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FACTORS CONTROLLING THE GROUNDWATER CONDITIONS OF THE CARBONIFEROUS STRATA IN THE UPPER SILESIAN COAL BASIN, POLAND

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Abstract: Hydrogeological conditions vary between the various geological structures of the Upper Silesian Coal Basin (USCB). They depend on geological and mining factors. The most important geological factors which control the groundwater conditions within the USCB include: 1) incomplete insulation of Carboniferous strata by Tertiary clays, 2) occurence of gypsum and salt deposits in the Tertiary strata, 3) regional dislocation and fissility of Carboniferous rock complex, 4) distinct tendency of decreasing permeability of Carboniferous water-bearing sandstones with depth.

The influence of mining activity on groundwater conditions in the USCB depends on the duration, size, depth and system of coal exploitation. Displacements, cracks and relaxation of rocks, which accompany mining works, increase permeability and provide hydraulic contact between waters in different aquifers by interruption of the insulating layers. Drainage of rocks by mine workings disturbs the natural hydrogeological regime in the USCB.

Generally, groundwater salinity in the investigated depth interval, to 1,200 m, decreases with time due to replacement and mixing of atmospheric waters with buried brines.

Abstrakt: Warunki hydrogeologiczne w obrębie Górnośląskiego Zagłębia Węglowego (GZW) są zróżnicowane pomiędzy poszczególnymi strukturami geologicznymi. Najważniejszymi czynnikami wpływającymi na środowisko wód podziemnych są: 1) niepełna izolacja warstw karbońskich iłami trzeciorzędowymi, 2) występowanie gipsu i soli w utworach trzeciorzędowych, 3) tektonika blokowa, 4) wyraźna tendencja obniżenia przepuszczalności karbońskich piaskowców z głębokością.

Wpływ działalności górniczej na warunki hydrogeologiczne w GZW zależy od czasu trwania, rozmiarów, głębokości i systemu eksploatacji węgla. Przemieszczenia, spękania i odprężanie skał, towarzyszące robotom górniczym, zwiększają przepuszczalność skał i doprowadzają do hydraulicznego kontaktu pomiędzy wodami różnych poziomów wodonośnych przez naruszenie ciągłości warstw izolujących. Odwodnienie skał w wyniku prac górniczych zakłóca naturalny reżim hydrogeologiczny GZW. Ogólnie, zasolenie wód podziemnych w badanym przedziale głębokości do 1200 m obniża się z upływem czasu w wyniku wypierania przez wody atmosferyczne pogrzebanych solanek i mieszania obu typów wód.

Key words: Mining, hydraulic properties, hydrochemistry, isotopes, flow systems, Carboniferous, Upper Silesian Coal Basin.

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OUTLINE OF GEOLOGY AND MINING

The Upper Silesian Coal Basin, 7,500 sq. km in area (including 5,500 sq. km in Poland), lies in the Upper Silesian Variscan intermontane depression. Several second-order geological structures have been distinguished within the Variscan depression (Kotas, 1985).

The molasse sediments of the productive Upper Carboniferous strata within this depression are 8,200 m thick. Coal-bearing Carboniferous rocks occur beneath Quaternary and Mesozoic strata in the northeastern part of the basin and beneath clayey Tertiary strata in its southern and northwestern parts (Fig. 1). Salt deposit occurs locally within the Tertiary formation. The Tertiary strata are up to 1,000 m thick in the Alpine depressions.

The USCB is now one of the biggest coal basins in the world by its resources and output of hard coal (about 150 mln T/y). Mining has been active here since the second half of the 18th century. The coal fields cover an area of about 2,000 sq. km. The depth of mining works varies from 400 m to 1,200 m (Fig. 1). The majority of coal mines lie in the area of shallow occurence of productive Carboniferous series in the northeastern part of the USCB. The deeper coal deposits overlain by Tertiary clays are now intensely mined.

It should be stressed that the mean depth of min-

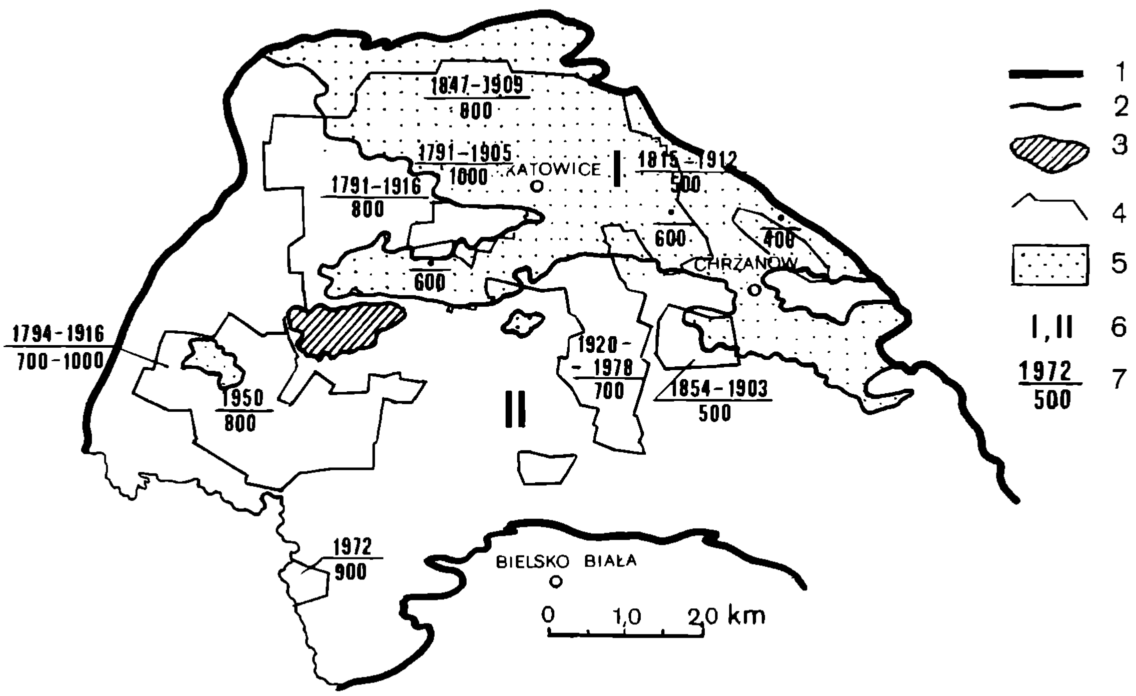


Fig. 1 Upper Silesian Coal Basin (USCB). *1* – extension of the USCB; *2* – extension of the isolating series of the Tertiary formation; *3* – salt deposits in the Tertiary formation; *4* – mine areas; *5* – recharge areas of the Carboniferous aquifers; *6* – hydrogeological regions; *7* – year of mine construction and depth of mining

Górnośląskie Zagłębie Węglowe (GZW). *1* – zasięg GZW; *2* – zasięg izolującej serii trzeciorzędowej; *3* – zasięg trzeciorzędowego złoża soli; *4* – obszary górnicze; *5* – obszary zasilania karbońskich poziomów wodonośnych; *6* – regiony hydrogeologiczne; *7* – rok budowy kopalni i głębokość eksploatacji

ing works and mean mineralization (i.e. total dissolved solids – TDS) of mine waters markedly increases due to the construction of new, deeper exploitation levels in old mines and building of new deep mines in the southern part of the USCB. The mean depth of mining works was about 200 - 400 m in 1957 (Marchacz & Stolarzewicz, 1960) but 650 m in 1989 (Różkowski, 1989). The mean mineralization of mine water discharged to rivers increased from 4.9 g/dm^3 in 1970 (Pałys & Rosielski, 1971) to 10.9 g/dm^3 in 1984 (Różkowski, 1989), while the volume of water pumped by coal mines increased only from 986,000 m^3/day to 1,042.000 m^3/day (Wilk *et al.*, 1990). This indicates the growing inflow of high mineralized groundwater into mines in the last period.

GENERAL HYDROGEOLOGICAL CHARACTERISTICS OF THE USCB

The results of recent hydrogeological studies in the USCB have been presented by Rogoż *et al.* (1987), Różkowski (1987), Różkowski *et al.* (1991), Różkowski & Witkowski (1988), Wilk *et al.* (1990).

Several hydrogeological structures of the depression or block types have been distinguished in the Upper Silesian Variscan basin. They differ in hydrogeological profiles and groundwater regimes.

Three aquifers have been identified in the hydrogeological cross-section of the USCB: Quaternary, Mesozoic and Carboniferous. Tertiary clays are the insulating formation.

