Parametric assessment of groundwater vulnerability to pollution within an open pit reclaimed by gangue

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Abstract
The use of post-mining wastes in the reclamation of an open pit may act as a source of pollution that has a very strong impact on the groundwater environment. One such facility in Poland is the CTL Maczki-Bór S.A. sand mine filled with waste rock from hard coal mines. The current hydrodynamic conditions in the Quaternary aquifer causes that the wastes are in the bottom part of the open pit under the constant influence of groundwater. Due to the sub-level nature of the pollution source, the author of the study modified the classic rank-weight method of assessing the groundwater vulnerability to pollution in order to adapt it to the atypical type of the pollutant emitter. An individual approach was proposed by modifying the range of parameters as well as the assigned ranks and weights. Six key parameters were indicated, i.e. the thickness of the aeration zone, the thickness of the saturation zone, the filtration coefficients of the deposits in both of these zones, the recharge of the aquifer and the surface topography. The correctness of weight selection was verified by sensitivity analysis in the sensitivity variant of one parameter. It has been proposed to classify the groundwater vulnerability to 5 classes from moderately high to extremely high. For theoretical and effective weights, the obtained values of the index of groundwater vulnerability to pollution allowed to divide the area of the reclaimed open pit into two zones with high and very high groundwater vulnerability to pollution.

Keywords Groundwater · Groundwater vulnerability to pollution · Water quality · Post-mining wastes · Open pit · Reclamation

Introduction
The principles of sustainable development require all plans for economic and social activity of country to be implemented while safeguarding the quantity and quality of groundwater and surface waters. In Poland, aquifers are the main source of drinking water supply for the population, especially due to their vast reserves, broad geographic distribution and high quality (Krawiec and Sadurski 2021). For this reason, the assessment of the sensitivity of aquifers to surface pollution should be one of the main criteria considered in establishing Spatial Development Plans. Therefore, groundwater vulnerability to pollution analysis should be one of the decision-making factors regarding investments undertaken in a given area.

The concept of groundwater vulnerability to pollution (GVP) was first introduced in the late 1960s (Albinet and Margat 1970), but its definition has not been unified to this day (Moraru and Hanninan 2017). It was originally defined as the ability to penetrate of impurities into an aquifer from a source located on the surface and concerned only natural conditions. The concept of determining vulnerability only by natural factors and not by associating it with the type of pollution source was strongly advocated in the 1970s (Olmer and Razac 1974). The development of environmental awareness and problems caused by the dynamic flourishing of industry and cities caused this terminology to be gradually modified over the years. The need to consider the quantitative and qualitative aspects of the impacts of impurities on groundwater was also recognized. The issue of anthropogenic factors and the impact of anthropopressure as a measure of risk imposed on groundwater have been raised in several discussions (Sotornikowa and Vrba 1987; Vrba and Zaporozec 1994; Harter and Walker 2001). Depending on the type of factors...
involved in the assessment of the sensitivity of aquifers to pollution, as well as the methodology of the assessment itself, the vulnerability of groundwater to pollution is also understood as (Krogulec 2004):

- the aquifer’s resistance to pollution and its ability to return to its original state after the outbreak of pollution,
- the risk of the impact of the pollution emitted from the surface on the groundwater quality,
- the aquifer’s resistance to all natural and anthropogenic impacts,
- the natural properties of the system, defining the risk of the migration of anthropogenic pollutants from the land surface.

Over time, the concept of specific vulnerability, which is a term more broadly understood than natural vulnerability, crystallized (Vrba and Zaporózec 1994; Krogulec 2004; Duda et al. 2011; Duda et al. 2020). Specific vulnerability considers the type of pollutant, its charge and exposure time as well as the spatial characteristics of the source of pollution on the surface (Van Beynen et al. 2012, Machiwal et al. 2018).

Due to the complex nature (dynamic or static) of natural factors, and depending on the scope and availability of data, the scale of the analysed area, the degree of recognition of the geological, hydrogeological and ecological conditions and the individual approach to the problem being solved, the assessment of groundwater vulnerability to pollution can be carried out using many methods. Researchers can use, inter alia, estimation and statistical methods, parametric and rank assessments, methods of numerical and hydrogeochemical modelling, as well as markers methods (Aller et al. 1987; Foster 1987; Van Stempvoort et al. 1993; Civita 1994; Civita and De Regibus 1995; Daly et al. 2002; von Hoeyer and Soffner 1998; Doerfliger et al. 1990). Noteworthy are the methods that take a measurable criterion as the basis, can be described qualitatively, for example, based on the time of migration of impurities from the surface to the aquifer, the thickness of the aquifers or the size of the adopted hydrochemical indicators (Krogulec 2004; Duda et al. 2011).

