Groundwater vulnerability to pollution in degraded coal mining areas: modifying the DRASTIC method using the factor of exploitation impact on land surface

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Abstract: Mining activities such as underground exploitation of hard coal deposits and open cast mining are strong factors on groundwater depending on mine life cycle phases. The impact of coal mining activities on groundwater have been reported from many countries. In this case, a vulnerability assessment was conducted base on standard DRASTIC method and its modification DRASTIC MINE (DRASTIC^{M}) method. In order to take into account, the impact of mining activities, a new parameter was added which defined the impact of coal seams on the rock mass above, including the degree of its drainage and the range of its impact. In the standard DRASTIC method, the results indicate that groundwater vulnerability with high (38.6%) and very high occurrence classes (16.9% of the area), mostly covers the central part of the cast mine. In contrast, the reclaimed area of the excavation is a low-class area. The DRASTIC^{M} method increased the vulnerability index from 3 to 24 on 95% of the area, so a new vulnerability class of extremely high was delineated, which occurred in 1.6% of the area. This indicates areas that should be treated as a priority in order to avoid pollution, and in the final stage to plan activities in the field of the reclamation of mining areas. The results showed that groundwater vulnerability assessment in coal mining areas can be significantly improved.

Keywords: groundwater vulnerability to pollution, mining area, coal activities, mining exploitation phases, Upper Silesia Coal Basin, Poland

INTRODUCTION

Mining activities linked with the underground exploitation of hard coal deposits coupled with open cast mining have a diverse and wide impact on the natural environment. These types of areas are characterized by specific and unique elements of spatial management. The most important include transformations of the land surface, changes to the surface water network and its regime, alterations in the hydrogeological conditions and the presence of specific contamination sources, the character of which undergo changes during the mining activity and after its cessation.

Such areas display strong anthropogenic transformation which is reflected in changes on the land surface. Processes of subsidence occur, leading to depression formation, stress fractions appear in the infrastructure and buildings, and a simultaneous expansion of negative (exploitation pits) and positive landforms (gangue dumps) takes place. Transformation of the hydrographic network includes changes to watercourse flow, channel isolation and regulation, and increase of flow due to drainage water discharge. All these processes lead to ecosystem change resulting in steppe formation (Bell et al. 2001).

An inextricable feature of mining areas is their impact on the quality and quantity of groundwater resources. Quantitative threats to groundwater include changes to the water balance in various range and extent, flow conditions, circulation systems, overexploitation and overdrainage. Large-scale mining operations have the potential to produce adverse environmental effects and result in changes in the hydrodynamic system (Qiao et al. 2011). A typical phenomenon in mining areas is the possible increase of groundwater quality threat from gangue dumps (Li et al. 2018) and other potential groundwater pollution sources (Wu et al 2019). In effect, a distinct decrease of groundwater quality takes place due to the percolation of acidic infiltration and discharge water, followed by ecosystem change. Enhanced groundwater contamination in coal mining areas takes place due to chlorides, sulfates, and heavy metals, which originate due to the oxidation of substances present in waste rock and mill tailings (Galhardi & Bonotto 2016). In effect, acid mine drainage (AMD) generation waters occur (Fungaro & Izidoro 2006).

Land reclamation, as well as the vicinity of other mines or open cast pits, particularly those backfilled with gangue, may negatively influence the water quality and change filtration conditions as sources of contamination (Li et al. 2018).

Factors having an impact on environmental conditions change with time (Ghosh et al. 2015) and are directly related with the existing phase of exploitation. This results from the variable intensity of rock mass drainage, changes and simplification of mine drainage systems, ultimately leading to the drainage closing down, and complete mine flooding (Bukowski et al. 2019).

Vulnerability assessment is a universal tool used for verifying the degree of groundwater contamination, often discussed in the literature from the end of the 1960s when Margat (1968) defined vulnerability to pollution, till present (e.g. Machiwal et al. 2018, Krogulec 2006, 2013, Krogulec et al. 2019). Groundwater vulnerability defines the risk of the migration of contaminants from the land surface to the subsurface aquifer. Commonly applied methods assessing groundwater vulnerability to pollution do not usually take into account the variability of the mining activity, so their application may be restricted. Therefore, the method should be verified to test its applicability in mining areas and modified through the implementation of additional parameters and data, which include supplementary parameters of resource exploitation areas (Góra & Szczepański 2009, Góra 2011, Karan et al. 2018).

DRASTIC, the range method for assessing natural vulnerability (Aller et al. 1987), is often applied in such areas. Due to its popularity, the method is considered as a standard tool of water resource management, and is used for legislation, control, and in technical aspects of water management in numerous countries. In the original concept, the method was not intended for mining areas, contrary to the SINTACS method (Civita 1994), however, it takes into account the same parameters, whose range and weight may be changed during particular stages of vulnerability assessment, and their adjustment to the specific character of mining areas does not cause additional problems (Karan et al. 2018). Ghosh et al. (2015) applied the classical approach to vulnerability assessment with the DRASTIC method with an indication that recharge in mining areas may also take place through the infiltration of surface water at a significant, regional scale of groundwater table depression.

The presented studies were performed in southern Poland, in the Upper Silesia Coal Basin (GZW), where intense, industrial exploitation of hard coal and metal ore deposits has been conducted since 1748, when the first mines were built.

The study area includes the Maczki-Bór open cast mine in Sosnowiec where the exploitation of backfill sand takes place. This area is situated in the range of former hard coal exploitation from Carboniferous deposits. At present, four coal mines have ceased and the mines have been closed down. Two of them were transformed into pumping stations, to protect nearby active mines against water hazards. Beside the residual exploitation of backfill sand, the open pit is presently under reclamation including the backfilling of the exploited space with Carboniferous gangue rocks (post mining wastes).

After analyzing the individual components of the environment in the area, it can be concluded that in relation to the conditions unchanged by the presence of open cast mine and coal mining (phase A according to Bukowski et al. (2019)), the following changes occurred: morphology of the area (lowering up to 50 m), depth to the groundwater table (lowering in relation to neighboring areas by at least 30 m), infiltration recharge (sealing part of the surface), soil cover (reduction or its elimination or creation of new soil types), lithology and conductivity of aquifer (changes by depositing gangue rock), lithology of vadose zone (gangue rock or removal of rocks).

The main aim of the work was vulnerability assessment by performing the DRASTIC method, followed by the application of its modified version DRASTIC MINE ($DRASTIC^M$). The present state of deposit exploitation in the study area classifies it according to Bukowski et al. (2019) as at the beginning of the C phase – terminal, which means that the vulnerability assessment required factors causing the change of this assessment in the range of transformation of the rock mass and hydrogeological conditions to be taken into account. The results obtained were verified with the application of chemical data from groundwater monitoring.

STUDY AREA

The study area is located in southern Poland, in the Silesian Province, within the city limits of Sosnowiec. In terms of geology, it is located within the Paleozoic West European Platform, within the Upper Silesia Block, in the NE part of the Upper Silesia Coal Basin. The pre-Quaternary basement is mainly composed of Carboniferous rocks, with Triassic strata occurring in the S and NW part of the area (Fig. 1).

The main study object is the exploitation pit of the Maczki-Bór open cast backfill sand mine, comprised of a western and eastern field (Bór-East and Bór-West fields). The spatial range of the vulnerability analysis was 8.84 km^2 also including coal storage, municipal waste landfill and areas directly adjacent to the open pit, where the impact from underground and surface mining overlaps, and the nearby hydraulic windows occur, facilitating the filtration of groundwater to the Carboniferous aquifer.

The study area is characterized by complex hydrogeological conditions which result e.g. from the overlapping impact of hard coal exploitation from Carboniferous strata and the existence of an open cast mine. Three aquifer horizons can be distinguished: Quaternary, Triassic (only in the margins of the open pit) and Carboniferous.

The Quaternary aquifer is composed of poorly sorted sands with gravel interbeddings, and gravels with sand (Gajowiec & Siemiński 1997, Wagner & Chmura 1997, Kropka et al. 2013). In natural conditions, one main aquifer was distinguished (locally, in the presence of interbeddings of ice-dammed deposits, the horizon is bi- or tri-partite). During the undisturbed regime, the Pleistocene aquifer was mainly recharged through the direct infiltration of precipitation and drained by the Biała Przemsza and Bobrek rivers. At present, the main drainage of the Quaternary aquifer is the drainage system of the open cast mine with the main drainage sump and drainage ditches, and partly the mining pits of the former hard coal mines located in the vicinity of the exploitation pit (Fig. 2). Dewatering of exploitation slopes and the pit is maintained by a gravitational system. The network of ditches and channels changed its course along with continuing mining activities and the exposure of subsequent layers of the sand deposit, adequately to the course of reclamation works (Kropka et al. 2013, Różkowski et al. 2017).

