Groundwater system of Grodziec Syncline in Iwiny region (SW Poland) 10 years after abandonment of dewatering in "Konrad" mine

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Abstract Grodziec Syncline is situated on Kaczawskie Foothills in vicinity of Bolesławiec Town (Lower Silesia, SW Poland). The "Konrad" mine stopped the exploitation at the end of 1989 after 37 years of activity and its dewatering was suspended in 2001. The natural effect of long-term mining drainage was large cone of depression in Zechstein water-bearing horizon and indirectly in Quaternary aquifer due to hydraulic connection. The "Konrad" mine flooding began at 2001 in two stages. During the first stage the dewatering pumps were switched off on 830 and 650 excavations levels and after then in second stage on 550 and 240 excavations levels. After 2001 water from old mine workings which observed at piezometers AQ-1, AQ-2 and shafts K-I, K-II became more acid and more contaminated by high sulphates and iron concentration. Nearly 10 years after abandonment of dewatering in "Konrad" mine the cone of depression started to refill. Groundwater table level of Zechstein aquifer increases about 16 mm/d in shafts piezometers (K-I, K-II) and about 10—16 mm/d in others. There are no significant changes in Quaternary aquifer yet.

Key Words mining drainage, cone of depression, groundwater chemistry, ion ratios

Introduction

Grodziec Syncline is situated on Kaczawskie Foothills in vicinity of Bolesławiec Town (Lower Silesia, SW Poland) (fig. 1). The exploitation in this area included copper-bearing Zechstein marls and marly limestones. The beginning of exploitation took place in 1940, due to K-II shaft of "Konrad" mine launching. Few years after that, "Upadowa Grodziec" and "Lubichów" mines were opened. The copper exploitation in this region has been held for almost 50 years, till the end of 1989, when "Konrad" mine operation was suspended.

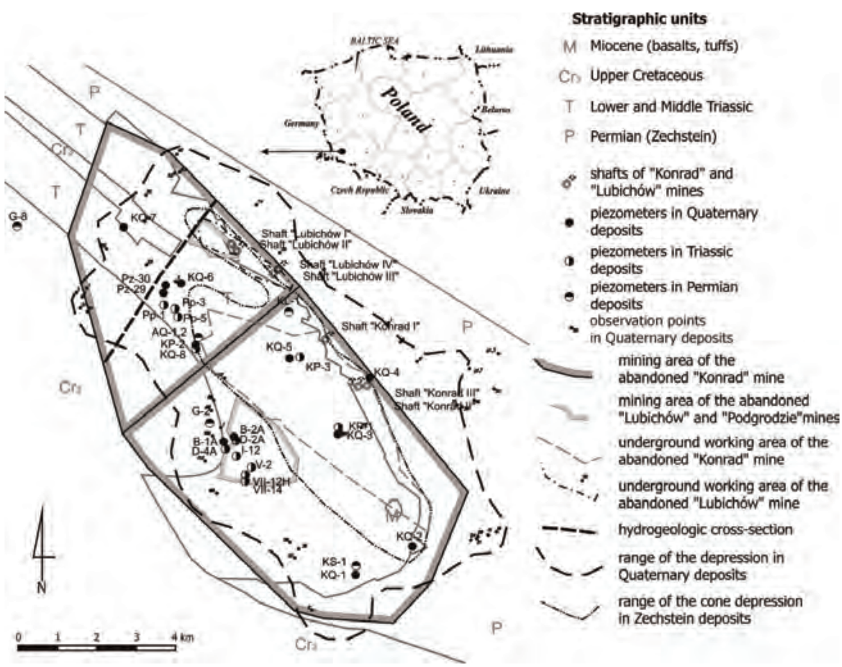

***Figure 1** Groundwater monitoring network on geological map of Grodziec Syncline without Quaternary deposits.*

Hydrogeological conditions

"Konrad" mining enterprise is located in the area of Grodziec Syncline (NE part of North Sudetic Trough). The Grodziec Syncline is filled with Permian, Triassic and Upper Cretaceous sediments, underlain by crystalline older Paleozoic bedrock (Piestrzyński, 1996). Permian and Mesozoic rocks are covered by glacial and fluvioglacial Quaternary deposits (fig. 1, 2).

