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PAPER

Hydrogeological definition and applicability of abandoned coal mines as water reservoirs

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Hydrogeologically, the Central Coal Basin (Asturias, Spain) is characterized by predominantly low-permeability materials that make up a multilayer aquifer with very low porosity and permeability values, where the sandstones act as limited aquifers, and wackes, mudstones, shales and coal seams act as confining levels. Preferential groundwater flow paths are open fractures and zones of decompression associated with them, so the hydraulic behaviour of the system is more associated with fracturing than lithology. Thus, abandoned and flooded mines in the area acquire an important role in the management of water resources, setting up an artificial "pseudo-karst" aquifer. This paper evaluates the potential application of the abandoned mines as underground reservoirs, both for water supply and energetic use, mainly through heat pumps and small hydropower plants. In particular, the groundwater reservoir shaped by the connected shafts Barredo and Figaredo has been chosen, and a detailed and multifaceted study has been undertaken in the area. The exposed applications fit with an integrated management of water resources and contribute to improve economic and social conditions of a traditional mining area in gradual decline due to the cessation of such activity.

Introduction

Extensive areas of flooded coal mines underlie many populated areas of the world and become an efficient option for water and energy use.[1] Mining operations distort the natural flow of groundwater and create new voids, forming a new "aquifer" or "mining reservoir", whose resources can be regulated. Mine water has recently been started to be used as a source of low-grade, geothermal energy.[1–6] Studies of coal mines as underground reservoirs are less numerous, mainly because the poor quality of water from most abandoned coal mines makes it unattractive; for example, T. Cairney[7] considered in 1973 utilizing disused coal mines as water storage reservoirs. However, the conjunctive use of surface and groundwater stored in a mining reservoir for water supply and energy applications has not been extensively studied.

The study area is located in the Central Coal Basin (hereafter, CCB) of Asturias, in NW Spain (Fig. 1). The CCB, with a mining history extending back to over 200 years, is the main Spanish coal mining district (the largest Carboniferous outcrop of the peninsula), having contributed 70% of the total coal production in the country in the 1990s. The pumped flow in all the mining shafts in the CCB during a hydrological year can be considered equivalent to the annual recharge provided by the effective rainfall.

An average flow of 40 hm^3 per year is pumped in the entire coal mining reservoirs in the CCB.[8] The anthropogenic changes induced by mining should be seen not only as an uncorrectable environmental impact, but as being responsible for the creation of a system which provides new opportunities to exploit.

This paper is organized to provide a description of the hydrogeological setting of the CCB and the results of the investigations carried out in a particular mining reservoir (Barredo–Figaredo), which is characterized in detail, exploring its potential as a water reservoir. The defined methodology can be extended to other coal mining reservoirs, considering their peculiarities.

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Environmental impact

Mine water can be considered and exploited as a water and energy sustainable resource. This article provides a complete definition of flooded mines as "mining reservoirs", which, hitherto unused, can be regulated and used with clear economic, environmental and social benefits. The employed methodology, applied here to a coal underground reservoir, is exposed in detail, to enable its application to other mining districts in the world.

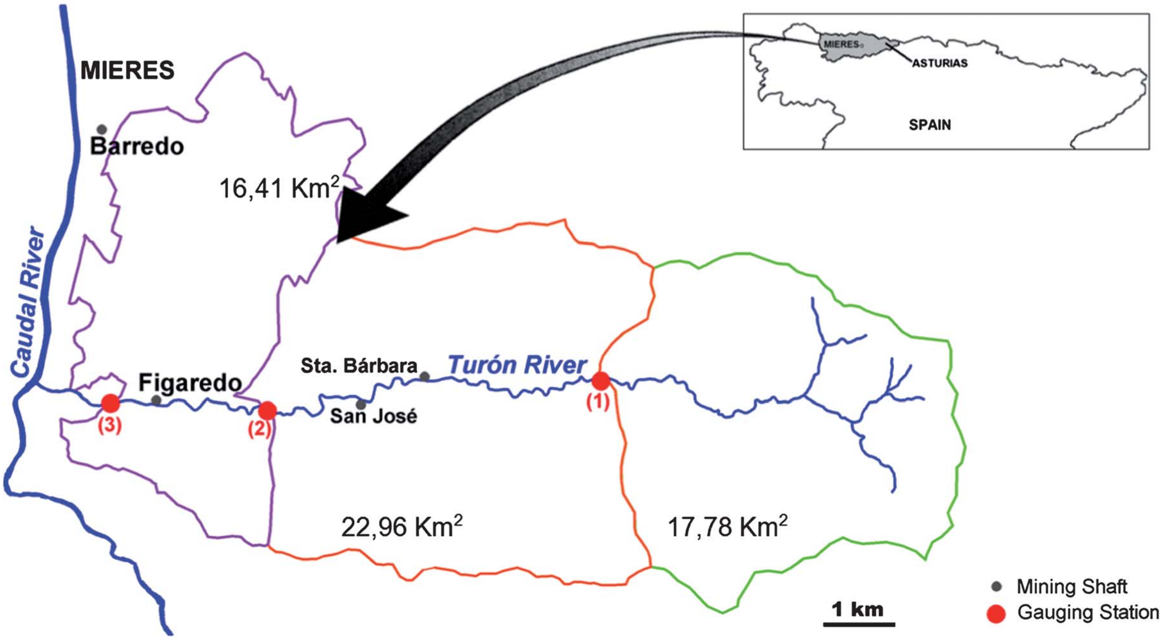

Fig. 1 Location of the studied area, showing gauging stations in the Turón River (CCB) and associated sub-basins.

Description of study area

Climate

The general climate in Asturias is oceanic, with rainfall spread throughout the year and mild temperatures in both winter and summer. A climate study was undertaken taking into account the records of 31 meteorological stations (covering 1170 km^2, centred in the studied area). Datasets were corrected and completed for a period of 37 years and stable maps of isohyets, isotherms, Thornthwaite evapotranspiration and effective rainfall were obtained. Finally, a detailed climate study of the Turón River valley was undertaken.

It has been found that the average yearly rainfall in the Turón River valley is 1080 mm, of which almost 60% is lost to evapotranspiration, so the annual effective rainfall is 440 mm.

Moreover, the monthly balance estimates that the soil moisture deficit is zero for seven months a year (taking a value of 100 mm of effective reserve). There are deficits in the months of July, August and September and surplus (runoff excess) in the period from November to May. In addition, the effective rainfall is lacking during the summer months.

