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Study Of The Flooding Of Coal Mines In Asturias – Possibilities For The Use Of Mining Reservoirs

Almudena Ordóñez[1], Rodrigo Álvarez[1], Carmen García-Fernández[1], Silverio García-Cortés[1]

[1]University of Oviedo, Escuela Politécnica de Mieres, 33600 Mieres, Asturias, Spain aoalonso@uniovi.es, ORCID 0000-0002-0055-1828; alvarezrodrigo@uniovi.es, ORCID 0000-0002-2651-1103; garciafercarmen@uniovi.es, ORCID 0000-0002-3598-9790; sgcortes@uniovi.es, ORCID 0000-0001-5695-1268

Abstract

This study focusses on the water and energy utilisation possibilities of the coal mines in the central sector of Asturias, most of which are already flooded. In order to estimate the potential for exploitation, the capacities of the mining reservoirs and the water recharge they receive have been estimated, highlighting the importance of hydrogeological studies of mining reservoirs for their use. Several examples illustrate a way to enhance the value of mining heritage after mine closure, creating wealth in often depressed areas, in line with the European Union's roadmap for energy transition.

Keywords: Underground mining reservoir, Flooding, Hydrogeological characterization, Mine water energy use, Coal mines

Introduction

The reduction of greenhouse gas emissions and the increase in the implementation of renewable energies is aligned with the EU proposals for 2030, as well as with the Paris Agreement. The EU Energy Efficiency Directive 2023/1791 requires Member States to increase the use of renewable energy and obliges them to migrate their district heating and cooling systems to 100% renewable energy, waste heat or a combination of both by 2050. Geothermal energy, often underestimated in the renewable energy scene, stands out as an innovative and sustainable alternative to meet energy demands, e.g. that used for space and district heating/cooling by means of a heat pump (low and very low enthalpy resources). Resolution 2023/2111(INI) adopted by the European Parliament calls for a European strategy to accelerate deployment and investment in geothermal energy. In addition, more support is requested for regions whose economies are dependent on fossil fuels, in order to help them make the transition to geothermal energy. This could be the case in Asturias (NW Spain), whose core industries have traditionally been coal mining and power generation through thermal power plants. Mine water, traditionally seen as waste, is increasingly being recognized as a valuable resource. In the context of the global shift toward clean energy, the energy market is pursuing creative solutions for its generation and storage. Underground pumped hydroelectric energy storage systems (UPHS) are gaining attention as efficient, flexible options for managing the intermittency of renewable energy sources.

It is worth highlighting the Asturian geothermal mine water systems as thermal energy storage applications (Menéndez *et al.* 2019, 2020). Near the Barredo shaft (Mieres), the company HUNOSA implemented more than a decade ago the first district heating using mine water, which has served as an example for other similar systems in Europe. Subsequently, another district heating associated with the Fondón shaft (Langreo) has been implemented. Accumulated experience has shown that the distance from mining reservoirs to consumers greatly influences the viability of the project. Therefore, this study considers systems with potential customers close to the reservoirs, such as the aforementioned Barredo and Fondón and others such as Carrio (Laviana), San Antonio (Aller) or La Camocha (Gijón). In addition to the above, it is also possible to consider the use of UPHS in mining infrastructures, as well as considering the mine water as a water resource. This work highlights the need and relevance of carrying out a complete hydrogeological study of mining reservoirs prior to their water and energy use.

Methods

Study Area

For over two centuries, up to 70% of Spain's coal production came from the Asturian Central Coal Basin (CCB), but all the mines are closed now. Underground mining progressed reaching depths up to 1,000 m. This process fractured the rock, increasing rainwater infiltration, which required constant drainage through pumping while the mines were operational. In total, about 40 Mm^3 per year of water were pumped when the mines were active. When the mines were closed, pumping stopped, leading to gradual flooding or 'groundwater rebound' (Younger *et al.* 2002). The flood rate is influenced by seasonal infiltration and void volume, slowing near large underground galleries and rising faster between them (Ordóñez *et al.* 2012). If pumping were not restarted, mine water would eventually come to the surface through the lowest mine adit or any connected permeable rock, leading to uncontrolled discharge. To prevent this, controlled pumping is often reinstated in the Asturian coal mines, balancing discharge with recharge to maintain a stable water level and creating an underground 'mining reservoir'. This regulated underground reservoir can serve various purposes, such as water supply, river flow support, and energy -mainly geothermal- applications.

