 was used in the proposed method, and an additional parameter was the nitrogen load classified into ten ranges. Such multiplication is a kind of additional weight transferred to all seven parameters of the DRASTIC method, which means that its value is assumed to be a decisive factor in the risk assessment. The nitrate pollution risk index was defined as follows:

$$NV\text{-}L = (7.48\,D_r + 2.22\,R_r + 2.31\,A_r + 2.63\,S_r + \\ + 1.68\,T_r + 5.02\,I_r + 1.66\,C_r)\,L_r \qquad (3)$$

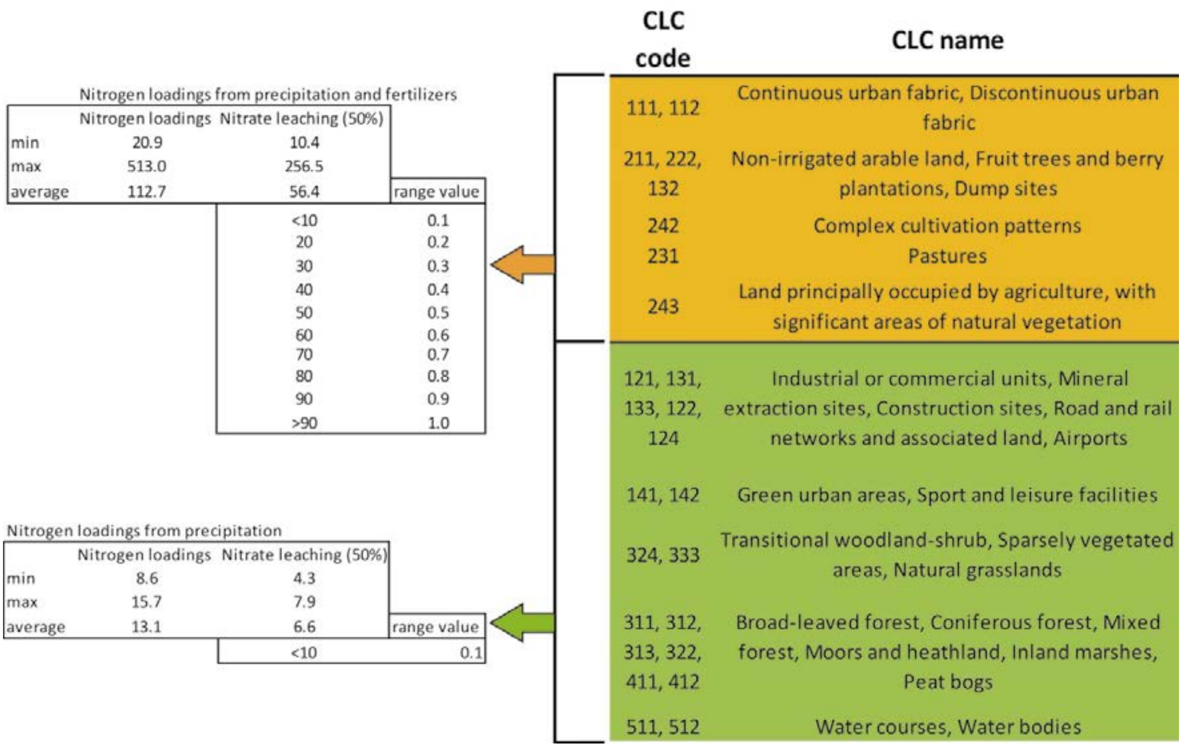
where: $L$ – nitrate leaching parameter, $r$ – parameter range.

Nitrate leaching parameter was classified into ranks similarly to the other parameters. The wide range of values made it possible to distinguish 10 classes in order to diversify the parameter value as much as possible after its transformation into rank values.

A constant amount of nitrogen leaching from the soil profile was assumed as 50% of total nitrogen load, according to the Regulation of the Minister of the Environment (2002). 10 ranges of $L_r$ were related to the following values: from $L_r = 0.1$ for areas with the lowest load (<10 kg N/ha·year), to $L_r = 1.0$ for areas with the highest load (>90 kg N/ha·year), while for areas characterized in CLC level 3 as natural or partially natural areas (CLC CODE >300), where there is no agricultural activity, the N load value was set as 50% of the precipitation load (Figure 8). The assumed high value of nitrogen leaching complies with the Report on the implementation of Directive 91/676/EEC in the years 2016–2020 (2021) performed for the Ministry of Maritime Economy and Inland Navigation, where the nitrogen leaching was assessed as 41–56% of the loadings.