Geology

The CCB, located within the so-called Palaeozoic unit, is situated in the central part of the Cantabrian Zone (external zone of the Hercynian belt in northwest Spain, following the Iberian Peninsula geological division of Lotze[9]). It occupies an area of about 1400 km^2 and its sediments reach a maximum thickness of about 6000 m. The CCB presents a wide outcrop of a thick mainly terrigenous synorogenic Carboniferous succession, which begins with Westphalian lutites, limestones and sandstones of the (approximately 2700 m thick) Lena Group, situated on top of the Namurian limestones of the Caliza de Montaña Formation. The Upper Westphalian Sama Group overlies the Lena Group and comprises lutites, sandstones (predominantly litharenites and sublitharenites), coal beds, some limestones in the lower part, and local conglomerates. The Sama Group reaches 3000 m of thickness in the most complete sections, and its lowest series of seams were mined in the studied area.[10–12]

Hydrogeology

From a hydrogeological perspective the CCB consists of sediments of very low primary permeability that may lead to only scarce and small aquifers. The materials that can be found in the area can be classified into four main types, according to their permeability (the first three are Carboniferous sediments):

(1) Very low permeability materials: these could be classified as shale or siltstone.[13] Studies in the CCB[14,15] estimated permeability values below 10^{-7} m s^{-1} in natural conditions (a practically impermeable virgin solid) and values around 10^{-6} m s^{-1} in exploited areas where the rock mass is fractured.

(2) Low permeability materials due to fissuring: they are represented by quartzarenite, calcareous and siliceous sandstones, siliceous microconglomerates and conglomerates. Their permeability is related to cracking, although original values are generally very low[16] (10^{-6} m s^{-1}).

(3) Variable permeability materials due to fissuring and karstification: constituted by thin limestone and dolostone levels sandwiched between series of shale and siltstone. Although primary permeability of these materials is very low, they have developed a secondary one by cracking and/or karstification. Medium to low permeabilities are often assigned to these levels, although they are variable depending on the degree of karstification and subsequent filling.

(4) Materials of variable permeability due to intergranular porosity: composed predominantly of quaternary deposits (from clay to gravel), widely represented in the studied area, with thickness not exceeding 10 m. Although not considered

important aquifers, they can be hydraulically connected with the mining voids. Permeability values vary in the range of 10^{-5} to 10^{-6} m s^{-1} for clayey sands and sandy clays, and in the range of 10^{-4} and 10^{-5} m s^{-1} for gravel.[8]

The main coal mines were located in the productive series (Sama group), constituted by an alternation of shales, sandstones, conglomerates and coal seams. Therefore, the affected materials relate mainly to types 1 and 2 (defined above), and the area behaves as a multilayer aquifer with very low porosity and permeability (sandstones act as limited reservoirs and shale and coal beds as confining layers). The only water flow paths worthy of consideration are open fractures and zones of decompression associated with them, as evidenced by the (scarce) leaks inside the mines. Thus, the hydraulic behaviour is more closely linked to the state of cracking of the rocks than to lithology.

The rock mass in the studied area is formed vertically by three overlapping areas: (i) the upper clay-rich one, formed by surface alteration (soil), (ii) an intermediate rocky, fissured, decompressed and partly altered layer, of a thickness usually between 10 and 20 m, and (iii) a third deep and unaltered mass of rock, of low or very low effective porosity and low hydraulic conductivity. Mine workings are located on the third and deepest area, and they together constitute a complex and extensive catchment which drains the rock mass. Groundwater recharge is produced mainly by direct infiltration of rainwater and to a lesser extent by runoff infiltrated through the overlying material.

Conceptual model of the mining system

Historically in the CCB, a first phase of drift mining or "mountain mining" was undertaken from the level of the valleys to the highest outcrop of the coal layers. Once it was depleted, exploitation continued through vertical or inclined shafts to access lower heights. This led to the opening of main galleries on rock. Progressive coal exploitation led to working depths of up to 700 m below the valley, leaving in some cases an affected massif of around 1000 m thickness, considering the outcrop at the surface. Since drift mining left a fractured rock mass, and protective pillars were not always properly left, the infiltration of water was facilitated, both through the rock mass and the coal seams.

When permeable sediments are crossed by the mining works, a gravity-induced movement of groundwater from each affected aquifer level to the mining void is produced. Thus, artificial drainage of the hydrogeological system occurs, depleting the local water table and possibly reducing the flow of linked springs. In drift mining, the lowest drift is the drainage reference level, causing a slow and gradual decline of the initial water table to the front of advance (Fig. 2a). Old springs are replaced by mine portals, from which mine water is naturally discharged. In underground mining, if pumping is active, the base level of drainage is the deepest gallery (Fig. 2b). Additionally, fractures might constitute preferential routes for water.

Also, mining causes the upper sediments to crack, altering significantly their hydrological parameters. Sandstones and wackes, even shales, behave rigidly against the stresses caused by exploitation (fissuring and facilitating infiltration and circulation of water), while layers of coal have a plastic behaviour compared to the same stress. Once underground mining is developed in multi-layered sandstone aquifers originally of porous-type (intergranular porosity), they resemble karst-type aquifers, since their permeability is not only due to primary porosity, but mainly due to mechanical cracks, crevices and man-made holes (triple porosity). Therefore, mining-derived aquifers are very similar in structure to karst aquifers, characterized by their complexity and unpredictability.[18] The hydrogeological parameters of these materials increase significantly from their initial values. According to some studies in sandstones of the area,[19] fracturing can increase their porosity from initial values around 1% to values over 10%, permeability can vary from 10^{-6} to 10^{-3} m s^{-1}, storage coefficient from 10^{-3} – 10^{-4} to 10^{-1}, and transmissivity from 10^{-4} to 10^{-2} m^2 s^{-1}.

When mining exploitation ends, pumping can be stopped, proceeding to the gradual flooding of both the mine voids and the open pores in the materials hydraulically connected with them. This phenomenon is known as "groundwater rebound".[20,21] Afterwards, the free flow of groundwater will lead to potentiometric equilibrium (the new level may not match the original). Therefore, the flow of groundwater during the active life of the mine could be very different from that expected after closure.[22] During the groundwater rebound, water level rises through each channel, the rate reflecting the hydraulic conductivity. Consequently, water usually moves faster through free mine voids than through those connected pore passages that have permeable lithologies. This process would produce first the total filling of mining voids and after a small period of time, the saturation of the permeable lithological units connected with those voids, until the hydrodynamic equilibrium is reached.[16]

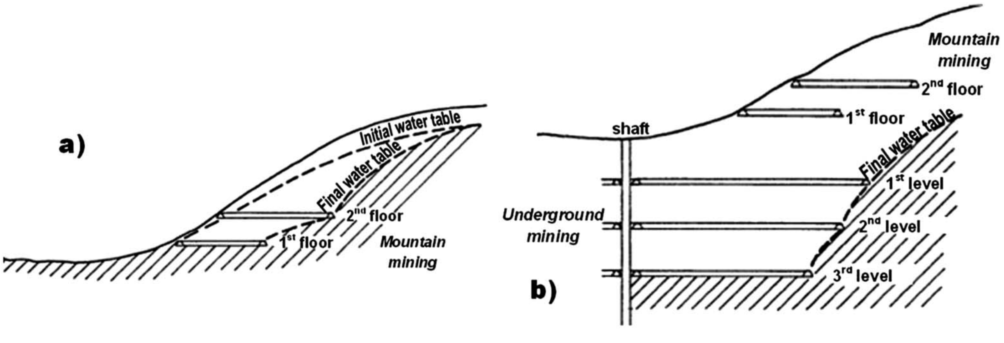

Fig. 2 Sketch of initial situation (before mining) and drainage caused by drift mining – by gravity (a) and underground mining – while shaft is still pumped (b) (modified from ref. 17).

