What Polish mining owes to Polish hydrogeology?

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A b s t r a c t. Poland is endowed with the wealth of mineral resources, especially resources of coal and lignite, metal ores and mineral raw materials for chemical industry. Exploitation of these resources as a rule leads to inflow of water to mine workings and thus to various technical problems which have to be solved. Such problems arise at all the stages of management of mineral deposits, from reconnaissance and prospecting and exploration to preparing of a deposit for exploitation and exploitation and closing of mines.

The water can have significant negative influence on prospecting and exploration and preparation of deposits to exploitation and creates a risk for mining operations and miners. Water inflow also results in environmental changes and increases extraction costs. The arising problems are technical and economic in character and the key for their solution is hydrogeology or, more precisely speaking, one of its more specialized branches – that is mining hydrogeology.

The aim of this paper is to show the role and significance of hydrogeological works in management of mineral resources. A special attention is paid to the major achievements of Polish hydrology, which contributed to the developments in mining in our country and the world. Moreover, significance of contribution of hydrogeology at all the stages of mineral resources management, from reconnaissance and prospecting to exploitation of mineral deposits and closing of mines, is discussed. The presentation is of the review type and comprises examples of contributions of hydrogeology to exploration and documentation of individual mineral deposits, including assessments of mine water inflow and risks, environmental impact of mining operations and water management issues. It is worth to note that achievements of the mining hydrogeology from the last twenty years were mainly connected with working out methods for forecasting and assessments of environmental impact of closing the mines. In short, it may be stated that the actual contribution of Polish hydrogeology to the developments of mining sector is well shown by the presented examples concerning practically all the major mineral resources and the whole process of their management.

Keywords: *hydrogeology, mining, mine water, mine water risk, environmental impact, mine closure*

Poland is a country rich in many natural mineral resources: hard coal, lignite, copper, zinc and lead ores, as well as chemical resources and rock minerals (Fig.1). For centuries they have been extracted to fulfil economic needs. Their extraction is always accompanied by water inflow. In 2001–2002, the biggest ever groundwater inflow to all mines in the history of Polish mining was recorded. It was estimated at 1 km^3/yr, 80% of which was freshwater and the remaining 20% saline water and brines. Occurrence of water in mines causes various problems that need to be solved. They occur in every phase of bed exploration, starting from the search, initial prospecting and exploration, through accession and exploitation until the closure phase.

Water makes identification and documentation of natural resources very difficult: it hinders their availability, causes a danger to functioning of mines and their employees, causes a transformation of the natural environment and increases costs of exploitation. Solving these problems has technical, economic and ecological aspects, but hydrogeology, and specifically mining hydrogeology, is its foundation.

The purpose of this article is to present the role that hydrogeological investigations and research play in managing mineral resources. This work provides a presentation of the most important achievements of Polish hydrogeology that led to the development of the mining industry in Poland and worldwide. In this article, hydrogeological achievements at subsequent phases of managing natural resources are presented, i.e. from prospecting and exploring deposits, their extraction and finally a mine's closure. The article presents numerous case studies and includes descriptions of Polish hydrogeological achievements and its input in identifying and documenting individual mineral beds, identifying and assessing groundwater inflow rates

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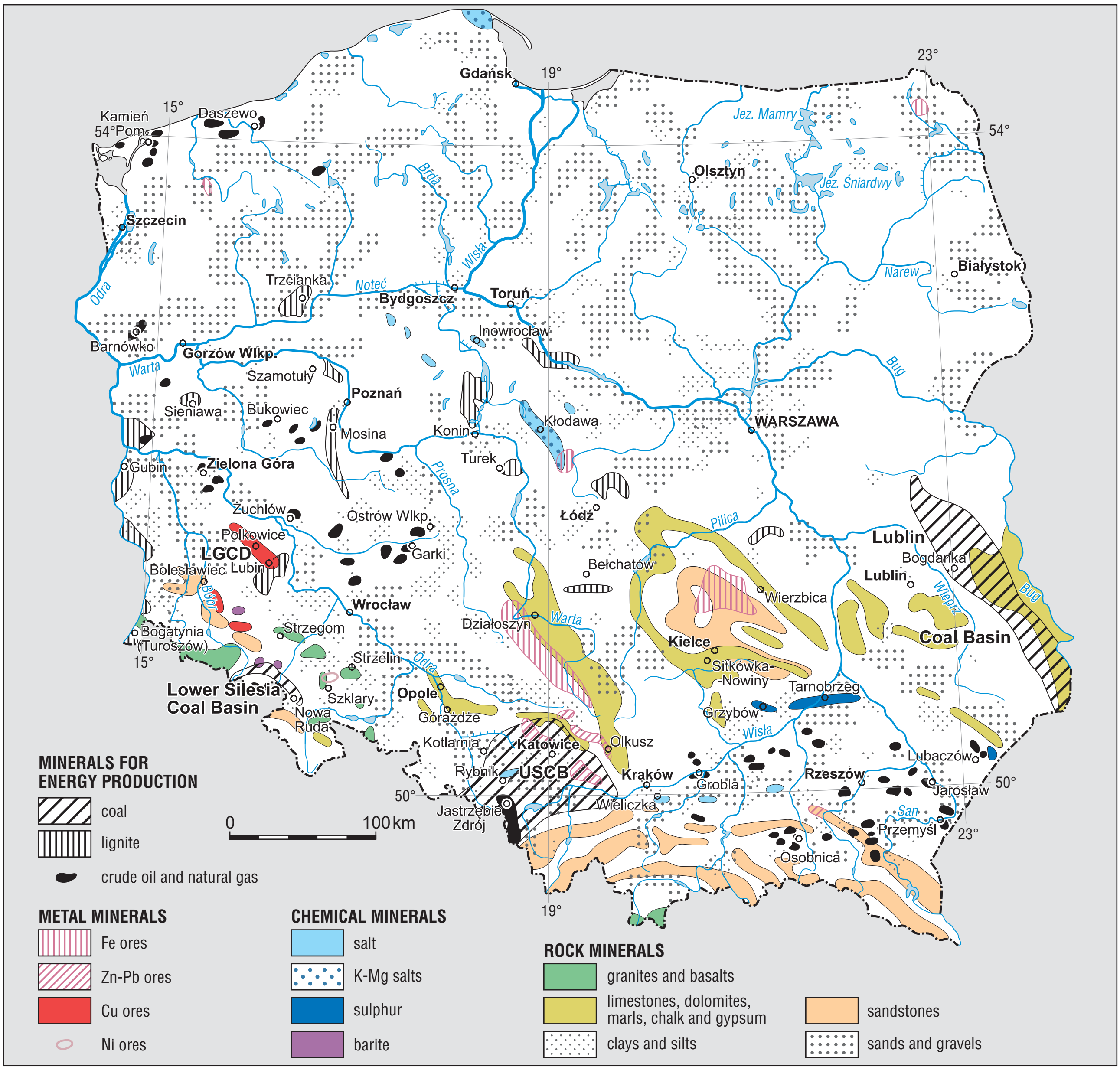

Fig. 1. Mineral resources of Poland (*Geographical atlas*..., 2000)

into a mine and associated water hazards and defining environmental impacts resulting from mining. Over the past 20 years, Polish hydrogeology has been especially successful in developing methods for forecasting and assessing impacts resulting from mine closure on water environment. Examples discussed in the article refer to all types of ore beds in Poland and to all phases of their mining exploration.

Nevertheless, most attention is given to interactions between hydrogeology and mining of coal. This is justified by the extent of the coal mining industry, its history as well as the complexity of hydrogeological conditions occurring in coal regions.

Mining activities and groundwater

Poland is a country that has long mining traditions, which go back to the prehistoric times. The first evidence of mining are traces of flint mining from 3000 BC (the flint pits of Opatów) and the bog iron ore mines from the fourth century BC. On the territory of Poland salt was extracted as early as in the 9th century. Zinc and lead, silver, iron and copper ores have been extracted since the 12th century. The first half of the 20th century was a period of time in which the most intensive development of mining in Poland took place. Copper, iron, zinc and lead, nickel, hard coal, lignite, salt, sulphur, gypsum and anhydrite, barite, phosphorite, rock materials, crude oil, earth gas were extracted in that time. Since the 1970s a continuous decline in mining activities has been observed in Poland. After the great political changes of 1989, a widespread abandonment of mines started (Table 1). Desertion of all iron ore mines, open-cast sulphur mines, all collieries of the Lower Silesia Coal Basin, many coal mines in Upper Silesia and most of the zinc-lead ore mines are examples of that movement. Currently, there are over 2400 open-cast mines and 39 underground mines active in Poland. About 200 million tonnes of various minerals and lignite are extracted in open-pit mines. Polish deep mines extract coal, copper ore, zinc and lead ores and salt. Sulphur is extracted using the Frash method.

