Mine water as geothermal resource in Asturian coal mining basins (NW Spain)

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Abstract The Asturian Central Coal Basin is characterized by the presence of predominantly low porosity and permeability materials. Groundwater flow occurs mainly through mining voids, open fractures, and zones of decompression associated with coal mining. Thus, abandoned and flooded mines constitute artificial karst-type aquifers. These created underground reservoirs can be economically managed to supply both water and energy (mainly by means of heat pumps) to villages around the shafts. This potential application of mine water, profitable in both economic and environmental terms, could contribute to improve economic and social conditions of traditional mining areas in gradual decline.

Key Words abandoned mine, mine water reservoir, mines and geothermal energy, water resources management

Introduction

Underground coal mining in the XIX and first half of the XX century led to the establishment of villages around the mining centres. During this time, Asturias (NW Spain) produced more than 50% of all domestic coal, basic energy source at that time. From late 1980's, most shafts are being closed and the mining areas try to find their future outside the coal industry (Raymond and Therrien 2008; Moreno and López 2008).

Mining operations have altered the natural flow of groundwater. The mining voids, together with the spaces created due to the fracturing induced by mining, can be filled up with water, once the mines are closed and inundated, materializing then a new aquifer or "mining reservoir". This stored mine water can be successfully used for water supply, as well as a source of energy, particularly as geothermal resource.

The temperature of water from the coal mining reservoirs in Europe is usually above 14ºC, so modern heat pumps using it as cold source are competitive, considering current prices of electricity and fuel (Jardón, 2010). There has been research and applications of mine water as a source of low enthalpy geothermal energy in the world: Poland (Malolepszy 2000), UK (Sutton 2002; McLoughlin 2006), Slovakia (Bajtos 2001), Germany, The Netherlands and France (Demollin *et al.* 2005), USA (Watzlaf & Ackman 2006), etc. The application to the closed coal mines in Central Asturias is discussed here.

Area of study

The studied area is located in the Central Coal Basin (hereafter, CCB) of Asturias. With an area of about 1400 km^2, the CCB is the largest carboniferous outcrop of the peninsula and the main Spanish coal mining district.

Geology

The area of study lies within the so-called "Cantabrian Zone", which constitutes the external part of the Variscan Orogen in the NW of Spain. Julivert (1971) divided the Cantabrian Zone into several geologic domains on the basis of stratigraphic and structural features (Figure 1); this proposal has generally been accepted into the literature up to now, although many authors (Alonso *et al.* 2009) proposed a regrouping of several units, not yet completely accepted by the scientific community.

Previous studies carried out in the CCB (Carboniferous age) mainly focused on its stratigraphy and sedimentology (García-Loygorri *et al.* 1971; Colmenero *et al.* 2002, among others), paleontology (Wagner 1971; Horvath 1985), tectonics (Aller & Gallastegui 1995), thermal evolution (Castro *et al.* 2000; García-López *et al.* 2007), composition, rank and geochemistry of coals (Piedad-Sánchez *et al.* 2004; Colmenero *et al.* 2008) or economic geology (Cienfuegos & Loredo 2010). Considering detailed structural and stratigraphic characteristics, the CCB can be subdivided into different units (from W to E, figure 1): 'Riosa-Olloniego', 'La Justa-Aramil', 'Caudal-Nalón' and 'Lois-Ciguera'. This work has been carried out in the Caudal-Nalón domain (considered the most representative of the CCB), close to the locality of Mieres. The sedimentary sequence of this area comprises about 6000 m of Upper Carboniferous siliciclastic-dominating rocks, mainly conglomerates, sandstones, greywackes and mudstones, with a few limestone horizons.

