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***Preliminary investigation on temperature, chemistry and isotopes of mine water pumped in Bytom geological basin (USCB Poland) as a potential geothermal energy source.***

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## Abstract

Mine water from both operating and abandoned mines can be used for individual space heating projects, district heating/cooling systems or for preheating air for mine ventilation. Examples of such applications are already known from Canada, US, Netherlands, UK, and Spain. The Upper Silesian Coal Basin (USCB) in Poland, where 34 of 65 hard coal mines have been abandoned since 1989, represents a potentially large opportunity for mine water heating schemes. This paper describes the mines from Bytom (northern USCB) as a potential location for ground source heat extraction projects. Hydrogeological and hydrogeochemical studies of pumped waters have been carried out in order to better understand the potential of the Bytom heat resource. The monitoring program is still ongoing, but initial results compare favorably with existing mine water geothermal source systems where water temperatures are comparable or lower than those found at Bytom. Initial hydrochemical and isotope data demonstrate stability in water composition at most of the monitoring points. These data elucidate the hydrogeological cycle during active dewatering and provide a baseline for understanding the geothermal behavior of the system, which is crucial for optimizing heat extraction. Preliminary results also reveal very stable mine water temperatures in the pumped, and hydrologically connected, Szombierki system and suggest remarkable stability in the characteristics of the main hydrothermal reservoirs.

**Keywords**: mine water, isotopic analysis, heat recovery, thermogeology, geothermal energy

## 1. Introduction

Coal mining in the Upper Silesian Coal Basin (USCB), located in southern Poland and representing the nation's largest coalfield, has been transformed over the last few decades, largely due to mine closures and associated abandonment flooding. Since 1989, 34 of the 65 hard coal mines in the USCB have been abandoned and the remaining collieries have been forced to adopt a free-market approach. In 2014 the restructuring process of the polish mining industry reached its second phase and 5 further hard coal mines are going to be closed down due to economic and technical problems (depletion of coal deposits etc.). In the Bytom Syncline (northern USCB) intensive underground exploitation of coal and Zn-Pb ore since the 19th century has changed the local groundwater flow and chemistry regime.

Much of the northern USCB is characterized by complicated geological and mining conditions that create intricate and potentially interconnected hydrological systems. Due to these connections, abandoned mines have to be continually dewatered so as to maintain safe working water levels in adjacent active working mines. Dewatering of abandoned mine workings is conducted using pumping systems in open air, exposed voids (stationary pumping) or deep-well systems in inundated, submerged voids (submersible pumping). Pumping of abandoned mines, from 15 unique pumping systems, contributes over 1/3 (80 million $m^3$/year) of total direct mine water discharge (230 million $m^3$/year) into local USCB river catchments. Mines can essentially be classified as: operating with constant dewatering during coal exploitation; or non-operating, but dewatered, for purposes of protecting adjacent mines interconnected with abandoned and partially flooded workings. Most of the mines in the USCB are interconnected directly or indirectly by drifts, boreholes, goaf, roadways or intact coal barriers of limited thickness. In most mines, water enters as infiltration from the surface, as groundwater from adjacent, overlying or underlying aquifers or from adjacent older mine workings, or as process water (Hall, et al 2011). In an operating mine, this water is usually removed by some form of pumped dewatering operation to prevent the mine from flooding. Many non-operating mines are still being pumped, and will be for many decades, either to protect still-operating mines or for environmental protection purposes (guarding against pollution or mine gas issues; Younger et al. 2002). As such, an opportunity arises to extract energy from these waters, enhancing the sustainability of long-term pumping. Some abandoned mine overflow at the surface, and such uncontrolled discharges are often highly polluted.

Due to Poland's historical dependence on coal for energy generation, alternative energy sources are largely underdeveloped. Realizing the potential of mine waters as a low enthalpy geothermal resource represents a key challenge for the Polish mining industry if it is to contribute to local heating demand. In order to understand the true potential of abandoned mine workings as a sustainable, low-carbon, and relatively low cost heat source it is important to define the provenance, physiochemical characteristics, and hydrological transport history of resident mine waters at sites of particular interest. After mine abandonment, dewatering is continued to protect hydrologically connected low-lying coal deposits and active mines from water inundation. The significant costs associated with dewatering, which include the pumping process itself and environmental fees for mine water discharge to surface water, provide a key incentive for mining operators to explore the use of mine water heating/cooling systems. To better understand the potential of abandoned and dewatered coal mines as a heat resource, preliminary hydrogeological and hydrogeochemical studies of an active pumping system in the northern USCB are presented. Mine water from both operating and abandoned mines can be used for individual space heating projects, district heating/cooling systems or for preheating air for mine ventilation. Such applications offer the possibility of converting the popular perception of coal mines as an unsightly, potentially polluting environmental liability, to a "green", low carbon source of clean renewable energy.

Given the extensive history of coal mining across Europe, the potential exists to unlock a resource that will make a major contribution at a local scale to reduce the costs of operations using heat from mine water and contribute to a decrease of $CO_2$ emissions. Examples of such applications from around the World are already known. Watzlaf and Ackman (2006) have reviewed the applications existing by 2006, such as: Springhill, Nova Scotia, Canada; Park Hills, Missouri, United States; Shettleston, Scotland, United Kingdom; as well as Lumphinnans, Scotland, United Kingdom. Mine water heating and cooling systems are operating at Heerlen, Netherlands (Minewater Project, 2008; Ferket et al., 2011; Verhoeven et al., 2014). In Mieres, Asturias, Spain, mine water from Barredo shaft is used by HUNOSA mining company also for both heating and cooling (Loredo et al., 2011; Klinger et al., 2012; Jardón et al., 2013). Recently, in Markham Colliery just north of Bolsover, Derbyshire, Alkane Energy is also using geothermal heat from mine (Athresh et al., 2015, 2016). Last, but not least: in the abandoned Saturn coal mine, several kilometers from Bytom in the USCB, there is also a recent example of using mine water for heating purposes (Tokarz and Mucha, 2013).

Our study focuses on the abandoned but continuously dewatered Szombierki coal mine and the adjacent Bolko Zn-Pb mine within the EU Coal and Steel project: Low-Carbon After-Life (LoCAL). We report preliminary data from a monthly monitoring programme of hydrochemistry, physiochemistry (T, conductivity, pH) and stable isotopes (H, O and S). First results from the sampling campaign reveal relatively high temperature and stable chemistry parameters of mine water from the Szombierki pumping system and indicate good potential for considering the use of mine water for geothermal purpose.

## 2. Study area

The study area is located in the Bytom Syncline, in the northern part of the Upper Silesian Coal Basin in Poland. Records of coal mining in Bytom Syncline date back to the 16th Century, with initial shallow workings of coal mines and Zn-Pb ore mines. The area of mining exploitation (active and abandoned) and dewatering fields covers c. 60 $km^2$ and has an average altitude of 270 – 295 m asl, with a maximum depth of mining exploitation of c. 900 m bgl (-630 m asl). Active exploitation of coal is conducted in three mining fields (Bobrek, Centrum and Piekary), and dewatering of abandoned mines is continued in Powstańców Śl – Bytom I, Szombierki (coal mines) and Bolko – (Zn-Pb mine) (Figure 1).

Bytom city is massively influenced by the legacy of historic subsurface mining, surface subsidence has reached 14-32m in some locations and the present morphology and hydrology of surface water courses is largely a result of the local mining activities (Czaja and Chydzik, 2005). The study area is located on the border of the watersheds of two major polish rivers Wisła (with its tributary Szarlejka river) and Odra (with tributary Bytomka river). Mining has significantly affected the water regime of these rivers, moreover, there is frequent water loss in upper courses of the rivers. Mine water discharges in this area have changed the chemistry of natural streams and rivers, with negative consequences for the quality of surface water bodies. Local climate is typical for the moderate cold climate of southern Poland, with average temperature in winter -3.3$^{o}$C (January) and in summer 18.6$^{o}$C (July). According to the Köppen Climate Classification System the area is classified as *Dbf* - moist continental mid-latitude climate with warm to cool summers and cold winters (Pidwirny, 2006). The Silesian Region is the second largest region in Poland, after the Masovian district and capital city – Warsaw, and has a very high population density (374 people/$km^2$). In Bytom city, population density at the end of 2014 was 2484 people/$km^2$ (Demographic yearbook of Poland, accessed 12.10.2015), while average population density in Poland is 123 people/$km^2$. The public demand for power and water in the USCB region is one of the highest in the entire country.