Poland is one of the best-known coal producers in the world. Hard coal deposits occur in Poland in three Carboniferous coal basins: Lower Silesia, Upper Silesia, and the Lublin Coal Basin (Fig. 1). Origins of mining in the Lower Silesia Coal Basin (Wałbrzych and Nowa Ruda) date back to the 15th century. In the 1970s, four mines extracted about 25 million tonnes of coal. The process of abandoning the mines had started in 1972. All mines in the town of Wałbrzych were closed down between 1991 and 1998 and in 1994, flooding of mines started. In the surroundings of Nowa Ruda, gradual closure of mines had started in 1972 and the last one was flooded in 2000.

The first coal extraction in the Lublin Coal Basin began in 1982 and has been continued until the present day. There is one mine there with an output of 3.8 million tonnes of raw coal. Water inflow to this mine ranges from 8 to 10 m^3/minute.

The Upper Silesia Coal Basin is the most important of all coal basins as it holds about 85% of Poland‘s coal reserves. The coal mining industry in the region was developed in the 17th century and peaked in the 1970s. In the 1980s, some 75 collieries operated there. After the political changes, i.e. since 1989, unprofitable mines have systematically been abandoned (Fig. 2). Currently, there are only 32 coal mines in operation. Intensive mine drainage operations that were continued for many years, produced wide-

Table 1. Changes in mining activity in Poland over the 1989–2005 period

Mineral	Exploitation: minerals in million tonnes				
	1989	**1994**	**1999**	**2002**	**2005**
Minerals for energy production					
Oil	0.16	0.17	0.19	0.73	0.82
Coal	176.00	134.10	109.99	103.7	93.01
Lignite	72.00	66.8	60.86	58.24	61.60
Metal minerals					
Zn-Pb ores	4.20	4.82	4.92	4.73	4.57
Cu ores	26.50	23.74	26.93	29.0	25.44
Non metal minerals					
Sulphur	5.00	2.13	1.18	0.76	0.82
Salt	4.00	3.18	3.16	3.56	3.91

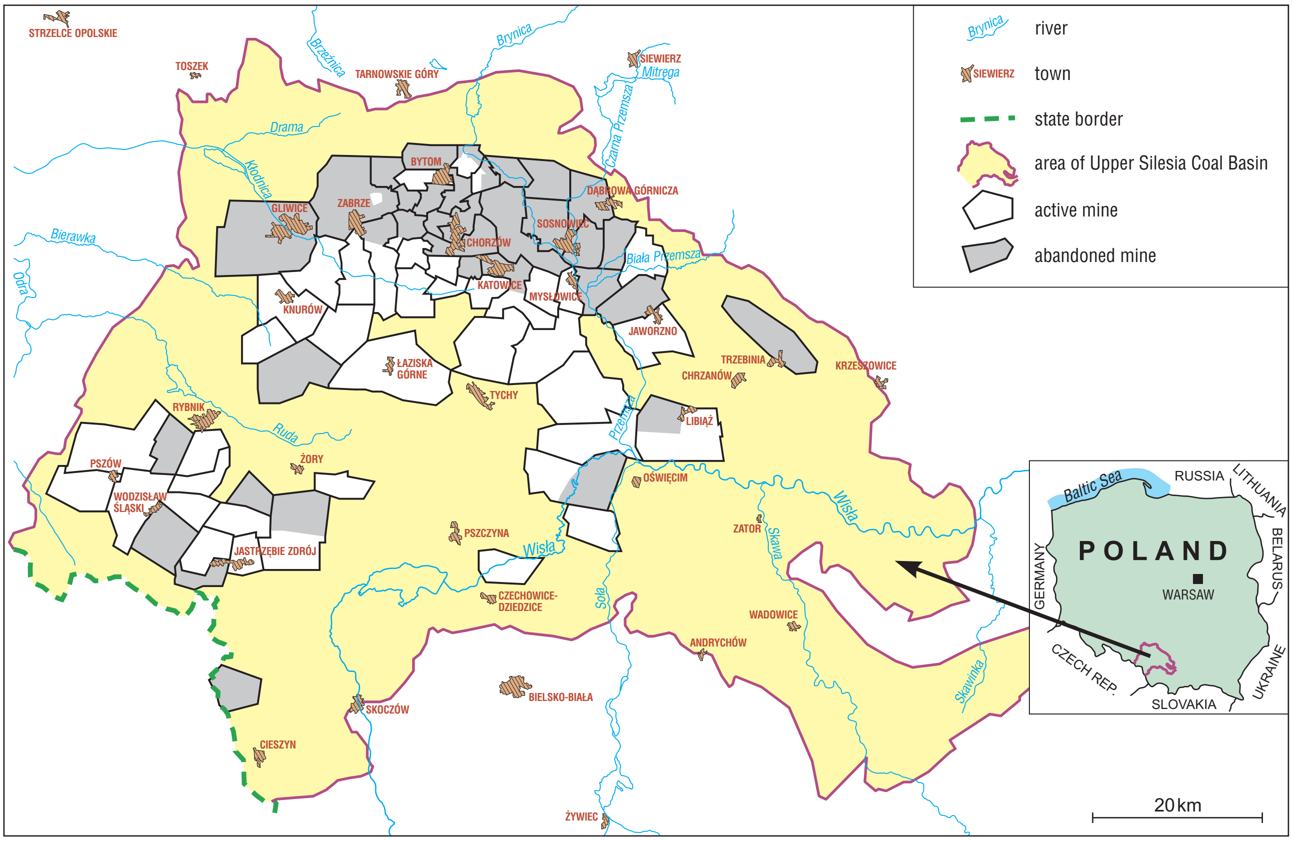

Fig. 2. Locations of coal mining areas within the Upper Silesia Coal Basin (USCB), 2006

spread cones of depression with a total surface area of abt. 1750 km^2 and a depth ranging from 300 to 700 m, locally up to 1160 m below the ground surface (Wilk, 2003). It is estimated that drained Carboniferous deposits amount to a volume of ca. 100 km^3 (Wilk, 1990).

The total coal production in Poland in 2005 amounted to 93 million tonnes, which is about 54% less than the maximum output of 201 million tonnes that was reached in 1979.

In 1996, mines pumped out ca. 355 million m^3 of mining water. An average water inflow to a single mine ranged from 200 m^3/24h to 70 000 m^3/24h. In 2005, the total volume of drainage water decreased up to 234 million m^3, i.e. ca. 642 m^3/24h (Table 2). Almost 57% of mining water is discharged to rivers, which constitutes a primary risk for the aquatic environment. In this situation, the most important problem is utilisation of huge volumes of saline mining water with TDS (total dissolved solids) concentrations ranging from several to 110 g/L (Różkowski, 2004).

Currently, lignite (Tertiary deposits) is exploited in four large mines (see Figs. 1, 3 and 4): Adamów (three open pits), Bełchatów (two open pits), Konin (three open pits), Turów (Turoszów region; one open pit) and one small in Sieniawa. The total lignite production in 2005 amounted to 61.6 million tonnes. The largest mine, Bełchatów, produces more than 57% of that amount. In 2005, ca. 328 million m^3 of water was pumped out from lignite open pits, which produced cones of depression over 1200 km^2. The well drainage method (well barrier) prevails in Polish mines. In general, drained groundwater is of good quality and therefore it is not environmentally hazardous. Exceptions are waters from a Tertiary aquifer in the mine of Turów, and waters stemming from draining a salt diapir in Bełchatów. Locally, these waters have mineralisation of over 5g/L. Between 1991 and 2005 five open pits were abandoned and filled up with overburden or water.

Poland has one of the largest copper deposits (Permian) in the world. They are located in Lower Silesia (SW Poland, see Fig. 1). The copper ore is extracted in Lubin-Głogów Copper District (LGCD) in three mines (Lubin, Polkowice-Sieroszowice and Rudna). The oldest mine, known as *Konrad*, was closed down in 1989 and since 2001 it remains flooded. Currently, between 26 and 29 million tonnes of ore are being extracted in Poland (570 000 tonnes of copper). In 2005, some 256 million m^3 of water were pumped out of mines, which produced a massive cone of depression reaching ca. 850 km^2 within the Permian aquifer. Mineralisation of mine water varies between 2 and 112 g/L, but water of low mineralisation (practically below 10 g/L) constitutes over 96% of the total volume. Mine water is used for various technological purposes. Processes included in ore preparation produce vast volumes of tailings (26–27 million tonnes per year). These are discharged into two huge tailing dams at Gilów (6 km^2–64 million m^3) and at Żelazny Most (126 km^2–350 million m^3) (Wilk & Bocheńska, 2003).