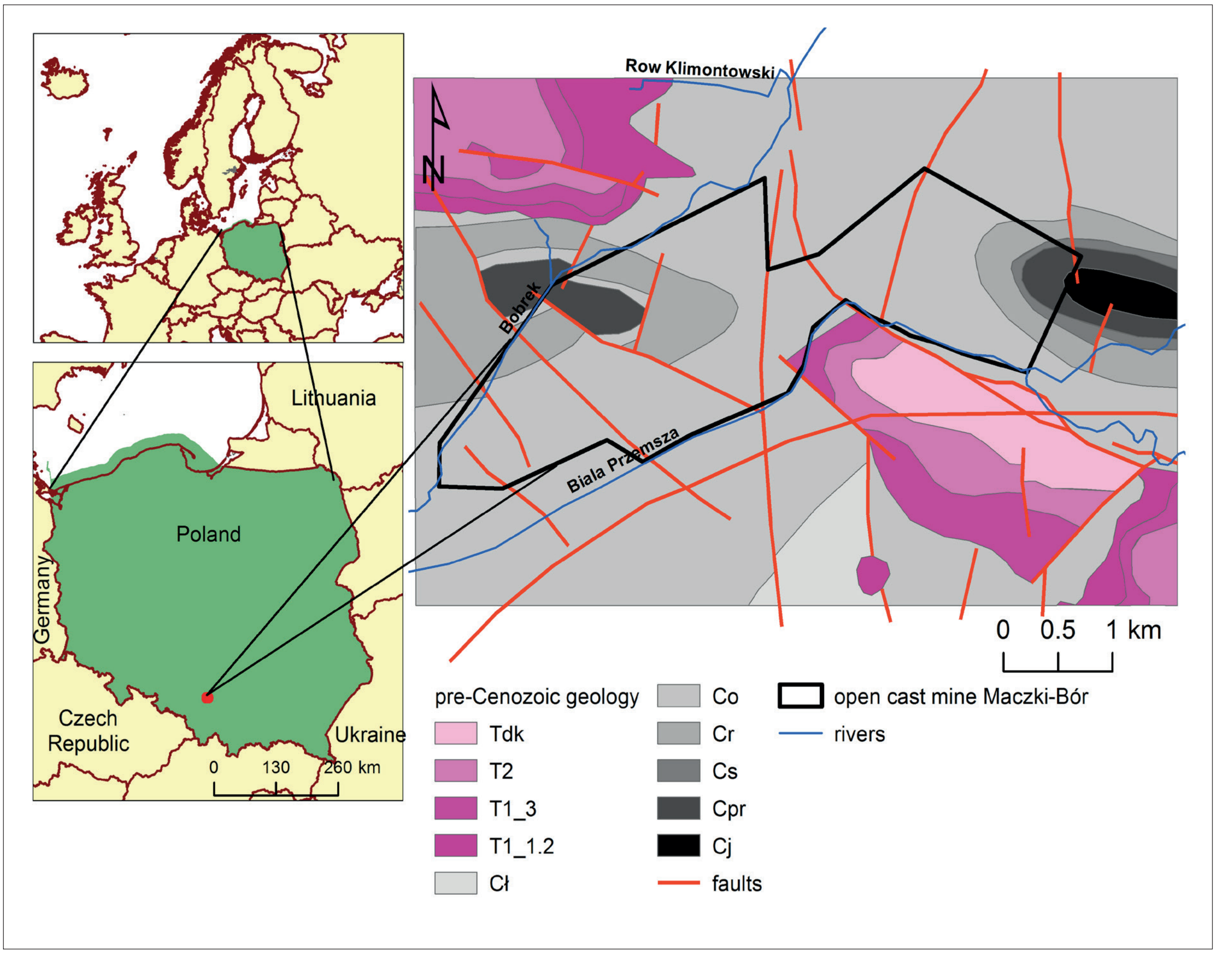

Fig. 1. *Location of the study area and its pre-Quaternary geology (Gajowiec & Siemiński 1997)*

The presence of hydrogeological windows between the Quaternary and Carboniferous deposits causes a partial drainage of the Pleistocene aquifer by hard coal mine workings.

A Triassic aquifer was noted in the open pit margins to the north of the Western Field and to the south-east of the Eastern Field. Water occurs in Röt dolomites and Bundsandstein sandstones. The Triassic aquifer is poorly recognized and because of its small thickness, does not have an influence on the flooding of the open cast pit. The recharge of the aquifer horizon takes place through direct infiltration of precipitation on the aquifer outcrops and locally, indirectly from the Pleistocene aquifer near hydrogeological windows (Kropka et al. 2013). The Carboniferous aquifer is linked with interbeddings of sandstones within the mudstone series of the Orzesze s.s., Załęże s.s., Ruda s.s. and Siodło beds, characterized by variable hydrogeological properties (Gajowiec & Siemiński 1997, Wagner & Chmura 1997, Kropka et al. 2013).

The fracture-pore Carboniferous horizons conduct water under pressure increasing with depth. Recharge is by infiltration through permeable Quaternary strata or directly on outcrops of permeable deposits of the productive Carboniferous series. A Pleistocene-upper Carboniferous horizon may develop on the contact of permeable productive Carboniferous series with permeable Quaternary deposits (Kropka et al. 2013).

Four former coal mining areas: Kazimierz-Juliusz, Jan Kanty, Porąbka-Klimontów, and Niwka-Modrzejów, occur in the study area. The occurrence of all coal seams, numbered 404, 405, 408_2, 407_8, 09_w2, 418, 510 (Figs. 2, 3), was taken into account in the vulnerability assessment.

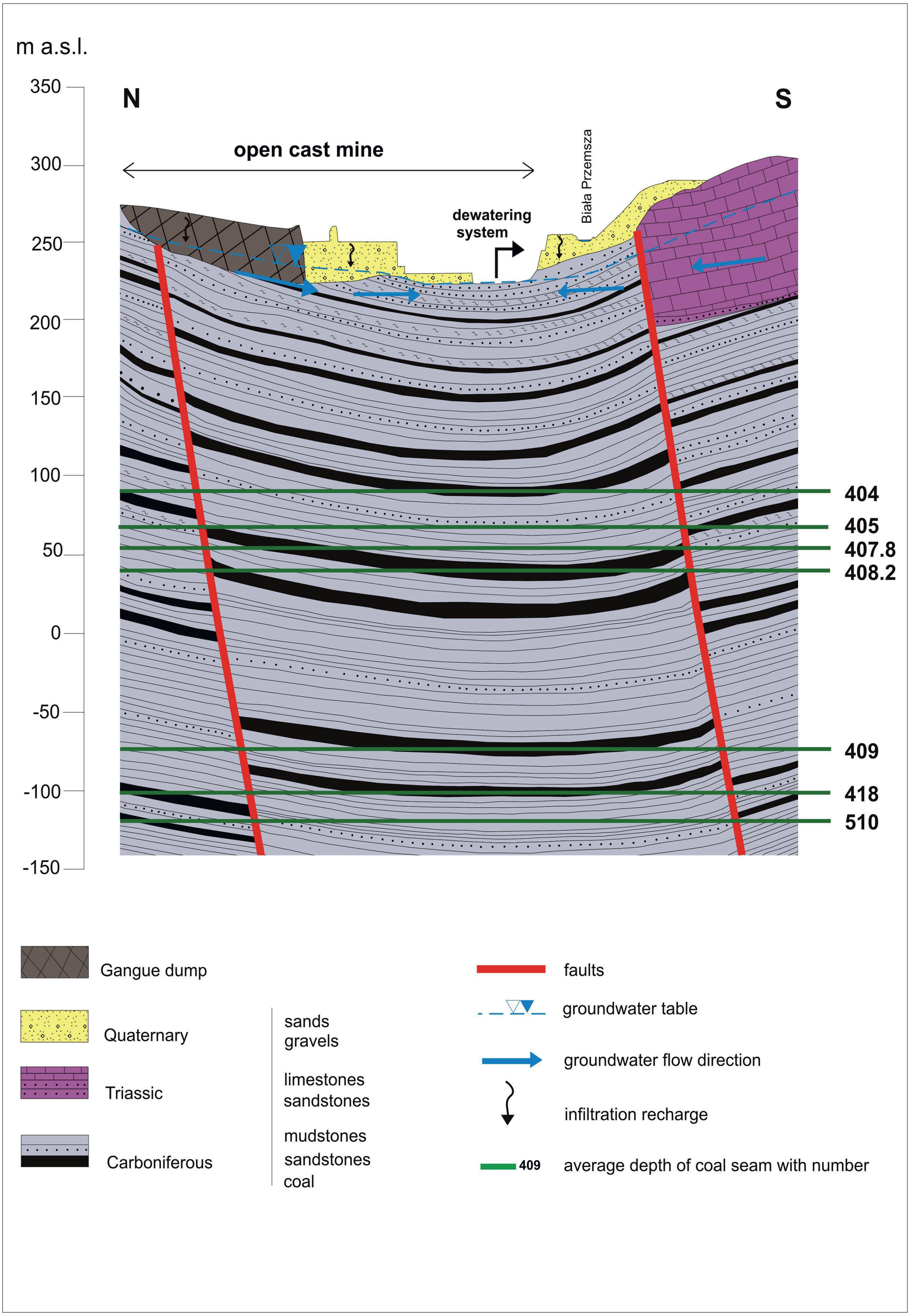

Fig. 2. *Scheme of groundwater conditions with average depth of coal seams (Gajowiec & Siemiński 1997, changed)*

