Assessment of potential risk of groundwater contamination in areas subjected to the intensive mining drainage. Case study from Poland – Olkusz Zn-Pb ore mining region

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ABSTRACT
The intensive long lasting drainage carried out by Zn-Pb ore mines in the Olkusz region resulted in significant changes in hydrodynamic conditions and in groundwater quality of the Triassic main aquifer. This drainage has caused significant lowering of groundwater table up to over 120 m and has created thick anthropogenic unsaturated zone. Because of a great heterogeneity, reliable assessment of the potential load of pollutants originated in this zone is very difficult. Method of indirect assessment of a potential risk of groundwater contamination by pollutants (mainly sulphates) from anthropogenic unsaturated zone has been presented in this paper. Authors have assumed that the degree of a relative risk of groundwater contamination depends on two major factors: thickness of the unsaturated zone within the Triassic carbonate series (rocks hosted sulphides of metals) and a net recharge of the Triassic aquifer. Results have been presented on maps at the scale 1:25000. The point count system model has been applied for compilation of the risk map which final version was produced as a result of computer-based overlays of mentioned two factors maps. Five classes of relative risk of potential contamination were distinguished: very low, low, medium, high and very high (the higher index value, the largest risk). Proposed method of groundwater contamination risk assessment is reliable and was verified by groundwater quality.

INTRODUCTION
Karst-fissured Triassic aquifers are the most important and valuable source of potable water for Upper Silesia, the most urbanised and industrialised part of Poland. However, due to an extremely high negative human impact (Zn-Pb ores mine, industrial and communal landfills, and lack of sewerage network) deterioration of groundwater quality has been observed.

A serious problem with groundwater contamination mainly due to sulphates has been noticed in areas subjected to an intensive mining drainage. Recently problem of groundwater vulnerability and quality in such areas has been investigated within the framework of the project No 9T12B01116, financed by The Polish State Committee for Scientific Research (Witkowski and others 2001). Two Triassic carbonate aquifers called Olkusz-Zawiercie and Chrzanow were selected. Taking into account existing results of groundwater quality assessment as well as results of investigation of the isotopic data ($\delta^{34}S$ and $\delta^{18}O$) of sulphates shows that the processes of oxidation of sulphide minerals taking place in the extended unsaturated zone are the most significant endogenic factors causing groundwater contamination within both mentioned Triassic aquifers. Therefore assessment of a risk of groundwater contamination by contaminants originated in the athropogenic unsaturated zone is very important for areas of the regional cones of depression. This problem is particularly well visible in Olkusz Zn-Pb ore mining region which has been selected as a case study area for application of the proposed method of risk assessment.

HYDROGEOLOGICAL SETTING

The Olkusz Zn-Pb ore mining region belongs to the Silesian-Cracow Monocline built up of the Triassic and Jurassic formations discordantly overlying folded and faulted Palaeozoic basement. There are Quaternary, Jurassic, Triassic and Palaeozoic aquifers in the hydrogeological profile of the Olkusz area. Most important and resourceful is the Triassic karst-fissured carbonate aquifer (dolomites and limestones with marl interbeddings). Generally two water-bearing horizons can be differentiated within this aquifer: the Muschelkalk horizon and the Roethian one. These two horizons are often considered jointly as one aquifer (Różkowski ed. 1990). Considered Triassic aquifer is partly covered by clayey Rhaetian-Keuper sediments (Fig.1). Hydraulic structure of fissured and karstified Triassic rocks consists of three types of spaces: pores, fissures and caverns (Motyka 1998). Limestones represent fissured-cavernous type of the aquifer while dolomites represent porous-fissured-cavernous type (Motyka 1998). Fissures and karstic channels are favourable pathways of groundwater flow while the pore space is the main water reservoir. It resulted in a vertical and horizontal differentiation of rock permeability. The thickness of this aquifer reaches about 150m.

