Modeling and monitoring of mine water rebound in an abandoned coal mine complex: Siersza Mine, Upper Silesian Coal Basin, Poland

Article *in* Hydrogeology Journal · March 2010

DOI: 10.1007/s10040-009-0534-z

David Banks
University of Glasgow

Adam Frolik
Główny Instytut Górnictwa

Grzegorz Gzyl
Główny Instytut Górnictwa

Modeling and monitoring of mine water rebound in an abandoned coal mine complex: Siersza Mine, Upper Silesian Coal Basin, Poland

David Banks · Adam Frolik · Grzegorz Gzyl · Marek Rogoż

Abstract A variable-volume, head-dependent mine water filling model (MIFIM) has been utilized to simulate the post-abandonment flooding of the Siersza coal mine in the Upper Silesian Coal Basin of southern Poland. It is demonstrated that desaturated pore space in the aquifer adjacent to the mine comprises a significant component of the resaturable mine-related void. The model results are very sensitive to the value of this poorly constrained parameter. Nevertheless, the model successfully predicted the first appearance of mine water in an observation well and its subsequent rise. Despite this apparent success, it is concluded that such modeling approaches generally lack predictive power for mines in permeable, porous host rocks. As real monitoring data accumulate, however, such models can be calibrated and their utility increased.

Keywords Conceptual models · Groundwater monitoring · Numerical modeling · Poland · Mine water

Introduction

The Siersza mining unit is located between Katowice and Krakow, in southern Poland. More specifically, it lies to the east of Jaworzno town and north of the town of Trzebinia, towards the northeastern flank of the Upper Silesian Coal Basin (Fig. 1). Since 1808, the mine has worked a number of seams of coal within the Upper Carboniferous Coal Measures via various workings and shafts. These were independent at first, but in 1947 a drift (i.e., an approximately horizontal underground passageway or tunnel) between the Artur and Zbyszek Mines created a large interconnected "Siersza Mine" complex (Rogoż et al. 1999). During 1999–2001, the mine was progressively closed, pumping was ceased, and the mine is being allowed to flood.

Considerable work on the mine has been performed by the Polish Central Mining Institute (*Główny Instytut Górnictwa* - GIG) and has been published in reports in the Polish language (e.g., Rogoż et al. 1999; Szyszkowski et al. 2006). The overall objectives of this work have been to assess the potential effect and associated risks of the recovering mine water levels at Siersza on the:

- hydrogeological flow regime;
- groundwater chemistry in the adjacent aquifers. In particular, the risk of pollution to:
  - the Upper Carboniferous Krakow Sandstone aquifer complex (which also contains the coal reserves)
  - the Triassic limestone/dolomite aquifer complex which partially overlies the mined area (the most important aquifer of the region)
  - the predominantly sandy Quaternary aquifer units
  - the Trzebionka lead-zinc mine, which was closed in 2009 and is located in a downthrown block of Triassic strata adjacent to the Siersza Mine (Szuwarzynski 1993; Gajowiec and Witkowski 1993).
- surface water flow and quality.

This paper considers one part of this overall study: it attempts to quantify the rate at which mine water is likely to be rising within the Siersza Mine complex, in the absence of any comprehensive post-closure mine water monitoring data. The complete study is documented by Banks (2006a).

Mining history

Mining is believed to have taken place at Siersza since at least the first half of the 18th century, when the local

Received: 22 September 2008 / Accepted: 15 September 2009

D. Banks (✉)
Holymoor Consultancy Ltd,
8 Heaton Street, Chesterfield, Derbyshire S40 3AQ, UK
e-mail: david@holymoor.co.uk
Tel.: +44-1246-230068
Fax: +44-124-6230068

D. Banks
Sir Joseph Swan Institute for Energy Research,
Newcastle University, NE1 7RU,
Newcastle-upon-Tyne, UK

A. Frolik · G. Gzyl · M. Rogoż
Department of Geology and Geophysics,
Główny Instytut Górnictwa (Central Mining Institute),
Plac Gwarków 1, 40-166, Katowice, Poland

 DOI 10.1007/s10040-009-0534-z

Published online: 16 October 2009

Fig. 1 Geological map of the top surface of the coal-bearing Carboniferous of the Upper Silesian Coal Basin (USCB). 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. After Gzyl and Banks (2007), redrawn and simplified after Buła and Kotas (1994). The *inset* map shows the location of the USCB as a *grey rectangle* within northern Europe

population extracted coal from outcrops of seams (Fig. 2). Exploitation was most intense towards the northern part of the currently mined coalfield (i.e., around Zofia shaft), due to the near-surface occurrence of seams 118 and 207 (see Table 1) below only a sparse Quaternary cover. In 1808, the Izabella Mine was established, followed by Zofia (1822), Trentowiec (1840), Elżbieta (1843), and New Izabella (1868). The Artur Mine was established in 1880, taking workings to the depth of Level II (90 m depth, ca. +260 m a.s.l.). Following 1914, workings were deepened to Level III (130 m depth, ca. +220 m a.s.l.) and then Level IV (190 m depth, c. +160 m a.s.l.).

Further east, workings were opened up through the new Zbyszek (1920–22) and Paula (1923–26) Shafts. Zbyszek reached a depth of 260 m (Level V) as well as accessing workings in Levels II-IV. In 1947, the Artur and Zbyszek Mines were linked by a roadway at Level IV and the term “Siersza Mine” came into being.

In the 1970s, Zbyszek was deepened to access Level VI (350 m depth). Furthermore, the Ligia drift was opened up in Level V and the Wschodni (Eastern) drift in Level VI. These and associated water conduits allowed the drainage by gravity of the entire eastern section of the mine to the main dewatering installations around the Artur Shafts.

Closure of the mine commenced in the 1990s, with the abandonment of Walter, Paula, and Artur Auxiliary shafts. The mine was finally abandoned, with all shafts and the surface drift sealed and dewatering pumps switched off, in 2001.

Mining geometry and operation

Coal seams in the Upper Silesian Coal Basin (USCB) are numbered according to stratigraphic units, with numbers increasing with increasing depth (Table 1). The Siersza

 DOI 10.1007/s10040-009-0534-z

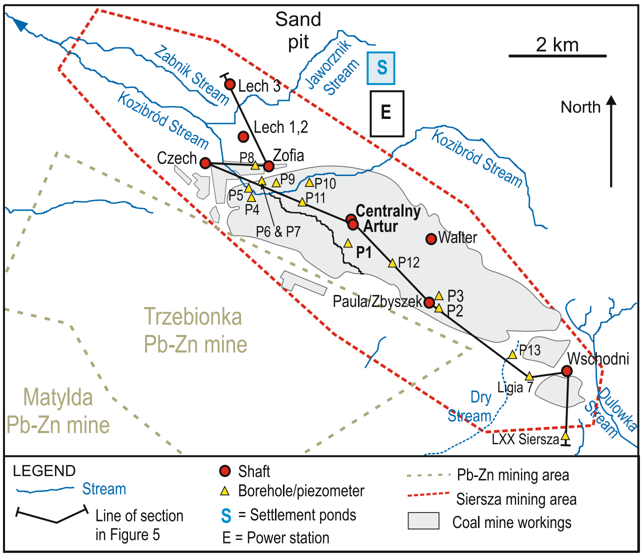

Fig. 2 Location map of the Siersza mining complex and the adjacent Trzebionka Pb-Zn mine (within Triassic strata). Modified after Banks (2006a)

Mine is divided by faults into four discrete mining "fields" (Rogoż et al. 1999; Williamson 2005; Fig. 3).

- ***The Central Field*** – most extensive area of mining, including the Zofia, Artur and Zbyszek Shafts, with mining occurring right through the entire profile (seams 118, 207, 208, 209, 210, 214, 301, and 303).
- ***The Eastern Field*** – only three seams mined down to 210 seam, accessed from the Wschodni (Eastern) Shaft.
- ***The Western Field*** – comprises two subfields. The ***Lech Field*** (north of the "Siersza II Fault") is essentially unworked, while parts of the ***PKL*** field (west of the "Boundary Fault", north of "Siersza I Fault" and south of "Siersza II Fault") have been worked in Seam 208. Mining in PKL took place largely from the Central Field, despite the existence of the Czech Shaft.
- ***The Southern Field*** – lies to the south of the so-called "Southern Fault". It was mined in the 1990s in seams 207, 209–210, from the Central Field.

To the north of the mining concession is located the Siersza electrical power station (Fig. 4). During the operation of the Siersza Mine, coal was transported out of the mine direct to the power station via the Magistrala Węglowa (*Coal Highway*) drift (Fig. 3). This drift was also used to pump dewatering water from Siersza Mine to settlement basins (*osadniki*) immediately north of the power station. The dewatering water was then further discharged into the Jaworznik stream. A portion of the dewatering water was also used by the power station, presumably for cooling purposes.

Immediately west of the settlement basins and WNW of the power station is a major sand extraction pit, on the north bank of the Jaworznik stream. This Quaternary sand deposit was used as slurry for backfilling of worked-out long-wall faces. This sand slurry was injected into mine voids via boreholes such as borehole P1 (in use today as an observation well).

