

**THE ABANDONED UNDERGROUND CHERNO MORE
COAL MINE (SE BULGARIA) – A SOURCE OF LOW
GRADE GEOTHERMAL ENERGY**

**Klara Bojadgieva, Aleksey Benderev, Petar Gerginov,
Vladimir Hristov**

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Abstract

Flooded abandoned coal mines are a potential source of geothermal energy, which could be used for heating and cooling of energy efficient buildings. Chernomore Coal Mine is located in SE Bulgaria and has been closed for more than 20 years. It represents a large human-induced subsurface reservoir which consists of three interconnected coalfields (“Brigadir”, “9.IX.” and “Blagoev”). Their total volume of about $2.0 \times 10^6 \text{ m}^3$ has been calculated considering the size of the stone drifts. The mine water temperature is measured to be about 16°C in the only accessible vertical shaft (“9.IX.” coalfield). This is the first study of an abandoned coal mine in Bulgaria aiming at assessing its low-valued energy potential and evaluating the opportunity for heating and cooling buildings. The geological and hydrogeological characteristics of Chernomore Mine have been analyzed by using existing archive data and conducting additional chemical analysis of water samples and temperature measurements in the mine. The obtained data were used to develop a regional groundwater model of the

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area and a local hydrothermal model for a thermally-insulated furniture factory located in the vicinity of the vertical shaft. The simulated temperature distribution in the mine during exploitation showed no impact on the production temperature by reinjected water under defined steady state conditions, which created a reliable basis for mine water energy use.

Key words: mine water, geothermal energy use, coal mine, hydrogeology

Introduction. The principle of using mine water for geothermal energy is based on the fact that with the increasing depth the rock temperature increases depending on the locally prevailing geothermal gradient. The heat of the rocks warms the water, which could then be used as input to heat pumps for heating and cooling buildings. The abandoned mine workings create a large underground artificial reservoir. This is the first such survey in Bulgaria to assess the geothermal energy potential of the water in a flooded coal mine.

Burgas coal basin is located in SE Bulgaria and only the shallowest eastern part of it has been exploited in the previous century (Fig. 1). The subject of this study is Chernomore mining complex, which started flooding after the closure of the coal fields and shut down of the pumping stations. The selected Chernomore Mine in Bulgaria forms part of the EC Remining-lowex project that aims to demonstrate a new approach for using abandoned coal mines for low grade thermal energy recovery. The other locations are Heerlen, the Netherlands; Zagorje, Slovenia and Czeladz, Poland. The four selected sites are at different stages of development and present specific mining conditions. The town of Heerlen (the Netherlands) takes advantage of flooded underground mine drifts, using their thermal energy to power a large-scale district heating system, which provides about 300 homes and businesses in the town with hot water and heating in winter and cooling during summer [1-4]. Some experience in geothermal exergy use in low-exergy schemes exists in the community of Zagorje, while feasibility studies are carried out in Poland and Bulgaria.

Chernomore mining village is located 16 km north of the town of Burgas. The exploitation of brown coal in the area started at the beginning of the 20th century. Chernomore Mine is located about 2 km south of the village. It consists of three interconnected coalfields – “Brigadir”, “9.IX.” and “Blagoev” of a total area of about 4 km². The coal exploitation reached a depth of about 300 m after more than 30 years of operation. Two vertical shafts were constructed in “9.IX.” mine, while inclined galleries were used for the other two – “Brigadir” and “Blagoev”. The three coalfields were gradually closed in the period 1970–1988. Currently, all coal mines in Burgas region are flooded except Chernomore-2, which produces about 200 000 tons/year of brown coal.

The study went through analysis of the geological structure and hydrogeological regime of the region followed by temperature measurements in the mine. These data were used to set up a steady state hydrodynamic model aiming to derive the hydraulic conductivity and pressure head distribution in the region and

a local hydrothermal model assuming mine water exploitation for the thermally-insulated furniture factory located in the vicinity of “9.IX.” shaft.

Geological background. Burgas coal basin is situated in the central part of a vast tectonic depression superimposed on the Burgas Upper Cretaceous synclinerium (Fig. 1). Paleogene and Upper Cretaceous formations are present in the area of the abandoned coalfields, (Fig. 2). The litho-stratigraphic units of Paleogene age are Ravnets and Mugris Formations. The Upper Cretaceous volcano-sedimentary complex is the underlying formation of the Burgas coal basin. It is composed of tuffs, lava overflows and sub-volcanic bodies. The thickness of this complex is probably over 5000 m [5]. The Ravnets Formation discordantly overlies the Upper Cretaceous and has a total thickness of up to 160 m at Chernomore mine area. It consists of clays, sandstones, sands, clayey marls and coal seams. The Mugris formation overlies the Ravnets Formation and consists mainly of compact grey marls. The total thickness of Mugris Formation in the studied area is about 80–100 m. Quaternary sediments of the local rivers and their tributaries directly cover the productive coal layer of the Ravnets Formation at the northern periphery of the coal basin. They mainly consist of sands and sandy clays and play an important role in the groundwater recharge of the basin. A detailed geological investigation in Chernomore Mine was carried out during 1921–1922. The geological survey was completed in 1970. After that, all prospecting wells were decommissioned and no information is presently available for them.