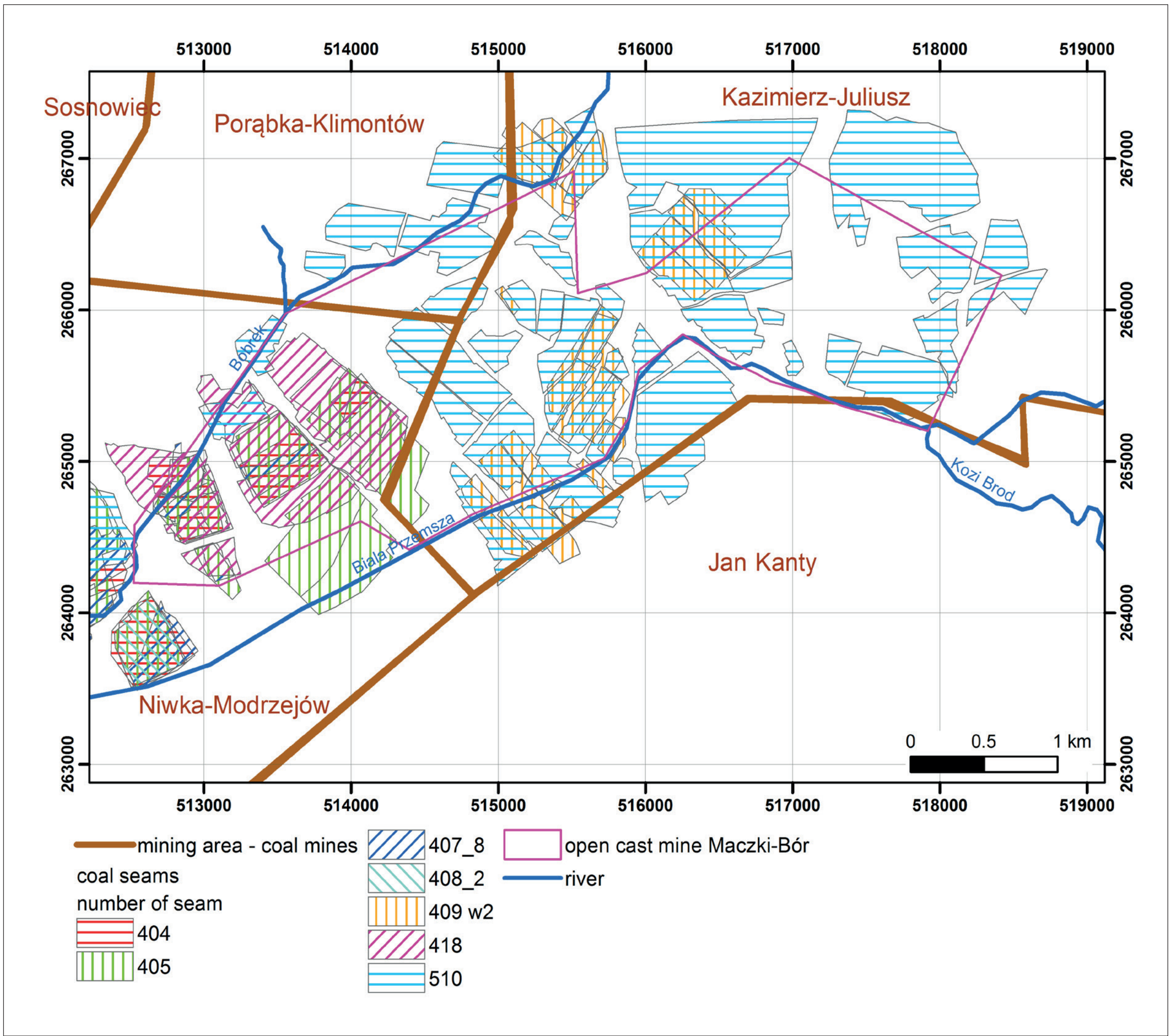

Fig. 3. *Location of the fields of former, exploited parts of coal seams*

METHODS

DRASTIC method

The name of the DRASTIC method is taken from a combination of the symbols used for the seven criteria (parameters) included in the assessment: *D* – depth to groundwater, *R* – net recharge, *A* – aquifer media, *S* – soil media, *T* – topography, *I* – impact of vadose zone, and *C* – aquifer conductivity. The DRASTIC method assumes that the final vulnerability index *V* is a sum of the products of ranks and weights of seven basic parameters describing the natural properties of the groundwater environment occurrence, according to the following formula:

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

where:
- V – vulnerability index,
- r – rank,
- w – weight;

for symbols used for parameters see Table 1.

High-resolution space discretization to a block with a size of 50 m × 50 m was applied for all parameters and vulnerability results.

The variability of particular parameters used in the DRASTIC method is presented in Table 1. The spatial scope of the gathered data applied to the entire region in order to obtain full range of their class variability and to increase objectivity for the distinguished classes within the boundaries of the research area, especially for *A* and *I* parameter (Table 1). The share of the area of individual class only concerns the research area. The methods used relate to the vulnerability assessment in phase C (Bukowski et al. 2019) of the coal and sands exploitation.

Table 1
Ranges, ranks and weights of DRASTIC parameters

Parameter		Parameter class	Weight P_w	Rank P_r	Percentage of area [%]
D	Depth to groundwater [m b.g.l.]	>100.0	5	1	0.0
		50.0–100.0		2	0.0
		30.0–50.0		3	1.2
		20.0–30.0		4	22.4
		15.0–20.0		5	17.5
		10.0–15.0		6	23.0
		5.0–10.0		7	24.9
		2.0–5.0		8	8.7
		1.0–2.0		9	1.0
		<1.0		10	1.3
R	Infiltration recharge [mm/year]	<50	4	1	0.0
		50–70		2	23.2
		70–90		3	0.0
		90–110		4	3.7
		110–130		5	17.2
		130–150		6	8.0
		150–170		7	12.8
		170–190		8	9.6
		190–210		9	0.0
		>210		10	25.5
A	Aquifer media	Glacial tills	3	1	0.0
		Mudstones and clays with sandstone layers and coal-paraleic series		2	2.0
		Deluvial sands and tills with local rock fragments		3	0.0
		Eluvial sands and weathered tills		3	0.0
		Muds, clays, sands and gravels of river upper terraces (5.0–8.0 m above river level (a.r.l.))		4	1.0
		Muds of river bottoms, sands and gravels		4	0.0
		Sands, clays, mudstones and sandstone		4	0.0
		Gravels, agglomerate, sands, sandstones, clays and mudstones (Bundsandstein)		5	0.0
		Sands, sandstones, clays, mudstones – Świerklanieckie layers		5	0.0
		Sandstones and agglomerates with layers of mudstones and coal – Cracow sandstone series and Upper Silesia sandstone series		5	0.0
		Limestones, marls, agglomerate limestones – Gogolin layers		6	0.0
		Dolomites, marls, limestones (Röt)		7	0.0
		Sands, gravels, muds of floodplains (2.5–5.0 m a.r.l.)		7	0.0
		Ore dolomites		8	0.0
		Sands, gravels with gangue rock; aeolian sands, dunes		8	62.1
		Sands of alluvial cones		9	0.2
		Fluvioglacial sands and gravels, river sands and gravels of upper terranes (5–10 m a.r.l.)		10	34.7