Geology

Siersza Mine lies on the northeastern flank of the USCB of southern Poland (Fig. 1). The USCB takes the form of a synformal basin structure of approximate extent 90 km from north to south and 120 km from east to west. The coal mines of the basin have provided the main source of fuel for heating and energy production, as well as raw materials for Poland's main heavy industrial area (iron and steel industries, chemical industry), centered around the metropolitan areas of Katowice, Sosnowiec, and Gliwice. To the southwest, the USCB extends across the international border with the Czech Republic, forming the basis for the industrial activity of the Ostrava-Karvina area. The coal-bearing sequence of the USCB can reach 8,000 to 8,500 m in thickness (Gmur and Kwiecińska 2002; Nowak 2004). The sediments therein are regarded as having been laid down in the Variscan foredeep basin. Four main lithostratigraphic series can be recognized within it (Table 1): the Krakow Sandstones, the Mudstone Series, the Upper Silesian Sandstones, and the Paralic Series.

The Carboniferous strata of the Siersza Mine (Krakow Sandstones) subcrop below Quaternary drift deposits (some tills, mainly glaciofluvial and fluvial sands and gravels) in the northern part of the mining area. The thickness of Quaternary material is reported to vary from

Table 1 Stratigraphic sequence within the coal-bearing portion of the Carboniferous (after Buła and Kotas 1994). Note that "Seams 1xx" refers to coal seams with numbers between 100 and 199, and so on

Series	Age	Unit
Krakow Sandstone Series	Stephanian	Kwaczała Arkose
	Westphalian D	Libiąż Beds (coal seams 1xx)
	Westphalian C, D	Łaziska Beds (coal seams 2xx)
Mudstone Series	Westphalian A, B	Orzesze Beds (coal seams 3xx)
	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)

DOI 10.1007/s10040-009-0534-z

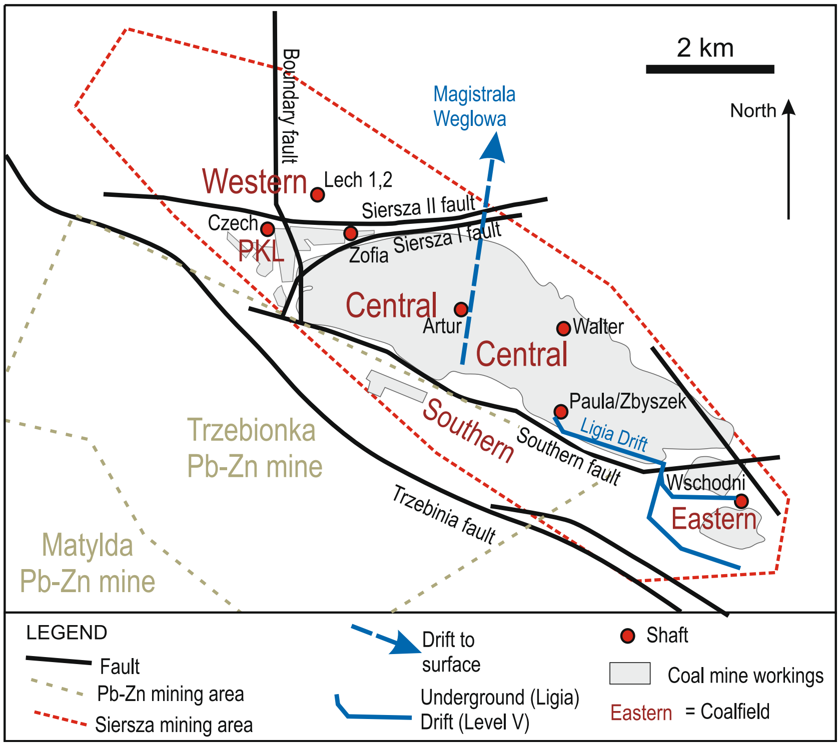

Fig. 3 Map showing locations of the various (hydraulically interconnected) mining areas in the Siersza complex and the major faults. Modified after Banks (2006a)

0.2 to 49 m with the greatest thicknesses in the northwest (Williamson 2005). Towards the south and east, a relatively thin overburden of Triassic and Permian limestones, dolomites, marls, sandstones, and conglomerates intervenes (Fig. 5).

The exploited coal deposits of Siersza Mine are dominantly within the Krakow Sandstone Series (seams 118–301), and the upper part of the Orzesze beds of the Mudstone Series (seams 301–304). The Krakow Sandstone Series typically comprises medium-to-coarse-grained molasse-type sandstone units and some conglomerates, laid down in braided river conditions in the Variscan foredeep basin. Samples and mineralogical/chemical analyses of these deposits are described by Banks (2006b). The coals within the Krakow Sandstone tend to occur within finer-grained units sandwiched between the thick sandstone successions. These finer sedimentary units may represent infills of inactive channels. The sandstones are lithified and moderately well cemented. In some locations, however, the degree of cementation is poor and running sands can occur in excavations. The coals within the Krakow Sandstones, which have been worked at Siersza, include seams 118, 207, 208, 209, 210, 214, and 301.

Fig. 4 Siersza power station (photo by David Banks)

Seam 301 forms the nominal boundary with the underlying Mudstone Series, within which, logically enough, siltstones and argillites dominate over sandstones. The main worked seam (at Siersza) within the Mudstone Series, in addition to 301, is seam 303.

The coals themselves are typically banded and banded bright coals of very low coalification rank, deposited in wet forest swamp (peat bog) conditions. The sulphur content of coals exploited by Siersza Mine are reportedly some of the highest in the USCB, with Chmura and Nowak (1990) reporting a mean for the mine of around 2.5% and the map of Kaziuk (1994) reporting 3.46%.

The mine workings within Siersza are constrained by faults (Fig. 3), at least to the south, southwest, and northwest. To the north of the Siersza II fault, there has been no active working. North of this fault the Krakow Sandstones were found to be, in part, poorly lithified and highly permeable. Attempts at shaft sinking in the Lech area foundered due to unmanageable quantities of groundwater inflow and running sand, despite the utilization of

 DOI 10.1007/s10040-009-0534-z

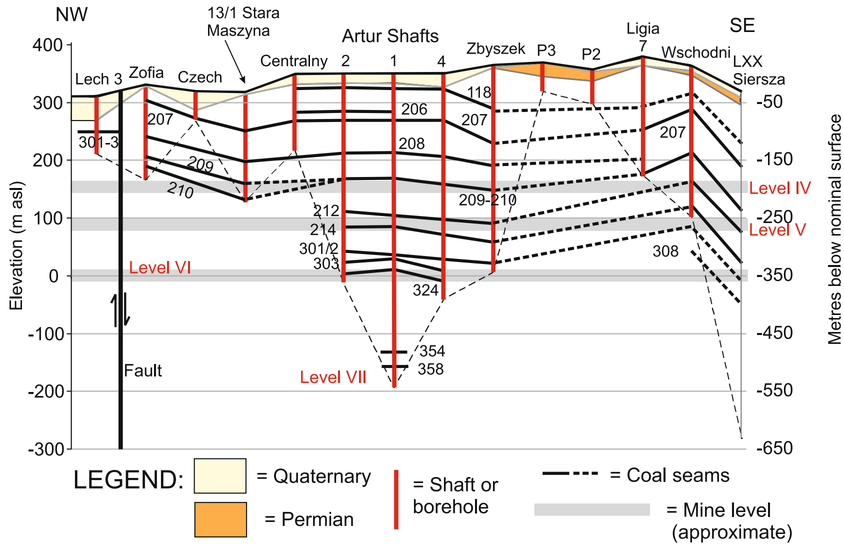

Fig. 5 Schematic cross section approximately along strike of Carboniferous strata, from NW to SE through the Siersza Mine (the strata dip to the SW). The horizontal axis is not to scale. Note that some of the apparent dip may be due to faults that are not shown. The numbers 118 to 358 refer to coal seam numbers. After Banks (2006a)

dewatering and ground-freezing techniques. The boreholes around the Lech Shaft, used for dewatering and ground-freezing, are now used for public water supply.

For many years, mining did not progress substantially south of the Southern Fault, until the late 1990s, when the Southern Coalfield was opened. A little further south, a major NW-SE trending fault, named (unofficially) the "Trzebinia Fault" in this project, downthrows a block of Triassic strata against the Carboniferous strata of the Siersza Mine (Fig. 6). The throw on this fault appears to be variable, but seems to exceed 100 m in some locations.

Figure 6 is a regional geological section (see Fig. 1) showing presumed zones of dewatering in the Janina coal mine (still working; Banks 2006b), the Trzebionka Pb-Zn mine (closed in 2009) and the Siersza coal mine (abandoned in 2001; i.e., since the drawing was constructed). Note that, around the Siersza Mine, the extent of the zone of dewatering appears to be constrained by the Southern Fault to the SW and the level of the lowest worked seam in the NE. This is, to some extent, conjecture. Since the section was produced, the mine has extended to the south of the Southern Fault (Southern Field) and some degree of dewatering must have taken place there also.

