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GROUNDWATER VULNERABILITY IN THE LIGHT OF INFORMATION LAYERS OF THE HYDROGEOLOGICAL MAP OF POLAND, SCALE 1:50,000

Piotr HERBICH[1], Elżbieta PRZYTUŁA[1], Małgorzata WOŹNICKA[1]

Abstract. Determination of the possibility of natural groundwater protection is one of more important issues currently undertaken in connection with the implementation of the Water Framework Directive strategy in Poland. It refers both to shallow groundwater circulation systems and main usable aquifers. This report presents information layers of the Hydrogeological Map of Poland, scale 1:50,000, which determine vulnerability of the first aquifer and a groundwater degradation risk of the main usable aquifer.

Key words: first aquifer, main usable aquifer, vulnerability, groundwater degradation risk, Hydrogeological Map of Poland.

Abstrakt. Określenie naturalnych możliwości ochronnych wód podziemnych jest jednym z ważniejszych zadań jakie podejmowane są obecnie w związku z wdrażaniem w Polsce ustaleń wynikających z Ramowej Dyrektywy Wodnej. Dotyczy to zarówno płytkich systemów krążenia wód podziemnych, jak i głównych użytkowych poziomów wodonośnych. W niniejszym opracowaniu przedstawiono warstwy informacyjne Mapy hydrogeologicznej Polski w skali 1:50 000, które określają wrażliwość na zanieczyszczenie pierwszego poziomu wodonośnego oraz stopień zagrożenia głównego użytkowego poziomu wodonośnego.

S³owa kluczowe: pierwszy poziom wodonośny, główny użytkowy poziom wodonośny, podatność, stopień zagrożenia, Mapa hydrogeologiczna Polski.

INTRODUCTION

A groundwater vulnerability, also referred to as a groundwater sensitivity, is an important issue for the assessment of the groundwater quality, necessary in the development of water management strategies within groundwater bodies (GWB). It is also very useful for local physical planning. This is a really complex issue difficult to be precisely defined. Therefore, the terminology referring to these problems is broad in the literature. In general, 2 types of groundwater vulnerability are distinguishable: the natural vulnerability – understood as a natural property of the groundwater system, determining the risk of pollution migration from the ground surface into the groundwater, and the specific vulnerability – involving also the knowledge on the contamination type, its quantity, time of interaction and the related spatial nature of the pollution source (Vrba, Zaporożec, 1994; Żurek *et al*., 2002; Krogulec, 2004, 2005; Neukum, Hötzl, 2005). The natural vulnerability is thus dependent only on the geological structure and natural hydrogeological conditions, the most important of which are recharging infiltration, hydrodynamic conditions, and filtration parameters of the aquifer and vadose water zone. Basing on the natural vulnerability, it is possible to make specific vulnerability assessments by creating so-called vulnerability scenarios involving the effect of groundwater pollution sources and the degree of land management. An equivalent to the specific vulnerability is the degree of the groundwater degradation risk shown in the Hydrogeological Map of Poland, scale

[1] Polish Geological Institute, Rakowiecka 4, Warsaw 00-975, Poland; e-mails: piotr.herbich@pgi.gov.pl, elzbieta.przytula@pgi.gov.pl

1:50,000. It defines the risk to groundwater quality of the main usable aquifer posed by both anthropogenic pollution sources and endogenic factors, developed in the conditions of isolation of the main usable aquifer and of land accessibility for activities harmful to the groundwater quality (Herbich, 2004).

FIRST AQUIFER – GROUNDWATER VULNERABILITY

An identification of occurrence conditions and the assessment of groundwater quality of the first aquifer is necessary to protect shallow groundwater systems directly connected with groundwater-dependent land ecosystems, including the NATURA 2000 protected areas, and those systems which are often the drinking water sources for rural people. Therefore, the continuation of work on the Hydrogeological Map of Poland is the development of successive thematic layers referring to the first aquifer understood as the first water-bearing layer below the ground surface, showing good hydraulic communication and complying with the following criteria: permeability to water $k \geq 3$ m/24h, total thickness $m \geq 2$ m (at average retention conditions) and continuity over the area of $A \geq 20$ km^2.