The Carboniferous strata either crop out or are overlain by permeable Mesozoic strata, mainly Triassic dolomites and Quaternary sands in the northeastern part of the basin. In its southern and western parts the Carboniferous strata are overlain by impermeable Tertiary clays (Fig. 1).

The Upper Carboniferous strata are a series of clays, mudstones and sandstone with coal seams. The Carboniferous water-bearing sandstones and mudstones range in thickness from 0.5 to several dozen meters. They are separated by intercalations of impermeable claystones except of fault zones, zones of sedimentary wedging and areas of mining works.

The Carboniferous aquifers are recharged in the outcrop zones or through permeable cover rocks in the northeastern part of the USCB. The recharge takes place also locally in the central part of the basin in the areas of the so called hydrogeological windows, where Tertiary sediments have been eroded (Fig. 1).

Pressure head values of the Carboniferous hori-

Table 1

Arithmetic means values of hydraulic properties of Carboniferous sandstones and mudstones within 200 m depth intervals

Średnie arytmetyczne wartości własności hydraulicznych karbońskich piaskowców i mułowców w dwustumetrowych interwałach głębokościowych

Parameter	Depth intervals below the surface						
	0-200	200-400	400-600	600-800	800-1000	1000-1200	1200-1400
open porosity (%)	18.0	12.5	11.0	10.5	9.5	7.1	6.7
specific yield (%)	12.0	9.0	8.0	8.4	7.2	5.1	4.4
permeability (mD)	300.0	80.0	20.0	19.0	1.6	0.17	0.16

zons have been determined from pressure buildup curves registered during the production tests in the southern part of the USCB. The normal pressure gradient is about 0.09 to 0.10×10^5 Pa/m. The lowest horizons investigated at the depth of aproximately 1,500 m have elevated formation presssures, so called surpressures (Fertl, 1976). The pressure gradients are about 0.12×10^5 Pa/m. Abnormal formation pressures are developed in the southern part of the USCB, where the clayey Tertiary beds act as a pressure barrier.

The recharge of the Carboniferous horizons through Quaternary sands from recent and buried valleys is the most active. Taking into account the recharge conditions of the Carboniferous water-bearing sandstones, two hydrogeological regions (I, II) may be distinguished in the USCB. Their boundaries are delineated by the extent of the insulating Tertiary strata (Fig. 1).

Aquifers of the productive Carboniferous series under natural drainage conditions were drained by river valleys in the first region (I), and along fault zones in the second hydrogeological region (II). Drainage along the regional fault zones of deep Carboniferous horizons is strongly marked by the increase in groundwater salinity in the vicinity of these zones, observed by the author in the southern and central part of the USCB along the faults zones Kłodnica and Bzie - Czechowice. They were also investigated by Kleczkowski & Witczak (1968), Vu-Ngoc-Ky (1973) in the southern part of the USCB.

Pumping in the USCB coal mines of about 1 mln m^3/day drains the Carboniferous water-bearing rocks. Triassic and Quaternary rocks are drained too, but only in the first hydrogeological region. The area of decreased piezometric pressures occupies about 1,720 sq. km. High index of underground runoff ranging from 5 to 7 $l \cdot s^{-1} \cdot km^{-2}$ in the first hydrogeological region is a measure of mining drainage intensity.

At present, the mean drainage depth due to mining works is about 650 m, while the maximal – 1200 m.

HYDRAULIC PROPERTIES OF THE CARBONIFEROUS SANDSTONES AND MUDSTONES

The knowledge of hydraulic properties of its rocks is very important for the recognition of the flow condition and for determination of the hydrodynamic zonality in the Carboniferous strata. Laboratory measurements of open porosity, specific yield and permeability of the Carboniferous sandstones and mudstones have been carried out by Kleczkowski & Witczak (1967), Kleczkowski *et al.* (1968, 1976), Witkowski (1987), Różkowski *et al.* (1992). The method of rock samples vacuum-saturated with liquid has been used for the determination of open porosity, and capillary drainage and centrifuging methods for the specific yield.

Variations of open porosity, specific yield and permeability values of the Carboniferous sandstones and mudstones are caused by variation in granulometric and mineral composition of these rocks as well as by their various diagenesis (Witkowski, 1987; Różkowski & Witkowski, 1988). A marked trend of downward decrease in hydraulic properties of water-bearing sandstones and mudstones is apparent in the laboratory results (Table 1).

The data on permeability of Carboniferous sandstones and mudstones come from analyses of samples collected from the depths of 60 - 2,000 m. The values of permeability vary from 1,400 mD to 0.005 mD with a tendency of declining with the depth. The values of hydraulic conductivity vary from 1.34×10^{-5} m/s to 4.8×10^{-12} m/s, after convertion of the above numbers into hydraulic conductiivity (K), without the Klinken-

Fig. 2 Hydrochemical regions and depth of occurence of brines (TDS>35 g/dm^3). *1* – depth contour; *2* – extension of the isolating series of the Tertiary deposits; *3* – extension of the salt deposits; *4* – extension of the coalfields; *5* – hydrogeological regions; *6* – hydrochemical regions

Rejony hydrochemiczne i głębokość występowania solanek (o koncentracji soli >35 g/dm^3). *1* – zarys głębokości występowania; *2* – zasięg izolującej serii osadów trzeciorzędowych; *3* – zasięg złoża soli w utworach trzeciorzędowych; *4* – zasięg obszarów górniczych; *5* – regiony hydrogeologiczne; *6* – rejony hydrochemiczne

berg's correction for the "slip effect". The position of sandstone in the stratigraphic column, i.e. its stratigraphic depth, has the strongest influence on its permeability.

Within the outcrops areas of Carboniferous series, where the erosion and rock relaxation occur, permeabilities of Carboniferous sandstones are high, regardless on geological age of the rocks.

The results of test pumpings and drill-stem tests confirmed the results of laboratory examinations of sandstones and mudstones samples, but mainly in deeper part of the Carboniferous series. Field investigations carried out by Kleczkowski & Witczak (1967) in the eastern part of the USCB have shown very clearly the increase in hydraulic conductivity of sandstones until the depth of about 500 m, due to fissurity of rocks. The values of K differ from 5.0×10^{-5} m/s to 3.0×10^{-7} m/s (mean value 1.0×10^{-6} m/s). Below this depth the fissurity of rocks slowly disapeared and hydraulic conductivity was due to matrix porosity of sandstones. The results of test pumping and subsurface sampler tests carried out by Różkowski & Wagner (1988) in the depth interval from 600 to 1,600 m have shown declining hydraulic conductivity values with depth from 1.0×10^{-7} to 4.0×10^{-11} m/s.

Specific capacity of the Carboniferous water-bearing sandstones and mudstones ranges from 10.26 to 0.00001 $m^3 \cdot h^{-1} \cdot m^{-1}$. It is decreasing with the depth. Representative values for the depth interval of 700 to 1,000 m are about 10^{-3} $m^3 \cdot h^{-1} \cdot m^{-1}$ while for the deeper aquifers they are usually 10^{-4} $m^3 \cdot h^{-1} \cdot m^{-1}$.

The results of the laboratory and field investigations indicate that Carboniferous sandstones and mudstones below the depth of 700 - 800 m are practically impermeable. It does not concern the areas of mining where slides, cracks and unstressing of rocks, accompanying mining excavation, cause an increase of rock permeability.

HYDROCHEMISTRY

The groundwaters in the USCB vary in chemical composition and total mineralization (Różkowski, 1987; Różkowski *et al.*, 1989, 1991). Fresh waters occur in the Quaternary, Jurassic and Triassic formations of the cover and in the outcropping Carboniferous strata.

Mineralization of the groundwaters in the Tertiary strata ranges from 0.5 to 220 g/dm^3; the waters originally belong to the Cl-Na chemical type (Różkowski, 1971). The total mineralization of groundwaters in the coal-bearing Carboniferous strata ranges from 0.5 to 372 g/dm^3.

Fresh waters (TDS < 1 g/dm^3) are mainly of hydrochemical types: HCO_3-Ca, HCO_3-SO_4-Ca, SO_4-HCO_3-Ca-Mg. Their hydrochemical coefficients have values: r(Na/Cl) > 1, r(Ca/Mg) > 1, and r(100 × SO_4/Cl) > 1. Nitrogen predominates in gaseous composition of these waters. The described waters occur in oxidation zone.

