Geothermal resources of former coal mine Nowa Ruda, Poland

Zbigniew Malolepszy

University of Silesia, Chair of Fundamental Geology
Bedzinska 60, 41-200 Sosnowiec, Poland
e-mail: malol@us.edu.pl

ABSTRACT

The flooded coal mine of Nowa Ruda in south-western Poland is presented as an example. In the Piast mining field the abandoned workings in the Carboniferous Lower Zacler beds contain about 5,000,000 cubic meters of water at a temperature of 16•26°C. The exploitation of the mine water for geothermal heat pumps is planned. Two two-dimensional (2-D) numerical models based on the TOUGH2 program have been developed to introduce heat exchange modeling into this mining field. The model of temperature recovery of abandoned workings shows the time required to return to natural thermal conditions in a rock massif that has cooled down during coal mining. The expected time for temperature recovery is approximately 10 years. The model of a geothermal doublet producing water at a temperature of 23°C from abandoned workings presents the rate of cooling of the reservoir at production rates of 10 l/s (thermal output power ~800 kW_t) and 20 l/s (thermal output power ~1600 kW_t).

Keywords: coal mine, modeling, low-temperature resources

INTRODUCTION

In recent decades coal mining has declined in many regions of the world, causing abandonment of underground mines. Problems of reclamation and utilization of surface and underground remains of the former mines arise as an important aspect of sustainable development of post-mining industrial areas. There are many abandoned coal fields around the world. Mines in France, Germany, Great Britain, the Netherlands, Poland, Spain and the Ukraine are the subjects of detailed reservoir engineering studies and development of geothermal utilization in abandoned workings. Several installations based on geothermal heat pumps are already working in Canada, Germany, and Scotland [6, 14, 2]. These show that mines that have extracted fossil fuel in the past can produce clean and renewable geothermal energy. Underground openings of abandoned, flooded mines can also be utilized as stores for discarded thermal energy from industry or that recovered from cooling systems [11, 12].

Several examples from Poland [9, 7] show that temperatures of water in flooded mines reach more than 45°C at depths of up to 1000 m. However, it is known from some European coal fields that formation temperatures at this depth exceed 50°C. Abandoned workings of individual coal mines contain tens of millions of cubic meters of warm waters, which can be recovered at the surface and utilized in heat pumps for heating as well as cooling purposes. In some cases warm mine waters can be utilized directly in agriculture and snow melting systems [5].

The former coal mine of Nowa Ruda is located in south-western Poland in the Sudety Mts. (Figure 1). The mine is divided into four mining fields. One of these is the Piast mining field, where underground workings follow several parallel coal seams which dip from east to west at an average angle of 23° (Figure 3). The abandoned workings are located under the northern suburbs of the town of Nowa Ruda, approximately 1 km from the town center. Abandoned workings are divided into two parts due to their depth. The deeper part is distributed between 460 and 890 m under the surface (+40 to •390 m a.s.l.) over a lateral area of 1 km^2. The total water capacity of this part of the workings was evaluated by mine staff to be approximately 5,000,000 m^3. Accordingly to estimations from the Nova Scotia mines [6], this volume of water at an average temperature of ca 21°C, if cooled down to a temperature of 3°C, would yield 376 x 10^{12} J or 105 GWh of thermal energy. Following the termination of mining at Nowa Ruda in 1994, the de-watering system was shut off in 1995 and during the following 5 years most of the workings were filled with water. It is expected that at the deepest levels of the mine the temperature of water filling these workings may reach 26°C. The idea of the utilization of heat from warm mine waters using heat pumps has been considered for a few years by local authorities and the Board of the former mine in Nowa Ruda. It may be possible to pump water from abandoned mine shafts, as well as from wells drilled from the surface down to the mine workings.