**Table 3.** LU parameter classified according to the CLC classes

| CLC code | CLC name | LU |
|---|---|---|
| **111, 112** | Continuous urban fabric, Discontinuous urban fabric | 1 |
| **211, 222, 132** | Non-irrigated arable land, Fruit trees and berry plantations, Dump sites | 0.9 |
| **242** | Complex cultivation patterns | 0.8 |
| **231** | Pastures | 0.7 |
| **243** | Land principally occupied by agriculture, with significant areas of natural vegetation | 0.6 |
| **121, 131, 133, 122, 124** | Industrial or commercial units, Mineral extraction sites, Construction sites, Road and rail networks and associated land, Airports | 0.5 |
| **141, 142** | Green urban areas, Sport and leisure facilities | 0.3 |
| **324, 333** | Transitional woodland-shrub, Sparsely vegetated areas, Natural grasslands | 0.2 |
| **311, 312, 313, 322, 411, 412** | Broad-leaved forest, Coniferous forest, Mixed forest, Moors and heathland, Inland marshes, Peat bogs | 0.1 |
| **511, 512** | Water courses, Water bodies | 0.1 |



Nitrogen loadings from precipitation and fertilizers

| | Nitrogen loadings | Nitrate leaching (50%) |
|---|---|---|
| min | 20.9 | 10.4 |
| max | 513.0 | 256.5 |
| average | 112.7 | 56.4 |

| | range value |
|---|---|
| <10 | 0.1 |
| 20 | 0.2 |
| 30 | 0.3 |
| 40 | 0.4 |
| 50 | 0.5 |
| 60 | 0.6 |
| 70 | 0.7 |
| 80 | 0.8 |
| 90 | 0.9 |
| >90 | 1.0 |

Nitrogen loadings from precipitation

| | Nitrogen loadings | Nitrate leaching (50%) |
|---|---|---|
| min | 8.6 | 4.3 |
| max | 15.7 | 7.9 |
| average | 13.1 | 6.6 |

| | range value |
|---|---|
| <10 | 0.1 |

| CLC code | CLC name |
|---|---|
| 111, 112 | Continuous urban fabric, Discontinuous urban fabric |
| 211, 222, 132 | Non-irrigated arable land, Fruit trees and berry plantations, Dump sites |
| 242 | Complex cultivation patterns |
| 231 | Pastures |
| 243 | Land principally occupied by agriculture, with significant areas of natural vegetation |
| 121, 131, 133, 122, 124 | Industrial or commercial units, Mineral extraction sites, Construction sites, Road and rail networks and associated land, Airports |
| 141, 142 | Green urban areas, Sport and leisure facilities |
| 324, 333 | Transitional woodland-shrub, Sparsely vegetated areas, Natural grasslands |
| 311, 312, 313, 322, 411, 412 | Broad-leaved forest, Coniferous forest, Mixed forest, Moors and heathland, Inland marshes, Peat bogs |
| 511, 512 | Water courses, Water bodies |

**Fig. 8.** Procedure for determining the L parameter value

### *Result normalization and validation*

In order to compare the results of all methods with each other, including the original DRASTIC method and its optimized version, the calculation results were normalized to be presented on a uniform scale of vulnerability or pollution risk index from 0 to 1, as expressed by equation (4), (Yang et al. 2017):

$$\text{Normalized Index} = \frac{V - V_{min}}{V_{max} - V_{min}} \tag{4}$$

where: $V$ – vulnerability/risk index, $V_{\text{min}}$ – minimum vulnerability/risk index, $V_{\text{max}}$ – maximum vulnerability/risk index.

After normalization, the final indexes were divided into equal intervals, creating 5 classes of groundwater vulnerability/pollution risk as follows: 0–0.2 – very low, 0.2–0.4 – low, 0.4–0.6 medium, 0.6–0.8 – high, 0.8–1.0 – very high.

The validation of the methods was performed in relation to the values measured at the 1679 observation points, including 110 points where observations were carried out regularly.

The validation performed at the points where $NO_3^-$ concentrations were measured was related to the average nitrate concentrations within the vulnerability/pollution risk classes developed with all methods.

