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The Occurrence and Quality of Mine Water in the Upper Silesian Coal Basin, Poland

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Abstract The mining of coal in the Upper Silesian Coal Basin and the relatively recent closure of many of these mines during the past two to three decades has affected surface and underground water quality. Regulations in Poland are designed to protect active mining operations rather than water quality and water environment. Dewatering mechanisms in abandoned coal mines and characteristics of water pumped (quality, temperature) are discussed.

Keywords Abandoned mines · Aquifer dewatering · Geothermal resource · Mine closure

The Geology of the Upper Silesian Coal Basin

The Upper Silesian Coal Basin (USCB) has an area of about 7,500 km^2, of which 5,500 km^2 is within Poland and the remainder in the Czech Republic. It is a synformal structure associated with the Variscan orogenic episode (Figs. 1, 2). The productive, coal-bearing strata reach 8,500 m in total thickness and are underlain by Lower Carboniferous, Devonian, and Precambrian rocks. The coal-bearing succession is subdivided into four lithostratigraphic series (Table 1) of Namurian and Westphalian age, comprising sandstones, siltstones, claystones and coal seams. The thickness of the succession decreases gradually towards the east and southeast. The coal-bearing strata of the USCB are overlain by a cover of Permian, Triassic, Jurassic, Tertiary, and Quaternary deposits. The Permian and Jurassic deposits cover a very small part of the USCB, along the northeastern boundary of the Carboniferous subcrop. The Triassic cover is more extensive, represented by dolomites and limestones up to 200 m thick. Argillaceous Tertiary strata conceal the southern and northwestern portions of the USCB, reaching over 1,000 m in thickness in the south of the area. Superficial Quaternary sediments include both glacial deposits and glaciofluvial sands and gravels (Różkowski 2001).

A Brief History of Coal Mining in the USCB

Coal has been mined in Upper Silesia since around 1540 near the subsequent Wawel mine, near Ruda Śląska. The first discrete mine, Murcki, was established in 1657, at Rudne Kotliska, very close to Katowice–Kostuchna, where the coal outcropped. The first shaft was sunk near there in 1755, at the oldest underground coal mine in Upper Silesia (Włodarska 1957), though the claim is contested by a shaft in Ruda, which was initiated in 1751 by the landowner Baron Von Stechow for the exploitation of iron ore. The Saxon shaft sinkers found coal rather than iron and Von Stechow rented them the shaft for 48 florins. They, in turn, experienced problems working the mine due to gas and water, and sold the mine to local peasants, who were formally granted the mining concession in 1770 (Zaleski 1967). Figure 3 shows the location of the Upper Silesian

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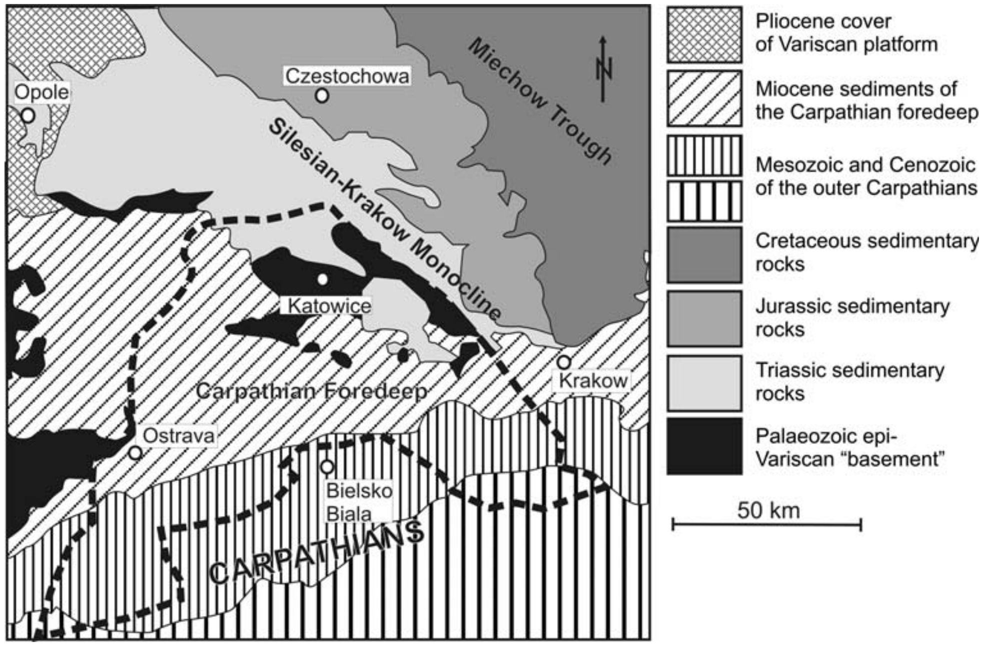

Fig. 1 Regional setting of the Upper Silesian Coal Basin (USCB) on the Alpine framework (redrawn after Kotas 1985); the *thick dashed line* shows the boundary of the USCB