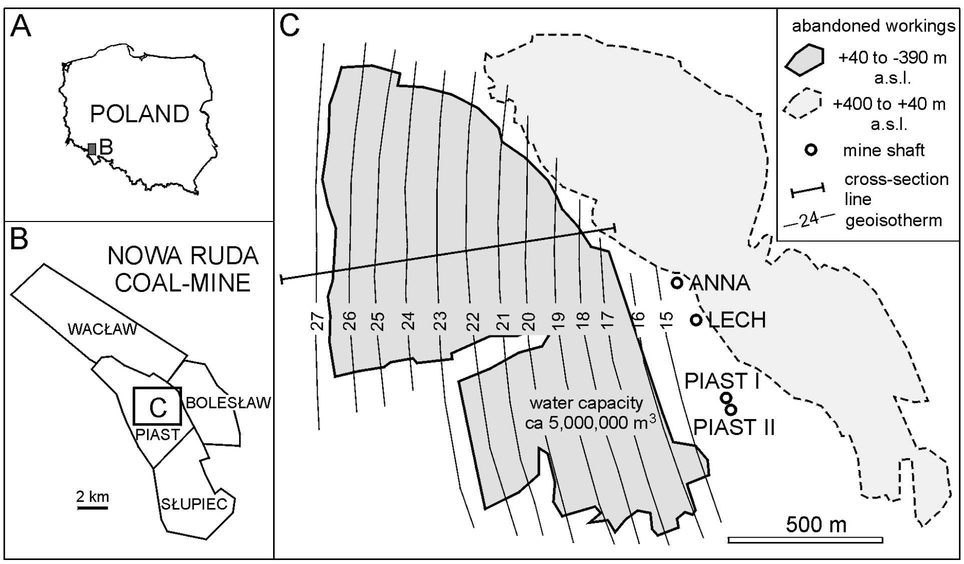

Figure 1. Location map of abandoned workings within the Piast mining fields of the Nowa Ruda coal mine. Formation temperatures at the base of deeper workings demarcated with the solid bold line are shown by geo-isotherms (after "Nowa Ruda" Mining Survey Documentation)

MINE RESERVOIR CHARACTERISTICS

Water reservoirs can be found in almost all kinds of underground mines after termination of exploitation and abandonment of mine workings. However, this paper focus on coal mines and their specific geological conditions. Extraction of laterally distributed coal seams forms large areas of horizontal or sub-horizontal zones of empty openings and voids which are defined after flooding of the mine as water reservoirs in abandoned workings (Figure 2). The site-specific conditions of each coal field or coal-mining area impact on the potential utilization of reservoirs for geothermal purposes [8, 10]. Some of the factors are described below.

Rock formations of coal fields generally consist of a variety of thin intercalated layers of terrigenous deposits which are horizontally bedded in most cases. Claystone, siltstone, and sandstone rather than conglomerates are characterized by low porosities and permeabilities.

The hydrogeological regime of an abandoned mine gradually returns to its natural state if de-watering systems are terminated. At present that process is only possible in isolated mining areas without hydraulic connection to adjacent mines that are still in operation. Therefore, de-watering systems in abandoned mines are maintained, and waters are pumped from levels at which connected mines are preserved from. The deepest levels of abandoned workings are flooded out with cold water flowing from the shallower levels.