Regional hydrogeology

Williamson (2005) has examined daily rainfall data from the meteorological station at Katowice for the period January 1995 to July 2005 and concluded that annual average precipitation is 753 mm, with mean monthly precipitation varying from approximately 40 mm in winter to 130 mm in summer. He also calculated evapotranspiration from daily temperature data at Katowice airport and estimated that, in areas with permeable soil around Siersza, groundwater recharge amounts to some 39% of annual average rainfall, with surface run-off 2.5% and evapotranspiration 58.5%. Thus, Williamson's model would predict a mean groundwater recharge around Siersza of 294 mm/a, with a surface run-off of 19 mm/a and an evapotranspirative loss of 441 mm/a. The relatively

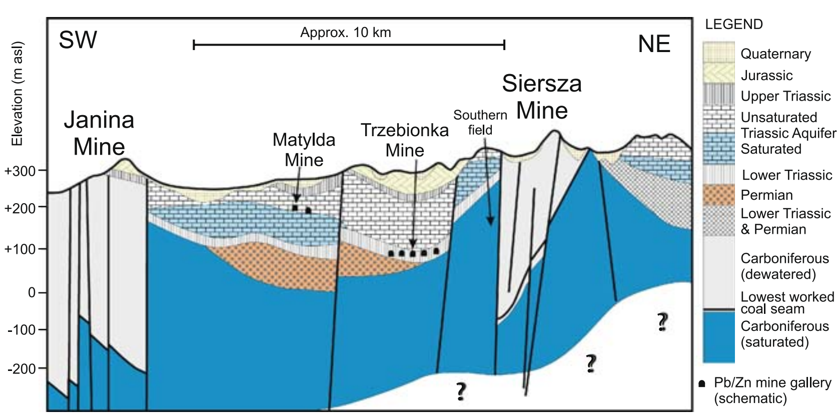

Fig. 6 Hydrogeological cross section through the Siersza, Trzebionka, Matylda, and Janina mining fields, from SW to NE (Banks 2006a, redrawn after Różkowski and Chmura 1996). *Vertical axis* shows elevation in m a.s.l.

 DOI 10.1007/s10040-009-0534-z

high recharge rate and low run-off rate can be ascribed to the very sandy, permeable nature of the soils and the subdued topography. Some uncertainty is associated with Williamson's (2005) estimates, due to the relatively short series of available data upon which they are based.

Regarding hydrogeological conceptualization of the area, it is not unreasonable to regard the mine as being worked within a single aquifer system, comprising Quaternary sandy deposits overlying Carboniferous Krakow Sandstones. Naturally, the real situation is more complex than this, with some Mesozoic strata adjacent to and even overlying parts of the mining concession. However, given the need for a relatively simple conceptual model upon which to base the mathematical model and given the fact that the modeling work only considers the initial portion of the recovery (while mine water levels are still within the Krakow Sandstones), this is regarded as an acceptable degree of simplification.

It is commonly stated by mining hydrogeologists working in the Siersza area that the Quaternary aquifer has been drained by the dewatering of the underlying Siersza and Trzebionka mines. The evidence upon which this statement is based is as follows:

- The bed of the Kozibród stream (Fig. 2) to the NE of Siersza needed to be sealed with concrete to prevent loss of flow through its base.
- The dry tributary of the Chechło River (marked as "Dry Stream" in the bottom right of Fig. 2) has clearly flowed in the past.
- A few shallow monitoring piezometers in the Quaternary deposits have been (or are) dry.

The above evidence suggests that the water table may have declined as a result of mining activities and that a vertical downwards head gradient may have been induced. It does not constitute evidence, however, that the entire Quaternary aquifer has been dewatered. Indeed, of a monitoring network comprising shallow piezometers in the Quaternary and uppermost Carboniferous aquifers, a substantial number show measurable groundwater levels, demonstrating that these strata are still saturated. Furthermore, even in the central part of the mining area, groundwater is still present in a number of household wells in Siersza, with groundwater levels (in 1997–1999) of 1.4–5.5 m b.g.l. However, evidence from the piezometer network in the Quaternary and shallow Carboniferous suggests that, the deeper the monitoring well, the lower the groundwater head (Fig. 7). This in turn suggests that dewatering of Siersza Mine has not resulted in full dewatering of the overlying strata, merely a strong downwards hydraulic head gradient (see the conceptual model in Fig. 8).

Conventional hydrogeological understanding within the mining community contends that the Siersza II fault constitutes a hydraulic "barrier". This would indeed seem to be the case, as the Lech water wells (related to the former aborted Lech mine shaft) exhibit a static water level of some 12 m b.g.l. (Korczak et al. 1999), despite

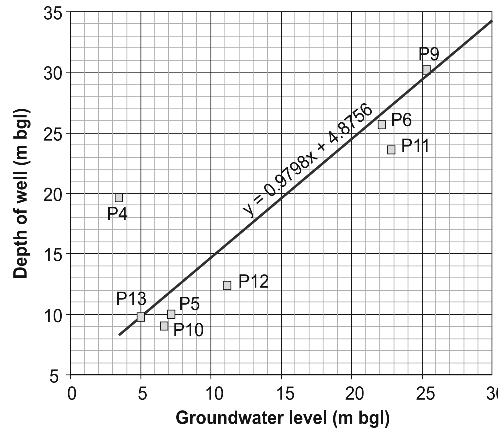

Fig. 7 Groundwater level (m b.g.l.) plotted against depth of well (m b.g.l.) for the shallow piezometer network at Siersza (piezometers numbered P4 to P13). Data are derived from a monitoring round of May 18, 2006. Note that groundwater head decreases as depth increases. After Banks (2006a)

being located only a few hundred meters from Siersza II fault and the dewatered Central Coalfield. Similarly, the Southern Fault is regarded by miners as being poorly permeable, with very few water leakages from the Southern to the Central Field, prior to the opening up of the Southern Field. After the Southern Field was worked in the 1990s (albeit on a small scale), it was connected to the Artur Shafts, and some degree of dewatering of the Southern Field must be presumed.

Regarding the hydraulic conductivity of the Krakow Sandstones, Banks (2006a) reports a geometric mean hydraulic conductivity of around 3 to 6×10^{-7} m/s from the Krakow Sandstones in the nearby Janina and "Piast" Ruch II mines. The mean effective porosities of the Libiąż, Łaziska and Orzesze beds in the Janina Mine were 17.7, 16.4, and 11.0%, respectively. Rogoż et al. (1999) have previously estimated that for a typical total porosity of 13–26% in the Krakow Sandstones, one might expect specific yields of 4.7 to 10%.

Mine water inflows during operation

The main water inflows to the mine during operation were believed to be associated with the Krakow Sandstone Series. The mine complex was drained by a network of drifts at levels IV (190 m depth or +160 m a.s.l.), V (256 m depth or ca. +94 m a.s.l.) and VI (350 m depth or ca. 0 m a.s.l., see Fig. 5). There were (in 1999) three main dewatering pumping stations corresponding to these levels. All of the pumping stations were situated around the Artur shaft area:

- Level IV: Receiving water from the level at nominal 190 m depth, around the level of the seam 209–210 drainage system. This includes drifts extending to the Zofia area.
- Level V: Receiving water draining from the drainage system at nominal 256 m depth. This drainage system

 DOI 10.1007/s10040-009-0534-z

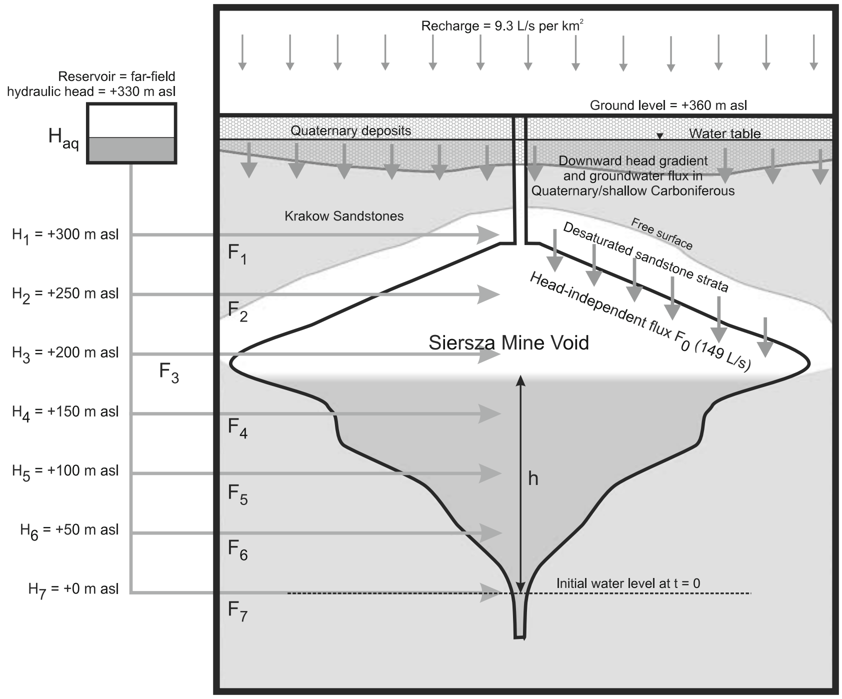

Fig. 8 A schematic conceptual model of the simplified hydrogeology of Siersza Mine, as applied to the MIFIM model. F_0 - head independent inflow, which is taken to be approximately equal to areal recharge, migrating downwards through saturated Quaternary strata. F_1 to F_7 = head-dependent lateral inflows at elevations H_1 to H_7, of equal conductance C_1 to C_7. h = mine water level, H_{aq} = static far-field groundwater head

includes the main "Ligia" drift running towards the eastern mining field, and drifts running NW to the PKL field.

- Level VI: Receiving water draining from the drainage system at nominal 350 m depth. This system includes the deep "Wschodni" and "Zachodni" drifts, draining the deepest seams to the NW and SE of Arthur, respectively. It also includes the main drift into the Southern field.