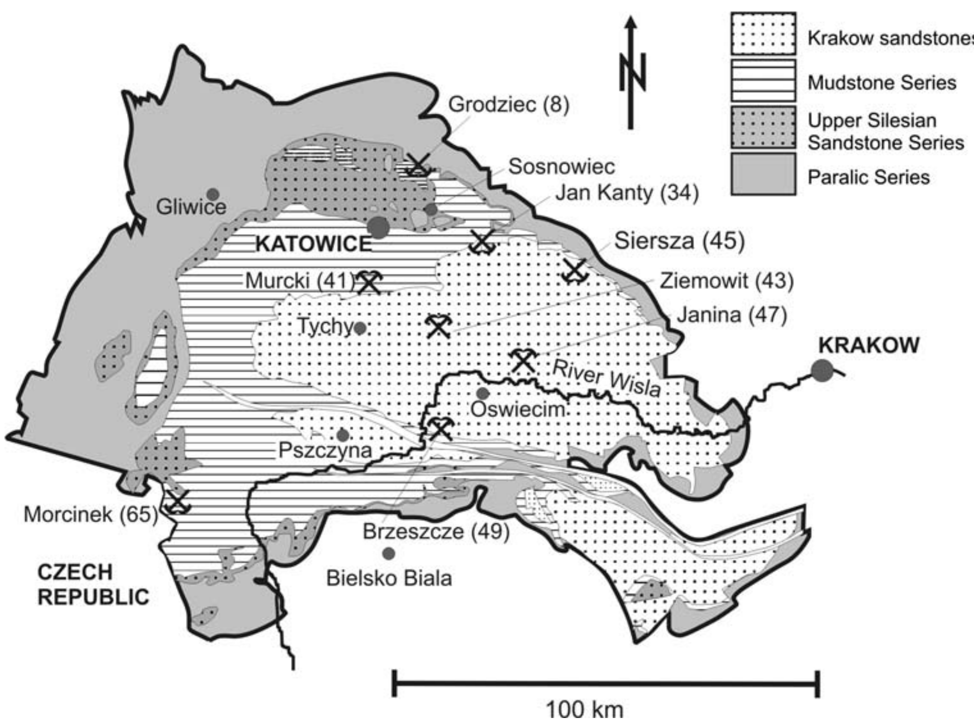

Fig. 2 Geological map of the top surface of the coal-bearing Carboniferous of the Upper Silesian Coal Basin. Note that this is not a conventional geological map of a land surface; it is a map at the level of the unconformity between Carboniferous and post-Carboniferous strata. The Carboniferous strata are themselves covered by various deposits of Permian to Quaternary age. Selected mines are shown, the *numbers* refer to Fig. 3. Modified after Gzyl and Banks (2007), redrawn and simplified after Buła and Kotas (1994)

collieries and the dates of their commencement and (in many cases) abandonment.

During the industrial revolution of the 19th Century, Upper Silesia was a crucible of social and technological progress. The developments during this and subsequent periods cannot be divorced from the political situation (the tri-partite division of Poland between Austria, Germany, and Russia from the late 18th century until the early 20th century and, later, the World Wars) and the stimulus provided by the interaction of Slavic, German, and Jewish cultures in the region. The main developments of the industrial revolution in Upper Silesia occurred during the period 1831–1870, when foundries and mines proliferated (Perlick 1943). Around this time, the foundations of today's Upper Silesian conurbation developed rapidly: towns such as Bytom, Gliwice, Nikiszowiec, and

Table 1 Stratigraphic sequence within the coal-bearing portion of the Carboniferous (after Buła and Kotas 1994)

Series	Age	Unit
Krakow Sandstone Series	Stephanian	Kwaczała Arkose
	Westphalian D	Libiąż Beds
	Westphalian C, D	Łaziska Beds
Mudstone Series	Westphalian A, B	Orzesze Beds
	Westphalian A, B	Załęże Beds
Upper Silesian Sandstone Series	Namurian C	Ruda Beds
	Namurian B	Anticlinal (Siodłowe) Beds
	Namurian A	Jejkowice Beds
Paralic Series (Upper)	Namurian A	Poruba (Porębskie) & Jaklowieckie Beds (western USCB)
		Grodziec Beds (central and eastern parts of USCB)
Paralic Series (Lower)	Namurian A	Gruszow and Pietrzkowice Beds (western USCB)
		Flora & Sarnów Beds (central and eastern parts of USCB)

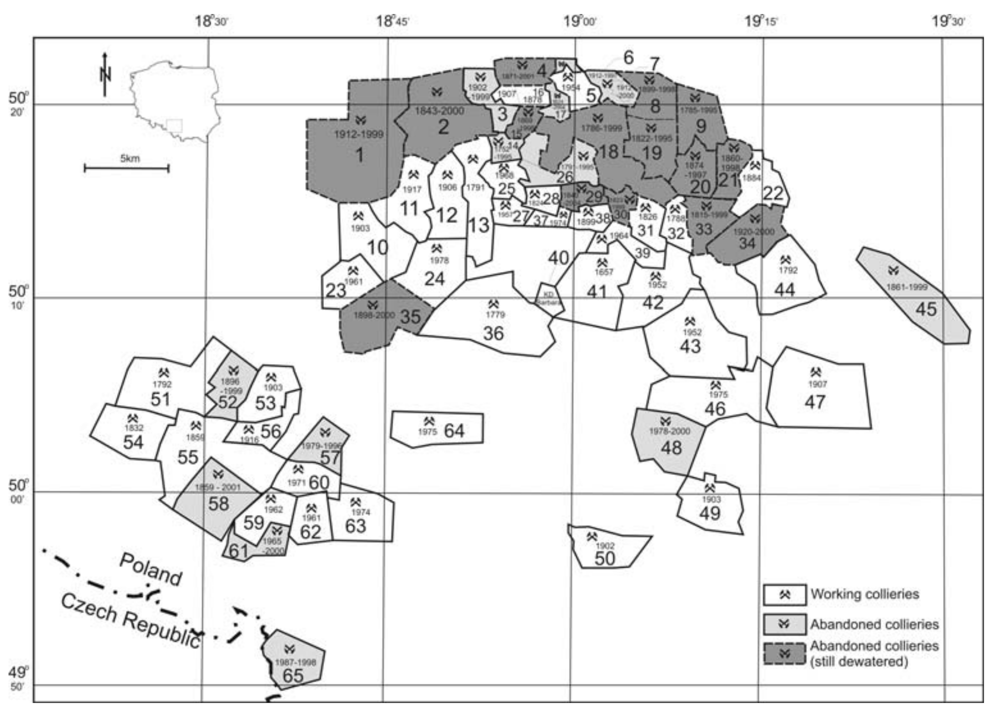

Fig. 3 Location of hard coal mines in Upper Silesian Coal Basin, Southern Poland: 1, Gliwice; 2, Pstrowski; 3, Bobrek Miechowice; 4, Powstańców Śl., Bytom I; 5, Julian (Piekary); 6, Jowisz; 7, Wojkowice; 8, Grodziec; 9, Paryż; 10, Knurów; 11, Sośnica; 12, Makoszowy; 13, Bielszowice; 14, Wawel; 15, Szombierki; 16, Bobrek, Centrum; 17, Rozbark, Bytom II; 18, Siemianowice, 19, Saturn; 20, Sosnowiec; 21, Porąbka Klimontów; 22, Kazimierz Juliusz; 23, Szczygłowice; 24, Budryk; 25, Pokój; 26, Polska; 27, Halemba; 28, Polska, Wirek; 29, Kleofas; 30, Katowice; 31, Wieczorek; 32, Mysłowice (joined with Wesoła mine); 33, Niwka Modrzejów; 34, Jan Kanty; 35, Dębieńsko; 36, Bolesław Śmiały; 37, Śląsk; 38, Wujek; 39, Staszic; 40, KD (experimental mine) Barbara; 41, Murcki; 42, Wesoła; 43, Ziemowit; 44, Sobieski; 45, Siersza; 46, Piast; 47, Janina; 48, Czeczott; 49, Brzeszcze; 50, Silesia (joined with Brzeszcze mine); 51, Rydułtowy; 52, Rymer; 53, Chwałowice; 54, Anna; 55, Marcel; 56, Jankowice; 57, Żory; 58, 1 Maja; 59, Jas Mos; 60, Borynia; 61, Moszczenica; 62, Zofiówka; 63, Pniówek; 64, Krupiński; 65, Morcinek); after Państwowy Instytut Geologiczny (2005) and Jureczka and Galos (2007)

Giszowiec enjoyed a 'boom' time, thanks to coal tycoons such as Georg von Giesche and his successors (Szejnert 2007). Production of coal increased from 0.5 million tonnes (Mt) in 1840 to 9.5 Mt in 1865. By 1913, it had reached 110 Mt, but the advent of the First World War significantly restricted production. By 1918, Poland was independent again, but the output of coal mines was still limited by an ongoing trade war with Germany and by the world economic crisis. Production was 40% less than the 1913 levels.