Hydrogeological characterisation of mining reservoirs

From a hydrogeological perspective, the CCB consists mainly of Carboniferous rocks with low permeability, preventing the formation of major aquifers. The undisturbed rock mass is nearly impermeable, with only certain sandstones acting as small, confined aquifers due to surrounding mudstones and shales. As a result, groundwater primarily flows through mining voids and open fractures. Mining operations have created artificial, pseudo-karstic aquifers where most stored water is found in mining-induced voids (Ordóñez *et al.* 2012). Additionally, the hydrogeological properties, such as porosity or permeability of the originally low-permeability materials improve considerably due to mining. Therefore, these mining reservoirs can be considered isolated systems, surrounded by nearly impermeable Carboniferous rocks, which prevent lateral groundwater inflow. Thus, the infiltration of effective rainfall is considered its source of recharge.

The basin linked to a reservoir refers to the area where rainfall can infiltrate into the mine workings. Its boundaries are defined by topographic divides and the extent of the mined area, which may enhance permeability in the overlying materials. Firstly, it is necessary to carry out a climatic study to determine the effective rainfall (total rainfall minus evapotranspiration) in the basin affected by the mining reservoir. This effective rainfall divides between infiltration into the reservoir (recharge) and runoff into the basin's watercourses. The average pumped flow from the shafts in the reservoir during the mine's active period must be determined. As mentioned, in this area the pumped water can be made equivalent to the infiltrated effective rainfall, representing the reservoir's average recharge (Ordóñez *et al.* 2012). The geology of the area and the effect of potential loosing rivers must be taken into account. Once all these parameters have been estimated, it is possible to define a conceptual hydrogeological model of the operation of the mining reservoir.

To predict flooding and determine potential uses, the reservoir's storage capacity must be estimated. This involves assessing mining voids, considering historical mining activity and connections to adjacent workings. The volume of voids of the mining reservoir determines the usable water storage capacity and influences regulation possibilities by adjusting recharge and withdrawal rates. One method to determine void volume at different depths involves estimating the infiltrated water volume during flooding -if it has already occurred-. This requires monitoring groundwater rebound (measuring water level rise in shafts) and assessing effective rainfall infiltration during the flooding period. On the other hand, this volume can be also estimated by calculating the volume of mining galleries using their total length (several hundreds of km, Table 1) and an average cross-section as well as estimating the voids from coal extraction based on historical production data and coal density, taking into account the void loss due to backfilling, compaction, or collapse, depending on the mining method used (Álvarez *et al.* 2016).

According to the conceptual model, after pumping stops, the groundwater level in the mining reservoir will gradually rise, filling the voids over time. Using the gathered information, the flooding process can be predicted, considering its typically slow nature due to the extensive mine workings and related volume of voids relative to water inflow. A rough estimate of the time required to fill the reservoir, and its average filling velocity can be calculated based on the void volume and the average recharge rate. In addition, the expected flood evolution can be modelled using specific software, such as the GRAM model (Groundwater Rebound in Abandoned Mineworkings; Adams and Younger, 2001) or the software FEFLOW (Finite Element subsurface FLOW system; Andrés et al 2015).

Potential uses of mine water

Water supply: Mining reservoirs are often located near urban settlements, allowing treated mine water to be used as a water source. By considering average recharge, the reservoir's annual supply curve can be determined and compared to demand. Regulation through reservoir capacity enhances supply by offsetting seasonal water deficits with stored water from other periods.

Energy resource: Mine water has significant geothermal potential due to its stable temperature and flow. Using it as a low-enthalpy resource for heating and cooling through heat pumps can reduce energy consumption, CO_2 emissions and costs by more than 50% compared to conventional systems (Matas-Escamilla *et al.* 2023). Additionally, if some of the water used for geothermal purposes is returned to the reservoir, hydraulic power can be efficiently generated using a turbine during peak-load hours. Energy storage using mining reservoirs in UPHS systems is especially advantageous for mines requiring continuous pumping. These systems help address the intermittency of renewable sources like solar and wind while also revitalizing abandoned mines through job creation and community development.

Apart from the temperature of the mine water, for the long-term geothermal exploitation of the reservoirs, it is very important to know the thermal conductivity of the rock mass, particularly for modelling the thermal exploitation of the reservoir (Andrés *et al.* 2015, 2016), as well as some hydrochemical parameters. In particular, the Barredo-Figaredo mine waters are near neutral, net alkaline, high metal waters of Na-HCO^3 type. Their suspended and dissolved solids and particularly their iron content have caused some scaling and clogging on heat exchangers of the geothermal installations.

Results

Fig. 1 shows simplified examples of conceptual model of two Asturian mining reservoirs, considering the water balance in the basin affected by each of them.