Saline waters, with TDS < 35 g/dm^3, belong to multi-ion and Cl-Na hydrochemical types. The following values of coefficients are typical for them: r(Na/Cl) = 1.3 - 0.87 and r(100 × SO_4/Cl) from 0.07 to 9.1. Nitrogen predominates in gaseous composition of these groundwaters in the upper part of their occurence, and methane predominates in the lower one. This evidence allows one to assume that saline waters may occur in the oxidation as well as reduction zones.

Brackish mine waters from the oxidation zone are enriched in sulfate ions in the mining excavations, due to oxidation of pyrites and sulphur in coal seams.

The brines with TDS content above 35 g/dm^3 belong to hydrochemical types Cl-Na and Cl-Na-Ca and have the following values of hydrochemical coefficients: r(Na/Cl) = 0.72 - -0.96 and r(100 × SO_4/Cl) < 1. They occur in the reduction zone only. Highly mineralized waters in insulated structures are buried

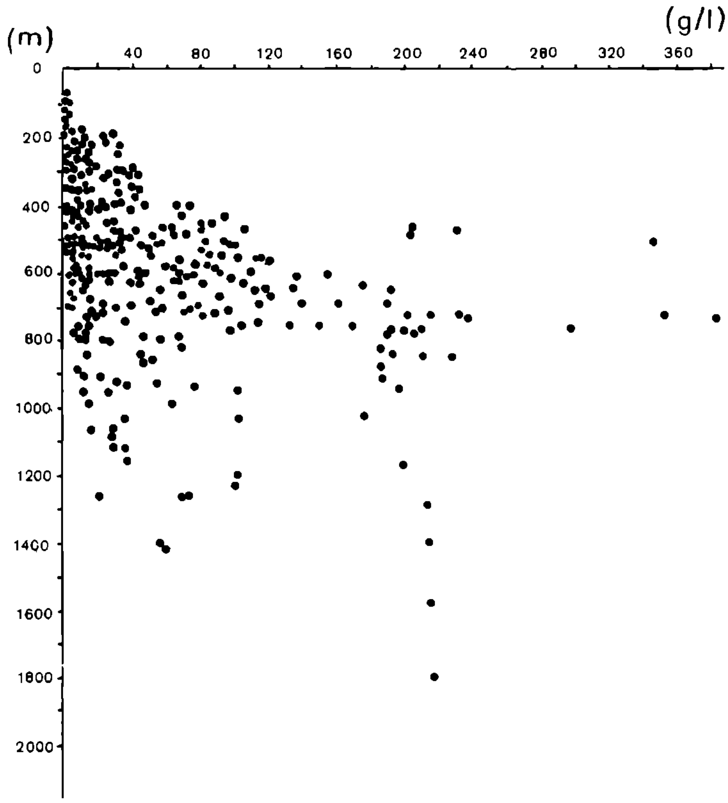


Fig. 3 The dependence of groundwater mineralization on depth

Zmiany mineralizacji wód podziemnych z głębokością

brines of the Cl-Na-Ca types. Methane from degazation of coal seams predominates in gaseous composition of those brines.

The presented hydrogeochemical data demonstrate a vertical succession of hydrochemical zones in the Carboniferous strata of the USCB. Three hydrochemical zones have been distinguished: the zone of infiltration waters, the intermediate zone of mixed waters, and the lower zone of buried brines (Kleczkowski & Vu-Ngoc-Ky, 1970; Pałys, 1966, 1971; Różkowski, 1965, 1987; Różkowski *et al.*, 1989, 1991; Vu-Ngoc-Ky, 1973). These zones are defined on the basis of the values of hydrochemical coefficients and ground-

Table 2

The characteristics of hydrochemical regions (after Różkowski *et al.*, 1990)
Charakterystyka regionów hydrochemicznch (wg Różkowski *et al.*, 1990)

Regions	Interval of depth	Mineralization of groundwater g/dm^3 from - to	Main hydrochemical tpes of waters	Hydrogeochemical gradient $g \cdot dm^{-3} \cdot 100m^{-1}$
R1	0-500	0.3-80	HCO_3-Ca, HCO_3-SO_4-Ca-Mg, Cl-SO_4-Na, Cl-Na	6*
R1	500-1000	1.7-329	Cl-Na, Cl-Na-Ca	40* (60)**
R2	0-500	0.3-23	HCO_3-Ca, HCO_3-SO_4-Ca-Mg, Cl-SO_4-Na, Cl-Na	2* (4)**
R2	500-1000	2.2-212	Cl-Na, Cl-Na-Ca	15* (40)**
R3	0-500	0.3-50	HCO_3-Ca, Cl-SO_4-Ca-Mg, Cl-Na	2* (10)**
R3	500-1000	1.0-250	Cl-Na, Cl-Na-Ca	40* (50)**
R4	0-500	0.4-28	HCO_3-Ca, HCO_3-SO_4-Ca-Mg, Cl-SO_4-Na, Cl-Na	2* (5)**
R4	500-1000	2.8-120	Cl-Na, Cl-Na-Ca	22* (22)**
R5	0-500	0.5-100	HCO_3-Ca-Mg, HCO_3-SO_4-Ca-Mg, Cl-Na	8*
R5	500-1000	14.0-282	Cl-Na, Cl-Na-Ca	23* (50)**
R6	0-500	0.3-400	HCO_3-Ca, HCO_3-SO_4-Ca-Mg, Cl-Na	80*
R6	500-1000	5.5-351	Cl-Na, Cl-Na-Ca	130*
R7	0-500	0.5-79	HCO_3-Ca, HCO_3-Cl-Na, Cl-Na	5*
R7	500-1000	2.5-150	Cl-Na, Cl-Na-Ca	20* (30)**

* mine waters (wody kopalniane)
** natural environment (wody występujące w środowisku naturalnym)

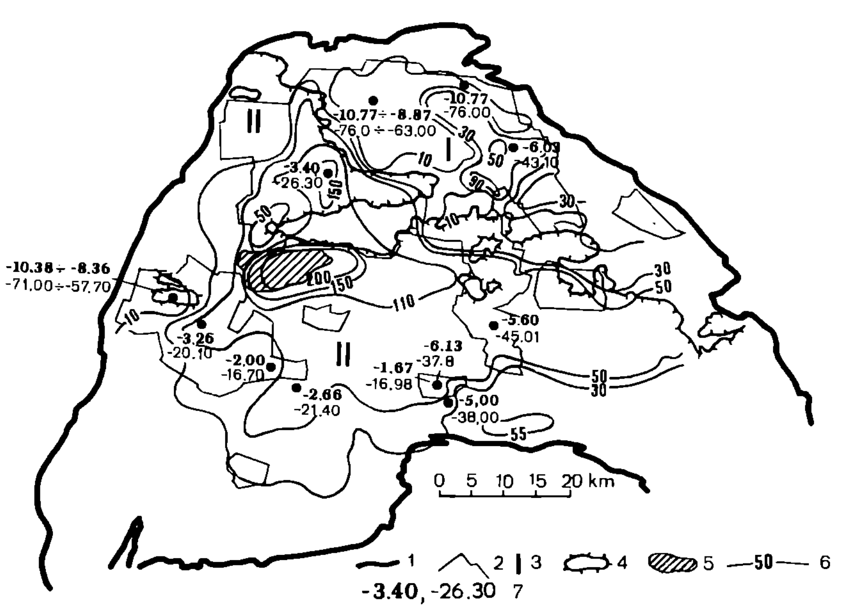


Fig. 4 Sketch-map of the groundwater mineralization and isotopic composition (USCB) at the depth of 250 m below sea level. *1* – extension of the USCB; *2* – extension of the coalfields; *3* – hydrogeological regions; *4* – extension of the isolating series of the Tertiary deposits; *5* – extension of the salt deposits in the Tertiary formation; *6* – isolines of TDS (g/dm^3); *7* – $\delta^{18}O$ and δD values. Hydrochemical setting according to A. Różkowski *et al.*, 1990

Szkic mineralizacji i składu izotopowego wód podziemnych (GZW) na głębokości 250 m ppm. *1* – zasięg GZW; *2* – zasięg obszarów górniczych; *3* – regiony hydrogeologiczne; *4* – zasięg izolującej serii utworów trzeciorzędowych; *5* – zasięg złoża soli w utworach trzeciorzędowych; *6* – izolinie koncentracji soli w wodach podziemnych (g/dm^3); *7* – wartości $\delta^{18}O$ i δD w wodach podziemnych. Szkic hydrochemiczny wg: A. Różkowski *et al.*, 1990