The Second World War (at a time when coal fulfilled 75% of the world's demand for energy) led to increased production from Polish mines under German occupation. The mines were managed by Germans, while Polish miners were employed in inferior positions with low salaries and poor conditions. The mines also made extensive use of conscript and prisoner labour. Prisoners from Auschwitz (*Oświęcim*) convicted of '*Handel mit Zivilisten*' (trafficking with civilians) ended doing hard labour at Gleiwitz (*Gliwice*), Janina, or Heidebreck (*Kędzierzyn*), maybe in the coal mines, which often meant a rapid death from exhaustion in the course of a few weeks (Levi 1996). After the departure of the Germans towards the end of the Second World War, Silesia fell under the sphere of Soviet influence. Most of the mines established factory committees. Their members were communist trade union activists and they were instrumental in securing the nationalisation of the mines following the formal cessation of hostilities in 1945. In the post-war state-controlled economy, mining was centrally administered and production targets were specified at a political level (Jaros 1975). During these years, increased coal production was the overriding aim, although efficiency was seldom scrutinised. As a result, by the end of the 1980s, Polish coal production was at an all-time high, reaching some 180 Mt. Following the political upheaval of 1989, culminating in the collapse of the Warsaw Pact, coal production steadily decreased and by 2007, it was down to 82.7 Mt (Gientka 2008).

Mine Closure

As in many other nations, the nature of the (largely unprofitable) mining industry has been dramatically altered during the past two to three decades. Since 1989, 34 of the 65 hard coal mines in Upper Silesia have been abandoned and the remaining collieries have been forced to adopt a free-market approach. According to the Polish State Mining Authority (www.wug.gov.pl), 31 underground mines were still working at the end of 2007. In the north of the USCB, most of the mines (working and abandoned) are potentially hydraulically interconnected, either directly or indirectly, by drifts, roadways, boreholes, goaf, or intact coal barriers of limited thickness (Fig. 4). The objective of dewatering is to maintain the level of water in the abandoned mine under the level of the "over-spill" connection to the adjacent working mine. This criterion is codified in Polish geological and mining law.

Dewatering Mechanisms

The Central Department of Mine Dewatering (*Centralny Zakład Odwadniania Kopalń* or "CZOK") was formed in 2001 and charged with responsibility for management of mine water and dewatering operations in abandoned mines in the USCB. CZOK is also engaged in the monitoring of mine water levels, the management of discharge water chemistry, and the rationalisation of mine dewatering systems. Two main systems are used to dewater abandoned mines (Fig. 5):

1) The so-called "stationary pumping system" comprises pumps located in an underground plant room in a partially dewatered mine. Such a system requires continued ventilation, staffing, and mechanical infrastructure in the shaft and mine.
2) Submersible pumping systems have been installed in flooded shafts. The system is controlled from above ground and, in case of failure, pumps and motors can be removed by mobile cranes for inspection and repair. Water levels are automatically measured by transducers and recorded by data-loggers.

Mixed pumping systems are employed in the Saturn mine in Czeladź, where two sets of stationary pumps lift water from the 210 m level to the surface. One set pumps iron- and sulphate-rich mine water, which is in turn lifted by underground submersible pumps from the workings in the pyrite-rich Carboniferous strata. Another set of pumps captures clean ground water draining down into the workings from the Triassic limestone roof strata. This clean water is kept separate from the contaminated mine water and is pumped to the surface to supplement the public drinking water supply.

In a few other abandoned coal mines, water is deliberately drained under gravity, via dedicated drifts or boreholes, towards adjacent working coal mines, from which it is discharged. Figure 5 illustrates the main systems for dewatering abandoned mines in the USCB (Kropka et al. 2005).

In total, 82.7 million m^3 per year are pumped; about 5.6% (from the Saturn and Dębieńsko mines) are used for drinking water (the relevant Polish standards for potable use are: 250 mg/L for SO_4 and Cl) or industrial water supply (the Pstrowski, Szombierki, and Jan Kanty mines), especially for cooling or stowage.

Characteristics of Water Pumped from Abandoned Coal Mines

Underground mining inevitably disturbs the hydrogeological environment. Some of these disturbances may be