The most popular method for assessing groundwater vulnerability to pollution is the DRASTIC method (Aller et al. 1987) developed by the US Environmental Protection Agency. This method is based on the assumption that the potential threat from the ground surface for groundwater is conservative impurities, i.e. of a permanent nature, which move linearly at the velocity of groundwater in the pore centre. Depending on the variability of the water–ground medium and the degree of environmental transformation as a result of human activity, this method has been (and still is) subject to numerous modifications. Most often, these changes consist of adjusting the range of parameters taken into account in the vulnerability assessment by eliminating or verifying the existing components of the assessment or implementing new factors such as:

- the degree and manner of land development (Secunda et al. 1998),
- the impacts of pesticides, nitrates and chlorides (Javadi et al. 2011; Neshat et al. 2014),
- the thickness of the aquifer and the rate of groundwater flow (Witkowski et al. 2003).

Modification of methods of groundwater vulnerability to pollution assessment in terms of the adopted ranks, weights and parameters should be treated with special care in the area of overlapping influences from underground exploitation. In such areas, due to the significant transformation of the natural environment, the methods of assessing the groundwater vulnerability to pollution of a simple structure are not applicable. The impact of underground mining (including, for example, hard coal mining) is most often manifested in the formation of continuous and discontinuous deformations in the rock mass, which changes the hydrogeological properties of the overburden (Sciagala and Szafulera 2020). So far, for such areas, the well-known methods of GVP assessment have not been widely used. The few assessments carried out so far required modification of the methods by taking into account additional parameters. In the area of underground mining of gold deposits in Nicaragua, in order to assess the groundwater vulnerability to pollution in the conditions of a fissured rock mass, it was necessary to analyse the additional degree of rock mass fracture (Mendoza and Barden 2006) by taking into account the length, density and degree of communication of the fractures. On the other hand, within the Upper Silesian Coal Basin in Poland, in the conditions of the existence of active and closed hard coal mines, it turned out to be optimal to take into account the amount of water ascension, the rate of flooding of the mines, the difference in piezometric pressure (Bukowski et al. 2006), the thickness of the insulating layers and the degree of their deformation (Góra and Szczepański 2009) and the intensity of the exploitation impacts on the ground surface and the surface of the aquifer bottom (Góra and Szczepański 2009; Góra 2011, 2012). All these factors, in the conditions of the simultaneous coexistence of underground mining with opencast mining in a given area, may result in the formation of privileged migration routes for groundwater pollutants from the surface or from materials stored in the opencast (Rowe and Osore 2013). The scale and extent of the impact of an opencast mine reclaimed by backfilling (e.g. with waste rock) depends primarily on the local hydrogeological conditions and the amount and type of stored material, as well as on the used waste storage technology. Thus, loosen of the rock mass as
a result of underground mining activities may expose the deeper aquifers to pollution from the overburden.

For the areas of sub-level waste collection in opencast, the commonly known standard methods of assessing the groundwater vulnerability to pollution for conservative substances have not been used so far. This is due to the fact that the wastes deposited in the pit are at least partially under the influence of groundwater, which is in contradiction with the main assumption of the ranking methods on the location of the pollutant emitter on the surface (Niedbalska et al. 2016). Such a phenomenon may occur both in the conditions of complete liquidation of the open pit and in the case of its partial reclamation simultaneously with the exploitation of the deposit, when the mine drainage system is still maintained (Johnson and Carroll 2007). An example of such a facility in Poland is the CTL Maczki-Bór S.A. backfilling sand mine, reclaimed in exploited parts with Carboniferous waste rock. On the example of this testing ground, the author of the article modified the method of GVP assessment DRASTC in terms of the analysed parameters and the assigned ranks and weights. Particular emphasis was placed on the analysis of the expected changes in the filtration properties of the material used in reclamation in spatial terms, mainly as a function of depth, as a result of the vertical pressure of the overlying rock masses. Based on the results of hydrodynamic modelling, the range and thickness of the aeration and saturation zones, as key parameters determining the value of the groundwater vulnerability to pollution index, were distinguished. Statistical (factor) analysis was performed to assess the correctness of the adopted ranks and weights of individual parameters.

**Characteristics of the research object**

Modification of the groundwater vulnerability assessment method was carried out for an open-pit mine exploiting Quaternary filling sand, located at the fork of two rivers, in southern Poland. Exploitation has been carried out there continuously since the 1950s. Simultaneously with the mining of a deposit, the excavation is being reclaimed by filling it with Carboniferous gangue from hard coal mines. The original boundaries of the mine excavation covered an area of 7.79 km², of which 65% was the western mining field and 35% the eastern field. Currently, residual exploitation and major reclamation works are carried out within three mining areas with a total area of 3.25 km² (Fig. 1).

The Quaternary aquifer is fed by direct infiltration from precipitation due to the favourable conditions (mainly due to the presence of sandy formations with good permeability in the aeration zone), slight slopes and mining drainage. For a given area, the main drainage base is a network of slope ditches and collecting channels, draining water from the pit and dump to the mine sump, in which the water table is maintained at an ordinate of 222.0 m asl. Many years of mining activity and drainage of the sand deposit have contributed to the lowering of the groundwater table by nearly 27 m compared to the original state and the formation of an extensive cone of depression. Currently, as the upper layer of sand has been depleted, the Quaternary aquifer within

![Fig. 1 Map of the location of the mine drainage network, groundwater monitoring and excavation development status](image-url)
the mine boundaries is only a partly watered layer of sands located close to the Pleistocene floor (Fig. 2).