***Table 1** cont.*

Parameter		Parameter class	Weight P_w	Rank P_r	Percentage of area [%]
S	Soil media	No soil, buildings, halls, parking lots	2	3	13.4
		Fluvic histosols		4	15.8
		Cambisols and acid cambisols		5	1.9
		No soil cover, coal storage		6	0.9
		Podzols and entic podzols		7	23.9
		Initial soils in a reclaimed area		8	12.2
		Initial soils on sand, gravel		9	4.6
		No soil cover, surface water		10	26.8
T	Topography [%]	>9	1	1	11.4
		8–9		2	4.2
		7–8		3	3.9
		6–7		4	4.1
		5–6		5	5.4
		4–5		6	6.8
		3–4		7	8.2
		2–3		8	11.9
		1–2		9	19.6
		0–1		10	24.5
I	Impact of vadose zone	Glacial tills	5	1	0.0
		Weathered clay and tills of Carboniferous		2	2.0
		Deluvial sands and tills with local rock fragments		3	0.0
		Eluvial sands and weathered tills		3	0.0
		Muds, clays, sands and gravels of river upper terraces (5.0–8.0 m a.r.l.)		4	0.0
		Muds of river bottoms, sands and gravels		4	0.0
		Weathered sandy gravel of Bundsandstein		5	0.0
		Weathered sandy gravel of Carboniferous		5	0.0
		Gangue rock		6	39.5
		Coal, fluvioglacial sands and gravels		6	0.9
		Limestones, marls, agglomerate limestones – Gogolin layers		7	1.2
		Dolomites, marls, limestones (Röt)		7	0.0
		Isolated municipal waste, fluvioglacial sands and gravels		7	2.0
		Sands, gravels, muds of floodplains (2.5–5.0 m a.r.l.)		8	2.0
		Ore dolomites		8	0.0
		Sands, gravels, gangue rock		8	18.0
		Aeolian sands, dunes		9	3.0
		Fluvioglacial sands and gravels with till layers (10–20%)		9	10.1
		Fluvioglacial sands and gravels, river sands and gravels of upper terraces (5–10 m a.r.l.)		10	21.3
C	Hydraulic conductivity [m/d]	<2	3	1	0.0
		2–4		2	5.2
		4–8		3	40.7
		8–12		4	22.5
		12–16		5	18.9
		16–20		6	10.3
		20–30		7	2.2
		30–50		8	0.0
		50–100		9	0.0
		>100		10	0.0

Green color – class of parameter out of mine bounds.

D – depth to groundwater

The depth to the groundwater table of the first aquifer was determined based on a digital elevation model (DEM) and a groundwater contour map. The contours of the Quaternary aquifer table with an interval of 2.5 m were obtained during work on the groundwater flow model (Niedbalska et al. 2011, 2014). The value range changed from 222.5 m above sea level (a.s.l.) in the central part of the excavation pit near the sump and pumping station no. 6, to 252.5 m a.s.l. in the western part of the Bobrek valley. The DEM raster with a resolution of 100 m × 100 m taken from the GUGiK (Head Office of Geodesy and Cartography, n.d.) archives was processed to a resolution of 50 m × 50 m (the accepted discretization of assessing groundwater vulnerability to pollution). The range of elevations obtained was from 225.09 m a.s.l. in the central part of the excavation pit near the sump and pumping station no. 6, to 252.5 m a.s.l. to the NW and SE of the Maczki-Bór pit margin (exposures of the basement, mainly Carboniferous rocks). Groundwater contour lines were processed in the ArcGIS 10.5 environment into a raster map, which was then subtracted from the DEM raster. Following the calculations, the obtained depth map was from –2.70 m below ground level (surface water occurance, b.g.l.) to 49.51 m b.g.l., at an average value of 14.5 m b.g.l. and standard deviation of 8.19 m b.g.l. Specific features of the area are local groundwater manifestations on the surface, in the bottom of the excavation pits along the southern margin of the mining area, and in the northern part of the Western Bór excavation pit near the active communal waste dump. In relation to the Bobrek and Biała Przemsza valleys, the groundwater table occurs at 5–10 m b.g.l., or even 10–20 m b.g.l. Around 25% of the area is covered by class no. 7, where the depth is 5–10 m b.g.l., 23% represents class no. 6 with depth in the range of 5–10 m b.g.l. and class no. 4 with a depth range of 20-30 m b.g.l. (22.4%), (Fig. 2).

R – infiltration recharge

Infiltration recharge, similarly to the depth to the groundwater table, was determined through groundwater flow modelling (Niedbalska et al. 2011, 2014). The values obtained in cubic metres per day [m^3/d] were recalculated to mm/year, and the variability range allowed ten classes of parameter *R* to be distinguished. The variability of infiltration recharge was from 58.4 to 328.5 mm/year, with an average value of 159 mm/year and a standard deviation of 43 mm/year. Analysis of annual sums of precipitation from 2005–2019 measured in two precipitation stations in the area (Maczki-Bór, Ciężkowice) shows that the mean annual precipitation is at 756 mm. Therefore, the infiltration index for the obtained recharge values was an average of 0.21, in a range of 0.077 to 0.43. Values exceeding 210 mm/year (>30%) of precipitation were considered as extremely high, taking into account the infiltration index classification according to Pazdro & Kozerski (1990), and were of anthropogenic origin.

Class no. 10 covers 25.5% of the surface, where infiltration reaches values exceeding 210 mm/year, 23.2% is covered by class no. 2 with recharge at 50–70 mm/year, and 17.2% represents class no. 5 with recharge at 110–130 mm/year. The lowest recharge values occur in the central part of the study area within the range of the reclaimed part of the Maczki-Bór Western excavation pit, whereas the highest were noted along the northern and southern margins of the pit (Fig. 4).

A – aquifer media

The lithology of the aquifer was determined based on geological descriptions of lithological units from the detailed geological map of Poland (Wilanowski 2016, Kurek et al. 1991) and cross-sections from hydrogeological reports determining hydrogeological conditions related with change of dewatering for sand exploitation in the open cast pit CTL Maczki-Bór S.A. (Kropka et al. 2013).

Lithological units of the aquifer, which were originally marked on the geological map as land with anthropogenic impact within the range of the exploitation pit, were precisely described. The range of fluvioglacial sands and gravels was narrowed. The new unit, comprising sands, gravels, and gangue rocks, is underlain by fluvioglacial deposits; in the top the groundwater table contacts with the gangue rock deposited in the excavation pit. In the central part around the sump an additional unit comprises sands in the top and Carboniferous claystones, mudstones, and sandstones in the bottom (possible water flow in the upper part of these deposits).

Class no. 8 dominates, comprising sands, gravels with gangue rocks, and aeolian sands (62.1%), followed by class no. 10, comprising fluvioglacial sands and gravels (34.7%). The third highest contribution has class no. 2, including mudstones and clays with sandstone layers and coal, is described as the paraleic series (2%) (Fig. 4).

S – soil media

The basis for this data was the map of soil genetic types at the scale of 1:500 000 (Institute of Soil Science and Plant Cultivation, n.d.), with more detailed information from the detailed geological map of Poland at the scale of 1:50 000 (Kurek et al. 1991, Wilanowski 2016), and the analysis of a high-resolution orthophotomap (resolution 10 cm, as for 2020, Geoportal, n.d.), which was the key material for the interpretation of soil occurrence within the excavation pit margins. Numerous areas were distinguished: lack of soil cover (development on a technically reclaimed area), initial soils on a reclaimed area, lack of soil cover within the coal storage site, initial soils on fluvioglacial sands and gravel, lack of soil cover on the exploitation site of fluvioglacial sands and gravel, and the active communal waste dump. Class no. 10, i.e. no soil cover, occurs on 26.8% of the surface. The second class is represented by podzols and entic podzols soils, reaching up to 23.9%, and the third – class no. 4 – represents fluvic histosols and occurs on 15.8% of the surface (Fig. 4).

T – topography

The DEM raster with a resolution of 100 m × 100 m taken from the GUGiK database (Head Office of Geodesy and Cartography, n.d.) was processed to the resolution of 50 m × 50 m. Using the ArcGIS Slope tool, it was transformed into a slope map expressed in percentages. Flat areas with slope not exceeding 1% (class no. 10) cover 24.5% of the surface, of which the largest part occurs in the northern part of the reclaimed area within the Maczki-Bór Western excavation pit. Subsequent classes with larger slope values include class no. 9 (slopes 1–2%; 19.6% of the surface) and class no. 8 (slopes 2–3%; 11.9% of the surface) (Fig. 4).

I – impact of vadose zone

The lithology of the vadose zone was determined based on data from the detailed geological map of Poland at the scale of 1:50 000 (Kurek et al. 1991, Wilanowski 2016), profiles of piezometers from the observation network in the excavation pit, and hydrogeological cross-sections (Kropka et al. 2013). In the northern and eastern margin of the excavation pit, clay lenses occur within fluvioglacial sands and gravels, with a thickness not exceeding 20% of the vadose zone. Within the excavation pit occur areas with only gangue rock comprising the vadose zone. Along the northern margin deposits of anthropogenic origin are also present: communal waste underlain by mineral and synthetic isolation and coal underlain by fluvioglacial sands and gravels. Beside fluvial sands and gravels, the Biała Przemsza valley comprises fluvial muds and silts. In class no. 6, including gangue and coal, fluvioglacial sands and gravels comprise 39.5% of the surface. Deposits with good permeability, such as fluvioglacial sands and gravels, and fluvial sands and gravels of overbank terraces occur in class no. 10 (21.3%), sands, gravels, gangue rocks, as well as sands, gravels and gangue rock represent class no. 8 (18%) (Fig. 4).