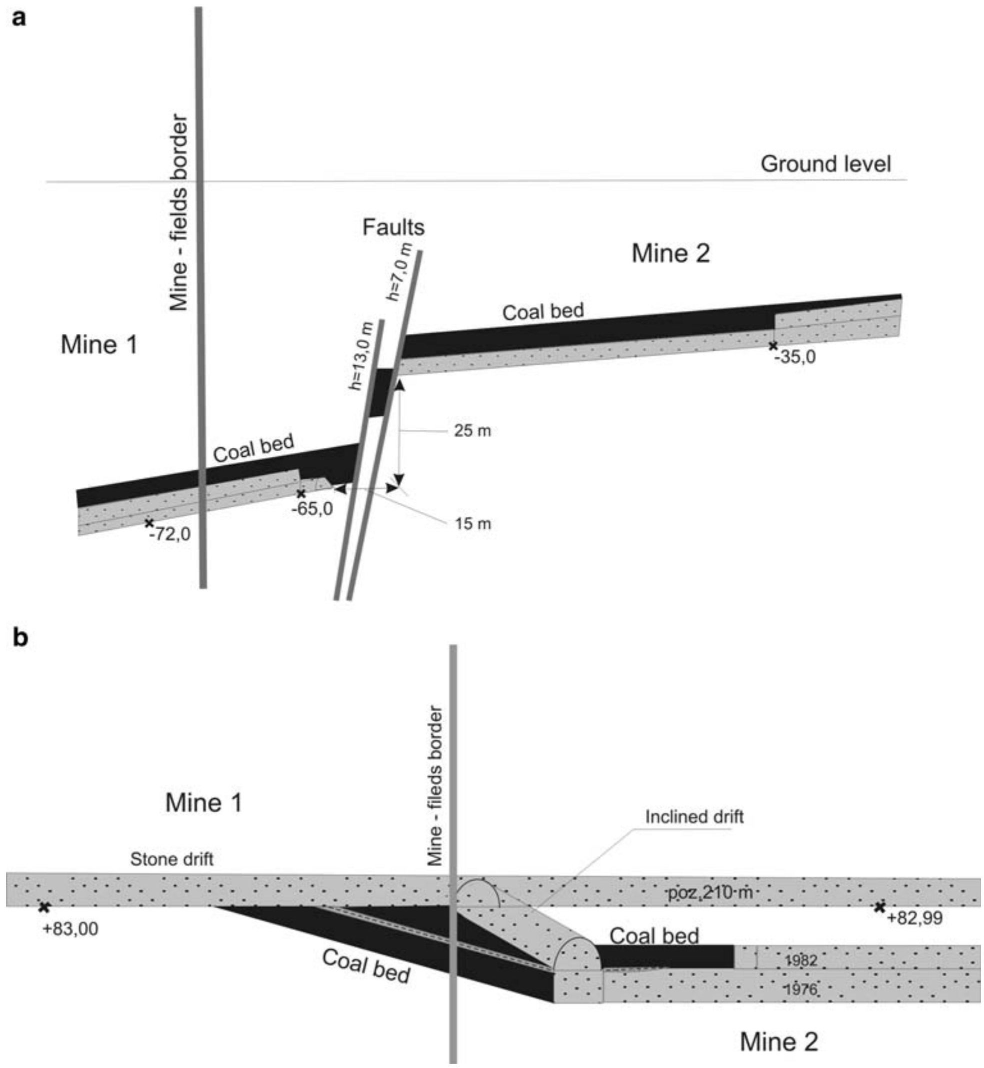

Fig. 4 Examples of indirect and direct connections of mine workings (after Kropka et al. 2005): **a** indirect hydraulic connection of mine workings, **b** direct hydraulic connection of mine workings

permanent (changes in subsurface transmissivity and storage) while some are more temporary in nature (the dewatering of mines, desaturation of adjacent strata, and induced steep head gradients in the saturated strata adjacent to and above the mine). Once pumping has ceased, ground water floods the mine and the zone of depressed head in the rocks adjacent to the mine rebounds (Gandy and Younger 2007; Kortas and Younger 2007). As mine flooding progresses, the sulphate- and metal-contaminated mine water can flow into adjacent aquifer strata, causing widespread ground water pollution (Neymeyer et al. 2007; Razowska 2001). The area of dewatered mines in the USCB covers approximately 500 km^2, with the deepest mine workings at a depth of 1,160 m in the Pstrowski mine. Permissible water levels in abandoned mine workings are determined by a Commission of Water Hazards (CZOK) within Poland's Mining Authority (Table 2). Following abandonment, CZOK monitors the influxes, levels, and quality of mine water. During this period, there is a general tendency for decreasing influxes of water to the mine, as regional head gradients decrease during their rebound towards a less stressed condition (some of the curves in Fig. 6, for example). The influx rates may also be affected by variations in rainfall, although it is difficult to conclusively demonstrate a direct relationship. In Fig. 6, annual rainfall is compared with average annual discharge. In most of the cases, rainfall and discharge correlate but long-term observation is required. The possible retardation of an abnormally high recharge or low recharge episode before it is manifested as inflow in the mine workings remains unknown (and is most likely highly variable between different mines).

In the dewatered area of the USCB, there is a general tendency for increased ground water mineralisation with depth; the anion composition tends to evolve along a sequence that is typical for the Silesian coalfields, $HCO_3^- \rightarrow SO_4^{2-} \rightarrow Cl^-$. Down to a depth of 650 m in this part of the USCB, both fresh and brackish ground

