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Technical Communication

Using the DRASTIC System to Assess the Vulnerability of Ground Water to Pollution in Mined Areas of the Upper Silesian Coal Basin

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Abstract. An attempt was made to use the U.S. EPA DRASTIC ranking system to assess the vulnerability of ground water in the Upper Silesian Coal Basin. Analysis of the various system components indicate that several DRASTIC factors would have to be modified to consider the effects of mining, subsidence, and ground water rebound.

Key words: DRASTIC; ground water; Poland

Introduction

The Upper Silesian Coal Basin (USCB) is Poland's most developed urban and industrialised area. It has been subjected to several hundred years of long and intense development. One of the more conspicuous effects of this anthropogenic activity has been the impact of coal mining on water resources and the use of these resources. Due to coal output reduction measures undertaken in Poland in the 1990s, the area adversely affected by active mining in the USCB is shrinking. However, the flooding of abandoned mine workings is becoming more and more important. From the viewpoint of protecting economically usable aquifers, the essential problem is pollution derived from subsidence-induced flow from the surface and contaminated mine water, which has become important as the water table has rebounded.

Subsidence that occurs above the closed mines and subsidence-induced swallow-hole events (e.g. Bromek et al. 2001; Kotyrba 2002) can cause land to become inundated and can induce ground water contamination as waters of differing quality infiltrate the aquifers. The cones of depression of the mines being closed are not very extensive, and so ground water tends to stabilise at an intermediate piezometric water level between the original water level and the average level of the overburden water-bearing strata resting on the Carboniferous rocks. This has already occurred in a few, shallow, physically disconnected old mines at the northern and northeastern margin of the USCB (Pałys and Różkowski 1965; Kleczkowski and Jaśkowski 1967; Bukowski 1991, 1995; Rogoż et al. 1995; Bukowski and Augustyniak 2005).

Since the end of the 1980s, a U.S. Environmental Protection Agency (EPA) system named DRASTIC has been increasingly used to evaluate pollution migration from the land surface to ground water. This system consider aspects of the geologic environment of the study area, such as: depth to ground water, head of infiltration water recharge, and characteristics of the strata within the aquifer, such as hydraulic conductivity, characteristics of the soil and water zone structure, and land slope assessment. The value ranges of the both the individual components of the system (including the assigned factor values) and the adjusting weighting factors have been demonstrated since the 1980's (Aller et al. 1987). In Poland, they were converted into metric units (Kajewski 2000), and adapted to assess ground water vulnerability to pollution in various environments (Kajewski 2001; Kowalczyk 2003; Witkowski et al. 2003).

Published information (Kajewski 2001; Witkowski et al. 2003) on using DRASTIC to assess ground water vulnerability to surface–related pollution can be obtained for areas not affected by mining. In compiling a Polish map of ground water vulnerability to contamination and in making methodical foundations for its compilation (Duda et al. 2003), we attempted to assign components of the DRASTIC system to aspects of the active and inactive USCB mine lease areas. This systemic modification had to consider both direct and indirect interactions between the mining operations and certain DRASTIC system components. Changes in mine water quality and the contamination of aquifers during the mine flooding process and water table rebound were key concerns. This paper assesses factors that have to be considered in implementing the DRASTIC system to the USCB mine lease areas.

The Relationship of Mining in the USCB to the Vulnerability of Ground Water

Impact of Various Phases of Mining

Underground mining operations, such as those carried out in Upper Silesia, can be associated with many socio-economic and environmental effects. From the viewpoint of assessing the vulnerability of ground water to pollution, the effects of mining on useful aquifers, particularly on those of Quaternary and Triassic strata, mainly depends on: local geological and hydrogeological conditions, the level of activity in a mine (whether a mine is active or closed, connected or unconnected, etc.), and the significance of the mine to the hydrogeologic region.