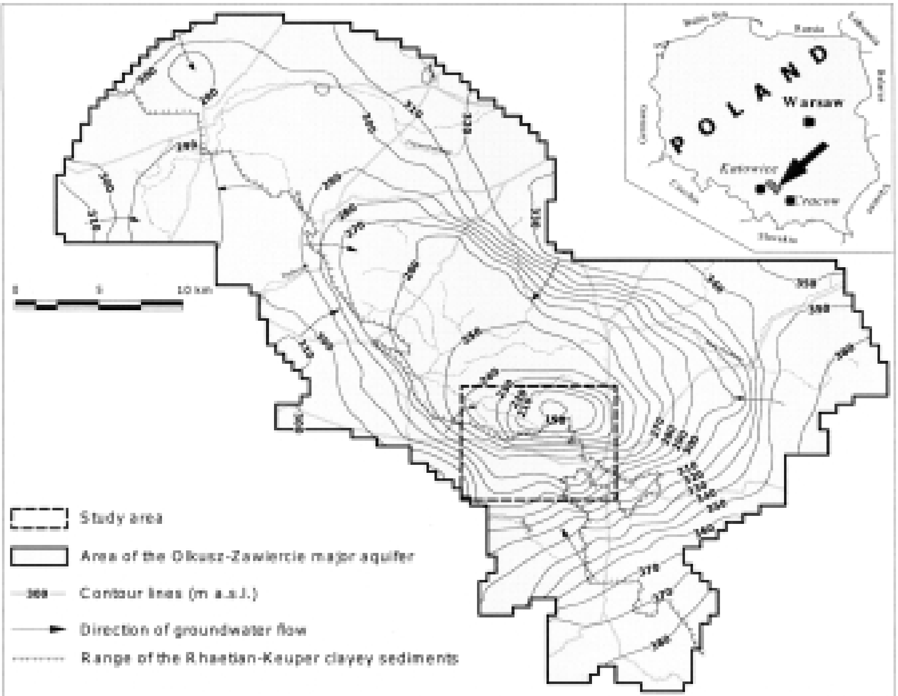

Figure1. Hydrogeological sketch of the Olkusz-Zawiercie Triassic major aquifer (according to Witkowski and others 2001)

Triassic aquifer is recharged directly in outcrop areas or indirectly through permeable Quaternary, Jurassic or Palaeozoic sediments. Other sources of recharge include water downward leakage from the shallow aquifers through poorly permeable Upper Triassic, Lower and Middle Jurassic sediments as well as water seepage from rivers, mainly from Biala Przemsza river (Motyka and Witkowski 2002).

In natural conditions, Triassic aquifer in Olkusz region was drained by springs and rivers. Currently this aquifer is intensively drained by Zn-Pb ores mines (“Bolesław” – abandoned at the end of 1996, “Olkusz” and “Pomorzany”) and numerous groundwater intakes (Fig.2). Long lasting drainage has caused lowering of groundwater table up to over 120 m and resulted in changes of flow directions, increase of hydraulic gradients and creation of the extensive regional cone of depression covering an area of about 470 km^2 (Fig.1). In this way a new extended unsaturated zone has been created. Thickness of this zone exceeds 100 m in the area of “Pomorzany” mine.

GROUNDWATER QUALITY

Considered region is subjected to a serious risk of groundwater contamination. Many sources of pollution (landfills, tailings dams) in this area as well as fluid wastes injection into the ground have led to significant contamination of groundwater in the shallow Quaternary aquifer. Negative changes in hydrodynamic conditions caused by intensive long lasting mining drainage have resulted in activation of many natural connections between aquifers. It has led to the contamination of the Triassic aquifer.

Additionally geochemical processes in the extended unsaturated zone have caused an increased contamination of the Triassic aquifer, reflected mainly in very high contents of sulphates (locally exceeding 5000 mg/dm^3) as well as iron (locally 90 mg/dm^3) and zinc (locally 40 mg/dm^3) (Motyka and Witkowski 2002). Before the intensive mining activity started, the average concentration of sulphates and zinc in groundwater of the Triassic aquifer was 37 mg/dm^3 and 0.52 mg/dm^3 respectively (Adamczyk and Wilk 1976).