Sand exploitation and reclamation of the open pit are conducted simultaneously and completely independently in a three-shift system within both mining fields. Reclamation works began in the mid-1970s within the western mining field. The original direction of reclamation of this area of the mine was to create a forest complex on its surface. Currently, this area is intended for investment purposes (Fig. 1). The reclamation of the eastern field has been carried out since 2004. Currently, the reclamation covers an area of approximately 1.90 km². Ultimately, open-pit excavations are to be completely filled with post-mining material (mainly Carboniferous wastes rocks like mudstones, claystones and sandstones), until the original elevation of the land surface is restored and forest areas are created there in the succession process.

Based on the adopted project of reclamation, the open pit in both mining fields is filled with coal mining wastes and also with wastes from the energy sector (e.g. fly ashes). The wastes collected in the open pit are gangues from all Carboniferous lithostratigraphic series, characterized by different granulometric and petrographic composition. The waste dump is dominated by mudstones, claystones and sandstones characteristic for Carboniferous rock mass of the Upper Silesian Coal Basin in Poland. Clay minerals, feldspar and quartz are the dominant components. Pyrite, siderite, dolomite and calcite are less common (Bieczek 2007). The material stored in the pit is susceptible to intensive weathering processes and washing with rainwater and groundwater. These processes favour the emission of a large load of salt (mainly chloride and sulphate ions) to the soil and water environment (Różkowski et. all 2017). To reduce the risk of spontaneous combustion of wastes, fire prevention technologies are used. These methods consist in sealing the post-mining waste dump with power plant wastes in the form of slags and ash–slag mixtures (Rzepecki et. all 2021). Pursuant to the provisions of Polish law, all wastes used are non-hazardous wastes. Before accepting waste for use in reclamation, the entrepreneur managing the open pit requires suppliers to provide information on their physicochemical properties.

**Data for the assessment of groundwater vulnerability**

The method developed and used on the testing ground was based on a simple calculation algorithm that is a combination of ranks and weights.

The reliability of assessment of groundwater vulnerability to pollution relay on the accuracy and degree of recognition of hydrogeological conditions in the area of the reclaimed open pit. The first stage of the research was a detailed recognition of hydrogeological conditions, supported by field and laboratory tests, model methods and GIS tools (Fig. 3).

All calculations were carried out in the MODFLOW environment using the available Tables of a calibrated numerical
model of the hydrogeological conditions of the open-pit region (the tables concerned topography, water table level, bottom of the excavation, rainwater infiltration indicator and filtration coefficient of deposited post-mining waste). The resulting maps of assessment of groundwater vulnerability to pollution were presented using GIS tools.

The numerical model of water circulation conditions in the open-pit area was implemented using Processing Modflow Pro ver. 7 (Zdechlik 2016). The calculations covered the area of 15.3 km², of which 7.79 km² was directly related to the open pit. The assessment of groundwater vulnerability to pollution was carried out for the reclaimed part of the open pit, i.e. for the area of 4.59 km² contained in 459 calculation blocks with dimensions of 100 × 100 m.

The confirmation of the correctness of the adopted hydrogeological schematization as well as the boundary conditions and the values applied for individual parameters is the piezometric pressure distribution of the aquifer obtained with the model. For benchmark points, these values should show high convergence with the image of the actual filtration field, determined by direct field measurements. Calibration of the open-pit region model was carried out based on the monitoring of the groundwater table level in 13 piezometers (Fig. 4).

There is a linear relationship with high correlation between the ordinates of the groundwater table measured at benchmark points and the filtration conditions obtained with the model. An additional calibration criterion is the amount of calculated error, which constitutes a quantitative measure of the correctness of changes introduced to the model. One quantitative measure is the mean square error, which for the indicated piezometers is 0.96 m of the average difference between the actual water table level and the ordinate of the groundwater table obtained on a calibrated model.
The biggest uncertainty as to the reliable mapping of processes inside the dump refers to the internal conditions assumed in the model, representing the filtration parameters of the rock material deposited in the open pit. At dumps of post-mining wastes, it is extremely difficult to determine the change in permeability of these materials due to the time and depth of their storage. Generally, overfilling of wastes causes grain disintegration of the lower deposited material (Gwoździewicz 2012), which also is compounded by their mechanical compaction to a compaction index of at least 0.95 (Bieczek 2007). The method developed at the Central Mining Institute in Poland can be used to determine changes in the filtration properties of materials deposited in an open-pit excavation as a function of depth. It was originally created for the purposes of determining changes in the permeability of the backfill material used in mine shaft decommissioning (Bromek and Bukowski 2002; Bukowski 2010) using a variable gradient test model. To provide a full picture of changes in the filtration coefficient inside the dump, samples from its top were taken. The test consisted of cyclic flooding and draining of a material weighing approximately 12 kg placed in a cylinder with a perforated bottom, preventing lateral expansion of the sample during its compression on a test press.