In terms of hydrogeology, three multiaquifer formations in Grodziec Syncline area can be distinguished: Quaternary, Permian and Mesozoic (Wilk, Bocheńska, 2003). Quaternary aquifer, which includes Pleistocene and Holocene sands and gravels, lies directly on Mesozoic rocks (fig. 2). Mesozoic formation is made of three aquifers: Upper Cretaceous, Muschelkalk and Buntsandstein. Upper Cretaceous aquifer, composed of sandstones, stays in hydraulic connection with fractured Muschelkalk limestones, lying directly below. Buntsandstein aquifer, hosted in fine-grained sandstones, can be considered as the most capacious groundwater reservoir of Grodziec Syncline. Permian water-bearing formation includes Rotliegend sandstone aquifer, as well as Upper and Middle Zechstein aquifers. Groundwater of Upper Zechsteinian deposits is contained inside fine-grained sandstones and dolomites. "Kaczawski" dolomite is charged with groundwater from Quaternary formation through its outcrop and with groundwater from Buntsandstein formation in tectonic areas. Middle Zechstein aquifer are represented by fractured and porous limestones, with average thickness of 30 m. The porosity of carbonate deposits is equal to 13.5%, and their hydraulic conductivity varies from 0.1 to 31 m/d. Middle Zechstein aquifer, because of its good hydraulic properties and hydraulic connection with Quaternary aquifer, was responsible for water inflow into the mine and water table recovery after exploitation ending.

Grodziec Syncline area is characterized by strong tectonic engagement. The faults, with their NW-SE orientation, caused breaking of Zechstein formation into blocks, and its vertical and horizontal dislocation. This phenomena had an impact on groundwater cycle and allowed various aquifers and deposits layers to become connected with water-bearing rocks.

The boreholes, located directly inside the main excavation, were used for systematic mining drainage. "Konrad" mine disposal began in 2001, through two-stage excavations flooding. During the first stage, the dewatering pumps were switched off on 830 and 650 excavations levels and after then in second stage on 550 and 240 excavations levels. In order to water table level observations, shafts K-I and K-II were adapted. In 2001, before mine flooding, four drainage holes on 830 excavation level were put in the sewer, which was connected with two boreholes AQ-1 and AQ-2.

Hydrodynamic

Hydrodynamic conditions at a time of flooding start-up

The Middle Zechstein aquifer has been dewatering for almost 50 years, including 10 years of dewatering after "Konrad" mine closure. The deposit was entirely dewatered in this period of time, to the depth of 650 m in its marginal zone and 800 m in central region. During the copper exploitation in "Konrad" mine, mine-water inflow was equal to 7 m^3/min in 1952 and rose up to 46 m^3/min in 1988. The area of totally dewatered Middle Zech-