The water from each pumping station was discharged via the main surface drift (the Magistrala Węglowa) to surface settlement ponds.

Rogoż et al. (1999) and Szyszkowski et al. (2006) document the total water make (i.e., the water pumped out) from each mine level in the years 1989 to 1999 (Table 2). In each year, the water make is subdivided into natural water inflow to the mine and water introduced to the mine by artificial processes (largely water introduced by pumping sand slurry into the mine for void filling). One can see that in the 3 years prior to mine closure (representing the most reliable data), the natural water inflow was estimated to be 457 l/s. Prior to closure, mine plans indicate that the lowermost down-dip worked seams were flooded to the 350 m b.g.l. level (0 m a.s.l.).

Table 2 Average dewatering rates (l/s) from the three main pumping stations at the Artur Shafts. Data to 1998 are derived from Rogoż et al. 1999; data from 1999 are from Szyszkowski et al. 2006. The 1996–1998 data are believed to be the most reliable. In the 1999 data, the distinction between natural and backfilling water is unclear

	Natural inflow				Backfilling water				Total water			
	Level				Level				Level			
Year	IV	V	VI	Total	IV	V	VI	Total	IV	V	VI	Total
1989	97.5	234.3	272.0	603.8	0.0	35.8	36.2	72.0	97.5	270.2	308.2	675.8
1990	77.0	215.2	271.0	563.2	0.0	36.2	24.7	60.8	77.0	251.3	295.7	624.0
1991	83.5	199.0	339.0	621.5	0.0	31.2	40.0	71.2	83.5	230.2	379.0	692.7
1992	80.3	217.5	314.5	612.3	0.0	49.3	40.7	90.0	80.3	266.8	355.2	702.3
1993	72.7	205.0	332.0	609.7	0.0	25.3	31.5	56.8	72.7	230.3	363.5	666.5
1994	65.5	175.2	312.7	553.3	0.0	2.5	16.8	19.3	65.5	177.7	329.5	572.7
1995	56.5	172.3	316.8	545.7	0.0	4.3	21.8	26.2	56.5	176.7	338.7	571.8
1996	38.7	164.3	260.7	463.7	0.0	8.2	9.7	17.8	38.7	172.5	270.3	481.5
1997	40.8	201.3	192.0	434.2	0.0	4.8	5.3	10.2	40.8	206.2	197.3	444.3
1998	40.7	233.8	198.5	473.0	0.0	1.7	2.2	3.8	40.7	235.5	200.7	476.8
Average (1989–1998)	65.3	201.8	280.9	548.0	0.0	19.9	22.9	42.8	65.3	221.7	303.8	590.9
Average (1996–1998)	40.1	199.8	217.1	456.9	0.0	4.9	5.7	10.6	40.1	204.7	222.8	467.6
1999	40.2	225.7	208.8	474.7								

 DOI 10.1007/s10040-009-0534-z

Modeling approaches to mine water recovery

Early approaches to modeling the post-closure rebound of water in abandoned mines tended to regard the mine as an empty "bucket", which is filled up at a constant rate by inflowing mine water. In more recent times, modeling approaches have tended to fall into three categories:

(i) the use of conventional finite difference or finite element numerical models to simulate the mine as an irregularly shaped "well" or "drain" within a porous medium aquifer. An example of this approach, using the finite difference code, MODFLOW (McDonald and Harbaugh 1988) is documented by Banks et al. (2002) for a polymetallic sulphide mine in Bolivia. This conventional modeling approach has several limitations: the most common numerical models tend to (i) assume relatively homogenous, porous medium aquifer host rocks; (ii) be able to simulate processes in the aquifer, while the processes within the mine itself are necessarily simplified; (iii) be rather poor at realistically simulating complex in-mine storage and turbulent flow within mine roadways. Of course, with increasing computing power, more complex models can be run and modern discrete/finite element modeling codes allow the explicit simulation of mine tunnels or fractures.

(ii) Other modeling groups retained the "filling bucket" approach for individual mines or hydraulically interconnected groups of mines (mine "ponds") within a mining domain. Emphasis was placed on the hydraulic interaction of adjacent "ponds" by laminar or turbulent overspill along interconnecting roadways or goaf connections. Possibly the earliest functional model of this type was the GRAM (Groundwater Rebound in Abandoned Mine workings) model, developed at Newcastle University (UK) by Sherwood (1993). Examples of the application of this approach are given by Burke and Younger (2000), Burke et al. (2005), Gandy and Younger (2007) and Kortas and Younger (2007).

(iii) Still other researchers focused on developing more nuanced variants of the "filling bucket" approach to apply to single mines. They tried to avoid the assumptions of a constant volumetric mine profile and constant water inflow made by the earliest versions of models such as GRAM. This approach led to the Polish LIKOP model of Rogoż (1994) and the MIFIM (mine water filling) model of Banks (2001), which form the basis for this paper and which are described below. An example of the application of the MIFIM model to the hard-rock San José mine of Oruro, Bolivia is given by Banks et al. (2002).

Naturally, as computing power has progressed further, these various approaches have been reintegrated into rather complex, but powerful, modeling approaches that can consider floodable mine volumes, the adjacent porous medium aquifers and the hydraulic interconnections (roadways, etc.) between mines. Adams and Younger (2002) describe a model of a Cornish tin mine complex (UK), based on the SHETRAN/VSS-NET codes (Ewen et al. 2000). The German BOXMODEL (Eckart et al. 2004) has been applied to the northeastern part of the USCB, including Siersza (Eckart and Klinger 2006), and there have even been attempts to couple hydrochemical processes to this type of interconnected mine water flooding model (Blachere et al. 2005).

The MIFIM model

The MIFIM (MIne water FIlling) Model of Banks (2001) is a simple numerical model, running in a spreadsheet environment, which assumes:

- that the mine can be represented by a void space that is progressively filled up by water in a series of time steps.
- that the change in mine water level in a given time step is defined by the total water inflow and the mine's floodable cross-sectional area.
- that the water inflows can be represented by constant flux or constant impedance boundary conditions.

A conceptualizsation of the MIFIM model for Siersza is shown in Fig. 8. MIFIM differs from earlier mine-water filling models, such as GRAM (Groundwater Rebound in Abandoned Mine workings – Sherwood 1993), inasmuch as it allows:

(i) the void profile of the mine to change with depth (i.e., the effective open surface area available for flooding changes as the mine fills with water).

(ii) the water inflow to vary with mine water level. The total inflow of the mine is split into two components:

  - a "head invariant" component that enters the mine at a constant rate (F_0 in Fig. 8) every time step. This is often considered to be surface recharge infiltrating through the area overlying the mine. This is essentially a "constant flux" (Neumann or second-type) boundary condition.
  - any number of "head-dependent" variable inflows F_n (F_1 to F_7 in Fig. 8) associated with different horizons of the mine (elevations H_1 to H_7 in Fig. 8). Each of these inflows is assigned a conductance or "specific capacity" (C_1 to C_7). When the mine water level (h) is below the level of the *n*th inflow (i.e., $h < H_n$), the inflow rate is constant and given by

$$F_n = C_n \times \left(H_{aq} - H_n\right),\ \text{when}\ h < H_n \tag{1}$$

where H_{aq} is some "static", far-field groundwater head beyond the mine. As the inflow level becomes submerged by rising mine water, however, the rate of inflow decreases:

$$F_n = C_n \times \left(H_{aq} - h\right),\ \text{when}\ h > H_n \tag{2}$$

In other words, the rate of inflow is then in proportion to the difference between the mine water level and the "far-

DOI 10.1007/s10040-009-0534-z

field" groundwater head H_{aq}. This is essentially a "constant impedance" (Robin or third-type) boundary condition.

For every time increment Δt, the change in mine water level (Δh) is calculated by:

$$\Delta h = \frac{\Delta t \times \left(F_0 + \sum_{n=1}^{n} F_n \right)}{A_{eff}} \tag{3}$$

where A_{eff} is the effective open cross-sectional area of the mine. This varies with depth according to the mine void space associated with each particular mine level.

The model itself is described in detail by Banks (2001). The model was originally designed to simulate mines with low rates of inflow from discrete features in low-permeability fractured rock environments. The application of MIFIM to the Siersza mine would be the first time it was applied to a high-permeability mining environment with large rates of inflow.

In fact, a very similar methodology has been independently developed in Poland, using a code called LIKOP, programmed in Turbo C (Rogoż 1994). This was applied to Siersza by Rogoż et al. (1999), albeit with somewhat differing input parameters to those applied below in the context of the MIFIM model.

Model boundary conditions and parameterization

Water inflow

During the period 1996–1998, the average natural water inflow to the Siersza Mine is reported to be 457 l/s (Table 2). Given that small quantities of water may have been pumped directly from other shafts (Zofia, Wschodni, Level VII of Artur I) in addition to the main pumping stations, an initial inflow of 460 l/s (39,740 m^3/day) was assumed for the MIFIM model.