The presence of nearly 300 post-mining inundated areas adversely affected 8-10 km^2 over 31 mine lease areas (Sikorska-Maykowska 2001). Investigations (from 1985 to 1993) by the Central Mining Institute of this surface flooding show that the inundated areas and the first water-bearing horizon or aquifer can be endangered by various surface pollution sources. The enhanced vulnerability of ground water to contamination can only be defined in mining-affected regions after taking into account the hydrogeological conditions and changes in the water table with respect to the ground surface. In the USCB area, the relative rise in ground water and the disturbance of ground and surface water flow changes the rate of mineral dissolution and the extent of contamination.

In the closed USCB mines, the method and nature of mine closure affects ground water contamination. Ground water rebound leads to a ground water quality imbalance. Water from deeper water-bearing horizons and from shallow uncaptured strata of varying hydrochemical characteristics can change in quality and mix while flowing into and through the mine. Due to the long-term dewatering of the portion of a rock mass and the enlargement of the vadose zone during mining, undesirable, secondary chemical enrichment of infiltrating waters occurs. The ground water rebound in the mines being closed brings about dissolution and elution of mineral components. This process, tending towards a geochemical and hydrostatic equilibrium, endangers the quality of water-bearing strata in the overburden and Carboniferous aquifers, which otherwise could be economically utilised. This can affect all mines that drain overlying good-quality aquifers (due to dewatering boreholes, adits, dip-heading, shafts, drainage and testing galleries, faults, and fractures). The influence of post-mining disturbance demands that ground water vulnerability be assessed for most sites. The most important direct and indirect impacts of mining on ground and surface water systems are:

In active mines

Surface subsidence changes: land slope and hydraulic gradients in aquifers, intensity and direction of the run-off, and net recharge conditions;

Changes in water courses can include increases in ground water inflow, flow losses (infiltration), and erosion of riverbeds;

Changes in the surface and ground water catchment boundaries and changes in the base level of ground water drainage;

Relative changes in the water table, along with surface and ground water flow disturbances (various types of inundated areas); and

Surface transformation due to waste disposal and dumping can lead to soil and ground water contamination and water flow barrier development.

In active and closed mines

Ground water drainage can: dewater host rock and overburden aquifers, lower ground water levels, and deplete water resources; and

Mine water discharges can contaminate surface and ground water, including (sometimes) elevated levels of radiation.

In closed mines

Contamination of good quality, usable Carboniferous waters and those of younger water-bearing strata due to mine-water rebound in abandoned mine workings;

Ground surface endangered by flooding and inundated areas due to the cessation of mining and dewatering; and

Fracturing of consolidated younger, shallow multi-aquifer formations and water-bearing horizons due to discontinuous subsidence can change ground conditions to favour enhanced infiltration of surface water and precipitation.

The Relationship of Mines to Hydrogeological Regionalisation in the USCB

The effects of hydrogeological regionalisation in the USCB on the recharge of the carboniferous bed rocks, water dynamics, and geochemistry was considered (vide: Różkowski 1997, 2003) and improved. It is possible to distinguish three main and various strata systems situated above the Carboniferous formation: Quaternary strata (Figure 1 A), Quaternary and Triassic strata (Figure 1 A), and Quaternary and Tertiary strata (Figure 1 B).

Two systems with only locally occurring Middle and Upper Jurassic Carbonate and terrigenous rocks determine the superposition of aquifers in hydrologic sub-region I. A third system, with locally occurring Cretaceous and Tertiary Carpathion flysch formations, comprises hydrogeologic sub-region II, located in the

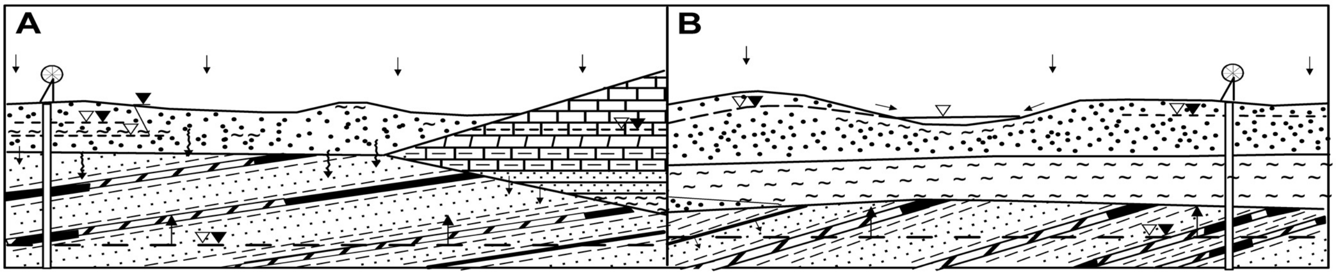

Figure 1. The main lithology structures situated on the roof of the Carboniferous strata in the USCB (main structures: A – outcropped, B – covered).