The research currently has been going on the characteristics of occurrence and hydrodynamic conditions of the first aquifer (414 map sheets constructed during the 2005–2006 period). Also, a work has started to investigate the groundwater vulnerability and to assess the groundwater quality of the first aquifer (85 map sheets during the period of 2006–2008). It is planned to determine the natural vulnerability of the first aquifer, with a simultaneous registering of potential pollution sources accompanied by groundwater sampling in the field in order to measure selected groundwater quality indicators of the first aquifer (Herbich, 2004). Due to the variable approach to the problem, there are a considerable number of methods for determination of groundwater vulnerability classes. Ranking methods which rely on assigning a specific weighing to each parameter (DRASTIC, DIVERSITY, SEEPAGE, EPIK and others), and methods which are based on estimations of migration time of conservative contaminants are most popular (Aller *et al*., 1987; Macioszczyk, 1999; Ženišová, Fl'aková, 2002; Witkowski *et al*., 2003; Witczak, 2005; Różkowski, 2005).

Methodology, created by Witczak and his research team, has been adopted for the need of development of the "first aquifer – groundwater vulnerability" information layer in the *The Groundwater Vulnerability Map at scale of 1:500,000*, constructed by Arcadis Ekokonrem (2005). That methodology was in part modified by adjusting it to the more detailed map scale for the analysis of hydrogeological conditions. The vulnerability classes were determined based on the Mean Residence Time (MRT) of infiltrating rainwater in the soil and unsaturated zone. It determines the migration time of conservative contaminants dissolved in groundwater from the ground surface to the water-bearing layer according to the piston flow model under conditions of rainwater infiltration on the long-term average rate. It depends on both the depth to the first aquifer and moisture capacity of soils and unsaturated zone rocks. The calculation algorithm is as follows:

$$MRT = MRT_S + MRT_1 + MRT_2 \text{ (years)} \quad [1]$$

where:

MRT_S – Mean Residence Time of soil profile (years):

$$MRT_S = \frac{(1000 \cdot 1.5 \cdot w_{og})}{R} \quad [2]$$

where:

MRT_1 – Mean Residence Time of permeable rocks in unsaturated zone (years):

Table 1

Groundwater vulnerability classes of the first aquifer

MRT Estimated Mean Residence Time in unsaturated zone (years)	Groundwater vulnerability class in1:500,000 Map*	Groundwater vulnerability class HMP-FA1:50,000	Remarks*
<5	very highly vulnerable	very high	vulnerable to most contaminants
5–25	vulnerable	high	vulnerable to many pollution types, except to strongly sorbable (e.g. heavy metals)
25–50	moderately vulnerable	moderate	vulnerable to some of pollution types, but only if introduced or leached in a continuous way.
50–100	low vulnerable	low	vulnerable only to conservative contaminants introduced or leached in large amounts and in a continuous way
>100	very low vulnerable	very low	not vulnerable to most contaminants

* after Witczak, 2005 (modified)

$$MRT_1 = \frac{1000\Big((m_A - m_{PZ} - 1.5)\cdot(1 - S_p)\cdot w_{op}\Big)}{R} \quad [3]$$

where:

MRT_2 – Mean Residence Time of poorly permeable and sealing/isolating/confining rocks in unsaturated zone (years):

$$MRT_2 = \frac{1000\Big((m_A - m_{PZ} - 1.5)\cdot S_p \cdot w_{oi}\Big)}{R} \quad [4]$$

where:

m_A – thickness of unsaturated zone [m]

m_{PZ} – thickness of perched aquifers [m]

R – recharging infiltration [mm/year]

w_{og} – storage capacity of soil profile [-]

w_{op} – storage capacity of permeable rocks in unsaturated zone [-]

w_{oi} – storage capacity of sealing isolating/confining rocks in unsaturated zone [-]

S_p – contribution of sealing/isolating/confining rocks in unsaturated zone [-]

The classification of the first aquifer groundwater into 5 vulnerability classes (Table 1), shown with colour in the composite map (Fig. 1), is made based on the estimated Mean Residence Time of soils and unsaturated zone rocks.