## Results and Discussion

### *Intrinsic vulnerability*

The result of the application of the DRASTIC method is the spatial distribution of intrinsic vulnerability to pollution (Figure 9A). The presented classes were determined after normalizing the vulnerability index. The fraction of each vulnerability class is similar. The very low class covers 18.9% of the area, mainly in the central part where glacial uplands occur. The low class occurs on 14.9% of the area, also within the uplands. The medium class covers 21.4% of the area, the larger river valleys, such as the Noteć and the Warta, as well as smaller watercourses cutting the uplands. The high vulnerability class covers 24.6% of the area and includes upland slopes and parts of valleys. The very high class consists mainly of areas with continuous covers of fluvioglacial deposits, it covers 20.2%.

Within the boundaries of the designated NVZ areas, the average normalized vulnerability index was 0.43, the medium class, although the highest share of about 25% area has values between 0.18 and 0.22 (low/very low vulnerability class). Outside the NVZ areas, the average vulnerability index is much higher, 0.55 in the medium class range.

### *Parameter Sensitivity Analysis*

The sensitivity analysis showed that the weight for the *D* (depth to groundwater) parameter was significantly underestimated. Too little weight was also assigned to the *S* (soil media) and *T* (topography) parameters. In the initial assumptions, too high weight was presumed for the parameter of *R* (net recharge), *A* (aquifer media) and *C* (hydraulic conductivity, whose weight was overestimated almost twice). The weight for the *I* (impact of vadose zone) parameter remained unchanged (Table 4).

After recalculation, the optimized DRASTIC (hereinafter an abbreviation DRASTIC-E) distribution was obtained, which showed values in the range 43.8–214.1, on average by 15.4 higher than DRASTIC (Figure 9B). The increase in value was recorded for 98% of the study area (for 8.4% of the area, the vulnerability has changed by two classes), mainly the fraction of high and low class as well as medium class increased (Table 5). The change in vulnerability is strongly correlated with the change in weights of *D* parameter (Pearson's coefficient R = 0.79) and *T* parameter (R = 0.53).

Within the NVZ areas, the average vulnerability index of DRASTIC-E was 0.50 (medium class), with a significant share of areas with values ranging from 0.32–0.36 (23%). Outside the NVZ zones, the average value of groundwater vulnerability index was 0.58.

### *Groundwater pollution risk map*

The methods of groundwater risk assessment have given various results (Figure 10). The greatest fraction of areas with a very high vulnerability class was obtained by the A-DRASTIC method – 26.4% (Figure 10). They occur in the same areas as for the original DRASTIC method. The high class covers the largest area (40.9%) in the AHP-DRASTIC method, including river valleys, the areas of occurrence of fluvioglacial deposits. In the case of the middle class, the NV method obtained the largest area – 36.2%, which covers most of the glacial uplands and part of the river valleys. The low class has a similar area fraction in the A-DRASTIC and CD method, it is 20.4 and 20.6% respectively. The highest fraction of the very low class was found for the NV method, i.e., 29.2%, while in the other methods the fractions were lower than 2%

**Table 4.** Original and effective weight of parameters

| Parameter | "Theoretical" Weight | "Theoretical" Weight (%) | "Effective" Weight | "Effective" Weight (%) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean | Min | Max | Standard Deviation |
| **D** | 5 | 21.74 | 7.48 | 32.51 | 3 | 90 | 10.12 |
| **R** | 4 | 17.39 | 2.22 | 9.66 | 2 | 22 | 4.11 |
| **A** | 3 | 13.04 | 2.31 | 10.04 | 1 | 48 | 5.58 |
| **S** | 2 | 8.70 | 2.63 | 11.44 | 1 | 26 | 4.10 |
| **T** | 1 | 4.35 | 1.68 | 7.30 | 1 | 27 | 2.72 |
| **I** | 5 | 21.74 | 5.02 | 21.83 | 3 | 43 | 8.11 |
| **C** | 3 | 13.04 | 1.66 | 7.22 | 1 | 25 | 2.45 |
| **Total** | 23 | 100 | 23 | 100 | | | |

(Figure 11). The most similar results were obtained by the CD and AHP-DRASTIC methods. The most distinctive method in relation to the others is the NV method, which indicates a very low risk in places where very high or high classes were obtained by other methods.

For NVZ areas, average values of risk index were lower than for the rest of the area in the case of using: A-DRASTIC, CD and AHP-DRASTIC. A-DRASTIC method gave the average value for NVZ 0.57, of which 33% was in the range 0.40–0.45. For the CD method, the average value was 0.54, of which 20% were values in the range 0.43–0.45. On the other hand, the average value of AHP-DRASTIC index is 0.57, of which 23% of the area is within the values of 0.45–0.50.

