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Groundwater pollution risks assessment in Ukraine-Poland transboundary aquifers

Halyna Medvid [1]
PhD (Geology), Head of the Laboratory of Geoecology Problems,
[1] Institute of Geology and Geochemistry of Combustible Minerals of NAS of Ukraine, Lviv, Ukraine,
e-mail:halmedvid@gmail.com, https://orcid.org/0000-0002-5059-245X;
Luibov Yanush [2]
MSc (Geology), Leading Engineer,
[2] Subsidiary Enterprise of PJSC NJSC "Nadra Ukrayny" Zahidukrgeologiya, Lviv, Ukraine,
e-mail:liubovyanush@ukr.net, https://orcid.org/0000-0002-4225-8646;
Tatiana Solovey [3]
DSc (Geography), Associate Professor,
[3] Polish Geological Institute – National Research Institute,
Department of Groundwater Recognition and Protection, Warszawa, Poland,
e-mail: tatiana.solovey@pgi.gov.pl, https://orcid.org/0000-0001-8949-4075;
Vasyl Harasymchuk [1]
PhD (Geology), Senior Researcher, Laboratory of Geoecologic Problems,
e-mail: v_harasymchuk@ukr.net, https://orcid.org/0000-0002-4377-2655

ABSTRACT

Problem statement. For states that share a common border it is important to have reliable and up-to-date information on the condition of groundwater used for water supply. Transboundary aquifers (TBA) are rather a complicated object for controlling, monitoring research and management due to inherent transboundary flows. Within the framework of the international project EU-WATERRES, the development of a concept for coordinated management and harmonized monitoring of the TBA at the border areas of Ukraine and Poland has been launched. Among many aspects of the project's research scope, it was important to study the risks of groundwater pollution. The study of potential scenarios of anthropogenic impact within the aquifers will make it possible to predict changes in the quantitative and qualitative parameters of transboundary groundwater, which, in turn, will allow qualitative planning of economic activities with minimal risks.

The purpose of the study is to qualitatively assess the risks of pollution of transboundary groundwater used for drinking water supply taking into account their vulnerability and the overall anthropogenic pressure.

The research methodology is to analysis the cumulative impact of hazards and the degree of vulnerability of transboundary aquifers using the index-rating method as well as to map pollution risks using the overlay method.

Research results. The substantial volume of groundwater in the transboundary catchments between Ukraine and Poland (85.3%) is classified as vulnerable and very vulnerable. Within the Polish territory, their share is 99.9%, and within the Ukrainian territory it amounts to 79.5%. In contrast, the study area is marked by a low degree (4.74%) of groundwater pollution hazards. High and very high hazards in Ukraine account for 6.5% of the study area, and in Poland to 0.55%. The calculations and risk mapping showed that low vulnerability minimizes the impact of pollution hazards, and in the absence of anthropogenic pressure the risk may be modest. This is especially important for assessing the quality of groundwater in the main useful aquifers (MUA), which is a valuable water supply resource for both countries. The Roztochchia area is a vivid example of a territory where high anthropogenic pollution hazards are offset by the low vulnerability of the Lower Neogene aquifer, resulting in a significant reduction in risks.

Scientific novelty of the research. For the first time, an assessment of groundwater pollution risks for the Polish-Ukrainian transboundary area was carried out. The results of the research can be used in the management and protection of transboundary groundwater between Ukraine and Poland.

***Keywords**: transboundary aquifers, anthropogenic impact, groundwater vulnerability, hazards and risks of pollution.*

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Introduction. There are 1,386 million km^3 of water on the planet Earth, but only 2.5% of it is fresh water that can be used by the humankind. In addition, more than half of the fresh water volume is in the form of glaciers and snow caps. That is, humans can use only about 1% of the planet's total water resources (surface and underground), which is actually very little. Therefore, groundwater is an important water supply resource along with surface water. However, they are a difficult object to control, monitor and manage. Their peculiarity is transboundary flows invisible to people. So, it is important for neighboring countries to have reliable and up-to-date information on the condition of groundwater, which is shared by both countries and migrates in both directions. The issue of studying and continuously monitoring the condition of water resources in transboundary water basins requires arranging international cooperation in this sphere. Assessment of transboundary anthropogenic pressure on groundwater has been an object of interest to the European Union (EU) for decades. The EU legislation aimed at creating a framework for the protection and sustainable management of water resources includes the Water Framework Directive (WFD). It sets out objectives and measures to achieve good water status in EU Member States (EU, 2000). To support its implementation, EU Member States have developed a common strategy that focuses on methodological issues related to common understanding of technical and scientific implications of the WFD. These recommendations are aimed at promoting a harmonized approach among the community states to the assessment and management of transboundary water resources. To date, countries bordering the EU and heading towards the full membership in the European Union are actively involved in the implementation of the said strategy.

Problem statement. The task of developing the concept of coordinated management and harmonized monitoring of transboundary aquifers was faced by a team of researchers from five countries participating in the international project “EU-WATERRES: European Integrated Management System for Transboundary Groundwater Resources and Anthropogenic Hazards”, funded by Iceland, Liechtenstein and Norway through the European Economic Area Grant Fund and the Norwegian Regional Cooperation Grant Fund.

Among many aspects of the project's research, the study of groundwater contamination risks was important. Risks are defined as the likelihood of undesirable events that could lead to negative consequences. The study of potential scenarios of anthropogenic impact within the aquifers will make it possible to predict changes in the quantitative and qualitative parameters of transboundary groundwater, which, in turn, will allow for qualitative planning of economic activities with minimal risks.

Review of previous studies. Over the past decades, various models and approaches have been developed and tested to assess the quality of groundwater, its internal and specific vulnerabilities, anthropogenic pressure, and pollution risks.

Groundwater vulnerability is most often assessed using the DRASTIC, GOD, and SI methods. The advantages and disadvantages of the most popular index-based methods are analyzed and presented by the authors (Fannakh & Farsang, 2022). The globally recognized method of qualitative assessment of groundwater vulnerability to pollution is DRASTIC (Aller et al., 1987), although some shortcomings have also been identified in its application. These relate mainly to the use of qualitative parameters, overestimation of the vulnerability of porous media compared to fractured media, and the specific vulnerability of groundwater in certain types of aquifers.

