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Spatial risk assessment of drinking water contamination by nitrates from agricultural areas in the Silesia province

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ABSTRACT

The main purpose of presented study was to show the potential threat of the access to drinking water of uncertain quality. Protection against contamination of natural aquatic ecosystems is the main action taken to reduce the danger of different threats. The European Union using legislation, through issuing the Water Framework Directive, established a plan in the field of water policy, aiming at protecting groundwater better. The Directive orders each Member State to use water in a rational way and obliges them to protect the water resources in accordance with the principles of sustainable development. The target of this paper is to analyze the variability of nitrates concentration in water intended for Silesian inhabitants consumption in the period of 2008–2012. In research methodology, water supply systems were divided into categories, depending on the daily demand of water or alternatively on the number of settlement units supplied with water. This variable was connected with the amount of quality water control and the probability of exceeding the maximum permissible concentration of nitrates in drinking water. The areas with the highest risk of nitrates contamination in a tap water were defined using the land cover layer and nitrates concentration in surface raw water and drinking water.

Keywords: Drinking water; Nitrates; GIS; Vulnerable areas; Human health; Spatial data

1. Introduction

The high pollution of water resources was the impetus, in the first place, to take the appropriate legal measures aimed at eliminating these processes and making the gradual improvement of the quality of water resources. In 2000, the Water Framework Directive (WFD) of the European Community was enacted establishing a single framework for water policy [1]. Water is not a commercial product like any other, but rather a heritage which must be protected, defended, and treated as such. The Directive obliges Member States to the rational use of water and protection of water resources in accordance with the principles of sustainable development. However, the WFD did not solve all the problems connected with the protection of water resources as a source of drinking water for

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people. One of the main threats to human health is drinking water of poor quality, which in spite of treatment in modern purification systems, does not always meet the required quality standards. These standards were clearly defined in the Council Directive 98/83/EC of 3.11.1998. on the quality of water intended for human consumption [2]. This Directive specifies, among other things, the limits of the concentration of nitrates in water at level 50 [mg/dm^3]. One of the main problems requiring urgent solution was a steady increase of pollution of Europe's water resources with nitrogen compounds, mainly as a result of improper functioning of agricultural policy. This was the reason for the establishment of the European Union Council Directive 91/676/EEC [3] concerning the protection of waters against pollution caused by nitrates due to improper agricultural policy. It is known as a Nitrates Directive, the aim of which was to make the Member States take measures to reduce water pollution by nitrates. The problem of environmental pollution by nitrates is frequently represented in the literature.

One of the main causes of pollution of water by nitrates is the impact of improper agricultural practices, resulting from the incorrect application of fertilizers and pesticides [4,5]. This problem is present not only in Europe but around the world: e.g. in Korea [6], Pakistan [7], Nigeria [8], and China [9]. Thus, reducing the amount of nitrates entering the environment through reasonably conducted agricultural economy seems to be an essential activity which provides improvement in the quality of both surface and underground water. This effect can be achieved, for example through proper management of the agricultural economy [10], or a drastic reduction in fertilizing the agricultural areas [5]. In addition to the change of the agricultural economy, the quality of water in the environment is also affected by the distance of the aquifer from the surface of the ground. A direct correlation of this is the depth of the wells. Aquifers located closer to the surface are more vulnerable to nitrate pollution [11]. The seasonal variability of nitrate concentrations in water resources [5,9,12] is also of a great importance.

It is concluded that the concentration of nitrate in the groundwater is higher in the summer season than in periods characterized by low temperature [13]. Then the plants do not receive ammonium and nitrate nitrogen, and there is lack of nitrification. In summer, during periods of higher temperatures, higher level of nitrites is due to the nitrification process converting ammonia into nitrites and nitrates. In addition, the rainy season increases the amount of nitrates in the waters when compared to the periods of drought [14–16]. The overall effect of the application of the Nitrates Directive [3] is to improve the quality of groundwater and surface water, as a result, improving the access to safe drinking water. To ensure the safety of health for consumers, it is essential to lift the water requirements regarding the standards of drinking water quality and, consequently, to use larger financial outlays on modernization of water treatment technology [17], to provide a high technological effect of its treatment.

Based on the definitions contained in the Decree of the Minister of the Environment [18], in terms of utilization of water resources as a source for the production of drinking water, the contaminated water shall be adopted as: inland surface water, especially water that is taken or intends to be taken for the purposes of public supply of water intended for human consumption, and underground water, where the nitrate content is above 50 mg/dm^3. In addition, compromised water pollution by nitrates adopted inland surface water, especially water that is taken or intends to be taken for the purpose of water supply for human consumption and groundwater with nitrate contents from 40 to 50 mg/dm^3.

The use of drinking water contaminated with nitrates is very dangerous. The literature has repeatedly described the adverse impact of excessive doses of nitrates on the health and lives of human being. Nitrates in the human body are reduced to nitrite, while the oxidation of the iron as Fe(II) to Fe(III) in the form of a heme molecule, resulting in inability to carry oxygen in the bloodstream. This is especially dangerous for infants, young children and pregnant women. Mehaemoglobinaemia symptoms are referred to as "blue baby syndrome" [19–22]. Furthermore, in the human body nitrates pass through metabolic cycles to N-nitroso compounds, which can affect the increased risk of cancer [22–24]. Thus, providing into the human body an increased amount of nitrates may increase the risk of cancer [16]. The problem of health hazard caused by nitrates in drinking water is so serious that the authorities and institutions involved in protection of public health have prepared brief warning information on concentrations of nitrates in water that is safe for health and thresholds threats, which after being crossed, make that water undrinkable. These are the contact details for offices terrain, depending on the structure of the organization of the office of your region / country. This information is available to the public at the headquarters office, website, or even your local water companies [25].

2. Materials and methods

2.1. Study area

The aim of this analysis was to evaluate the content of nitrates the quality of water intended for human consumption by the inhabitants of the Silesia province, one of the largest urban and industrial agglomerations in the south of Poland. An integral element of the study was to determine areas with the highest level of risk and to estimate the level of risk of nitrate pollution risk of water intended for human consumption by the inhabitants of the Silesia province.