If pumping is not resumed, and some of the upper lithological units connected to any mining work of the flooded system intersect the surface at a level lower than that of the mouth of the mine shaft, a water upwelling (spring) will occur. If these springs are unable to evacuate the entire filtered rainwater, water will finally overflow from the pit head.

If pumping is resumed, and it is graded so that its discharge (D) is equal to the recharge (R), the water level will be the same throughout the ductwork of the new aquifer. The stored volume is then equivalent to that of the filled voids and an "underground reservoir" has been created. When $R/D < 1$, obviously a progressive decrease in the flood level takes place, and if $R/D > 1$, flooding would resume. When water in the underground reservoir is used, a permanent flood level will not be established, even assuming an annual consumption equivalent to the annual recharge (equilibrium); in natural conditions, the ratio R/D naturally oscillates above and below 1 throughout the year depending on climatic fluctuations and demands, producing temporary groundwater level changes.

Estimating the capacity of this "reservoir" requires a rigorous analysis of the voids, as a function of the local mining history and the interconnections with adjacent mining works, as very often a mining shaft does not constitute an isolated system.

To estimate the storage capacity, the method of extraction should be taken into account: (i) back filling gives rise to wall convergence, compaction of filling materials and fracturing of strata above the exploited layer, so the result is an "aquifer" with both filling and fracturing porosity; (ii) caving exploitation produces a roof collapse which creates successive collapses in the above strata until stable; this results in an "aquifer" with porosity similar to that of a karst aquifer and fracture porosity in the upper strata of the stabilized area. The final effective void is the result of multiplying the volume of extracted coal by a coefficient depending on the type of exploitation, which represents the percentage reduction of the initial open hole.[23]

This underground reservoir is not just a passive recipient of infiltration of rainwater, but, as any surface reservoir, it can be regulated, allowing its use for various purposes: water supply to nearby users, strengthening of low flows of nearby rivers to maintain ecological flows, as storm tunnels, *etc.*

Barredo–Figaredo mining reservoir

The findings of a study of the underground reservoir formed by the mining works of Barredo and Figaredo mine shafts is provided in this paper. Barredo shaft is located near Caudal River (Fig. 1), but its underground workings extend mainly to the south, connecting with those of Figaredo, which is located near Turón River. Barredo shaft intersects the ground surface at a height of 220 m.a.s.l.; it has 5 levels and a total depth of 360 m. Barredo extractive activity lasted from 1926 to 1993. Figaredo includes 2 close shafts: San Vicente and San Inocencio, whose entrances are at 279 and 254 m.a.s.l, being 520 and 650 m deep, respectively. Figaredo mining exploitation started in the second half of the 19th century and ended in 2007. Both wells are clearly connected through faces and galleries at −135, −29 and +23 m.a.s.l. Figaredo workings are supposed to be interconnected with other neighbouring wells, such as San Jose and Santa Barbara (Fig. 1), also abandoned, but this connection was proven to be ineffective during the inundation period, so it is not considered here.

Drift mining took place in several places in the area during the early 20th century, so its influence was considered when defining the Barredo–Figaredo sub-basin, which extends to 16.41 km^2 (Fig. 1). This sub-basin was defined as that area, which may allow entry of water into the mining underground reservoir, usually by infiltration of rainwater. Its boundary, shown in Fig. 1, does not coincide necessarily with the topographical divide definition. Infiltration is prone to take place in those areas where the rock mass is fractured due to, for example, drift mining. Also, when the uppermost exploited strata exceed the topographical divide, the sub-basin boundary was defined by the edges of the subsidence basins, calculated according to the depth of the work and their angles of incidence.

An absolute lack of correlation between the increase of mining voids and the pumping rate has been found. That is, infiltration depends only on the effective rainfall and surface recharge area; the increase in exploitation voids and possible interception of the scarce permeable levels does not alter the volume of water percolating beyond the natural oscillations of the interannual variations of precipitation.

The average pumped flow in the Barredo–Figaredo system, over 2002–2007 (before Figaredo closure), was 4.1 hm^3 per year. As both wells have ceased production, the maintenance of drainage is not necessary, allowing in 2007 the flooding of mine workings up to a height of +150 m.a.s.l., the current upper limit of the mining reservoir.

Methods

Hydrology

A hydrologic study of the Turón River basin was undertaken. Firstly, the maximum probable flood was estimated using the Gumbel fit. River flow was directly gauged monthly by two methods (current-meter and chemical gauging) at three points, upstream and downstream of the main mine workings (Fig. 1): (1) at the river head, upstream of any mine workings; (2) upstream of the Barredo–Figaredo sub-basin; (3) near the outlet of the basin, downstream of Figaredo works. Additionally, the water level was read daily by local people on staff gauges expressly placed at those points. The following parameters were determined in-situ: pH, salinity, conductivity, dissolved oxygen, turbidity and temperature, using a multiparameter probe.

Precipitation – recharge

Comparing pumping and rainfall data, the "period of infiltration delay" (time ranging from the infiltration of rainwater on the surface until it is pumped out again from the mine workings) was estimated for the Barredo–Figaredo system. For the conceptual model, vertical flow, defined by fracturing, was considered. The flooding process of the mining works was analyzed in detail, correlating water rebound with the infiltrated rainwater in the estimated void volume. The flooding process was expected to be slow, taking into account the significant cumulative linear extension of mine workings and the volume of voids to fill, in relation to the reduced input of water.

Void volume and groundwater rebound

The residual void left after coal extraction, together with other openings (galleries, shafts, landings, and others), was estimated. The tonnage of coal extracted at each level in Barredo and Figaredo was determined, for which 59 mining work plans (since 1970), preserved in the Historical Archives, were consulted. Depending on the method of operation (back filling or caving), different coefficients were applied to calculate the residual voids;[23] these varied in the range of 10–20% and 20–40% for back filling and caving, respectively. Groundwater rebound during flooding was also studied and used to better define the voids.