Researchers often adapt the DRASTIC method to their data or objectives by considering additional indices of the internal vulnerability assessment framework, such as land use type (L) (Zhang et al., 2022; Kozłowski & Sojka, 2019), nitrate pollution (Ravindranath & Thirukumaran, 2021), nitrate nitrogen (Shrestha et al., 2016), or petroleum products (Fang et al., 2022). Sometimes they replace several indices with others or remove certain indices due to insufficient sensitivity or inaccurate data (Zhang et al., 2022; Kazakis & Voudouris, 2015).

Some researchers combine two different index-based methods to compare results (Abdullah at al., 2016; Campoverde-Muñoz et al., 2023). The DRASTIC method can be used both for regional studies and for processing a large dataset, as the authors did to assess groundwater vulnerability and risk at the pan-African scale (Ouedraogo at al., 2016).

The SINTACS method, which is an evolution of the DRASTIC method, is also widely used to determine groundwater vulnerability. According to authors (Canora, et al., 2022), it better suits Mediterranean hydrogeological environments. The anthropogenic impact can be taken into account using the SINTACS-LU method, in which the land use parameter (LU) is added (Noori, et al., 2019).

To assess the vulnerability of karst aquifers, the PI method is applied. This is a GIS approach to mapping groundwater vulnerability with a special focus on karst aquifers. Vulnerability is classified based on the product of two factors: The I-factor takes into account infiltration regimes (lithology, fractures, soil classes, aeration zone capacity, aquifer recharge), and the P-factor indicates the effectiveness of protective cover (Zwahlen, 2003; Goldscheider et al., 2000; Aliewi & Al-Khatib, 2015).

To calculate the pollution hazard index, the POSH (Origin Surcharge Hydraulically Pollutant) method is usually engaged, which is based on two easily assessed characteristics: the origin of pollutants (agricultural land, urban agglomerations and rural areas without centralized sewage, landfills and wastewater discharge sites) and their hydraulic impact on the environment (diffuse or point) (Foster et al., 2002; Campoverde-Muñozet et al., 2023).

Risk assessment, compared to vulnerability and contamination hazard assessments, is much more accurate because it takes into account both of these factors. The concept involves combining a groundwater vulnerability map with a pollution hazard map. In other words, the risk of contamination will depend on both potential contaminants and groundwater vulnerability (Daly at al., 2002; Campoverde-Muñoz et al., 2023; Shrestha et al., 2016). Attempts are being made to conduct multidimensional, spatio-temporal, and long-term serial assessments of groundwater pollution risks. For example, Haoli Xu with colleagues have proposed a new comprehensive method that combines the advantages of cloud computing for remote sensing, long-term groundwater modeling using Modflow + MT3DMS, and GIS technology to effectively address the problem (Xu et al., 2023). There are also proposals to consider not only the vulnerability of groundwater and the pollution hazards, but also to take into account the value of the groundwater function, which is determined by its quality and reserves (Fang et al., 2022). The high importance of the groundwater function, according to the authors, is that the territory showes significant reserves and high quality of groundwater, so it has a greater sensitivity and susceptibility of groundwater to pollution.

However, qualitative assessment of the pollution risk is widely used. Polish researchers Robert Duda with colleagues also proposed their own qualitative classifications of the potential impact of the main forms of land use on groundwater quality and the risk of groundwater pollution (Duda et al., 2020). So, in order to obtain a more accurate assessment of groundwater pollution risk that would better match the specifics of land use, the authors recommend developing a quantitative method. It should combine a quantitative assessment of the potential impact of land use with a quantitative assessment of the internal vulnerability of groundwater to pollution. In particular, it is proposed to assess the internal vulnerability of groundwater per the time of infiltration of conservative pollutants through the vadose zone. The quantitative assessment of internal vulnerability, first performed by us for the Polish-Ukrainian transboundary area, was also based on the calculation of the time of contamination penetration through the aeration zone.

The purpose of the study is to qualitatively assess the risks of pollution of transboundary groundwater used for drinking water supply, taking into account their vulnerability and the overall anthropogenic pressure.

The methodology of the study is to analyze the cumulative impact of hazards and the degree of vulnerability of transboundary aquifers using the index-rating method, as well as to map pollution risks using the overlay method.

The research area hydrographically belongs to the transboundary groundwater reservoirs (TGR) of the Buh, San and Dniester (Fig. 1). It is located on both sides of the Polish-Ukrainian border along its entire length from the Carpathians in the south to Polissia in the north. The 537 km long border between Poland and Ukraine passes through the Eastern Beskydy, Northern Subcarpathia, Lublin-Lviv Upland, Volyn-Podillia Upland, and Volyn Polissia. The total area of the study area is 26,073 km^2, of which 15,575 km^2 falls within the Buh catchment, 4,569 km^2 within the San catchment, and 5,929 km^2 within the Dniester catchment (Solovey et al., 2021).