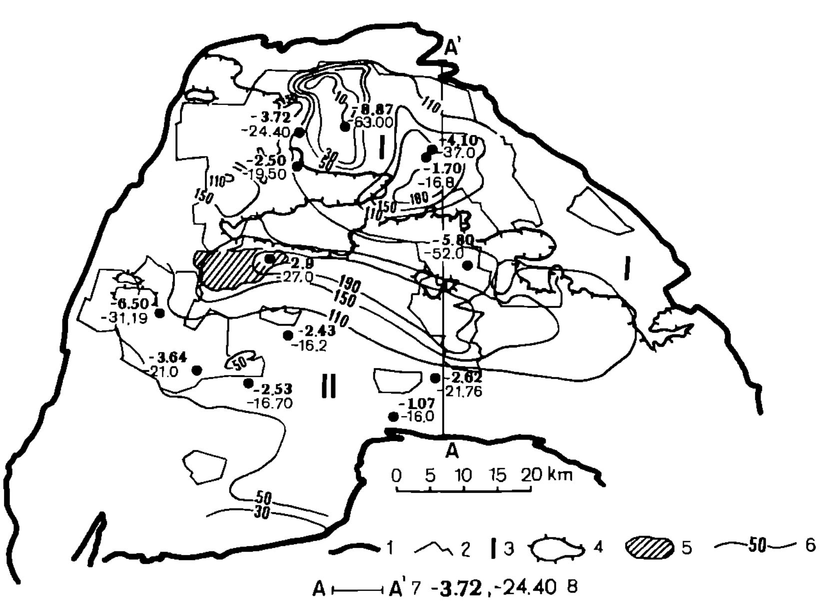


Fig. 5 Sketch-map of the groundwater mineralization (USCB) at the depth of 500 m below sea level. *1* – extension of the USCB; *2* – extension of the coalfields; *3* – hydrogeological regions; *4* – extension of the isolating series of the Tertiary deposits; *5* – extension of the salt deposits in the Tertiary formation; *6* – isolines of TDS (g/dm^3); *7* – hydrogeological cross-section; *8* – $\delta^{18}O$ and δD values. Hydrochemical setting according to A. Różkowski *et al.*, 1990

Szkic mineralizacji wód podziemnych (GZW) na głębokości 500 m ppm. *1* – zasięg GZW; *2* – zasięg obszarów górniczych; *3* – regiony hydrogeologiczne; *4* – zasięg izolującej serii utworów trzeciorzędowych; *5* – zasięg złoża soli w utworach trzeciorzędowych; *6* – izolinie koncentracji soli w wodach podziemnych (g/dm^3); *7* – przekrój hydrogeologiczny; *8* – wartości $\delta^{18}O$ i δD w wodach podziemnych. Szkic hydrochemiczny wg: A. Różkowski *et al.*, 1990

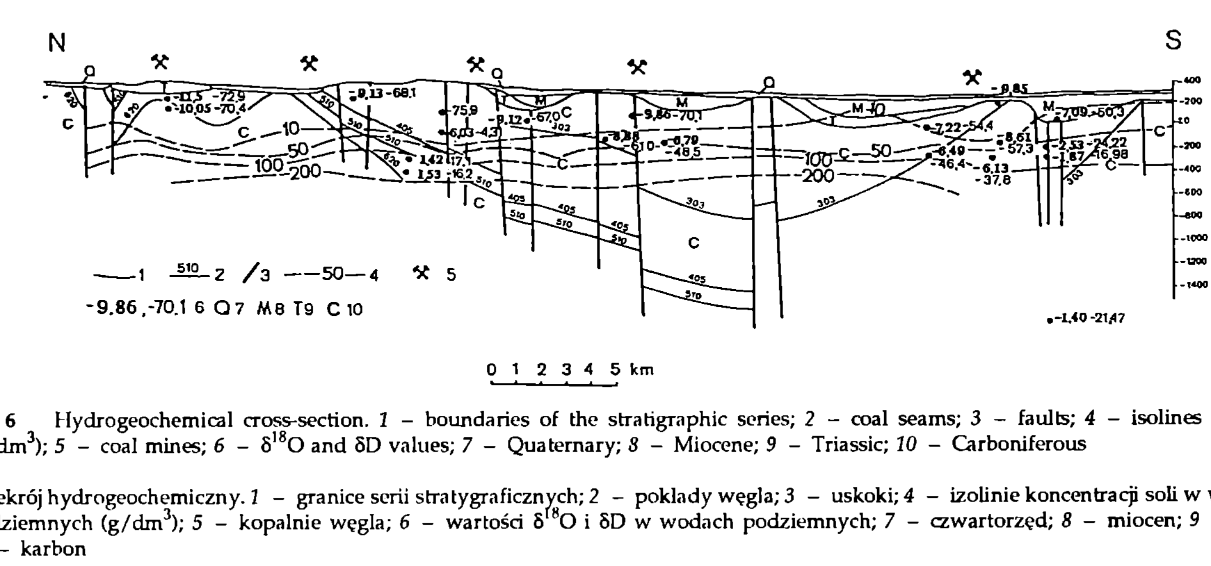


Fig. 6 Hydrogeochemical cross-section. *1* – boundaries of the stratigraphic series; *2* – coal seams; *3* – faults; *4* – isolines of TDS (g/dm^3); *5* – coal mines; *6* – $\delta^{18}O$ and δD values; *7* – Quaternary; *8* – Miocene; *9* – Triassic; *10* – Carboniferous

Przekrój hydrogeochemiczny. *1* – granice serii stratygraficznych; *2* – pokłady węgla; *3* – uskoki; *4* – izolinie koncentracji soli w wodach podziemnych (g/dm^3); *5* – kopalnie węgla; *6* – wartości $\delta^{18}O$ i δD w wodach podziemnych; *7* – czwartorzęd; *8* – miocen; *9* – trias; *10* – karbon

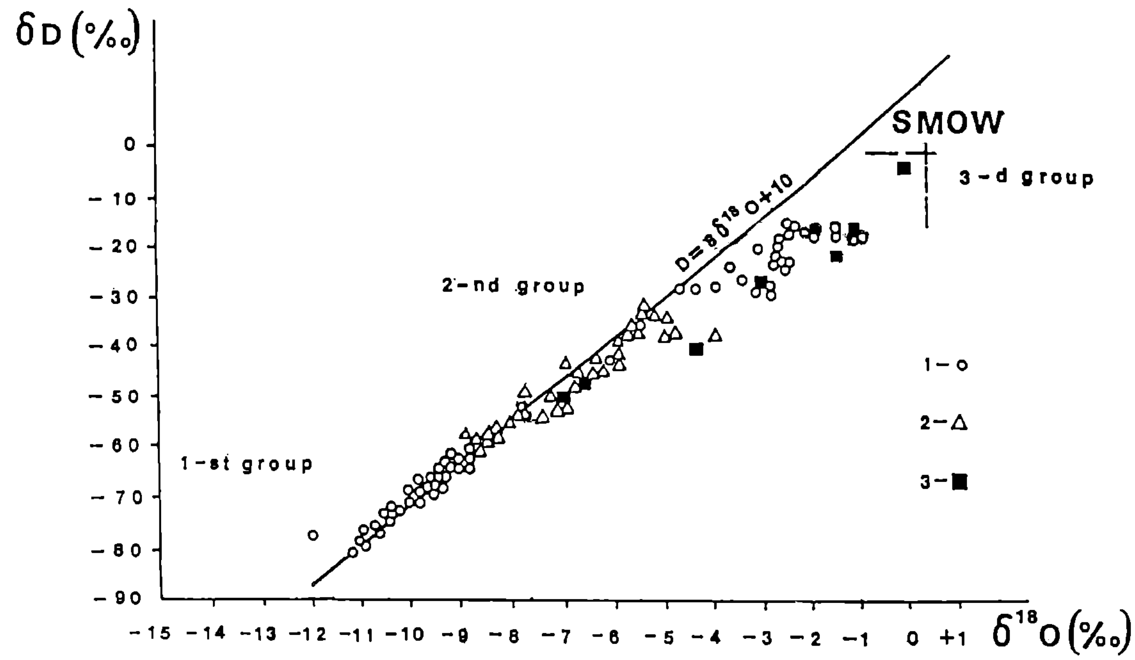


Fig. 7 $\delta^{18}O$ plotted against δD for USCB groundwaters. *1* – waters from Carboniferous under permeable cover (I-st region); *2* – waters from Carboniferous under impermeable Tertiary (II-nd region); *3* – waters from Tertiary formation

Współzależność $\delta^{18}O$ i δD dla wód podziemnych GZW. *1* – wody z karbonu pod przepuszczalnym nadkładem (I region); *2* – wody z karbonu pod nieprzepuszczalnym nadkładem trzeciorzędowym (II region); *3* – wody z trzeciorzędu

water mineralization (cf. Collins, 1975).