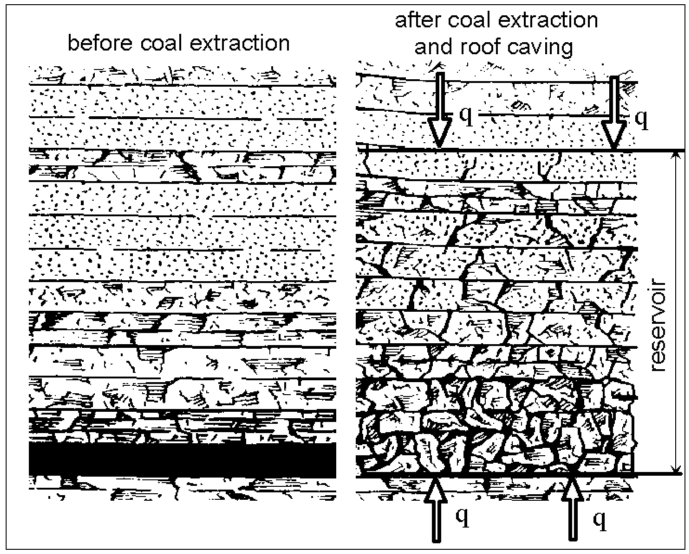

Figure 2. Water reservoir in the mine workings after extraction of coal seam and caving in of the roof. Arrows q mark heat inflow.

Geothermal surveying in coal exploitation areas is one of the most important branches of the underground mining industry. Numerous formation temperature measurements are made during the evaluation and monitoring of climatic conditions to ensure safe and efficient mining. This is especially important at deeper levels (depths of 1000 m and even up to 1300 m in some localities). Temperatures of rocks are measured in exploration wells drilled from the surface as well as in horizontal shallow holes drilled in shafts, roadways or coal faces deep in the mine. Results of both types of measurements can be used for the estimation of the cooling rate of the rock mass during periods of mining when ventilation air and mine waters flowing down from shallower strata act as heat absorbents. The necessity for detailed research on rates of cooling of mine rock formations and the estimation of their thermal recovery period is at odds with some opinions that cooled-down mine workings are useless as sources of geothermal energy. Preliminary research presented later in this paper shows optimistic results.

Generally, coal fields are located in areas of mean geothermal gradient varying between 17 and 45°C/km, with an average value of 32°C/km in Polish coal fields, for example. These values give temperatures of 30•50°C at the deepest levels of the mines. The geothermal gradient has significant changes in the depth of exploitation caused by lithological variation in geological profiles of mining areas.

Terrestrial heat flow measured in coal-mining areas does not exceed average values which for European coal fields fit in the range of 40•80 mW/m^2 with regional anomalies of up to 110 mW/m^2 in south-western Upper Silesian Coal Basin where formation temperatures are higher. Horizontally bedded rock layers with low heat conductivity coefficients form cap rocks for the inflow of geothermal heat. It is expected that thermal anomalies occur beneath thick layers of coal-bearing formations, as in many other sedimentary basins. The local anomalies are observed at exploitation depths of 1000 m in coal-mining areas where there are vertical tectonic structures and vertical or inclined rock stratification, but they do not have much impact on overall formation temperatures.

Spontaneous coal-seam fires in mines often occur in protecting pillars and other unexploited parts of the mines. Together with sulfide mineral oxidation processes they cause considerable local temperature anomalies which disturb the natural thermal regime of the mine. Flooding of the abandoned mines extinguishes fires but the oxidation processes can be continued by oxygen dissolved in the water [6].

The water reservoir in a mine working is created by extraction of coal and waste rock. The volume of the mined spaces is equal to the volume of removed material, but after removal of the pillars supporting the roof the volume of the remaining openings decreases significantly due to subsidence and back-filling. Depending on natural and technological conditions, 5•40% of the initial volume remains open and after flooding of the mine is filled with water.

In many cases the convergence of the roof with the floor occurs under high pressures at deep levels. Generally debris and rubble which have fallen from the roof protect against this. A considerable part of the volume of a reservoir is distributed above the extracted coal seam in the form of fractures created in the de-stressed roof (Figure 2). Many of the shafts, drifts, and roadways remain open if the roof-supporting devices have not been removed. These open tunnels, accounting for considerable volumes in the mine as a whole, could act as possible routes of inflow/outflow into/from reservoirs in mine workings.