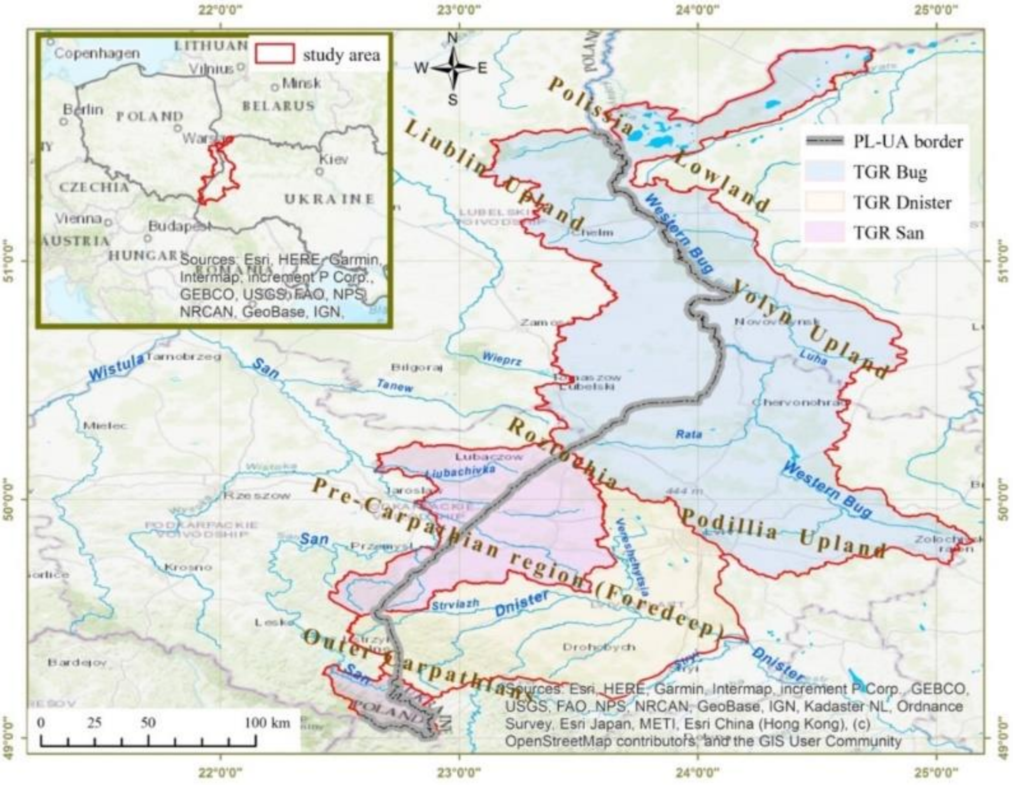

Fig. 1. Location of the research area

Results of the study. The risks of pollution of transboundary aquifers in the study area were assessed by analyzing the cumulative impact of the hazard and the degree of vulnerability of these aquifers. The risk mapping methodology involves an overlay method against the groundwater vulnerability map and the hazard map.

GIS technology was used for calculations and mapping. The territory was divided into calculation blocks with a constant sampling step of 1,000 m. As a result, a discretization grid consisting of 27,024 calculation blocks was created (Fig. 2). Hydrogeological data from the funds of the Subsidiary Enterprise Zahidukrgeologiya and open data on potential sources of pollution were used for the research.

The groundwater pollution risk assessment was carried out stage-wise (Medvid et al., 2023; Solovey et al., 2023). The first stage of the study was a quantitative assessment of the internal vulnerability of groundwater in the Polish-Ukrainian transboundary area. The degree of vulnerability of groundwater in the study area was assessed by calculating the time of water infiltration through the aeration zone using the Bindemann formula, modified by T. Matsoshchyk (Matsoshchyk, 1999) as follows:

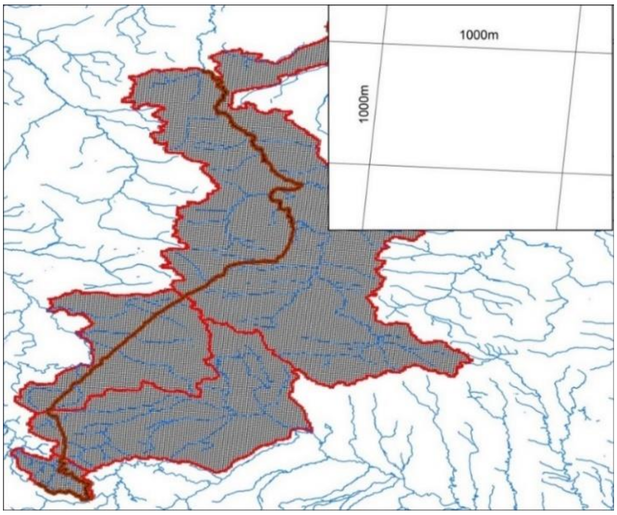

Fig. 2. Computational grid of the study area within the catchment area of the Buh, San and Dniester rivers

$$t = \frac{m \times W_0}{\sqrt[3]{i^2 \times k_z}},$$

where t is the infiltration time of precipitation through the aeration zone, days; m – the thickness of the aeration zone, m; W_0 – the volumetric moisture of sediments in the aeration zone, i – the annual effective infiltration, $i = P \times k*$, m/day (where P is the precipitation indicator, m/day; $k*$ – the coefficient of effective infiltration); k_z – the vertical infiltration coefficient of the aeration zone, m/day.

Vulnerability classification per the time of pollutants migration from the surface was carried out and reported in article (Medvid et al., 2023), which provides a detailed description of the calculation methodology and results. Initially, the vulnerability was calculated for the main aquifers identified within the EU-Waterres project.

The Poland-Ukraine transboundary aquifers include the unconfined aquifer of alluvial Quaternary sediments (alQ) and the unconfined-confined aquifer of Upper Cretaceous sediments (K2). In addition, in the Ukrainian part of the study area, there is a confined aquifer of Lower Neogene sediments (N1), and in the northern part of the Polish study area there is an unconfined aquifer in undivided Upper Cretaceous-Quaternary sediments (K2-Q) (Fig. 3).

However, for the calculation of pollution risks, the territory qualified with the absence of MUAs was also taken into account (Fig. 3), as sporadic local groundwater used by the local population in households is widespread in this area. These include low-flow, unconfined horizons, mainly Quaternary ones, in the plain territory of the Precarpathian artesian basin and layer-fracture waters of the folded Carpathian system in Cretaceous and Paleogene flysch deposits. These groundwaters have been added to the category of unprotected, highly vulnerable groundwaters, as they occur close to the surface and are not covered by impermeable sediments. The issue of their protection and prevention from pollution is no less important.

The resulting vulnerability map of the first aquifers from the surface of the study area is shown in Figure 4.

The territorial statistical distribution of groundwater vulnerability classes is as follows. Within the better half of the study area (85.3% of the area) groundwater is classified as vulnerable and very vulnerable (Fig. 5a). Comparison of the distribution of vulnerability in the Polish and Ukrainian parts of the transboundary area shows that the categories of vulnerable and highly vulnerable ground-