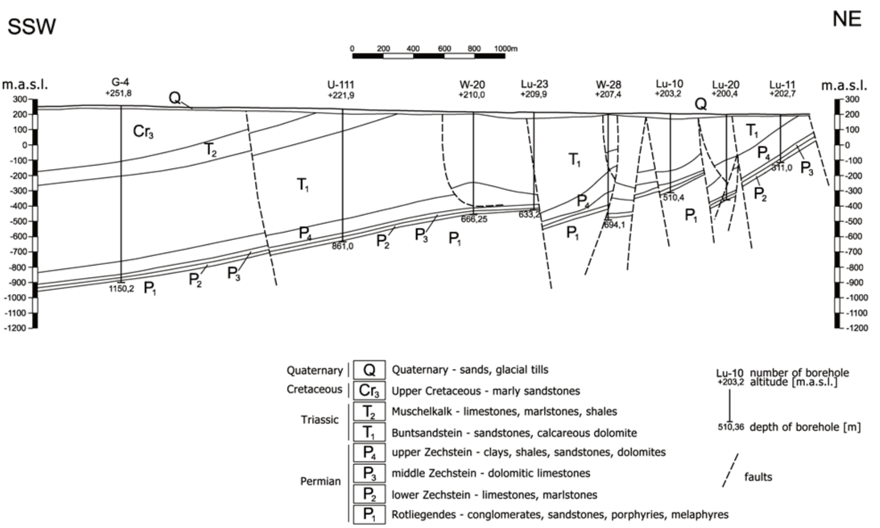

Figure 2 *Hydrogeological cross section of the Grodziecka Syncline.*

stein deposits accounted to 29 km² (fig.1). The long-lasting drainage of this horizon, in regard of the nature of hydraulic connections, caused overlying layers dewatering, including Quaternary aquifer. The large-scale observation possibilities covered only the Quaternary aquifer, thus on the basis of field studies, the cone of depression was calculated on 64 km² (fig.1).

"Konrad" mine flooding prediction

For 10 years after the end of exploitation in "Konrad" mine, dewatering of excavations has been still keeping, due to providing local people with drinking water. 42 m³/min of water has been pumping, to fill drinking water demand equal to 3 m³/min. On account of economic aspects, the forecast of hydrogeological effects of "Konrad" mine flooding has been developed (Fiszer and Kijewski, 2004).

The prediction was supported with numerical model of Grodziec Synline, created using the computer program based on finite-element method (FEM). Model calibration was designed, based on the method of successive approximation, consisted of proper filtration parameters selection, relevant to "Konrad" and "Lubiechow" mine-water inflow and pressure in Middle Zechstein limestone horizon, measured in drainage holes on 830 and 650 excavation levels.

The prognosis of water table rise in "Konrad" mine workings was developed, providing deep well water intake equal to 5 m³/min and 3 m³/min, as well as without intake (fig.3).

According to preceding forecast, the water table in "Konrad" mine excavations should reach the Quaternary deposits outcrop level, placed about 180 meters a.s.l, in K-I shaft region.

Hydrodynamic conditions 10 years after abandonment of dewatering

For the last 10 years, every aquifer in "Konrad" mine has been systematically monitored, especially Middle Zechstein and Quaternary horizons (fig.1). During the year 2010, water table level in 78 different boreholes has been observed.

One year after switching the pumps off, water table in excavations increased about 591 m (70% of the largest exploitation depth). During the whole 10-year period, the groundwater table level in "Konrad" mine workings increased about 805 m (97% of the largest exploitation depth), so there was barely 27% water increment. The average daily water table level rise, in period from January 2001 to January 2002, was equal to 1,62 m and varied between 10—15 m/d during first two months and 1 m/d at the end of 2001. Annual groundwater table rise turn out to be slower year after year (fig. 3), and finally stabilized at the level of 6 m/a in 2009—2010 period. At the end of 2010, average daily water table rise in excavations, monitored in K-I shaft, was equal to 0,02—0,05 m/d. In the second half of 2009, water table level in K-I shaft and AQ-1 piezometer exceeded 180 meters a.s.l. (datum level, Quaternary outcrop level). According to preceding forecast, the excavation filling happened with 2,5-year delay (fig.3). The water table in piezometers and shafts within old cone of depression (AQ-1, G-2, K-I, K-II) was placed at the same level as the water table outside the cone of depression (G-8) (tab. 1). It can be the evidence of restoration the water conditions in Zechstein aquifer.

Water table level of Triassic water bearing complex is placed higher than water table level of Zechstein aquifer (between 190—215 meters a.s.l.), and