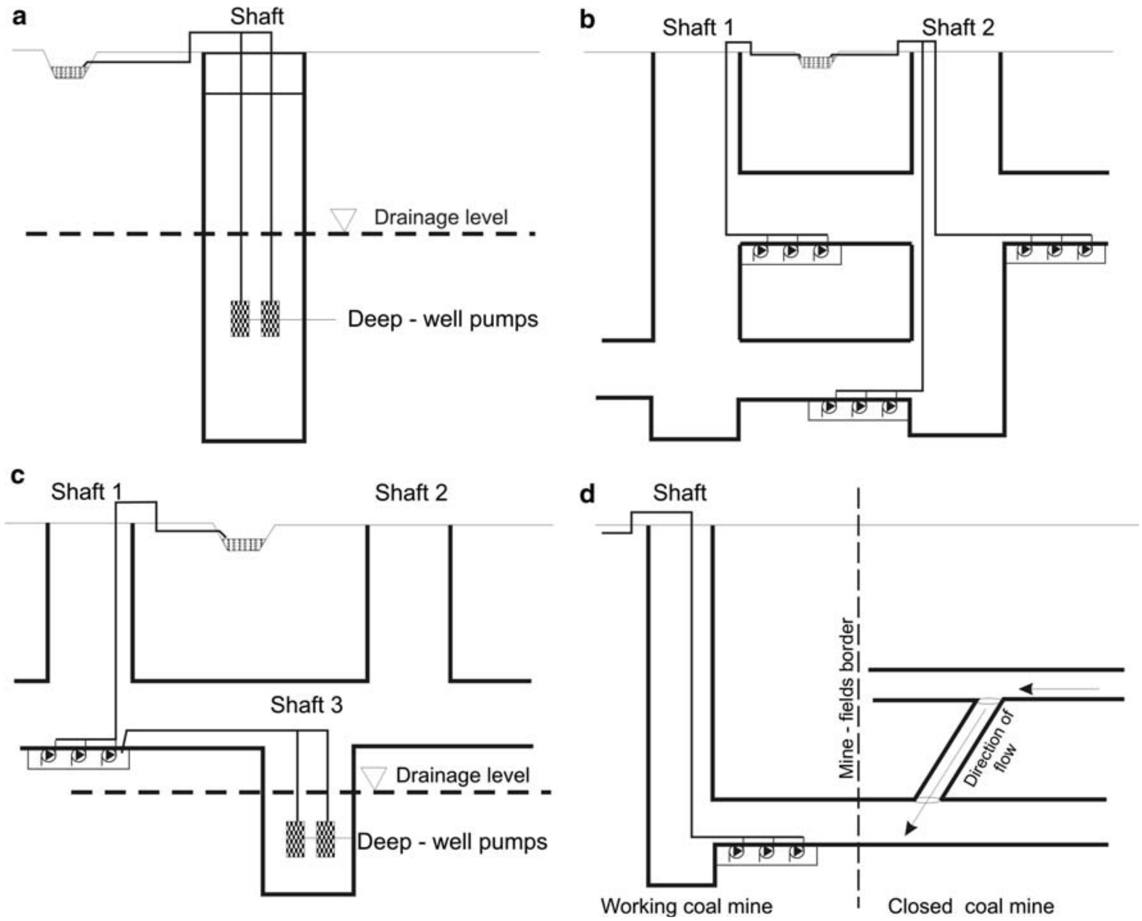

Fig. 5 Scheme of dewatering systems in abandoned mines (after Kropka et al. 2005): **a** submersible pumping system, **b** stationary pumping system, **c** mixed, stationary, submersible pumping system, **d** gravitational drainage

waters occur, with mineralisation ranging up to 4.5 g/L (Różkowski 2006). During and after flooding, the accumulated products of sulphide (dominantly pyrite) oxidation leach into the mine water (Barnes and Clarke 1964; Gzyl and Banks 2007; Singer and Stumm 1970), typically resulting in large increases in iron and sulphate concentrations.

CZOK has systematically collected water samples at least two to three times a year since 2001. After the EU Water Framework Directive was implemented in Polish legislation, around 2004, the sampling frequency has been increased to about 6 times a year. Temperature and pH are measured in the field, while water samples are collected as unfiltered aliquots into clean, acid-washed bottles. The aliquots destined for metals/cation analysis are then acidified in the field with concentrated nitric or sulphuric acid, while those destined for ammonium, nitrate, and nitrite analysis are acidified with hydrochloric acid. Water samples are typically analysed for both major and minor dissolved chemical constituents: Ca, Mg, Na, K, NH_4^+, NO_2^-, NO_3^-, Fe, Mn, Pb, Zn, Cd, Cu, Cr, SO_4^{2-}, Cl^-, alkalinity (HCO_3^-), total dissolved solids, suspended solids, and hardness. The analyses are performed at a certified laboratory selected by competitive tendering.

Characteristic analyses of pumped mine waters from abandoned USCB coal mines in Upper Silesia Coal Basin from 2007 to 2008 are presented in Table 3. The water from the 15 dewatered, abandoned mines has a range of total dissolved solids from 874 to over 91,000 mg/L, with the maximum value occurring at a depth of 690 m (−500 m) above sea level (asl) in the Dębieńsko mine. Ammonium occurs at the mg/L level in the deeper, more saline waters. The pH is circum-neutral, ranging from 6.08 to 7.72. During post-abandonment flooding, pH values as low as 5.44 were observed in some mines (e.g. Paryż, Sosnowiec, Niwka Modrzejów). Of the major cations, calcium ranges from 47 to 1,940 mg/L, magnesium from 19 to 1,300 mg/L, sodium from 26 to 22,000 mg/L, and potassium from 6 to 604 mg/L. Amongst the anions, sulphate ranges from 234 to 1,910 mg/L, chloride from 74 to

Table 2 Characteristics of dewatered coal mines in Upper Silesia Coal Basin: *STA* stationary pumping station; *SUB* submersible pumping station; *MIX* mixed pumping system (submersible + stationary)

Mine	Mining area (km^2)	Deepest working [m bgl (m asl)]	Max. permissible water level (m asl)	Water volume in flooded mine (million m^3)	Pumping system	Water pumped from mine (million m^3/year)		
						2005	2006	2007
Saturn	29.0	700 (−430)	69.0	7.5	MIX	9.05	10.63	12.36
Sosnowiec	20.4	450 (−200)	90.0	10.1	SUB	2.51	3.45	2.95
Paryż	27.0	510 (−240)	50.0	8.1	SUB	5.48	5.34	5.63
Porąbka Klimontów	17.4	550 (−270)	−190.0	5.4 (under water level 200.0 m ASL)	SUB	2.70	2.53	2.45
Grodziec	33.9	800 (−540)	90.0	11.6	SUB	0.03	1.29	0.51
Niwka Modrzejów	29.1	910 (−660)	−145.0	5.8	SUB	5.52	5.30	4.53
Katowice	8.7	780 (−500)	−177.5	7.2	SUB	2.82	3.02	3.06
Kleofas	15.8	700 (−524)	−294.0	0.9	SUB	–	2.54	
Gliwice	101.7	520 (−270)	−261.3	0.6	SUB	3.12	3.08	3.17
Pstrowski	34.0	1160 (−860)	−555.0	1.9 (under water level 559.0.m.ASL)	STA	7.46	7.87	8.69
Szombierki	10.3	950 (−690)	−498.0	0.1	STA	1.23	1.13	2.65
Powstańców Śl.- Bytom I	17.7	650 (−470)	−467.5	0.5	STA	1.54	1.57	1.53
Siemianowice	45.9	780 (−450)	−327.0	2.5	STA	12.45	12.49	13.27
Jan Kanty	30.9	360 (−90)	11.9	1.3	STA	16.86	17.26	15.34
Dębieńsko	46.6	850 (−600)	−460.0	0.15 (under water level 506.8 m ASL)	STA	6.00	5.62	5.09
Total	468.4					76.77	80.58	83.77

54,780 mg/L, and bicarbonate from 134 to 787 mg/L (2.2–12.9 meq/L). The concentration of sulphate in mine waters of the USCB is typically less than 2,000 mg/L, which has tentatively been ascribed to a saturation ceiling with respect to gypsum and/or jarosite by Banks (2006). Calcium and sulphate increase in concentration as the result of neutralisation by carbonates such as calcite and dolomite. Usher and Vermeulen (2003–2006) showed that Ca^{2+} and $SO_4{}^{2-}$ only increase up to a limit imposed by the solubility of gypsum ($CaSO_4$ $2H_2O$).

Figure 7 is a Piper diagram of the chemistry of mine water pumped from abandoned coal mines. Regional trends are indicated. Hydrogeological sub-region I (after Różkowski 2004) is hydrogeologically open, with infiltration and oxidation conditions, and is mostly HCO_3–SO_4–Ca–Mg type (signed dotted line on Piper diagram). Hydrogeological sub-region II is hydrogeologically closed with limited infiltration and reducing conditions, so that the mine waters are the Cl–SO_4–Na–Ca type (dashed line on Piper). In sub-region II, the mines were deeper (e.g. Pstrowski—1,160 m bgl, Szombierki—950 m bgl) than in sub-region I (e.g. Sosnowiec—450 m bgl, Paryż—510 m bgl); thus mine water chemistry is related to depth.