The tests were carried out in the pressure range from 0.0 to 1.0 MPa for 5 samples of materials varied due to the time of their storage in the open pit. During the test, the samples and the cylinder were immersed in a tank, which was then filled with water. Slow submergence (flooding) of the material from below caused deaeration of the samples. This process was repeated in each subsequent measurement cycle, after the test material was compressed. For all pressure values assumed in the tests, after total flooding the sample, the determination of the falling time of the water level was carried out for the assumed heights of the water column units.

The conducted tests showed a significant differentiation of the filtration coefficient value together with the time of post-mining waste storage and the depth of their deposition modelled on the laboratory scale (by exerting vertical pressure on the sample surface). The oldest wastes, with storage time over 35 years, are characterized by the lowest permeability (Fig. 5).

Materials with the shortest storage time (up to half a year) are characterized by the best filtration parameters. Generally, according to common observations, the intensive processes

![Graph of changes in the value of the filtration coefficient for the longest deposited waste on the dumping ground as a function of depth](image)
of rock disintegration occurring on the surface and inside the dump are mainly caused by weathering in the aeration zone (Gwoździewicz 2012) and the impact of water and the weight of overburden in the saturation zone. In the vertical profile, for samples selected for laboratory tests, the filtration coefficient values range from 0.00004 to 10.4 m/d for the oldest waste and from 0.38 to 629.6 m/d for the shortest deposited wastes. In the calculation blocks, in the areas where samples were taken for laboratory determinations, both the aeration and saturation zones were assigned values that were weighted averages in relation to the thickness of individual zones differentiated in terms of their permeability. Ultimately, the values of the filtration coefficient adopted to the model are the resultant values obtained from laboratory tests and the values corrected during the calibration process of the numerical model.

Assessment of groundwater vulnerability to pollution using a modified method

The main criterion for selecting factors for assessing the vulnerability of groundwater to pollution was the analysis of the relationship between the dump and the groundwater table. In the proposed solution, one of the main assumptions is the impact of groundwater on at least the bottom part of the collected wastes. At the considered training ground, such a situation was forced by a functioning mine drainage system, and this condition is met on the entire surface of the reclaimed open-pit excavation. The analyses carried out so far using the classic DRASTIC method (Niedbalska et al. 2016) and the first attempts at its modification (Niedbalska et al. 2017) enabled the final selection of optimal factors shaping the sensitivity of groundwater to the impact of anthropogenic pollution source. Finally, six main factors were selected and assigned appropriate weights due to the importance of their impact on groundwater vulnerability (2—the least importance, 6—the most important). Depending on the values of the individual factors, they were assigned numerical values in the range from 1 (for conditions significantly limiting migration of impurities) to 10 (for conditions favourable for migration).

The value of an index of the groundwater vulnerability to pollution for the purposes of this publication was named PGVPI (Pit Groundwater Vulnerability to Pollution Index), which is the sum of the product of the ranks and weights assigned to individual factors and is calculated in accordance with the following formula:

\[
PGVPI = \left[ T_{a(w)} \cdot T_{a(r)} \right] + \left[ T_{s(w)} \cdot T_{s(r)} \right] + \left[ R_{w} \cdot R_{r} \right] + \left[ M_{w} \cdot M_{r} \right] + \left[ P_{a(w)} \cdot P_{a(r)} \right] + \left[ P_{s(w)} \cdot P_{s(r)} \right]
\]

where

- \( T_a \) is the thickness of the waste in the aeration zone,
- \( T_s \) is the thickness of waste in the saturation zone,
- \( R \) is the aquifer recharge from precipitation,
- \( M \) is the terrain topography,
- \( P_a \) is the filtration coefficient of the formations building the aeration zone,
- \( P_s \) is the filtration coefficient of formations building the saturation zone.

(w), (r) are the lower indexes next to each of the discussed factors denoting, respectively, the weight and rank of the parameter.

\( T_a \)-The thickness of the wastes in the aeration zone is defined as the difference between the elevation of the land surface and the elevation of the water table for each calculation block in the numerical model, i.e. it corresponds to the depth to the groundwater table. \( T_s \) is the most accurately identified factor, which results from conducting long-term observations of groundwater levels in the monitoring network located throughout the analysed area. These tests allowed the determination of the average annual and seasonal fluctuations of the groundwater table, which were then verified by numerical simulations. In the area of the open pit reclaimed by gangue, there is a significant variation in depth to the groundwater table. This piezometric pressure system determines the functioning of the network of ditches and channels constituting the mine drainage system. The depth to the groundwater table within the post-mining waste dump ranges from several dozen centimetres (mainly on the outskirts of the reclaimed western field) to over 29.0 m in the region of the sump belonging to the mine’s main drainage system. The values of the thickness of the aeration zone were divided into 6 classes, which were assigned ranks from 3 to 10 (Table 1). On over 31.0% of the surface, the groundwater table is located at a depth from 7.0 m to 12.0 m. The smallest surface is occupied by calculation blocks in which the water table has been found to be up to 2.0 m deep below the surface (6.0%) and above 25.0 m (5.0%).