The area underlain by mine workings at Siersza is estimated as 16.5 km^2. However, the Southern Field is overlain by Triassic strata containing the Trzebionka Pb-Zn workings and any recharge falling on this area would be expected to be intercepted by the cone of depression associated with the Trzebionka workings. It was therefore assumed that the area of Siersza mine workings potentially accepting recharge from the surface is ca. 16 km^2. Given Williamson's (2005) estimate of 294 mm/a, the groundwater recharge predicted to the area underlain by mine workings (16 $km^2 \times 9.3$ l/s/km^2) is 149 l/s (12,870 m^3/day). Even if one takes the total area of the mining concession of 28.5 km^2 south of the Siersza II fault, the predicted recharge is 265 l/s (22,900 m^3/day). Thus, the actual dewatered quantity of 460 l/s (39,740 m^3/day) is two to three times greater than can be explained by direct recharge onto the mining area. The dewatered mine must have had a zone of influence (or "cone of depression") extending beyond the confines of the mining concession area. This may have extended to the northeast, to the southeast, or to the southwest into saturated Carboniferous strata below the Trzebionka Mine (via the Southern Field workings). Any cone of depression does not seem to have extended to the northwest, as the Lech abstraction appears not to have been impacted by dewatering. Note that the "unaccounted for" water cannot be explained by re-infiltration of dewatering water through the bed of the Jaworznik stream. Stream-flow monitoring data (documented in Banks 2006a) indicate no loss of flow during the stream's passage through mining area. It is concluded that the "unaccounted for" inflow is simply lateral flux of groundwater from the adjacent aquifer units towards the huge irregular "well" that is the dewatered Siersza Mine.

Boundary conditions

The MIFIM model of the Siersza Mine (Banks 2006a) is a significant simplification of the real, complex hydrogeology of the area. The boundary conditions of the model are therefore largely conceptual in nature: they are designed to replicate observed inflows rather than necessarily coincide with specific geological features.

Head independent flux (type 2 boundary condition)

A single head-independent inflow (F_0) (type 2 Neumann boundary condition) was set at 149 l/s=12,870 m^3/day. Conceptually, this represents rainfall recharge entering the Quaternary aquifer system overlying the mine and percolating downwards (along the hydraulic head gradient demonstrated in Fig. 7) to the mine void. It is based on Williamson's (2005) estimate of 9.3 l/s/km^2 recharge multiplied by the area of 16 km^2 underlain by mine workings.

Lateral, head-dependent fluxes (type 3 boundary condition)

The "unaccounted for" inflow to the mine (460–149 l/s= 311 l/s) is presumed to represent lateral groundwater inflow. This is simulated as seven head-dependent inflows, each with a conductance or specific capacity (C_1 to C_7) of 21.3 m^2/day (0.247 l/s/m) evenly distributed at 50-m intervals throughout the mine depth (i.e., an even distribution of hydraulic conductivity throughout the mine is assumed). Banks (2006a) has demonstrated that this is consistent with typical geometric mean hydraulic conductivities in Krakow Sandstone of the order of $3\text{–}6 \times 10^{-7}$ m/s. In each case, the far end of each conductor is fed by a constant "baseline" head H_{aq} set at +330 m a.s.l. (i.e., static, "far-field" head for the aquifer beyond the influence of the mine complex). A single value for this head is, of course, an oversimplification: the selected value is, however, approximately representative of shallow groundwater levels in dug wells and streams/springs in and around the Siersza area.

The magnitude of each inflow is calculated as the product of the conductance and the head difference along the conductor.

- Head-dependent inflow 1 at H_1=+300 m a.s.l.; F_1= 7.4049 l/s
- Head-dependent inflow 2 at H_2=+250 m a.s.l.; F_2= 19.7464 l/s

 DOI 10.1007/s10040-009-0534-z

- Head-dependent inflow 3 at H_3=+200 m a.s.l.; F_3= 32.0879 l/s
- Head-dependent inflow 4 at H_4=+150 m a.s.l.; F_4= 44.4294 l/s
- Head-dependent inflow 5 at H_5=+100 m a.s.l.; F_5= 56.7709 l/s
- Head-dependent inflow 6 at H_6=+50 m a.s.l.; F_6= 69.1124 l/s
- Head-dependent inflow 7 at H_7=0 m a.s.l.; F_7= 81.4539 l/s

The initial sum of the head-dependent inflows is 311 l/s (26,870 m^3/day), giving a grand total of all inflows of 460 l/s (39,740 m^3/day).

Overflow boundary condition

A "drainage" boundary condition has been set at an elevation of +350 m a.s.l., corresponding to the likely minimum elevation of mine openings at the surface. If and when the mine has filled to this level, this boundary condition becomes activated, keeping the mine water head constant at +350 m a.s.l. and designating the net difference between groundwater inflow and groundwater outflow as surface overflow.

Initial condition

The mine water head within the model was initially set to h=0 m a.s.l. at t=0. This corresponds with the actual water level in the mine at the time of final closure and pump switch-off at the beginning of 2001.

Distribution of void space

Rogoż et al. (1999) have calculated the void space available to be flooded within the mine system. They have divided it into four "compartments"

1. Void space in workings V_z
2. Void space in tunnels, drifts, and galleries V_k
3. Voids in fractures induced above workings $V_{sz}{}^c$
4. Void space in pores in dewatered sandstone strata V_g.

The magnitude of each of these components is calculated according to a set of formulae (Rogoż 1978; Rogoż et al. 1999) widely accepted by mining engineers in the USCB.

Void space in mine workings V_z

The void space contribution from mining voids is calculated according to the formula (Rogoż 1978; Rogoż et al. 1999):

$$V_z = \frac{cA_zM_z}{\cos\alpha} \tag{4}$$

where

A_z the area of the worked seam
M_z the exploited thickness of the seam
α dip of seam (in this case, assume cosα=1)
c available porosity in mine void (dependent on compression and type of working).

- For controlled collapse to goaf, $c = 0.485 \times e^{-0.00205.H}$
- For hydraulic backfilling of workings with sand slurry, $c = 0.275 \times e^{-0.0003675.H}$
- For dry backfilling of workings $c = (P - S)/100$; $S = (40 - 19p^{0.2})/100$

Where H = depth of seam below ground (m), P = porosity of backfill (%), p = pressure exerted by rock overburden on seam (MPa), S = pressure-dependent decrease in porosity (%).

Void space in tunnels etc. V_k

The formula used by Rogoż et al. (1999) was:

$$V_k = LA_kc_k \tag{5}$$

where

L length of tunnel (m)
A_k cross sectional area of tunnel (m^2)
c_k correction factor to take account of decrease in void due to compression or backfilling. For open tunnels in massive rock, c_k=0.9 to 1.0; for tunnels in compressible rocks (e.g., Orzesze mudstones), c_k=0.6; for infilled shafts and tunnels, c_k=0.1 to 0.2.

Voids in fractures above workings $V_{sz}{}^c$

The formula used by Rogoż et al. (1999) was:

$$V_{sz}^c = V_p(1 - a - c) \tag{6}$$

where, if (1-a-c)<0, then $V_{sz}{}^c = 0$

and where

V_p volume of seam extracted
a factor accounting for loss in volume due to subsidence at the surface (in Siersza, a = 0.6 to 1.0, so an average value of 0.72 was used).
c a factor to account for the proportion of void space available for filling with water.

Void space in overlying desaturated rock V_g

The formula used by Rogoż et al. (1999) was:

$$V_g = U_pF_dJ_o\Delta Z \tag{7}$$

where

U_p Proportion of overburden which is water-bearing
F_d surface area underlain by workings, corrected for

enlarged extent of cone of depression (m^2). It is assumed that F_d=1.15 × area underlain by workings.

ΔZ depth interval under consideration (m).

J_o Proportion of open void space – i.e., floodable porosity. In a freely drained rock under gravity, this will essentially be the specific yield of the rock. Rogoż et al. (1999) applied a value of 2.5% for their calculations.

Table 3 and Fig. 9 show the total void space, calculated by Rogoż et al. (1999), for each successive 50-m depth interval in the Siersza Mine. It will be noted that the fracture and tunnel void space (V_k and $V_{sz}{}^c$) are numerically negligible in the overall void budget. The void space in the mine workings (V_z) is based on geometric and geotechnical calculations by experienced mining engineers and geologists. The void space in the adjacent aquifer (V_g) is, however, based on two major, unsubstantiated assumptions:

1) that the effective resaturable porosity (J_o in Eq. 7) for the dewatered zone around the mine is 2.5%.
2) that the area drained by the mine workings (F_d in Eq. 7) is 1.15 x the area underlain by the workings themselves.

Thus, the term V_g is associated with a major degree of uncertainty. Unfortunately, it is also the dominant term in the void calculation. This highlights why the void-filling approach, while good for low-inflow mines in low-porosity hard rock aquifers (Banks et al. 2002), is very difficult to apply with any degree of certainty in permeable, porous aquifer conditions, such as Siersza.

The calculation of Rogoż et al. (1999), which is essentially a very similar approach to the MIFIM model, predicted rather rapid recovery of mine-water levels in the mine, which, by Autumn 2005, were essentially demonstrated to be implausible by the non-appearance in mine water in monitoring well P1. Rogoż et al. (1999)'s void space distribution formed the basis for "Model 1" (Fig. 9) of MIFIM. The main source of uncertainty in the calculation was identified as being the void space to be resaturated in the adjacent aquifer (V_g) and, in particular, it was felt that the value of resaturable porosity (J_o=2.5%) was too low in the context of a mean effective Krakow Sandstone porosity of 16–17% (see above).