Hydrogeology

From a hydrogeological point of view, the CCB is constituted by materials of very low porosity and permeability, but may lead to small aquifer systems (thin sandstone layers), acting wackes, mud-

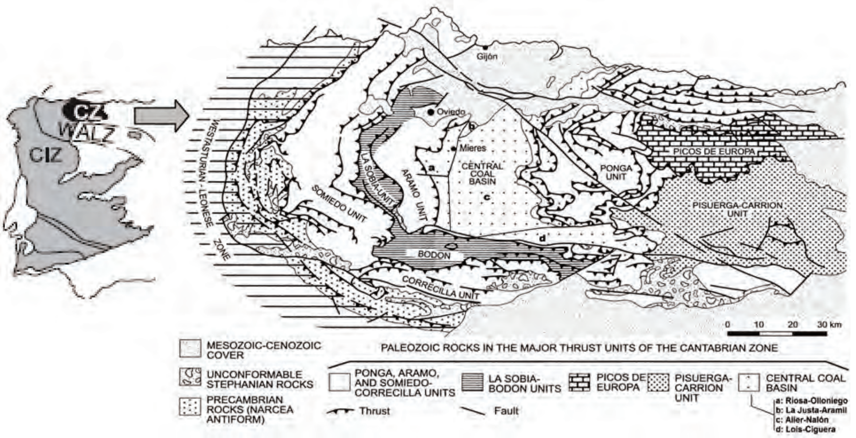

Figure 1 *Cantabrian Zone and subdivision used in this work (modified from Julivert, 1971). CZ: Cantabrian zone; WALZ: West Asturian Leonese zone; CIZ: Centre Iberian zone.*

stones, shales and coal seams as confining levels. Quaternary alluvial deposits, with thickness < 10 m, variable intergranular porosity and appreciable permeability, are not considered significant aquifers, but they can be hydraulically connected with mining voids.

Mining began by galleries into the coal seam, advancing from the valley to the outcrop of surface layers ("mountain mining"). Afterwards, the exploitation continued by vertical shafts (underground mining). Although massifs of protection up to 50 m were left in place, they resulted to be generally useless to prevent infiltration, so pumping was required during mining activity. As a result, the water table suffered a progressive decline to the lowest levels of exploitation. Additionally, mechanical effects of mining caused changes in the hydrogeological parameters of the affected materials. Thus, values of porosity, permeability, transmissivity and storage coefficient increased significantly from their initial values, as shown in Table 1.

From an initial situation before mining, with only small aquifers (multilayer sandstones), the coal mining and the associated fracturing creates a new hydrogeological system. This new "aquifer" behaves similarly to a karst aquifer, with a triple porosity (intergranular pores, fracture spaces, and mining voids for galleries and exploited layers), similar to that of the karst carbonate aquifers (Pendás & Loredo 2006). Under these conditions, if the discharge is interrupted, recharge by infiltration causes the flooding of mine voids and creates an underground reservoir.

The mining reservoirs can be constituted by the mining voids associated to one or more shafts, as they are frequently connected underground.

Methods

Hydrological balance

Considering data from 31 meteorological stations during the last 30 years, a complete climate study was undertaken at the CCB, resulting in maps of isohyets (Figure 2), isotherms and evapotranspiration. This allows calculating the water balance for each mining reservoir and its associated drainage basin. Water comes into the system by means of effective rainfall (precipitation minus evapotranspiration) and then divides between runoff and infiltration. The latter can be assimilated to the flow that was as an average pumped from the mining works in the reservoir. The excess of effective rainfall which is not infiltrated into the ground (in the case of the CCB this part is generally low, due to the reduced permeability) generates runoff that ends into the streams/rivers of the basin. Additionally, it has been found that part of the river flow can be infiltrated into the mining system, due to the increased permeability in highly fractured areas induced by mining. Also, a period of delay between the episode of rain and the entrance of the water to the mining works, takes

Table 1 *Variation of hydrogeological parameters as a consequence of coal mining in Aller area (CCB) (after García-Fuente 1996).*

Porosity (%)		Storage coefficient		Permeability ($m \cdot day^{-1}$)		Transmissivity ($m^2 \cdot day^{-1}$)	
Initial	Final	Initial	Final	Initial	Final	Initial	Final
1	>10	$10^{-3} – 10^{-4}$	10^{-1}	10^{-1}	100	10	1000