Outside the NVZ areas, the average value of risk index is higher: A-DRASTIC – 0.64, CD – 0.58, AHP-DRASTIC – 0.60.

From the presented results, it is necessary to distinguish the NV method, the results of which indicated a higher average value of the risk index in the NVZ areas – 0.48, of which 31% are results in the range 0.4–0.5. Outside the NVZ zones, a lower average value was recorded 0.40, and 27% of the area is below 0.1 (very low class of risk).

The results obtained by new method – NV-L indicated the highest fraction of the very low class of pollution risk (30.6%), the low class – 27.8% and the medium class – 30% (Figure 12). The fraction of the remaining classes is very small and does not exceed 12% in total: high class – 10%, and very high class 1.6%. The analysis of the results showed that in the areas of the Nitrate Vulnerable Zone (NVZ), the average risk class was significantly higher *NV-L* = 0.46, of which 35% is between 0.4–0.6 (medium class). For the remaining area average *NV-L* index was equal to 0.31, of which 27% are values below 0.05 – very low risk class.

Vulnerability map of Poland in the scale 1:500 000 (Duda et al. 2011) showed actual scenario of groundwater pollution risk, where nitrogen load was estimated from average consumption of fertilizer from 2006–2008. Wielkopolska Province stands out from rest of the country, where 13,250 km$^2$ was recognized as areas where nitrate concentrations exceed 100 mg/l (very high risk). This is 44% of the whole province, and it follows that it constitutes 68% of the agricultural land area. A strong diversification of the results of the calculated concentrations of nitrates can be observed, as the areas not classified by

**Table 5.** Vulnerability class area changes after DRASTIC optimization

| Vulnerability class | Class area for DRASTIC [%] | Class area for optimized DRASTIC [%] | Class area change |
|---|---|---|---|
| **very low** | 18.9 | 5.8 | -13.0 |
| **low** | 14.9 | 24.4 | 9.5 |
| **medium** | 21.4 | 21.7 | 0.34 |
| **high** | 24.6 | 27.9 | 3.2 |
| **very high** | 20.2 | 20.1 | -0.06 |