The Silesia Region covers an area of 12 334 km^2, which accounts for 3.9% of the total area of Poland. It is characterized by a great diversity of geographical environment and it is located within the three provinces of the Central Lowlands, Polish Highlands, and The Western and The Lower Carpathians. The subsoil is composed of rocks of different ages, different positioning and lithological characteristics, which determines the varying resistance to erosion and denudation. A tectonic unit that lies within the province and is called the Upper Silesia sinkhole, and which is characterized by the presence of the biggest in Poland and one of the largest in Europe coal deposits, deserves a particular note due to its economic importance. The northern and western parts of the region are the uplands and agricultural areas, while the south consists of the Beskidy Mountains and a part of the External Carpathians. Silesian voivodeship is the province with the highest degree of urbanization and population density. 4,635 million people representing 12.14% of the Polish population live in Silesia [26]. In this area, in 2012, a total of 392.7 cubic hectometers of water was used, out of which 128.5 was used by industry, 77 by agriculture, and 186.5 as public water supply for drinking. 137.9 [hm^3/year] was delivered to people living in that region. The total length of the water supply network is 20,300.7 [km], which brings water to 584 thousand connections [27]. More than 51% of the Silesian province is dedicated to agriculture. In contrast, water areas occupy only 1.45% of the province. Due to such a large share of agricultural land and incorrect agricultural economy surface water and deep water have always been exposed to danger of nitrates contamination.

In the Silesia province, a vast majority of drinking water is supplied from the subsystem surface water uptake (Tables 1 and 2). Over 2.5 million inhabitants of the Silesia province use water from these sources of water supply, which represents 55% of the total population. Water treatment plants in the research area which use surface water resources are independent subsystems of water production with a really large diversity of performance, such as large subsystems located in the southern part of the region's water intake on the Goczałkowice tank on the Vistula River (180,000 m^3/24 h) and the Czaniec tank on the Soła river (100,000 m^3/24 h). These large subsystems of uptake and WTP subsystems supply water for hundreds of thousands of people. Small subsystems with a small capacity of 7–8 m^3/24 h, supply water to several tens of residents (Table 1). The subsystems of uptake and treatment of water with high efficiency, supply water to the central regions of the province, especially to the Upper Silesian Industrial District, which is a large population center with a lot of and industrial plants.

A special role in water supply system (WSS) of the Silesia province in addition to a significant surface water resources of the Vistula and the Soła rivers plays the Lubliniec-Myszków aquifer (in Polish—GZWP), with its code GZWP327. Due to a small degree of low permeability layers cover of the aquifer is rated as one of the highly susceptible to human pressure. In 2003, the underground waters reservoir were officially determined as sensitive to pollution with nitrogen compounds from agricultural sources [30]. At the same time, due to the improvement of the quality of the environment, as early as in 2008 [31] the above decree was abolished. This meant that in the province there is no problem with nitrates water pollution; therefore, the access to safe drinking water is guaranteed. As part of the study, the results of surface water quality used for public supply of water intended for human consumption and the results of quality of water intended for human consumption were analyzed. Data were obtained from the Chief Sanitary Inspectors archives of databases [28] for the Silesian province for 2008–2012.

The data on land cover was made available by the Chief Inspector for Environmental Protection as part of the Corine Land Cover project [32]. The Corine Land Cover 2006 project (CLC2006) is a continuation carried out by the European Environment Agency CLC1990 and CLC2000 projects, and its primary purpose is to document further the changes in land cover, as well as to collect and update comparable data across Europe. Poland participated in the implementation of CLC1990 and CLC2000 projects. Filed Program Corine Land Cover and the details of the data collected are mainly adapted to the needs of all members and various bodies of the European Union, such as EU committees, national offices. The adopted land cover nomenclature includes all forms occurring on the European continent and includes five main types of coverage of the globe: anthropogenic areas, agricultural areas, forests and semi-arids, wetlands and water.

Table 1
The distribution of WSS exploiting surface water resources divided into categories in the time period 2008–2012 [28,29]

	Category of WSS				
	Individual	Small	Medium	Large	Total
Number of subsystems of surface water uptake for WSS	19	0	6	29	54
% part of subsystems of surface water uptake to total subsystem water uptake for WSS	4.6%	0%	3.6%	40.8%	6.8%
Number of people using water from each category of WSS (in thousands)	1.5	7.5	63	2,400	2,500

Table 2
Number of WSS exploiting surface water resources in the Silesia province in 2008–2012 [29]

Year	Number of surface water uptake subsystems
2008	52
2009	58
2010	57
2011	59
2012	60

2.2. Data sources

In the province of Silesia, on the basis of the act of law on Sanitary Inspection (SI) [33], on the province level the uptake of surface water used for water supply and drinking water is officially controlled by the Silesian Province Official Sanitary Inspector (in Polish: Śląski Państwowy Wojewódzki Inspektor Sanitarny) and on the districts level twenty District Official Sanitary Inspectors (in Polish: Państwowy Powiatowy Inspektor Sanitarny) do that. The research is done in 10 accredited SI laboratories. For the purpose of the assessments of temporal and spatial variability of nitrate concentrations in surface water, water quality data, derived from database resources made available by the Chief Sanitary Inspector were used. Archive databases were created on the basis of quality control of drinking water implemented in accordance with the Regulation of the Minister of Health [34], representing implementation of the Directive 98/83/EC [2]. In addition, SI monitors the quality of surface water resources used for public supply of water intended for human consumption [35], but only at the uptake point. The analyses did not include groundwater quality, due to the lack of appropriate databases which resulted from the lack of formal legal requirements to control these resources by the SI.

Nitrate tests are performed using a colorimetric method according to the Polish Standard PN-82 C-04576/08 regarding water and wastewaters. Examination of nitrogen compounds. Determination of nitrate nitrogen by the colorimetric method' [36].

In this study, as an analytical tool for spatial analysis MS ACCESS database program, a package of STATISTICA and software from Environmental Systems Research Institute ESRI ARCGIS ENTERPRISE were used.