Poland has also one of the largest reserves of zinc-lead ores in Europe, which are located in the Silesian-Cracow region (Southern Poland, Triassic deposits). These used to be extracted in the following four major areas: Tarnowskie Góry, Bytom, Olkusz, and Chrzanów. Over 800 years of mining in these areas caused huge environmental damage. Intensive drainage in these mines has caused significant lowering of the groundwater table (from 100 m to 260 m), and resulted in creating extensive, regional cones of depression covering an area of about 500 km^2 near Olkusz and over 170 km^2 near Chrzanów (Witkowski, 2005). In 2005 over 152 million m^3 of water of various quality was pumped out of the mines. At present, mining operations in Olkusz are carried out only temporarily. There is only one mine that is sill active – Olkusz-Pomorzany with a groundwater inflow over 300 m^3/minute. Tailings from this mine are dumped at a few tailing dams located around Olkusz which, in total, cover an area of about 1.1 km^2 and hold about 40 million tonnes of tailings.

Deposits of native sulphur (in the Miocene limestone) occur in Poland near Tarnobrzeg (SE Poland, Carpathian Foredeep). Sulphur exploitation in this region started in 1960. In the past, there were two open pits and three deep sulphur mines, exploiting sulphur using the Frash method (underground smelting by hot water). Both open pit mines are currently closed down and partially flooded. At present, native sulphur is extracted only at the Osiek mine (the Frash method).

Poland has large deposits of rock salt. Salt deposits are exploited in two regions: the Subcarpathian (Miocene; Southern Poland) and the Kujavia (Permian; Central Poland).

There used to be 10 mines extracting salt in Poland in the past: six of them were deep mines and four of them were open pit mines. The oldest salt mine in Poland, called Wieliczka, is situated near Cracow and is of a great historical value (Brudnik et al., 2010 – this volume). The mine is 700 years old and is visually very attractive, for which it is one of the most popular Polish monuments. It is also registered on UNESCO's World List of Cultural and Natural Heritage. At present, there is only one active deep salt mine in Poland, in Kłodawa, and two open pit mines. Since 1993 salt has been extracted in Sieroszowice-Polkowice Copper Mine as a by-product of copper.

Table 2. Volumes of mine water pumped out from mines exploiting the most important minerals in Poland, 1966–2005

Mineral	Mine water pumped out in thousand m^3/d				
	1966	1988	1996	2002	2005
Coal	1 028	1 033	973	700	642
Lignite	317	1 044	561	989	898
Zn-Pb ores	220	444	412	551	418
Cu ores	1,21	81	85	71	70
Fe ores	255	–	–	–	–

Fig. 3. Konin Lignite Mine, open pit Lubstów during reclamation (June 2010). Photo by M. Galczak

After World War II, 21 deep iron ore mines were built near Czestochowa. Until the end of the 1960s, the mines were extracting some 2 million tonnes of iron ore per year. Some 255 000 m^3 of mine water per day was pumped out of the mines. Between 1970 and 1984 all iron ore mines were closed down. Since then, all mines have been continuously flooded. A negative impact on local groundwater quality, resulting from mining activities, is still observed within the Middle Jurassic aquifer (concentration of SO_4 up to 1100 mg/L, Mn up to 66 mg/L and Fe up to 271 mg/L) (Razowska, 2000).

Many rock minerals are also extracted in Poland. This includes building stone, limestone, dolomite, gypsum and anhydrite, clay and back-filling sand. It is estimated that the total quantity of water pumped out of open-pit mines amounts to 700 000 m^3/day. This water is usually of good quality. Such intensive, long term and often strongly concentrated mining activities must have had some influence on the natural environment. Intensive drainage operations, which continued for many years, produced extensive cones of depression with a total area of about 4600 km^2 and a maximum depth of over 1100 m beneath the ground surface. Mining operations caused a profound transformation of hydrodynamic conditions of groundwater causing changes in flow directions, increased hydraulic gradients, and changes in hydrogeochemical conditions and/or contamination of groundwater on a regional scale. In 2001, over 1039 million m^3 of mine water was pumped out of Polish mines, over 162 million m^3 of that was saline water with some 153 million m^3 (94%) discharged to surface water courses. Following the calculation, a total amount of around 25 million tonnes of Cl and SO_4 ions was discharged to surface waters. Also in 2001, all mining and preparation plants together produced about 70 million tonnes of waste with 10 million tonnes placed at special dumps for mining waste. At the end of 2001, the total quantity of waste gathered on dumps amounted to over 1280 million tonnes, therein about 558 million m^3 of tailings (Bolewski et al., 2002). The total area of tailing dams amounted to 20 km^2.

Hydrogeological problems related to mining

Occurrence of water and its role in mining of mineral resources creates a natural need for bonds between the mining industry and hydrogeology. The biggest challenge for mining is provision of safe exploitation in conditions of an intense groundwater inflow which causes a continuous hazard to mining operations. This problem occurs, however, when mining operations continue at depths below the natural water table. Exploitation of deposits from depths below the groundwater table started to develop in Poland in the 16th century. Mining in hazardous situations caused by large groundwater inflows became an impulse for developing modern dewatering techniques which became a necessity to render deposits available for extraction. This subsequently caused a need for more detailed recognitions of groundwater environments within mining regions. In literature, the first information regarding water-bearing capacity of formations that comprised mineral beds and assessments of water hazards in relation to mining operations started to occur in the middle of the 19th century. These concerned the water bearing capacity of Triassic deposits in Upper Silesia, where zinc and lead mining was developing at that time. These documents prove that, even then, systematic hydrogeological observations were used and this did not only concern the exploitation phase. Undertaking hydrogeological assessments became not only a necessity but also a common practice at early stages of prospecting and documenting the natural resources. Undertaking hydrogeological studies at this stage of an investment, prior to extraction, is therefore a common practice in Poland, which has been exercised for many years now. At present, most mining operations occur below the groundwater table. Dewatering that is necessary for undertaking such operations creates a constant need for undertaking hydrogeological assessments of groundwater regimes around mines.

This is driven not only by a need to develop appropriate, safe exploitation techniques but also to assess impacts that mining has on the natural environment. Links between mining and the environment are complex and inter-related. The major one is a risk of flooding a mine. Water discharges, including brines and radon water, to surface waters are closely linked with this problem. Dewatering of rock masses leads to a transformation of natural groundwater conditions. A new hydrogeological model develops with a completely new water circulation system, possible inflows from surface waters, changed hydrochemical conditions and finally limited groundwater resources. Mining is often accompanied by storing waste materials, which can also cause impacts on various elements of the environment including groundwater.

Abandonment of mines creates additional problems that need solving, such as deciding on closure procedures, assessing impacts it will have on the environment or changes in the groundwater balance. Each of the above problems has been and is still solved in consultations with hydrogeologists. The input by hydrogeologists in developing the mining industry in Poland has been documented in Polish literature since the middle of the 19th century.

Hydrogeology and deep coal mining

Achievements of Polish hydrogeology in relation to deep coal mining concern aspects of the initial prospecting and exploration phase, as well as subsequent phases of accession, extraction and mine closure and reclamation.

Geological prospecting and exploration of deposits. The hydrogeological input in prospecting and documenting deposits of coal has been developing in Poland since the second part of the 20th century and concerns methodical hydrogeological and geological studies that were undertaken within the coal basins of the Upper Silesia Coal Basin (USCB) and the Lublin Coal Basin (LCB). The most spectacular examples of regional and local hydrogeological assessments were studies carried out within coal basins of the Carboniferous Period, specifically those undertaken during prospecting studies of the newly recognised coal deposits in the LCB and studies of deep coal beds in the major basin of the USCB.

The Lublin Coal Basin is the only coal basin in Poland where hydrogeological assessments were undertaken in parallel to geological studies during all stages of documenting the basin, i.e., from the prospecting and exploration stage, through its accession and finally, during the mining exploitation.

Complex analyses of regional and local geological data of the coal basin made it possible to create a hydrogeological conceptual model of the basin (Różkowski & Rudzińska, 1978; Rudzińska-Zapaśnik & Różkowski, 2003). Assessment of hydrogeological conditions within the mining area allowed the production of hydrogeological prognoses and the planning of a rational and safe development of mining operations and also an initial assessment of anticipated changes in the natural environment.