Mining areas are very well mapped. Underground mapping survey work at the large scale of 1:1000 gives very detailed documentation on the abandoned workings of every extracted coal seam. Post-mining conditions occurring underground in the flooded abandoned mine can be precisely estimated when considering the potential for geothermal reservoirs. The water reservoirs in abandoned mines are very accessible. Many of the vertical shafts remain for mine de-watering or other technological purposes and give access to deep levels of the mines where geothermal reservoirs can be located. Proper adaptation of the shafts before abandonment can help in further development of geothermal installations. Some of the wells drilled from the surface down to coal seams can still be recovered for use as production or injection wells.

In many abandoned mining areas the coal-bed methane is extracted from deep levels. This process requires many wells to be drilled; some of them are negative, but still can be useful for geothermal purposes if there is any possibility of pumping warm waters from mine workings. Additionally, in sites of coal-bed methane exploitation where geothermal potential is observed, a hybrid installation can be build, for example geothermal heat pumps driven by gas engines.

For efficient geothermal utilization, local users should be in the area above the reservoirs. In mining fields there are commonly densely populated urban areas where today many people are looking for new and environmentally clean sources of energy. The concepts of establishing low-temperature geothermal reservoirs in mine workings below these areas should meet their requirements.

THE "NOWA RUDA" COAL MINE

The Piast mining field of the Nowa Ruda coal mine is located on the eastern flank of the Nowa Ruda coal basin, which is part of the Intra-Sudetic Depression. The Carboniferous formation represents the oldest sedimentary rocks in the area. They were deposited on a gabbro massif, the upper surface of which was inclined at about 30° to the west (Figure 3). Overlying rock beds follow the dip at angles decreasing to 23°. The profile of the Carboniferous is divided into four parts:

1. The Bialy Kamien Formation lies directly on the gabbro. It is represented by coarse conglomerate and sandstone with slate. The thickness of this formation is 10•50 m.
2. The lower part of the Zacler Formation (Westphalian A) is developed as sandstone and claystone and contains 20 coal seams [1]. The thickness of the series reaches 100 m.

3. The upper part of the Zacler Formation (Westphalian B) is 250 m thick and is composed primarily of sandstone and conglomerate and contains a few coal seams.
4. The Glinik Formation is represented primarily by sandstone, conglomerate, and claystone. The thickness of this formation reaches 150 m.

The Carboniferous rocks are covered with deposits of Lower Permian (Rotliegende): conglomerate, sandstone, and shale, which dip at the same angle of about 23° to the west. Quaternary deposits are represented in the area by layers of sand and clay a few meters thick.

Low hydrogeological properties are characteristic of the sedimentary rocks of the Nowa Ruda mine. Some of the layers of the Carboniferous formation form non-permeable horizons. During coal mining the water inflow into workings proceeded along excavations, faults, and fractures. The inflow to the underground workings observed and measured during periods of mining activity varied between 2.9 and 4.8 m^3/min, with an average of 3.4 m^3/min. Water flowing into workings of the Piast mining field includes 2•2.5 g/l of dissolved solids and is of the type HCO3–SO4–Ca–Mg with a low content of free CO_2.

The thermal properties of sedimentary rocks in the area, which were measured by Chmura [4], are characterized by a highly anisotropic heat conductivity coefficient. The average values of this coefficient have been calculated for the proposed models (Table 1).

Geothermal gradient in the area was calculated on the basis of temperature logs of wells GN-17 and GN-12 located in the western part of the mining field. Bottom temperatures measured in the wells are 34.8°C in well GN-17 at 1220 m depth and 30°C in well GN-12 at 930 m depth. Considering the annual average air temperature of 8°C, the average value of the geothermal gradient is ca 23°C/km. Terrestrial heat flow in the area has been evaluated at approximately 60 mW/m^2 on the basis of published maps [3].

Numerical Simulation

Conceptual models

Two 2-D models have been developed to introduce numerical simulation for heat exchange processes in the flooded workings of the Nowa Ruda mine.

1. A vertical cross-section in the E•W direction based on a geological section line (Figure 1).
2. A planar model of the deeper part of the abandoned workings of the Piast mining field.