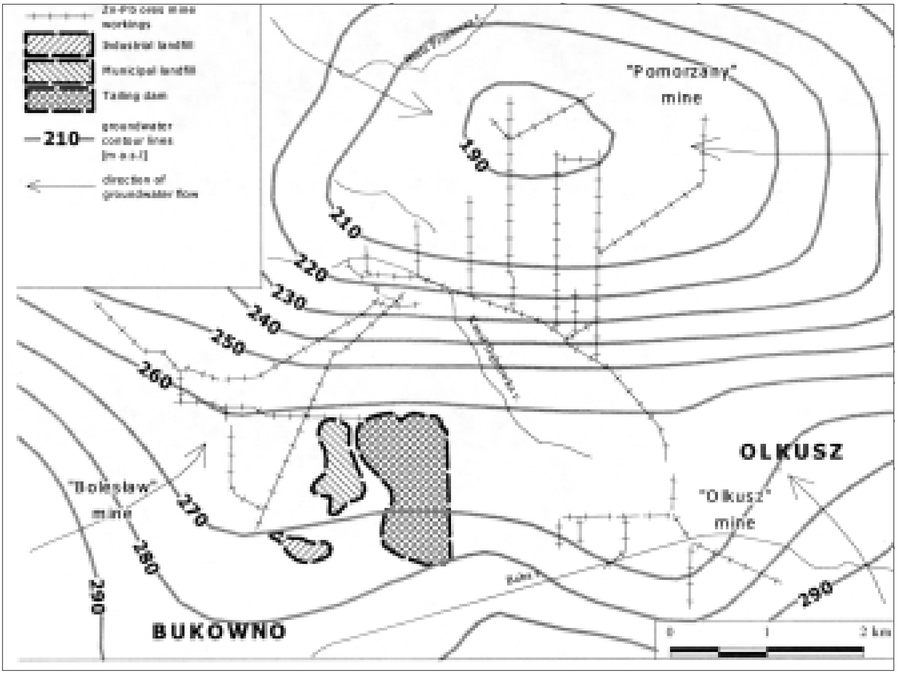

Figure 2. Groundwater contour map of the Triassic aquifer – Olkusz region

Analysis of groundwater quality in Olkusz area has been already presented by authors (Motyka and Witkowski 1999, 2002, Adamczyk and others 2000). Observed deterioration of groundwater quality in the considered area is a result of an overlapping negative impact of both endogenic and exogenic factors (Motyka and Witkowski 2000). Analysis of the spatial distribution of SO_4 concentrations in mine water (Fig.3), shows that the processes of oxidation of sulphides minerals taking place in the rocks are the most significant factors influencing these concentrations. Comparison of mentioned constituent concentrations to concentrations of NO_3 (Fig.4) shows an additional significant impact of local human sources of pollution (tailings dams, municipal and industrial landfill, injected lignosulfonates) on groundwater quality. Negative impact of the exogenic factors on groundwater is visible not only in very vulnerable, uncovered parts of the Triassic aquifer in the area of “Bolesław” mine but also in the area of “Pomorzany” mine in parts of local hydraulic contacts between Quaternary, Jurassic and Triassic aquifers (Motyka and Witkowski 2002).

CONCEPT OF POTENTIAL RISK OF GROUNDWATER CONTAMINATION ASSESSMENT

Due to intensive mining drainage a new extended anthropogenic unsaturated zone with thickness exceeding 100 m has been created. Amount of the potential and real load of contaminants originated in this zone depends on the quantity and type of sulphide minerals occurring there as well as on intensity and duration of oxidation processes. Evaluation of a potential load of contaminants (mainly sulphates) created in the new anthropogenic unsaturated zone is very difficult due to the zone's great heterogeneity. Results of the ion leaching laboratory tests show a very changeable leached load. In this situation authors propose an indirect method of assessment of a potential risk of groundwater contamination by contaminants (mainly sulphates) coming from the anthropogenic unsaturated zone. This can be used mainly for the areas of extensive cones of depression. A simplified model that has been applied to this evaluation assumes that the amount of potential contaminants created in this zone depends on its thickness whilst the real load of contaminants directed to groundwater depends also on quantity of water percolated through unsaturated zone. Authors have assumed that the degree of a relative risk of groundwater contamination depends on two major factors: thickness of the unsaturated zone within the Triassic carbonate series (rocks hosted sulphides of metals) and a net recharge of the Triassic aquifer (Fig. 5).