Hydrogeological background. Burgas coal basin is one of the water-bearing structures in the country, with a complex relationship between five permeable sand layers, which form one multilayered aquifer in the lower part of Ravnets Formation. The mined coal seams are situated below the aquifer and at some places have a direct contact with it. The thickness of the sand layers varies from (0.5–1) m to (10–12) m. The aquifer is recharged by meteoric and surface water penetrating the Quaternary sediments, by the outcropping Paleogene sands and by the Upper Cretaceous fractured effusive rocks building up the hills north of the region.

The underground flow is directed from the highest relief levels in the north-northwest to the Black Sea in the south-southeast. The drainage occurs mainly in the Black Sea shelf zone. The first estimation of the total natural groundwater inflow from the recharge area to the study region was calculated to 70 L/s [6]. No deforestation and significant climate changes have been observed since then. The three coalfields form one reservoir. Two of them – “9.IX.” and “Blagoev”, are connected by stone drifts, while the third one – “Brigadir”, is linked to “9.IX.” by galleries. The volume of void space as a result of the mine construction and the subsequent coal exploitation was estimated to $4.8 \times 10^6 \text{ m}^3$ [6]. The reduced total mine volume comparable to the size of stone drifts was calculated to $2.0 \times 10^6 \text{ m}^3$, assuming that they are still preserved. Some residual porosity in the collapsed and compacted zones probably exists but it was not considered for the great

uncertainty of its estimation. Groundwater monitoring during the last 5–10 years registered water levels in Chernomore Mine varying between 1.3 and 1.9 m below the surface [7]. They probably recovered to approximately pre-mine levels because the exploitation was terminated more than 20 years ago and no further activity associated with water table lowering was carried out in the area. No evidence of swamping from the pre-mining period before 1920 also confirmed that the present water levels correspond to the undisturbed natural environment.

The only currently available access to the mine water was Shaft 1 in “9.IX.” coalfield, Fig. 2. The shaft was built during the period 1929–1931 and is still preserved. Its current depth is about 117 m and the diameter is 3 m [8].

Another shaft, number 2, was constructed later on and located at about 60 m east of Shaft 1 and is currently sealed off by a 50-cm-thick concrete slab. Both shafts are indirectly connected by drifts.

Data on groundwater dewatering rates measured during 20-year period (1957–1977) of coal production have been analyzed. According to them, a minimum inflow of about 18 L/s can be expected to be sustained for the next 20 years, ignoring water that is extracted and subsequently injected back into the mine. The main quantity of pumped groundwater came from the “9.IX.” coal field.

Another important aspect for mine water use is its temperature. The “9.IX.” coalfield was closed in 1977, flooded and the groundwater has currently reached thermal equilibrium with the surrounding rocks. An Electronic tool – Cera-Diver was placed at 100 m depth in the vertical Shaft 1 and water temperature has been measured to be 15.9 °C in steady state regime.

Mine water chemical composition is also an important factor with respect to scaling and corrosion during exploitation. Water samples were taken for laboratory analyses from several depths in Shaft 1. The mine water is of bicarbonate-sulfate-sodium-calcium type, pH is varying between 7.18 and 7.31 and TDS is ranging between 1.3 and 1.7 g/l. Data from the laboratory tests were analyzed together with the available archive information [7]. Chemical composition (major and minor components) has not been changed significantly compared to the analysis made 14 years ago. Iron content is very low – 0.030 mg/L. The electric conductivity is almost constant – between 1.750 and 1.802 mS/cm.

Fig. 1. Burgas coal basin and location of Chernomore Mine →

Fig. 2. Vertical cross-section along the profile line I–II (SW–NE direction): 1 – Mugris Formation (Pg – marls, clays); 2 – Ravnets Formation (Pg – sands, sandstones, clays, coal); 3 – Upper Cretaceous (volcano-sedimentary rocks); 4 – Faults →

Fig. 3. Layout of the modelled regional area and stone drifts location →

Hydrodynamic model. The collected geological and hydrogeological data were used to develop a regional hydrodynamic model. It aims to simulate the hydrodynamic regime in the region, to estimate the groundwater balance, to obtain the hydraulic conductivity distribution of the sand reservoir and to provide initial and boundary conditions for a local hydrothermal model. MODFLOW software, included in Groundwater Modelling System (GMS), has been used for data processing. This hydrogeological computer programme solves general transport equations.