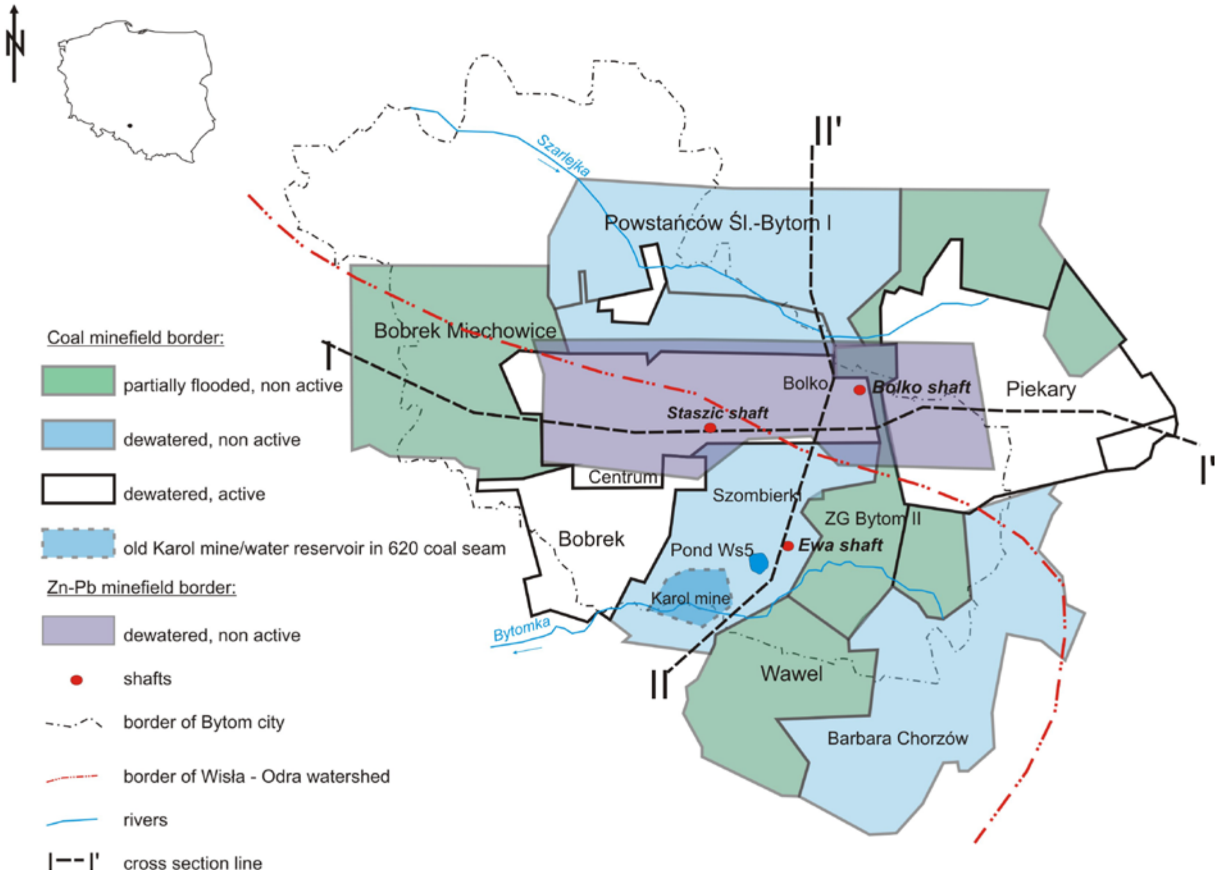


**Figure 1. Location of study area in Northern part of USCB – Bytom Syncline.**

### 2.1. Geology and hydrogeology of study area

The Bytom Syncline was formed at the end of the Carboniferous Period in an area of intense sedimentation where thick successions (a few km) of sandstone, mudstone, limestone and conglomerate were deposited. As a result of folding, a syncline with relatively steeply dipping limbs developed. Coal bearing formations of the coal basin are connected with molasse deposits of the Pennsylvanian (Upper Carboniferous, Namurian-Westphalian). Post-Carboniferous sedimentation includes Triassic and Quaternary deposits. Triassic deposits are mainly limestone and dolomite, and contain Zn-Pb ore deposits formed by an Early Cretaceous hydrothermal event (Heijlen et al., 2003).

The USCB is split into two hydrogeological subregions based on geological structure: the north-eastern (I) and south-western (II) (Różkowski A, 1995; Różkowski K et al., 2015). A boundary between these two subregions follows the extent of a continuous cap of clayey Miocene isolating deposits. The study area is located in the first subregion, where Miocene deposits are absent; therefore the infiltration of meteoric waters is much easier than in the case of the second subregion. The main groundwater aquifers in the Bytom area are present in Triassic and Carboniferous rocks. A simplified geological map of study area is shown in figure 2.

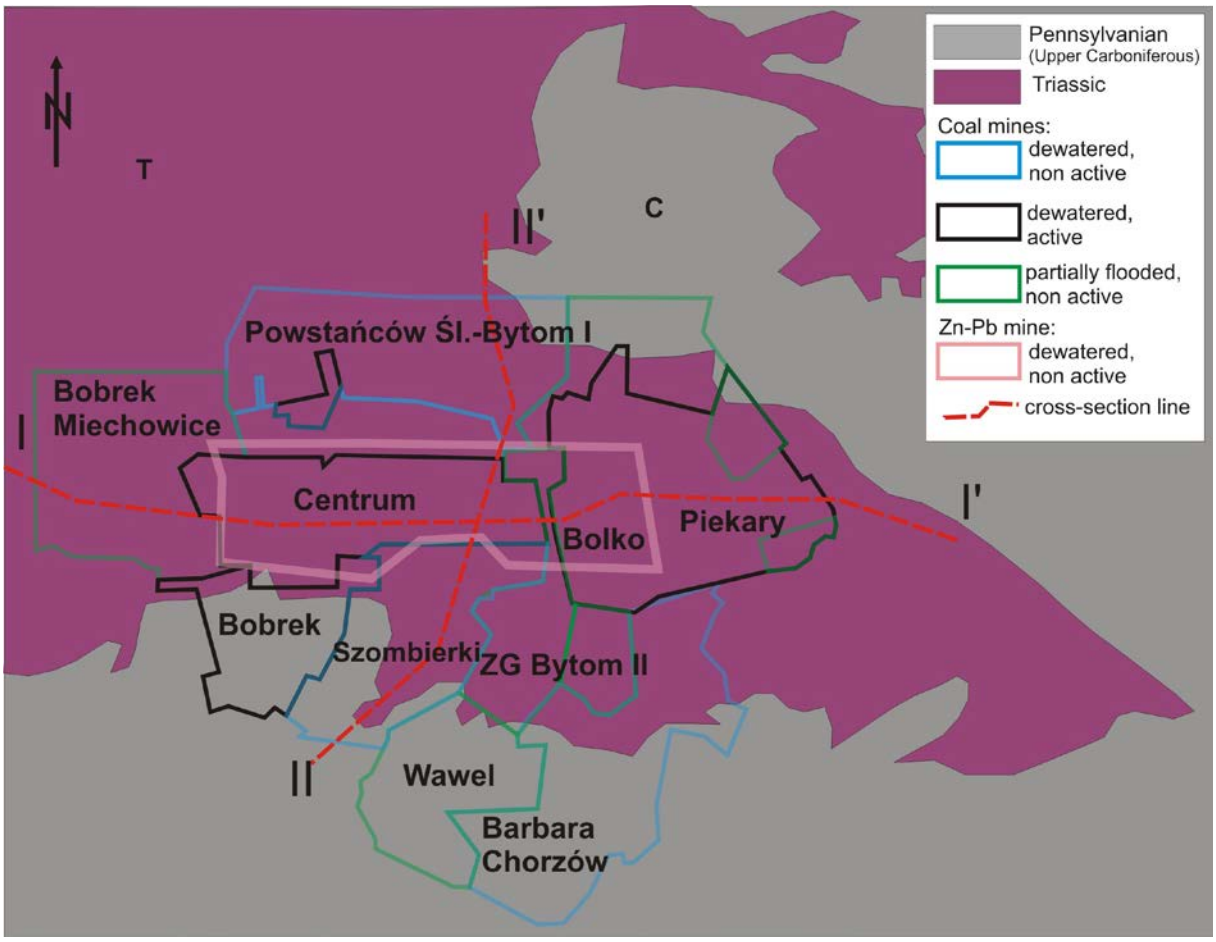


**Figure 2. Simplified geological map of study area (without Quaternary) redrawn from Geological Map of Poland 1 : 200 000, Gliwice, Kraków.**

The Triassic aquifer is of a fissured-karst type; formed by a 150 m thick series of Lower (Roet) and Middle (Muschelkalk) Triassic limestones and dolomites. The Carboniferous aquifer is of a fissured-porous type and is formed by a series of intercalated Upper Carboniferous sandstones, mudstones and coal seams. However, the feature that currently dominates groundwater conditions within both Triassic and Carboniferous strata of the Bytom area is the long history of underground mining. The Triassic strata have been mined down to over 120 m bgl for Pb-Zn ores (Figure 3 and 4). The underlying coal-bearing Carboniferous strata are still exploited down to over 900 m bgl. However, zinc and lead mining in this area is no longer active, and coal mine production is reducing. Nonetheless, the mine galleries are still being pumped in order to protect either the surface environment or the adjacent mines from flooding.