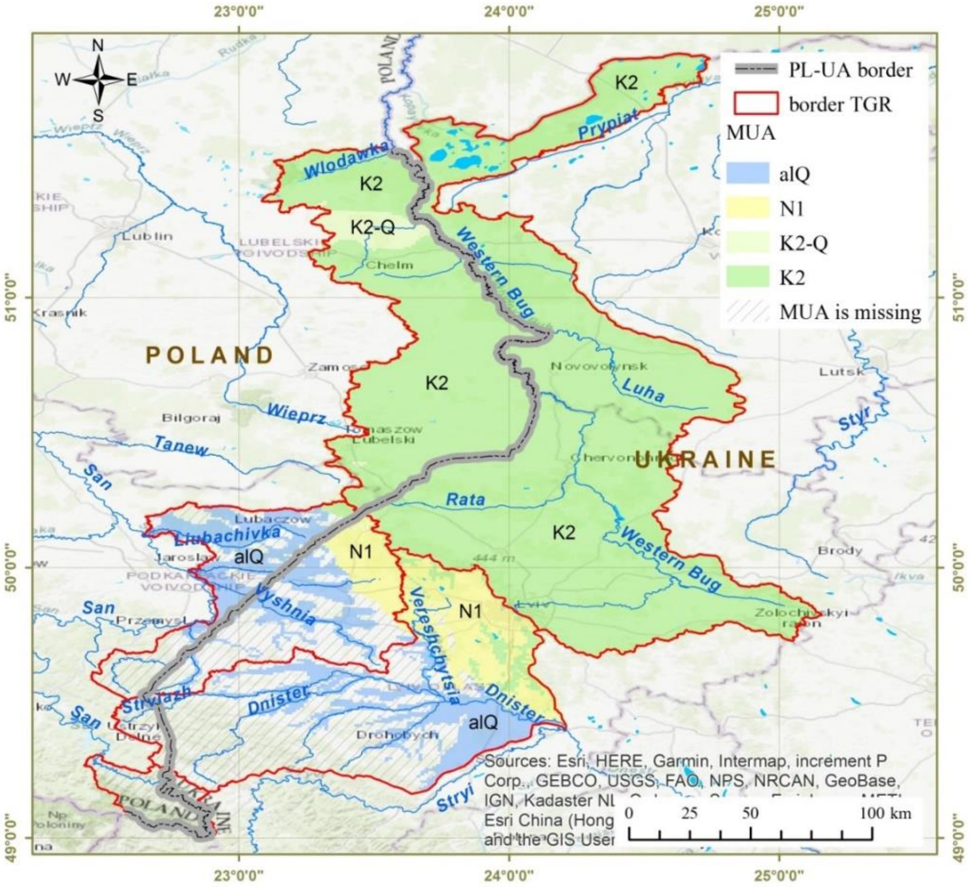

Fig. 3. Map of the main useful aquifers

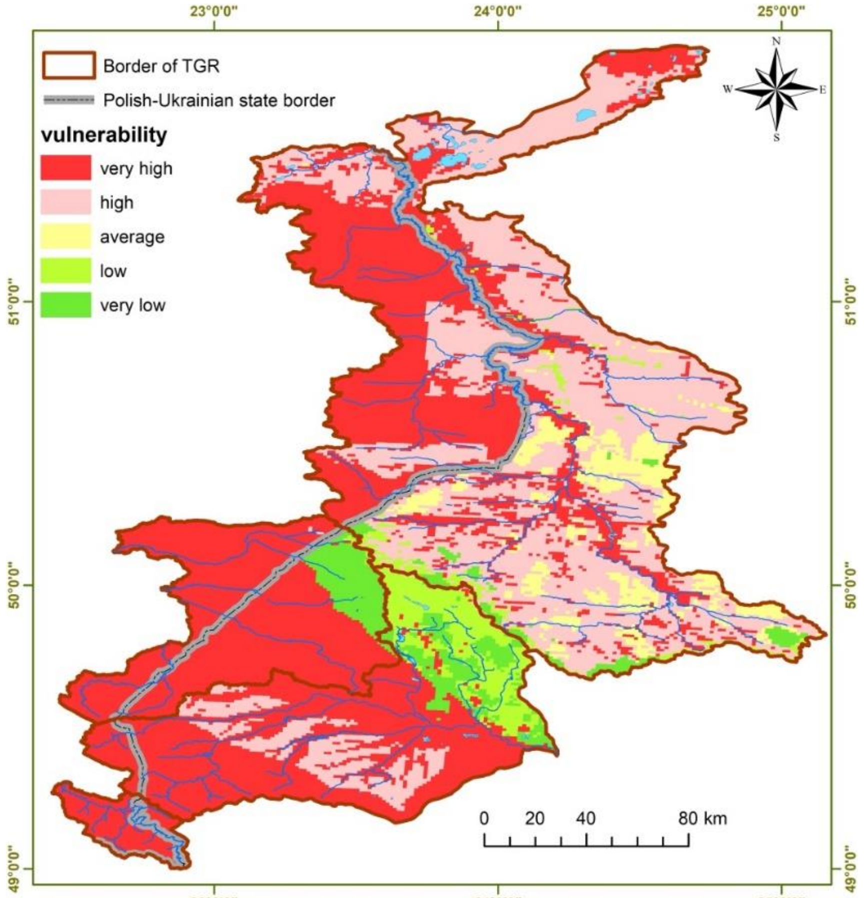

Fig. 4. Map of groundwater vulnerability

water are characteristic of almost the entire Polish territory (99.9%), while in Ukraine this percentage is 79.5 (Fig. 5b).

We present separately the results of the statistical distribution of groundwater vulnerability for MUAs. The unconfined alluvial Quaternary aquifer (alQ) and the undivided Upper Cretaceous-Quaternary aquifer (K2-Q) are the most vulnerable. (Figures 6a and 6b). The Upper Cretaceous aquifer (K2) is less vulnerable, and the Lower Neogene aquifer is the most resistant to pollution (naturally protected) as compared to the others (Figures 6d and 6c).

To assess the risks within the Polish-Ukrainian transboundary territory, the vulnerability of groundwater was additionally indexed into 5 classes (Table 1).

The assessment and mapping of groundwater pollution hazards were performed by identifying potential diffuse and point sources of pollution and calculating their total pressure while assigning them ranks and weights, as described in (Solovey et al., 2023).