Results of long term studies and hydrogeological prognoses were later confirmed with hydrogeological observations carried out during the construction and exploitation of Bogdanka coal mine, so far the only operating coal mine within the LCB (Różkowski & Wilk, 1989; Wilk, 2003).

Hydrogeological studies within the Upper Silesia Coal Basin were carried out after World War II, with an aim to start running the newly recognised mining areas. These areas were located mainly within the southern parts of the basin, within the Carpathian Foredeep. Coal deposits occur deep here and are usually covered by isolating deposits of the Miocene formation. Natural hydrogeological conditions were defined through hydrogeological assessments undertaken during documenting of 21 new mining areas. Studies on Carboniferous coal beds were undertaken by Geological Enterprise, the Upper Silesian Branch of the Polish Geological Institute and by Shaft Sinking Enterprise (Różkowski, 2003). The above studies allowed researchers to come up with a conceptual hydrogeological model of coal deposits and an initial assessment of water and gaseous hazards, as well as to forecast potential groundwater inflows to the projected mines and their salinity. Results of geological and hydrogeological studies led to designing and then building a few new mines.

Innovative and original studies were undertaken by the Polish Geological Institute over the period of 1986–1990, which aimed to define mining conditions of the deep Carboniferous deposits of the Upper Silesia Coal Basin, at depth intervals of 1000–2475 m b.g.l. One of the major aims of these investigations was forecasting the water inflows and gas emission into the deep mine workings (1000–1500 m) as well as defining the salt content in mine water.

Accession and exploitation of beds. Among major problems which occur while extracting natural resources are water hazards that occur with regards to mining operations and finding effective mitigation measures against these threats. No less important is the prediction of environmental impacts and mining damage resulting from mineral extraction operations and dewatering of mines. These issues require good recognition of groundwater conditions and reliable forecasting of groundwater inflows into mines.

After II World War, in Polish scientific institutions, mainly in the Central Mining Institute (CMI) in Katowice and in the AGH University of Science and Technology (AGH–UST) in Cracow, many research studies were undertaken, which focused on creating precise and trustworthy methods for forecasting groundwater inflows into mines. The first solution called the trend line method was proposed and the non-linear regression methods were then suggested. This work was continued in the Central Mining Institute and was finalised by creating the inflow and extraction trend method and the modified water-production index method. These methods are still used by the Polish coal mining industry.

In the first part of the 1970s, in the Central Mining Institute, work on the applicability of numerical modelling for forecasting groundwater inflows into coal mines had been initiated. The usability of these methods was later developed in the AGH University of Science and Technology using standard, commercial programmes. Application of the above methods allowed experts to accurately predict groundwater inflow volumes into mines, to choose adequate dewatering techniques and eventually, to minimise costs of coal extraction.

One of the measures of water hazards is the number of water inrushes into mine workings. In the post war period, together with increased mining operations, an increased number of water inrushes into mines was observed. The highest number of 30 water inrushes was observed in 1961. Since then, the number of water inrushes has been systematically decreasing. Within the past 15 years, no major flooding of a mine has occurred, which means that the threat of flooding in coal mines has been practically controlled, what contributed to that was the development of research focused on counteracting water hazards and implementation of new regulations emerging from these studies regarding safe mining practice.

Hydrogeology is also useful when assessing environmental impacts resulting from exploitation of coal deposits and especially in assessments of draining activities on groundwater conditions, i.e. regional water balance, effects on aquifers, surface waters, on draining and flooding a pit, on creating artificial wetlands and flooding areas and others. One of the significant environmental problems is deposition of waste materials resulting from mining and discharge of saline mine waters to local surface water courses. All these problems are solved within research studies and expert evaluations as well as standard during the preparation of hydrogeological reports by hydrogeologists. Research studies on these issues were prepared by, among others, Szczepańska, Witczak, Szczepański, Wilk (AGH–UST). One of the most important achievements in this subject was defining conditions for safe disposal of wastes from mines and coal power stations and safe discharge of saline mine waters within a mine workings, which was undertaken by a team of researchers from the AGH–UST under the leadership of Szczepański. Results and conclusions following this work are often used and implemented, especially during the closure phase of coal, lignite, metal ore, sulphate or rock mines.

A mine's closure. It means the ceasing of drainage operations and this leads to natural flooding. Since 1989, 24 mines of the Upper Silesia Coal Basin and 4 mines of the Lower Silesia Coal Basin have been abandoned (Rogoż & Posyłek, 2000). This created a new challenge for the mining industry and required the development of safe and economical drainage systems for mines that underwent closure. Such a system was developed by specialists of the AGH–UST in Cracow in cooperation with the Central Mining Institute. The system comprised replacing a stationary dewatering system with submersible pumps. Implementation of a shaft pumping system using submersible pumps brought significant benefits to the mining industry and economy due to the limited financial requirements of the method. This is associated with liquidation of the entire underground infrastructure from a abandoned mine. Besides that, it allows flexible, controlled and gradual flooding of mine workings up to designed depths that are safe for neighbouring, still operational mines. This mine closure methodology was later patented and the environmental and economic effects gained by implementing the method should be considered as a significant input by hydrogeologists into the mining industry and the national economy.

Hydrogeology and lignite mining

Lignite mining in the Wielkopolska region. For the past 60 years, hydrogeology of lignite deposits and their exploitation in the Wielkopolska region, have been intensively studied with regards to regional and environmental aspects (Wilk, 2003).

The Konin mine exploits lignite beds deposited in the Kujavian Lakeland district (Fig. 4), i.e. north of the Warta River Valley (Warsaw-Berlin ice-marginal valley), and the Adamów mine extracts beds located in the lakeless Turek Upland, south of the Warsaw-Berlin ice-marginal valley (Fig. 4). At present, localisations of mining areas and the level of drainage causes strong conflicts related to Natura 2000 sites and natural parks. In the case of the Konin mine, the problem relates especially to lakes and the Gopło glacial trough (the Tomisławice pit). With regard to the mine in Adamów, the conflict is associated with a Natura 2000 site that is designated along the Warta river. Highly complicated hydrological and hydrogeological conditions within the mining area are reflected in high groundwater inflow rates into mines. This causes considerable water hazards that require a significant hydrogeological input from the early stages of the geological assessment of a bed.

The most important achievements of hydrogeology with respect to the lignite mining in the Wielkopolska region are listed below:

- ❏ good recognition of conceptual models and their parameters including hydrogeological conceptual models for specific coal pits and/or water bearing layers hydraulically connected with pits. There are numerous published and archival studies which concern hydrogeological recognition of beds in the regions of Konin and Turek (Wilk, 2003);
- ❏ improvement of well-drainage systems and supervision of drilling within drainage areas;
- ❏ implementation into practice of numerical computations and modelling programmes for assessing water balances and groundwater inflow volumes into a specific pit, including identification of components within their structures. Modelling studies using numerical programmes for pits in the lignite mines in Konin and in Adamów and their impact on groundwater systems on a regional scale were being done over the period of 1992–2009 by Fiszer in the Wrocław University of Technology, Szczepiński in POLTEGOR, Nawalany in the Warsaw University of Technology, Dąbrowski in HYDROCONSULT, and Czabaj (Proxima) with their teams;
- ❏ development of a method for organising and implementing an integrated groundwater monitoring system within an open pit mine, with a specific focus on measuring all components of the water balance.