2.3. Algorithm testing procedures

Based on the decree [34] in adopted research methodology, WSS were divided into four research categories, depending on the daily demand for water or alternatively on the number of settlement units supplied with water (Table 3).

Based on the defined criteria divided into four categories and on the basis of water quality data from Chief Sanitary Inspector national databases [28], in the Silesia province operates a structure of division, in which in the last four years, the collective WSS constitute an average of 43% (Table 4) of all WSS. Water quality data collected in these systems for the years 2008–2012 was a collection of the analysis of random variables.

The proposed analytical methodology, based on a mathematical formula (1) was determined for the i'th year research sensitivity parameter of the threat of contamination by nitrates $R_i(\mathrm{WSS}_t)$ for each category of dedicated WSS (individual, small, medium, and large). This parameter specifies the number of exceedances per year attributable to each separate WSS in a given size category.

$$R_i(\mathrm{WSS}_t) = N_{\mathrm{s\_MAC}}/N_{\mathrm{WSS}_t} \quad (1)$$

where $R_i(\mathrm{WSS}_t)$ is the average number of exceedances for the ith year for each category of WSS; $N_{\mathrm{s\_MAC}}$—number of samples exceeding a maximum admissible concentration of nitrates; $N_{\mathrm{WSS}t}$—number of WSS in each type of category.

In the research methodology of risk analysis of human health threat due to exposure to nitrates in

Table 3
The rules of separation of WSS categories

Category of WSS	Daily efficiency system Q, $m^3/24$ h	Size of population
Small	$Q < 100$	–
Medium	$100 < Q < 1{,}000$	Below 5,000
Large	$Q > 1{,}000$	Over 5,000
Individual*	$Q < 10$	Less than 50

*Commercial or public activities.

Table 4
Number of WSS in Silesia province [28]

		Category of collective WSS			
Year	Individual	Small	Medium	Large	Total no
2008	No data	232	188	81	501
2009	466	137	172	64	839
2010	623	143	171	68	1,005
2011	583	136	174	64	957
2012	411	140	169	71	791

drinking water, three classes of pollution levels were collected (Table 5), by defining the boundaries of the two ranges. The requirements of Polish act of law were used to determine the value of the first boundary. They determine the nitrates concentration value of 40 mg/dm^3 as the maximum permissible concentration of nitrates in surface and ground water resources, causing no significant risks to human health.

Determination of the nitrates concentration value as the second threshold at 50 mg /dm^3 was based on normative legal guidelines for drinking water [34] (Table 5). Drinking water containing nitrate in excess of this limit is dangerous to health and life. It should be noted that this value is identical to the criteria set out in the Nitrates Directive [3], according to which in the case of excess nitrate concentration of 50 mg/dm^3 natural water resources (groundwater or surface water) are considered to be contaminated with nitrates.

The pure analysis of water quality results connected with data characterizing the WSS, without spatial variable, does not give a complete situation picture of the location of the area where it may occur to consume water contaminated with nitrates.

For a complete analysis of the spatial variability of distribution of nitrate concentrations in water, ArcGIS Enterprise software was used. The Silesia province was divided using grid squares chosen with randomly chosen 15 km side length.

The spatial analysis of the variability of nitrates concentration in the water takes into account the number of exceedances of the limit values in the checkpoint. The checkpoint is assigned to a category of WSS. On the basis of the formula (2) a probability of exceeding the maximum admissible concentration for each category of WSS in the area of research was determined:

$$P_{\mathrm{WSS}_t} = N_{\mathrm{s\_MAC}}/N_{\text{s-all}} \tag{2}$$

where $P_{\mathrm{WSS}t}$ is probability of exceeding the maximum admissible concentration for each category of WSS in the research area; $N_{\mathrm{s\_MAC}}$—number of samples exceeding the maximum admissible concentration of nitrates; $N_{\mathrm{s\_all}}$—number of all samples of nitrates in each category of WSS in the research c area.

In the next step of research methodology, for each checkpoint in a separate area of WSS, the calculated probability of exceeding $P_{\mathrm{WSS}t}$ was assigned. Then, the spatial intersection for drinking water quality checkpoint with a layer of Corine Land Cover 2006 with selected agricultural land was made. For each grid cell, the control index (IC) was calculated according to Eq. (3):

$$\mathrm{IC} = \sum_{\substack{i=1 \\ k=1}}^{\substack{i=1 \\ k=K}} P_{\mathrm{WSS}k}\,(x_i, y_i)\,\cdot C\,(x_i, y_i) \tag{3}$$

where $C(x_i,\ y_i)$ is the weight of land cover; for the agricultural area $C = 2$, for other areas $C = 1$; $P_{\mathrm{WSS}k}$ $(x_i,\ y_i)$ - probability of exceeding the maximum

Table 5
Categories extent of nitrate pollution

Class	Category of threat	Values of the threshold nitrate concentrations, mg/dm^3
A	Lack	$X < 40$
B	Average	$40 \le X < 50$
C	Big	$X \ge 50$

admissible nitrates concentration for kth WSS; i—ith point of quality water control for kth WSS area, $i = 1, \ldots, I$; I—the number of control points throughout the research area; k—kth WSS throughout the research area, $k = 1, \ldots, K$; K—the number of WSS throughout the research area.

3. Results and discussion

3.1. Assessment of the risks of occurrence of nitrate in surface waters used for public supply of water intended for human consumption

Within the timespan of 2008–2012, a total of 654 analyses of nitrate concentrations in samples of raw surface water resources were made. There was not even one case where the nitrate concentrations were above 40 mg/dm^3.