The zone of infiltration waters reaches the depth of about 300 m in the first hydrogeological region and 80 m in the second one. The lower boundary of the intermediate zone lies at depth of 450 - 600 m, 800 m at maximum, in the first hydrogeological region. The zone is about 200 - 300 m thick. In the second hydrogeological region, the lower boundary of this zone lies at depth of about 400 m, and its thickness attains about 320 m. The zone of buried brines underlies the intermediate zone. Hydrochemical studies (Różkowski *et al.*, 1989, 1991) have shown that brines occur at various depths in the USCB (Fig. 2), depending on the varying geological conditions and mining activity in the individual geological structures.

There is a general trend of increasing groundwater mineralization with depth, independently of the age of the rocks (Fig. 3). This general trend is disturbed by hydrochemical anomalies. The anomalies have been observed, among others, in the uppermost part of the Carboniferous series in the Carpathian Foredeep, near the Tertiary salt deposit in the Zawada Graben, and along some regional fault zones (Kleczkowski & Witczak, 1967; Pałys, 1966; Różkowski *et al.*, 1989, 1991). Antropogenic anomalies are due to mining activity (Różkowski, 1985; Różkowski & Kempa, 1993).

The variation of TDS zones in the USCB was studied on 1,233 chemical analyses of groundwater samples from mine works and boreholes. Seven hydrochemical regions have been distinguished within the Carboniferous strata of the USCB (Różkowski *et al.*, 1990, 1991). Hydrogeochemical gradients vary considerably between these regions (Table 2). The positions of the regions are shown in Fig. 2.

The first region is situated within the Gliwice folds (R1). The second one (R2) includes the western part of the Bytom syncline and the main antycline of the USCB, where mining works reach down to about 1,000 m. The third region (R3) covers the eastern part of the mentioned structures where mining works usually do not descend below 500 m. The Jejkowice and Chwałowice synclines lie in the fourth region (R4). The fifth (R5), sixth (R6) and seventh (R7) regions comprise the main syncline of the USCB. The area of the Tertiary Zawada graben which includes the salt deposit (R6), and the foredeep of the Carpathian Mountains ss. (R7) are distinguished within this structure. The remaining part of the main syncline belongs to the fifth region (R5).

Hydrogeochemical gradients were calculated using the recent data under natural conditions and those changed by mining activity (Table 2). The rate of increase in mineralization is uneven. Hydrogeochemical gradients in the depth intervals of 0 - 500 m and 500 - 1,000 m vary in separated structures from 2 to 8 $g \cdot dm^{-3} \cdot 100\ m^{-1}$ and from 6 to 65 $g \cdot dm^{-3} \cdot 100\ m^{-1}$, respectively (Różkowski *et al.*, 1989).

Spatial variation of the groundwaters mineralization is clearly visible on the hydrochemical maps

(Figs 2, 4, 5) and on the cross-section (Fig. 6).

ISOTOPE DATA

Isotope data indicate origin and residence time of groundwaters and of the depth of their occurence in the USCB. The isotope data (tritium and stable isotopes) permit also to recognize the effect of mining activity on the natural hydrochemical zonation and flow systems.

ISOTOPIC COMPOSITION AND ORIGIN OF GROUNDWATERS

The results of isotope investigations have shown that groundwaters of different origin and residence time can be distinguished in the USCB down to 1,200 m depth, i.e. to the maximum depth of coal mining (Pluta, 1988; Zuber & Pluta, 1989; Pluta *et al.*, 1993; Różkowski & Przewłocki, 1974, 1978, 1987; Zuber & Grabczak, 1985).

Stable isotope data (Fig. 7) allowed to asign the groundwaters to the four main groups: 1) meteoric waters of the last infiltration period, 2) mixed infiltration and paleoinfiltration waters, 3) paleoinfiltration waters of different age and 4) Tertiary synsedimentary waters (Różkowski & Przewłocki, 1987).

Groundwaters of the last infiltration period are of Holocene, Pleistocene and pre-Pleistocene age. Zuber & Grabczak (1985) and Zuber & Pluta (1989) have shown that Tertiary waters from the last stage of the last infiltration period occur in the Carboniferous strata at the depth of few hundred meters below the surface.

Meteoric waters of the last infiltration period were sampled from the Quaternary, Jurassic, Triassic and the uppermost parts of the Tertiary and Carboniferous strata. In the diagram at the background of precipitation line, described by the equation $\delta D = 8\ \delta^{18}O + 10$, one can distinguish infiltration waters whose projection points are plotting at the precipitation line (Fig. 7).

Meteoric waters of the last infiltration period squeeze out the relic waters and mix with them. Mineralized groundwaters which are a mixture of the relic and meteoric waters of the last infiltration period belong to the second group of waters distinguished on the precipitation line (Fig. 7). They have been found in Carboniferous (mainly) and in Tertiary strata.

Relic groundwaters occur in the deeper part of the Carboniferous strata. They are palaeoinfiltration waters of Permian age, according to Zuber & Grabczak (1985), Pluta (1988) and Zuber & Pluta (1989). They form a separate cluster at the precipitation line.

The present author also assigned the described waters to paleoinfiltration groundwaters (Różkowski & Przewłocki, 1974, 1987). Taking into acount the paleohydrogeological evolution of the USCB, one may accept the presence of younger paleoinfiltration waters (Różkowski *et al.*, 1979; Różkowski & Rudzińska-Zapaśnik, 1983) in the Carboniferous formation. The results of recent isotopic analyses by Pluta *et al.* (1993) confirmed this possibility.

Furthermore, considering geological history of the USCB, within deep Tertiary grabens, down to 1,000 m deep, we can postulate the occurence in the top part of the Carboniferous formation of pore waters squeezed out from Tertiary clays as a result of compaction and dehydration processes (Oszczypko, 1981). Though no isotopic evidence has been yet found for the presence of these waters, some hydrochemical data favour such supposition (Różkowski *et al.*, 1991).

A separate group of waters at the precipitation line (Fig. 7) represents synsedimentary Cl-Na saline waters of Tertiary age found by Dowgiałło (1973) in sandy intercalations within the Tertiary clays in deep Alpine grabens, at the depth of about 600 m.

Detailed studies on isotopic composition of groundwaters in the Carboniferous strata were carried out by Pluta (1988) and Zuber & Pluta (1989). An interpretation using both, the isotope and chemical data, enabled the authors to present a new identification of groundwater types. Taking into account their identification, contemporary infiltration waters of Holocene and Pleistocene age, have the $\delta^{18}O$ values varying from -12.1 to -9.0 per mill and δD from -78.0 to -67.9 per mill. In general, they belong to the multiions hydrochemical type of groundwater and their TDS ranges from 0.2 to a few g/dm^3.

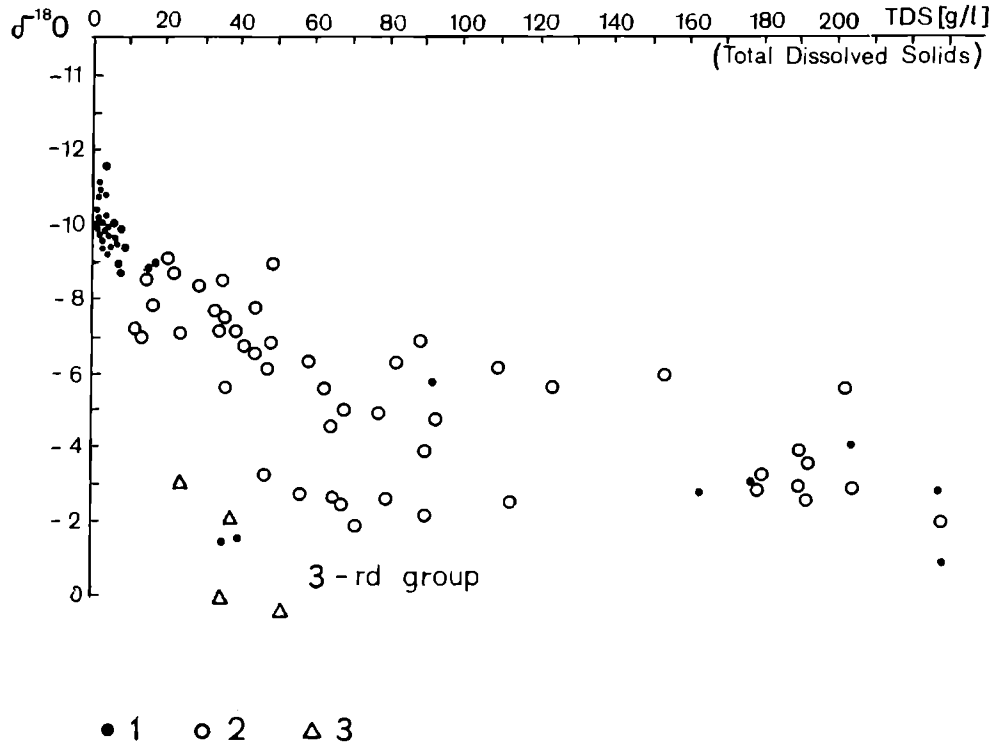
More detailed subdivision of contemporary infiltration groundwaters may be done by estimating tritium contents. Tritium content was estimated in more than 200 mining water samples taken from the areas of Carboniferous outcrops in the first hydrogeological region. Tritium contents exceeding detection limit were estimated down to the depth of 150 to 250 m, locally even deeper.