Assigned classes of relative risk of groundwater contamination have been presented on a map at the scale 1:25000. The proposed method was tested in Olkusz Zn-Pb ore mining region. The reliability of the risk map was verified based on an observed groundwater quality.

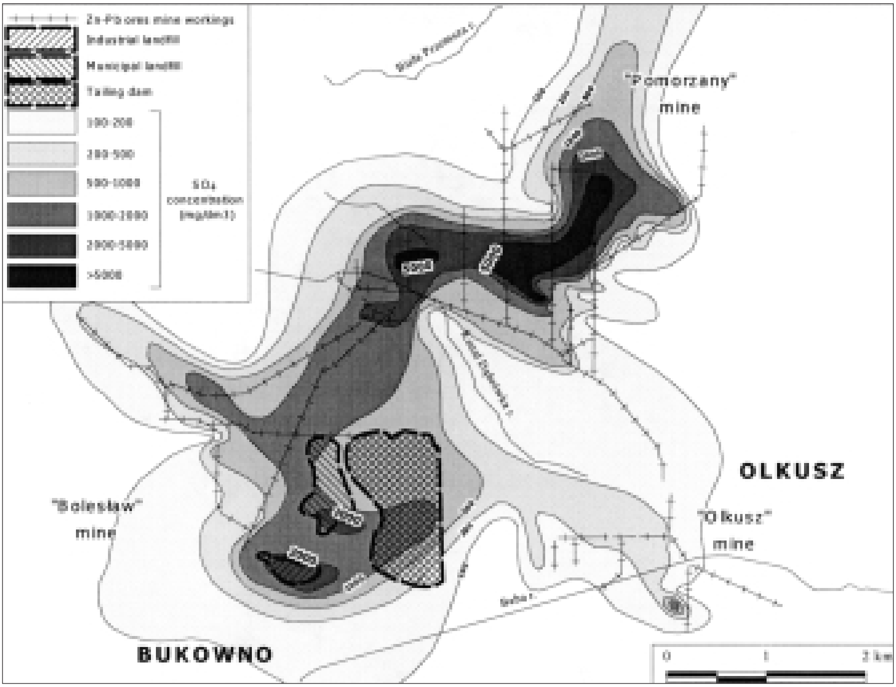

Figure 3. Spatial distribution of sulphates in groundwater of the Triassic aquifer (according to Adamczyk and others 2000)

Proposed map of potential risk of groundwater contamination by contaminants (mainly sulphates) originated in an anthropogenic unsaturated zone at the scale 1:25,000 was produced using the following methodology:

- potential contaminants are present in the unsaturated zone and they are introduced into the groundwater as a result of a rainwater percolation (Fig.5),
- it was assumed that two factors considerably influence the risk of groundwater contamination: thickness of the anthropogenic unsaturated zone within the Triassic carbonate series (rocks hosted sulphides of metals) and a net recharge of the Triassic aquifer.
- amount of potential contaminants depends on the thickness of an anthropogenic unsaturated zone (bigger load from thicker zone),
- amount of potential contaminants reaching groundwater depends on the quantity of water percolated through the unsaturated zone (bigger recharge - bigger load),
- map of the area of about 73 km^2 was divided into 28773 cells of the dimension of 50 m,
- net recharge has been derived by mathematical model calibration (Witkowski and others 2001),