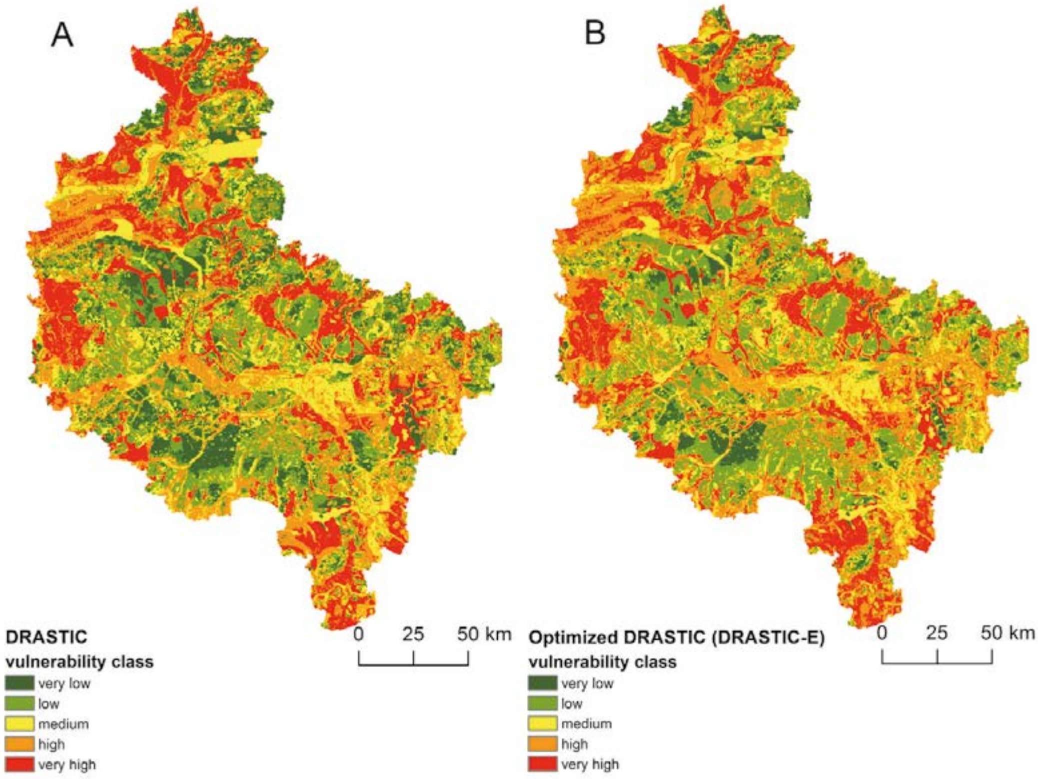


**Fig. 9.** Vulnerability classes of: A – DRASTIC; B – optimized DRASTIC

agricultural activity were classified as having groundwater concentrations of nitrates lower than 10 mg/l (very low risk).

### *Validation*

The lowest match was found with the results of intrinsic vulnerability methods – DRASTIC and its version after optimization (DRASTIC-E in Figure 13). Strong but negative correlation was obtained ($R^2 = 0.89–0.97$). The risk assessment methods developed by other researchers did not bring strong correlations, as within the high and very high classes, the average concentrations were lower than for the medium and low classes. The lowest mean values occurred both in the very low and very high class, which resulted in the lack of linear correlation and $R^2$ values at the level of 0–0.06.