Mine water

Hydrochemistry of mine water was characterized by means of analyses of pumped water samples as well as the measuring of selected parameters along the vertical profile of the shaft, to find possible hydrochemical stratification. This often occurs in flooded underground mines, so that the samples taken from the water surface inside the flooded shaft cannot be regarded as representative of the quality of the entire water column.[24] It is more likely that this stratification occurs in slow recovery systems with few inputs and outputs of water; the recharge waters, more superficial and less mineralized, occupy the top of the column, while those more mineralized tend to remain at the bottom of it. Stratification usually disappears when a disturbance by pumping occurs or when the groundwater level reaches an outlet of the system, such as a former gallery.[25]

Three potential uses of the mine water are considered here: public water supply, energy use by means of heat pumps and hydraulic use (if part of the water used for the heat pumps is returned back to the reservoir, and then used to power turbines).

Results

Hydrology

The maximum probable flow calculated for Turón River is about 50, 150 and 250 m^3 s^{-1} for return periods of 2, 50 and 500 years, respectively. However, the final stretch of the river has been recently channelled to avoid flooding after storm events.

Considering the gauging results, the flow at the last station (downstream of the most mined area of Figaredo) is generally lower than that in the previous station (upstream of Figaredo). This difference between both flows is not so clear when they reach a peak, but generally corresponds to an average of 61 l s^{-1}, *i.e.*, about 5300 m^3 d^{-1}, which are infiltrated into the Barredo–Figaredo sub-basin, more mined and therefore more fractured, coming this water from runoff from upstream sub-basins. Hydrographs obtained at each station are shown together in Fig. 3, which shows that the flow peaks coincide with high values of effective rainfall. The annual average flow of Turón River has been estimated to be about 700 l s^{-1}, so its environmental flow is estimated around 70 l s^{-1}.

With regard to the surface water quality, gauging station 1 (above mining works) clearly differs from the other two, especially once pumping in San Jose shaft (Fig. 1) was resumed, and the river receives a significant amount of mine water. The parameters that demonstrate this difference are mainly electrical conductivity and turbidity, which vary within a small range in station 1, but clearly increased in the other two, especially in the penultimate one, closer to the point of mine water discharge. Electrical conductivity of the Turón River goes from values around 0.5 mS cm^{-1} upstream of the discharge to figures 5 times higher after receiving mine water, whereas temperature increases up to 3 degrees. However, there has been no significant change in pH (which is circumneutral in all cases), and other parameters

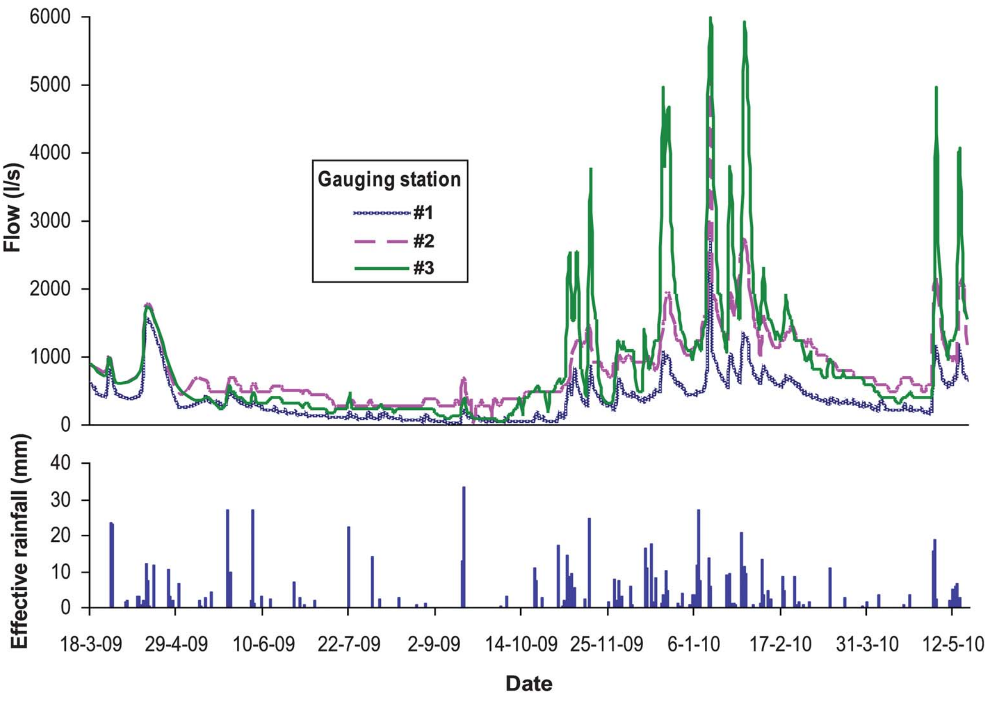

Fig. 3 Hydrographs at the three gauging stations compared to effective rainfall.

measured. The discharge of water pumped from mines to the river, while making a significant increase in river flow, affects its quality, increasing its temperature and content of solids, both dissolved (related to electrical conductivity and salinity) and suspended (related to turbidity).

Precipitation – recharge

The "period of delay" of rainwater infiltration into the Barredo–Figaredo system was estimated to be 19 ± 5 days, which is in agreement with similar values calculated for other shafts in the CCB.[19] It can be noted that a certain pumping in dry periods is also maintained; this indicates that there is a "constant" contribution in addition to infiltration from precipitation (infiltration of water from Turón River in the most fractured area, already mentioned). A relationship between pumped flows (*i.e.*, infiltrated water) and effective rainfall has been established. Considering the Barredo–Figaredo sub-basin (16.41 km^2), monthly infiltration accounts for approximately 20–23% of the monthly effective rainfall, together with a constant input (5300 m^3 per day), not subject to rainfall contribution. In this extra contribution, input from neighbouring aquifers is not involved, due to the low permeability of the rocks. In contrast, this independent term corresponds to the contribution of river water that infiltrates when circulating through the sub-basin; it is responsible for maintaining pumping during periods without rain, as well as the relatively rapid rise of water level during the flood period. The expression that most closely relates the effective rainfall with the infiltration into the Barredo–Figaredo mining reservoir is:

$$\text{Infiltration (m}^3\text{ per day)} = 0.23\text{ effective rainfall (m}^3\text{ per day)} + 5300\text{ (m}^3\text{ per day)} \quad (1)$$

An average effective yearly rainfall of 300 l s^{-1} divides into 69 l s^{-1} of infiltration and 231 l s^{-1} of runoff (water that having been infiltrated through drift mining voids does not percolate in depth, together with general subsurface runoff, which is drained towards Caudal River). Total infiltration in the underground mine is that coming from rainfall (69 l s^{-1}) and from the river (61 l s^{-1}), which is in agreement with the average pumped flow (130 l s^{-1}). This relationship was verified when creating a conceptual hydrogeological model for an average year at the Barredo–Figaredo sub-basin (Fig. 4).