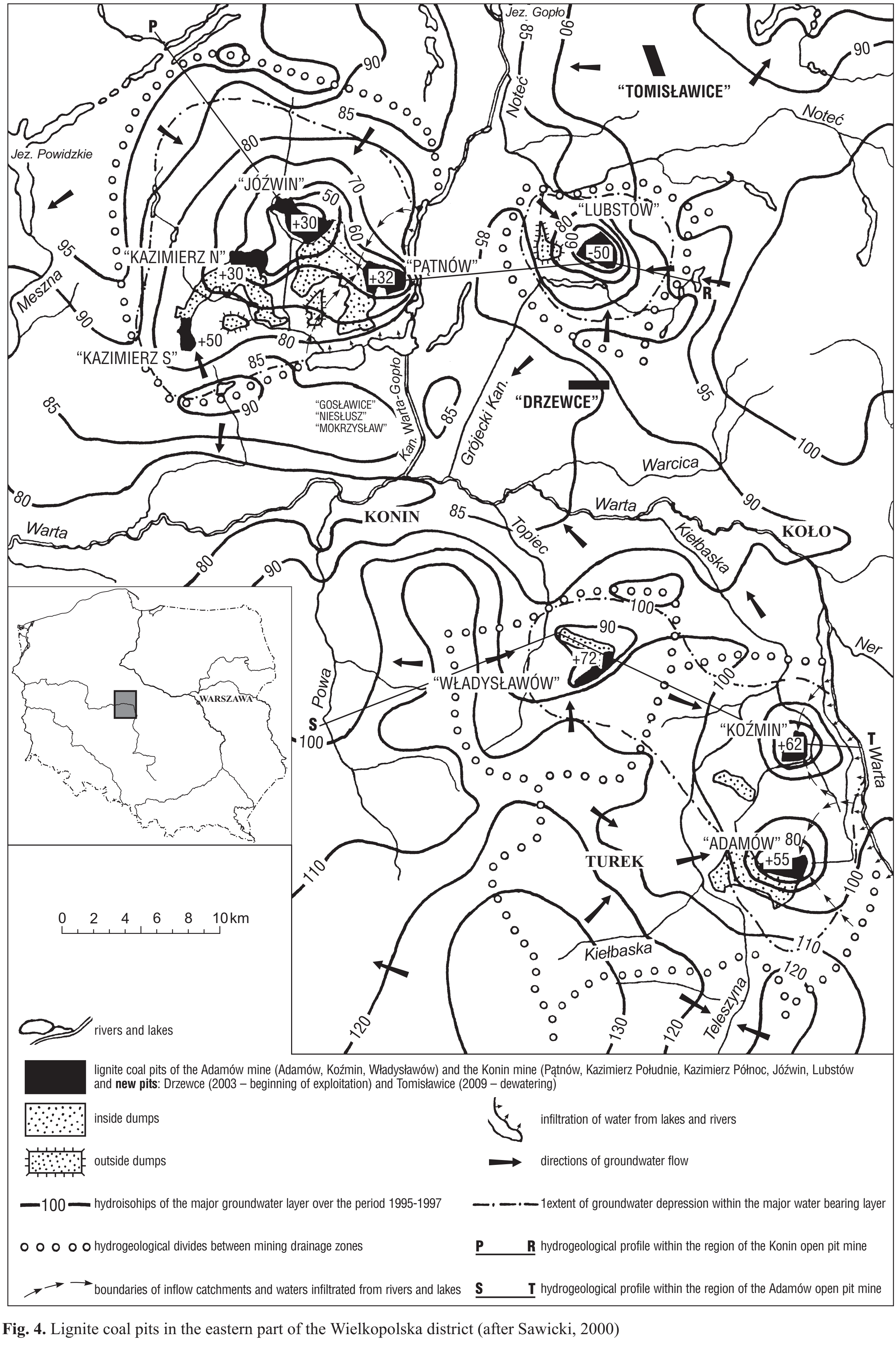

Fig. 4. Lignite coal pits in the eastern part of the Wielkopolska district (after Sawicki, 2000)

An example of a well organised, integrated groundwater observation network is the network that has been functioning around the mine in Konin since 1995. Since 1995, measuring results from this network have been analysed and published by the IMiGW in Poznań in the form of an annual hydrological and meteorological publication for the region of Konin open pit mines. The publication includes also numerous aspects of groundwater problems, including development of a depression cone and quality of water in surface water courses.

The lignite coal mine in Bełchatów. The deepest open pit mine in Europe belongs to KWB Bełchatów and its drainage causes a drawdown that reaches 280–290 m. The drainage system is a well barrier system (partly with wide diameter wells) (Fig. 5), and induced a regional cone of depression that comprises an area of 600 km^2. The yield of the draining systems reaches 380 m^3/min in Bełchatów, 320 m^3/min in Szczerców and 13 m^3/min in Dębina. The inside dewatering system (so called perched waters) discharges additionally over 60–80 m^3/min.

A groundwater monitoring system that controls dewatering operations includes some 260 wells within the Bełchatów pit, abt. 250 wells within the Szczerców pit and abt. 50 wells surrounding a dome, as well as over 1000 other observation points. Most of the measurements are operated automatically. Dewatering of the Bełchatów deposit started in 1975 and it is planned to be ceased in the 2050s.

In POLTEGOR, a reclamation strategy for the mine, based on filling the pits with water, has already been prepared (Szczepiński, 2000). Abandoned pits will be made shallower by dumping overburden rock material in them and later gradually filling them with water producing two mine pit lakes. In all aspects of mine operation, i.e. when designing dewatering of pits or their modification during exploitation of lignite deposits and prediction of undertaking processes of mine abandonment, hydrogeologists follow the following rules:

- ❏ assurance of safety during mining operations,
- ❏ minimisation of environmental impacts,
- ❏ minimisation of costs of optimum drainage operations.

Despite complex conditions that characterise the coal deposits in Bełchatów, thanks to cooperation with the mine's personnel, water threats have been successfully minimised, such as environmental impacts, and the rational water management system has been implemented.

Hydrogeology and metal ore mining

Mining of zinc and lead ores. Extensive hydrogeological investigations of the new Zn-Pb deposits were carried out in the 1960s and 1970s. In total, 20 ore fields were documented, 7 of which were accessed and exploited in later times. The most complex hydrogeological studies were carried out in regions surrounding Olkusz, Chrzanów and Zawiercie. Deposits of Zn-Pb ores occur in the Triassic carbonate formation at depths reaching up to 300 m b.g.l. Deposits were documented by Geological Enterprises and the Upper Silesian Branch of the Polish Geological Institute.

The fundamental aim of the work was to:

- ❏ define hydrogeological conditions of ore deposits,
- ❏ forecast the rate of groundwater inflow into designed mines and to define potential hazards caused by water inrush into the mine,
- ❏ define potential changes in groundwater and surface water environments due to proposed mining activities.

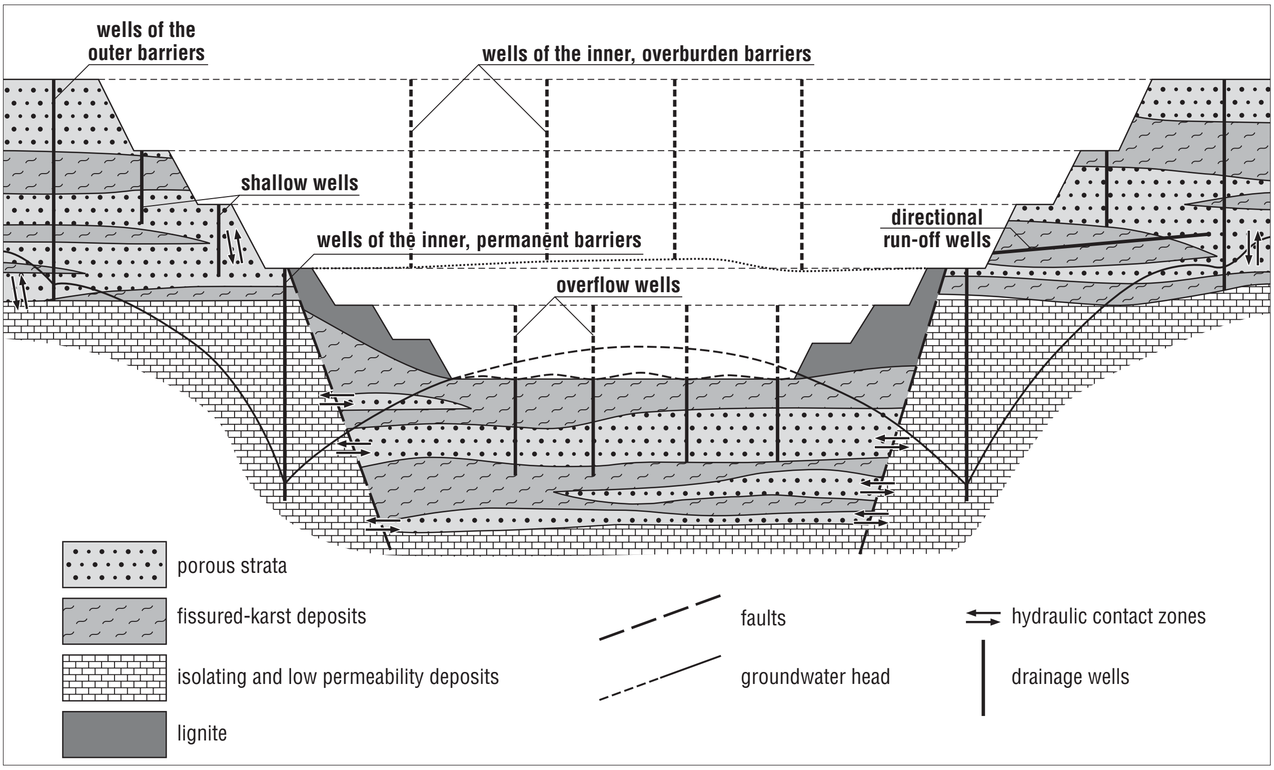

Fig. 5. Schematic diagram of the Bełchatów pit mine dewatering system (after Seweryn, 1984)

Hydrogeological and geological studies comprised geological and hydrogeological cartography of deposits in 1 : 25 000 scale and hydrogeological investigations and observations carried out in boreholes including groundwater sampling for chemical and isotopic analysis. Due to the specifics of the bedrock in which the studied ores occur, additional complex hydrogeological and geophysical investigations were carried out to define rocks and massive structure and complicated heterogenic karst-fractured groundwater flow systems.