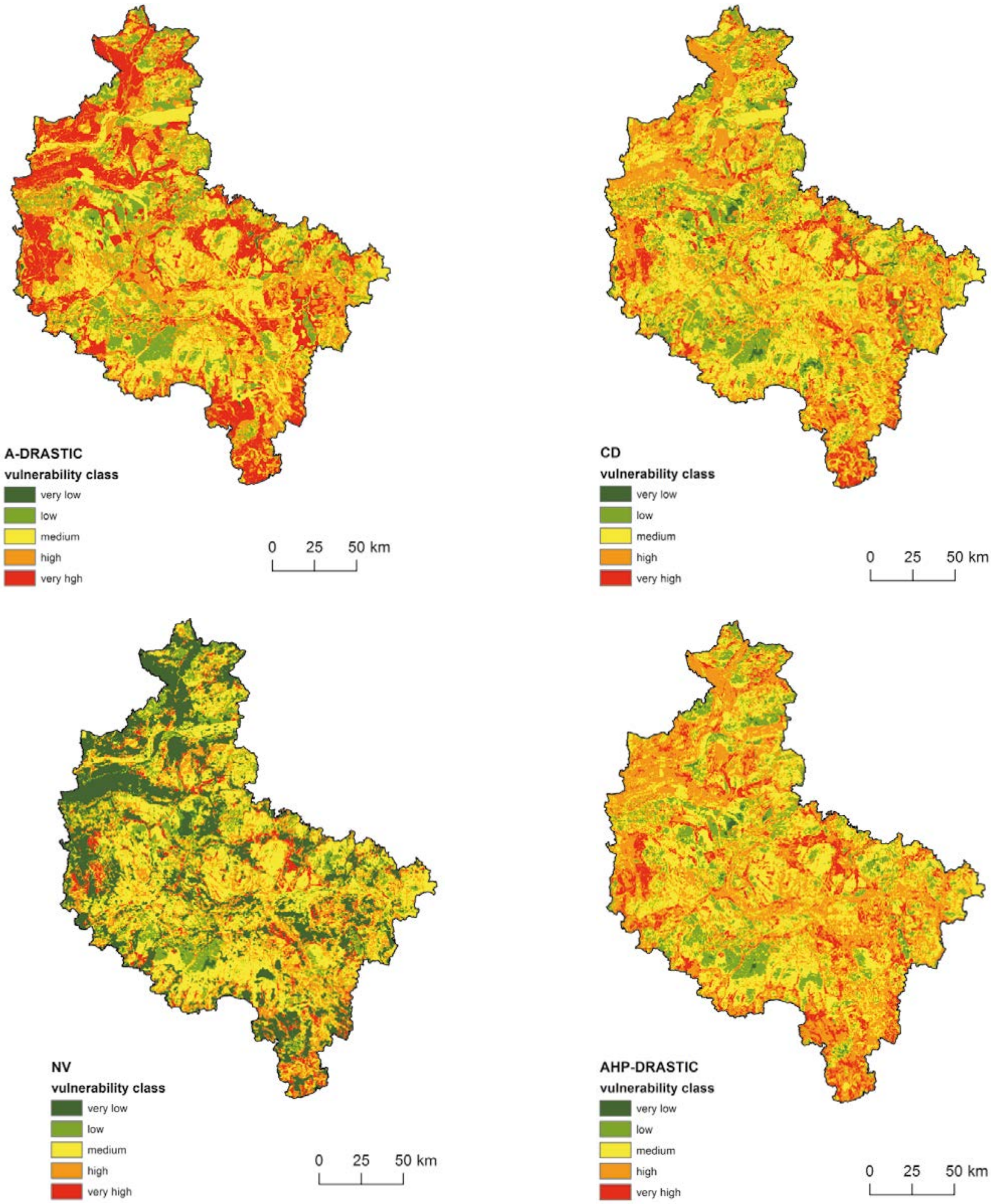


**Fig. 10.** Groundwater pollution risk calculated by selected methods

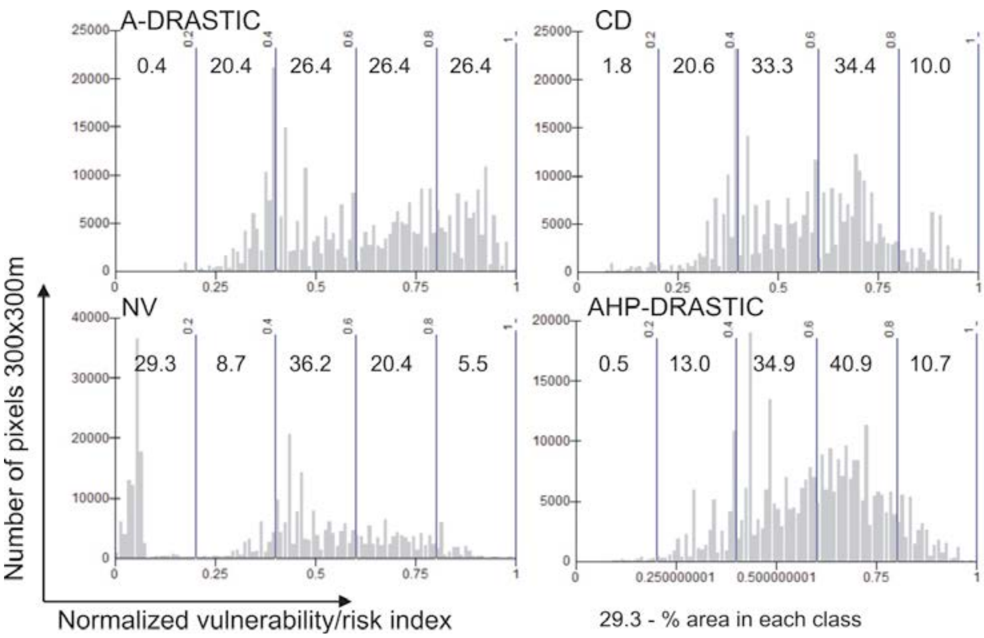


**Fig. 11.** Normalized index distribution histograms

The applied NV-L method is the only one with a strong positive correlation at the level of $R^2 = 0.80$, where the increase in the average nitrate concentrations occurs with the increase in the pollution risk class. The same conclusion can be observed when NV-L index was correlated with $NO_3^-$ in particular monitoring points. This is the only method where strong correlation was found ($R^2 = 0.33$) (Figure 14).

Most of the results of the methods used should be considered as overestimated. The share of areas classified as very high risk is surprisingly high in relation to the results of groundwater monitoring. Due to the significant share of points with nitrate concentrations lower than 10 mg/l (44%), the NV-L method is more appropriate for the real situation. The same concerns the highest concentrations of nitrates, 16% of the points exceed the value of 100 mg/l, while very low and low risk classes occupy 12% of NV-L results.

## Conclusions

The main goal of this study, which was to assess the risk of groundwater pollution from agricultural activities, has been achieved. The five popular and independent methods of groundwater vulnerability used in this study pointed to completely different areas of high risk of nitrate pollution to shallow groundwater. The selection of the reliable method was possible only at the stage of verification of the results by groundwater chemistry observations, and prompted the authors to look for new solutions in the assessment of pollution risk, which resulted in the NV-L method. Detailed conclusions are presented below.