Void volume and groundwater rebound

The volume of galleries was estimated considering 8 m^2 of midsection – taking into account convergence –, which was multiplied by the length of galleries on each floor (400 km in total). The gap left by the shafts was calculated by multiplying its length by a cross-section of 25 m^2; finally, for the major landing areas, a cross-section of 20 m^2 and a total length of 300 m per landing were estimated. The tonnage of coal mined by filling and caving obtained (consulting work plans) for each level in both Barredo and Figaredo shafts was divided by coal density (1.6 t m^{-3}) to obtain volume, and then multiplied by the already mentioned coefficients representing the reduction of the initial open hole, which were adjusted as follows.

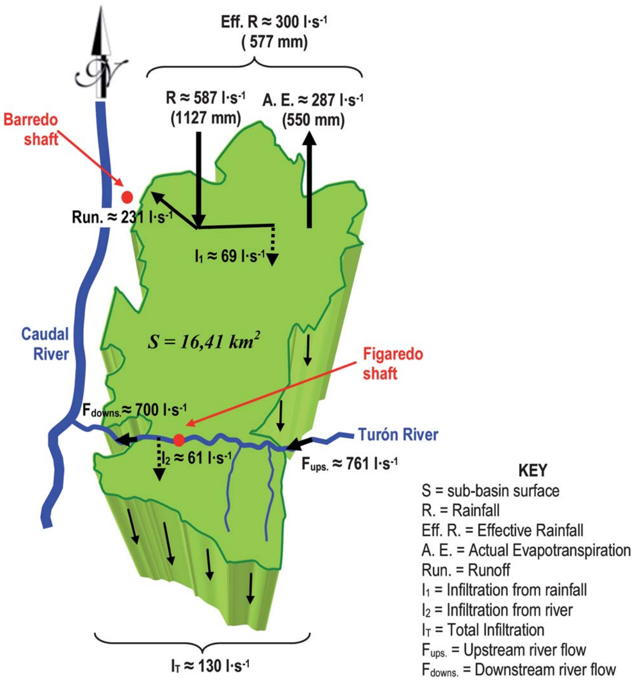

Fig. 4 Simplified hydrogeological conceptual model for the Barredo–Figaredo sub-basin.

The total void volume was calculated from the volume occupied by the infiltrated water during groundwater rebound. This was calculated from daily rainfall during the flooding period from which the actual evapotranspiration during the same period was subtracted (effective rainfall). Knowing the average period of infiltration delay (19 days), the infiltration for each day was estimated from the effective rainfall produced 19 days earlier, according to eqn (1). Daily infiltration during the flooding period represents the volume that filled the reservoir daily. As the rise of water table was registered during the rebound, the cumulative infiltrated water for each day and each elevation was compared to the cumulative volume of voids estimated from the coal production (Fig. 5).

The resulting volume considering tentative reduction coefficients was contrasted with the real volume of water infiltrated during the flooding period, so the best adjusted coefficients were obtained. The subsequent void after the operation was found to be 20% of the original hole exploited by back filling and 30% of

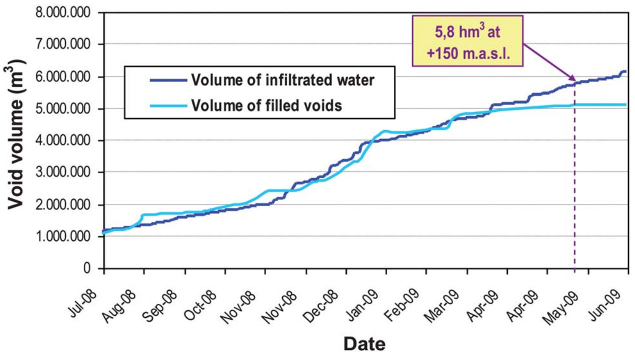

Fig. 5 Cumulative water infiltrated in the Barredo–Figaredo reservoir during its flooding compared to cumulative filled calculated voids.

the hole exploited by caving. This void evaluation is imprecise (underestimated) in the upper levels of both shafts, because their coal production is not accounted for, as the oldest work plans could not be accessed. Thus, both curves of Fig. 5 fit well in the low and intermediate levels (better known in their operation) and differ significantly (almost 1 hm^3) in the upper ones. Void volume in those levels was then increased to fit both curves, and the resulting void volume is shown in Fig. 6.

The model was validated, defining the reduction coefficients for the best fit of both curves and gathering the total volume of voids in the mining reservoir at each elevation. In particular, at +150 m, which is currently the water level in the reservoir, the total volume of voids is estimated to be 5.8 hm^3.

Also, Fig. 6 shows water level recovery curves for both shafts during flooding, which are very similar, only distanced 3–4 m from each other. The ascent depends on the volume of infiltration (and thus on precipitation), but it is generally higher among mining levels, being reduced when sections of higher void volume are reached (galleries); the curve slope is especially reduced at those elevations where mining levels practically coincide for both shafts.

An attempt was made to model the flood using the GRAM model (Groundwater Rebound in Abandoned Mine workings), a tool developed by the University of Newcastle upon Tyne to raise awareness of abandoned mine systems, evaluating conceptual alternatives, given the general lack of historic hydrogeological records.[26,27] As flow in large, open mine voids is often turbulent, standard techniques for modelling groundwater flow (which assume laminar flow) are inappropriate for predicting groundwater rebound. The GRAM model conceptualizes extensively interconnected volumes of workings as ponds, which are connected to other ponds only at discrete overflow points, such as major inter-mine roadways, through which flow can be efficiently modelled using the Prandtl–Nikuradse pipe-flow formulation.[28]

A critical dependence on factors, such as the volume of water entering the system, the percentage of runoff and the storage coefficient, was observed. Assigning the latter a value of 0.08