Thus, in September 2005, the MIFIM Model was re-run three more times, using alternative, more hydrogeologically realistic void distribution scenarios. The re-runs modified Rogoż et al. (1999)'s original assumptions by:

(i) utilizing a more realistic "floodable" void volume. Previous estimates (Rogoż et al. 1999) of Krakow Sandstone specific yield range from 4.7 to 10%. In the revised MIFIM model runs (models 2 and 4), a value of J_o=7.5% (Eq. 7) was used.
(ii) assuming that the aquifer above the maximum extent of the workings is drained to the same areal extent as in the worked interval +150–200 m a.s.l. (i.e., the level containing the maximum extent of working). By their assumption that the dewatered area of strata exceeds the actual mine void by a factor of F_d=1.15 (Eq. 7), Rogoż et al. (1999) tacitly assume the area of dewatered strata above +200 m a.s.l. is very low.

Thus, three re-runs of the MIFIM model, which differ only in their void space distribution (see Table 4), were run in September 2005:

Model 2. The average resaturable pore space used in the calculation of V_g is 7.5% rather than 2.5%. Here the value of V_g has been multiplied by three relative to model 1.

Model 3. Here it is assumed that the drained aquifer void space does not reduce in area above +200 m a.s.l., i.e., it is assumed that the aquifer above the maximum extent of the workings is drained to the same extent as in the worked interval +150 to 200 m a.s.l. The exception is in the uppermost 50 m, which is assumed (from field piezometer evidence) to be fully saturated, and here V_g is set to zero.

Model 4. Combination of models 2 and 3.

The values of V_g and V_{tot} applied in models 2–4 are shown in Table 4 (and Fig. 9).

Table 3 Total void space (m^3) associated with each level in the Siersza Mine, as calculated by Rogoż et al. (1999)

Elevation Interval m a.s.l.	V_z	V_k	$V_{sz}{}^c$	V_g	V_{tot}
+300 to +350	811,100	23,000	0	348,600	1,182,600
+250 to +300	4,292,800	115,400	0	3,411,200	7,819,400
+200 to +250	6,959,800	217,700	12,400	6,349,900	13,539,800
+150 to +200	9,154,300	321,600	37,100	9,223,400	18,736,400
+100 to +150	4,888,400	245,700	23,100	6,464,300	11,621,500
+50 to +100	4,073,200	233,700	68,700	5,946,200	10,321,900
+0 to +50	1,930,400	133,500	169,400	3,189,100	5,422,400
–50 to +0	1,110,100	75,600	233,100	1,977,000	3,395,800
–100 to –50	383,100	21,800	61,300	499,900	966,200
–150 to –100	0	200	0	0	200
–200 to –150	0	22,800	0	0	22,800
Total	33,603,200	1,411,000	605,100	37,409,600	73,029,000
Total 0 to +350 m	32,110,000	1,290,600	310,700	34,932,700	68,644,000

DOI 10.1007/s10040-009-0534-z

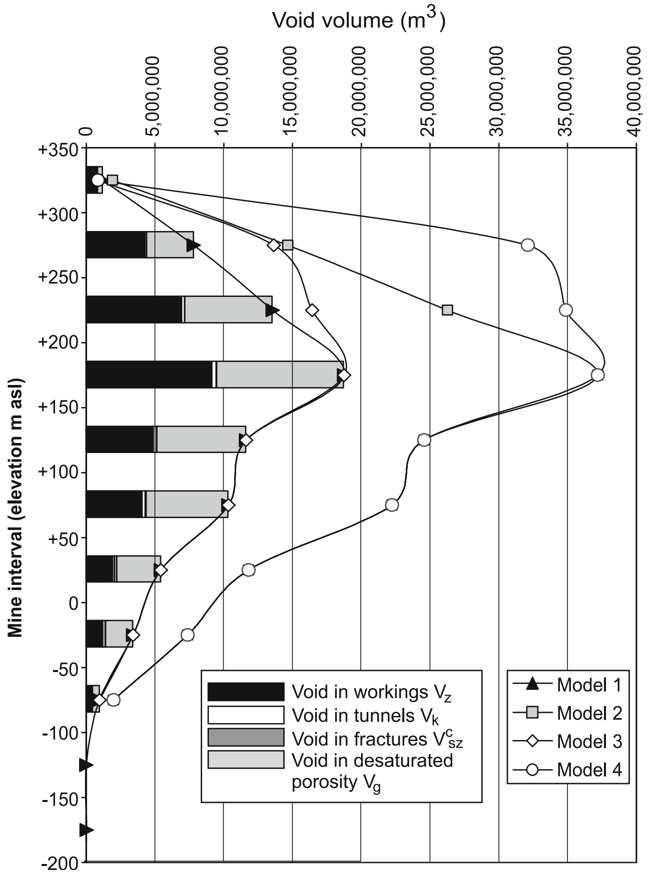

Fig. 9 The distribution of resaturable void space in the Siersza Mine in each 50-m vertical interval. The *bars* show the distribution of void space in the initial Model Run 1, while the *curves* show the total void space in each of the Model Runs 1 to 4. The data correspond to Table 4

Modeling results

The results of models 1 to 4 are compared in Fig. 10. As would be expected, models 3 and 4 only diverge substantially from runs 1 and 2 (respectively) in the latter part of the curve (after water level exceeds +200 m). Model run 2 results in a significantly slower rate of water rise compared with run 1.

When considering how realistic the results of the MIFIM modeling might be, one should recognize that the choice of resaturable pore volume of 7.5%, while more realistic than 2.5%, is still essentially arbitrary. Varying the area of dewatering or the distribution of inflow horizons has not yet been considered here. The MIFIM/LIKOP mine water filling models can probably do no more than (a) constrain the likely worst-case scenario for mine water recovery (model 1) by choosing very conservative parameters, and (b) make a very rough order-of-magnitude prediction of mine water infilling rates (model 2) in such porous and hydraulically conductive rocks.

At present, there exists only a single borehole (P1) capable of directly monitoring mine water levels in the workings in the Siersza Mine. It was drilled as a slurry injection borehole and its location is shown in Fig. 2. P1 is 179 m deep and is drilled into the mine's Level IV workings (at a level of +161 m a.s.l.). At the time of modeling (September 2005), P1 was still dry (Fig. 10).

Models 2 and 4 predicted that mine water would be observed in borehole P1 after around 1,800–1,850 days from the commencement of the model run, i.e., around the end of 2005. In reality, mine water was first detected in borehole P1 at a level of +162.42 m a.s.l. (177.88-m depth) in February 2006 (ca. 1,860–1,880 days, if it is assumed that pumping ceased at the beginning of 2001). By March 9, 2006, the water had risen to +163.08 m a.s.l. (177.22-m depth). Shortly afterwards, the borehole P1 was lost for observation due to it being blocked by vandals dropping timber into the well. This borehole was made fully usable again after drilling through the timber obstruction in August 2007, when around 20 m depth of water was found in the borehole, only slightly lower than predicted by models 2 and 4 (Fig. 10).

Sensitivity to input parameters

In the foregoing section, it has been assumed that the main source of uncertainty in the model has been the volume of desaturated pore space in the aquifer around the Siersza Mine. It is this uncertainty that is reflected in the variant

Table 4 Total void space (m^3) associated with each level in the Siersza Mine, as applied to each of MIFIM modeling runs 1 to 4

	Model 1		Model 2		Model 3		Model 4	
Elevation Interval (m a.s.l.)	V_g	V_{tot}	V_g	V_{tot}	V_g	V_{tot}	V_g	V_{tot}
+300–350	348,600	1,182,600	1,045,800	1,879,900	0	834,100	0	834,100
+250–300	3,411,200	7,819,400	10,233,600	14,641,800	9,223,400	13,631,600	27,670,200	32,078,400
+200–250	6,349,900	13,539,800	19,049,700	26,239,600	9,223,400	16,413,300	27,670,200	34,860,100
+150–200	9,223,400	18,736,400	27,670,200	37,183,200	9,223,400	18,736,400	27,670,200	37,183,200
+100–150	6,464,300	11,621,500	19,392,900	24,550,100	6,464,300	11,621,500	19,392,900	24,550,100
+50 to 100	5,946,200	10,321,900	17,838,600	22,214,200	5,946,200	10,321,800	17,838,600	22,214,200
+0 to +50	3,189,100	5,422,400	9,567,300	11,800,600	3,189,100	5,422,400	9,567,300	11,800,600
–50 to +0	1,977,000	3,395,800	5,931,000	7,349,800	1,977,000	3,395,800	5,931,000	7,349,800
–100 to –50	499,900	966,200	1,499,700	1,965,900	499,900	966,100	1,499,700	1,965,900
–150 to –100	0	200	0	200	0	200	0	200
–200 to –150	0	22,800	0	22,800	0	22,800	0	22,800
Total	37,409,600	73,029,000	112,228,800	147,848,100	45,746,700	81,366,000	137,240,100	172,859,400
Total 0 to +350	34,932,700	68,644,000	104,798,100	138,509,400	43,269,800	76,981,100	129,809,400	163,520,700

DOI 10.1007/s10040-009-0534-z

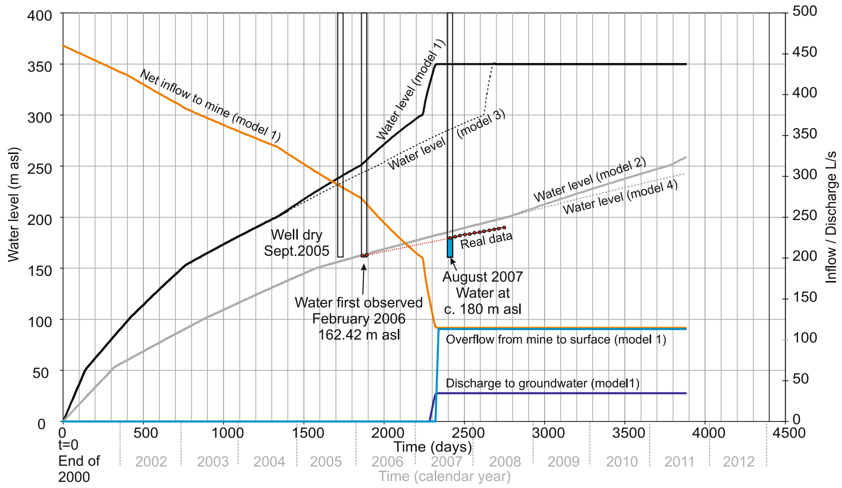

Fig. 10 MIFIM model results for various void distribution scenarios in the Siersza Mine. The same inflow conditions are applied in each case (after Banks 2006a). Actual monthly observations from monitoring well P1 ("real data") are superimposed on the plot

models 1, 2, 3, and 4. Comparison with real data suggests that models 2 and 4 best represent the actual distribution of void space in the mine. The differences between models 2 and 4 lie in the distribution of void space in the uppermost portions of the mine and monitoring data cannot distinguish them until recovery has progressed to a further stage.