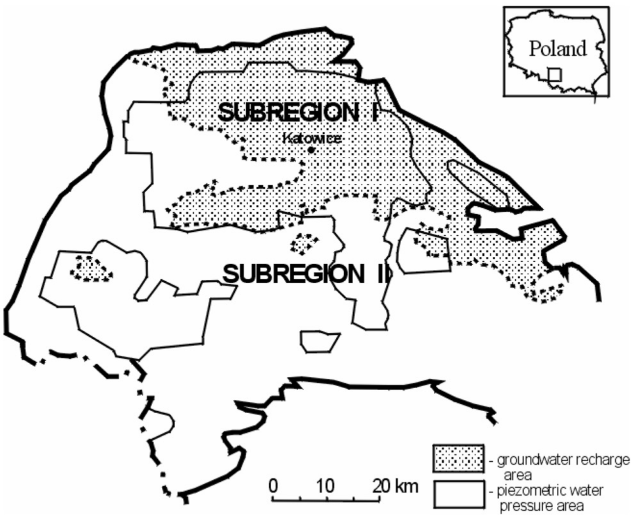

Figure 2. The hydrogeological sub-regions within the USCB area (Różkowski 2003)

southwestern part of the USCB (Figure 2) (Różkowski 2003).

Depending on the location of individual lithostratigraphic systems, two USCB Carboniferous rock masses can be distinguished:

- Hydrogeologically outcropped sediments of sub-region I;
- Hydrogeologically covered sediments of sub-region II and/or impervious Triassic sediments of sub-region I.

The post-glacial and alluvial Quaternary sediments from the hydrogeologically outcropped area constitute, in general, easy infiltration pathways for precipitation and surface water, and cause an increased water inflow rate into mine workings.

The carbonate and terrigenous Triassic sediments can contribute to mine flooding depending on the foot wall rock strata. The marine Tertiary (Baden) clays and claystones usually constitute an impervious barrier layer that can effectively reduce infiltration inflow of Tertiary and Quaternary formations waters as well as surface and precipitation water into the Carboniferous strata.

Of the total water inflow to the USCB mines (718,000 m^3/day):

- In the hydrogeologically, outcropped sub-region (38% of the mined area), infiltrating surface water accounts for about 57% of the total inflow;
- In the hydrogeologically, partly covered and partly outcropped sub-regions (30% of the mined area), infiltrating surface water accounts for about 32% of the total inflow;
- In the hydrogeologically covered sub-region (32% of the mined area), infiltrating surface water accounts for about 11% of the total inflow.

A reversed relationship can be observed between the mines situated in hydrogeologically outcropped and covered sub-regions with respect to the sum of Cl^- and SO_4^{2-} ions discharged by mines. The sum of Cl^- and SO_4^{2-} ions discharged in the hydrogeologically outcropped and covered sub-regions account, respectively, for about 20% and 27% of the total amount discharged over the entire USCB (Figure 3). Water flowing into mines in the hydrogeologically outcropped sub-regions are infiltrating mainly from the surface and from higher water horizons characterised by low mineralization, including some water drained from the static resources of Carboniferous strata. The inflow of slightly mineralised water (<1000 mg/dm^3; sum of the Cl^- and SO_4^{2-} ions content <600 mg/dm^3) amounts to about 21% of the total water inflow to the USCB coal mines; a total of about 31% of this relatively fresh water is being selectively pumped (hydrologic sub-region I in Figure 2) (Solik-Heliasz and Augustyniak 2003).