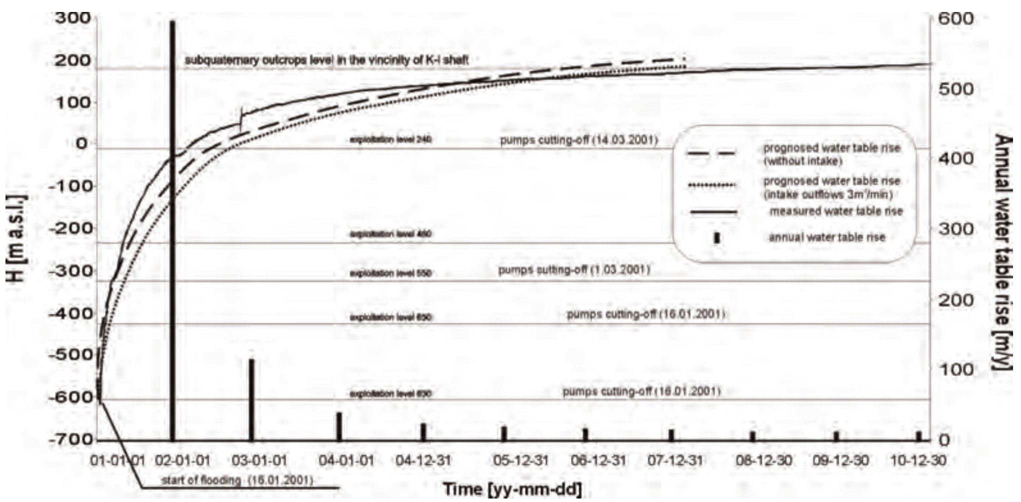

Figure 3 Predicted and measured raising of the water level in flooded "Konrad" mine workings. (due to: Fiszer and Kijewski 2004, modified)

Table 1 *Groundwater table level in Zechstein aquifer on 8.11.2010.*

Number	Type	Groundwater table level [m a.s.l.]
AQ-1	piezometer	187,24
G-2	piezometer	188,16
G-8	piezometer	189,73
K-I	shaft	188,02
K-II	shaft	188,15
KL-1	piezometer	168,08
KS-1	piezometer	173,49

there is no upward trend observed. There is also no significant impact of "Konrad" mine flooding on Triassic groundwater resources restoration so far. The same pattern can be noticed in respect of the Quaternary reservoir. Most of the wells and piezometers, drained in the process of dewatering, remain dry, while the rest of them don't indicate reaction to hydrodynamic changes in Zechstein aquifer. The main factors affecting water table level fluctuations in Quaternary aquifer are atmospheric conditions and precipitation (Kisielewicz, 2010).

Hydrogeochemistry

The groundwater of Quaternary aquifer belongs to highly mineralized, low acid and acid water, and indicates following water types: SO_4-HCO_3-Ca-Mg, HCO_3-SO_4-Na-Ca, or HCO_3-SO_4-Ca-Mg. At first, the hydrochemical changes were noticed in KQ-7, KQ-1 and KQ-2 piezometers, located it the marginal zone of the cone of depression. Water of Triassic aquifer belongs to HCO_3-Ca-Mg, SO_4-Cl-Ca-Mg and HCO_3-SO_4-Na-Ca water types. Mineralization balances in the range of 114—1208 mg/dm³, and pH values vary from low acidic to low alkaline. Before mine flooding, HCO_3-Ca-Mg and SO_4-Ca-Mg water types in Zechstein aquifer were dominant, and after 2001, the third type (SO_4-Cl-Na-K) appeared.

Groundwater mineralization increase (above 2000 mg/dm³) and decline in pH can be observed in almost every borehole. Significant contamination with sulfates and iron becomes more common. Groundwater, occurring in K-I and K-II shafts, is the mixture of water from every aquifer, so it has to be considered separately. It also has a reflection on groundwater types: SO_4-Ca-Mg, SO_4-Na-K and HCO_3-Na-K, or HCO_3-Na-Ca. Mineralization reaches 2056 mg/dm³, and pH value 11,72 (highly alkaline). Considering hydrochemical ratios ($r\frac{Na^+}{Cl^-}$ and $r\frac{Na^+ + K^+}{Cl^-}$), it could be assumed, that chemical composition of water of Triassic and Zechstein aquifers (before 2001) was formed in the active water exchange zone (tab. 2). After dewater ing abandonment, $r\frac{Na^+}{Cl^-}$ values indicated dy namic and hydrochemical groundwater stagnation in Zechstein aquifer, and the water mixing zone within Quaternary horizon.