Tertiary infiltration waters, according to Zuber & Pluta (1989), are those in which $\delta^{18}O$ values vary from -6.2 to -8.1 per mill, and δD from -45.0 to -54.0 per mill. TDS values of these waters are up to 100 g/dm^3. The hydrochemical coefficients have the following values: $r(Na/Cl) > 0.83$ and $r(100 \times SO_4/Cl) > 1$. The depth of occurence of these waters, based on isotope characteristics, is down to 480 - 500 m.

Zuber & Pluta (1989) and Pluta (1988) include to the mixed type those waters which are: (i) a mixture of Tertiary waters of the last infiltration period with Quaternary waters, (ii) Tertiary waters mixed with buried brines. According to them the $\delta^{18}O$ values

Fig. 8 $\delta^{18}O$ values of groundwaters versus TDS. *1* – waters from Carboniferous under permeable cover (I-st region); *2* – waters from Carboniferous under impermeable Tertiary (II-nd region); *3* – waters from Tertiary formation

Współzależność wartości $\delta^{18}O$ i koncentracji soli w wodach podziemnych. *1* – wody z karbonu pod przepuszczalnym nadkładem (I region); *2* – wody z karbonu pod nieprzepuszczalnym nadkładem trzeciorzędowym (II region); *3* – wody z trzeciorzędu



range from -3.7 to -5.2 per mill and δD from -27.0 to -36.0 per mill. They are mainly brines of TDS values up to 160 g/dm^3. The depth of occurence of examined waters is down to 500 - 600 m. The position of stable isotopes values of groundwaters from the Tertiary strata at the precipitation line (Fig. 7) confirms the mixing process.

The examined buried paleoinfiltration brines in the Carboniferous formation, according to Zuber & Pluta (1989), and Pluta (1988) have $\delta^{18}O$ values from -1.4 to -3.8 per mill and δD from -16.9 to -26.0 per mill. The r(Na/Cl) coefficient has value < 0.75, while r(100 × SO4/Cl) < 1. The brines are highly mineralized, sampled already at the depth of 480 m in the second hydrogeological region and at 600 - 700 m in the first hydrogeological region.

EFFECTS OF MINING WORKS ON ISOTOPIC STRATIFICATION OF GROUNDWATERS

Mining activity is the fundamental factor modifying natural chemical and isotopic composition of groundwaters in the USCB. Deep penetration of low-TDS waters from the overlying horizons and of technological mine waters gradually desalinate paleoinfiltration brines and change their isotopic composition. The foregoing phenomena are intensified due to considerable recharge of Carboniferous horizons by atmospheric waters in the first hydrogeological region.

A close correlation exists between isotopic composition of groundwaters, groundwater mineralization in the Carboniferous strata, permeability of the overburden, and mining activity. The relation between $\delta^{18}O$ and TDS in vertical profile is shown in Fig. 8 and on the hydrochemical cross-section (Fig. 6).

The influence of geological and mining factors on the stable isotopic composition and groundwater mineralization in the USCB is shown on the sketch-maps of the groundwater mineralization and isotopic composition at the depth of 250 m (Fig. 4) and 500 m (Fig. 5) below sea level. A decrease in groundwater mineralization and stable isotopes values within the coal-mine fields is visible in these maps. This indicates mixing of groundwaters in these areas. As we can see in Fig. 4, the TDS values in the first hydrogeological region, where exploitation proceeds below the depth of 500 m (250 m below sea level), usually do not exceed 10 g/dm^3. Stable isotope values are typical for groundwaters of the last infiltration period, mainly of Quaternary age. An increase of TDS to 200 g/dm^3 and stable isotope values typical for the mixed and paleoinfiltration types are observed in the second region. The highest TDS value is noted in the place where Tertiary salt deposits are present atop the Carboniferous strata. Unfortunately, no isotope data are available for these waters.

The sketch-map of groundwater mineralization and isotope composition at the depth of 780 - 800 m (500 m below sea level) shows different relations (Fig. 5). The mineralized waters (below 10 g/dm^3), showing stable isotope composition typical for infiltrating waters, have been recognized only locally in the first

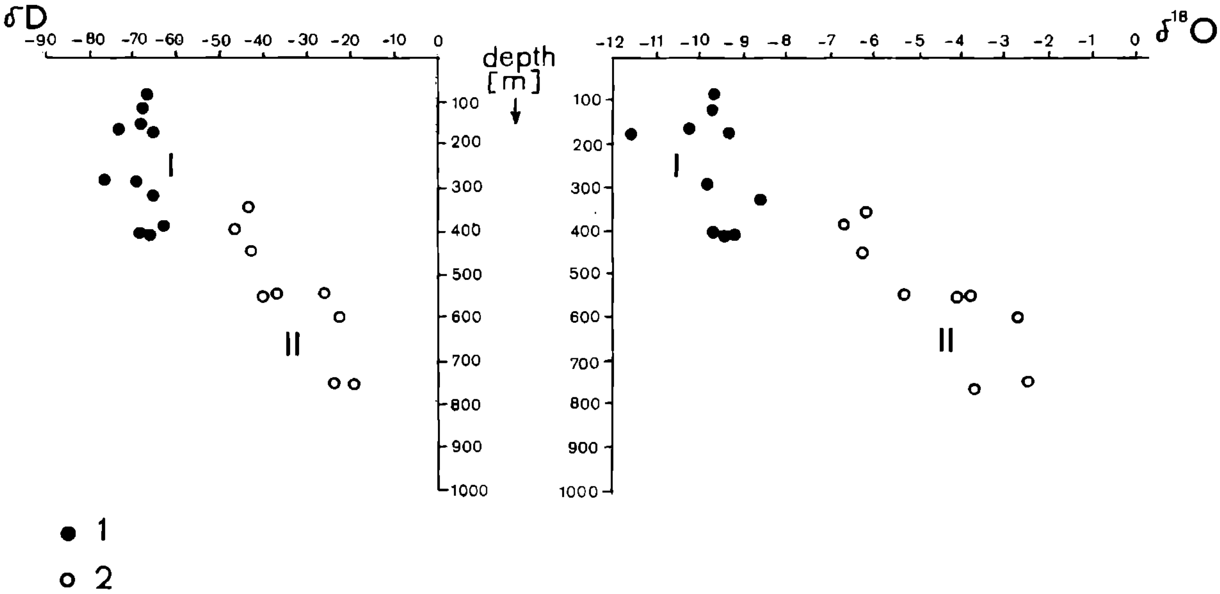


Fig. 9 Isotopic composition of groundwaters from the Westphalian formation. *1* – I-st hydrogeological region; *2* – II-nd hydrogeological region

Sklad izotopowy wód podziemnych w utworach westfalu. *1* – I region hydrogeologiczny; *2* – II region hydrogeologiczny