Among significant hydrogeological achievements, the most prominent are studies carried out by Motyka & Wilk (1980) and Motyka (1998) presenting the complex hydrogeological conditions of the ore deposits taking into account the hydraulic structure of the carbonate Triassic formation consisting of karstic, fissured and porous flow systems. Hydrogeological descriptions of regions where Zn-Pb ores occur are presented in monographs by Różkowski and Wilk (1980) and Wilk and Bocheńska (2003).

Based on results of complex geological and hydrogeological investigations of ore mining areas it was possible to prepare initial hydrogeological prognoses regarding rational management of ore deposits and to define safe conditions for mining. Results of these studies allowed researchers to determine quantities and qualities of groundwater inflow into the designed mines and also allowed to assess potential environmental impacts resulting from mine exploitation and drainage activities. Investigations of geological and hydrogeological conditions led to designing and later, after World War II, building the following mines: in the Olkusz region – Olkusz and Pomorzany, in the Chrzanów region – Trzebionka mine (Fig. 6). Specifically good and precise determination of hydrogeological conditions played an important role in choosing an appropriate conception and technology for digging mine workings in the Pomorzany mine. The abundant water-bearing capacity of carbonated Triassic formation and resulting from that, large water inflows into Zn-Pb mines caused a significant water hazard to these mines. The largest inflow to the single mine (Pomorzany) reached 230 m^3/min. For that reason, hydrogeological conditions within the mine are continuously monitored during ore exploitation. Environmental impacts

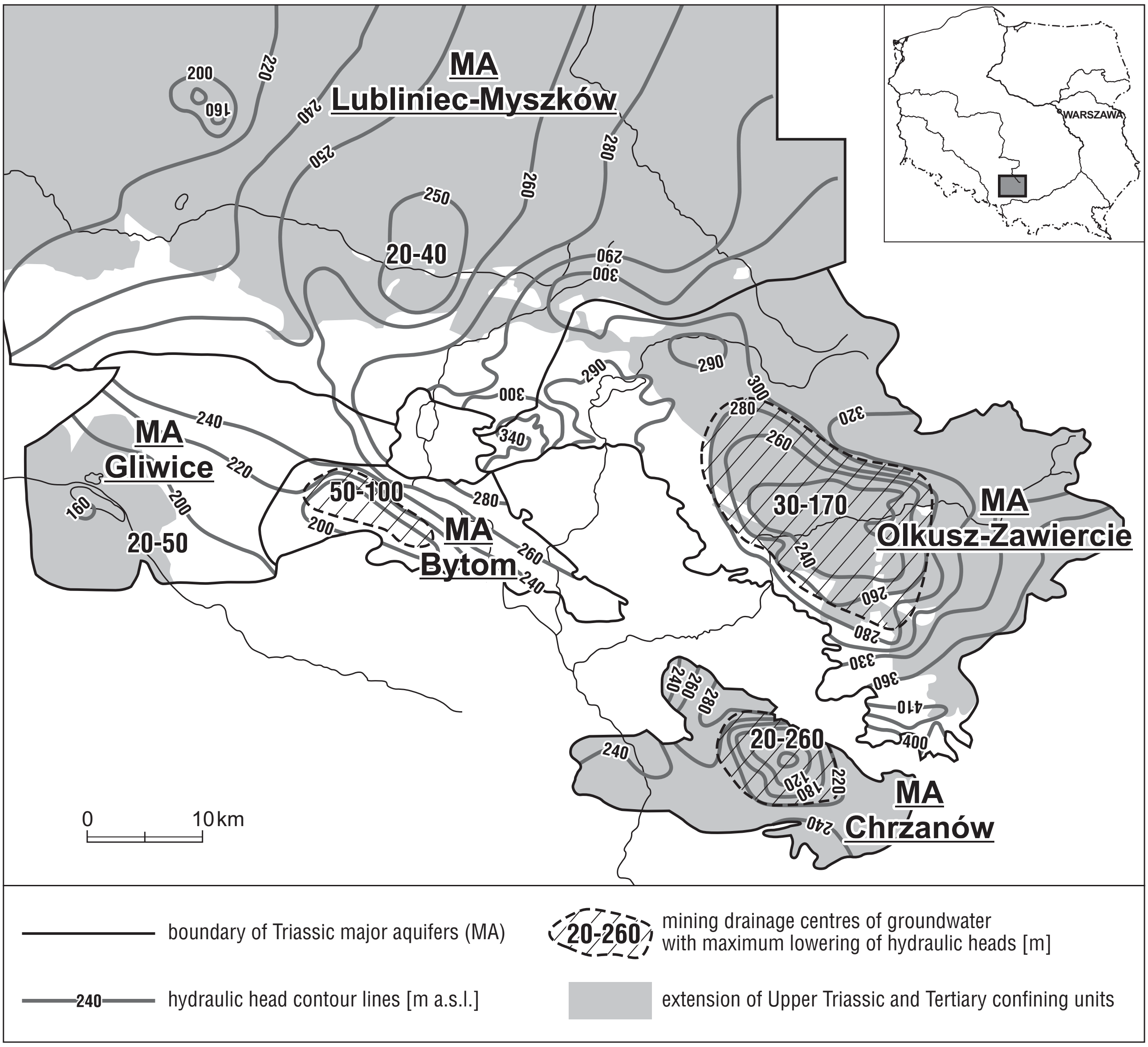

Fig. 6. Hydrogeological map of regional Triassic groundwater formation in the Zn-Pb mining area

resulting from the ore extraction are also well monitored (Motyka & Witkowski, 2002). Studies that were undertaken during a partial flooding of the Trzebionka mine allowed the determination of impacts that a mine closure has on the groundwater environment. These studies were carried out by a team of hydrogeologists from the AGH University of Science and Technology in Cracow, which was led by J. Motyka (Czop et al., 2003).

Mining of copper ores in the Lubin-Głogów Copper District. Exploitation of metal ores in Lower Silesia is associated with numerous problems related to the prognosis of groundwater inflow rates, changeable over time, to mine workings, mine dewatering (Staśko, 2009) and impacts from this mining on the water environment. Accession and the copper ore extraction in the Lubin-Głogów Copper District required a significant hydrogeological input. It is an excellent example showing the role that hydrogeology plays in the functioning of the copper ore mining industry.

In the LGCD, since the early 1960s, mining operations have been accompanied by dewatering activities and the monitoring of changes in hydrogeological conditions (Bocheńska, 2003; Bocheńska & Kalisz, 2003; Kleczkowski et al., 2007; Downorowicz, 2007).

After discovering the copper ore, its further recognition and documentation was an on-going process. This process was split into two phases. Between 1957 and 1985, documentation of the deposits was based only on data from borehole logs that were drilled in a regular net from the ground surface. In the next stage also results of investigations carried out inside the mine workings were used. This phase lasted until the end of exploitation of the deposits. Hydrogeological tests were undertaken in nearly all boreholes, which allowed good hydrogeological recognition of the deposits. The final effect of this recognition, gathered in dozens of hydrogeological reports, is a hydrogeological model of a water bearing system, hosted in the ore beds. This system is extremely complex, which conforms to a complicated structure of local geological setting. Such a good recognition of this environment allowed the forecast of groundwater inflow rate into designed and constructed mines. Nevertheless, the making of a proper prognosis, due to the existence of highly saturated Cenozoic sedimentary formations and imperfections of available methods of calculation, were difficult for all phases of the mine's development. In the early 1980s, mathematical modelling methods were applied, firstly electrohydrodynamic methods and later numerical modelling methods (Bocheńska et al., 1998; Bocheńska et al., 2000). Complex hydrogeological identification of the LGCD and its improvement during ore extraction allowed the optimisation and improvement of the safety of the exploitation.