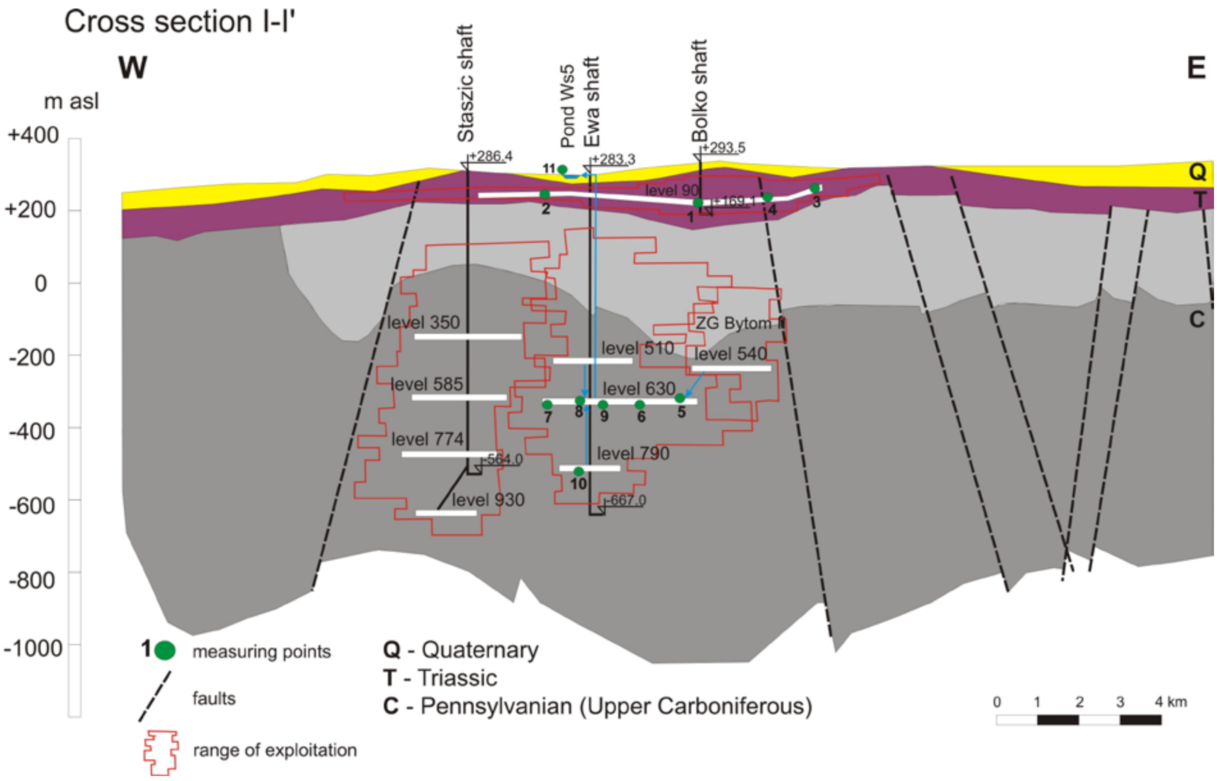


**Figure 3. Cross section WE redrawn and adapted after Kropka, Respondek (2000).**

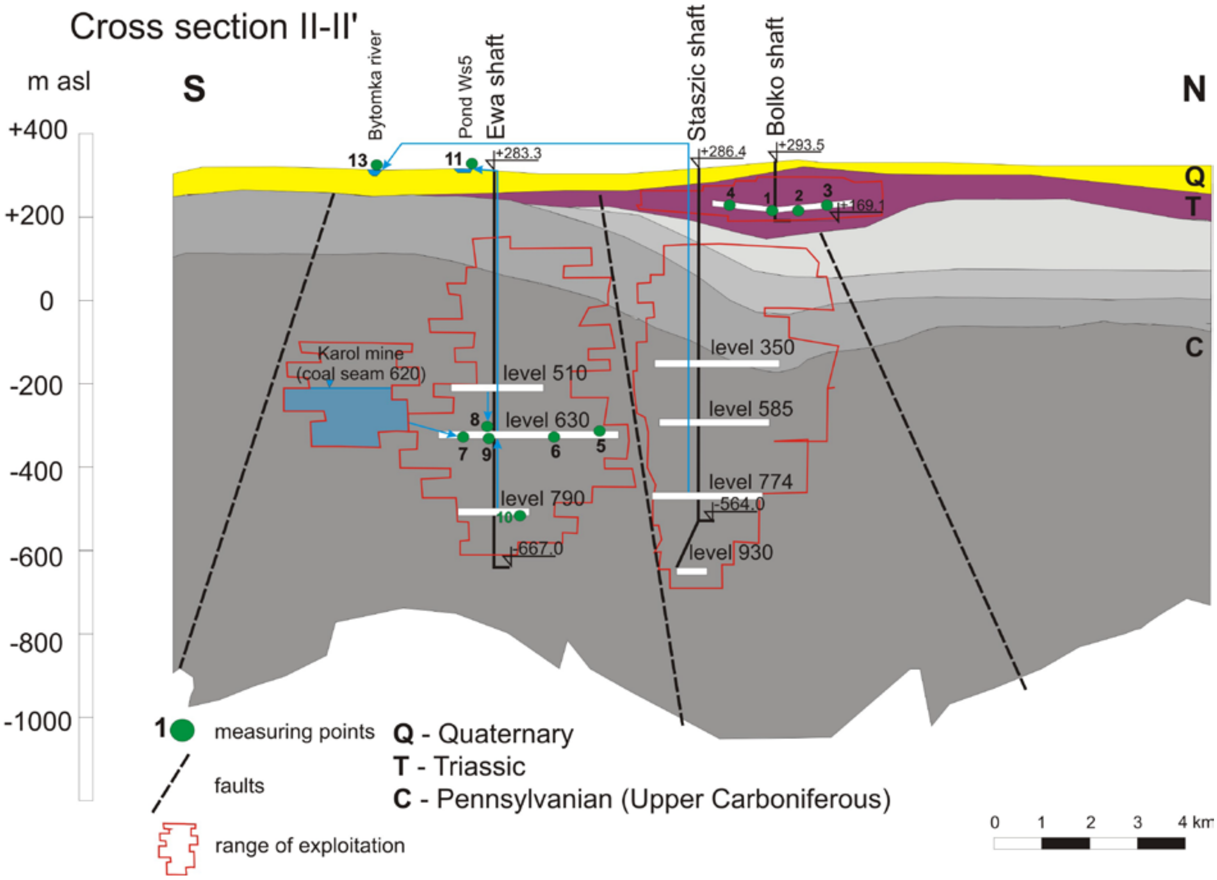


**Figure 4. Cross section SN redrawn and adapted after Kropka, Respondek (2000).**

Exploitation of the deeper coal seams began in the mid-19th Century, in the German territory of Poland (tri-partite division of Poland between Austria, Germany and Russia). The Szombierki mine was established in 1870 from several smaller coal fields, and mined a total area of 10.3 $km^2$ over nearly 150 years. Coal exploitation ended in 1999 with continuous dewatering of mine workings interconnected with the adjacent active KWK Bobrek-Centrum and ZG Bytom II mines. During operation of the Szombierki coal mine, No 418 and 419 seams were exploited in Rudzkie Beds (with total sulfur content 1.0%), No 507/510 seams were exploited in Siodlowe Beds (with total sulfur content up to 0.7%) and seam No 620 in Poreba Beds (with total sulfur content 0.8%) (Dokumentacja hydrogeologiczna, 2000).

Due to a connection between Centrum and Szombierki at 840 m bgl it was necessary to keep the water table below this level to protect the active mine against water flow exceeding the capacity of its pumping system. In 2002, the Szombierki dewatering system was taken over by the Central Department of Mine Dewatering (CZOK), which is responsible for dewatering of abandoned mines all over the USCB. In 2004, the ZG Bytom II mine was closed down, and pumping was ceased until mine water was redirected to the pumping station on level 630 m of the Szombierki dewatering field. Since 2007, pumped mine waters from Szombierki and ZG Bytom II (total area 17.4 $km^2$) have been discharged to Ws5/65 reservoir and Bytomka river.

Mining and dewatering of large areas have been associated with Zn-Pb and Ag ore related Triassic strata since the $12^{th}$Century (Czaja and Chydzik 2005). Abandonment of Zn-Pb mines in the Bytom Syncline in 1978 resulted in the need for continuous dewatering of Zn-Pb workings to protect surface and low-lying coal deposits and excavations.

### 2.2. Pumping system in abandoned coal mine Szombierki in Bytom Syncline

The pumping system in the abandoned Szombierki mine (Figure 5) continuously dewaters the excavations of Szombierki, ZG Bytom II and the old Karol mine (water from reservoir in coal seam no.620). There are three active dewatering levels: 510 m (-225.3 m asl), 630 m (-345.6 m asl), 790 m (-507.9 m asl), and a main pumping station on level 630 m. Mine water from the Ewa shaft is discharged to pond Ws5 and ultimately the Bytomka river.