Total iron in unfiltered, acidified sample aliquots ranges from 0.18 to 39 mg/L, but large variations in concentrations typically occur during the flooding process due to flushing of the secondary products of pyrite and marcasite oxidation (Gzyl and Banks 2007). Increasing concentrations of Zn, Pb, Cu, and Ni were also observed during this post-flooding period (e.g. zinc concentrations increased from <0.3 to 17.8 mg/L during the flooding of the Porąbka Klimontów mine). Zinc concentrations were typically between <10 and 300 μg/L in the mine waters pumped by CZOK in 2007-2008. Lead concentrations ranged from <10 to 4.68 mg/L, copper from <10 to 350 μg/L, and nickel from <10 to 920 μg/L. Chromium was consistently <10 μg/L.

Mine Water Temperature

The water temperatures from abandoned and dewatered coal mines in the USCB vary significantly. They are generally elevated and exhibit an increasing tendency with depth (a tendency which is readily observed in mines with stationary pumping systems at discrete levels). The USCB has an annual mean air temperature of around 6.9°C, while monthly 24 h means range from −3.9°C (in January) to 17.5°C (in July). An ‘urban heat island’ is observed around the Katowice conurbation, where temperatures are significantly warmer than the surrounding rural areas. This heat island effect is typically around 1–2°C, but can be as much

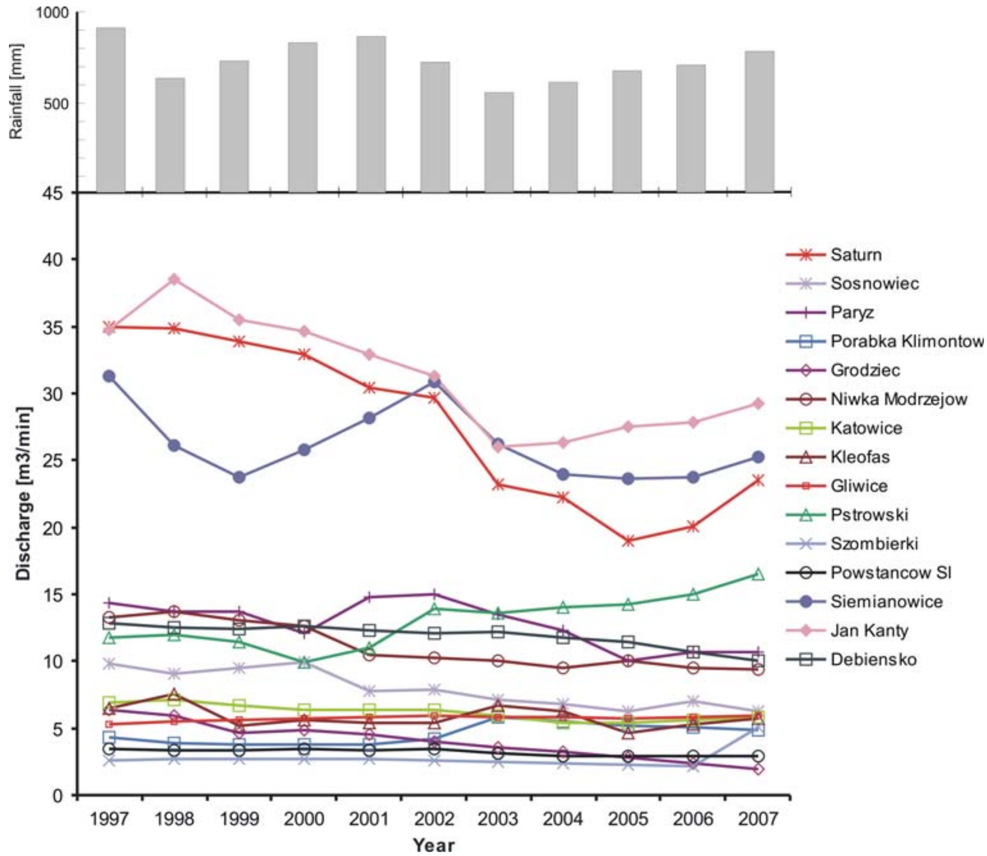

Fig. 6 Annual discharges [m^3/min] of water pumped from abandoned mines in the USCB in the years 1997 to 2007, compared with annual rainfall [mm]

as 5°C in Central Katowice (Czermińska et al. 2001). Pumped mine water temperatures range from 11.3 to 29.2°C, generally increasing with depth. Given that many of these waters are pumped in urban areas (where there is a demand for space-heating and cooling) and given that several of the former colliery sites are ripe for redevelopment (Fig. 6), the mine waters have a high potential for ground source heating and cooling via the use of heat pumps (Banks et al. 2004; Gudek 2006; Karwasiecka 2001; Małolepszy et al. 2005; Solik-Heliasz and Małolepszy 2001; Watzlaf and Ackman 2006). The viability of this has been demonstrated at a small scale with coal mine water in Scotland and elsewhere and at a large (district heating) scale at Heerlen, Netherlands (Demollin-Schneiders 2008) (Fig. 8).

Challenges for the Future

At present, the active dewatering that is undertaken by CZOK is primarily designed to protect still-active mines from excessive water inflows. Indeed, in the USCB, there is a legal obligation to perform this function, so that environmental protection is, at best, only a secondary motive for continued dewatering. Nevertheless, CZOK is becoming increasingly aware of the water quality issues associated with pumped mine water, both from an operational point of view (elevated hardness causing mineral scaling in pumps and other equipment), from a legal point of view (compliance with discharge consents for salinity), and from the perspective of general environmental protection, especially the water environment, according to the EU Water Framework Directive.