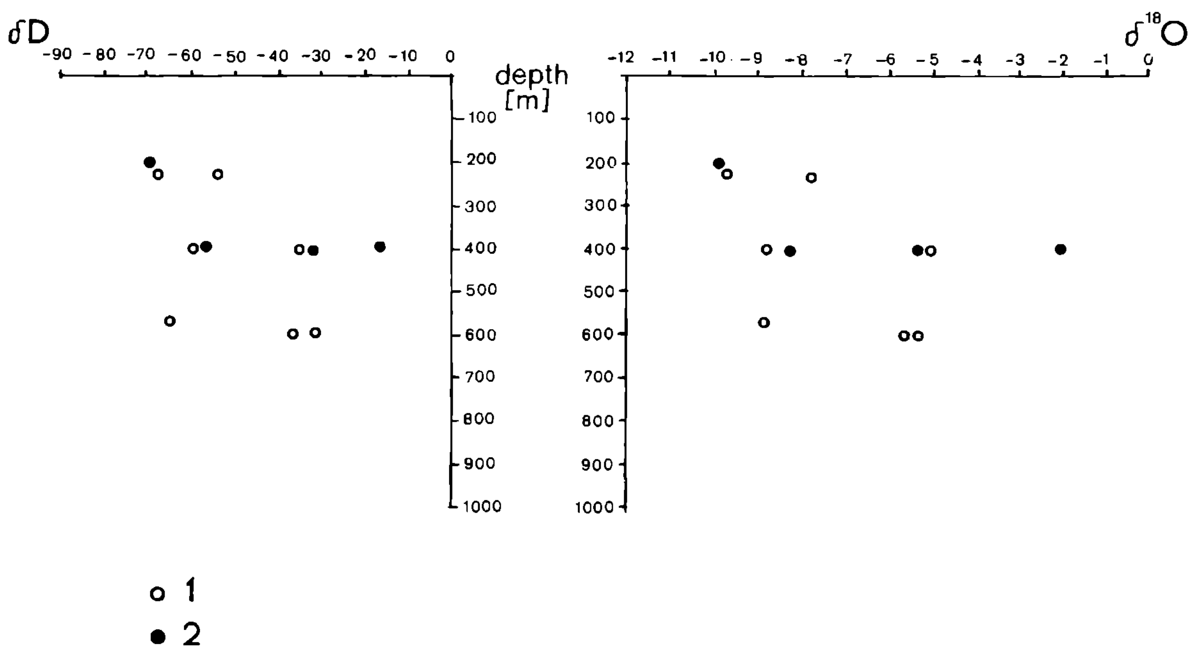


Fig. 10 δD and $\delta^{18}O$ versus depth. *1* – groundwaters from Jankowice mine; *2* – groundwaters from Marcel mine

Wartości δD i $\delta^{18}O$ w zależności od głębokości. *1* – wody podziemne z kopalni Jankowice; *2* – wody podziemne z kopalni Marcel

hydrogeological region, where the mining activity has taken place to the depth of 900 m or more, and lasted for a long time. Brines with TDS values of 110 - 190 g/dm^3, showing high values of stable isotopes ($\delta^{18}O$ -1.0 to -5.8 per mill and δD – 16.0 to -52.0 per mill) occur in the remaining part of the USCB. As for their isotopic composition, these brines belong to the mixed waters and paleoinfiltration groups.

Variation in stable isotope composition of waters in the Westphalian horizons, at the depths down to 800 m, are shown in Fig. 9. The values of stable isotopes are low in the recharge area (the first hydrogeo-

Table 3

Characteristics of flow systems in the USCB
Charakterystyka systemów przepływu wód w Górnośląskim Zagłębiu Węglowym

Flow systems	Depth of occurrence (m)	Depth of mining (m)	Geological formations	Hydraulic conductivity (m/s)	Groundwater mineralization (g/dm^3)	Hydrochemical coefficients		Gaseous chemistry zones	Isotope composition			Origin of groundwaters
						rNa$^+$/Cl$^-$	r100·SO$_4^{-2}$/Cl$^-$		T(TU)	δ^{18}O (‰)	δD (‰)	
Local	80-300	300	Q, T, M, C	10^{-4}-10^{-8}	below 4.0	above 1	above 1	N	above 2.0±1.5	-12.1- -9.0	-78.0- -67.9	1)
Intermediate	up to 240	-	T	10^{-5}-10^{-7}	3.0-31.0	1.0-0.87	below 1	N, CH$_4$	0.0	-8.1- -6.2	-54.0- -45.0	2)
Intermediate	up to 650	mainly up to 650	C	10^{-7}-10^{-8}	4.0-160	0.96-0.87	0.07-9.1	N, CH$_4$	0.0	-11.7- -5.2	-77.0- -36.0	3)
Regional	up to 1100	-	T	10^{-4}-10^{-8}	24-220	below 0.87	below 1	CH$_4$	0.0	+0.34- +0.70	-3.6- -1.2	4)
Regional	below 650-850	up to 1200	C	10^{-8}-10^{-11}	up to 372	0.72-0.96	below 1	CH$_4$	0.0	-1.0- -5.8	-16.0- -52.0	5)

Explanations:
Q - Quaternary
T - Tertiary
M - Mesozic
C - Carboniferous

1) infiltrating Quaternary waters
2) mixed waters of the last infiltration period with synsedimentary brines)
3) mixed waters of the last infiltration period with paleoinfiltration brines
4) synsedimentary buried brines
5) paleoinfiltration buried brines

Objaśnienia:
Q - czwartorzęd
T - trzeciorzęd
M - mezozoik
C - karbon

1) infiltracyjne wody czwartorzędowe
2) mieszane wody ostatniego okresu infiltracyjnego z solankami synsedymentacyjnymi
3) mieszane wody ostatniego okresu infiltracyjnego z solankami paleoinfiltracyjnymi
4) synsedymentacyjne solanki pogrzebane
5) paleoinfiltracyjne solanki pogrzebane

logical region). There occur mine waters belonging to the recent infiltration period of Quaternary age. Less negative values of stable isotopes, typical of mixed and paleoinfiltration types of groundwaters, have been observed in the Westphalian horizons under the impermeable cover of the Tertiary clays, in the second hydrogeological region. A general trend of increasing of heavy isotopes and TDS content in waters with depth is observed in the second hydrogeological region. Isotope composition of groundwaters sampled at the depth down to 420 m in the first region is much the same (δ^{18}O from -11.7 to -8.7 per mill and δD from -77.0 to -64.0 per mill). This is due to the replacement of waters in the mine area.

The chemical and isotope composition of groundwaters changes continuously during mine exploitation. This is clearly shown on the diagram of stable isotope values versus depth (Fig. 10). The samples of brines were collected from the mines Jankowice and Marcel at the same time, from the depth of 400 and 600 m. Waters sampled from the same depth have different isotope composition. So, e.g. the brine from the Jankowice mining level -400 m has isotope composition varying from δ^{18}O -2.0 to -8.3 per mill and δD from -18.0 to -62.0 per mill. It means that mixed and paleoinfiltration waters occur at the same depth. This is due to different timing of exploitation and drainage in separate mining fields at the same level.

Tritium analyses in the first hydrogeological region allow one to decipher the exchange process of mine waters in more detail (Różkowski, 1986). Tritium content of about 5 ± 2 TU is characteristic down to the depth of 150 m in the northeastern part of the USCB, outside the mining areas. Recently, mine waters with such a tritium content have been recorded at the depth of about 300 m in the same area. This indicates that the zone of young water distribution is about 100 - 150 m deeper. In the meantime, within the same area, mineralization of waters in one of the mines, at the depth of 300 m, decreased from 11.0 g/dm^3 in 1961 to 1.9 g/dm^3 in 1988, thus confirming active infiltration process of atmospheric waters into the mine workings.

FLOW SYSTEMS

The USCB may be classified as a Variscan artesian basin, according to the Pinneker's (1983) hydraulic criterion. Gravitational flow systems dominate in such old basins (Jeżow & Wdowin, 1970).

Three groundwater flow systems may be distinguished in the USCB according to the Toth's (1963) classification. The groundwater flow systems are controlled by topography of the basin and hydraulic conductivity of the rocks, through which the groundwater moves. Mining activity and, especially, mining drainage have recently become very important factors of flow system control.

The difference between the elevation of the recharge area and of the mining level determines the potential energy available to a unit mass to move it from a recharge area in the higher part of the basin to a discharge area in its lower part in the mining areas.

Hydraulic conductivity determines the rate at which a volume of groundwater will move through a section area of rock under hydraulic gradient. Stratification of Carboniferous sandstones controls the flow rate of groundwaters. This regularity is disturbed in mining areas.

The subdivision of groundwaters into flow systems in the USCB, proposed by the present author is somewhat arbitrary. The flow systems have been distinguished on the base of: (i) the earlier discussed variation of permeability in the Carboniferous section, (ii) the depth and activity of mining, (iii) hydrochemical and gaseous zonality, (iv) present-day hydrodynamic potential distributions and flow rates, and (v) environmental isotope data. The hydrochemical sequence (Chebotarev, 1955), described in terms of three main zones, correlated in a general way with depth (Domenico, 1972; Freeze & Cherry, 1979) was also taken into account.