In contrast, in the hydrogeologically covered sub-regions, most of the inflow to the mines consists of highly mineralized Carboniferous water. This simple distinction in the hydrogeologic systems is often disturbed by mining, particularly longwall mining, and can also be disturbed by boreholes. Mining-induced fissures and fractures, particularly in the coal seam outcrop areas, can create hydraulic connections between goaf and overlying aquifers.

Adapting DRASTIC for Use in the USCB

The DRASTIC components, which together spell out the name of the system, have been converted into metric units (vide: Kajewski 2000):

Factor D (**D**epth to ground water – higher values indicate better ground water protection) – 1 to 10 points are assigned to seven gradations in the depth to ground water, six from 0 to 30 m, with the seventh being >30 m, with a recommended weighting factor of 3.

Factor R (Net **R**echarge – lower values indicate better ground water protection) – 1 to 9 points are assigned to five gradations in recharge, four from 0 to 250 mm/yr, with the fifth being >250 mm/yr, with a recommended weighting factor of 4.

Factor A (**A**quifer media – stronger, more massive, unfractured rocks improve ground water protection) – from 1 to 10 points are assigned, from massive shale and metamorphic/igneous rocks to sand, gravel and karstic limestone, with a recommended weighting factor of 4.

Factor S (**S**oil media – the less soil, the less ground water protection) – from 1 to 10 points are assigned to 11 categories, from non-shrinking and non-aggregated clay to sand, gravel, thin or absent soil media, with a recommended weighting factor of 3 – 5.

Factor T (**T**opography – higher values indicate better ground water protection) – from 1 to 10 points are assigned to five ranges in the inclination of the surface, with four from 0 to 18% and a fifth for inclination >18%, with a recommended weighting factor of 1 – 3.

Factor I (**I**mpact of the vadose zone – less permeable confining layers improve ground water protection) – from 1 to 10 points are assigned to 11 categories of media type, from silts, clay, and impermeable strata to permeable media such as sand, gravel, and karstic limestone, with a recommended weighting factor of 4 – 5.

Factor C (Hydraulic **C**onductivity – lower conductivity improves ground water protection) – from 1 to 10 points are assigned to six ranges, from $5 \cdot 10^{-5}$ cm/s to > $1 \cdot 10^{-1}$ cm/s, with a recommended weighting factor of 2 – 3.

The lower the number of points obtained from the general assessment balance, the lower the risk category, indicating less ground water vulnerability to pollution.

To use the DRASTIC system to assess ground water vulnerability to pollution over the USCB area, we had to determine which components of the system could be applied to underground mining, which components were not applicable, and which components had to be either adjusted or changed. We found that the majority of the DRASTIC components could not be directly used in mining area assessment operations.

Active Mines: Potential Pollution Sources at the Land Surface

The phase of a mine's life, including its location characteristics, and whether it is interconnected with other mines, affects the possibility and time of occurrence of a specific environmental impact. Thus, factors such as whether a mine is located in the hydrogeologically outcropped or covered sub-regions (sub-regions I and II) of the USCB has to be considered in any system of assessment of ground water vulnerability to pollution (Table 1).