The TOUGH2 program has been used. This program is a general-purpose fluid- and heat-flow simulator, with applications in geothermal reservoir engineering, nuclear waste disposal, and environmental contamination problems [13]. The two models are described separately below.

The parameters of materials used in the models represent hydrogeological and thermo-physical properties of the main lithological units (Table 1). In addition, one type of material has been defined for abandoned workings. Rock properties have been collected from archival data and the literature [4]. No laboratory measurements have been done for this work, and the lack of detailed data on hydrogeological properties shows the necessity for further research. The boundary conditions of both models were arrived at by trial-and-error matching of the initial temperature and pressure distribution.

Vertical cross-section

This model (Figure 3) was developed along the line of geological cross-section in an E•W direction. It preserves natural dips and thicknesses of rock beds. The model has only 336 blocks and it represents rather coarse discretization of geological formations. In this model faults are neglected due to the rough geometry and size of grid blocks. Further refinement of the grid to enable a better fit of most of the geological features is expected in the next step of research.

Simulations of heat exchange were run in three stages.

1. The natural-state conditions were calculated in the initial run.
2. The conditions under mining activity were simulated in a set of 14 runs representing gradual excavation of the workings over 200 years. The cooling of the excavated workings was assumed at 8°C - the average annual air temperature in the region. Results are shown on Figure 4.
3. The temperature recovery in the workings after termination of mining and flooding of the mine was calculated in the final run.

The conductive heat flow from the surrounding rock mass into five grid blocks representing abandoned workings at various depths is shown on Figure 5. According to simulation, in the deepest part of the workings heat flow exceeds 1.2 W/m^2, which is 20 times greater than terrestrial heat flow in the area. The temperature rise due to heat flow into separate blocks is also presented and it shows the time for temperature recovery. The highest increase of temperature is predicted to occur during the first 10 years, when it would reach 80•90% of the natural temperature (Fig. 5). This is a rather optimistic result compared to the expectation of temperature recovery over a few hundred years [6].

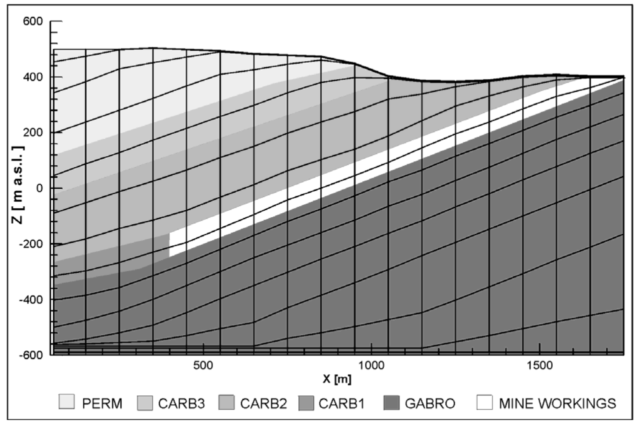

Figure 3. Grid of 2-D model of vertical cross-section through the Piast mining field of the Nowa Ruda coal mine (see cross-section line on Fig. 2). The grid preserves natural dips and thicknesses of rock beds.

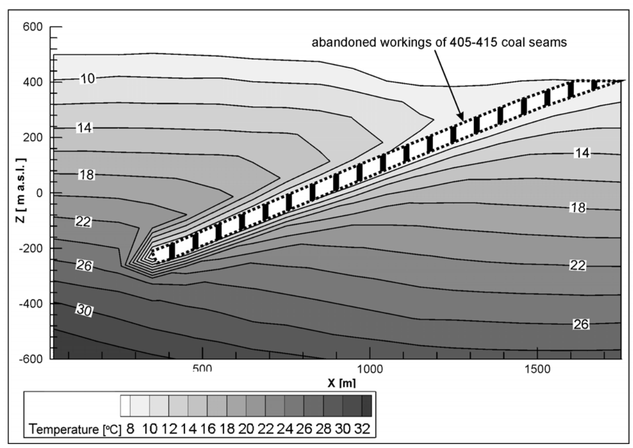

Figure 4. Formation temperature disturbance around mine workings cooled down over 200 years of coal mining.