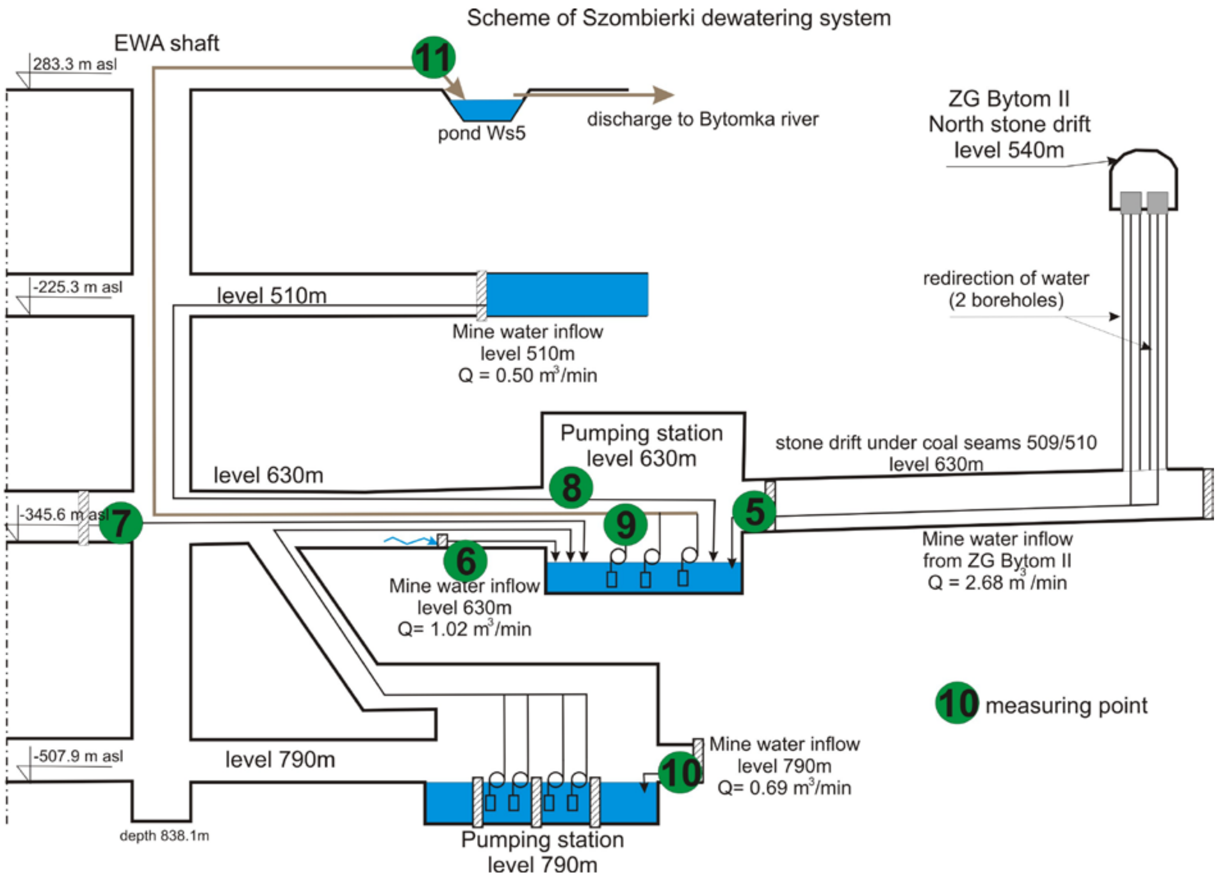


**Figure 5. Scheme of Szombierki dewatering system.**

The most important direct connection between Szombierki mine and active Centrum mine is located on level 840 m (-470 m asl.). The water table in the abandoned mine is kept beneath this 'over-spill' connection. According to Polish geological and mining regulations monitoring of the quantity and quality of mine water inflows and discharge is the responsibility of the operator – Central Department of Mine Dewatering (CZOK).

## 3. Methods

For the purpose of the present study, archive data were collected from the period of coal exploitation, end of exploitation, changes of dewatering system and redirection of water from adjacent ZG Bytom II from 1995 to the present day, with average year inflow [$m^3$/min] to pumping system given as total mine water inflow to mining area (excavations, galleries and pumping system).

Chemistry parameters of Szombierki mine waters were monitored at characteristic inflow points on each level. Available archive data from active mines and CZOK monitoring (CZOK reports) covered 1996-2013 and were measured mostly twice a year at underground measuring points and four times a year at the discharge point to Ws5/65 pond. Collected historical data were analyzed as background investigations and aided planning of monitoring for current parameters of mine waters in study area. Taking into consideration the range of parameters determined in archive analyses and the purpose of the present study, the sampling campaign encompassed two underground pumping systems: Szombierki and Bolko. While the Szombierki dewatering system is considered as a potential geothermal heat source, the Bolko pumping station and Centrum mine were taken into account as background investigations of the hydrogeological cycle of mine water and mixing of waters from different strata to determine factors which can impact main source of geothermal energy. In May 2015, before the start of sampling campaign, an initial environmental site inspection was completed. During the site inspection all potential sampling points were photographed and documented (as recommended by Jacobs et al., 2014) and preliminary field measurements of temperature, conductivity and pH were recorded.

Measuring points are marked on Figures 3, 4 and 5. Sampling points in Bolko pumping station are representative for different Zn-Pb old mining fields and generally are divided into two main directions of mine water inflows: Eastern and Western. Szombierki pumping station is considered with special awareness as the main source of water for heat recovery installation, and numerous measuring points were located in underground workings. Samples are representative for different levels or main inflow points from different underground reservoirs with varied quantity and quality parameters.

| Number of measuring point (figure 2,3) | Description and location |
|---|---|
| 1 | Main pumping station (124.4 m depth), Bolko shaft, mixed water from Zn-Pb abandoned mines – Central Pumping Station Bolko |
| 2 | Isolating dam no 2 – Western gallery, Central Pumping Station Bolko |
| 3 | Isolating dam no 4 – Eastern gallery, Central Pumping Station Bolko |
| 4 | Isolating dam no 3 – Eastern gallery, Central Pumping Station Bolko |
| 5 | Inflow point from ZG Bytom II, level 630 m, Ewa shaft, Szombierki pumping station |
| 6 | Inflow to level 630m, Ewa shaft, Szombierki pumping station |
| 7 | Inflow from abandoned Karol mine (reservoir in coal seam No. 620), level 630m, Ewa shaft, Szombierki pumping station |
| 8 | Inflow from level 510 m (measuring point on level 630 m), Ewa shaft, Szombierki pumping station |
| 9 | Main pumping station on level 630 m, Ewa shaft, mixed water from Szombierki pumping station |
| 10 | Inflow to level 790 m, Ewa shaft, Szombierki pumping station |
| 11 | Discharge point to Ws5 pond from Szombierki pumping station |
| 12 | Meteoric waters (Jaworzno or Bytom) |
| 13 | Discharge from Centrum mine to Bytomka river |

**Table 1. Measuring points in pumping systems in Bytom Syncline.**

Sampling parameters preferred for mine water studies were taken into account according to recommended sampling strategies (Jacobs et al., 2014; Watson, 2005). Parameters measured in the field (temperature, pH, conductivity, and dissolved oxygen), were determined immediately after sampling with the use of WTW Multi 340i handheld meter. Alkalinity of water samples was determined in the field using MColortest$^{TM}$ MerckMillipore.

Parameters determined in the laboratory (with procedures of sampling preservation: 0,45µm filtration) for each sample were major ions: $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO_4^{2-}$,$NO_3^{-}$, redox indicators Fe and Mn, minor constituents Br, Sr, Ba and total hardness. Laboratory standard procedures such as ion chromatography (IC) and atomic emission spectrometry with inductively coupled plasma (ICP–OES) were used for analytics of $Br^-$, $Cl^-$, $SO_4^{2-}$ and $NO_3^-$ (IC) and Fe, Mn, Ba, Sr, Ca, Mg, Na, K (ICP–OES) respectively.

Stable isotopes of $\delta^{18}O$, $\delta^2H$ and $\delta^{34}S$procedures of sampling and analytics are fully detailed in Burnside et al. (2016) within this journal volume.

Underground sampling was carried out every two months from June to November 2015, and further sampling is planned up to June 2016. Additionally, samples of mine water discharges from Szombierki pumping station to pond Ws5/65 and Centrum mine to Bytomka river were taken every month; and regular meteoric waters from Bytom and Jaworzno (eastern boarder of USCB) were taken with relation to regional climate changes (summer/winter periods).

## 4. Preliminary results and discussion

In complex hydrogeological environments affected by mining the effective management of dewatering operations and possible mine water use can be most confidently achieved if the mixing dynamics induced within the aquifer by pumping are well understood. Recently published work (Elliot and Younger, 2013) has demonstrated the utility of using natural tracer patterns (temperature, conductivity, major ions and stable isotopes of O, H and S) to elucidate the dynamics of mixing and thermal transfer when previously-stagnant flooded workings are suddenly pumped again.

Mine water parameters were measured during coal exploitation, and have continued to be monitored following closure and subsequent continuous dewatering. Archive data of average total mine water inflow are taken from hydrogeological documentation after mine closure (Dokumentacja hydrogeologiczna, 2000), and from CZOK monitoring data (CZOK reports). Average year inflow changed after redirection of water from closed ZG Bytom II, in general total inflow is stable and does not correlate with annual precipitation (Figure 6), measured at the nearest weather station Katowice-Muchowiec (IMGW data, access 20.10.2015).