It was assumed that the local flow system is characterized by active groundwater flow through the rocks. The intermediate flow system is described by less active groundwater circulation, while the regional flow system is characterized by a very sluggish groundwater flow, for length of time of millions years.

The travel distance and the time of flow tend to increase from the upper flow system to the lower one. The characteristics of the distinguished flow systems are shown in table 3.

A local flow system is developed in the zone of active groundwater replacement in Quaternary, Tertiary, Mesozoic and Carboniferous strata. The aquifers within this zone are well recharged and drained. Discharge level in the first hydrogeological region and in the areas of hydrogeological windows in the second hydrogeological region is mainly delimited by mining excavations which have drained the rock massif for a long period. Locally, the river valleys are the discharge areas of this flow system. The thickness of this zone varies within broad limits – from 80 to about 300 m – depending on criteria used to define it: the values of hydrochemical coefficients, low groundwater mineralization (below 1 g/dm^3), and isotope data. In the first hydrogeological region it usually attains 200 - 300 m and in the second one, covered by Tertiary sediments, less than 80 m.

An intermediate flow system is developed in the zone of hindered exchange and mixing of Quaternary and Tertiary waters of the last infiltration stage with buried brines. It occurs in the Tertiary and Carboniferous strata in which brackish, saline waters and brines occur. Mixing processes are intensified in this zone due to mining activity. The lower boundary of this zone, as determined by the values of hydrochemical coefficients and isotope data is located at the depth of 450 m to 650 m, with a maximum at 850 m, in the first hydrogeological region and in the areas of hydrogeological windows in the second region. The zone is about 200 - 350 m thick. In the second hydrogeological region, the lower boundary of this zone lies at the depth to about 450 m, while it is about 300 m thick.

A general trend of deepening and enlargement of the infiltration and intermediate zones is observed during the last 40 years due to deeper exploitation and intensive mining drainage (Różkowski, 1985; Różkowski *et al.*, 1989, 1991; Różkowski & Kempa, 1993; Wilk *et al.*, 1990).

The regional flow system occupies the zone of buried stagnant brines of paleoinfiltration origin. The upper boundary of this zone lies at the depth of 450 - 850 m (Fig. 2), in Carboniferous strata in the first hydrogeological region and in the lower part of Tertiary grabens and in Carboniferous strata in the second region.

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Streszczenie

Czynniki wpływające na stan wód podziemnych w karbońskich osadach Górnośląskiego Zagłębia Węglowego

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W pracy podsumowano wyniki kompleksowych badań hydrogeologicznych Górnośląskiego Zagłębia Węglowego (GZW) w aspekcie określenia głównych czynników kształtujących reżim wód podziemnych w utworach karbonu produktywnego.

Opis warunków hydrogeologicznych karbonu produktywnego oparto na analizie wyników badań geologiczno-strukturalnych, laboratoryjnych i polowych pomiarów parametrów hydrogeologicznych karbońskich poziomów wodonośnych, pomiarów ciśnień złożowych wód podziemnych oraz oznaczeń ich składu chemicznego i izotopowego.

Uwzględniono również działalność górnictwa węglowego. Górnośląskie Zagłębie Węglowe (GZW) położone jest w zasięgu waryscyjskiego zapadliska międzygórskiego. Utwory karbonu produktywnego w północno-wschodniej części zagłębia przykryte są przepuszczalnymi utworami triasu i czwartorzędu, zaś w południowej i zachodniej części – praktycznie nieprzepuszczalnymi utworami trzeciorzędu (Fig. 1, 6).

Hydrogeologiczne warunki GZW są kształtowane przez czynniki geologiczne i eksploatację górniczą kopalń węgla kamiennego. Aktywność wpływu eksploatacji górniczej jest uzależniona od rozmiarów, głębokości, czasu i systemu eksploatacji. Poeksploatacyjne spękania i zeszczelinowanie skał zwiększają przepuszczalność górotworu oraz przerywają izolujące poziomy. Górnictwo węgla kamiennego na skalę przemysłową rozwija się w zagłębiu od drugiej połowy XIX wieku. Przeciętna głębokość kopalń wynosi ok. 650 m, natomiast maksymalna głębokość ok. 1200 m (Fig.1). Wyrobiska górnicze stanowią obecnie główną podstawę drenażu karbońskich poziomów wodonośnych. Zasięg oddziaływania górnictwa wzrasta z biegiem lat, co powoduje stałe pogłębianie się strefy aktywnej i utrudnionej wymiany wód.

Do najważniejszych czynników geologicznych kontrolujących reżim wód podziemnych w utworach karbonu produktywnego należą:

1) występowanie izolujących utworów trzeciorzędu w stropie karbonu (Fig. 1),

2) obecność serii osadów chemicznych w utworach trzeciorzędu (Fig. 1), 3) blokowa tektonika i zeszczelinowanie górotworu, 4) obniżanie się wartości własności hydrogeologicznych skał karbonu z głębokością na skutek procesów diagenezy (tab. 1).

Uwzględniając warunki zasilania karbońskich poziomów wodonośnych obszar zagłębia podzielić można na dwa regiony hydrogeologiczne (I, II). Zasięg regionów określa granica występowania nieprzepuszczalnych utworów trzeciorzędu. Zasilanie poziomów wodonośnych odbywa się w zasięgu I-go regionu hydrogeologicznego położonego w NE części zagłębia, oraz poprzez okna hydrogeologiczne w regionie II-gim (Fig. 1, 2).

Wodonośność utworów karbonu związana jest z występowaniem wkładek piaskowców w kompleksie iłowcowo-mułowcowym. Obserwuje się wyraźny trend obniżania się wartości własności hydrogeologicznych piaskowców wraz z głębokością. Poniżej głębokości 700 - 800 m ppt są to skały praktycznie nieprzepuszczalne i niewodonośne.

Badania środowiska hydrogeochemicznego wskazują na występowanie w GZW normalnej strefowości hydrochemicznej zaburzonej działalnością górnictwa, występowaniem stref ascenzji wód podziemnych wzdłuż stref regionalnych dyslokacji i oddziaływaniem złoża soli w utworach trzeciorzędowych.

Ogólna mineralizacja wód jest zmienna w granicach 0.5 - 372 g. dm^{-3} i posiada trend wzrostu z głębokością (Fig. 3). Wysoko zmineralizowane solanki typu Cl-Na-Ca występują w strukturach pogrzebanych, w skałach zbiornikowych praktycznie nieprzepuszczalnych. Działalność górnictwa powoduje wysładzanie się wód na skutek obniżania się podstawy drenażu, spękania górotworu i aktywnego drenażu (Fig. 4, 5, Tab. 2).

Wyniki badań hydrochemicznych, hydrodynamicznych oraz izotopowych wód pozwoliły na umowne wydzielenie w profilu karbonu produktywnego 3 stref przepływu (Tabela 3):

1) lokalny, drenowany przez rzeki oraz płytkie wyrobiska górnicze, do głębokości maks. 350 m. Prowadzi on wody słodkie i słabo zmineralizowane – holoceńskie i plejstoceńskie;

2) pośredni, którego podstawa drenażu położona jest na głębokości ok. 650 m, tj. na przeciętnej głębokości eksploatacji górniczej. Prowadzi on wody ostatniego etapu infiltracyjnego mieszające się z pogrzebanymi solankami paleoinfiltracyjnymi;

3) regionalny, obejmujący strefę stagnacji hydrodynamicznej. Prowadzi on solanki paleoinfiltracyjne.

Należy podkreślić, iż zasięg stref przepływu w poszczególnych strukturach geologicznych jest zmienny, w zależności od budowy geologicznej i aktywności górnictwa.

Stwierdzona stratyfikacja izotopowa wód (Fig. 7-10) jest odzwierciedleniem strefowej zmienności przepuszczalności skał, izolacji karbońskich poziomów wodonośnych przez trzeciorzędowy nadkład, drenażu wód wzdłuż regionalnych stref dyslokacji, oraz działalności górnictwa.

Obserwowane różnicowanie się składu izotopowego wód kopalnianych w okresie ostatnich dwudziestu lat wskazuje na zmieniający się w czasie zasięg stref hydrodynamicznych. Jest to warunkowane zwiększającą się glebokością wyrobisk górniczych i intensywnością drenażu. Pompowanie przez kopalnie węgla kamiennego około 1 mln m^3 wód na dobę jest podstawowym czynnikiem obserwowanych zmian strefowości hydrochemicznej, dynamicznej i izotopowej.