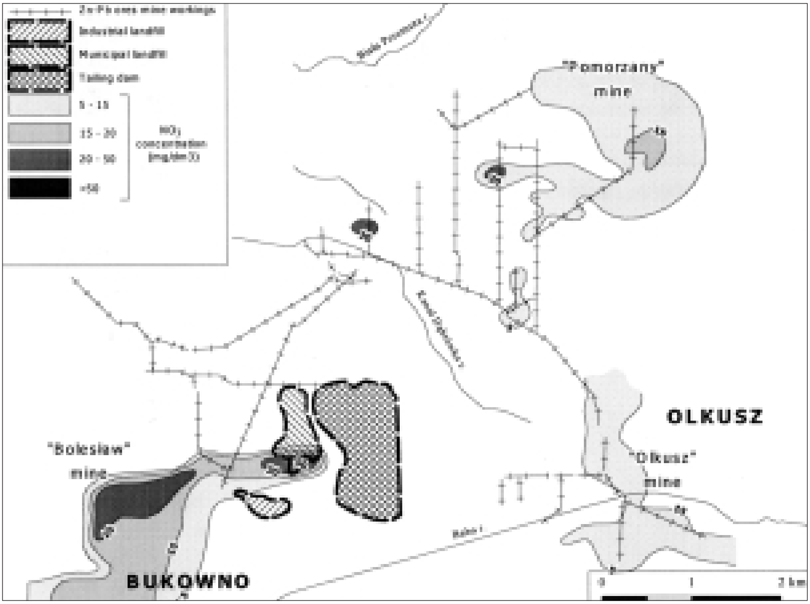

Figure 4. Spatial disribution of nitrates in groundwater of the Triassic aquifer (according to Motyka and Witkowski 2002)

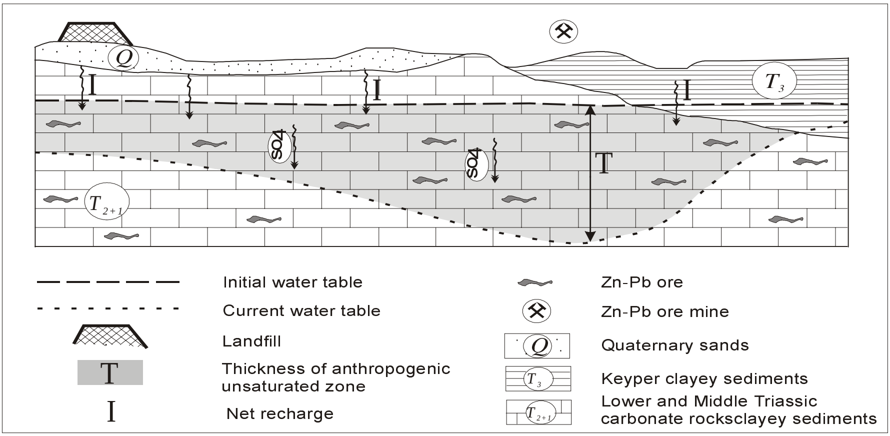

Figure 5. Schematic cross section showing applied model of a potential risk of groundwater contamination assessment

- map of the thickness of unsaturated zone was digitised from raster sheets and transferred to the model grid,
- the point count system model was applied for compilation of the final map (Aller et al., 1987, Vrba and Zaporozec eds, 1994, Witkowski et al, 2003),
- taking into consideration the relative importance of each factor, the weights were assigned. It was assumed that the net recharge is slightly more significant (weight 5) to the thickness of unsaturated zone (weight 4) (Tab.1).

Table 1. Weights of factors for risk assessment

Factor	Weight
1. Net recharge derived by mathematical model calibration	5
2. Thickness of the antropogenic unsaturated zone within the Triassic carbonate aquifer	4

- The range of the net recharge was divided into 8 classes (Tab. 2) and suitable rating according to a general scale from 1 (smallest risk) to 10 (highest risk) was assigned to each class.

Table 2. Ratings of net recharge factor

Factor 1 – Weight 5 Net recharge (mm/y)	**Rating**
0-20*	1
20-50	2
50-100	4
100-150	6
150-200	7
200-250	8
250-300	9
300-350*	10

** - classes not present at the map*

- The range of thickness of the unsaturated zone was divided into 9 classes (Tab. 3) and suitable rating according to a general scale from 0 (no risk - confined aquifer and the thickness of unsaturated zone within the Triassic carbonate series is 0) to 10 (highest risk) was assigned to each class.