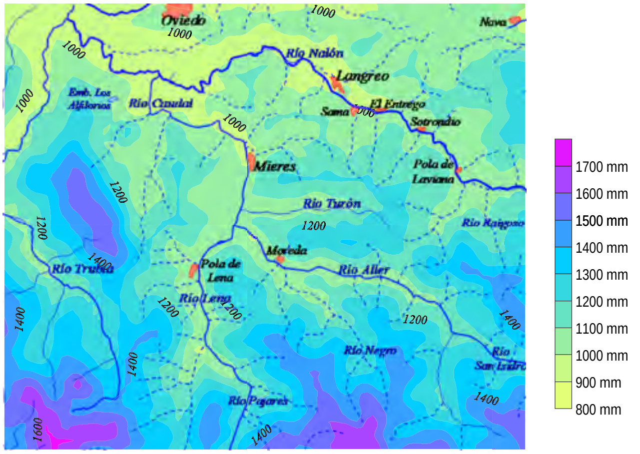

Figure 2 *Average annual isohyets in the area of the CCB where coal mining is concentrated (Ordóñez et al., 2010).*

place; this period has been calculated in the area to be around 19 days (Ordóñez *et al.* 2010).

An example of water balance applied to the mining system defined by the mines located at Nalón River valley, is shown in Figure 3. It can be observed that more than 55% of rainfall is lost to the atmospheres as evapotranspiration, leading to an effective rainfall of less than 500 mm. Approximately 80% of the effective rainfall becomes runoff and about 20% is infiltrated into the mining system, to be later pumped out from it and discharged into the river. Considering a basin of 131 km^2, Nalón River flow increases about 13% after going through it. It is fundamental to establish a hydrogeological model and a water balance for each one of the coal mining systems that are defined within the CCB.

Mining reservoir characterization

In order to better regulate the mining reservoir, it has to be properly characterised. According to the water balance already defined, water inputs and outputs of the system are known. However, the geometry of the voids and the variation of volume of stored water with depth should be established. Some of the mining voids are constituted by galleries, landing areas, shafts, etc. These can be quite accurately calculated from the mining company records, and considering, for example, a reduction of the gallery section due to convergence. Additionally, the extraction of coal generates a void which depends on the method of exploitation and varies with time. To estimate this volume of voids, the coal tonnage extracted by each method is required (it can be determined consulting work plans); assuming a reduction of the initial open void in each case, and a density for the coal (about 1.6 t·m^{-3}), the final void volume can be calculated for each mine level. This volume can be contrasted with that of water infiltrated during the flooding of the reservoir. Once pumping is interrupted, leading to the 'groundwater re-

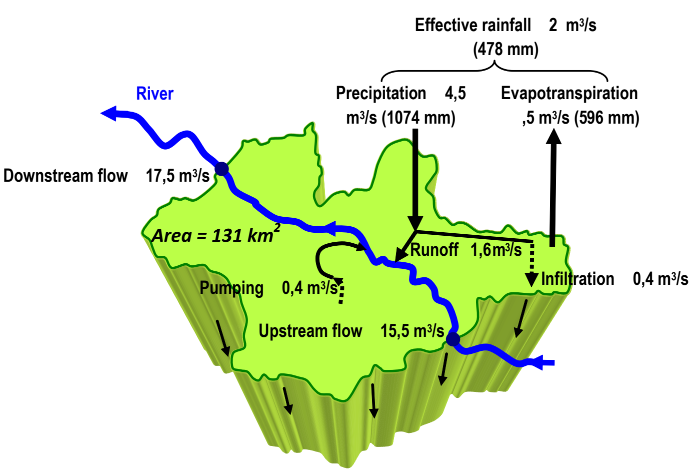

Figure 3 *Conceptual model and water balance for the system defined by the mines placed in the Nalón River valley.*

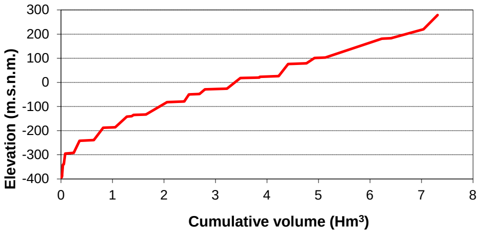

Figure 4 Cumulative volume of Barredo-Figaredo mining reservoir, for each elevation.

bound' (Gandy & Younger 2007), that portion of the effective rainfall which infiltrates in the ground, fills the voids. If the time evolution of the water level is monitored during this process, knowing the relationship between infiltration and effective rainfall, as well as the period of delay, the volume of voids at each elevation can be obtained (Figure 4).