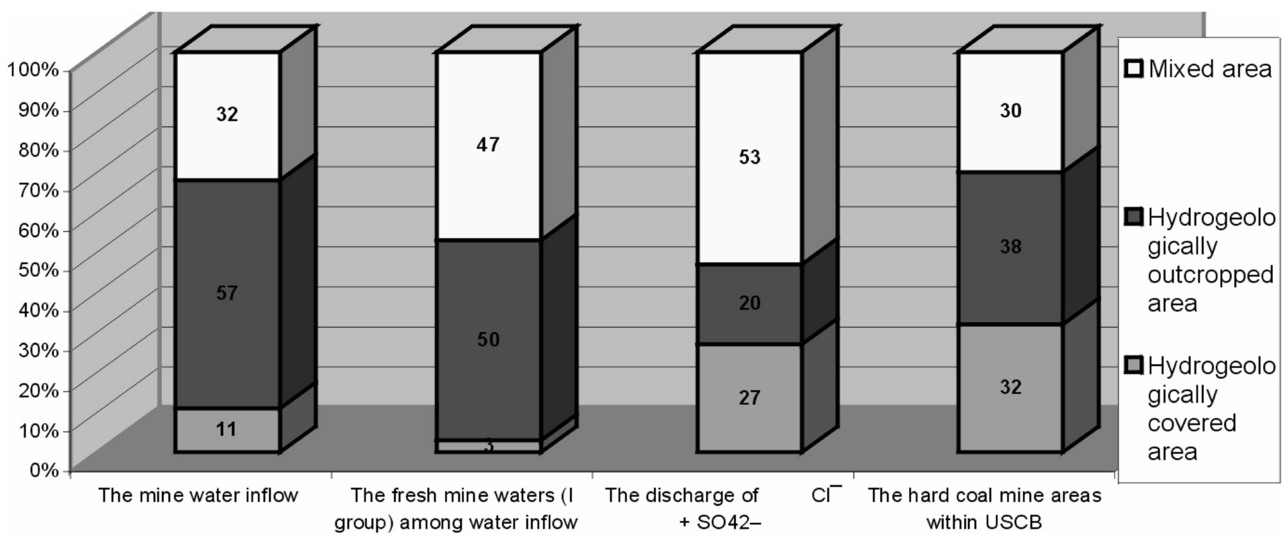

Figure 3. The relative proportions of surface water inflow and mine water discharges, and the area of land mined for coal in each of the hydrogeological sub-regions of the USCB

Table 1. How the DRASTIC system components have to be modified to reflect the influence of mining in the active hard coal mine lease areas of the Upper Silesian Coal Basin

<table>
<tr><th>Component</th><th>Hydrogeologically outcropped sub-region</th><th>Hydrogeologically covered sub-region</th></tr>
<tr><td>D</td><td>-Variable due to mining operations.
-Drainage of multi-aquifer horizons in overburden commonly leads to complete dewatering.
-Despite an increase in depth to ground water due to drainage, the overburden aquifers can be vulnerable to pollution owing to depletion of water resources and disturbance of flow of surface and ground water.
Modifications: corrections were made to the point ranges assigned to the factor and the weighting.</td><td>-Variable due to mining operations.
-Disturbances to surface and ground water flow are common.
Modification: corrections were made to the point ranges assigned to the factor and the weighting, depending on surface subsidence and relative changes in the water table, especially of the first water horizon.</td></tr>
<tr><td>R</td><td colspan="2">-Variable due to mining operations.
-Post-mine subsidence (horizontal strains of the compression and tension zones) can cause infiltration conditions to, zonally, either deteriorate or improve.
-Damage to hydrotechnical infrastructure and river-beds increase net recharge.
-Generally increases natural water infiltration.
Modification: For the Carboniferous strata overburden, corrections were made to the point ranges assigned to the factor and the weighting by taking into account differences in surface water flushing (run-off) conditions and discontinuous surface transformation. In the case of mine-water, the parameters were adjusted to account for the amount of water inflow into the mine workings.</td></tr>
<tr><td>A</td><td colspan="2">-Is not affected by mining operations.</td></tr>
<tr><td>S</td><td colspan="2">-Negligible impact of mining operations on the Carboniferous strata overburden.
-In host rocks, essential changes may be necessitated by mining-induced rock mass disturbance.
Modification: In the case of overburden strata and the first water horizon, modification of the point ranges and weighting values may be needed because of the secondary zones of compaction and rock fracturing. Depending on the behaviour of empty spaces in mine workings and in surrounding rock masses, the point ranges assigned to the factor and the weighting values may have to be adjusted.</td></tr>
<tr><td>T</td><td colspan="2">-Negligible impact of mining operations.
Modification: The point ranges and weighting values generally need modification only when subsidence significantly affects the original ground surface relief; such effects tend to be more significant in terrain that is less variable and generally flat-lying.</td></tr>
<tr><td>I</td><td>-Variable due to mining operations - it varies in accordance with the changes in parameter D, producing an increase in vadose zone thickness, up to the mine dewatering level.
Modification: Generally requires a change in approach, to consider the changes in water quality (e.g. the inorganic sulphur content in the deposit strata), and development of new parameter characteristics, including weighting and scoring ranges.</td><td>-Mining-induced changes due to changes in parameter D. Changes in thickness (mainly decreases) of the vadose zone for the first water horizon.
Modification: Is not required for overburden strata. The deposit strata should be treated the same as is done for the hydrologically outcropped sub-region.</td></tr>
<tr><td>C</td><td colspan="2">-Negligible impact of mining operations.
Modification: Changes are not generally needed for the Carboniferous strata overburden, except when the extent of fracturing significantly affects rock permeability.</td></tr>
</table>