Table 3. Ratings of thickness of the antropogenic unsaturated zone within the Triassic carbonate aquifer factor

Factor 2 – Weight 4 Thickness of unsaturated zone (m)	**Rating**
0 (confined aquifer)*	0
<10	2
10-20	3
20-50	5
50-75	6
75-100	7
100-150	8
150-200*	9
200-250*	10

** - classes not present at the map*

- the risk index (R_I) was calculated by summing the two results of factor ratings (0–10) multiplied by the weights (4-5),

$$\mathbf{R_I = I\,W_1 + TW_2} \qquad \text{where,}$$

R_I - relative risk index,
I - net recharge (infiltration) (mm/y),
T - thickness of the antropogenic unsaturated zone (m)
W - weighs ($W_1 = 5$, $W_2 = 4$)

- based on the obtained index values, 5 classes of relative risk of potential contamination were distinguished: very low, low, medium, high and very high (the higher index value, the largest risk) (Tab.4).

Table 4. Classes of the relative risk of groundwater contamination based on the risk index

Classes of the relative risk	**Risk index**
Very high	69 - 90
High	55 - 68
Medium	36 - 54
Low	21 - 35
Very low	5 - 20

- maps of two factors and the potential risk map was produced using Map/Info 5.5 software.
- the potential risk map was produced as a result of computer-based overlays of the two mentioned factors maps.
- the final version of the potential risk map was produced as a result of numerous simulations including the different range of the risk index for the individual five classes of relative risk. Reliability of this map was verified based on a observed groundwater quality.

RESULTS

For final risk assessment, a map of the two mentioned factors have been produced (Fig.6 and 7).

Distribution of net recharge in the considered area was determined as a result of the model calibration. MODFLOW computer code was used to simulate steady-state groundwater flow in Olkusz-Zawiercie Triassic aquifer (Witkowski and others 2001). The net recharge was divided into 8 intervals (Tab.2). Derived by model calibration, net recharge for the considered area varies from 36 to 292 mm/y. Therefore two extreme intervals (0-20 mm/y and 300-350 mm/y) are not on the map (Fig.6). The highest net recharge is located in the central part of the region in the area of "Pomorzany" Zn-Pb ore mine and in the SW part (outcrops of Triassic carbonate rocks). The lowest recharge has been observed in E and N parts of the considered area situated in the range of the Rhaetian-Keuper clayey sediments (Fig.6 and 1).

In the case of the second factor (thickness of the anthropogenic unsaturated zone within the Triassic carbonate aquifer), the division into 9 intervals was applied (from 0 to 250 m) (Tab.3). The real observed thickness varies from few to 120 meters. Therefore three intervals (0 m, 150-200 m and 200-250 m) have not been presented in the considered area (Fig.7). The thickest anthropegenic unsaturated zone has been noticed in the area of "Pomorzany" mine and the thinnest one in SW part (Fig.7).

As a result of computer-based overlays of the two mentioned factor maps (Fig.8), the final risk map of groundwater contamination for the considered region was compiled (Fig. 9).

The value of the risk index for each cell of the net was obtained by summing up two products of ratings and weights from individual factor maps. The final version of the risk map was produced as a result of numerous simulations including the different range of the risk index for the assigned individual classes. Taking into account the suggested ratings and weights, the theoretical range of the risk index for the two analysed factors was in the range from 5 to 90 points. Five classes of relative risk of potential contamination were distinguished (the higher index value, the higher risk): very low (risk index 5-20), low (risk index 21-35), medium (risk index 36-54), high (risk index 55-68) and very high (risk index 69-90) (Tab.4).

The real value of the risk index in the map of Olkusz region was in the range from 28 to 77 points. Therefore the class of a very low risk (risk index below 21) has not been presented on this map (Fig.9).