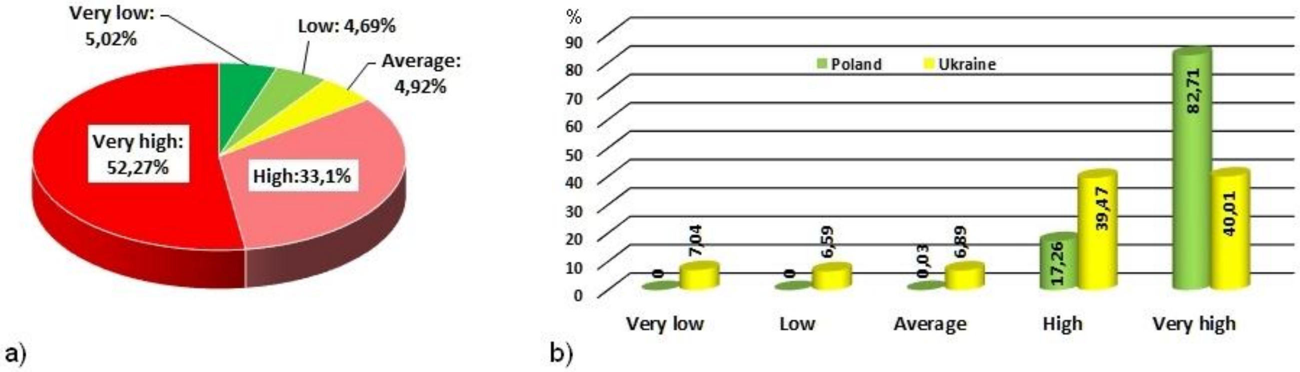

Fig. 5. Distribution of groundwater vulnerability by class: a) within the Polish-Ukrainian cross-border area; b) comparative for the Polish and Ukrainian parts of the cross-border area

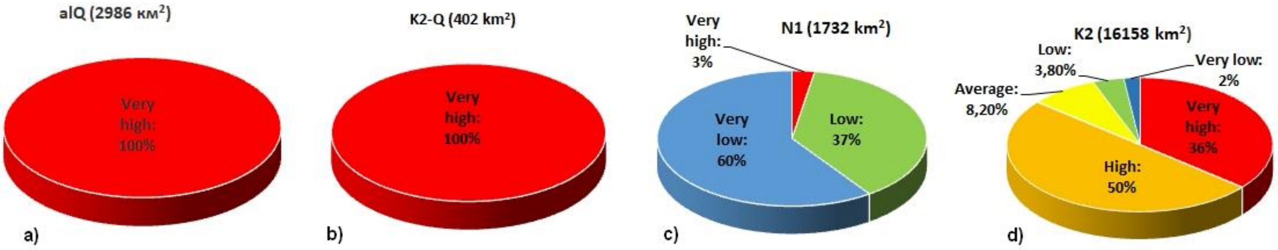

Fig. 6. Distribution of vulnerability classes for MUAs: a) alluvial Quaternary; b) Upper Cretaceous-Quaternary; c) Lower Neogene (Miocene); d) Upper Cretaceous

Table 1

Indexing of groundwater vulnerability classes

Vulnerability classes	**Vulnerability Index**
Very high	5
High	4
Average	3
Low	2
Very low	1

The score of total pressure of diffuse and point sources of pollution (GW hazard) within each computational cluster was calculated using the formula:

$$GW\ hazard = \frac{(\Sigma\ HLi \times F) + (\Sigma\ W \times R)}{n},$$

where HLi are hazard indicators of diffuse pollutants for the land use categories presented in Tab.1; F is the proportion of a given land use category in the computational cluster area, W – the point impact index weight; R – the rank of point impact index; n – the number of indicators included in the assessment in a given cluster (in our case, n=5 of which 3 are diffuse and 2 are point ones).

To classify the total degree of anthropogenic pressure we used the division of groundwater pollution hazards into 6 classes proposed by Stevanovich (Table 2) (Stevanović & Marinović, 2020).

As a result, a map of the spatial distribution of total anthropogenic pressure index values or a map of groundwater pollution hazards was created (Fig. 7).

Table 2

Classification of pollution hazards

GW hazard classes	Hazard Index
No hazard	0 - 0.10
Very Low	0.11 - 0.20
Low	0.21 - 0.30
Moderate	0.31 - 0.50
High	0.51 - 0.70
Very High	0.71 - 1.00