Fig. 1 Recharge basin and conceptual hydrogeological model of the Candín-Fondón (A) and the Lieres (B) mining reservoirs

The capacity of the studied underground mining reservoirs in Asturias varies between 5 and 9 Mm3 and the water recharge they receive varies between 0.8 and 5.6 Mm^3/year (through an area of the associated basin that ranges from 9 to 47 km^2), so by means of regulation, a large capacity of water is available as a water resource for urban or industrial uses (Table 1). The flooding periods of these systems vary from 1 to more than 15 years, depending on the hydrogeological characteristics and the exploitation schemes.

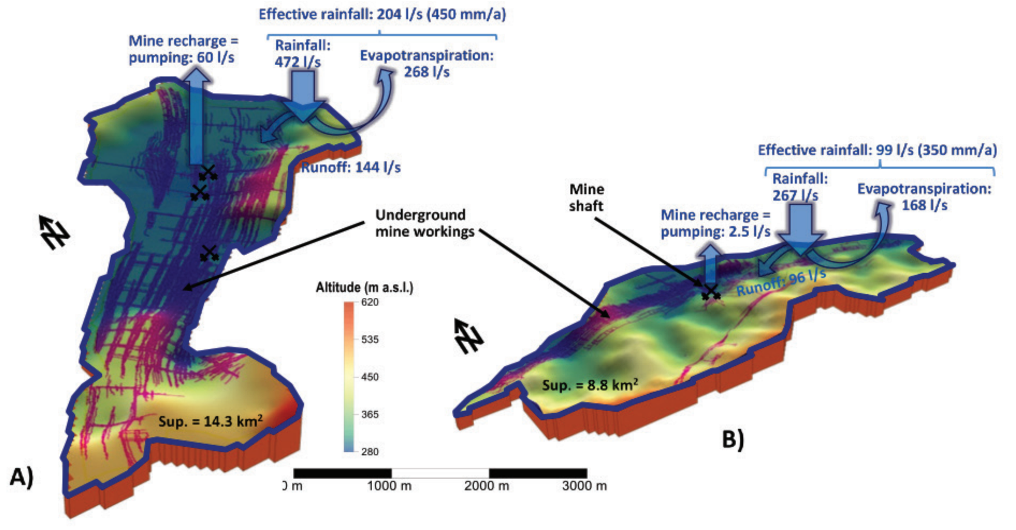

Figure 1 *Recharge basin and conceptual hydrogeological model of the Candín-Fondón (A) and the Lieres (B) mining reservoirs*

It is observed that the estimation of the flooding time of a mining reservoir depends on its volume of voids but is mainly negatively correlated with the water recharge it receives, which in turn depends primarily on the recharge area of the reservoir, as well as other factors such as the precipitation regime and the unexploited rock mass below the surface that will limit infiltration into the mining voids. All the considered mining reservoirs are located in the CCB, excepting La Camocha, that belongs to another sedimentary basin.

Fig. 2A shows the actual evolution of the Candín-Fondón reservoir flooding compared

Table 1 *Comparison of (approximate) data from different mining reservoirs*

Mining reservoir	Max. depth (m)	Length of galleries (km)	Aprox. volume of voids (Mm³)	Area of recharge (km²)	Water recharge (Mm³/year)	Aprox. flood duration (years)
Barredo-Figaredo (Mieres)	647	400	5.8	16.4	4.0	1
Candín-Fondón (Langreo)	700	598	8.0	14.3	1.8	5
Carrio-S. Mamés-Cerezal (Laviana-SMRA)	960	567	7.1	46.6	4.5	1
Santiago-S. Jorge-S. Antonio (Aller)	614	583	9.1	37.7	5.6	1.6
La Camocha (Gijón)	612	158	7.8	15.9	0.8	>15
Lieres (Siero)	780	242	7.0	8.8	0.08	>15

with that previously predicted with the GRAM and FEFLOW models. Analogies can be seen in the rise of the piezometric level and a good estimation of the total flooding period. However, accurately predicting the water level evolution is nearly impossible, and errors from using average values (recharge, hydrogeological parameters) must be considered. Model accuracy depends on the precision of input data, especially the hydraulic properties of the mined areas. Higher permeability and lower void volume (porosity, storage coefficient) lead to a faster water level rise, with the model being particularly sensitive to the storage coefficient (Álvarez *et al.* 2016).

Considering the recharge of the Mina La Camocha mining reservoir and assuming a constant daily consumption of 134 liters per person (average for Asturias), the minimum monthly recharge could supply over 4,200 people after proper water treatment. This estimate does not account for reservoir storage, but if it is considered, regulation becomes possible – allowing surplus water to be stored during high-infiltration months for use during drier periods. As shown in Fig. 2B, by storing excess water from October to February, the available supply could double to nearly 35,800 m^3 per month, meeting the needs of approximately 8,900 people. This would require only 0.05 Mm^3 of the reservoir's total 7.8 Mm^3 capacity.