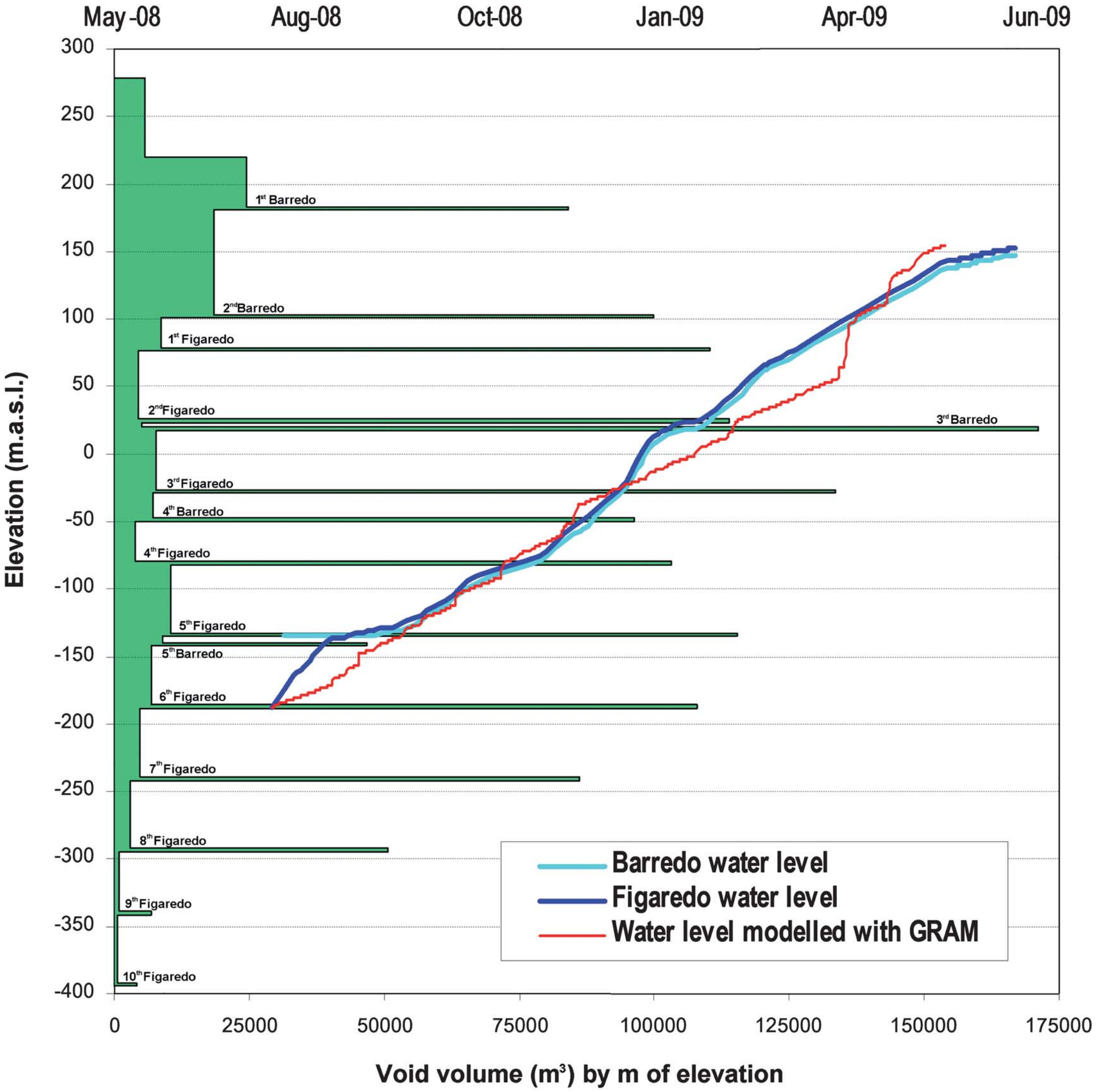

Fig. 6 Void volume per m of elevation calculated for the Barredo–Figaredo reservoir; the water level measured in Barredo and Figaredo shafts during their flooding compared to groundwater rebound modelled with GRAM.

(in agreement with values of the mined area[19]), successful results were achieved, as the obtained levels reproduce quite well those observed in practice (Fig. 6). This allowed a better understanding of the process of flooding, so that the experience gained in modelling can be applied to other similar mines in the CCB before being flooded, for predictive purposes.

Mine water

Regarding water quality, electrical conductivity varies between 1000 and 2000 μS cm^{-1} in Barredo, but it is much higher and variable in Figaredo (up to 5000 μS cm^{-1}), as its water is more mineralized. However, conductivity of Figaredo water decreased after flooding in 2008, mixing with water from Barredo. In both cases, pH is circumneutral. Both waters are generally classified as sodium (calcium)-sulphated, with elevated hardness, which can reach up to 100 French degrees. Coliform bacteria have also been found in some cases. Concentrations of iron, sodium, sulphate, manganese and solids in waters from both shafts are often above the Spanish drinking water limits,[29] in some cases up to one order of magnitude higher (Fe, Mn). In order to achieve the drinking water legal requirements, an intensive physico-chemical treatment, followed by disinfection, should be applied to this water. These values correspond to mine water pumped from near the air–water interface. To find out if hydrochemical stratification was occurring inside the shaft, a multiparameter probe (Aqua Troll), able to resist pressures for the water column at a high depth, was used. The profiles of temperature, conductivity, dissolved solids and salinity obtained in the Barredo shaft are shown in Fig. 7. Changes are noted when passing through the 2nd and 3rd levels of the mine; all the represented parameters increase up to the 3rd level, from which they become constant. Profiles of conductivity, dissolved solids and salinity are similar as they are closely related.

Temperature is quite similar in both shafts. The mining company maintains pressure transducers that continuously register both water level and temperature. The temperature of water in Barredo–Figaredo was around 20 °C, but it decreased during flooding to 15 °C. This parameter shows inertia, remaining fairly constant, regardless of fluctuations in ambient temperature. Notwithstanding, there are significant time variations: temperatures remain within a small range at deeper levels (20–22 °C), but more oscillations appear when approaching the surface (14–24 °C), since the water temperature is more influenced by atmospheric temperature. Generally, the average temperature increased with depth, but it suffered a significant drop at +20 m.a.s.l. (3rd Barredo level), where water drained from a surface drift mine was artificially infiltrated (Fig. 7). The thermal profile has established that the water extracted from the mining reservoir maintains a temperature between 19 and 25 °C, suitable for the operation of heat pumps.

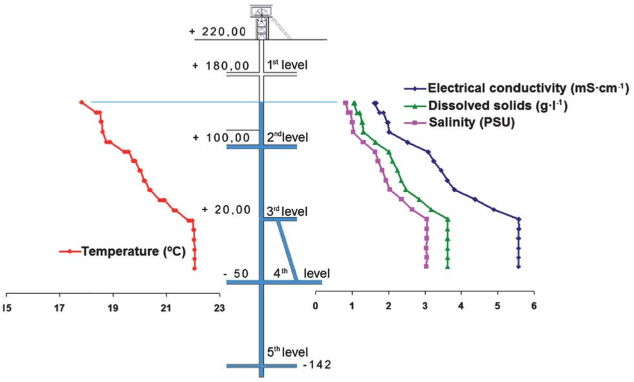

Fig. 7 Profiles of selected parameters measured down the Barredo shaft.