Iron ore mining in the vicinity of Częstochowa. Exploitation of iron ores in the vicinity of Częstochowa was ceased in the 1970s. However, hydrogeological assessments of the ore had been carried out as early as after World War II – during the construction stage, later during the ore exploitation period and during its closure. These studies aimed at characterising local groundwater conditions and forecasting groundwater inflow rates into the mines. They focused on identification of mining impacts on the groundwater environment. Hydrogeological investigations were also undertaken while designing and implementing the mine closure and were very important for the prognosis of the negative impact of the final abandonment of the mines on changes in the groundwater environment. Hydrogeochemical changes resulting from flooding the mine, and explanations regarding the causes and processes of these changes were gathered in papers by Razowska (2000).

Hydrogeology and mining of chemical minerals

Sulphate is one of the chemical compounds mined in Poland that have been exported by Poland for many years. Its large-scale exploitation started when sulphate deposits were documented near Tarnobrzeg (Fig. 1, 7). From the early prospecting and exploration up to building the open pit mine, hydrogeologists were involved in all stages of the mine's development. System was improved based on data gathered by hydrogeologists from the AGH–UST: Z. Śmietański, A. Szczepański and R. Kulma. After deciding on the mine's closure, the team of hydrogeologists from the same institution including A. Szczepański, R. Kulma and A. Haładus prepared a concept of a safe gradual flooding of the mines and construction of pit lakes.

Hydrogeologists also played a significant role in defining safe exploitation conditions of salt in the Subcarpathatian region (Wieliczka, Bochnia, Barycz, Łężkowice) and in the Kujawy region (Wapno, Kłodawa, Solno, Góra, Mogilno). Underground exploitation of mineral deposits is threatened by waters that surround these beds. It is the responsibility of a hydrogeologist to propose a safe method for mining, which prevents a groundwater inrush into a mine. Disregarding these safety conditions may lead to a water hazard situation in a mine (it happened, for example, in Wieliczka in 1992) or to flooding a mine (as it happened in the Wapno mine in 1977). One of the important instruments securing against groundwater hazards is a continuous seepage monitoring system, which is carried out by hydrogeologists employed by a mine. Thanks to continuous hydrogeological monitoring which allows appropriate preventive decisions to be taken, historical salt mines in Wieliczka and Bochnia still exist. Hydrogeologists played an important role in preventing accidental water inrushes into the mine in Wieliczka, by contributing to an effective concept of sealing a rock mass in the mine's foreland.

Conclusions

Exploitation of mineral resources in Poland requires dewatering of 1 km^3 of water every year. Groundwater is therefore one of the major factors that determined the development of the mining industry in Poland. The rapid mining development that happened in Poland in the 20th century was possible thanks to a common commitment of Polish hydrogeology and specifically mine and mineral deposits hydrogeology.

The importance of hydrogeology is reflected in its contribution to various stages of mine development; from the

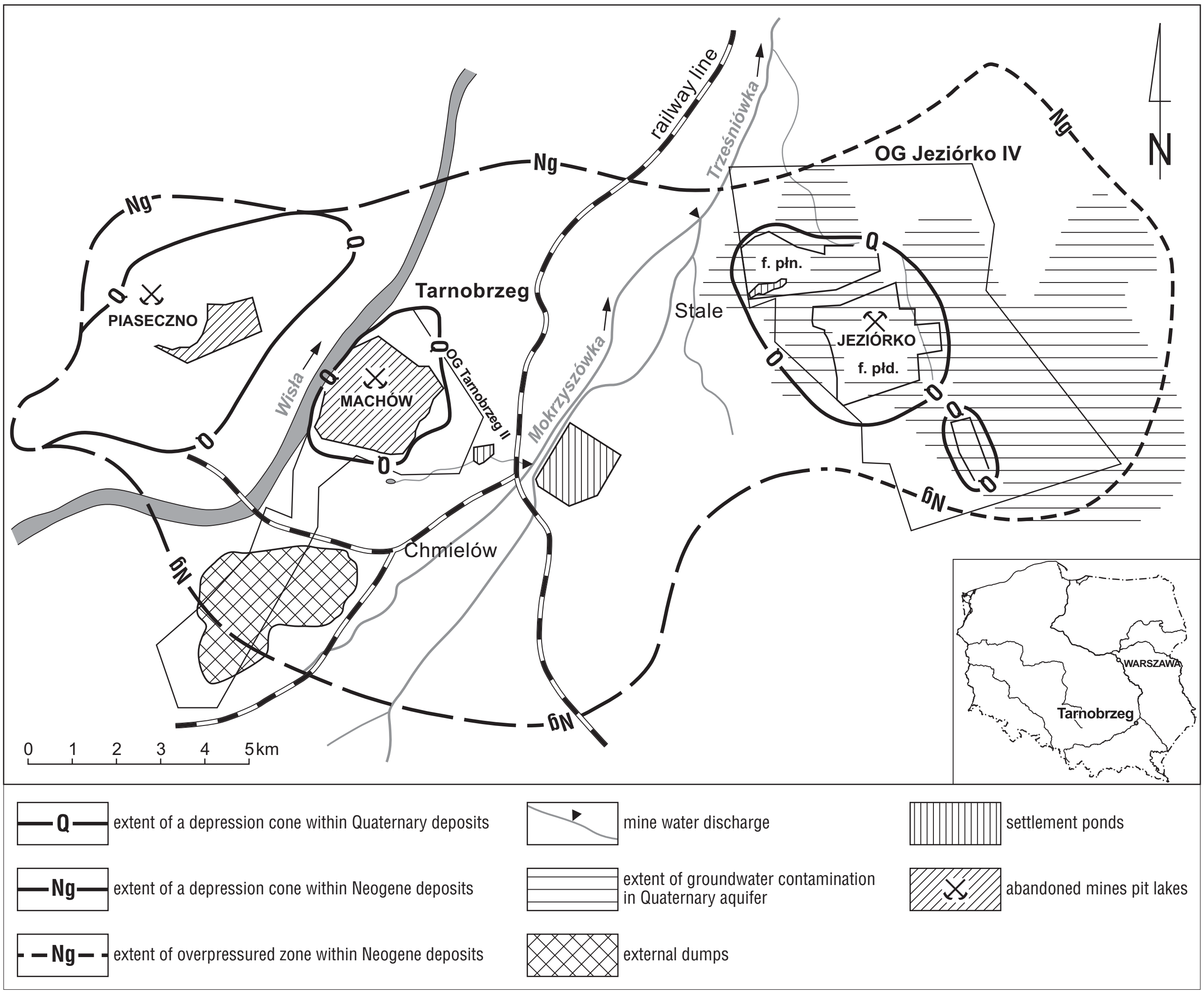

Fig. 7. Map showing the impact of sulphate mining near Tarnobrzeg on the water environment (after Wilk, 1990)

prospecting and exploration stage, through the resource estimation and undertaking accession, until its exploitation and finally mine closure and reclamation.

Undertaking complex hydrogeological studies of groundwater conditions of many ores and many deposits allowed the building, from scratch, of the Bogdanka Coal Mine (Lublin Coal Basin), the Lubin-Głogów Copper District, the lignite mine in Bełchatów, deep coal mines in the southern parts of the Upper Silesia Coal Basin, zinc and lead mines in Olkusz and Chrzanów, sulphate mines near Tarnobrzeg, as well as the development of the lignite mining in the Wielkopolska region. Despite large groundwater inflows and subsequently, significant water hazards, the fact is that these mines operate safely, which is confirmed by the lack of mining catastrophes related to flooding and a decreasing number of groundwater inrushes into mine workings. This is due to the great knowledge and professional experience of hydrogeologists who forecast the rate of groundwater inflows and assess water hazards using modern methods of mathematical modelling, as well as to the hydrogeological maintenance staff working in mines. The great and original hydrogeological achievement of all times was the methodological guidance for coal mine closure in the north eastern part of the Upper Silesia Coal Basin with a simultaneous assurance of working conditions for neighbouring still active mines. Also, an original achievement was the development of a methodology for sulphate mine closure near Tarnobrzeg.