The analysis of the obtained final map (Fig. 9) shows that the areas of a medium risk of groundwater contamination (risk index from 36 to 54 points) predominate in the considered area. They cover over 55% of the area (Fig. 9). The areas, where risk of contamination is high (risk index from 55 to 68 points) cover almost 30% of the map area and occur mainly in the central and central-southern parts of the region. The assigned area of very high risk of groundwater contamination (risk index over 69 points) is situated in the central part of the area in the range of "Pomorzany" mine and covers only about 4% of the map (Fig.9).

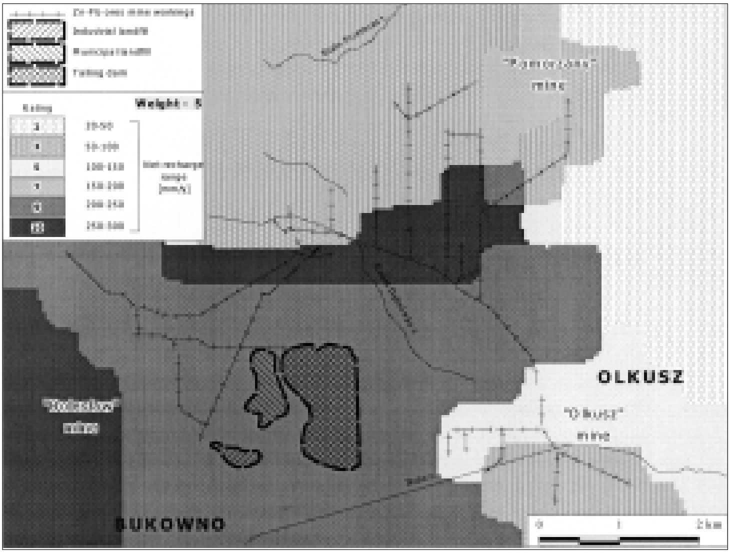

Figure 6. Net recharge of the Triassic aquifer (Factor 1)

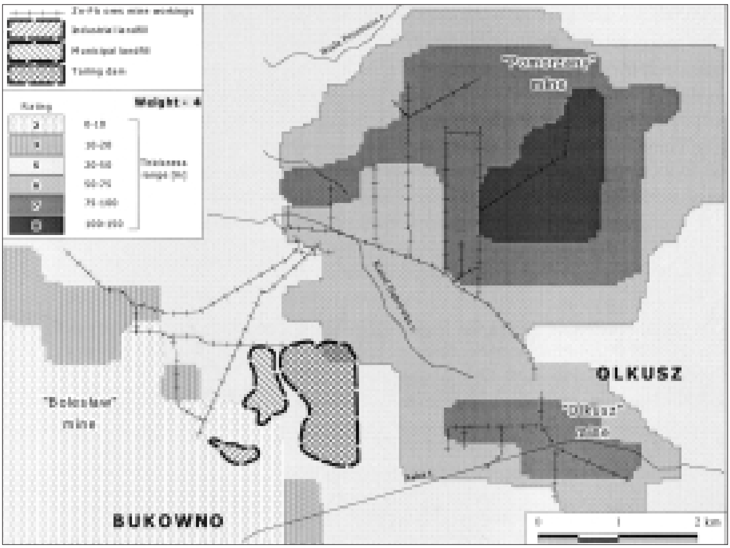

Figure7. Thickness of the anthropogenic unsaturated zone within the Triassic aquifer (Factor 2)

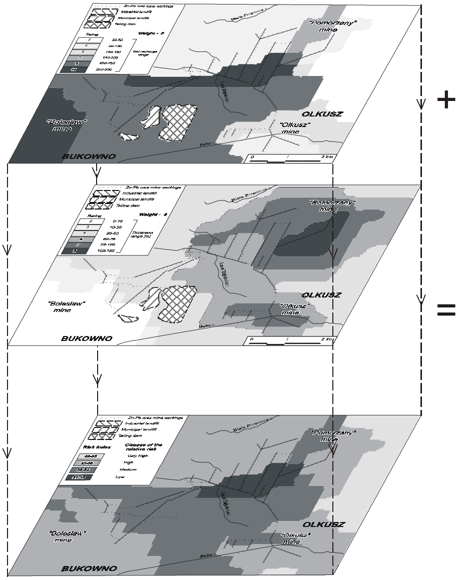

Figure 8: Procedure for the construction of the potential risk of groundwater contamination map