The multi-year average content of nitrate in surface water in uptake point (Fig. 1) was 4.084 mg/dm^3 with a standard deviation of 3.132 mg/dm^3 at the minimum value of 0.1 mg/dm^3 recorded on 26.07.2011 in the samples of water from the reservoir Czaniec in Porąbka and on 03.09.2012 from Dziećkowice tank in Chełm Śląski. The maximum value 22.66 mg/dm^3 was risen on 23.03.2009 in Zebrzydowice sample from the river Piotrówka. In this respect, recognized water quality meets the highest standards of regulation [34]. The obtained results allow one to conclude that the quality of surface water used for public supply, in place of its recognition is not threatened by nitrate pollution. Moreover, the situation is stable and there are no variations in water quality in this context. Also, extreme weather conditions, such as heat waves and heavy precipitation, combined with local flooding in no way caused a significant increase in the concentration of nitrates in the water. According to the information obtained from the Silesian Province Official Sanitary Inspector [29] the main, and practically the only reason for the reduction of surface water quality assessment in the Silesian agglomeration are microbiological contaminants, which classify these resources to the category below A1.

The spatial analysis of location linkages of surface water uptakes with agricultural areas (Fig. 2), made with ESRI ArcGIS model showed that 32% of the intakes are located in agricultural areas. This fact does not in any way affect significantly the degree of water pollution by nitrates. Thus, it can be stated unequivocally that the surface waters are neither contaminated nor exposed to pollution by nitrates and provide safe drinking water reservoir.

3.2. Assessment of the risks of occurrence of nitrates in drinking waters

The quality of drinking water should meet the requirements of the Decree of Minister of Health [34],

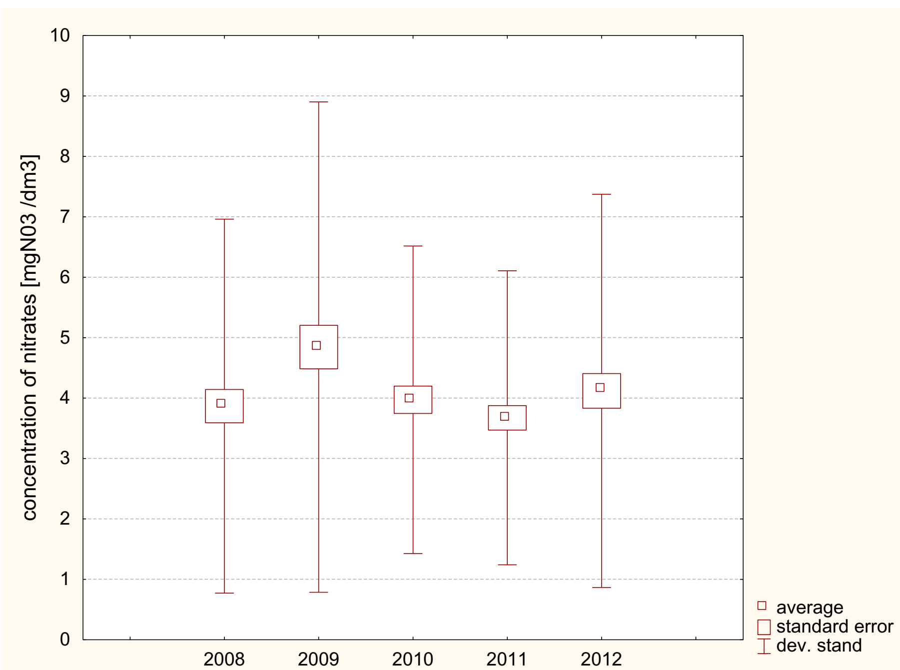

Fig. 1. The average nitrate concentration in surface water uptake subsystems in 2008–2012.

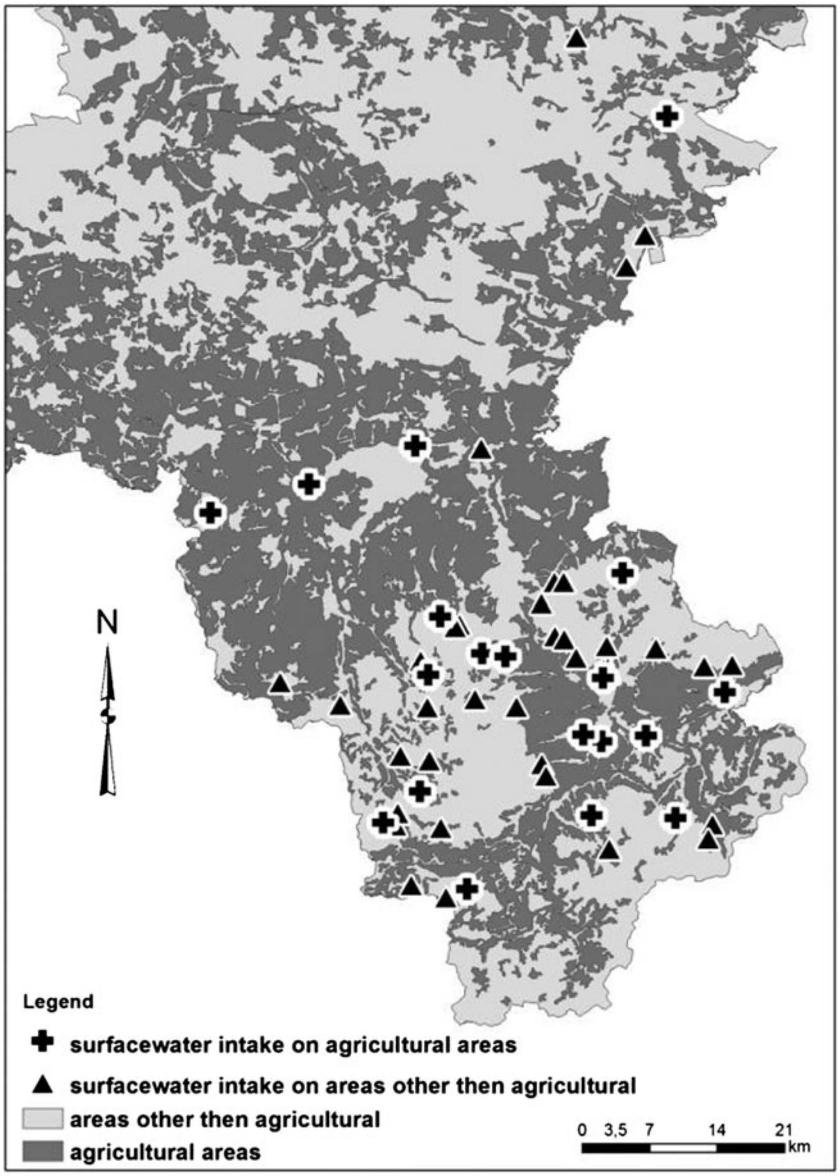

Fig. 2. Location of surface water intakes on agricultural areas.