The selected model includes an area of about 15 km² (Fig. 3). The attributed average thickness is 120 m. The area is divided into cells with a size of 60 × 60 m in the horizontal plane. Three layers are defined based on the geological structure of the region. The first (upper) layer consists of low permeable formations (marls and clays) and is assigned by a low hydraulic conductivity (0.005 m/d), consistent with estimates presented in the literature for similar type of materials. The aquifer is a multi-layered sand formation, which forms the second (middle) layer in the model. The hydraulic conductivity values obtained for the situation before the coal exploitation were low to moderate (between 0.22 and 8.60 m/d) because of the clayey sands forming the multi-layered aquifer [6]. The second layer is a confined aquifer with an average thickness of 15 m assumed for the whole area. The inverse model simulations showed hydraulic conductivity distribution in the discussed area likely ranging between 0.1 and 4.5 m/d (Fig. 4). The third (lower) layer represents the Upper Cretaceous volcano-sedimentary complex. Previously-conducted tests in the neighbouring boreholes derived very low hydraulic conductivity values (0.2–0.4) m/d for this complex [6]. The water flow from the Upper Cretaceous is negligible compared to the one from the sand aquifer. The modelled area is limited to the north by a contact between Upper Cretaceous volcano-sedimentary complex and Paleogene deposits. The northern and southern boundaries were set up as general-head boundaries (Cauchy or mixed conditions). The northern boundary coincides with a hydrogeological feeding zone. The southern boundary is associated with groundwater flowing through certain hydraulic head isoline and is a natural output element of the model. The drainage zone is probably located further away from the southern boundary of the model. There is no need to extend the size of the model as the water alti-

← Fig. 4. Regional hydraulic conductivity distribution

← Fig. 5. Modelled local area and stone drifts location

← Fig. 6. Local hydrothermal model: a) pressure distribution under operation; b) temperature distribution under operation

tude for the whole study region including the mine is higher than the level of the defined southern boundary. The eastern and western boundaries are assigned as impermeable. They are far off the zone influenced by mine activity and have no impact on the model output.

The groundwater flow direction is from north–northwest to south–southeast and the hydraulic gradient is 0.016 [6]. Hydraulic conductivity values are optimized by using the Parameter Estimation module (PEST) of GMS. The obtained hydraulic conductivity coefficients are consistent with the actually estimated values for the study region. The model suggests that the central part of the region is the most permeable, Fig. 4. The calculated and measured heads differ insignificantly in the central part of the region. Convergence of the hydrodynamic model is obtained by calibration on the measured water levels. An important factor for the model adjustment is the volume of water flow through the northern border of the area. According to the model balance calculations, the flow through the northern border of the discussed region is about 115 L/s.

Geothermal energy use. In order to evaluate the possibility of mine water use, a hydrothermal model for Cherno More Mine was set up. It aims to simulate the water movement in the region and the natural and disturbed temperature distribution during exploitation. Specialized software PetraSim 4.2 was used. It is based on TOUGH2 – fluid and heat flow simulator in geothermal and environmental studies. The operation of the simulated system includes pumping of minewater from one shaft and discharging the cooled down water into other shaft or in a newly-drilled well into the mine.

A furniture factory located at about 250 m north of Shaft 1 is a possible mine water user. It currently represents the best suitability for mine water application due to its short distance to the water source and the existing thermal insulation of the building. The modelling was focused on the temperature distribution in the area around “9.IX.” coalfield. It went through the following stages:

- initial run to calculate the steady state distribution of the head and temperature on a local scale;
- extraction and injection of mine water in steady-state.

Water extraction takes place in Shaft 1 and water injection – in Shaft 2 in “9.IX.” coalfield. The model area covers 2.5 km² around Shaft 1 and Shaft 2 (Fig. 5).

The two shafts are situated at the centre of the model area, which consists of two layers. The lower layer represents an aquifer with higher permeability and average thickness of 15 m, while the upper one is with low permeability and thickness of 85 m. The intrinsic permeability was set to 1⁻¹⁵ m² for the upper clayey layer and to 5⁻¹² m² for the sand layer. The abandoned stone drifts of the mine are more permeable than the aquifer and represent water conduits. Those highly permeable zones (Fig. 5) were presented in the simulation by a permeability value of 1⁻⁹ m². The difference in pressure head between northern

and southern boundary is 16 m. A constant temperature of 15 °C was set at the beginning of the simulation. A temperature decrease of 6 degrees was assigned according to the technical requirements for a heat pump operation. After fulfilling this condition, the return mine water would be injected with a temperature of 9 °C. Water extraction and injection were simulated with 2 L/s. The obtained pressure and temperature distribution under disturbed conditions are shown in Fig. 6. According to model simulation, no interaction between the water flows from the production and injection points exists. The temperature of extracted water remains constant.

Conclusions. Geothermal energy production by water use from flooded Chernomore Underground Coal Mine (SE Bulgaria) is analyzed for a thermally-isolated furniture factory situated in the vicinity of the water source. A closed system where water will be produced from one shaft of the mine, used for heating/cooling of the furniture factory and reinjected into another shaft in the same mine, could be realized. The mine water of about 16 °C is easily accessible and the water level is between 1.3 and 1.9 m below the surface. The developed regional hydrodynamic model provides information on the natural groundwater balance and hydraulic conductivity distribution of the multilayered sand reservoir. Convergence of the model is obtained and verified by calibration on the measured water levels. The simulated temperature distribution during mine water exploitation predicts no cooling of the production water under stationary conditions.

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*Geological Institute
Bulgarian Academy of Sciences
Acad. G. Bonchev Str., Bl. 24
1113 Sofia, Bulgaria*
e-mail: klaratb@geology.bas.bg
aleksey@geology.bas.bg
p.gerginov@mail.bg
vhh@geology.bas.bg