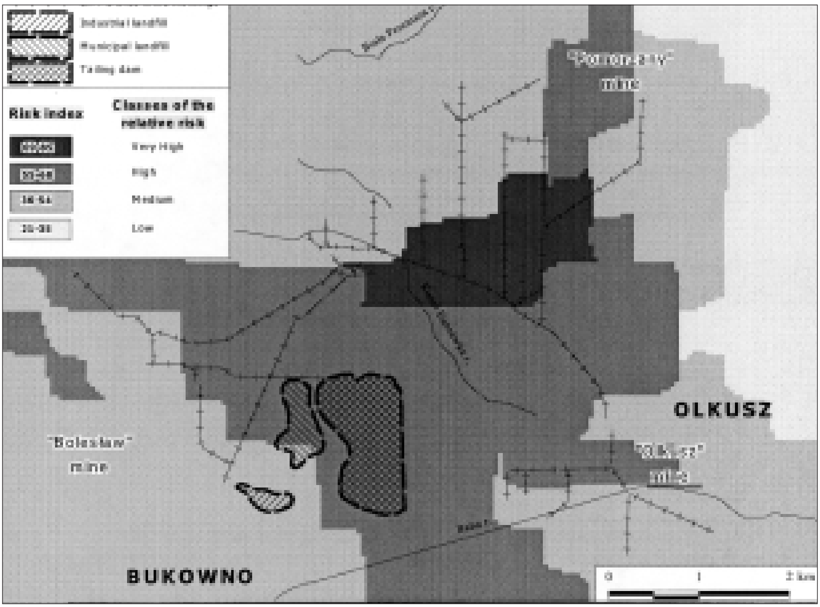

Figure 9: Map of the potential risk of groundwater of the Triassic aquifer contamination

An important question concerns reliability of the obtained map. It is expected that in areas of highest risk, groundwater of the Triassic carbonate aquifer should be of a bad quality with highest contents of sulphates. Comparing the risk of groundwater contamination map (Fig.9) to the map of spatial distribution of sulphates (Fig.3), a high positive correlation between the assigned risk degree and the sulphates concentration can be seen. There are some differences in the SW part of the area. This part according to the Figure 9 is assigned to medium class of risk but in fact there are quite high concentrations of sulphates in groundwater. In this area an overlapping negative impact of exogenic (landfill, tailing dams) and endogenic factors (unsaturated zone) on groundwater quality is observed. An additional information concerning the origin of sulphates in groundwater in this region can be obtained by a comparison of the spatial distribution of sulphates (Fig.3) and nitrates (Fig.4). Higher concentrations of nitrates in groundwater in considered region are related to such exogenic factors as municipal landfills, uncontrolled leaks of sewers from leaky septic tanks. Therefore it can be assumed that an additional sources of sulphates in that areas can be the same. Taking into account all mentioned facts, it can be said that the presented map of potential risk of groundwater contamination by contaminants originated in the extended anthropogenic zone is very reliable.

CONCLUSIONS

Proposed methods of indirect evaluation of potential risk of groundwater contamination by contaminants originated in anthropogenic unsaturated zone created by intensive drainage gives reliable information on a relative degree of this risk. This methodology can be effectively applied to other similar regions. This is particularly easy to apply for already modelled areas (using MODFLOW computer code) where the distribution of net recharge was derived by model calibration. Application of the combined methods, i.e. aquifer simulation model and geographical information system, gives very good results.

It is also necessary to verify the proposed method of risk assessment. This verification should be based on the data concerning groundwater quality.

It is important to remember that in proposed way we assess only relative differentiation of the risk of groundwater contamination in different areas. This is not an assessment of a total load of contaminants originated within the unsaturated zone which could contaminate groundwater of considered aquifer. The method assigns areas in which groundwater could be relatively more or less threatened by contaminants from extended unsaturated zone.

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