"*-variable due to mining operations*" – The effect on the parameter is site-specific, and depends on factors such as the extent of mining and the site location; "*-Negligible impact of mining operations*" – Generally, mining does not affect this parameter can be regarded as constant or designed for a specific state of mining operations.

Closed Mines: Potential Pollution Sources at the Surface and from Mining Excavations

In closed mines, all of the Carboniferous rock strata that are affected by ground water rebound and mine flooding are potential pollution migration pathways. As ground water rebounds into the mines, it is both vulnerable to pollution and a potential pollution source, creating hazards for younger multi-aquifer horizons and the surface. More than pyrite oxidation products (Frost 1979; Posyłek 1998; Younger 1998; Wood et al. 1999; Pluta 2000; Razowska 2001) and radioactive substances contaminate mine waters; other potential mining-related pollutants include the various waste materials used to fill post-mine voids and various biological and petroleum contaminants. Table 2 captures changes to DRASTIC that would be required to account for such considerations.

Conclusions

The conventional approach to assessing vulnerability of ground water to pollution reflects the properties of the water-bearing system, and defines the risk of

Table 2. How the DRASTIC system components have to be modified to reflect the influence of mining in the closed coal mines of the Upper Silesian Coal Basin

<table>
<tr><th>Component</th><th>Hydrogeologically outcropped sub-region</th><th>Hydrogeologically covered sub-region</th></tr>
<tr><td>D</td><td>-In the overburden and in deposit rocks, the need for modification varies with the mine flooding rate.
-Stable state for ground water in the overburden strata until the rebounding ground water completely recovers.
-Generally, this parameter can be used according to the EPA recommendations.
Modification: For mineralised and contaminated waters, this parameter should be considered in view of the distance to the overlying utilised aquifer or the ground surface. For mine-water reservoirs considered to be possible pollution sources, a change in approach is needed, including the development of another factor and its ranges and weights. It is advisable to take into account the time history of the ground water rebound process and the probability that it will endanger the surface.</td><td>- Stable state just as in the hydrogeologically outcropped sub-region.
-In the deposit strata, it varies with the mine flooding rate.
Modification: The mine-water reservoir is considered a pollution source for the deposit strata and poorly isolated overburden aquifers, and so a separate parameter must be developed to account for the high mine-water rebound rate, the presence of the vadose zone, and the ratio of the reservoir piezometric pressure to the endangered aquifer piezometric pressure.</td></tr>
<tr><td>R</td><td>-For the overburden strata, the factor can be used according to the EPA recommendations. Higher infiltration values should be taken into account in swallow-hole areas.
-In the deposit strata, the effect of the recharge depends on the mine flooding rate.
Modification: For the Carboniferous overburden, the scoring and weighting should be corrected to take into account the different surface water flushing (run-off) conditions and the effects of surface changes. For the mine waters, the component expansion or variation should take into account the water inflow into the mine.</td><td>- For the overburden strata, the factor can be used according to the EPA recommendations once the environmental transformations have been taken into account.
-In the deposit strata, the effect of recharge depends on the mine flooding rate.
Modification: The parameter requires a change and a different approach that could take water inflow into account.</td></tr>
<tr><td>A</td><td colspan="2">-Constant, it does not depend on the mine closure process.</td></tr>
<tr><td>S</td><td colspan="2">- For the overburden strata, the factor can be used according to the EPA recommendations after surface effects, such as swallow holes, erosion, ground compaction, and fracturing have been taken into account.
Modification: New ranges and weights and a separate component are needed for the deposit strata because the rock masses are disturbed (behaviour of the mine voids and adjacent rock masses) and overlying aquifers can be affected.</td></tr>
<tr><td>T</td><td colspan="2">-Constant, after the mining impact has stopped.</td></tr>
<tr><td>I</td><td>-In the deposit rock formation and in the overburden, it varies with the mine flooding rate.
Modification: It is necessary to consider the impact of weathering and dissolution of pyrite oxidation products, as well as the progress of mine flooding and the decrease in vadose zone thickness.</td><td>It can be applied to the first water horizon of the Carboniferous overburden once the mining impact ceases, according to EPA recommendations.
Modification: It is necessary to consider the impact of weathering and dissolution of pyrite oxidation products, as well as the progress of mine flooding and the decrease in vadose zone thickness.</td></tr>
<tr><td>C</td><td>-It varies with the changes in depth and the post-mine rock deformations.
Modification: One should consider the consequences of mining on the rock mass filtration parameters. A new component and new ranges and weights are needed.</td><td>-It is constant for the overburden, following the mining impact cessation and the factor and weight values verification.
-In the deposit strata, it varies in dependence on the extent of rock mass deformation.
Modification: For the deposit strata, it is just as in the hydrogeologically outcropped sub-region.</td></tr>
</table>