It must, however, be recognized that there are other sources of uncertainty in the model, for example:

- uncertainty in the total inflow to the mine. The water budget is believed to be relatively reliable for the most recent years, but it is recognized that this represents a relatively short (and therefore possibly unrepresentative) series of data. There must also be some uncertainty as to how well the water budget has accounted for evaporative losses in ventilation air and in how flooding might affect such losses.
- although the mine void distribution due to recent mining at deeper levels is thought to be well constrained, the void distribution at higher levels, due to historic mining, is less certain. In the Czech portion of the USCB, 19th-century workings are known to exist but are poorly mapped (N. Rapantova, Technical University of Ostrava, pers. comm., 2009). Uncertainty with respect to this would, however, only be expected to affect the latter part of the recovery curve and not the earlier portion considered in this study.
- the value of recharge to the Quaternary/Carboniferous aquifer complex, and hence the proportion of head-independent to head-dependent recharge. Figure 8 indicates that recharge falling on the Quaternary aquifer outcrop drains down a hydraulic gradient (Fig. 7) through saturated strata, via an unsaturated "halo" of rock and into the mine. This is largely speculative and assumes that all recharge migrates downwards and not laterally, and is thus associated with significant uncertainty.
- distribution of head-dependent inflows within the mine. In this paper, head-dependent conductance has, arbitrarily, been assumed to be equally distributed with depth.

Table 5 shows a comparison of models 1 to 4 in terms of four indicative output parameters: (i) the water level after 1,880 days recovery (when mine water was first noted in P1; (ii) the time for the mine water to reach +181 m a.s.l. (i.e., the approximate level in P1 in August 2007); (iii) the time for mine water to reach a hypothetical surface opening at 350 m a.s.l. and (iv) the predicted rate of overflow through such a hypothetical opening. From Table 5, it is seen that models 1 and 2 yield very different results - model 1 fills more rapidly than model 2 as the fillable void space is much less. The same observation pertains to models 3 and 4 (with model 3 filling much quicker). When model 3 is compared to model 1, and when model 4 is compared to model 2 the early portions of the recovery are similar, but the times to overflow are significantly longer, due to the additional void space in the upper parts of the mine. In all four models, the final rate of overflow is identical as F_0 and the distribution of conductances C_1 to C_7 are the same in all variants.

Next, model 2 has been taken as a baseline and the head independent inflow (F_0) has been varied from the maximum plausible value of 265 l/s (see above) down to a value of 90 l/s (60% of the best estimate of recharge of 149 l/s). In all cases, the total inflow has been kept constant at 460 l/s by reducing the value of conductances C_1 to C_7, while keeping them equal to each other). This has relatively little effect on the water level achieved after 1880 days and on the time taken to recover to +181 m a.s.l. (i.e., rate of recovery to the level of borehole P1). Over a longer time interval, however, it will be seen that water levels recover somewhat faster with a high value of F_0 than a low value (as would be expected). Moreover, the final rate of overflow is much higher (243 l/s) for an F_0 of 265 l/s than for an F_0 of 90 l/s (final overflow=49 l/s).

Finally, model 2 was modified to investigate the impact of the distribution of head-dependent inflows, while keeping the head-independent inflow (F_0) constant at 149 l/s. When the entire head-dependent inflow of 311 l/s was assigned to the base of the mine (F_7) the water levels in the mine recovered somewhat more slowly,

 DOI 10.1007/s10040-009-0534-z

Table 5 Results of limited sensitivity analysis of MIFIM model of the Siersza Mine

	Water level at t=1,880 days (m a.s.l.)	Time to recover to +181 m a.s.l. (days)	Time to overflow at 350 m a.s.l. (days), Overflow rate (l/s)
"Best estimate model" (model 2) F_0=149 l/s C_1 to C_7=21.33 m^2/d Sum F_1 to F_7=311 l/s	+164	2,300 days	4,640 days, 114 l/s
Sensitivity to Void Space Distribution (see Table 4)			
Model 1	+254	1,090 days	2,340 days, 114 l/s
Model 3	+245	1,090 days	2,680 days, 114 l/s
Model 4	+164	2,300 days	5,720 days, 114 l/s
Model 2. Sensitivity to proportion of head-independent recharge (F_0)			
F_0=265 l/s C_1 to C_7=13.37 m^2/d Sum F_1 to F_7=195 l/s	+166	2,200 days	4,080 days, 243 l/s
F_0=90 l/s C_1 to C_7=25.37 m^2/d Sum F_1 to F_7=370 l/s	+162	2,350 days	5,080 days, 49 l/s
Model 2. Sensitivity to distribution of head-dependent inflows			
F_0=149 l/s C_1 to C_6=0 m^2/d C_7=81.43 m^2/d Sum F_1 to F_6=0 l/s F_7=311 l/s	+153	2,670 days	5,480 days, 130 l/s
F_0=149 l/s C_1=896 m^2/d C_2 to C_7=0 m^2/d F_1=311 l/s Sum F_2 to F_7=0 l/s	+172	2,050 days	No overflow, Equilibrium at +344 m a.s.l. after 3,600 days

taking around 1 year longer to reach +181 m a.s.l. than the baseline case. If the entire head-dependent inflow of 311 l/s was assigned to the top of the mine (F_1), the water levels in the mine recovered more quickly, taking around 8 months less to reach +181 m a.s.l. than the baseline case.

In conclusion, the main factor controlling the early rate of mine water filling of the Siersza Mine is the assumed distribution of void space (i.e., the difference between model 1 and model 2). The distribution of head-dependent inflows with depth has a modest impact on the early rate of mine water recovery. The proportion of head-independent inflow has relatively little effect on the early rate of recovery, but a more significant one on the later phase and is a major influence on the final rate of mine water overflow at the surface. The void distribution (e.g., presence of unmapped historic workings) in the upper part of the mine has little influence on the early phase of recovery, but a significant influence on the latter phases (difference between model 2 and model 4).

Conclusions

The Siersza Mine complex was finally closed in 2001. As:

(i) the mine is hydraulically isolated from other nearby coal mines
(ii) there is no apparent significant hydrogeological connection with the adjacent Trzebionka Pb-Zn mine (in Triassic strata),
(iii) the mine complex is hydraulically internally interconnected by a series of drifts and roadways

the mine complex has been considered as a single mine "pond" or void space, gradually filling with mine water following cessation of pumping. Mining authorities have installed a network of shallow piezometers in the overlying Quaternary drift and shallow Carboniferous sandstones. These do not penetrate the mine workings themselves and are thus of no value for monitoring rising mine water levels. They have demonstrated, however, that the dewatering of the mine has failed to completely dewater the overlying Quaternary aquifer system (despite an apparently high degree of hydraulic connectivity). Wells and piezometers in the Quaternary strata above the mine are still largely saturated. Head measurements do, however, suggest that the dewatered mine has induced strong downwards vertical head gradients in the overlying strata (a similar situation has been noted in the Derbyshire coalfield of the UK; Banks et al. 1998). The shallow monitoring network will ultimately be valuable in quantifying the effects of the Siersza Mine (if any) on shallow groundwater levels and quality when flooding is complete.

Variable volume mine water filling models, with head-dependent and head-independent inflows, have been applied to simulate the progressive flooding of the Siersza Mine. Models assuming a resaturable porosity of 2.5% in the adjacent aquifer (Rogoż et al. 1999) predicted rates of mine water recovery, which have subsequently been proven to be too rapid. A revised MIFIM (Banks 2001, 2006a) model was run in September 2005, with the

 DOI 10.1007/s10040-009-0534-z

resaturable porosity having been increased from 2.5–7.5%. The new model (runs 2, 4) predicted that mine water levels would rise from 0 m a.s.l. to +161 m a.s.l. some 1,800–1,850 days after flooding commenced. In fact, water was first detected in the deepest available observation borehole in the mine workings (P1) at an elevation of +163 m a.s.l. in February-March 2006, corresponding almost exactly with the modeled mine water recovery curve.