During groundwater rebound, water level does not rise linearly, as its rise depends on the recharge rate and the volume of voids to fill, being slower when water has to fill mine levels with high volume of voids and quicker between those levels. In order to better understand this process, it can be modelled with software such as GRAM model (Groundwater Rebound in Abandoned Mineworkings; Kortas & Younger 2007), which can be also used to predict the evolution of future mine floodings.

Mine water stored at the reservoir can be used, after being treated if necessary, for water supply. Regulation of the reservoir allows storing water during times of excess and withdrawing it in periods of high demand. If the capacity of the reservoir is high enough, this supply can be easily increased importing water from close surface watercourses.

Geothermal application

One of the more attractive applications of mine water is to use it as geothermal resource. The energy use of mine water in the CCB by means of heat pumps is ideal, due to the high performance that can be reached with an average temperature of 20ºC. Considering an average total flow of 40 $Hm^3 \cdot year^{-1}$ pumped in the entire coal mining reservoirs in the CCB, 1700 $hours \cdot year^{-1}$ for heating (Ochsner 2008), the thermal potential of the cool (Pc) and the warm (Pw) sides are, in W (Bajtos 2001; Jardón 2010):

$$Pc = \Delta T \cdot F \cdot SH \cdot \rho$$

$$Pw = Pc \cdot COP \cdot (COP - 1)^{-1}$$

where:

ΔT= Difference of temperature of mine water going in and out of the evaporator, which is generally 5ºC for common heat pumps

F= pumped flow (6.53 $m^3 \cdot s^{-1}$)

SH = Water specific heat = 4,186.8 $J \cdot kg^{-1} \cdot (ºC)^{-1}$

ρ= Water density = 1000 $kg \cdot m^{-3}$

COP = Heat pump coefficient of performance (amount of heat in relation to the drive power required)

To produce hot water at 35ºC, a COP = 6.73 can be considered (Jardón 2010). Thus, Pc ≈ 136.8 MW and Pw ≈ 160.7 MW, so the work contributed to the compressor of the heat pump is Pw – Pc ≈ 23.9 MW. A heat pump available 1700 $hours \cdot year^{-1}$ would produce 273.2 thermal GWh, consuming 40.6 electrical GWh (Jardón 2010).

Producing energy by means of heat pumps using mine water, compared to conventional systems using natural gas, in several applications, means economic savings above 70% and reductions of CO_2 emissions between 20—40% (Jardón 2010; Cordero *et al.* 2010). Mine water from a mining reservoir in the CCB (Barredo-Figaredo) has been already used as geothermal resource to heat and cool some University buildings and there are ongoing projects to extend these applications to other potential future users in the area.

Conclusions

Closed and inundated coal mines in the CCB can constitute mining reservoirs which could be regulated and used as water and energy resource. It is essential to define the hydrogeological model, the water balance, and the volume of voids of the mining reservoir system previously to these applications, which fit with an integrated management of water resources, allowing regulating simultaneously both surface and underground resources.

Considering the pumping rates and the high COP values that can be reached for mine water in the CCB, their energy use by means of water-water heat pumps for heating and cooling is optimal. The entire coal mining reservoirs in the Asturian CCB involve a potential of energy supply higher than 270 thermal GWh per year. Compared to conventional systems, economic savings and a reduction in CO_2 emissions are achieved. These applications are encouraging and might be profitably extended to other minor coal mining basins in Asturias and other areas.

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