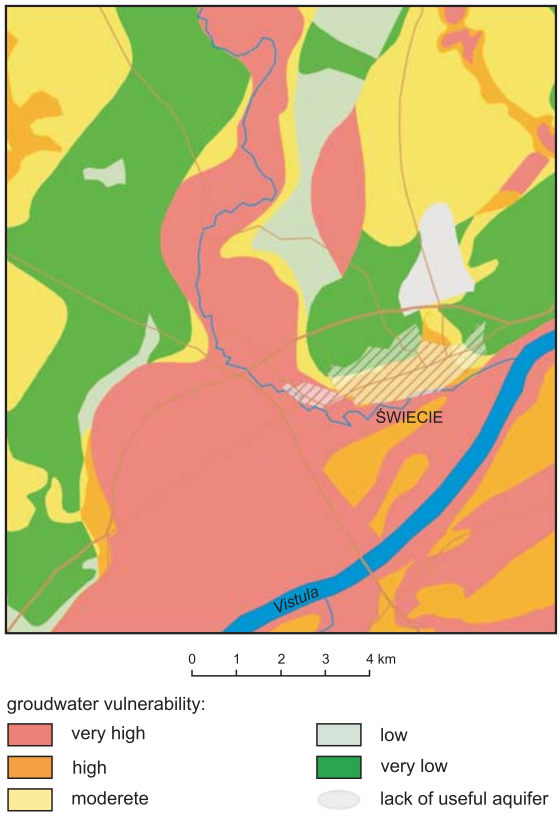

Fig. 1. The groundwater vulnerability classes of the first aquifer in Świecie region

MAIN USABLE AQUIFER – DEGREE OF GROUNDWATER DEGRADATION RISK

The Hydrogeological Map of Poland, scale 1:50,000, constructed during the period of 1997–2004, focused on the usable aquifers. A particular attention was paid to the interpretation of the main usable aquifer which is the primary water source (Paczyński, 1999). The *Main Usable Aquifer* (MUA) is the first usable aquifer below the ground surface. It has a dominant extent and large water resources within the hydrogeological unit distinguished in the HMP. The *Usable Aquifer* (UA) is a layer or a set of layers showing a hydraulic communication and necessary parameters such as: thickness of water-bearing deposits >5 m, transmissivity >50 m^2/24h, potential discharge of a well >5 m^3/h, to be qualified for the municipal production of water. The cartographic image of the occurrence conditions of the main usable aquifer includes, among others, the assessment of groundwater degradation risk as an equivalent to the specific vulnerability.

The following factors were crucial in qualifying the MUA for one of the five groundwater degradation risk classes:

– isolation degree of the main usable aquifer from ground surface pollution,
– possibility of lateral or upward (ascending) inflow of contaminated water,

Table 2

Pollution source categories in estimating the degree of groundwater degradation risk of the MUA

Small-area and point-site pollution sources	Linear and zonal pollution sources	Large-area pollution sources
Municipal and industrial waste landfills (solid or liquid waste)	motorways and high-traffic roads	of atmospheric origin: industrial gas and particulate emission
Sewage disposal sites: municipal and industrial	liquid fuel, chemicals and toxic substances pipelines	of geogenic origin
Factories: chemical, food-processing and agriculture, metallurgy, and other industry sectors	chemically and bacterial-polluted river waters (refers mainly to flood areas)	
Liquid fuel depots, filling stations		
Factory farms		