\( T_s \)-The thickness of the wastes in the saturation zone was determined as the difference between the ordinate of the groundwater table in each calculation block and the ordinate of the bottom of reclaimed pit excavation. The table of morphology of the bottom of the pit was reconstructed on the basis of geological data from boreholes and archival cartographic data, including situational and height maps obtained from the entrepreneur. The thickness of the saturation zone in the area recovered by gangue ranges from 2.5 m (in the vicinity of the sump of mine drainage) to sporadically over 40.0 m. The values of wastes thickness in the saturation zone were divided into 6 classes with assigned ranks from 3 to 10 (Table 1). The area of the reclaimed part of the open pit is dominated by calculation blocks with a saturation zone thickness from 15.0 to 22.0 m and from 22.0 to 30.0 m, which occupy 34% and 29% of the area, respectively.
The smallest surface (less than 1%) is occupied by calculation blocks in which the saturation zone thickness was found below 4.0 m.

R–aquifer recharge from precipitation was determined on the basis of the average rainfall for many years (20 years) and the assessment of the diversity of the materials forming the surface and slopes of the dump due to the time of their storage in the open pit and the lithological type of rocks. The amount of recharge was determined from the formula 

\[ I_E = P \cdot \eta \]

where \( P \) corresponds to the amount of precipitation (m/d) and \( \eta \) is the effective infiltration index depending on the type of collected wastes. Field studies conducted on various parts of the open pit have shown that the average value of infiltration recharge for the average rainfall for many years in this area ranges from 0.00023 to 0.00029 m/d. Six classes of possible aquifer recharge from precipitation were identified, and ranks from 1 to 10 were assigned (Table 1). Based on this division, two zones of differentiated infiltration recharge were found within the dumping area, with a recharge of 0.00023 m/d dominating on a large area (approximately 89%).

M–topography of the land surface was determined on the basis of digital data (digital terrain model), with EUDEM v.1.0. Being a hybrid product based on SRTM data (radar methods) and ASTER GDEM (radiometric methods). Moreover, the terrain elevation was verified on the basis of altitude data from current mine situational–altitude maps. The vast majority of both mining fields is relatively flat (up

| Factor/parameter | Parameter value | Rank | Weight |
|------------------|-----------------|------|--------|
| \( T_a \) waste thickness in the aeration zone [m] | 0.0 ÷ 2.0 | 3 | 5 |
| | 2.0 ÷ 7.0 | 5 | |
| | 7.0 ÷ 13.0 | 7 | |
| | 13.0 ÷ 18.0 | 8 | |
| | 18.0 ÷ 25.0 | 9 | |
| | > 25.0 | 10 | |
| \( T_s \) waste thickness in the saturation zone [m] | 0.0 ÷ 4.0 | 3 | 6 |
| | 4.0 ÷ 9.0 | 5 | |
| | 9.0 ÷ 15.0 | 6 | |
| | 15.0 ÷ 22.0 | 8 | |
| | 22.0 ÷ 30.0 | 9 | |
| | > 30.0 | 10 | |
| \( R \) infiltration recharge [m/d] | 0.0 ÷ 0.000000089 | 1 | 3 |
| | 0.000000089 ÷ 0.000000178 | 3 | |
| | 0.000000178 ÷ 0.000000267 | 5 | |
| | 0.000000267 ÷ 0.000000356 | 6 | |
| | 0.000000356 ÷ 0.000000445 | 8 | |
| | > 0.000000445 | 10 | |
| \( M \) land surface morphology [%] | 0.0 ÷ 2.0 | 10 | 2 |
| | 2.0 ÷ 6.0 | 9 | |
| | 6.0 ÷ 12.0 | 5 | |
| | 12.0 ÷ 18.0 | 3 | |
| | > 18.0 | 1 | |
| \( P_a \) aeration zone filtration coefficient [m/d] | 0.0 ÷ 0.000000001 | 1 | 5 |
| | 0.000000001 ÷ 0.000000001 | 2 | |
| | 0.0000001 ÷ 0.000000001 | 4 | |
| | 0.000001 ÷ 0.0000001 | 6 | |
| | 0.001 ÷ 0.0001 | 8 | |
| | > 0.1 | 10 | |
| \( P_s \) saturation zone filtration coefficient [m/d] | 0.0 ÷ 0.00009 | 1 | 6 |
| | 0.000009 ÷ 0.0009 | 2 | |
| | 0.009 ÷ 0.9 | 4 | |
| | 0.9 ÷ 9.0 | 6 | |
| | 9.0 ÷ 90.0 | 8 | |
| | > 90.0 | 10 | |
to 2% incline—approximately 72% of the area, and from 2 to 6%—approximately 19% of the area), which results from the implementation of open-pit reclamation plans assuming restoration of the original elevation of the area. However, significant land levelling occurs in the areas of steep slopes of the excavation (the remaining 9% of the area). Declines in the area vary from 0% to over 64%. For the purpose of determining groundwater vulnerability to pollution in the area under consideration, five classes of land slopes were distinguished and assigned ranks from 1 to 10 (Table 1).