- In the case of a description involving the parameter variability, its evaluation depends on the state of the flooding process or for the projected level where ground water rebound will stabilize.

contaminant migration from the ground surface to the first water horizon; it does not normally consider the potential impact of underground mining. Mining disturbs natural properties of water-bearing systems and can be a source of underground pollution. In addition, mine workings can drain aquifers and facilitate pollutant migration from the ground surface deep into the rock mass; closed mines can also form storage reservoirs of polluted waters. Once dewatering is no longer causing a cone of depression, mines and surrounding rock strata refill, typically approximating the original hydrogeological conditions. This process can lead to the pollution of individual aquifers and even the ground surface.

In compiling a ground water vulnerability map for the underground mining areas of the USCB, the impact of mining and its influence on individual components of the DRASTIC system must be considered. The following factors, above all, need to be considered:

▪ ground surface subsidence and deformations and their impact on the original hydrogeological conditions,

▪ the location of a mine with respect to hydrogeological sub-regions, with the extent of barrier isolation between the Carboniferous strata and the overburden aquifers being taken into account,

▪ possible occurrences of discontinuous subsidence such as swallow-holes, chimney caves, fractures, etc.,

▪ a method for using good quality ground water from the deposit strata and the possibility of using waters from the Carboniferous water bearing horizon, and

▪ the time required to recreate stable hydrogeological conditions in the area of a mine being closed.

These factors directly influence the DRASTIC system components, causing fundamental changes in final results of the assessment of the ground water vulnerability to pollution. It follows from the characteristics of a relationship between the system component factors and the mining and mine closure impact factors that the DRASTIC system needs to be modified for overburden aquifers. In the case of water-bearing strata or aquifers lying within the deposit rock formation, a change in approach to the assessment of ground water vulnerability to pollution of the Upper Silesian Coal Basin area is necessary.

The practical application of the DRASTIC system was assessed to be impossible for abandoned mines. The different character of water pollution sources relative to those accepted in the DRASTIC system and the way in which water rebound in flooding mine workings affects water quality is too significant. Adaptation of the DRASTIC system to assessment of ground water vulnerability to pollution in flooding mines would require such major modifications that one would be practically creating an absolutely new system to take into account expected changes in rock mass, and the effect of the interaction of the contaminated and fresh waters above or in the neighbourhood of mine pools.

The DRASTIC system could be useful, especially for administrators, in areas where younger water-bearing strata are isolated from the Carboniferous strata in which mining has occurred. Mainly, this would be in hydrogeological sub-region II (Figures 1 and 2), where surface subsidence occurs, but water-bearing strata are not endangered by mining operations. DRASTIC could thus serve as a preliminary system to assess groundwater vulnerability to pollution at active mines. DRASTIC could be used to initially assess the result of mining on the overburden strata. The relation of each factor to such a situation and the prognosis of final changes of hydrogeological conditions and each DRASTIC component would then be re-examined as mining proceeded (and was completed) in an area.

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