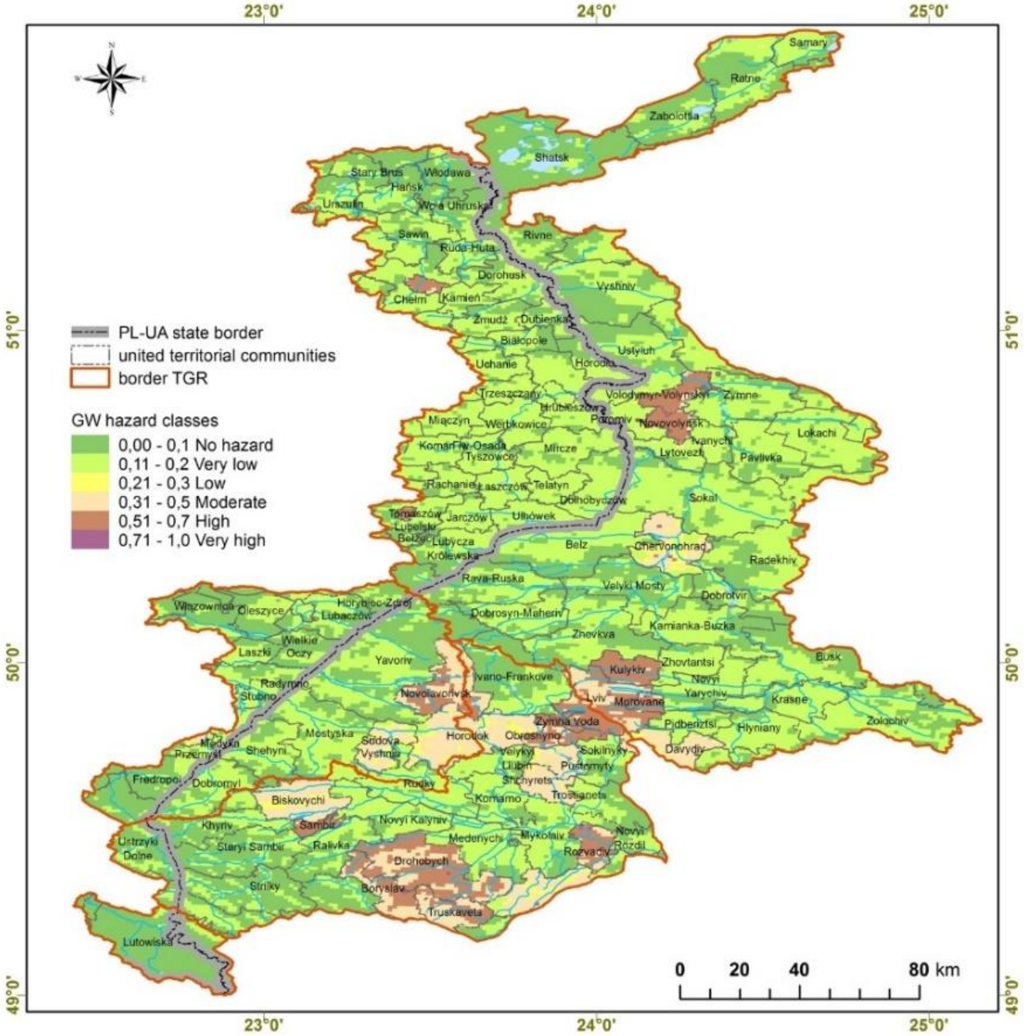

Fig. 7. Map of groundwater hazard – cumulative anthropopressure

The results of the distribution of pollution hazards classes are presented in the form of diagrams in Figures 8 and 9. In general, the study area is characterized by an insignificant degree of pollution hazards: high and very high levels of pollution hazards account for 4.74% of the transboundary area (Fig. 8a). However, the level of total anthropogenic pressure on groundwater in the Ukrainian part of the transboundary area significantly exceeds the pollution hazards on the Polish side. Areas with a high and very high degree of pollution hazards in Ukraine account for 6.5% of the study area, while in Poland – only 0.55% (Fig. 8b).

The distribution of high and very high degrees of pollution hazards within the MUAs areasis as follows: aquifer of Lower Neogene sediments (N1) - 15.07%; alluvial Quaternary sediments (alQ) - 7.2%, Upper Cretaceous (K2) - 2.95 %. MUAs in undivided Upper Cretaceous-Quaternary sediments are outside the zone of pollution hazards (Figs. 9a-9d).

At the final stage, the actual assessment of the probability of harmful effects or risks of pollution was performed, which is the main purpose of the study. The assessment of the risks of pollution of transboundary aquifers in the study area was carried out by analyzing the cumulative impact of the pollu-

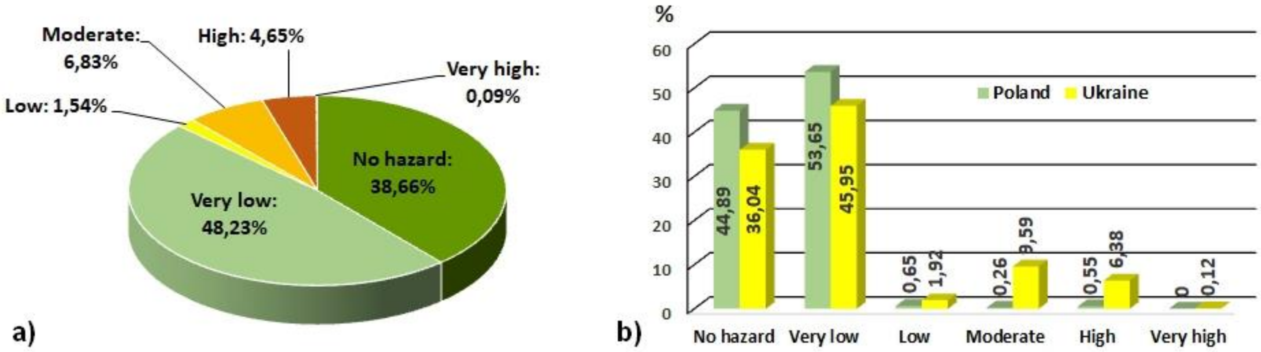

Fig. 8. Distribution of pollution hazards by class: a) within the Polish-Ukrainian transboundary area;
b) comparative for the Polish and Ukrainian parts of the transboundary area

tion hazards and the degree of vulnerability of these aquifers. Low vulnerability of groundwater can minimize the impact of a high degree of hazard. Conversely, in the absence of anthropogenic activities in a catchment area with a high degree of vulnerability the risk may be modest. The risk mapping methodology involves an overlay method based on the groundwater vulnerability map and the hazard map. The pollution risk index was calculated using the formula:

$$\text{GW Risk index} = \text{Hazard index} * \text{Vulnerability index}$$

To construct the map, the obtained values of groundwater risk indices were categorized into 6 classes (Table 3).

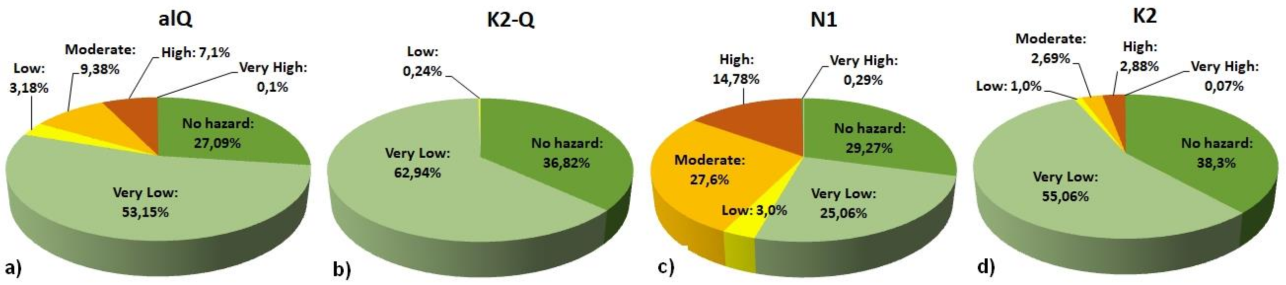

Fig. 9. Distribution of hazards classes for MUAs: a) Alluvial Quaternary;
b) Upper Cretaceous-Quaternary; c) Lower Neogene (Miocene); d) Upper Cretaceous

Table 3

Classification of pollution risks

GW risk classes	GW risk index
No risk	0.0 – 0.5
Very low	0.51 - 1.0
Low	1.1 - 1.5
Moderate	1.51 - 2.0
High	2.1 - 2.5
Very high	2.51 - 3.9

In general, the first two categories can be considered “no risk”, the next two as “potentially at risk”, and the last two as “at risk”.

The results of the risk assessment of groundwater pollution in the study area are presented in Fig. 10.