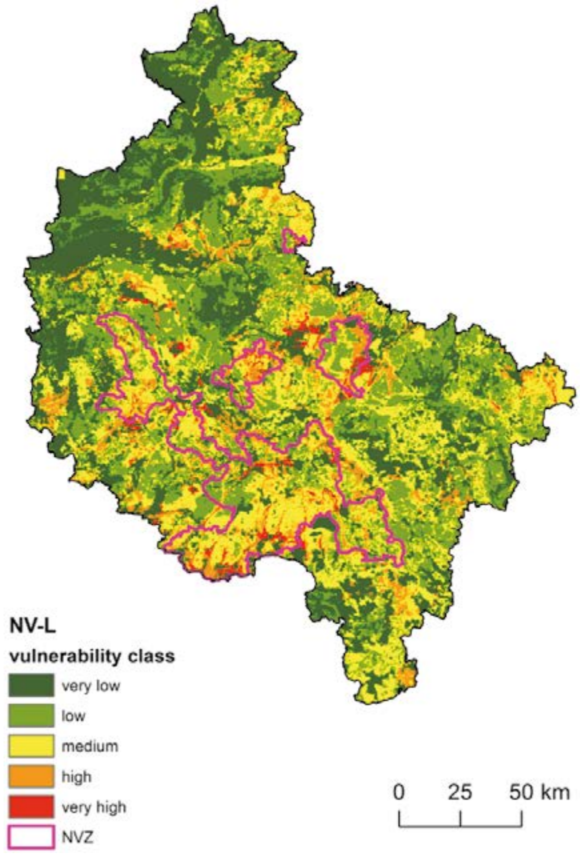


**Fig. 12.** Groundwater pollution risk calculated by NV-L method

a. Determination of the hydrogeological conditions of the uppermost aquifers made it possible to assess the intrinsic vulnerability using the DRASTIC method and to optimize its results through single parameter sensitivity analysis. The results for both assessments were similar and indicated the presence of a significant fraction of the medium, high and very high vulnerability class – over 20%. The low class dominated the central part of the area, in the glacial uplands.
b. To assess the groundwater pollution risk caused by nitrates, four methods were used based on the modified algorithms of the DRASTIC method: CD, NV, A-DRASTIC, AHP-DRASTIC method. Among them, the A-DRASTIC method was characterized by the largest surfaces of the very high class (26.4%), and the

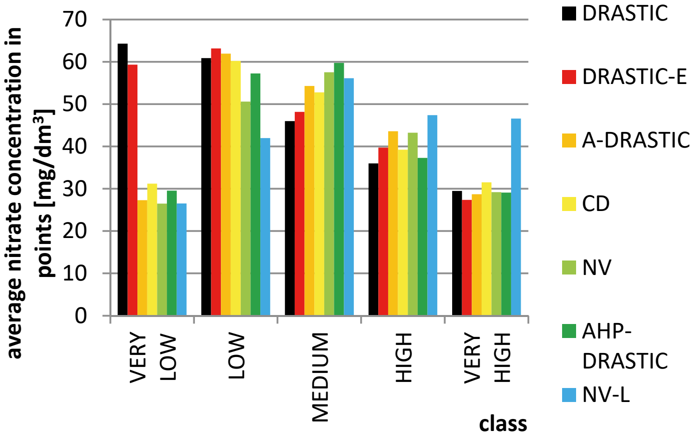


**Fig. 13.** Relation between average nitrate concentration in monitoring points and vulnerability/risk class

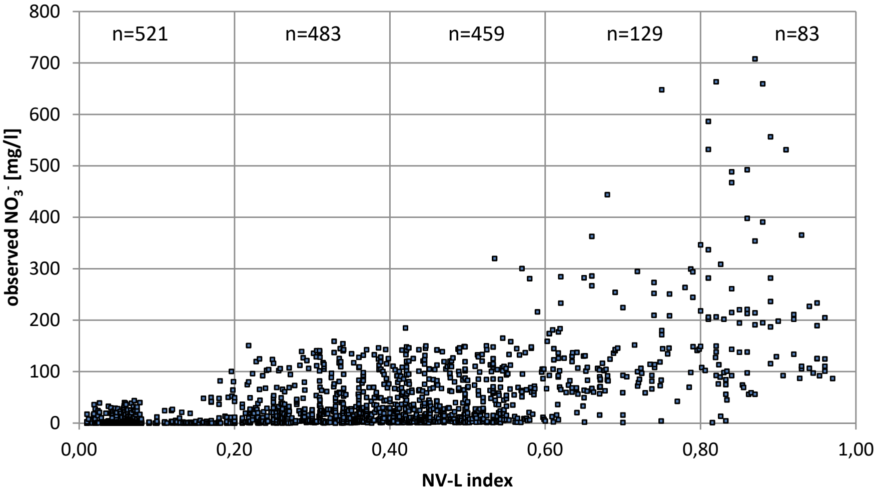


**Fig. 14.** Relation between nitrate concentration in monitoring points and NV-L risk class

NV method of the very low class (29.2%). The results of the applied risk assessment procedures did not correlate with nitrate concentrations observed in groundwater sampling point, so during the verification stage, it was found that these models do not describe well the process of leaching nitrates from the soil profile.