C – hydraulic conductivity

Data on hydraulic conductivity were obtained from groundwater flow modelling (Niedbalska et al. 2011, 2014). The variability of the obtained data was the basis for distinguishing six classes of parameter *C*. The values vary between 3 and 29 m/d. The largest surface area is covered by class no. 3 with the hydraulic conductivity in the range of 4–8 m/d (47%), the next is class no. 4 in the range 8–12 m/d (22.5%) and class no. 5, i.e. 12–16 m/d (18.9%) (Fig. 4).

Sensitivity analysis

In order to determine the influence of the weights of all parameters applied in the DRASTIC method, a sensitivity analysis was performed for particular parameters (Napolitano & Fabbri 1996, Al-Adamat et al. 2003, Babiker et al. 2005, Krogulec 2013, Krogulec & Trzeciak 2017). By comparing theoretical and effective weights, the analysis determined the possible optimization of the results emerging from the range of input data and relations between them.

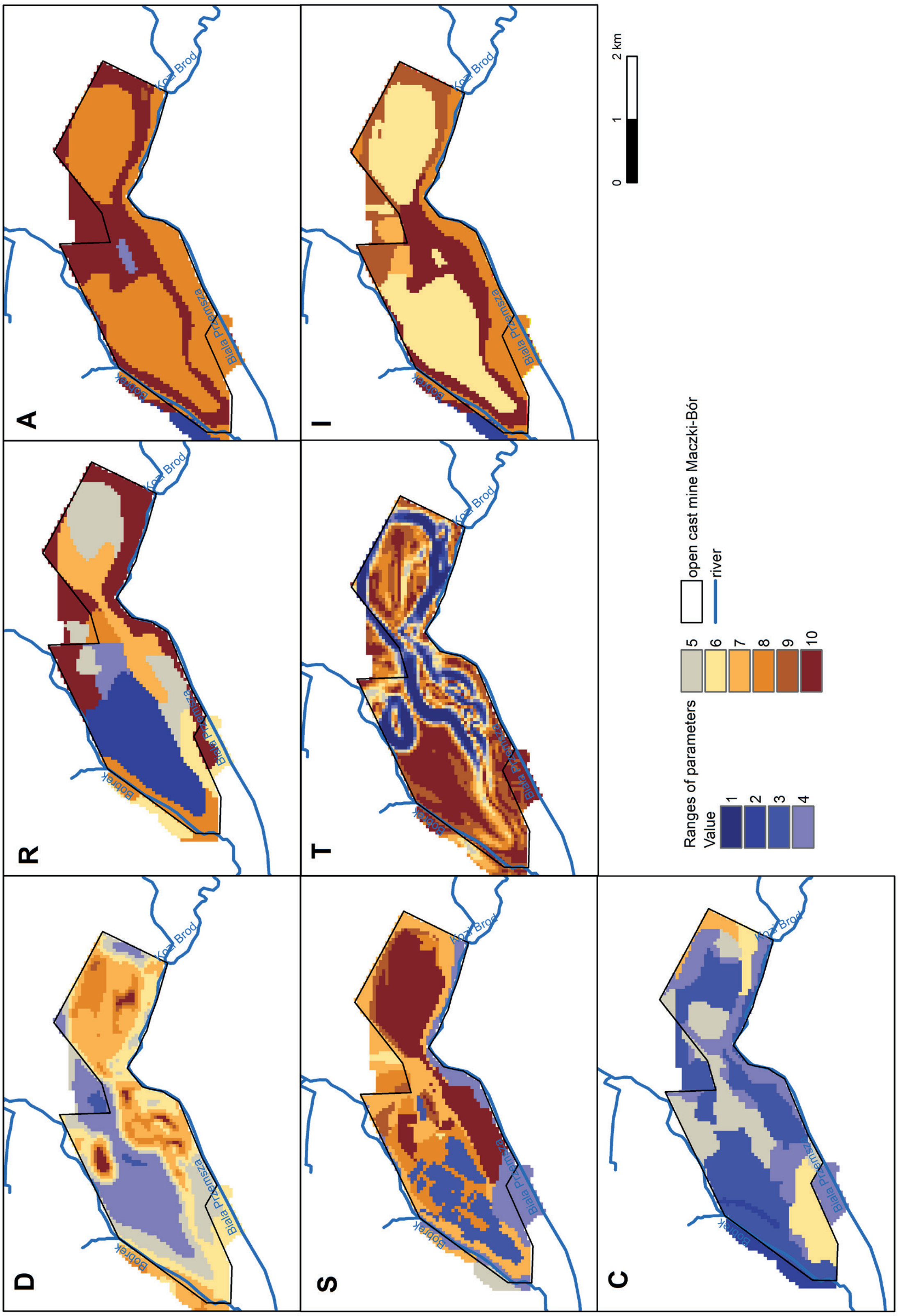

Fig. 4. *Spatial distribution of the DRASTIC parameters*

The sensitivity assessment allows the subjective approach related with weight assignment to DRASTIC parameters to be diminished. The single-parameter variant of the sensitivity analysis (Krogulec & Trzeciak 2017) is used to assess the influence of each parameter on the DRASTIC index by supplying information on the effective weight of the parameter, obtained from the formula:

$$W = \left(P \cdot \frac{P_w}{V} \right) \cdot 100 \qquad (2)$$

where:
W – effective parameter weight,
P_r – parameter rank,
P_w – parameter weight,
V – DRASTIC index for seven basic parameters.

DRASTIC^M method

Taking into account the specific character of the areas in which underground mining is performed, a vulnerability assessment was conducted by introducing an additional parameter to the DRASTIC method (Góra 2012). In the DRASTIC MINE (DRASTIC^M) method, the new Z parameter provides numerical values to the expected intensity of the mining impact on the land surface in the context of changes in the filtration parameters of rocks occurring above the coal seams and of changes to aquifer recharge conditions. The modification was thus focused on extending the range of particular parameters, assuming that the hydrogeological conditions of the area in which underground exploitation is conducted would change.

The Z parameter uses the observed three types of rock mass deformation, whose presence is strictly related with distance from the excavation's roof and whose numerical value is determined based on the multiplicity of the excavation height (Ryncarz 1992, Palchik 2003) and changes of water permeability of the transformed rock mass fragment (Table 2).

Parameter Z is defined as the expected intensity of the exploitation impact on the land surface, resulting from opening of the topmost part of the mass for infiltration from precipitation. Based on the earlier determined type of mass deformation and multiplicity of the exploited seam thickness, the range of the Z parameter was established (Table 2).

Table 2
Types of rock mass deformation above mining exploitation pits with range accepted in the DRASTIC^M (Góra 2012, changed)

Deformation of the rock mass	**Range**	**Multiplicity of the exploited coal seam thickness**	**Rock mass conductivity k [m/s]**	**Rank of the Z parameter**	
				presence of isolating deposits	**lack of isolating deposits**
Collapse zone (caved zone)	land surface under the influence of a full collapse zone	up to 3	$>10^{-3}$	10	10
Fracture zone (block zone and horizontal fracture zone)	land surface under the influence of the lower part of water permeable fractures	3–8	10^{-3}–10^{-4}	6–8	9
	land surface under the influence of the middle part of water permeable fractures	8–15	10^{-4}–10^{-5}	3–5	6
Zone of continuous deformations (deflection zone)	land surface under the influence of the upper part of water permeable fractures	15–40	$<10^{-6}$	2	3
Negligible deformation (imperceptible anthropopression with regard to deformation)	land surface devoid of the influence of exploitation impact	over 40	negligible changes in conductivity	1	1

The weight of the Z parameter depends on the dominating type of surface deposits. The following weights were taken in the original classification: 1–2 for productive Carboniferous series, and 3 for Triassic limestones and dolomites, Cracow Sandstone Series, and Quaternary sands of river valleys. Due to the presence of Quaternary sands and gravels in the entire area, weight 3 was accepted for all seams.

The procedure of attaining a respective rank and weight for the Z parameter for each seam was as follows:

1. A point cloud with a resolution of 50 m × 50 m was created for areas of seam occurrence.
2. The altitude of coal seams roof was collected.
3. The depths of the seams roof were determined.
4. The deformation zone of the mass was determined based on the seam thickness ($3g$–$40g$, g – coal seams thickness).
5. The Z parameter was classified according to its rank.
6. The weight of the Z parameter was attributed.
7. The impact range on the surface was determined based on the formula:

$$H = \frac{H}{\text{tg}\,\beta} \tag{3}$$

where:

H – exploitation depth, i.e. distance from the seam roof and the land surface,

$\text{tg}\,\beta$ = 2 as the mean for the Upper Silesia Coal Basin.

8. The buffer corresponding to value $r(H)$ was created.

The final layers presenting the product of the rank and weight for the Z parameter were transposed to the raster layers, and then summed up.

Adopted validation method

Chemical data used for the validation of the presented methods of vulnerability assessment include concentrations of chlorides and sulfates, determined in 13 local monitoring points in 2013–2019, with a frequency of twice a year (Table 3). The total number of data from that interval is 146 results of chloride and sulfate concentrations in groundwater, including determinations from two leachate wells St1 and St2 monitoring the quality of leachate water from the post-mining waste dump.