Table 3

Comparison of groundwater vulnerability classes and degree of degradation risk

FA		According to NMP (MUA)	
MTR [years]	Groundwater vulnerability class	Groundwater degradation risk	Remarks
<5	very high	very high	presence of numerous pollution sources with ascertained degradation of groundwater quality in areas of low resistance of the first aquifer to pollution (isolation *a*, *ab*)
		high	infrequent pollution sources with no signs of anthropogenic degradation of groundwater quality in areas of low resistance to pollution (isolation *a*, *ab*)
5–25	high	moderate	area of low resistance to pollution (isolation *a*, *ab*), but with limited accessibility (national parks and nature reserves, large forest complexes) and with no pollution sources, or area of moderate resistance (isolation *b*) with groundwater pollution sources
25–50	moderate		
50–100	low	low	area of low isolation (moderate resistance to pollution) of the main aquifer (isolation *b*), with no pollution sources
>100	very low	very low	area of high resistance of the main aquifer to pollution (isolation *c*), or of poor isolation (isolation *b*) and limited accessibility

– presence, type, density and strength of pollution sources,
– land accessibility for economic activity.

Additional elements in estimating groundwater degradation risk were the following:

– lithology of the MUA overburden, depth to the aquifer and its type (pore or fracture aquifer),
– hydrodynamic position of the MUA within the groundwater circulation system (recharge, transmission and discharge zones) and amount of groundwater production,
– results of tritium content determinations in MUA groundwater,
– mode of land management (including large forest complexes) and legal protection (national parks, nature reserves),
– geogenic factors posing degradation risk to the MUA,
– rock volume deformation in mine areas.

Isolation degree of the main usable aquifer, assumed for the map construction, was averaged within the hydrogeological unit. It was established depending on the thickness of poorly permeable ($k = 10^{-6}$–10^{-9} m/s) and impermeable ($k < 10^{-9}$ m/s) rocks of the overburden. The following thickness intervals of poorly permeable (or impermeable) rocks and corresponding estimated time of pollution migration from the ground surface to the MUA were used while establishing the isolation degree of the MUA:

– below 15 m (below 5 m) – no isolation (type *a*), migration time of pollution below 25 years,
– 15–50 m (5–10 m) – poor isolation (type *b*), migration time of pollution 25–100 years,
– over 50 m (over 10 m) – total isolation (type *c*), migration time of pollution over 100 years.

If the isolation degree was variable within the hydrogeological unit, then *ab*, *ba*, *bc* and *cb* symbols were applied, excluding however extreme combinations like *ac* or *abc*.

Another factor of primary importance in estimating the degree of groundwater degradation risk of the MUA was the presence of pollution sources, their type, density and intensity of the effect. Linear, areal and point-site pollution sources were taken into consideration (Table 2). The presence of pollution sources, their density and proved negative effect on the groundwater quality, in particular in the areas of poor isolation (type a, ab), determined the change of the groundwater degradation risk level from high to very high (Table 3).

In assessing the groundwater degradation risk of the MUA, land use risk and accessibility of the area were also considered. A lack of pollution sources, poor land management, low population density and limited land accessibility for economic activity due to either large forest complexes or legal protection, were the reasons for lowering the degradation risk class by one level in relation to that resulting from the degree of isolation.

A different approach was required in assessing groundwater degradation risk of the main usable aquifer in military ranges inside massive forests, especially there where the main usable aquifer is unconfined. Due to specific environmental conditions of military ranges and increased possibility of contamination, the isolation area of type a and ab was treated as accessible and considered highly endangered.

Another factor determining accessibility is legal protection of an area, enforcing limitations on economic activity in national parks, natural reserves and protected landscape parks. The assessment of this accessibility factor required an individual approach to each case.

In the specific conditions, the geogenic factors such as an upward migration of mineralized water from deeper aquifers and ingressions of seawater or inflow of shallow groundwater from boggy zones, remaining in communication with the main usable aquifer, were also taken into consideration in assessing the groundwater degradation risk classes (Table 2). These phenomena may have a crucial significance in assessing groundwater degradation risk, especially under conditions of a high groundwater production. The above presented factors were determinant in classifying the MUA area into one of the five groundwater degradation risk classes (Table 3). The classification is shown in a colour scale in the main sheet of the HMP (Fig. 2).