Pw–The groundwater in the aeration zone flows due to the effects of gravity, i.e. it is occur under the liquid’s own weight. This phenomenon relates to infiltration waters originating from atmospheric precipitation. The filtration properties of the soil–rock medium in the zone of incomplete water saturation were determined on the basis of laboratory tests (described in the previous chapter) and verified on a numerical model. In the reclaimed open pit, aeration zone deposits are characterized by a variable filtration rate depending on the type of rock formations and the time of their storage, and they range from approximately 0.07 m/d to sporadically above 65 m/d. The values of the filtration coefficient of the material building the zone of incomplete water saturation were divided into 6 classes according to the functioning division of the vertical filtration of loose formations (Gawicz 1983, vide: Witczak, Adamczyk 1994) and the ranks assigned to them varied from 1 to 10 (Table 1). Of all the computational blocks, nearly 73% of them were assigned the highest rank, which is because, according to observations and literature data (Gawicz 1983), in the case of vertical water filtration, it is a value of filtration coefficient already above 0.1 m/d that allows to classify the soil–rock material to formations with very high permeability.

Pw–In the case of analysis of the values of horizontal filtration coefficients, occurring in the zone of full water saturation, 6 class intervals were adopted in accordance with the commonly used classification of soil and rock permeability (Pazdro and Kozerski 1990), and they were assigned ranks from 1 to 10 (Table 1). In the reclaimed open-pit area, the average values of the horizontal filtration coefficient range from 0.05 m/d to approximately 55 m/d. The largest area (65%) is occupied by blocks with filtration coefficient values between 0.9 and 9.0 m/d. The presence of post-mining waste was found on only 1% of the land surface, whose horizontal filtration coefficients range between 0.09 and 0.9 m/d.

For the proposed method of ranking groundwater vulnerability to pollution in the areas of reclaimed open pit, the achievable index range is from 49 to 270. The calculations showed that the actual PGVPI index values are from 156 to 237. Because the authors of the first rank method of assessing the groundwater vulnerability to pollution (Aller et al. 1987) did not impose strict class ranges, the author also adopted the limit values of the ranges subjectively and intuitively in the newly developed method. To indicate the scale of the impact of materials used in reclamation on the groundwater environment, 5 classes were separated, in accordance with the division presented in Table 2. According to the classical division used in the DRASTIC method (Niedbalska et al. 2016), underground waters throughout the reclaimed open-pit area are characterized by high vulnerability. The proposed five-grade classification of waters with high vulnerability to pollution will therefore allow the indication of those areas that first require special care and intensive corrective and preventive actions.

Variable values of PGVPI, obtained by calculations, indicate that the area of reclaimed open pit is characterized by high (III class) and very high (IV class) groundwater vulnerability to pollution (Figs. 6 and 7). On the discussed area, zone with very high groundwater vulnerability to pollution dominates, and it covers 63.6% (2.92 km²) of the total area. Such water vulnerability was found in both mining fields. Within the western field where the oldest waste is stored, very high water vulnerability occurs in its central and southern parts. In these regions, the saturation zone within the waste is particularly thick. Within the western exploited field, a very high vulnerability class occurs mainly in its northern part, i.e. in the area with high filtration parameters of the aquifer.

| Table 2 | Division into grades due to the value of the groundwater vulnerability index in the area of direct contact of post-mining wastes with groundwater |
| --- | --- | --- |
| PGVPI ≤ 100 | I | Moderately high |
| 100 < PGVPI ≤ 150 | II | Medium high |
| 150 < PGVPI ≤ 200 | III | High |
| 200 < PGVPI ≤ 250 | IV | Very high |
| PGVPI > 250 | V | Extremely high |

Fig. 6 Percentage of individual classes of groundwater vulnerability to pollution in the reclaimed part of the open pit.
Sensitivity analysis

The proposed method of assessing the groundwater vulnerability to pollution is a subjective method, which results from intuitive attribution of ranks and weights to individual factors. One of the ways to assess and verify the impact of spatial diversity of the distribution of individual parameters on the result of calculations is sensitivity analysis (Napolitano and Fabbri 1996; Gogu and Dassargues 2000; Al-Admat et al. 2003; Babiker et al. 2005; Mohammadi et al. 2009). The single-parameter method provides information on the strength of the impact of each parameter on the final result, i.e. the value of the index of groundwater vulnerability to pollution. In this method, the theoretical weight values are compared with the effective weight values according to the following formula (Panapagopulos et al. 2006; Farjad et al. 2012):

\[ W = \frac{P_r \cdot P_w}{V} \cdot 100 \]

where \( W \) is the effective parameter weight, \( P_r \) is the parameter weight, \( P_w \) is the parameter rank, and \( V \) is the PGVPI index value.