regardless the type of water resources (surface or groundwater). In the Silesia province, subsystems of water distribution on a wide area are largely interconnected (e.g. ring system especially in the central part of the region), which in changeable dynamic conditions of water consumption makes identification of the sources of supply ambiguous. The lack of knowledge about the quality of the underground water in the Silesian province is another factor that determines that the evaluation of point nitrate pollution of drinking water is very difficult. Apart from that, the Regulation [34] determines the conduct of inspection and the frequency of its execution, depending on the amount of water produced or distributed in the area. The abovementioned facts allowed us to gather over the period of 2008–2012 data-set covering 19,189 random variables relating to the concentration of nitrates in water grasped at the recipient points (Table 6).

The largest number of inhabitants of Silesia agglomeration (Table 7) is supplied with drinking water from a large WSS. At the same time, about 300,000 people use their own wells, where water quality is deprived of any control. In accordance with Regulation [34], the control of water quality in the region of Silesia is closely linked to the size of efficiency of WSS (Table 8), which significantly

Table 6
Number of determinations of nitrate in drinking water in the period of 2008–2012

Year	Number of samples
2008	5,783
2009	6,823
2010	4,188
2011	1,145
2012	1,250
Total	19,189

Table 7
Structure of the people supplied by each category WSS in the Silesia province

Category of WSS	Percentage, %
Individual	2.5
Small	1.7
Medium	10.6
Large	79.4
Owners' wells	5.8

Table 8
Minimal number of controls in separate research areas in Silesia region

Category of WSS	Annual amount of controls, number per year
Small	2.5
Medium	5
Large	9–318*
Individual**	No minimum level

*The minimum number of control depends on the amount of water in WSS.

**Water is used as part of a commercial or public activity.

determines the high variability of the frequency of tests for nitrates concentration in water.

The collection of random variables from the research was statistically analyzed with the use of STATISTICA software (Table 9). The values of the minimum concentrations are similar for each type of WSS. The highest concentration of nitrates in water for ingestion in excess of nearly two times the maximum permissible concentration occurred in medium and small WSS, and these groups of such research facilities have the greatest dispersion of the results. It shows the existence of a large number of objects, while at the same time a small amount of water control tests carried out during the year for the WSS.

Table 9
Basic statistics of nitrates concentration [mg/dm^3] in the division by category of WSS

Category of WSS	Individual	Small	Medium	Large
Mean	7.74	15.68	13.49	7.65
Stand dev	10.02	15.63	15.3	9.39
Median	3.9	10.6	6.19	3.9
Min	0.01	0.02	0.01	0.02
Max	76	106	95	61

Based on the accepted size limit concentrations (Table 5) for the defined three classes of threats of water pollution by nitrates, the analysis clearly showed (Table 10, Fig. 3) that a small percentage of tests indicate a potential water pollution by nitrates. An important note is the fact that in the run-term studies in heavily industrialized Silesia province reported a gradual reduction of the annual quantity of tests. On the one hand, it is the effect of reduction of the number of WSS in the Silesian agglomeration. On the other hand, it is the consequence of dramatically reduced water consumption arising from the use of water efficient technology, and a reduced need for water for industry. As a result of elevated concentrations of nitrates in the water, the probability of occurrence of category B or C of human health risks arising from exposure to nitrates in drinking water for individual, small and medium WSS is ten times higher than for the large ones. Classification of large systems under risk category A, characterized by a lack of risk of water pollution by nitrates, results from among other things the work of these systems being based on the resources of a low concentration of nitrates in the water column (Fig. 3), the use of highly effective water treatment technology and larger financial expenditure incurred for more effective control of water quality.

The analysis of probability of non-compliance with the drinking water normative in particular areas of research (Table 10) showed that the average value of probability is 0.01875 reaching the highest value of 0.05 in 2011 in the small WSS. However, the mere fact of an occurrence of a violation is not unequivocally with the statement that the water in the WSS is contaminated with nitrates. This results directly from the amount of water supplied by WSS and the number of WSS in each research group. Table 4, which shows the number of WSS in Silesia in 2008–2012, and Table 11 with the sensitivity parameter of danger of contamination by nitrates $R_i(\mathrm{WSS}_t)$ supplement the carried out analysis. As part of the research procedures (Table 11), the sensitivity parameter of danger of contamination by nitrates $R_i(\mathrm{WSS}_t)$ was determined on the basis of formula (1).

Table 10
Characterization of risk of human health hazard due to exposure to nitrates in drinking water in the province of Silesia in the period 2008–2012

Year	Type of WSS class concentration of nitrates	Individual			Small			Medium			Large		
		A	B	C	A	B	C	A	B	C	A	B	C
2008	Number of samples	1,224	10	10	518	18	11	1,193	58	30	2,668	41	2
	probability	0.98	0.01	0.01	0.95	0.03	0.02	0.93	0. 045	0.025	0.98	0.015	0.005
2009	Number of samples	1,159	13	12	630	29	17	1,379	46	18	3,468	51	1
	probability	0.97	0.015	0.015	0.93	0.038	0.032	0.95	0.03	0.02	0.98	0.014	0.006
2010	Number of samples	612	9	4	397	28	12	791	35	11	2,264	21	4
	probability	0.975	0.015	0.01	0.929	0.044	0.027	0.94	0.047	0.013	0.989	0.009	0.002
2011	Number of samples	207	2	4	121	25	6	260	31	8	470	9	2
	probability	0.973	0.009	0.018	0.79	0.16	0.05	0.87	0.1	0.03	0.97	0.018	0.012
2012	Number of samples	298	1	2	146	20	3	264	30	10	472	3	1
	probability	0.99	0.005	0.005	0.86	0.11	0.03	0.86	0.1	0.04	0.99	0.005	0.005