Table 3
Mean concentration of chlorides and sulfates for particular monitoring points in 2013–2019

Monitoring point				Mean chloride concentration [mg/L]	Mean sulfate concentration [mg/L]
symbol	location	depth to groundwater table [m]	number of measurements		
Pz10	BZ	15.7	14	62.4	163.8
Pz11	BZ	25.4	14	161.4	414.2
H3	BZ	8.7	14	62.4	163.8
Pz5	BW	20.3	14	32.7	67.8
Pz12	BW	25.5	14	41.3	196.1
Pz13	BW	17.1	10	33.0	224.6
Pz14	BW	20.1	10	28.4	74.1
St1	BW	–	5	1086.2	1500.3
St2	BW	–	1	320.0	211.0

BZ – Western Bór field, BW – Eastern Bór field.

RESULTS

DRASTIC method (standard)

The application of the DRASTIC method allows the presentation of the spatial distribution of intrinsic groundwater vulnerability to pollution (Fig. 5). In the GIS-based analyses, the ranges of areas with particular groundwater vulnerability classes (very high, high, moderate, low, and very low) were determined.

The vulnerability index in the range of 91–193 was subdivided into five classes with an identical interval after its normalization. The contribution of particular classes is variable. The very low vulnerability class covers 10.9% of the surface, mainly in the western part of the study area, including the reclaimed part of the Western Bór field. The low vulnerability class occurs on 11% of the surface, also within the reclaimed part of the Western Bór field. The medium vulnerability class covers 22.5% of the area, both within the communal waste dumps and the excavation pits, including: the central part of the Eastern Bór field and the southern part of the Western Bór field. The high vulnerability class covers 38.6% of the surface, mainly areas within the excavation pits and river valleys. The very high vulnerability class occurs in the central part of the Western Bór pit, the marginal part of the adjoining river valley and the eastern part of the study area, also beyond the excavation pit, and the north part, amounting to 16.9% of the surface (Fig. 5).

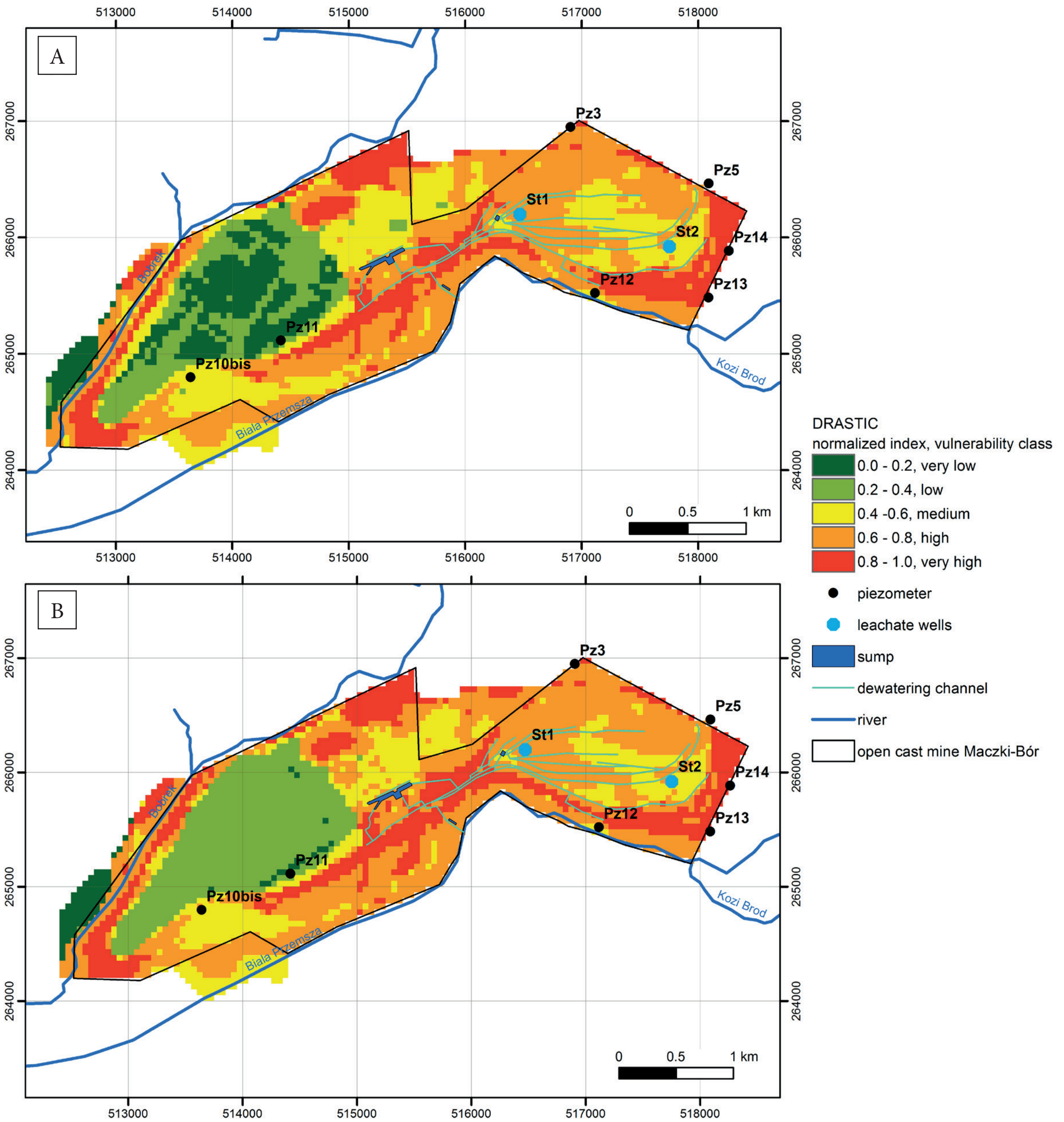

***Fig. 5.** DRASTIC vulnerability: A) original; B) optimized*

Analysis of parameter sensitivity

The performed sensitivity analysis indicated that the weights for parameters *A*, *S*, *T*, *I* have been underestimated, the largest difference was for *A* and *I*. In the initial assumptions, an over exceed value was attained for parameter *C*, where the largest overestimation was found, as well as *D* and *R* (Table 4).

After calculation with the use of effective weights, the optimized DRASTIC index attains values in the range of 88.22–201.02 and is on average 6.4 points higher than the DRASTIC index. Vulnerability increase was observed for 97.65% of the surface, with a higher contribution for the low, high, and very high vulnerability class areas, and a lower contribution for the very low and medium vulnerability class areas (Table 5, Fig. 5).

Table 4
Theoretical and effective weights of the DRASTIC parameters

Parameter	Theoretical weight	Theoretical weight [%]	Effective weight	Effective weight [%]			
				mean	minimum	maximum	standard deviation
D	5	21.74	4.50	19.58	10.20	38.10	4.25
R	4	17.39	3.64	15.81	4.68	30.19	6.40
A	3	13.04	3.98	17.30	5.13	423.79	3.21
S	2	8.70	2.11	9.19	3.59	16.39	3.22
T	1	4.35	1.11	4.82	0.53	9.80	4.50
I	5	21.74	5.82	25.31	8.55	38.46	4.59
C	3	13.04	1.84	7.99	3.30	16.07	2.36

Table 5
Vulnerability class area before and after DRASTIC optimization

Normalized index, vulnerability class	DRASTIC index	Class area for DRASTIC [%]	Optimized DRASTIC index	Class area after DRASTIC optimization [%]	Change of class area
0.0–0.2, very low	91.0–111.4	10.9	88.22–110.78	2.4	−8.5
0.2–0.4, low	111.4–131.8	11.1	110.78–133.34	19.1	8.0
0.4–0.6, medium	131.8–152.2	22.5	133.34–155.90	17.8	−4.7
0.6–0.8, high	152.2–172.6	38.6	155.90–178.46	41.7	3.1
0.8–1.0, very high	172.6–193.0	16.9	178.46–201.02	19.0	2.1

Vulnerability assessment using DRASTIC^M

The *Z* parameter was determined based on the depth of particular coal seam roofs and the defined range of their impact on the rock mass. In most cases, the seam thickness and depth classified the *Z* parameter to rank 1, with the exception of seams 418 and 510 which resulted in higher rank values. Locally, it was possible to reveal the influences from mining operations conducted in seams 418 and 510 in terms of continuous deformations (15*g*–40*g*). The obtained rank was 3 (rank multiplied by weight = 9) in areas of determined hydrogeological windows with possible flow between

Quaternary and Carboniferous aquifer horizons. For areas beyond hydrogeological windows, the accepted rank was 2 (rank multiplied by weight = 6), where isolation linked with the occurrence of rocks of mudstone series takes place. After obtaining the sum of particular products, the final value of the *Z* parameter was achieved (Fig. 6). According to the assumptions of the DRASTIC^M method, the summarized value of the rank and weight values of the *Z* parameter for all distinguished seams was added to the final DRASTIC index. In this case, the optimized DRASTIC index was used where the weight values were corrected for seven parameters.