Discussion

The applications of mine water could include:

(i) Public water supply

The Barredo–Figaredo reservoir is very close to urban settlements, such as Mieres, that could be provided with mine water, after being treated. Considering an average recharge of 4 hm^3 per year (equivalent to the average pumping rate during mining activity), there is enough water for 60 000 people's supply (average consumption rate of 185 l per person per day in Asturias[30]). Fig. 8a shows the curve of supply of the Barredo–Figaredo reservoir, compared to Mieres' average consumption. It can be noted that the regulated reservoir could satisfy a theoretical demand of 0.335 hm^3 per month, for which a reservoir of only 0.6 hm^3 would be required. Regulation increases supply, as the water deficit existing during half of the year is compensated with the water stored during the other 6 months (Fig. 8b).

As the reservoir capacity at its current level is 5.8 hm^3, it could be possible to better regulate it, importing external water. For example, a sustainable constant input of 137 l s^{-1} from a local

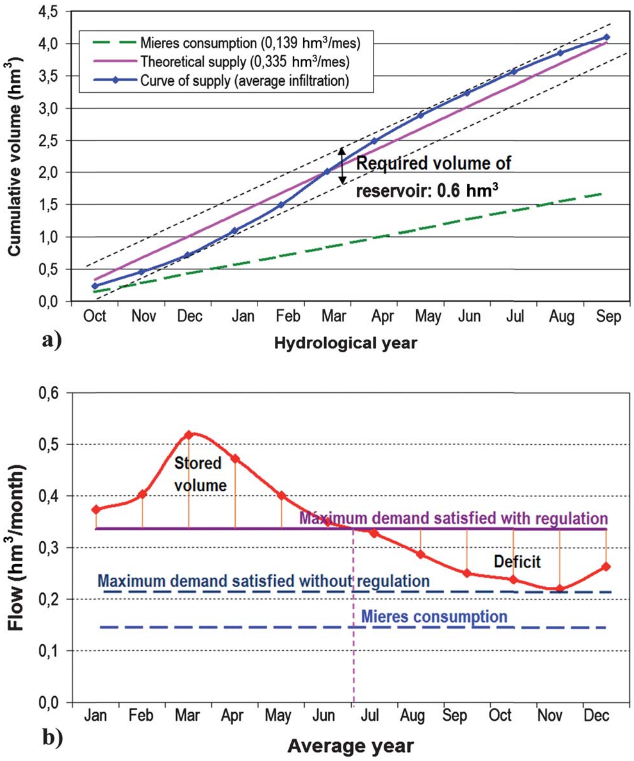

Fig. 8 (a) Curve of supply of the Barredo–Figaredo reservoir and (b) annual regulation of mine water compared to potential demand.

river (such as Caudal River or its tributary Aller River, with an average flow of 20 and 10 $m^3\ s^{-1}$, respectively) would double the satisfied demand (120 000 people's supply). The same result would be reached if an input of 274 $l\ s^{-1}$ was taken from the river only 6 months per year (July to December). Thus, not only Mieres, but the whole council, including also small industries, could be supplied with mine water from this reservoir. Obviously, the uncertainty of climate change over the long term was not included in the estimation.

Additionally, the reservoir could be used to guarantee the minimum ecological flow of Turón River.

(ii) Heat pumps

The mine waters of the CCB have a significant geothermal potential, due to their stable temperature and their high available flow. Considering an average temperature of 20 °C and an annual flow of 40 hm^3 per year pumped in the CCB, 1700 hours per year for heating,[31] the thermal potential of the cool side is:

$$P_c = \Delta T \cdot F \cdot \mathrm{SH} \cdot \rho \approx 136.8\ \mathrm{MW} \quad (2)$$

where ΔT = difference of temperatures of mine water going in and out of the evaporator, which is usually 5 °C for common heat pumps; F = pumped flow, which in this case is $40 \cdot 10^6\ m^3/1700\ h = 6.53\ m^3\ s^{-1}$; SH = water specific heat = $4186.8\ J\ kg^{-1}\ (°C)^{-1}$; ρ = water density = $1000\ kg\ m^{-3}$.

The coefficient of performance (COP) indicates the amount of delivered heat in relation to the drive power required.[31] To produce hot water at 35 °C, a COP = 6.73 can be considered.[8] The thermal potential of the warm side is:

$$P_w = P_c \cdot \mathrm{COP} \cdot (\mathrm{COP} - 1)^{-1} \approx 160.7\ \mathrm{MW} \quad (3)$$

The work contributed to the compressor of the heat pump is: $W_e = P_w - P_c = P_w \cdot \mathrm{COP}^{-1} \approx 23.9$ MW; that is, a heat pump available 1700 hours per year would produce 273.2 thermal GW h, consuming 40.6 electrical GW h.

Two university buildings in Mieres Campus are going to be heated and refrigerated by means of heat pumps using water pumped from the Barredo shaft. It is estimated that the use of this geothermal system will avoid a 74% energy consumption compared to that of a conventional heating system using a natural gas boiler and air-cooling, which is to say that CO_2 emissions would be reduced to a value greater than 40% (considering emissions of 0.204 kg CO_2 per kW h supplied by gas heating and 0.649 kg CO_2 per kW h used in heat pumps[32]). There are other singular buildings (hospital, malls, industrial and housing areas) near the reservoir which could also benefit from these advantages.

(iii) Hydropower

Considering in the Barredo shaft a net head of 70 m and an average returned flow of 0.1 $m^3\ s^{-1}$ (which depends on the geothermal applications), the instantaneous power is:[33]

$$P = 8.34 \cdot H_n \cdot Q \cdot e \approx 50\ \mathrm{kW} \quad (4)$$

where Q = flow rate, in $m^3\ s^{-1}$; H_n = net head, in m; e = efficiency factor, which is usually around 0.85.

Assuming that water is turbinated at peak-load hours (16 hours a day) and pumped at off-peak-load hours (8 hours a day), the energy that could be obtained with this use is approx. 292 000 kW h per year. According to current rates, the cost of pumping would be 23% of the income from the mini hydropower plant. Moreover, the cost of pumping should not be considered here, as it would be included in the economic balance of the heat pump and also, pumping of the mine water is maintained in the abandoned mines anyway.

Conclusions

The studied area, located within the CCB, concentrates a large number of closed and inundated mines, which made up "underground reservoirs" capable of being used as water and/or energy resources.