The temperature of the mine water in the Asturian coal mines usually exceeds 20 °C and, considering all the mines in the CCB, geothermal energy of more than 200 thermal GWh/year could be produced by means of heat pumps, while consuming only 40 GWh of electricity (Jardón *et al.* 2013). The thermal conductivity of the rock mass varies between 1 and 5 W m^{-1} K^{-1} (Fig. 3A). Fig. 3B shows a thermal FEFLOW model of the Barredo-Figaredo reservoir obtained after a simulation of 30 years, where the sub-superficial areas keep low temperatures. Figaredo shaft is cooler due to the influence of the recharge coming from the Turón River. The coolest

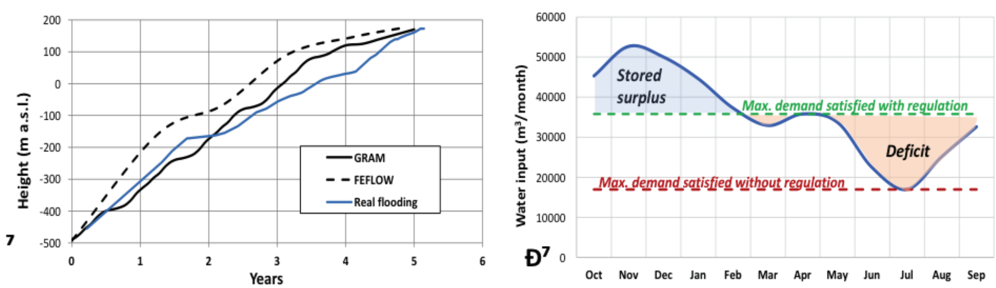

Figure 2 *Modelling of the flooding of the Candín-Fondón reservoir (A); Annual regulation of La Camocha reservoir for water use (B)*

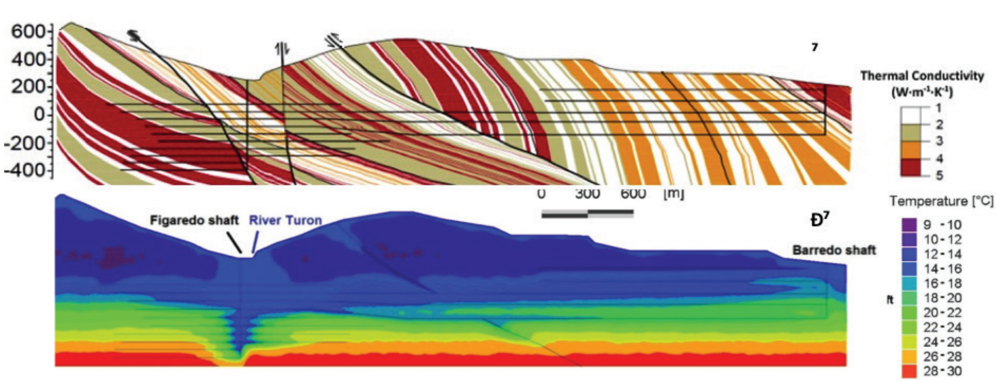

Figure 3 *Cross-sectional view of the Barredo-Figaredo reservoir depicting the thermal conductivity of the geological units (A) and thermal map of the reservoir after 30 years of simulated geothermal exploitation (B) (mod. Andrés et al. 2016)*

water is located near the shaft and advances through the horizontal galleries.

Álvarez *et al.* (2021) proposed a UPHS system for the Lieres coal mine in Asturias, featuring a 520 m net hydraulic head and a 40 MW capacity. The system's estimated cost is €75 million, but when integrated with wind turbines as a hybrid system, its economic viability improves, achieving a 19-year payback period and an NPV of €54 million. Following a hydrogeological study, this mine was chosen due to its depth, proximity to potential consumers, and low water recharge rate, which reduces pumping costs for controlled flooding. The design utilizes existing mine infrastructure to house most of the installation and the lower reservoir, cutting civil engineering costs, while the upper reservoir is located at the surface within the mining site.

Conclusions

A comprehensive hydrogeological characterization of the mining reservoirs improves the understanding of the flooding process, enabling its application to other mines for predictive purposes before flooding occurs. Additionally, a detailed reservoir assessment, is essential for managing mine water as both a water supply and energy resource.

Renewable energy storage is crucial for the future, and public-private partnerships are essential to rebuild economies towards greater sustainability. Geothermal and UPHS systems can be implemented in closed coal mines, but this requires prior hydrogeological characterisation of the reservoir. The methodology proposed here has potential applicability across various regions. These examples illustrate the value of heritage after mine closure, in line with the European Union's roadmap for energy transition.

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