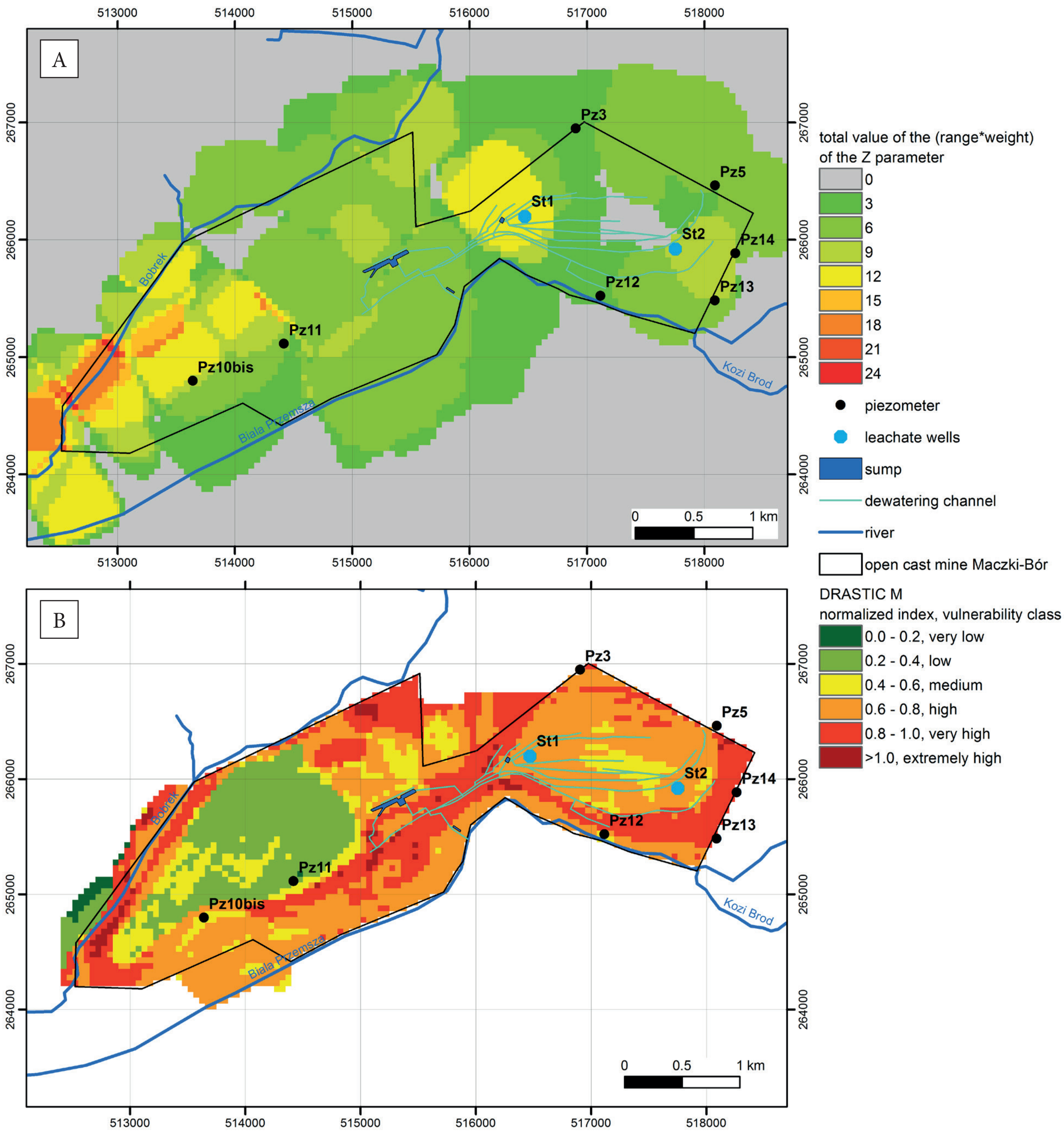

Fig. 6. *DRASTIC^M vulnerability: A) value of parameter Z; B) vulnerability class*

The vulnerability index increased from 3 to 24 on a surface of 7.37 km^2, i.e. on 95% of the area, and to 6 on 45% of the surface. The normalization procedure was performed in relation to indexes of the optimized DRASTIC method, and values exceeding 1 were attributed to an additional class of extremely high vulnerability (Fig. 6). The increase in the DRASTIC index, despite the fact that it occurred over almost the entire area of the study area, is not high due to the considerable depth of the occurrence of individual coal seams. The increase in the index amounted to a maximum of 12% of the index value after optimization, which means that some areas can be classified up to one class higher after using the $DRASTIC^M$ method.

The largest surface is covered by the high vulnerability class, 42.5% of the area, which occurs in the central part of the Eastern Bór excavation field, in the surroundings of the waste dump and in the southern part of the area along Biała Przemsza. The very high vulnerability class also covers large areas on 26.3% of the surface, along the margins of the Eastern Bór excavation field, in the vicinity of the waste dump, and along the Bobrek valley. The low vulnerability class, i.e. 16.4%, covers a relatively compact area near the Western Bór field in a technically reclaimed area, managed for trade and industrial use. This class is surrounded by the medium vulnerability class (12.3%). The very low vulnerability class, beside the excavation pit, only covers 0.8% of area. The extremely high vulnerability class areas cover 1.6% of the area in the central part of the exploitation pit, along the northern margin, and in the strip of land between Bobrek valley and the reclaimed area.

Validation of the vulnerability assessment

Vulnerability validation was performed using monitoring points located within the study area: Pz3, Pz5, Pz10, Pz11, Pz12, Pz13, Pz14, St1 and St2. It was related to the values of the vulnerability index determined with the application of the DRASTIC, optimized DRASTIC and $DRASTIC^M$ methods. The relationship of mean chloride and sulfate concentrations with values of vulnerability assessment parameters was also tested (Table 6). The correlation coefficient values were accepted so that strong correlation occurs for coefficient values exceeding 0.9, relatively strong correlation for coefficients within 0.7–0.9, and medium – for coefficients within 0.4–0.7.

Table 6
Pearson's coefficient for vulnerability assessments, parameters, and chloride and sulfate concentrations

	DRASTIC	DRASTIC optimized	$DRASTIC^M$	D	R	A	S	T	I	C	Z	Cl^-	SO_4^{2-}
DRASTIC	1.00												
DRASTIC optimized	0.99	1.00											
$DRASTIC^M$	0.98	0.97	1.00										
D	0.17	0.19	0.33	1.00									
R	0.79	0.78	0.68	−0.26	1.00								
A	0.62	0.60	0.51	−0.50	0.69	1.00							
S	0.16	0.18	0.26	0.40	−0.09	−0.05	1.00						
T	0.51	0.49	0.56	0.32	0.05	0.21	0.19	1.00					
I	0.57	0.55	0.45	−0.51	0.68	0.79	−0.58	0.17	1.00				
C	0.63	0.58	0.64	0.07	0.34	0.67	−0.07	0.34	0.63	1.00			
Z	0.09	0.04	0.28	0.78	−0.39	−0.30	0.50	0.42	−0.48	0.29	1.00		
Cl^-	−0.03	−0.03	0.12	0.67	−0.18	−0.43	0.66	0.15	−0.67	−0.25	0.68	1.00	
SO_4^{2-}	−0.14	−0.14	0.00	0.48	−0.18	−0.41	0.51	0.14	−0.58	−0.32	0.56	0.95	1.00

Values of the correlation coefficient exceeding 0.67 are statistically significant for test probability $p < 0.05$. An analysis of linear relationships indicated the lack of correlation between the mean concentrations of chlorides and sulfates with the obtained vulnerability values. The correlation coefficients indicate a rather strong negative correlation of chloride and sulfate concentrations with parameter *I* (−0.67 and −0.58) and strong correlation of parameter *R* with vulnerability assessments (0.68–0.79). Medium correlation of parameter *I* (0.45–0.57) occurs in relation to the values of vulnerability assessment. The relationship between the concentrations of chlorides and depth was moderate (correlation coefficient 0.67 and 0.48). The moderate correlation of parameter *S* with concentrations of chlorides and sulfates is also notable (correlation coefficients at 0.66 and 0.51, respectively). The new parameter *Z* is moderately correlated with concentrations of chlorides and sulfates (0.68 and 0.56, respectively).