One can speculate whether the apparent success of the re-run MIFIM model was due to insightful modeling and tightly constrained parameter selection. In reality, the choice of parameters was probably merely fortunate. However, in retrospect, it can be concluded that, given that the main element of model uncertainty was in the amount of resaturable porosity in the Sandstones adjacent to the mine:

- Where the mine host rock is substantially porous, it is very important to include the void space represented by resaturable porosity in any mine water filling model. This revised estimate of re-floodable porosity of 7.5% for the Siersza Mine was probably realistic.
- Simple void flooding models such as MIFIM lack predictive capability in permeable formations with a high content of resaturable porosity. At best, they may serve to constrain the range of possible flooding scenarios.
- However, if monitoring data exist to validate such models, mine water filling models are likely to become progressively more accurate and useful for prediction, as input variables can be "tuned" to calibrate the model. In the case of the Siersza Mine, the uncertainty in the resaturable aquifer porosity is likely to be much greater than any uncertainties related to the exact codification of the model.

Finally, one must conclude that holes in the ground (shafts or boreholes) penetrating abandoned and flooding mine workings are a valuable asset (and expensive to replace). Future monitoring should be facilitated during the closure of underground mines and monitoring facilities should be protected and vandal-proofed.

Acknowledgements The publication of this paper was facilitated by financing from the European Commission within the framework of the Marie Curie Host Fellowships for the Transfer of Knowledge, award number MTKD-CT-2004-003163. This paper was presented at the conference "Minewater Pollution and Remediation", held at Newcastle University, on October 24, 2007. The authors wish to thank Dr. Nada Rapantova, Dr. Mark Thomasson, and one anonymous reviewer for their constructive and detailed comments on an earlier version of the manuscript.

References

Adams R, Younger PL (2002) A physically based model of rebound in South Crofty tin mine, Cornwall. In: Younger PL, Robins NS (eds) Mine water hydrogeology and geochemistry. Geol Soc Spec Publ 198:89–97

Banks D (2001) A variable-volume, head-dependent mine water filling model. Ground Water 39:362–365

Banks D (2006a) Assessment of the mine flooding process on groundwater in aquifers surrounding the decommissioned Siersza Mine: conceptual hydrogeological and hydrochemical model of Siersza Mine (dated May 2006). Report of the Główny Instytut Górnictwa, Katowice, Poland

Banks D (2006b) Assessment of the impact of the mine flooding process on groundwater quality: chemical and mineralogical analysis of rock samples recovered from Janina Mine; Hydrochemical modelling of mine water evolution (Draft Rev B, dated 30/5/06). Report of the Główny Instytut Górnictwa, Katowice, Poland

Banks D, Nesbit NL, Firth T, Power S (1998) Contaminant migration from disposal of acid tar wastes in fractured Coal Measures strata, South Derbyshire. In: Mather JD, Banks D, Dumpleton S, Fermor M (eds) Groundwater contaminants and their migration. Geol Soc Spec Publ 128: 283–311

Banks D, Holden W, Aguilar E, Mendez C, Koller D, Andia Z, Rodriguez J, Sæther OM, Torrico A, Veneros R, Flores J (2002) Contaminant source characterisation of the San José mine, Oruro, Bolivia. In: Younger PL, Robins NS (eds) Mine water hydrogeology and geochemistry. Geol Soc Spec Publ 198, 215–239

Blachere A, Metz M, Rengers R, Eckart M, Klinger C, Unland W (2005) Evaluation of mine water quality dynamics in complex large coal mine fields. Proc. 9th International Mine Water Assoc Congr, Oviedo, Spain, pp 551–557

Buła Z, Kotas A (eds) (1994) Geological atlas of the Upper Silesian Coal Basin 1:100, 000; structural geological map of the coal-bearing Carboniferous. Państwowy Instytut Geologiczny, Warszawa

Burke SP, Younger PL (2000) Groundwater rebound in the South Yorkshire coalfield: a first approximation using the GRAM model. Q J Eng Geol Hydrogeol 33:149–160

Burke SP, Potter HAB, Jarvis A (2005) Groundwater rebound in the South Yorkshire coalfield: a review of initial modelling. Proc. 9th International Mine Water Assoc Congr, Oviedo, Spain, pp 223–227

Chmura A, Nowak Z (1990) Występowanie siarki w Polskich węglach kamiennych [Occurrence of sulphur in Polish hard coals - in Polish]. In: Chmura A, Dzieża J, Janusz J, Kozłowski C, Nowak Z, Romańczyk E (eds) Siarka w Węglu i jej Wydzielanie [Sulphur in coals and its emission]. Katowice, Poland, Główny Instytut Górnictwa (GIG)

Eckart M, Klinger C (2006) Assessment of the impact of the mine flooding process on groundwater quality: coupled 'mine-groundwater model' hydrodynamical and hydrochemical model - BOXMODEL. Report from DMT GmbH, Essen, Germany to Głowny Instytut Górnictwa, Katowice, dated 07/6/06.

Eckart M, Kories H, Rengers R, Unland W (2004) Application of a numerical model to facilitate mine water management in large coal fields in Germany. Proc. Congress "Mine Water 2004 - Process, Policy and Progress", Newcastle-upon-Tyne, UK, Vol. 2, 209–218

Ewen J, Parkin G, O'Connell E (2000) SHETRAN: distributed basin flow and transport modelling system. J Hydrol Eng 5:250–258

Gajowiec B, Witkowski A (1993) Impact of lead/zinc ore mining on groundwater quality in Trzebionka Mine (southern Poland). Mine Water Environ 12:1–9

Gandy CJ, Younger PL (2007) Predicting groundwater rebound in the South Yorkshire Coalfield, UK. Mine Water Environ 26:70–78

Gmur D, Kwiecińska BK (2002) Facies analysis of coal seams from the Cracow Sandstone Series of the Upper Silesia Coal Basin, Poland. Int J Coal Geol 52:29–44

Gzyl G, Banks D (2007) Verification of the "first flush" phenomenon in mine water from coal mines in the Upper Silesian Coal Basin, Poland. J Contam Hydrol 92:66–86

Kaziuk H (ed) (1994) Ocena występowania w GZW zasobów węgla ze względu na zawartość w nich składników szkodliwych dla środowiska [Estimating the impact of the environmentally

 DOI 10.1007/s10040-009-0534-z

harmful components of coal in GZW - in Polish]. Proc. Conf. “Problemy geologii i ekologii w górnictwie podziemnym [Geological and ecological problems in underground mining]”, 12–14 October 1994 at Szczyrk, Poland. Główny Instytut Górnictwa (GIG), Katowice, Poland

Korczak K, Zdebik D, Brągiel T, Caruk M, Krawczyk P, Filipek K, Motyka J (1999) Projekt prac geologicznych w celu ustalenia zasobów eksploatacyjnych ujęcia wód podziemnych “Lech” [Project for the geological component of the installation works to abstract groundwater at “Lech” - in Polish]. Report of the Główny Instytut Górnictwa, Katowice, Poland

Kortas L, Younger PL (2007) Using the GRAM model to reconstruct the important factors in historic groundwater rebound in part of the Durham Coalfield, UK. Mine Water Environ 26:60–69

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water Resources Investigations, book 6, chap. A1, 586 pp

Nowak GJ (2004) Facies studies of bituminous coals in Poland. Int J Coal Geol 58:61–66

Rogoż M (1978) Water capacity of abandoned workings in underground coal mines. Proc. International Symposium on Water in Mining and Underground Works (SIAMOS), 18–22 September 1978, Granada, Spain

Rogoż M (1994) Computer simulation of the process of flooding up a group of mines. Proc. 5th International Mine Water Congress, Nottingham (UK), September 1994, pp 369–373

Rogoż M, Frolik A, Staszewski B, Bukowski P, Augustyniak I (1999) Konsekwencje hydrogeologiczne likwidacją zakładu górniczego “Siersza” w Trzebini [Hydrogeological consequences of the abandonment of the “Siersza” mine at Trzebinia—in Polish]. Report of the Główny Instytut Górnictwa, no. MGM/359/99; 41156319-120, Katowice, Poland

Różkowski A, Chmura A (1996) Map of fresh-groundwater dynamics in the Upper Silesian Coal Basin and its margin (1:100,000). Państwowy Instytut Geologiczny, Warszawa

Sherwood J (1993) A lumped parameter of the groundwater rebound associated with the imminent closure of mines in the Durham coalfield. MSc Thesis, Department of Civil Engineering, University of Newcastle-upon-Tyne

Szuwarzynski M (1993) The lead and zinc ore deposits in the vicinity of Chrzanów. Geological Quarterly (Poland), Vol. 37–02

Szyszkowski B, Jarosz K, Ziarno R, Frolik A (2006) Dokumentacja hydrogeologiczna określająca warunki hydrogeologiczne w związku z zakończeniem odwadniania zlikwidowanego zakładu górniczego KWK „Siersza” (wg. stanu na dzień 25.03.2006r.) [Hydrogeological documentation to satisfy state requirements for the abandonment of Siersza Mine - in Polish]. Biuro Usług Geodezyjnych i Inżynierskich GEO-DEX. Trzebinia, Poland

Williamson J (2005) Assessment of mine flooding process on groundwater in aquifers surrounding the decommissioned Siersza Mine. Preliminary modelling report (Draft A, 20/7/05). Główny Instytut Górnictwa, Katowice

 DOI 10.1007/s10040-009-0534-z