Geologically, the area consists of a Carboniferous series of coastal parasequences of sandstones, shales and coal seams, which are predominantly "impermeable" and constitute multilayer "aquifers" with very low porosity and permeability. Preferential paths for groundwater are open fractures and associated zones of decompression, particularly those induced by mining. So much so that it was estimated that an average of 5300 $m^3\ d^{-1}$ of water is being infiltrated from Turón River to the Barredo–Figaredo mining reservoir. This constant input is added to a 23% of the effective rainfall that also infiltrates (with a delay period of 19 ± 5 days) to constitute the recharge of the reservoir.

Considering the residual voids left by the extracted coal during mining activity, together with the volume of water infiltrated during the flooding of the mining works, the total volume of the Barredo–Figaredo reservoir, up to 150 m.a.s.l., was estimated to be 5.8 hm^3.

This reservoir could be regulated to meet the demand of 60 000 persons, once water was treated for its Fe and Mn contents. This supply could be doubled just by taking a sustainable flow of 130 $l\ s^{-1}$ from a close river.

Mine water has an enormous geothermal potential given its steady temperature (17–23 °C) and flow. Heat pumps are now being applied to singular buildings using water from the studied reservoir, reducing 74% energy consumption and 40% CO_2 emissions, when compared with a conventional system. If part of the water used for geothermal purposes is returned to the reservoir, hydropower can be profitably generated by means of a turbine working in peak-load hours.

The methodology explained here to characterize the Barredo–Figaredo reservoir can be applied to other abandoned mines in the CCB, as well as to other mining areas in the world, where it can be also extrapolated. Mine water is a resource that until now was being wasted, but it can be successfully used, reviving the economy of the mining areas and allowing us to realize a sustainable cessation of the mining activity.

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References

1 G. R. Watzlaf and T. E. Ackman, *Mine Water Environ.*, 2006, **25**(1), 1–14.
2 K. Kranz and J. Dillenardt, *Mine Water Environ.*, 2010, **29**, 68–76.
3 A. Renz, W. Rühaak and P. Schätzl, *Mine Water Environ.*, 2009, **28**, 2–14.
4 J. Raymond and R. Therrien, *Geothermics*, 2008, **37**, 189–210.
5 J. W. Lund, D. H. Freeston and T. L. Boyd, *Geothermics*, 2005, **34**, 691–727.
6 E. Demollin, Z. Malolepszy and D. Bowers, in *Proceedings of the International Conference "Passive and Low Energy Cooling for the Built Environment"*, Greece, 2005.
7 T. Cairney, *J. Hydrol.*, 1973, **19**(3), 251–258.
8 S. Jardón, PhD thesis, University of Oviedo, 2010.
9 F. Lotze, *Geotekton. Forsch.*, 1945, **6**, 78–92.
10 J. Aller and J. Gallastegui, *J. Struct. Geol.*, 1995, **17**, 961–969.
11 N. Piedad-Sánchez, A. Izart, L. Martínez, I. Suárez-Ruiz, M. Elie and C. Menetrier, *Int. J. Coal Geol.*, 2004, **58**, 205–229.
12 J. R. Colmenero, I. Suárez-Ruiz, J. Fernández-Suárez, P. Barba and T. Llorens, *Int. J. Coal Geol.*, 2008, **76**, 187–204.
13 C. Alonso and C. Brime, *Clays Clay Miner.*, 1990, **38**(3), 265–276.
14 P. Fandos, F. Rodríguez, A. M. Gutiérrez and J. J. Álvarez, *El Yacimiento de Hunosa en la Cuenca Carbonífera Central*, Servicios de Geología del Caudal y del Nalón, HUNOSA report, 2004.
15 P. Cienfuegos and J. Loredo, *Int. J. Coal Geol.*, 2010, **83**(4), 366–376.
16 F. Arquer, M. Meléndez, C. Nuño and M. L. Rodríguez, in *Proceedings of Reunión Científico-Técnica "Gestión del agua en los procesos de cierre de minas"*, University of Oviedo, 2006.
17 J. González and A. Rebollar, *Interrelaciones de la minería y las aguas subterráneas en el Carbonífero de la Cuenca del Nalón (Sector Pola de Laviana-Olloniego)*, Spanish Geological Survey report, 1986.
18 A. Ordóñez, J. Loredo and F. Pendás, in *Proceedings of the Congress "Jornadas Hispano-Lusas sobre la aguas subterráneas en el Noroeste de la Península Ibérica"*, 2000, pp. 455–466.
19 P. A. García-Fuente, PhD thesis, University of Oviedo, 1996.
20 M. P. Henton, in *Quality of Groundwater (Proceedings of an International Symposium)*, Noordwijkerhout, The Netherlands, 1981, pp. 111–116.
21 C. J. Gandy and P. L. Younger, *Mine Water Environ.*, 2007, **26**, 70–78.
22 P. L. Younger, S. A. Banwart and R. S. Hedin, *Mine Water. Hydrology, Pollution, Remediation*, Kluwer Ac. Publ., UK, 2002.
23 A. Ordóñez, C. Andrés, S. Jardón, R. Álvarez, F. Pendás and J. Loredo, *Aprovechamiento de las aguas subterráneas como recurso hídrico y energético*, Final report, Fundación MAPFRE, Convocatoria 2008 de Ayudas a la Investigación, 2009.
24 K. L. Johnson and P. Younger, *Geological Society*, Special Publications, London, 2002, vol. 198, pp. 347–363.
25 C. A. Nuttal and P. L. Younger, *J. Contam. Hydrol.*, 2004, **69**, 101–114.
26 S. P. Burke and P. L. Younger, *Q. J. Eng. Geol. Hydrogeol.*, 2000, **33**, 149–160.
27 L. Kortas and P. L. Younger, *Mine Water Environ.*, 2007, **26**, 60–69.
28 R. Adams and P. Younger, *Ground Water*, 2001, **39**, 249–261.
29 *Real Decreto 140/2003, por el que se establecen los criterios sanitarios de la calidad del agua de consumo humano*, BOE 45(Sec. 1), pp. 7228–7245.
30 Instituto Nacional de Estadística, *Demografía y Población*, http://www.ine.es, accessed January 2008.
31 K. Ochsner, *Geothermal Heat Pumps. A Guide to Planning and Installing*, Earthscan, London, 2008.
32 Instituto para la Diversificación y Ahorro de la Energía, *Ahorro y Eficiencia Energética en Climatización*, Guía Técnica, 2007, http://www.idae.es/index.php/mod.documentos/mem.descarga?file=/documentos_10540_Contabilizacion_consumos_GT6_07_f9aaf178.pdf, accessed April 2011.
33 Instituto para la Diversificación y Ahorro de la Energía, *Minicentrales hidroeléctricas*, 2006, http://www.idae.es/doc/Minicentrales%20hidroelectricas_80594.pdf, accessed May 2006.