Calculations were carried out for each parameter in all calculation blocks. Effective parameter weights show some deviation from the theoretical weights. Table 3 summarizes

| Parameter | Theoretical weight | Theoretical weight [%] | Effective weight mean | Effective weight minimum | Effective weight maximum | standard deviation |
|-----------|--------------------|------------------------|----------------------|-------------------------|-------------------------|-------------------|
| \( T_a \) | 5                  | 18.52                  | 4.72                 | 17.48                   | 7.65                    | 27.32             | 3.99             |
| \( T_i \) | 6                  | 22.22                  | 6.07                 | 22.49                   | 10.53                   | 31.25             | 3.70             |
| \( R \)  | 3                  | 11.11                  | 2.04                 | 7.56                    | 5.00                    | 10.06             | 0.77             |
| \( M \)  | 2                  | 7.41                   | 2.44                 | 9.02                    | 0.96                    | 12.82             | 1.92             |
| \( P_a \) | 5                  | 18.52                  | 6.38                 | 23.61                   | 18.52                   | 27.93             | 1.59             |
| \( P_s \) | 6                  | 22.22                  | 5.36                 | 19.84                   | 12.37                   | 30.77             | 3.27             |
| total    | 27                 | 100.00                 | 27.00                | 100.00                  |                         |                   |                  |
the statistical data for the sensitivity analysis in the variant of the sensitivity of one parameter.

Calculations show that the theoretical and effective weights of thickness of the saturation zone are very similar. The theoretical weights defining the strength of the terrain surface impact (M) and the values of the aeration zone filtration coefficients (Pa) were underestimated by approximately 22% and 27.5%, respectively. In the case of other factors, they were initially assigned too much importance, increasing the value of theoretical relative to effective weights by 5.6% (in the case of aeration zone thickness–Ta), 10.7% (for the saturation zone filtration coefficient–Ps) and by 32% (in relation to aquifer recharge–R).

The procedure of assessing the groundwater vulnerability to pollution was repeated, and distribution of Pit Groundwater Vulnerability to Pollution Index for Effective Weights was presented (PGVPIef) (Fig. 8). The results of the calculations indicate that the values of the vulnerability index are in the range from 160.89 to 243.11, so they are in class III (high) and IV (very high). The average PGVPIef value using effective weights was 209.45 and increased by 3.16% relative to the average value obtained for theoretical weights (202.82).

The adoption of effective weights increased the area assigned to the very high vulnerability class by 19.5%. Changes in the spatial image of the distribution of the PGVPIef vulnerability index are particularly noticeable in the southern part of the western exploited field and in the central part of the eastern field. The largest differences between the vulnerability index for theoretical and effective weights (up to 5.5%) were observed in the southern and western parts of the western field, in the place where the particularly thick saturation zone is located. The smallest changes or lack of it occur were found in the western parts of this field (Fig. 9).

Basic statistical analysis was performed for all factors influencing groundwater vulnerability to pollution (Table 4). Calculations were done for the evaluation results of vulnerability assessment with theoretical weights and for the sensitivity analysis for the variant of sensitivity of one parameter (Table 5). Data for all computational blocks covering the area of reclaimed open pit were analysed.

The assessment of groundwater vulnerability to pollution, although complicated and multifactorial, is reflected in the correlation of the selected parameters with the obtained spatial distribution of PGVPI and PGVPIef (Table 6).

The highest correlation with the PGVPI and PGVPIef was obtained for the thickness of waste in the saturation zone and for the filtration parameters of this medium. This result indicates the correct attribution of the largest theoretical weights to these factors. In the case of waste thickness of the aeration zone and permeability of this material, correlation coefficients are similar.

The lowest correlation with the PGVPI and PGVPIef among all factors was obtained for effective infiltration and land surface morphology. This result proves that the parameters are given the lowest theoretical and effective weights.