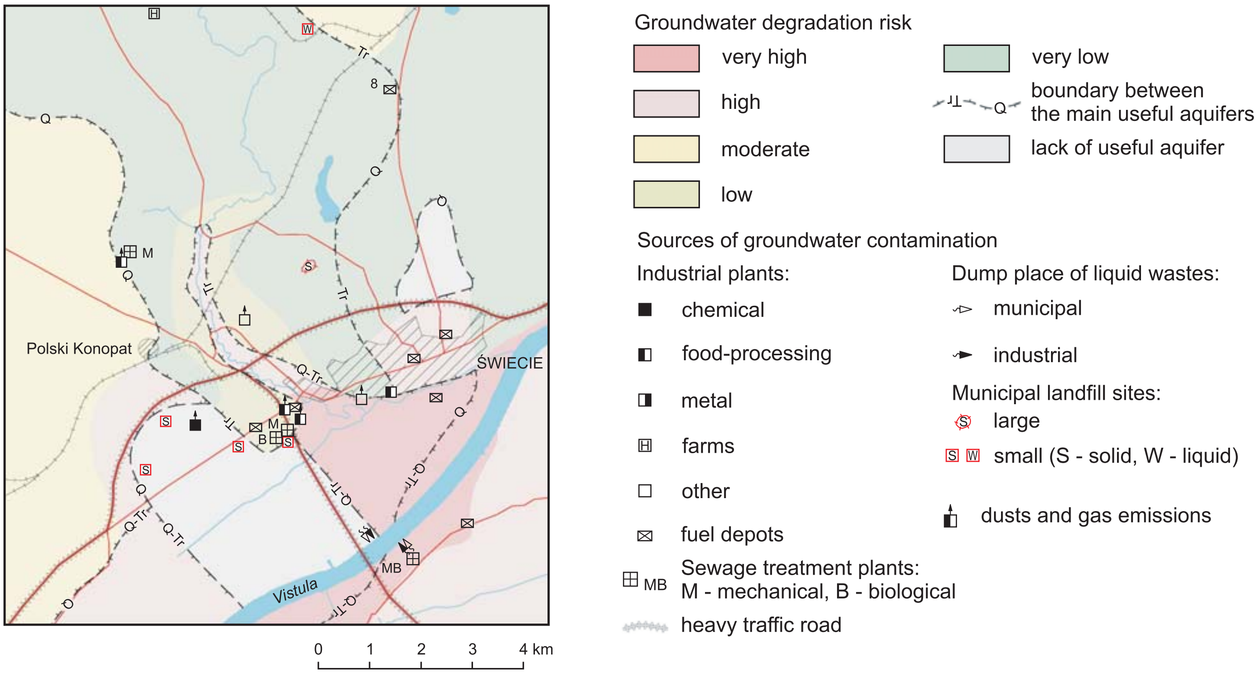

Fig. 2. Assessment of the groundwater degradation risk of the main usable aquifer in the Œwiecie region (Oficjalska, 2005)

SUMMARY

A comparison between the degree of groundwater vulnerability and the degree of groundwater degradation risk, which are presented as two separate information layers of the Hydrogeological Map of Poland, scale 1:50,000, is possible only to a limited extent when the condition of identity of the assessed aquifer is met. Such a comparison can be performed for areas where the main usable aquifer is equivalent with the first aquifer (FA = MUA). In case of FA # MUA, the assessment of groundwater vulnerability refers to different aquifers and the attempt of correlating the results is groundless.

While comparing the results, it should be borne in mind that the FA map shows natural vulnerability, whereas groundwater degradation risk of the MUA is equivalent to the specific vulnerability (Table 3). The presence of pollution sources causes a significant rise of the degradation risk, whereas limited land accessibility results in its lowering. Therefore, any comparison of these two information layers must be carried out based on the knowledge on methodology of both identification of the FA vulnerability and the MUA degradation risk, as well as on the recognition of hydrogeological conditions of the area under study.