The proportion of groundwater pollution risk classes (Figs. 11, 12) shows that aquifers on 90.12% of the study area are in the zone of no pollution risk, on 6.17% - are at potential risk, and only on 3.71% of the area groundwater is at risk of pollution (Fig. 11a).

The probability of harmful consequences from undesirable events is much higher in the Ukrainian part of the territory, i.e. here the risk of pollution extends to 5.01% of the territory, and 8.46% of the area is potentially at risk, while in the Polish part it is 0.61% and 0.76%, respectively. The qualification “no risk” for the Ukrainian territory corresponds to 86.53% of the area, while for the Polish territory - 98.63% (Figure 11b).

The highest risk of pollution among MUAs is inherent in the Alluvial-Quaternary one: 8.04% of the area is at risk and 11.73% is under potential risk (Fig. 12a). The figures for the Upper Cretaceous and Lower Neogene horizons are much lower: 2.35 and

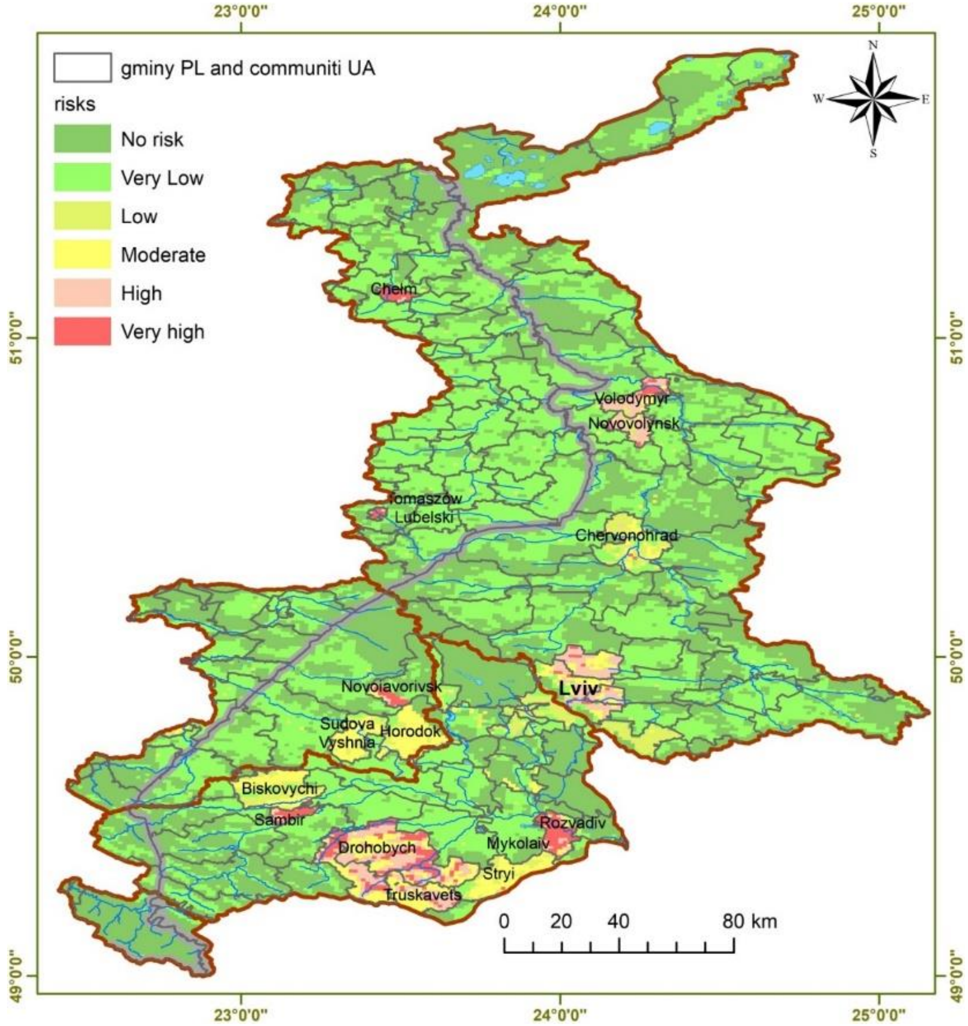

Fig. 10. Map of groundwater risks

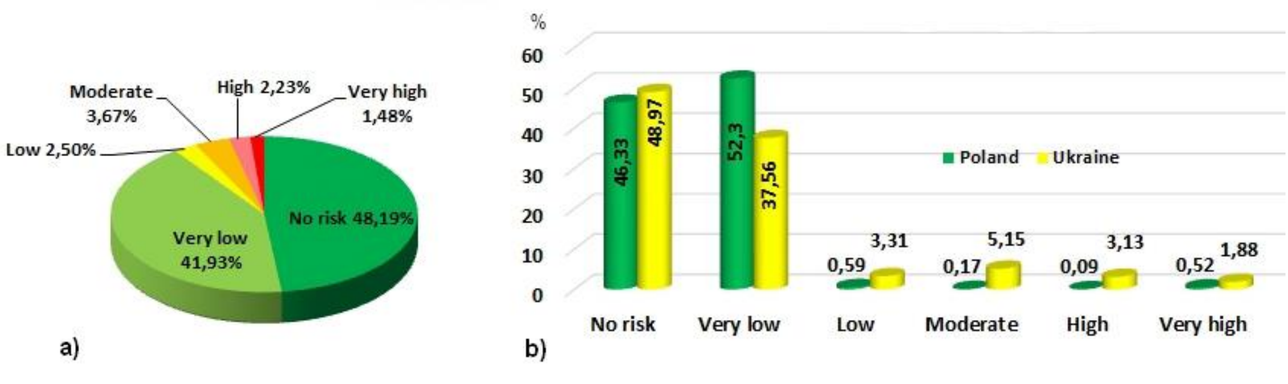

Fig. 11. Distribution of pollution risks by class: a) within the Polish-Ukrainian transboundary area; b) comparative for the Polish and Ukrainian parts of the transboundary area.

0.64 % of the area is at risk and 2.99 and 7.85 % is at potential risk, respectively (Figures 12d and 12c). Groundwater in the undivided Upper Cretaceous-Quaternary sediments is practically not at risk of pollution, despite its high vulnerability, due to the absence of hazards (Fig. 12b).