Table 1. Parameters of materials used in numerical models

Domain	Represented rock formation	Density (kg/m^3)	Porosity (%)	Permeability (m^2)		Heat conductivity (W/mK)	Specific heat (J/kgK)
				Parallel to stratification	Perpendicular to stratification		
PERM	Lower Permian	2.60	8	2×10^{-15}	1×10^{-15}	2.5	900
CARB3	Glinik Formation	2.65	4	1×10^{-15}	1×10^{-15}	2.3	910
CARB2	Upper Zacler Formation	2.7	3	1×10^{-15}	5×10^{-16}	2.5	850
CARB1	Lower Zacler Formation, Bialy Kamien Formation	2.6	15	13×10^{-17}	7×10^{-17}	2.0	950
GABRO	Gabbro	2.9	1	1×10^{-16}	1×10^{-16}	2.9	840
MINE	Abandoned workings	2.6	30	1×10^{-12}	1×10^{-13}	2.3	900

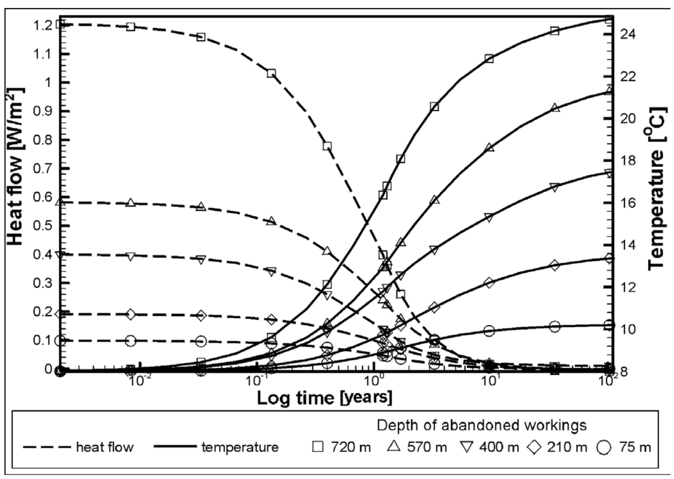

Figure 5. Graph of temperature recovery of the abandoned workings at various depth. Dashed lines show conductive heat flow to abandoned workings besides the terrestrial heat flow (0.06 W/m^2); solid lines show temperature raising in abandoned workings.

Planar model of abandoned workings

The 2-D model covers a total area of 4.5 km^2 and represents one 50-m-thick layer of rocks in the deeper part of the abandoned workings of the Piast mining field. This model has 1632 grid blocks. The layer dips to the west at an angle of 23°. In the first stage of simulation natural conditions were modeled assuming terrestrial heat flow from the lowest part of the model. In the next stage the production and injection of mine water were simulated. Two hypothetical wells of a geothermal doublet were placed at a horizontal distance of 1500 m (Fig. 6). The producer was drilled to the deepest part of the workings (660 m) in order to take the water at a temperature of 23°C. The injector was drilled to a shallow part of the workings (350 m). It injects water cooled to 2•4°C. Two production flow rates were considered: 10 and 20 l/s. Assuming cooling of water at the surface by 19°C, the doublet provides 800 or 1600 kW$_t$ according to flow rates. The temperature drop in the reservoir has been simulated. Figure 6 shows

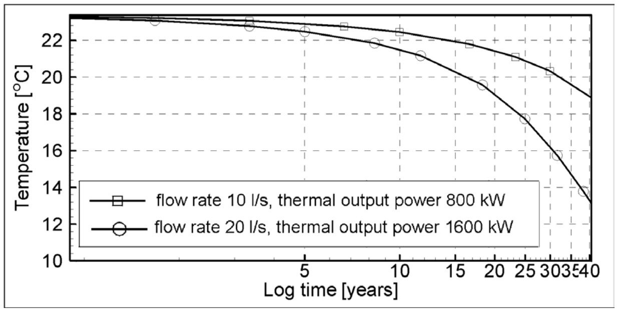

Figure 6. Simulated decrease of temperature of water produced from abandoned workings at a depth of 660 m, assuming reinjection of cooled water over a horizontal distance of 1500 m.