**Fig. 8** Spatial distribution of the PGVPIef using effective weights
Conclusions

Sensitivity analysis of groundwater from a source of anthropogenic pollution was carried out using the rank-weight method developed for the needs of the facility constituting the testing ground. The hydrodynamic characteristics of the aquifer of the open-pit area based on the results of field, laboratory and model tests were the basis for recognizing its functioning principles. This made it possible to indicate the optimal range of factors conditioning the impact of collected post-mining waste on groundwater. Six parameters were selected and were assigned appropriate ranks and weights based on the results of laboratory and model tests, literature analysis as well as the author’s experience and intuition, thus differentiating the degree of influence of given factors on the vulnerability of groundwater to pollution. To assess and verify the correctness of the adopted weights, a sensitivity analysis was performed on the variant of sensitivity of one parameter. Calculations confirmed the general correctness of adopted theoretical weights. This analysis allowed the identification of key parameters affecting the sensitivity of the aquifer system to pollution in the conditions of rock material storage within the open-pit excavation. Objectively, among the most important parameters, the following were

| Parameter | Mean | Median | Standard deviation | Minimum | Maximum |
|-----------|------|--------|--------------------|---------|---------|
| \( T_a \) | 12.54 | 12.00  | 6.89               | 0.50    | 29.19   |
| \( T_s \) | 19.08 | 19.45  | 7.28               | 2.50    | 40.42   |
| \( R \)  | 0.000234 | 0.000229 | 1.68 \times 10^{-5} | 0.000229 | 0.00029 |
| \( M \)  | 5.26  | 1.47   | 1.02               | 0.00    | 64.00   |
| \( P_a \) | 9.42  | 6.97   | 8.93               | 0.07    | 65.00   |
| \( P_s \) | 8.70  | 6.60   | 7.15               | 0.05    | 55.00   |

Table 4 A list of selected statistical values for the parameters of the proposed method for assessing groundwater vulnerability to groundwater pollution in areas of reclaimed open pit

| Vulnerability assessment | Mean  | Median | Standard deviation | Minimum | Maximum |
|-------------------------|-------|--------|--------------------|---------|---------|
| PGVPI                   | 202.82| 206.00 | 14.60              | 156     | 237     |
| PGVPI\(_{ef}\)          | 209.45| 212.16 | 15.56              | 160.89  | 243.11  |

Table 5 List of selected statistical values of groundwater vulnerability to pollution assessment results for theoretical weights and weights subjected to sensitivity analysis in the variant of sensitivity of one parameter

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Fig. 9 percentage difference between the PGVPI calculated for theoretical and effective weights
Table 6  Pearson’s correlation coefficient for all selected parameters indicated in the method of assessing groundwater vulnerability to pollution

| Parameter                                      | PGVPI | PGVPIef |
|------------------------------------------------|-------|---------|
| Waste thickness in the aeration zone $T_a$ [m] | 0.33  | 0.29    |
| Waste thickness in the saturation zone $T_s$ [m]| 0.37  | 0.42    |
| Aquifer recharge (infiltration) $R$ [m/d]       | 0.12  | 0.14    |
| Land surface morphology $M$ [%]                 | 0.16  | 0.20    |
| Aeration zone filtration coefficient $P_a$ [m/d]| 0.33  | 0.28    |
| Saturation zone filtration coefficient $P_s$ [m/d]| 0.32  | 0.37    |

distinguished: the thickness of the aeration and saturation zone ($T_a$ and $T_s$) and the filtration coefficients of the formations constituting both these layers ($P_a$ and $P_s$). Topography of the land surface ($M$) and infiltration recharge ($R$) are less significant.

The values of the index of groundwater vulnerability to pollution, being the sum of the products of ranks and theoretical weights of all parameters in each calculation block of the numerical model, in the entire area subjected to reclamation range from 156 to 237. This allows the allocation of individual blocks to two out of five possible vulnerability classes. Class IV (very high) dominates, which occupies over 63% of the reclaimed part of the pit. The remaining area is in class III. The class proportions change when using effective weights—the share of the very high class increased by 19.5% at the expense of the high class. Due to the constant impact of groundwater on at least the bottom part of the wastes, it was assumed that these waters throughout the open pit are characterized by high vulnerability to pollution. Separation of additional levels from moderate to extreme high will allow taking corrective pre-emptive action throughout the entire period of reclamation. It will help also to indicate areas that require priority in the process of securing the soil and water environment in the open pit, i.e. those that should be the subject of particular concern of the facility’s owner.

The developed method may be particularly useful at the stage of selecting, e.g. a method of reducing the value of waste filtration properties or lowering piezometric pressures in the aquifer and in forecasting changes in groundwater vulnerability at each stage of reclamation, until restoring the original surface of the site. Its use should allow the selection of effective methods to protect the aquatic environment around the open pit. The system of such assessment should be selected individually, taking into account local hydrogeological and geological and mining conditions, the method of open-pit reclamation, land development, future purpose of the reclaimed areas, etc. Such analyses enable advance planning of repair works in order to minimize leaching of pollutants from the wastes. The parametric system for assessing the groundwater vulnerability to pollution can be an important tool in the management of groundwater in the area of reclaimed open-pit excavations and in the selection of preventive measures, as well as an element of ongoing assessment of the state of the aquatic environment.

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Data availability  The data mainly come from field and laboratory work performed by the author of the article and partly from materials received from the entrepreneur managing the open pit constituting the testing ground.

Code availability  The article was written using licenced Word software, with the support of licenced ArcGIS and Processing MODFLOW programs.

Declarations

Conflicts of interest  The author states that there is no conflict of interest.

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