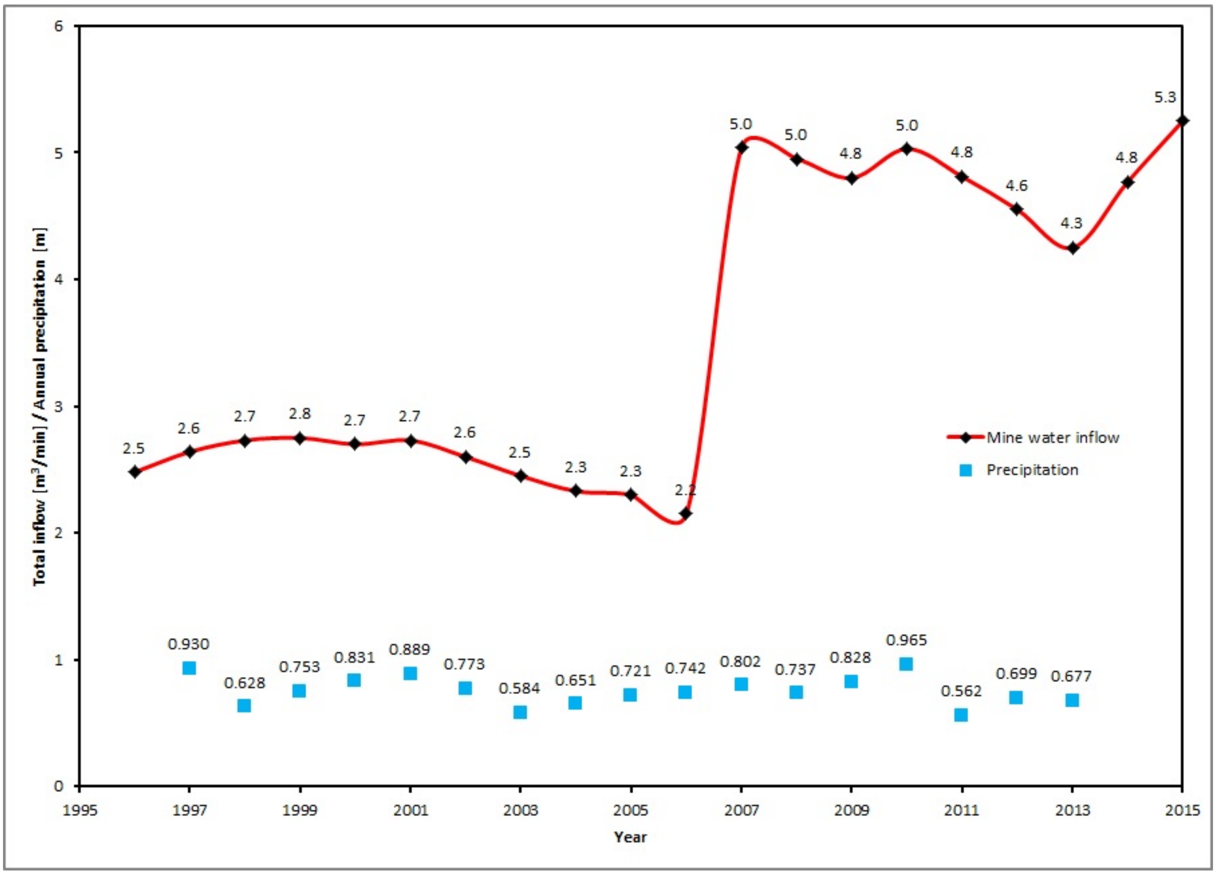


**Figure 6. Mine water inflow to Szombierki mine and annual precipitation in monitoring station Katowice – Muchowiec (IMGW data).**

Szombierki mine water chemistry was monitored at characteristic inflow points on each level. Available archive data from active mines and CZOK monitoring (CZOK reports), covering 1996-2013, revealed general trends of increasing chloride and sodium with depth, as well as total dissolved solids. However, the typical hydrogeochemical regime for the first hydrogeological sub-region in USCB, as seen in Szombierki, indicates that Pennsylvanian (Upper Carboniferous) formation deep waters become fresher with time. It is caused by deep, continuous and intensive mine drainage of the Carboniferous sequence with simultaneous active infiltration of water from Quaternary formation (Różkowski K. et al., 2015). Moreover, sulfate-rich waters occurred on level 510 m (-225.3 m asl) while the deepest inflow was of Cl-Na type (Figure 7). Comparison with first results of sampling demonstrate that chloride and sulfate values have remained very stable on each level during dewatering.

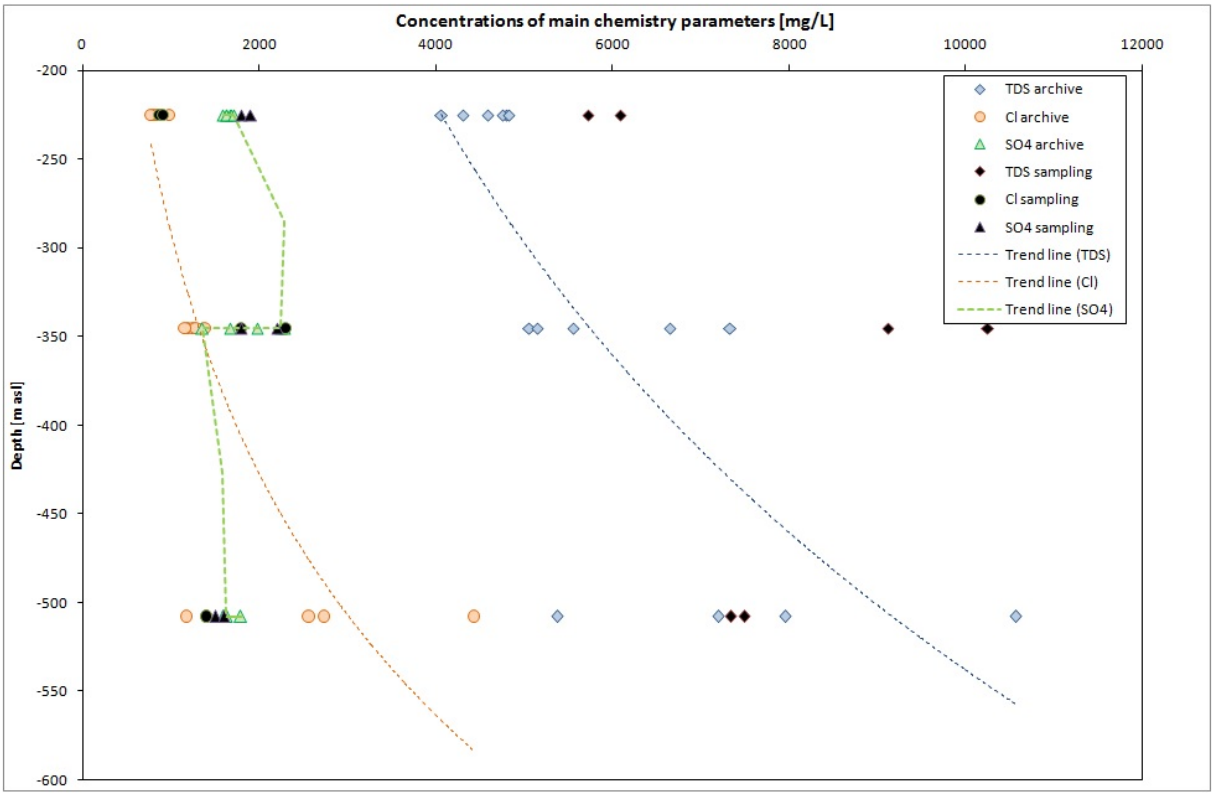


**Figure 7. Concentration of main ions and TDS in mine water inflows to levels in Szombierki dewatering field.**

In Szombierki mine there was no significant cessation of pumping or flooding of excavations after closure. Minor acid mine drainage generation as result of change of mining conditions (end of exploitation) was observed in a short period of dewatering (2002 – 2003) with increase of sulfate concentration – Figure 8. Mine water inflows to levels and mixed pumped water at the surface generally typified of slightly acidic to neutral pH (6.88-7.76) and low concentrations of total iron (maximum value measured on level 510 m – 3.3 mg $Fe_{tot}$/L), very low zinc and lead concentrations (0.39 mg Zn/L, 0.27 mg Pb/L).

Concentrations of chloride and sulfate have decreased steadily with time in the Szombierki dewatering field (Figure 8). This follows the typical trend of mine water quality recovery following mine abandonment observed elsewhere (e.g. Younger, 1997; 1998). However, unlike those previous observations, where an initial large quantity of vestigial oxidation products are flushed into solution during groundwater rebound, the Szombierki mine has been continually pumped and therefore never been allowed to completely flood post-closure. Instead the large quantities of ions in solution are likely supplied from the large area of hydrologically connected mines, where formerly ventilated mine workings have been submerged or were deep workings access comparatively saline deep-sourced waters. For example, within 6 months of water redirection from the abandoned and partially flooded ZG Bytom II mine in 2007, the chloride concentration of discharged Szombierki waters increased from an average of 912 mg/L to 3400 mg/L, before rapidly decreasing to an average 1200 mg/L (Figure 8). The single peak value of chloride concentration may derive from sampling error and unfortunately, there is no additional archive data with which to compare historic chloride trends.