The pumped water from abandoned mines is typically discharged into tributaries of the upper Wisła (Vistula) and upper Odra (Oder) river basins, causing more regional contamination issues related, in the main, to sulphate, chloride, and suspended solids (mostly, iron oxyhydroxide flocs). It is interesting to note that the main concerns in terms of discharged water quality hitherto relate to salinity (sulphate and chloride), as these are the parameters that are typically regulated by discharge consents issued by Polish environmental authorities. According to Polish environmental law, CZOK is obliged to pay for its discharged pollutant load of sulphate and chloride. In 2008, a 1 kg load of $Cl^- + SO_4^{2-}$ costs 0.40 PLN, translating into a total bill for CZOK of some 8.0 million PLN (about 2.0 million Euros). Nevertheless, active treatment (reverse osmosis, high-temperature, or physico-chemical treatment) would cost 5–6 times more than this sum, resulting in little motivation for treating these discharges. Arguably, discharges of iron and manganese could be regarded as

Table 3 Characteristic water chemistry data (2007–2008) from the mines that CZOK is actively dewatering

Mine	Location	pH	TDS (mg/L)	Alkalinity (meq/L)	Cl^- (mg/L)	SO_4^- (mg/L)	NH_4^+-N (mgN/L)	NO_3^--N (mgN/L)
Saturn	210 m level	7.54	985	6.8	78.9	234	0.2	0.62
	Andrzej	7.11	3,130	11.4	605	964	0.25	<0.1
Sosnowiec		7.51	1,380	8.6	153	360	0.32	0.33
Paryż		7.41	1,310	8.5	155	360	0.43	0.36
Porąbka Klimontów		7.26	2,160	12.9	238	523	0.1	1.72
Grodziec		7.05	3,765	11.1	74.3	1,500	0.42	0.78
Niwka Modrzejów		6.65	8,120	6.9	3,971	703	2.49	15.6
Katowice		6.95	4,500	7.4	1,470	910	1.14	1.1
Kleofas		7.13	11,400	6.6	4,042	1,923	1.24	9.55
Gliwice		6.97	13,280	10	5,920	1,910	0.81	4.06
Pstrowski		7.67	11,690	9.6	5,670	1,170	0.31	1.74
Szombierki		7.72	8,920	11.7	3,400	1,640	0.15	0.8
Powstańców	500 m level	7.59	2,200	6.4	592	490	0.15	0.29
	760 m level	6.08	58,100	2.2	35,100	240	14	4.3
Siemianowice	SIII 321 m level	7.16	2,175	7.4	138	918	0.19	<0.1
	Kolejowy 630 m level	7.4	7,469	8.4	2,907	1,403	0.22	<0.1
Jan Kanty	270 m level	6.78	1,020	3.5	152	353	0.21	0.47
Dębieńsko	202 m level	7.1	874	6	120	242	0.16	0.91
	410 m level	6.88	3,432	12.1	1,126	380	0.33	1.1
	690 m level	6.44	91,650	5.9	54,781	1,870	15.8	5.4

Mine	Location	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (tot) (mg/L)	Mn (mg/L)	Temperature °C
Saturn	210 m level	183	37.7	26.2	5.7	0.22	0.13	12.2
	Andrzej	197	102	301	36	7.2	0.95	14.4
Sosnowiec		145	71	100	17	5.1	1.32	14.5
Paryż		154	58.8	70	12.3	3.6	1.2	13.5
Porąbka Klimontów		180	121	180	45	5.8	1.21	17.6
Grodziec		236	238	241	27.4	18.2	6.1	14.8
Niwka Modrzejów		485	279	1,800	190	39	3.6	18.5
Katowice		297	213	780	65	4.66	1.8	19.5
Kleofas		713	462	4,800	103	2.8	4.21	18.5
Gliwice		335	198	4,000	315	2.86	0.64	20.2
Pstrowski		352	219	3,500	302	0.92	0.085	18.8
Szombierki		315	200	2,400	178	0.18	0.097	24.5
Powstańców	500 m level	125	43.9	400	117	<0.05	<0.03	18
	760 m level	1,940	1,217	1,6120	508	0.81	2.37	26.5
Siemianowice	SIII 321 m level	289	131	111	16	4.3	2.1	16.2
	Kolejowy 630 m level	212	196	2,070	110	0.48	0.09	23.1
Jan Kanty	270 m level	143	53.9	70	12.5	7.4	0.92	11.3
Dębieńsko	202 m level	74	19	209	8	<0.03	<0.02	12.3
	410 m level	47.3	62.9	610	16.7	<0.03	0.043	15.7
	690 m level	1,114	1,305	22,000	604	14.1	1.6	29.2

under-regulated; they are not widely recognised by Polish environmental authorities as priority pollutants, despite the fact that they are internationally recognised to cause some serious coal-mining related environmental impacts in surface waters. Under Polish environmental law, iron concentrations of up to 10 mg/L are permitted in industrial effluents, while manganese is not limited. Dissolved metals such as aluminium, iron, and manganese are recognised to oxidise and/or hydrolyse on emergence to the atmospheric environment, resulting in flocculation and precipitation of