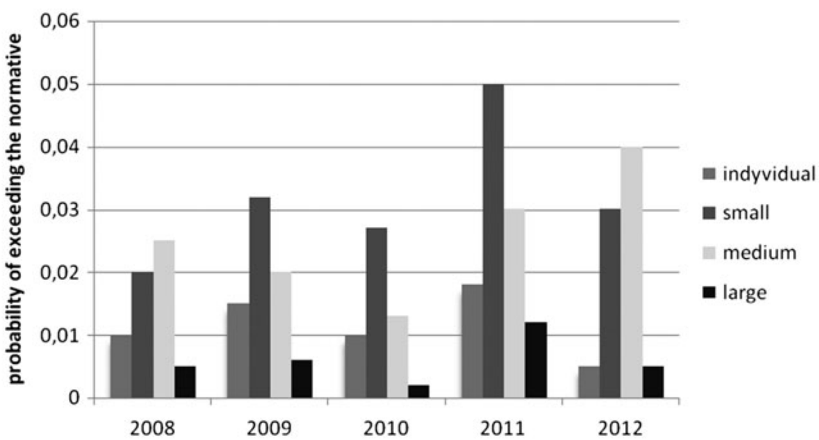

Fig. 3. Probability of exceeding the maximum admissible concentration of nitrates in drinking water in the province of Silesia in the period 2008–2012.

The sensitivity parameter reaches the highest value of 0.124 for small WSS in 2009. The parameter takes the smallest value for individual and large WSS. For individual WSS in 2011, one control of quality of drinking water per three years is carried out. This low frequency of inspections does not produce reliable results in terms of the quality of water pollution by nitrates. The average value of the sensitivity parameter is twice as big for a small WSS and three times bigger for a medium WSS than for a large one.

The frequency of conducting the quality control of drinking water should also be noted. This frequency is 2–3 times greater for small WSS than for the individual WSS. The difference between a frequency of a small WSS is less about 1.5–2 times than frequency for a medium WSS. In contrary, the amount of research during the year for large WSS is 15–30 times greater than for the individual WSS (Table 12). In contrast, the probability of an exceedance (of one of the samples) is an average of 2.5 times higher than for an individual

Table 11
Sensitivity parameter of danger of contamination with nitrates $R_i(WSS_t)$ for each WSS category

Year	Category of WSS—$R_i(WSS_t)$			
	Individual	Small	Medium	Large
2008	No data	0.047	0.160	0.025
2009	0.026	0.124	0.105	0.016
2010	0.006	0.084	0.064	0.059
2011	0.007	0.044	0.046	0.031
2012	0.005	0.021	0.059	0.014
Average	0.011	0.064	0.087	0.029

Table 12
Number of drinking water control per category of WSS

Year	Category of WSS—$R_i(\mathrm{WSS}_t)$			
	Individual	Small	Medium	Large
2008	No data	2.35	6.81	37.92
2009	2.54	4.93	8.38	51.6
2010	1	3.05	4.89	27.92
2011	0.36	1.11	1.71	10.37
2012	0.73	1.2	1.79	10.9

WSS than a large WSS (Table 13). Greater amount of controls causes that for the WSS in isolated areas inspections are more often made, e.g. on a monthly rather than a quarterly basis.

The increased level of risk (Fig. 3) of drinking water of uncertain quality is due to the fact that small WSS do not have the advanced and modern water treatment technology and the elevated costs of water treatment for implementation of modern technology are in a small subsystem unacceptable for the consumer. The conducted analysis also showed that the outcome of the risk assessment of the risks of water with elevated concentrations of nitrites is also influenced by the way of performing water quality control. Water controls in large WSS are distributed evenly over the entire year (Table 13). In contrast, water quality inspections in small WSS and individual WSS are carried out in most cases on randomly selected dates, taking into account the weather conditions which determine the access to the given object of measurement. Besides, the time between the quality control of water for the given WSS is not always similar. Furthermore, for individual and small WSS, a small amount of carried controls does not ensure continuous monitoring of water quality.

Consequently, it can be concluded (Table 10) that the WSS with lower productivity are characterized by greater intensity of exposure to water pollution by nitrates. The study confirms that a greater amount of controls makes the process of monitoring the quality of water more efficient and responsive to any excess.

Table 13
Number of WSS with water contaminated by nitrates

Year	Individual	Small	Medium	Large
2008	No data	4.64	4.7	0.405
2009	6.99	4.384	3.44	0.384
2010	6.23	3.861	2.223	0.136
2011	10.494	6.8	5.22	0.768
2012	2.055	4.2	6.76	0.355

3.3. Spatial analysis

For the spatial analysis of human health risks arising from exposure to nitrates present in the water, geographic information systems software from ESRI was used. In the first step of spatial analysis, locations of water quality control points along with the amount of control within the cell of the grid squares (Fig. 4) were assigned to allocated cells of the Silesia province division grid. For each cell of the division grid, the probability of exceeding the largest acceptable concentrations of nitrates for the WSS according to the formula (2) and the IC according to the formula (3) were determined.

The maximum value of the IC in Silesia for the study period 2008–2012 is 4.5. The theoretical maximum value of IC for a grid cell in the Silesia province with the largest number of control points (110 points) is 220, with exceeded permissible concentration of nitrate at each checkpoint ($P_{\mathrm{WSS}k}$ $(x_i, y_i) = 1$), and the total agricultural land development (C $(x_i, y_i) = 2$). Thus, the obtained maximum IC for the area of the Silesian agglomeration for the grid cell is only 2% of the theoretical maximum value of the IC, which indicates lack of the risks of nitrate pollution of water intended for consumption for residents of the Silesia province.

A detailed analysis of the spatial distribution of nitrate concentrations in water (Fig. 5) allowed to allocate five separate areas that should be monitored due to elevated concentrations of nitrate in drinking water nitrates.