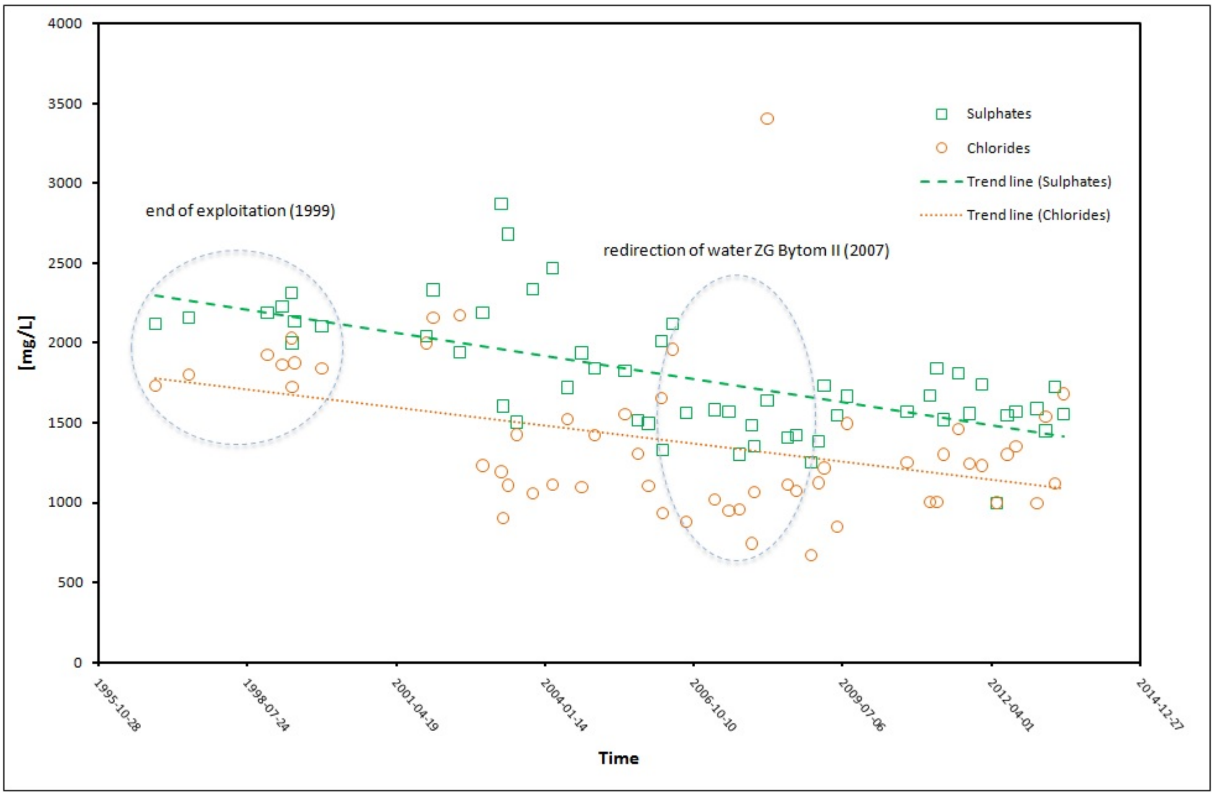


**Figure 8. Changes of chlorides and sulfates in mine water discharged from Szombierki dewatering field.**

Five sampling series and field measurements have revealed first results of observations and the potential of heat source in the abandoned Szombierki mine. Temperature of mine water in the Szombierki mine was never previously measured nor considered as a potential geothermal energy source. In 2008, single temperature measurements of mine water inflow were 24.5$^{o}$C on level 630 m and 27.6$^{o}$C on level 790 m. Within the sampling campaign and first site environmental inspection mine water temperature was measured throughout this pumping system and the adjacent Bolko pumping station in the abandoned Triassic Zn-Pb workings (Figure 9).

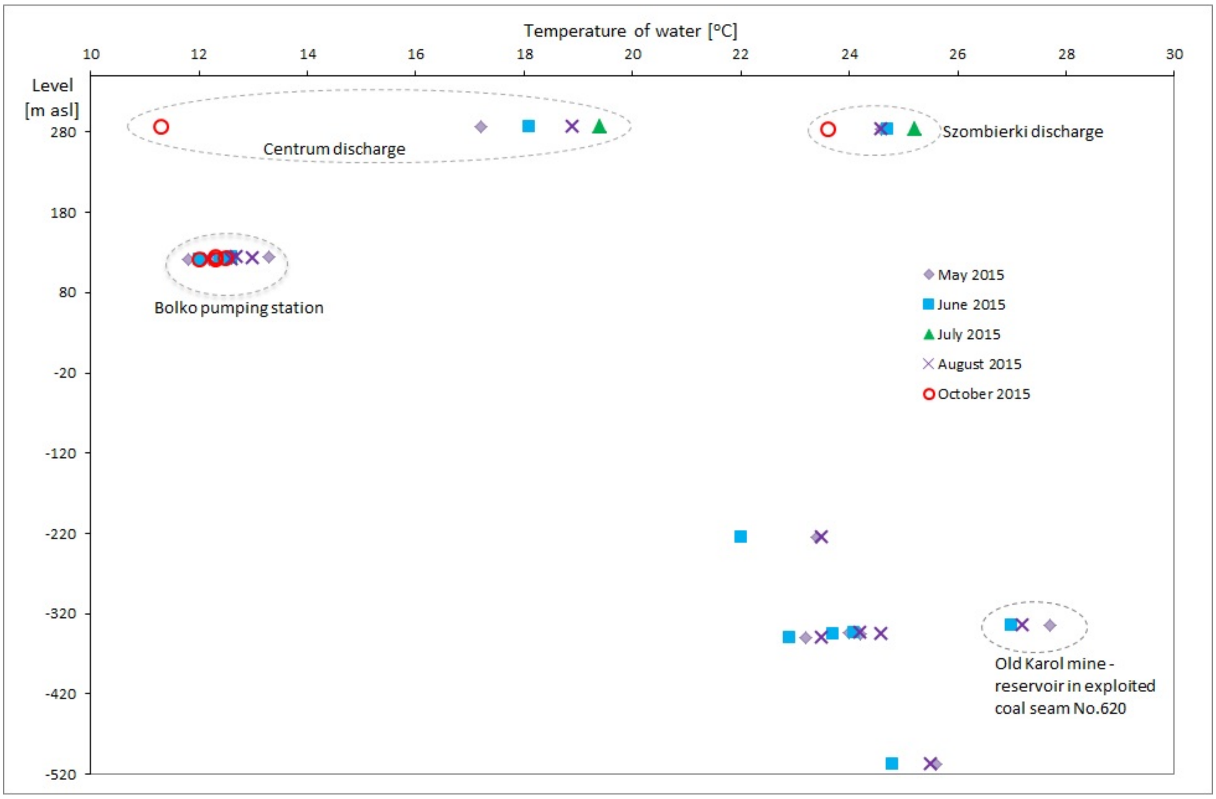


**Figure 9. Temperature of measured mine waters at underground sampling points across all monitored levels in the Szombierki and Bolko mines and at the surface discharge points from Szombierki and Centrum.**

Measured water temperatures are generally very stable for each monitoring point across both pumping stations (Bolko and Szombierki). The highest value of mine water temperature (27.7$^{o}$C) was measured at sampling point 7, which is mine water inflow from old Karol mine workings in exploited coal seam No 620. At the discharge point from Szombierki mine (measuring point 11), a very stable and relatively high temperature is observed with very low seasonal variation (about 1$^{o}$C). At the discharge point from Centrum mine (measuring point 13), seasonal variation of temperature is observed due to construction of pumping system at the surface - open system with several settlement ponds. Compared to known systems using mine water as a heat source the conditions in the monitored mines in Bytom seem to be very good. For example, Watzlaf and Ackman (2006) list several locations from the World where in geothermal systems mine water is used at temperatures comparable or lower than those reported in the current paper from Bytom mines in Poland. In Springhill, Nova Scotia, Canada, water is used at temperature of 18$^{o}$C (Jessop et al., 1995). In Park Hills, Missouri, United States, heat pumps works with mine water at 14$^{o}$C. In Shettleston, Scotland, United Kingdom, mine water at 12$^{o}$C is used. In Lumphinnans, Scotland, United Kingdom, mine water used for heating has 14.5$^{o}$C. In Markham Colliery just north of Bolsover, Derbyshire, Alkane Energy is using geothermal heat from mine water at 15$^{o}$C (Athresh et al., 2015; 2016; Burnside et al. 2016 submitted). In Mieres, Asturias, Spain, mine water from the Barredo shaft at temperatures of 20-24$^{o}$C is used for geothermal purposes (Klinger et al., 2012; Jardón et al., 2013). In USCB, Poland there is also an example of using mine water from the abandoned Saturn mine at only 13$^{o}$C for heating purposes (Tokarz and Mucha, 2013).

A Piper diagram showing chemistry of mine waters from Szombierki, Bolko, Centrum and meteoric waters is presented in Figure 8. Sulfate-rich waters with high concentrations of calcium and magnesium inflow to mine workings of Bolko pumping station in Triassic abandoned Zn-Pb workings (I – marked on Figure 8). First measurements of mine water quality on each level in Szombierki revealed two main types of water – so called 'natural inflow' to level 510 m and 630 m (II) – sulphate-rich with relatively high concentrations of calcium and remained inflows to measurement points below level 630 m, mixed water from ZG Bytom II and from pumping station 630 m as well as discharge from Centrum mine (III) – sulfate-rich with high concentrations of chloride and sodium.