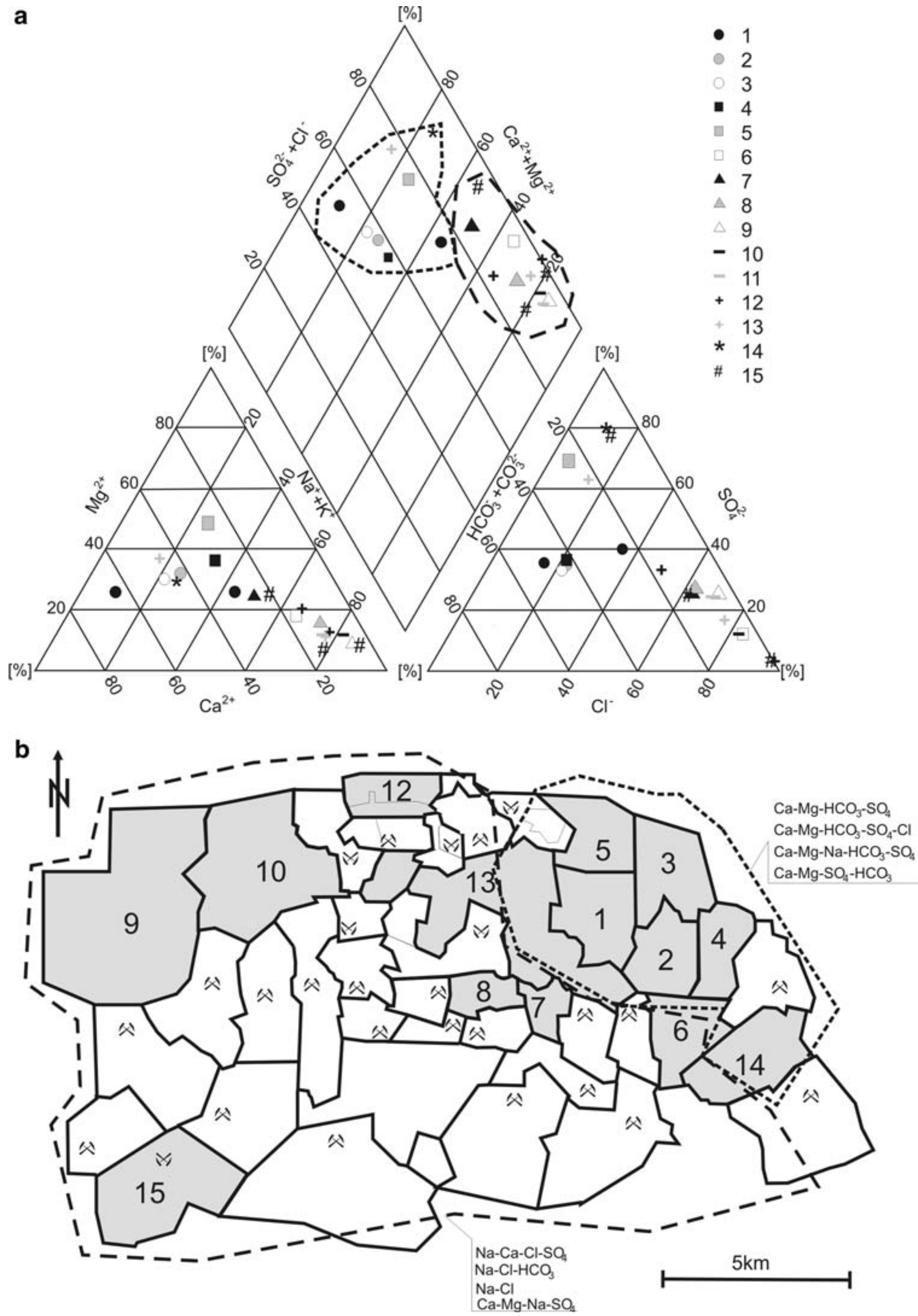

Fig. 7 (**a**) Piper diagram of mine water chemistry from dewatered mines indicating regional trends and hydrochemical facies; (**b**) (1-Saturn, 2-Sosnowiec, 3-Paryż, 4-Porąbka Klimontów, 5-Grodziec, 6-Niwka Modrzejów, 7-Katowice, 8-Kleofas, 9-Gliwice, 10-Pstrowski, 11-Szombierki, 12-Powstańców Śl, 13-Siemianowice, 14-Jan Kanty, 15-Dębieńsko; hydrogeological subregions after Różkowski 2004, *dotted line* subregion I, *dashed line* subregion II)

metal oxyhydroxide (e.g. ochre) or hydroxysulphate (e.g. jarosite) precipitates in surface waters. These precipitates smother the benthic fauna on which the higher aquatic food chain depends (Banks 2004; Hedin et al. 1994; Rose and Cravotta 1998; Younger et al. 2002). As a consequence of the under-regulation of discharges of dissolved hydrolysable metals, none of the pumped mine water discharges in the USCB is subject to the type of active or passive, wetland-based treatment that has become commonplace in other mining nations (Hedin et al. 1994; Jarvis and Younger 1999, 2001; PIRAMID 2003; Watzlaf et al. 2004; Younger et al. 2002).

Furthermore, at present, little emphasis is being placed on the long-term equilibrium condition for mine water in the anthropogenic aquifer system that the USCB has become. Much effort is expended in optimising pumping patterns in abandoned mines to protect active collieries and to minimise pumping costs. Until 2008, relatively little

Fig. 8 Examples of abandoned mine sites in the Katowice area: (**a**) submersible pumps in the the abandoned (but still dewatered) Katowice mine, adjacent to the Spodek stadium and the proposed site of the New Silesian Museum in Katowice, (**b**) development of the 'Silesia City Centre' shopping mall on the site of the former Kleofas mine (*photos by David Banks*)

modelling had been carried out on a possible future scenario when all active pumping stops and mine water is allowed to rebound to a non-pumped equilibrium condition (Burke et al. 2005; Eckart and Klinger 2006). The big question is: would such a condition involve uncontrolled discharge of mine water at the surface under gravity, or potential contamination of overlying Triassic or Quaternary aquifers? Only when such an analysis has been undertaken can a long-term strategy for managing mine water in the USCB be developed. Indeed, such an analysis is a planned outcome of the recently initiated FLOMINET project (Research Fund for Coal and Steel Contract No.: RFCR-CT-2008-00005), being coordinated by DMT GmbH, Essen, Germany.

The main challenges for the mine water regulators in Poland can thus be summarised as:

- Recognition of environmental protection as a motivation for mine water management, in addition to protection of active collieries (this will likely entail some modifications to existing legislation and codes of practice, particularly codes or guidelines for best practice in monitoring).
- Development of long-term modelling tools to assess the regional impact of mine water rebound in the USCB (planned in the framework of the FLOMINET project).
- Increasing recognition of the pollution potential of hydrolysable metals in mine water discharges, especially in the 'first flush' of water discharging from recently abandoned and flooded mines.
- Development and trialling of passive technologies for removal of hydrolysable metals from mine water prior to discharge, where this would potentially yield significant environmental benefits at acceptably low cost.
- Recognition and use of the huge geothermal resource located beneath urban areas in the USCB mine waters and demonstration of the utilisation of this resource via a high-visibility space-heating and cooling installation.

Conclusion

Many of the issues related to drainage of mine water have been present since mining began in the Upper Silesian Coal Basin. Two hundred years of underground coal mining in the USCB has significantly interfered with the hydrology of the region. Moreover, the underground interconnections beneath large parts of the USCB have created an anthropogenically enhanced aquifer system in the Carboniferous strata, the hydraulic properties of which have been irreversibly altered. The mining industry has hitherto focussed on the water management aspects of coal mine water, i.e. the maintenance of low enough water levels to permit working in active mines and the management of overspill into adjacent mines. Even today, after over half of the coal mines active in 1989 have been closed, the main task of the state mine dewatering body, CZOK, is the management of flooding in the abandoned mines to prevent them overspilling into adjacent, still active, workings.

In the last few years, European Union environmental legislation has forced mines and regulators to pay more attention to the environmental impacts of mining and mine dewatering. There is a broad willingness to comply with the spirit of such legislation but progress is hampered by structural, industrial, and social difficulties and, above all, costs. In particular, serious study of the hydrochemistry of coal mine drainage waters and consideration of water quality impacts has only developed in Poland during the past 10 years. Within this time frame, monitoring has become more rigorous and mine water modelling and forecasting tools have been developed. This is the first step towards improvement of the coalfield environment and responsible management of the mine water.

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