Area A in the northern part of the region—areas of Częstochowa district and Kłobuck district are located in part of the GZWP327 tank. An undoubted reason for the presence of nitrates in drinking water here is an intensive agricultural use of those areas. In this area, water treatment plants use processes to ensure a high degree of removal of nitrates from the water as, for example, denitrification in the WTP Wierzchowisko [37]. Due to the rural character of these areas, there are numerous scattered low-capacity separately recognized as individual and small WSS. The maximum designated in the analysis IC is 2.18.

Area B—Zawiercie district areas, where intensive agriculture and a large number of small WSS have a large impact on the water quality. The IC in this area is 1.74.

Area C is the area of the Gliwice district. Here, the reason for the increased risk of human health risks arising from exposure to nitrates in drinking water is an intensive fertilization on agricultural areas. Similarly, as in area A, here water treatment technology provides a high degree of its treatment [38]. The designated IC is 4.54.

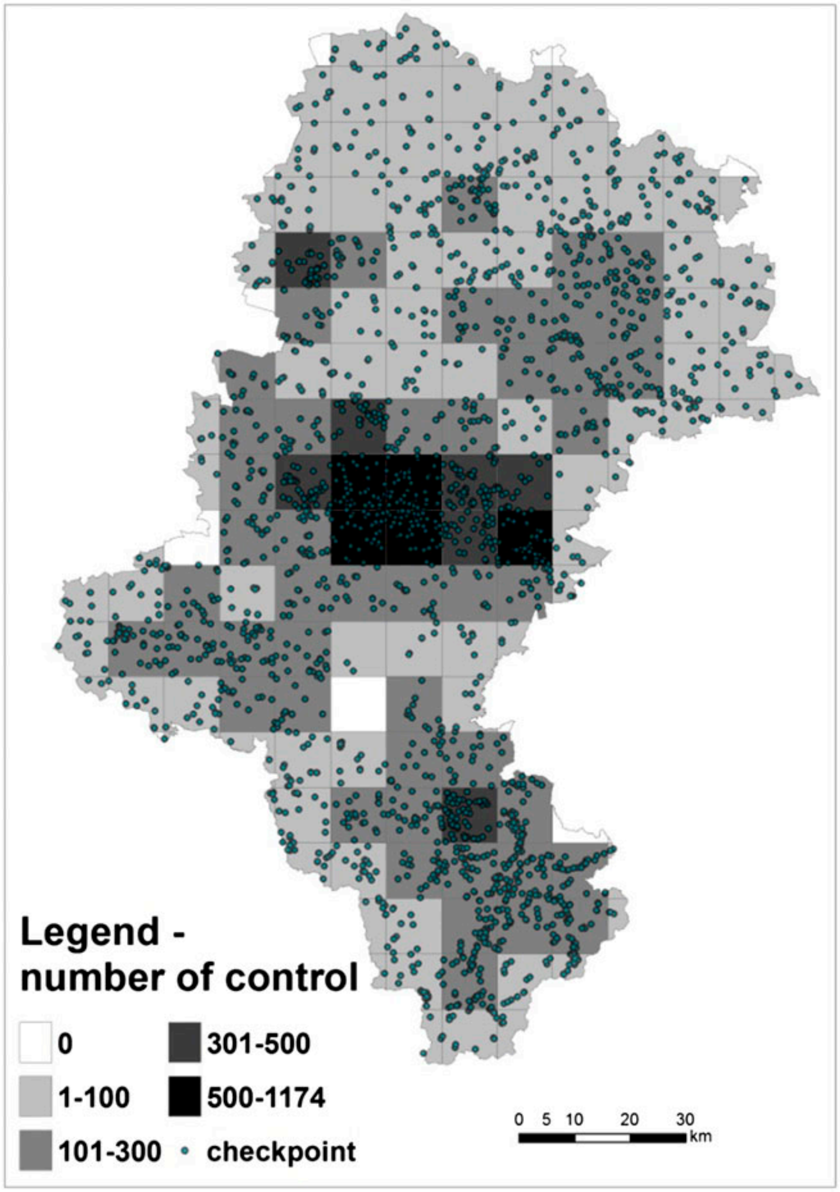

Fig. 4. Quality control of drinking water in the Silesia province in 2008–2012.

Area D is the Rybnik district area where intensive agriculture also influences the quality of water, resulting in IC 0.53.

Area E is created by areas of the Żywiec district. Due to a mountainous terrain, except for the intensive agriculture, water quality is affected by unregulated wastewater system. 70% of all individual WSS are located in this area and the maximum IC value in this region is 0.66.

In none of the analyzed WSS, in which the annual number of controls was greater than 1, there was a likelihood of exceeding the maximum admissible concentration for the WSS at level 1, and its value was in the range of 0–0.71, reaching the highest level for WSS supplying about 280 residents in the village Lgota Mała. The conducted analysis showed that for the two WSS in Kruszyna and Lgota Mała, classified as medium WSS, a set likelihood value $P_{\mathrm{WSS}t}$ reached a value of 1, due to one conducted analysis which reported exceedance of the maximum permissible concentration for nitrates. In 126 out of 161 grid cells IC = 0. For 19 grid cells, the IC value reached 1% of