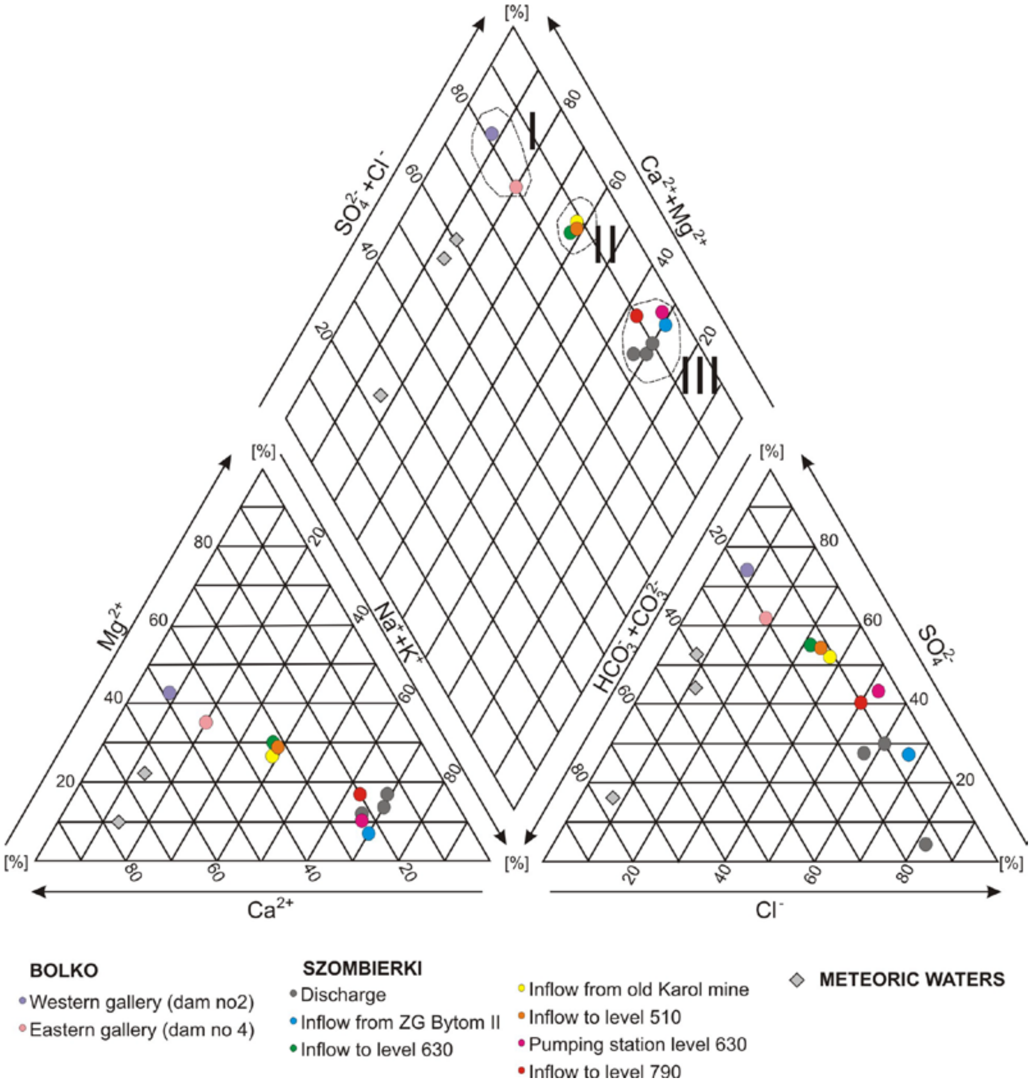


**Figure 10. Piper diagram of mine and meteoric waters in Bytom pumping systems.**

Total hardness in underground inflows and at the discharge waters from Szombierki is high. Its values range from 1640 – 2070 mg $CaCO_3$/L at the discharge while maximum value measured so far in underground inflow point on level 510 m (measuring point 8) was 2480 mg $CaCO_3$/L.

Iron concentrations in Szombierki are generally quite low 0.02 to 5.48 mg Fe/L, with the maximum value noted from measuring point 8 (level 510 m). Manganese ranges up to 2.51 mg Mn/L at the same measuring point. Assessment of trends and changes of concentrations those parameters will be possible after completion monitoring cycle, when investigations on occurrence of minor constituents and metals in Szombierki system will be more reliable.

First results of isotopic analysis revealed that mine water $\delta^{18}O$ and $\delta^{2}H$ values across all measuring points in the underground workings of the abandoned Szombierki and Bolko mines fit entirely to World Meteoric Water Line (figure 11), with no evidence of monthly variation correlating to pumping behaviors or local precipitation. Indeed the data are remarkably homogeneous with statistically tight means of $\delta^{18}O$ of -9.5‰ and $\delta^{2}H$ of -66‰. Mine water $\delta^{18}O$ and $\delta^{2}H$ values show no correlation with salinity or other parameters. The data fall out with the typical values measured in the local meteoric waters, which show variations along the meteoric water line, but to higher and lower values distinct from the underground waters. However, minewater values are similar to the 40 year average meteoric value measured at Krakow (IEA/WMO 2015).

| Measuring Point | Date (dd.mm) | $\delta^{18}O$ (VSMOW) | $\delta^{2}H$ (VSMOW) | $\delta^{34}S$ ($SO_4$) (VCDT) | Measuring Point | Date (dd.mm) | $\delta^{18}O$ (VSMOW) | $\delta^{2}H$ (VSMOW) | $\delta^{34}S$ ($SO_4$) (VCDT) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 21.05 | -9.4 | -67 | nd | 9 | 22.05 | -9.2 | -66 | nd |
| | 25.06 | -9.5 | -66 | 10.5 | | 25.06 | -9.6 | -66 | 16.8 |
| | 26.08 | -9.6 | -64 | 9.5 | | 28.08 | -9.4 | -65 | 18.0 |
| | 22.10 | -9.6 | -67 | - | | 30.10 | -9.6 | -62 | - |
| 2 | 21.05 | -9.6 | -71 | nd | 10 | 22.05 | -9.3 | -66 | nd |
| | 25.06 | -9.6 | -67 | 1.8 | | 25.06 | -9.4 | -65 | 24.6 |
| | 26.08 | -9.5 | -65 | 1.8 | | 28.08 | -9.2 | -65 | 23.9 |
| | 22.10 | -9.7 | -68 | - | | 30.10 | -9.4 | -66 | - |
| 3 | 21.05 | -9.5 | -72 | nd | 11 | 22.05 | -9.3 | -66 | nd |
| | 25.06 | -9.5 | -66 | 11.6 | | 26.05 | -9.5 | -67 | nd |
| | 26.08 | -9.5 | -65 | 9.9 | | 25.06 | -9.5 | -66 | 15.9 |
| | 22.10 | -9.7 | -66 | | | 27.07 | -9.5 | -65 | 18.7 |
| 4 | 21.05 | -9.8 | -68 | nd | | 27.08 | -9.4 | -67 | 19.0 |
| | 25.06 | -9.6 | -66 | 6.0 | | 25.09 | -9.4 | -66 | 12.2 |
| | 26.08 | -9.7 | -66 | 6.5 | | 29.10 | -9.6 | -69 | - |
| | 22.10 | -9.8 | -69 | - | | 25.11- A | -9.6 | -66 | - |
| 5 | 22.05 | -9.4 | -63 | nd | | 25.11- B | -9.7 | -69 | - |
| | 25.06 | -9.5 | -66 | 14.7 | 12 | 26.05 - Byt | -3.5 | -20 | nd |
| | 28.08 | -9.5 | -65 | 19.8 | | 25.06 – Byt | -6.2 | -43 | nd |
| | 30.10 | -9.8 | -68 | - | | 26.06 – Jaw | -7.7 | -48 | nd |
| 6 | 22.05 | -9.6 | -66 | nd | | 26.08- Jaw | -5.5 | -36 | nd |
| | 25.06 | -9.7 | -65 | 17.0 | | 29.10 – Byt | -10.3 | -73 | nd |
| | 28.08 | -9.3 | -66 | 16.9 | | 24.11 - Jaw A | -14.6 | -99 | nd |
| | 30.10 | -9.6 | -67 | - | | 24.11- Jaw B | -14.8 | -99 | nd |
| 7 | 22.05 | -9.5 | -68 | nd | 13 | 26.05 | -9.5 | -63 | nd |
| | 25.06 | -9.6 | -67 | 18.1 | | 26.06 | -9.4 | -63 | 13.9 |
| | 28.08 | -9.4 | -65 | 18.1 | | 27.07 | -9.5 | -65 | 13.9 |
| | 30.10 | -9.6 | -66 | - | | 26.08 | -9.4 | -64 | 13.8 |
| 8 | 22.05 | -9.5 | -64 | nd | | 25.09 | -9.5 | -66 | 17.6 |
| | 25.06 | -9.4 | -64 | 17.6 | | 29.10 | -9.6 | -68 | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 28.08 | -9.3 | -65 | 16.9 | 25.11- A | -9.6 | -64 | - |
| 30.10 | -9.5 | -63 | - | 25.11- B | -9.6 | -63 | - |

**Table 2. O, H, S isotope systematics of $H_2O$ and $SO_4$ for the Bytom study. Measuring points described in Table 1 in the paper.** All δ-values ‰ against Vienna Standard Mean Ocean Water (VSMOW) or Canyon Diablo Troilite (CDT) standards. Values represent triplicate analyses which reproduce well within error of reproducibility. Samples identified as 'A' and 'B' indicates repeat analyses. Abbreviations 'Byt' and 'Jaw' indicate meteoric samples from Bytom and Jaworzno respectively. 'nd' indicates not determined and dashes indicate analyses to be completed.