REFERENCES

ALLER L., BENNET T., LEHR J.H., PETTY R.J., HACKETT G., 1987 — DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic setting. Ada, Oklahoma.

HERBICH P., 2004 — The assessment of risk to groundwater quality in the Hydrogeological map of Poland 1:50 000. *In*: Groundwater vulnerability assessment and mapping. International conference, 15–18 June 2004, Ustroń.

HERBICH P. (ed), 2004 — Mapa hydrogeologiczna Polski w skali 1:50 000, udostępnianie, weryfikacja, aktualizacja i rozwój. Instrukcja, MŚ–PIG, Warszawa.

KROGULEC E., 2004 — Ocena podatności wód podziemnych na zanieczyszczenia w dolinie rzecznej na podstawie przesłanek hydrodynamicznych [in Polish with English summary]. Uniw. Warsz., Warszawa.

KROGULEC E., 2005 — Groundwater vulnerability in the central part of the Vistula River Valley (Kampinoski National Park) – Poland. *In*: Aquifer vulnerability and risk – 2nd Workshop, September 21–23, 2005, Parma.

MACIOSZCZYK T., 1999 — Czas przesączania pionowego wody jako wskaźnik stopnia ekranowania warstw wodonośnych [in Polish with English summary]. *Prz. Geol*., **47**, 8: 731–736.

NEUKUM Ch., HÖTZL H., 2005 — Unification and standardisation of vulnerability maps. *In*: Aquifer vulnerability and risk – 2nd Workshop, September 21–23, 2005, Parma.

OFICJALSKA H., 2005 — Baza danych GIS Mapy hydrogeologicznej Polski 1:50 000 „Pierwszy poziom wodonośny – występowanie i hydrodynamika”. Archives PGI, Warszawa.

PACZYŃSKI B. (ed.), 1999 — Instrukcja opracowania i komputerowej edycji Mapy hydrogeologicznej Polski w skali 1:50 000, Część I i II, MOŚZNiL–PIG, Warszawa.

RÓŻKOWSKI J., 2005 — Wody podziemne i zanieczyszczenia. *Ekologia*, 5/31/2005.

VRBA J., ZAPOROŻEC A., 1994 — Guidebook on mapping groundwater vulnerability. IAH. *In*: Int. contributions to hydrology Vol. 16. Heinz Heise Verlag. Hannover.

WITCZAK S. (ed.), 2005 — Mapa wrażliwości wód podziemnych na zanieczyszczenie 1:500 000 (Plansza 1 – Wody podziemne związane z wodami powierzchniowymi oraz ekosystemami lądowymi zależnymi od wód podziemnych; Plansza 2 – Podatność na zanieczyszczenie Głównych Zbiorników Wód Podziemnych). Arcadis Ekokonrem Sp. z o.o., Warszawa.

WITKOWSKI A., RUBIN K., KOWALCZYK K., RÓŻKOWSKI A., WRÓBEL J., 2003 — Groundwater vulnerability map of the Chrzanów karst-fissured Triassic aquifer (Poland). *Environ. Geol*., 44: 59–67. Springer Verlag.

ZAMBRZYCKA M., 2002 — Mapa hydrogeologiczna Polski w skali 1:50 000, ark. Chełmno (243), wersja cyfrowa wraz z objaśnieniami, Warszawa.

ŻUREK A., WITCZAK S., DUDA R., 2002 — Vulnerability assessment in fissured aquifers. *In*: Groundwater quality and vulnerability. *Prace WNoZ UŚ*. **22**. Sosnowiec: 241–254.

ŽENIŠOVÁ Z., FL'AKOVÁ R., 2002 — Groundwater vulnerability assessment of Quaternary aquifers. *Prace WNoZ UŚ*. **22**. Jakość i podatność wód podziemnych na zanieczyszczenie. Sosnowiec: 227–232.