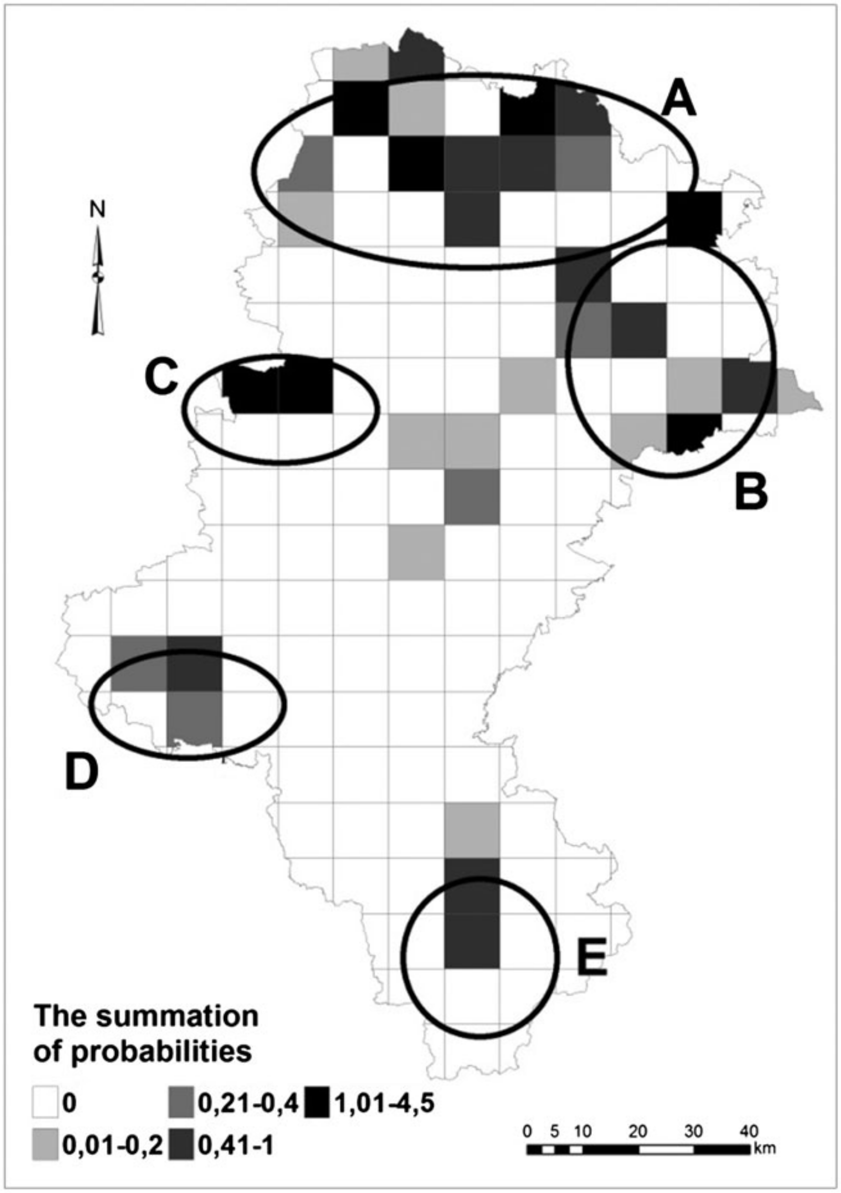

Fig. 5. Areas vulnerable to nitrate pollution of drinking water in the Silesia province in the 2008–2012.

the maximum value of the IC for the analyzed situation.

4. Summary

The IC in the risk analysis can be used as a parameter being an indicative value of remedial actions in the analyzed area, which are designed to provide consumers with access to safe water, for example, by means of using some new water treatment technology as well as by improving the agricultural economy. The higher the value, the faster the reaction should be.

The proposed spatial risk assessment methodology of the risks of the occurrence of abnormal drinking water contaminants concentrations may be applied to other water quality parameters defined in the Regulation of the Minister of Health.

Based on the results of the analysis of spatial and temporal variability of distributions of nitrates concentration in surface waters used for public WSS intended for human consumption, and in water intended for ingestion in Silesia, the following conclusions can be drawn:

(1) In the area of the Silesian province, surface water resources used for public supply of water intended for human consumption shall be classified in category A with lack of pollution and threats, as well as to category B with a medium risk pollution of nitrates.
(2) Using the WSS that produces and distributes large quantities of water is more secure, due to the use of more efficient methods of water treatment, which is confirmed by frequent water quality official inspections. Extensive WSS have several subsystems of recognition and treatment of water, which in the case of deterioration of grasped water quality, have some alternative sources of supply.
(3) Small WSS classified as individual schemes should be subjected to more frequent quality controls, especially in rural areas.
(4) The proposed algorithm typing the areas in which one should increase the amount of control can be used for most studies of WSS with the appropriate set of data on the structure of the WSS and the quality of the transported water. Without the details, it is impossible to assess the WSS, especially the "individual" ones. The limit criterion of the use of this methodology is a network of water quality control points. Increasing the grid resolution below the minimum distance, for the current analysis it is below 2 meters, between two points in the water distribution subsystem, will have no effect. The model can also be combined with some additional environmental data. A single non-compliance with the norm may be the result of an analytical error.
(5) Despite the lack of designation of particularly vulnerable areas in the Silesia province, the problem of assessing the level of the quality status of groundwater has not been definitively resolved. In the absence of regulated wastewater management, agricultural activities and the implementation of collective water supply by small WSS on the selected five regions, the number of conducted water quality controls should be increased. Undoubtedly, the lack of water supply infrastructure in some rural areas is problematic. It occurs mainly in areas where local people may have the access to water contaminated with nitrates.

Symbols

SI	—	Sanitary Inspection
WSS	—	water supply systems
$R_i(\mathrm{WSS}_t)$	—	average numbers of exceedances for the ith per year for each category of WSS
$N_{\mathrm{s\_MAC}}$	—	number of samples exceeding a maximum admissible concentration of nitrates
$N_{\mathrm{WSS}t}$	—	number of WSS in each type of category
$P_{\mathrm{WSS}t}$	—	probability of exceeding the maximum admissible concentration for each category of WSS in the area of research
N_{s_MAC}	—	number of samples exceeding a maximum admissible concentration of nitrates
$N_{\mathrm{s\_all}}$	—	number of all samples of nitrates in each WSS each category of WSS in the area of research
$C(x_i, y_i)$	—	the weight of land cover; for the agricultural area $C = 2$, for other areas $C = 1$
$P_{\mathrm{WSS}k}(x_i, y_i)$	—	probability of exceeding the maximum admissible nitrates concentration for kth WSS
i	—	ith point of quality water control for kth WSS area, $i = 1, \ldots, I$
I	—	the number of control points throughout the research area
k	—	kth WSS throughout the research area, $k = 1, \ldots, K$
K	—	the number of WSSs throughout the research area

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