Conclusions. Great amount of groundwater in the transboundary catchments between Ukraine and Poland (85.3%) is classified as vulnerable and very vulnerable. Within the Polish territory, their proportion is 99.9%, and within the Ukrainian territory - 79.5%. In contrast, the research area is marked by a low degree (4.74%) of groundwater pollution hazards. High and very high hazards in Ukraine account for 6.5% of the study area, and in Poland – 0.55%.

The calculations and risk mapping have shown that low vulnerability minimizes the impact of pollution hazards, and in the absence of anthropogenic pressure the risk may be modest. This is especially important for assessing the quality of groundwater

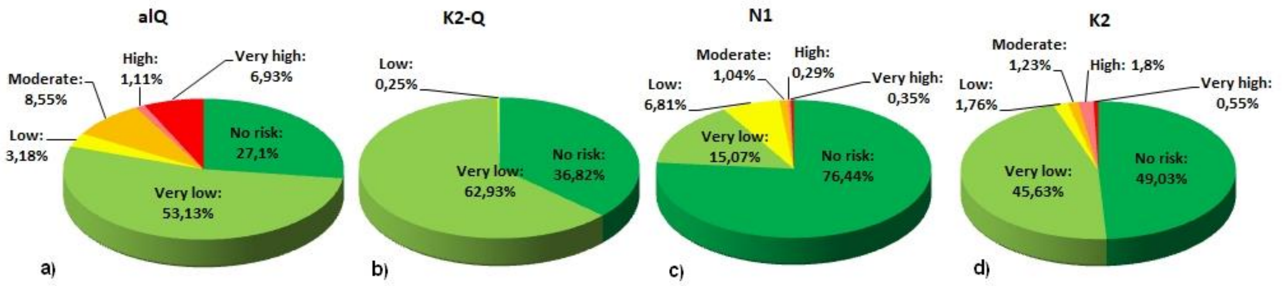

Fig. 12. Distribution of risk classes for MUAs: a) Alluvial Quaternary; b) Upper Cretaceous-Quaternary; c) Lower Neogene; d) Upper Cretaceous

in MUAs, which are valuable water supply resources for both countries. The Roztochchia is a prime example of an area where high anthropogenic pollution hazards are offset by the low vulnerability of the Lower Neogene aquifer, resulting in a significantly reduced risk. This tendency to mitigate the hazards of groundwater pollution by low aquifer vulnerability is inherent in a number of territorial communities in Volodymyr, Novovolynsk, Kulykiv, Lviv, Zymna Voda, Sokilnyky, Obroshyne, Novoyavorivsk, Rozvadiv, Sambir, Drohobych, Boryslav, and Truskavets on the Ukrainian side and in the most urbanized communes in Poland – Chełm and Tomaszów Lubelski. On the other hand, large areas of highly vulnerable unconfined aquifers do not fall into the zone of significant risks due to the absence of significant anthropogenic pressure hazards.

The results of the research can be used to ensure the management and protection of transboundary groundwater over the in-between territory of Ukraine and Poland.

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Ризики забруднення підземних вод транскордонних водозбірних басейнів між Україною і Польщею

Галина Медвідь [1]
к. геол. н., керівник Лабораторії проблем геоекології,
[1] Інститут геології і геохімії горючих копалин НАН України, Львів, Україна;
Любов Януш [2]
пров. інженер,
[2] ДП "Західукргеологія" ПрАТ НАК "Надра України", Львів, Україна;
Тетяна Соловей [3]
д. геогр. н., професор, [3]Польський геологічний інститут –
Національний науково-дослідний інститут, Варшава, Польща;
Василь Гарасимчук [1]
к. геол. н., ст. наук. співроб. Лабораторії проблем геоекології

Для держав, що мають спільний кордон, важливо мати достовірну і актуальну інформацію про стан транскордонних підземних вод, що використовуються для водопостачання. В рамках міжнародного проекту “EU-WATERRES” було розпочато розробку концепції скоординованого управління та гармонізованого моніторингу транскордонних водоносних горизонтів (ТВГ) прикордонних територій України та Польщі. Серед багатьох аспектів досліджень проекту важливим було вивчення ризиків забруднення підземних вод. Авторами проведено оцінку ризиків забруднення транскордонних водоносних горизонтів між Україною і Польщею шляхом аналізу кумулятивного впливу загрози та ступеня вразливості цих горизонтів. Переважна більшість підземних вод транскордонних водозбірних басейнів між Україною і Польщею (85,3 %) класифікуються як вразливі і дуже вразливі. У межах польської території їх частка становить 99,9 %, в межах української – 79,5 %. На противагу цьому територія досліджень характеризується незначним ступенем (4,74 %) загроз забруднення підземних вод. Високий і дуже високий ступінь загроз в Україні становлять 6,5 % досліджуваної території, у Польщі – 0,55 %. Проведені розрахунки і побудова карти ризиків показали, що низька вразливість мінімізує вплив загроз забруднення, а за умов відсутності антропогенного навантаження, ризик може бути незначним. Це особливо важливо для оцінки якісного стану підземних вод основних корисних водоносних горизонтів (ОКВГ), які є важливим ресурсом водопостачання для обох країн. Зона Розточчя є яскравим прикладом території, де високі антропогенні загрози забруднення нівелюються низькою вразливістю водоносного горизонту нижньонеогенових відкладів, внаслідок чого ступінь ризику суттєво знижується. Така тенденція до нівелювання загроз забруднення підземних вод низькою вразливістю водоносного горизонту притаманна низці територіальних громад Володимира, Нововолинська, Куликова, Львова, Зимної Води, Сокільників, Оброшиного, Новояворівська, Розвадова, Самбора, Дрогобича, Борислава та Трускавця зі сторони України та в найбільш урбанізованих ґмінах Польщі – Хелмі та Томашуві Любельському. З іншого боку, великі площі дуже вразливих безнапірних водоносних горизонтів не потрапляють до зони значних ризиків через відсутність значних загроз антропогенного тиску. Результати проведеної оцінки ризиків забруднення дадуть змогу передбачити зміни якісних параметрів транскордонних підземних вод, що може бути використано в ході забезпечення управління та захисту підземних вод на польсько-українському прикордонні.

Ключові слова: *підземні води, транскордонні водоносні горизонти, антропогенний вплив, вразливість водоносного горизонту, загрози і ризики забруднення.*

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