The values of $r\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$ for groundwater of Zechstein aquifer are higher than 0,5. In the same aquifer, before 2001, saturation index values for calcite ($-2,8<SI_{cal}<0,16$) and dolomite ($-6,96<SI_{dol}<0,2$) indicated non-saturated state. The similar phenomena could be observed in AQ-1 and AQ-2 piezometers (after 2001), with range of SI values: $-2,86<SI_{cal}<-0,31$ for calcite and $-6,23<SI_{dol}<-0,51$ for dolomite. In other piezometers and wells, the semi-saturated state could be noticed.

The groundwater of Quaternary and Triassic formations, with $r\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$ >0,5, characterizes silicate minerals weathering (Hounslow, 1995). On the other hand, the values of $r\frac{Ca^{2+}}{SO_4^{2-}}$ and $r\frac{Ca^{2+}}{Ca^{2+} + SO_4^{2-}}$ (tab. 2) suggest the

Table 2 *Values of ion ratios in groundwater of Grodziec Syncline.*

	Middle Zechstein Groundwater (before 2001) (n=43)		**Middle Zechstein Groundwater (after 2001)** (n=63)		**Triassic Groundwater** (n=68)		**Quaternary Groundwater** (n=37)	
Parameter	mean	standard deviation	mean	standard deviation	mean	standard deviation	mean	standard deviation
r Na^+/Na^++Cl^-	0,603	0,642	0,090	0,219	0,491	0,164	0,464	0,068
r Na^+/Cl^-	1,697	0,868	3,100	2,656	1,290	1,168	0,895	0,240
r Na^++K^+/Cl^-	2,047	1,034	4,055	3,498	1,699	1,501	1,183	0,366
r $Ca^{2+}/Ca^{2+}+SO_4^{2-}$	0,604	0,149	0,503	0,318	0,621	0,135	0,572	0,114
r SO_4^{2-}*100/Cl^-	929,319	973,849	496,174	583,409	443,766	417,750	471,580	342,639
r Ca^{2+}/SO_4^{2-}	1,952	1,273	24,301	53,259	2,220	2,093	1,564	0,925
r $Mg^{2+}/Mg^{2+}+Ca^{2+}$	5,790	3,857	7,117	6,491	5,130	2,835	4,617	2,039

other potential sulphates sources, different than gypsum and anhydrites dissolution (Hounslow, 1995). Although the values of $r\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$ and $r\frac{SO_4^{2-}*100}{Cl^-}$ don't indicate sulphates solution (tab. 2), such phenomena is highly possible.

SI values against sulphates, for every examined aquifer, indicate non-saturated state ($2{,}86<SI_{gyp}<-0{,}13$; $6{,}09<SI_{anh}<-0{,}63$). In Middle Zechstein aquifer, additional source of SO_4^{2-} ions can be copper and iron sulphides oxidation, which also explains higher Fe concentration (fig. 4). The sulphides oxidation leads directly to water acidification in the area of polymetallic deposits exploitation, called Acid Mine Drainage (AMD) (Wolkersdorfer, 2008). The iron sulphides oxidation causes Fe^{2+} and SO_4^{2-} concentration increase in groundwater (incomplete oxidation or only sulphates oxidation), and iron hydroxides (complete oxidation) (Appelo and Postma 2005). The sulphides oxidation is the cause of pH decrease in groundwater, as demonstrated by the analysis of AQ-1 and AQ-2 piezometers. In the environment buffered by carbonates dissolution, pH of solution decreases to the value of 5. Wolkersdorfer (2008) proves, that it is possible for carbonate mixture to buffer water pH values from 4,8 to 6,5. For calcite and dolomite, solution pH values range from 6,5 to 7,5. In KL-1, KS-1, G-2 and G-5 piezometers (fig.1), the water pH reaches maximum values of 9—12. It is caused by the fact that the piezometers are situated outside the "Konrad" mining area and the deposit has block structure, which significantly reduced the reach of AMD effect. The process of water mixing in all aquifers in the K-I and K-II shafts has caused that the chemism is the result of diffusion processes.