Hydrogeological achievements with regards to the mining industry have been well documented. However, only small numbers of these were published. These are numerous case studies and, less common, synthetic studies, which gather results from different teams of authors, summarising achievements of hydrogeologists in prospecting, recognising and documenting deposits and their exploitation. A good illustration of this is the monograph entitled *The hydrogeology of Polish mineral deposits and water problems of mining* consisting of three volumes edited by Wilk (2003), Wilk & Bocheńska (2003) and Wilk & Kulma (2004).

More abundant and more difficult to find are archival studies, design projects, reports, case studies, expert evaluations and others. A good illustration of this is a number of over 900 hydrogeological reports regarding hydrogeology of the Upper Silesia Coal Basin, summarised in a publication by Prof. Różkowski titled *History and state of hydrological investigations of the Upper Silesian Coal Basin* (2008).

In the post war history, in Polish scientific institutions, especially in the AGH–UST in Cracow, and in the Central Mining Institute in Katowice, scientific studies focused on developing more precise and more trustworthy methods for forecasting groundwater inflow rates to mines. Selected statistical methods and groundwater filtration models were developed and adapted to fulfil practical, hydrogeological requirements. Application of the above methods allowed experts to appropriately design mine drainage systems and techniques, and finally, to minimise exploitation and abandonment costs.

The presented review of accomplishments of Polish hydrogeology with regards to mining is not inclusive but comprises an extensive register of literature and reference materials and leads to a conclusion that is directly related to the question stated in the title of this paper: Polish mining owes a great deal to Polish hydrogeologists and their hard work. Good hydrogeological knowledge and cooperation between hydrogeologists and miners has resulted in safe long term intensive exploitation of diverse Polish mineral deposits in tens of mines located in very difficult and sometimes unpredictable water conditions.

References

BOCHEŃSKA T. 2003 – The hydrogeology of mineral deposits and water problems of copper mining. Fore-Sudetic Monocline. [In:] The hydrogeology of Polish mineral deposits and water problems of mining (in Polish). Wyd AGH, Kraków, 2: 20–56.

BOCHEŃSKA T., FISZER J. & KALISZ M. 2000 – Prediction of groundwater inflow into copper mines of the Lubin-Glogow Copper District. Environ. Geol., 39: 587–594.

BOCHEŃSKA T., GURWIN J., MARSZAŁEK H., POPRAWSKI L. & WĄSIK M. 1998 – Cenozoic groundwater reservoirs of the Lubin-Głogów region. Acta Univ.Wratisl., Hydrogeologia, 2109: 173.

BOCHEŃSKA T. & KALISZ M. 2003 – Water problems during mining operations. [In:] The hydrogeology of Polish mineral deposits and water problems of mining (in Polish). Wyd AGH, Kraków, 2: 81–93.

BOLEWSKI A., NEY R. & SMAKOWSKI T. (eds.) 2002 – The balance of the World's and Poland's mineral resources management in 1996–2001 (in Polish). PAN IGSMiE, Pracownia Polityki Surowcowej, s. 1011.

BRUDNIK K., CZOP M., MOTYKA J., D'OBRYN K., ROGOŻ M. & WITCZAK S. 2010 – The complex hydrogeology of the unique Wieliczka salt mine. Prz. Geol., 58: 787–796.

CZOP M., MOTYKA J. & SZUWARZYŃSKI M. 2003 – Changes of the sulphates concentrations in the groundwater inflowing to the Trzebionka mine, during first stage of the liquidation process (in Polish). [In:] Mat. XI Konf. Współczesne Problemy Hydrogeologii, Gdańsk-Jastrzębia Góra, wrzesień 2003.

DOWNOROWICZ S. 2007 – Opening of Lubin-Sieroszowice ore-copper deposit in complicated hydrogeological and geological-engineering conditions (in Polish). Biul. Państw. Inst. Geol., 423: 1–22.

HOFFMAN M. & SZYSZŁO D. 1974 – The use of the multiple correlation method for mine water inflow forecasting (in Polish). Technika Poszukiwań, 4: 29–33.

Geographical atlas of Poland for secondary schools (in Polish). PPWK, Warszawa-Wrocław, 2000.

KLECZKOWSKI A.S., DOWNOROWICZ S., ZIMNY W. & BECKER R. 2007 – Hydrogeology of bed series. [In:] Monografia KGHM Polska Miedź SA (in Polish). Wyd KGHM Cuprum, Wrocław, 133–142.

MOTYKA J. 1998 – A conceptual model of hydraulic networks in carbonate rocks, illustrated by example from Poland. Hydrogeology Journal, 6: 469–482.

MOTYKA J. & WILK Z. 1980 – The Olkusz region of mineral deposits. Hydrogeological characteristics. Multiaquifer formations and their characteristics. Hydraulic connections between multiaquifer formations. Groundwater circulation conditions. [In:] Różkowski A. & Wilk Z. (eds.) The hydrogeology of zinc and lead deposits in the Silesian-Cracow Region (in Polish). Pr. Inst. Geol., 151–167.

MOTYKA J. & WITKOWSKI A.J. 2002 – Groundwater contamination in the area of Zn-Pb ore mines situated in the southern part of the Olkusz-Zawiercie Triassic aquifer (Poland). [In:] Merkel B.J., Planer-Friedrich B. & Wolkersdorfer Ch. (eds.) Uranium in the Aquatic Environment, Spriger-Verlag, Berlin, Heidelberg: 1029–1036.

RAZOWSKA L. 2000 – Hydrochemical changes in the area of flooded iron mines in the Częstochowa region (in Polish). Biul. Państw. Inst. Geol., 390: 35–96.

ROGOŻ M. & POSYŁEK E. 2000 – Hydrogeological problems of the Polish coal mines (in Polish). Wyd. GIG, Katowice.

RÓŻKOWSKI A. 2003 – The hydrogeology of the Upper Silesia Coal Basin. [In:] Wilk Z. (ed.) The hydrogeology of Poland's mineral deposits and mining areas (in Polish). 1: 42–145.

RÓŻKOWSKI A. (ed.) 2004 – Hydrogeochemical environment of Carboniferous coal-bearing formations of the Upper Silesian Coal Basin (in Polish). Pr. Nauk. UŚ, 2244: 174.

RÓŻKOWSKI A. 2008 – History and state of hydrological investigations of the Upper Silesian Coal Basin (in Polish). Wyd. UŚ, Katowice.

RÓŻKOWSKI A. & RUDZIŃSKA T. 1978 – hydrogeological model of the central and northern Coal Region in the Lublin Coal Basin. Geol. Quart., 22: 395–411.

RÓŻKOWSKI A. & WILK Z. (eds.) 1980 – The hydrogeology of zinc and lead deposits in the Silesian-Cracow Region (in Polish). Pr. Inst. Geol.

RÓŻKOWSKI A. & WILK Z. 1989 – Hydrogeological conditions of the Lublin Coal Basin (in Polish). Pr. Inst. Geol., 125: 107.

RUDZIŃSKA-ZAPAŚNIK T. & RÓŻKOWSKI A. 2003 – Hydrogeological conditions of the LZW. [in:] Wilk Z. (ed.) The hydrogeology of Polish mineral deposits and water problems of mining (in Polish). AGH, Kraków.

SAWICKI J. 2000 – Changes in natural rainfall infiltration to aquifers due to deep mine drainage (in Polish). Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.

SEWERYN N. 1984 – Dewatering of the Bełchatów open-cast mine (in Polish). Górn. Odkryw., 10–12: 53–61.

STAŚKO S. 2009 – On some hydrogeological problems induced by underground mining in Lower Silesia (in Polish). Pr. Nauk. GIG, Górnictwo i Środowisko 4: 35–45.

SZCZEPIŃSKI J. 2000 – Predictive modeling of filling with water the Bełchatów Lignite Mine final excavations. [In:] Proc. of the IMWA Congress on Mine, Water & Environment, Ustroń.

WILK Z. (ed.) 1990 – Map of hydrogeological changes due to mining activity in Poland against the background of environmental conditions, scale 1 : 500 000 (in Polish). Państ. Inst. Geol., Warszawa.

WILK Z. (ed.) 2003 – The hydrogeology of Polish mineral deposits and water problems of mining (in Polish), 1: 611.

WILK Z. & BOCHEŃSKA T. (eds.) 2003 – The hydrogeology of Polish mineral deposits and water problems of mining (in Polish), 2: 477.

WILK Z. & KULMA R. (eds.) 2004 – The hydrogeology of Polish mineral deposits and water problems of mining (in Polish), 3: 235.

WITKOWSKI A.J. 2005 – Contemporary Reviews of Mine Water Studies in Europe, Part 2. Mine, Water and the Environment – Journal of the International Mine Water Association, 24: 13–16.