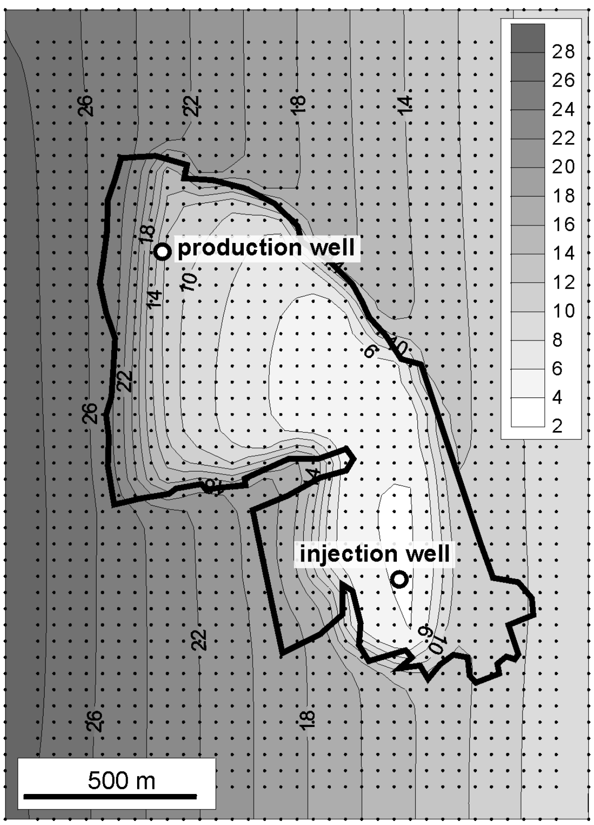

Figure 7. Temperature distribution (°C) in the model reservoir after 40 years of pumping at rate of 20 l/s.

temperatures of produced water over a period of 40 years. The temperature drop was calculated at 4°C for 10 l/s and 10°C for 20 l/s. The temperature distribution in the reservoir after 40 years of pumping and re-injection at 20 l/s is shown on Figure 7.

CONCLUSIONS

Abandoned, water-filled mine workings form reservoirs of low-temperature geothermal water. They constitute a significant, but little-studied, geothermal resource that can be used with the application of heat pumps for space heating, recreation, agriculture, and industry. Direct use of warm water from the mines is possible in, for example, snow melting systems.

The preliminary numerical simulations of heat exchange in abandoned workings within the Nowa Ruda coal mine show that the Piast mining field is the most suitable location for geothermal water exploitation. Developed 2-D models present the temperature recovery in cooled workings and the temperature drop in the reservoir due to production/injection of mine waters by a geothermal doublet. The temperature recovery time in abandoned workings was evaluated at approximately 10 years. Assuming natural-state temperatures in the second model, it is expected that producing 1.6 MW_t by pumping water at rate of 20 l/s would cause the water temperature to drop from 23 to 18°C over a period of 25 years.

The simulations of complex processes of heat and mass transport in porous media in the simple 2-D models presented have many limitations. One example is the lack of confining beds supplying the reservoir with heat in planar models of workings. This problem will be solved in further work by adding set of parallel layers at the top and bottom of the reservoir. Further refinement of the grid and extension to 3-D structures will improve simulation results and provide a more accurate description of heat-flow processes.

Numerical modeling of abandoned workings as man-made, low-temperature geothermal reservoirs appears to be an important part of research into ways of utilizing closed underground mines.

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