c. A new method called NV-L was elaborated. The basis of the method was the result of the optimized DRASTIC, but the key parameter of the evaluation turned out to be the new parameter *L*, which included in the procedure both: the land use type and the amount of total nitrogen leached from the soil profile.
d. The ranges of the new *L* parameter for agricultural and urbanized areas depended on the sum of the nitrogen load from the consumption of fertilizers and from wet deposition, for areas considered natural depended only on the nitrogen loads from precipitation.
e. The results of NV-L method indicated that a largest area is covered by very low class of pollution risk (30.6%), the low class – 27.8% and the medium class – 30%. The average normalized risk index is higher in the areas of the Nitrate Vulnerable Zones (*NV-L* = 0.46 – medium risk class), than for the remaining area (*NV-L* = 0.31 – low risk class).
f. Validation performed at 1679 points of observation of shallow groundwater chemistry showed that the applied new NV-L method is characterized by a high correlation of nitrate concentrations in relation to the risk classes. The other methods used to assess intrinsic vulnerability and pollution risk cannot be used as reliable methods in nitrate pollution risk, as they do not take into account the amount of nitrogen load leached from the soil profile.

The results show that some important information was missing in the vulnerability assessment procedures by the common methods. Therefore, their results should be treated as very simplified and cannot be used in further analysis as a useful tool for effective protection of groundwater. In addition, it is always important to consider other relevant elements in groundwater vulnerability or pollution risk as their contribution to the methodology may prove to be a key factor, as was the case with our research.

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## Wysokorozdzielcza ocena ryzyka zanieczyszczenia wód podziemnych azotanami pochodzącymi z działalności rolniczej na obszarze Wielkopolski

**Streszczenie:** Celem badań było określenie podatności wód podziemnych na zanieczyszczenie płytkich wód podziemnych w województwie wielkopolskim oraz ocena ryzyka zanieczyszczenia azotanami. Województwo wielkopolskie uważane jest za obszar, na którym od dawna znany jest problem zanieczyszczenia wód azotanami z powodu intensywnego rolnictwa. Do obliczenia indeksu podatności naturalnej wybrano metodę DRASTIC i jej zoptymalizowaną wersję, natomiast do oceny ryzyka zanieczyszczenia azotanami cztery metody będące modyfikacjami metody DRASTIC. Wynik żadnej z nich nie był skorelowany ze stężeniami azotanów odnotowanymi w 1679 punktach monitoringu wód podziemnych, dlatego zaproponowano nową metodę oceny zagrożenia wód podziemnych NV-L. Metoda opiera się na zoptymalizowanych wynikach systemu DRASTIC i parametrze L, który uwzględnia nie tylko typ użytkowania gruntów, ale także wielkość ładunku azotu, pochodzącego z wymywania z gleby nawozów mineralnych i organicznych oraz z mokrej depozycji w opadach. Wyniki metody NV-L wykazały, że największy obszar objęty jest bardzo niską klasą zagrożenia zanieczyszczeniami (30,6%). Klasa wysoka i bardzo wysoka zajmują 11,6% powierzchni, głównie na obszarach wyznaczanych do 2012 roku jako obszary szczególnie narażone na wymywanie azotu do wód powierzchniowych. Wyniki wskazują, że w procedurach zastosowanych metod oceny podatności brakowało pewnych ważnych informacji. Dlatego ich wyniki należy traktować jako szacunkowe i nie mogą one być wykorzystywane w dalszych analizach jako użyteczne narzędzie ochrony wód podziemnych. Uwzględnienie innych, nowych elementów do oceny podatności wód podziemnych lub ryzyka zanieczyszczenia, może okazać się kluczowym czynnikiem, jak miało to miejsce w przypadku metody NV-L i wykorzystania danych dotyczących ładunku azotu wymywanego z profilu glebowego.