Conclusion

Nearly 10 years after "Konrad" mine flooding startup, it can be certified, that all mine excavations are fully filled with water. After the period of rapid water table rise in the first year after switching the pumps off, the next few years brought decreasing flooding rate. Currently the flooding rate is stabilized at low level of about 0,02—0,03 m/d. In the middle of 2009, the groundwater table, measured in shaft holes, reached the depth of Quaternary outcrops and signalized water resources restoration in Zechstein aquifer. By now, there is no significant impact of hydrodynamic mine flooding on overlying multiaquifer formation.

Hydrogeochemical changes, caused by "Konrad" mine flooding, applied only the groundwater from old mine workings, observed in piezometers AQ-1 and AQ-2. The groundwater of Zechstein aquifer became more acid and more contaminated with sulphates and iron. In piezometers located outside the excavations, groundwater alkalinity increment, due to carbonates dissolution, could be recorded.

References

Appelo C.A.J., Postma D. (2005) Geochemistry, Groundwater and Pollution. Balkema, Rotterdam, Brookfield.

Hounslow W. (1995) Water quality data. Lewis Publ. New York.

Fiszer J., Kijewski P. (2004) Prognoza i przebieg zatapi-

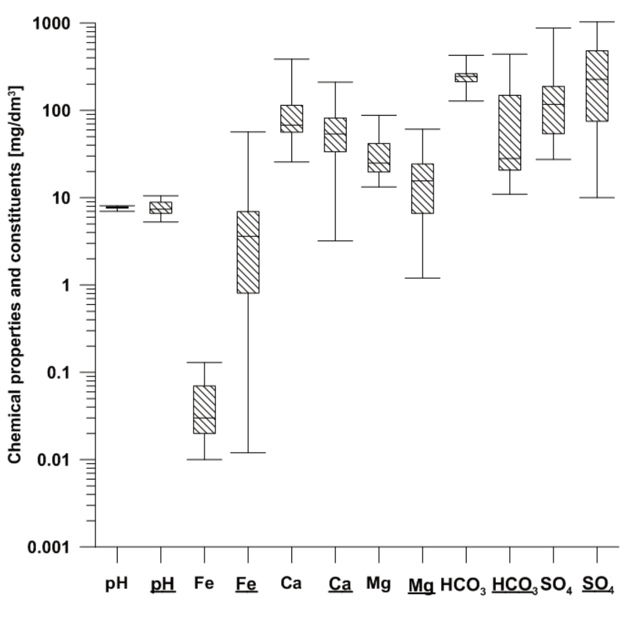

Figure 4. Statistical parameters of chemical properties and constituents in groundwaters of Zechstein aquifer. Chemical properties and constituents [mg/dm³]. Diagrams shows minimum-maximum values, 1-st & 3-rd quartile values and median value. Underline properties and constituents concerns to the period after 2001.

ania kopalni rud miedzi “Konrad” w Iwinach. In: Problemy hydrogeologiczne gornictwa rud miedzi. Seminarium naukowo-techniczne. TKP. Z O w Lubinie, KGHM Polska Miedź w Lubinie, Lubin, p:81—88

Kisielewicz Z. (2010) Ocena wpływu zatapiania kopalni Konrad na zmianę warunków geologicznych i hydrogeologicznych w leju depresji utworzonym przez były O/ZG Konrad w aspekcie likwidacji obciążeń z tytułu szkód górniczych, etap II. KGHM Cuprum (not published)

Piestrzyński A. (Edt.) (1996) Monografia KGHM Polska Miedż S.A. Wyd. CPBM Cuprum Sp. z o.o., Wrocław.

Wilk Z., Bocheńska T. (Edts.) (2003) Hydrogeologia polskich złóż kopalin i problemy wodne górnictwa. Tom 2. Wyd. Naukowo-Dydaktyczne AGH, Kraków.

Wolkersdorfer Ch. (2008) Water Management at Abandoned Flooded Underground Mines. Springer-Verlag Berlin Heidelberg.