Anthropopression in the vicinity of the Maczki-Bór excavation pit has a strong impact on groundwater chemistry, observed in local monitoring points since 1995 (Różkowski et al. 2017). Due to the character of the material used for reclamation of the open pit excavation, the waste dump constitutes the groundwater source of contamination. As a result of weathering processes, the oxidation of sulfides and leaching of sulfate ions and chlorides takes place. Other contamination sources include active and closed-down communal waste dumps, old dumps of mining waste, settler tanks of mine water, and settlements without sewage systems.

Taking into account such contamination sources, two groups of chemical data may be assumed:
- points Pz10, Pz11, St1, and St2 located in direct vicinity of the contamination source (Carboniferous gangue rock in the aquifer, occurrence of Quaternary-Carboniferous aquifer),
- points Pz3, Pz5, Pz12, Pz13, and Pz14 located close to the inflow of groundwater from the Quaternary aquifer to the excavation pit.

The presented subdivision is evident with regard to the results of vulnerability assessment. For points in the first group there is a strong relationship between chloride concentration and vulnerability value, and the correlation for the DRASTIC, optimized DRASTIC and the $DRASTIC^M$ is: 0.59, 0.53 and 0.67, respectively. In the case of sulfates, the relationship is weaker: 0.32, 0.25 and 0.41, respectively. For points from the second group, the correlation of chlorides with the results of vulnerability assessment is negative: −0.66, −0.59 and −0.53, respectively. For sulfates, the correlation is weaker: −0.44, −0.32 and −0.44, respectively.

DISCUSSION

The results obtained by the DRASTIC method generally differentiate the area into two groups. The first, low and very low vulnerability, concerns the reclaimed part of the excavation, where the characteristic features of the area influencing the final product of vulnerability assessment are: low recharge as 58 mm/year, depth to the groundwater table in the range of 20–30 m b.g.s., no soil cover and simultaneous sealing of the surface by buildings, parking lots, halls, etc. The second group concerns most of the open cast mine, where the groundwater table is shallow at 2–5 or 5–10 m b.g.s., the recharge is extremely high between 200 and 330 mm/year, and the profile is mostly built by fluvioglacial sands and gravels. The results indicate that the most vulnerable areas are associated with the edges of the excavation, especially in the east and south, areas where sand exploitation is still ongoing.

The sensitivity analysis made it possible to increase the objectivity of the DRASTIC method, as a result of which an optimized vulnerability distribution was obtained. This product is slightly different from the unadjusted results, mainly in terms of the coverage of individual vulnerability classes. This is mainly due to the higher weight of the *I* and *A* parameters. The *I* parameter itself attains the highest importance among all parameters, which happens relatively rarely taking into account the review of the results from the literature. Trzeciak (2018) showed that the highest effective weights for the *I* parameter only occurred three times out of 24 cases: El-Naga et al. (2006) – 5.49, Kabera & Zhaohui (2008) – 6.28, Al Hallaq & Elaish (2012) – 5.77. On the other hand, the *D* parameter is most often underestimated, in this case it has a lower effective weight than the initial weight, and such a case was recorded only once in 24 cases (Trzeciak 2018). It follows that the most appropriate for a given area is a complete and detailed recognition of individual geological units, taking into account their variability in the profile of the vadose zone and below the groundwater table, including those units formed as a result of anthropogenic activities related to deep and surface mining. The correlation between the *I* and *A* parameter at the level of 0.79 indicates that the information collected for these layers does not overlap (they are not duplicated), moreover, their correlation with other parameters is very weak (only *I* with *R* slightly above significant, i.e. 0.68), that is why their importance is high.

The presence of underground mining and its impact on the subsurface part of the rock mass should be considered small, which is the result of the obtained values of the *Z* parameter used for vulnerability assessment using the $DRASTIC^M$ method. On the ground surface, the multiplicity of the exploited coal seam thickness is usually in the range 15–40, which means that it is the zone of continuous deformations (deflection zone) or lower – in the range over 40, where there are negligible deformations. It is higher in regions with hydrogeological windows between the Quaternary and Carboniferous formations. In connection with the considerable spatial range of the 510 seam workings and the lowered ground surface in the open cast mine due to the exploitation of sands, the total increase in vulnerability locally reached the normalized value of 0.21, i.e. an increase of up to two classes. In the area of the reclaimed fragment of the excavation, thanks to the elevation of the ground level by approx. 30 m, there is no impact of deep excavations, or it is small (for three seams, the rank of the *Z* parameter is 1).

Taking into account the *Z* parameter in the $DRASTIC^M$ method resulted in the fact that the greatest changes – increased vulnerability – were recorded in the central (vicinity of St1 well) and eastern (vicinity of St2 well) areas. The areas near the municipal waste landfill, in the Boberek river valley and along the drainage ditches of the Bór Wschód and Bór Zachód fields are the most vulnerable areas, they were highlighted by extremely high class of vulnerability. In these areas, increased infiltration from the ground or from surface water should be expected, including drainage systems that carry polluted waters, the so-called AMD as shown by own chemical analyzes.

Validation of the methods used by determining the correlation with chemical compounds present in the groundwater, such as chlorides and sulfates, indicated a generally weak relationship, primarily due to the presence of the source of these chemicals located directly in the aquifer in the form of gangue rocks. The division of points into two groups taking into account such contamination sources, showed a significant differentiation of correlations. Points located in direct vicinity of the contamination source had a strong correlation of vulnerability indexes with concentrations of chlorides and sulphates, points located close to the inflow of groundwater from the Quaternary aquifer to the excavation pit has negative correlations. Despite the lower correlation values of concentrations of the chemical compounds with the results of the optimized DRASTIC method, this model was used for the vulnerability assessment by $DRASTIC^M$ method due to the need to reduce the degree of subjectivity, which is manifested in assigning classes to individual parameters, widely described in the literature (e.g. Al Hallaq & Elaish 2012, Trzeciak 2018). Also, the lower correlation with the optimized DRASTIC method is an interesting issue. It indicates that the final result is to a large extent less dependent on the individual parameters of the method, and the contamination cannot be directly correlated with overall natural conditions, but the anthropogenic aspect is important here.

CONCLUSIONS

The presented case of a highly transformed environment related to the exploitation of open cast and coal mines was used to assess the natural vulnerability to pollution. For both mine types, it was crucial to define the factors that influence the hydrogeological and environmental conditions occurring only at a given phase of operation (Bukowski et al. 2019). Both the open cast mine and coal mines are in the terminal (C) phase, but intensive drainage only applies to the open cast mine.

The conducted evaluation showed:

1. For open cast mine, the natural vulnerability assessment was made using the DRASTIC method together with the analysis of its uncertainty and the optimization method. The number of parameters included in the method fully characterizes the transformation of the land surface, changes in the hydrogeological conditions of occurrence, recharge, and environmental conditions (soils). It is important to identify and classify newly formed geological units (gangue rock) and soils (no soil cover or initial soils). The assessment is possible for the defined characteristics for the exploitation phase and the set conditions.
2. For the optimized DRASTIC method, the vulnerability index indicated areas with occurrence high (38.6%) and very high classes (16.9% of the area), mostly in the central part of the open cast mine, where the groundwater table is very shallow and there is no soil cover due to marginal exploitation of sands. On the contrary, the reclaimed area of the excavation is area where the infiltration recharge is small and groundwater table depth has increased significantly due to the partial backfilling of excavation and simplification of open pit drainage system by removing some of channels and ditches.
3. For coal mines, the vulnerability of the groundwater had to be extended by applying the DRASTIC^{M} method. An additional parameter defining the influence of underground mining is the *Z* parameter, which determines the condition of the rock mass: strongly fractured and transformed, with changed rock properties and changed hydrogeological conditions. These changes are expressed by higher water permeability relative to natural conditions. The increase in the permeability of rock mass is greater, the closer it is to the exploited coal seam. The presence of hydrogeological windows between Quaternary and Carboniferous aquifers was also taken into account. The applied method made it possible to assess the vulnerability in the conditions of the cumulative impact of underground mining, which was expressed through the impact of seven coal seams on the rock mass.
4. The final value of the *Z* parameter included in the DRASTIC^{M} method increased the vulnerability of the area of the Maczki-Bór excavation pit to 95%, and the change of vulnerability index was from 3 to 24 points. Therefore, it was necessary to indicate a new vulnerability class – extremely high, which occurred in 1.6% of the area. This indicates areas that should be treated as a priority in order to avoid pollution, and in the final stage to plan activities in the field of reclamation of mining areas, as well as to predict the effects of these changes.
5. The applied verification of the vulnerability assessment methods by indicating the correlation with chlorides and sulphates showed that in the event of the impact of a pollution source such as deposited gangue rock, the use of specific vulnerability should be considered.
6. The presented solution refers to the classic assumption that the pollution source is located on the ground surface. The vulnerability determined in this way indicates the areas with the greatest risk from objects with various purposes, those related to mining (e.g. dewatering systems, coal storage) and others (existing and future production halls, petrol stations, railway tracks, etc.). It also provides information on the possibilities of land development on the surface of the reclaimed area of the excavation.

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