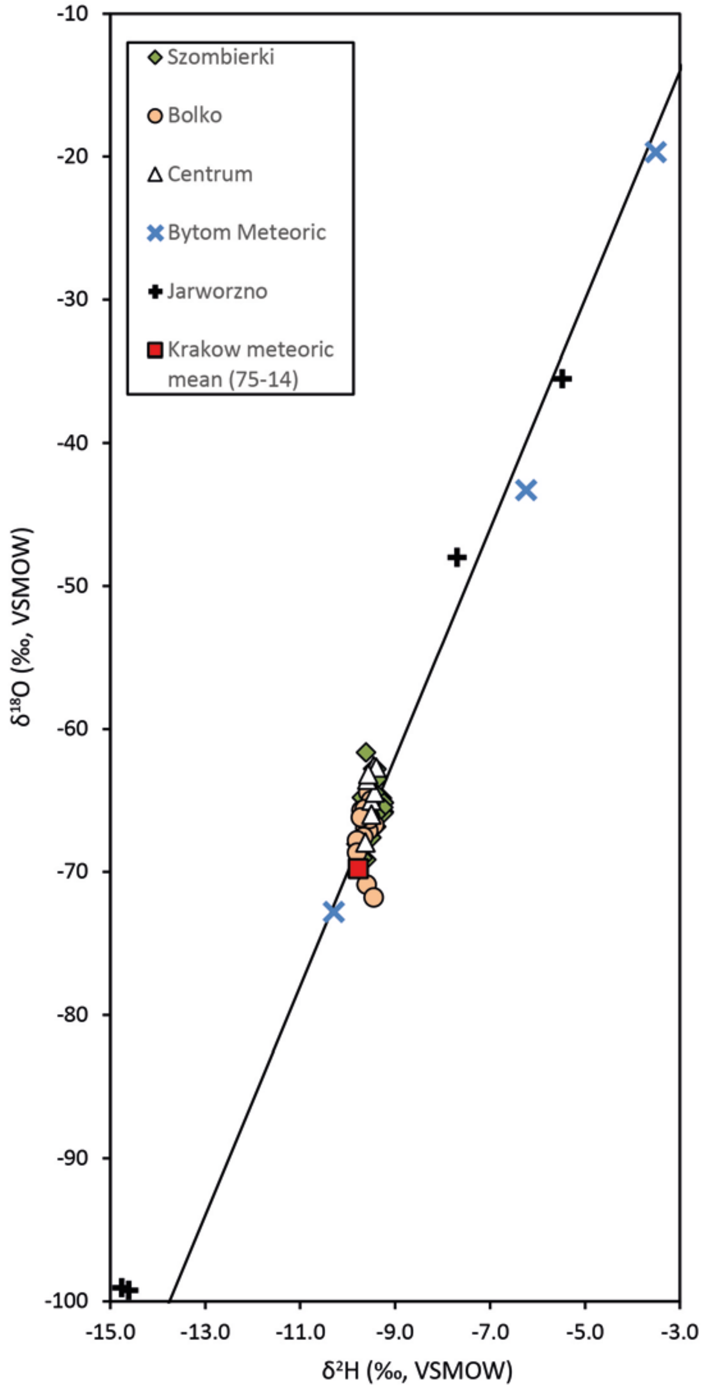

**Figure 11. Values of δ$^{18}$O versus δ$^{2}$H in Szombierki mine waters as compared to Bolko and Centrum mine waters, local meteoric values from Bytom and Jaworzno, and long term average (1974-2014) meteoric data for Krakow (IAEA/WMO 2015).**

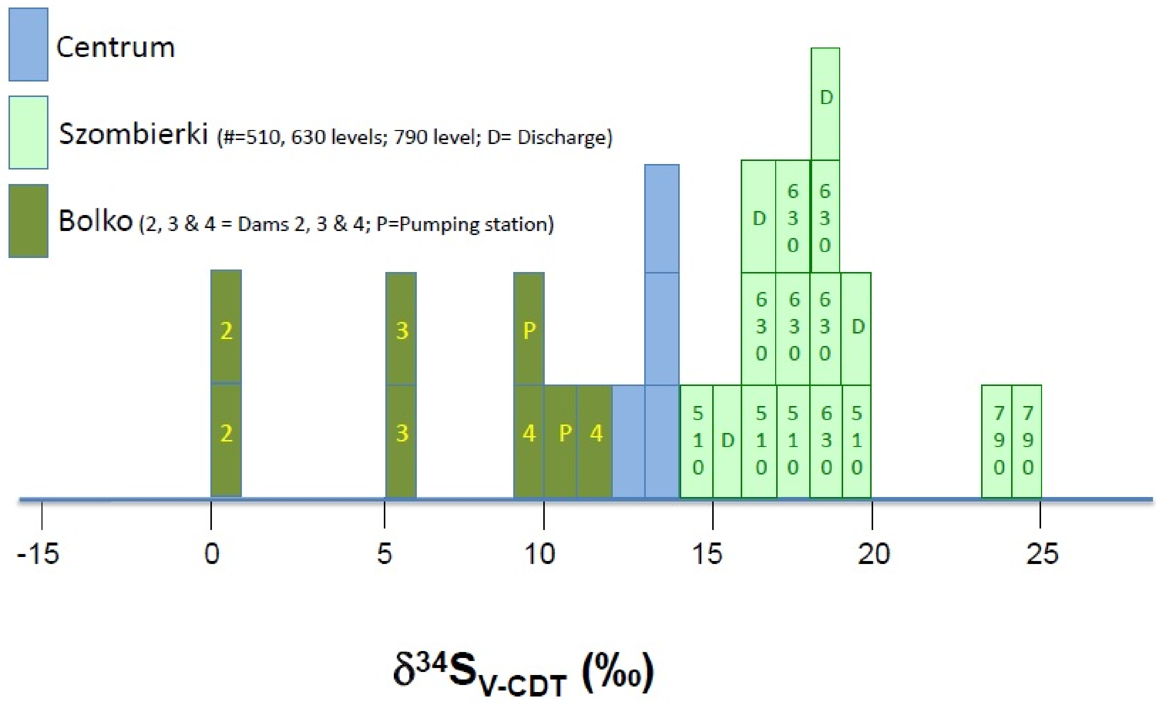


**Figure 12. Distribution of δ$^{34}$S measured in mine waters in underground measuring points of Centrum, Bolko and Szombierki pumping stations.**

In contrast to the O and H data, distinct differences are noted in δ$^{34}$S values between the three main mine areas (Figure 12; Table 2). Centrum has an average δ$^{34}$S of 13.5 ± 0.8‰ (1σ; n=4). Szombierki demonstrates unique values depending on the source of the waters. Data from the 510 - 630 levels averages 17.4 ± 1.3‰ (1σ; n=10) and this includes waters from the pumping station on the 630 level. The pumping station is an amalgamation of waters from a number of shaft inflows from the mine network. Unsurprisingly the discharge from this pumping station has and average value coincident with the station waters averages 17.8 ± 1.4‰ (1σ; n=4). However inflow at the deeper 790 level has distinct value which is consistent over 3 months of sampling between 23.9 and 24.6‰.

Bolko values across the three different dam sections are isotopically distinct with the resultant pumped waters demonstrating a predominantly dam 4 value around 10‰ (Figure 12). Lighter values are found in dam number 2 (western gallery), 1.8‰, and dam 3 (eastern gallery), from 6.0 - 6.5‰. A galena from the Bolko mine gave an S isotope value of 9.3‰, which suggests that the S isotope composition of the sulfate in dam number 4 and in bulk pumped mine waters are likely sourced from local oxidation of Zn-Pb ores, and have therefore seen little to no isotopic fractionation (Taylor et al., 1984; Heidel et al., 2009).

The S isotope character of the Carboniferous coal is unknown, but suggests an unusually high $\delta^{34}S$ value, if the mine waters are sourced from pyrite oxidation, although the possibility of evaporate remobilization is also being considered. The distinct S isotopic variation between coal mine waters and base metal mine waters, offers a potential tool for mine water compartment identification, and mass balance studies in the future.

## Conclusions

Very stable mine water temperatures throughout the underground measuring points of the Szombierki pumping system and the relatively high and consistent value of water temperature at the surface discharge point in initial phase of monitoring, show that these waters have great potential for geothermal energy generation. Bytom mine waters compare favorably to other known systems that use mine water as a heat source. Several geothermal systems from around the globe exploit mine water at temperatures comparable or lower than those reported in the current paper for Bytom mines in Poland. Where pilot installations for heating purposes are being planned, hydrochemical parameters such as total hardness, high concentrations of sulfates, and occurrence of dissolved iron should be taken into account to avoid potential encrustation problems, corrosivity of materials or ochre clogging.

At the early stage of field research and hydrogeological cycle investigations for the pumping systems in the Bytom Syncline it is significant to note that waters from the Szombierki mine have stable and relatively high temperatures (c. 24°C) and are generally dominated by meteoric influences.

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