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Research article

Prediction of the flooding of a mining reservoir in NW Spain

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ABSTRACT

Abandoned and flooded mines constitute underground reservoirs which must be managed. When pumping is stopped in a closed mine, the process of flooding should be anticipated in order to avoid environmentally undesirable or unexpected mine water discharges at the surface, particularly in populated areas. The Candín-Fondón mining reservoir in Asturias (NW Spain) has an estimated void volume of 8 million m^3 and some urban areas are susceptible to be flooded if the water is freely released from the lowest mine adit/pithead. A conceptual model of this reservoir was undertaken and the flooding process was numerically modelled in order to estimate the time that the flooding would take. Additionally, the maximum safe height for the filling of the reservoir is discussed.

1. Introduction

It is reported that coal is one of the major global economic contributor (Wolde-Rufael, 2009). The impact of coal mining on the environment, particularly on land use and surface and groundwater, is a global concern (Younger et al., 2002; Bell et al., 2006). Contaminative mine drainage waters constitute a major hydrogeological and geochemical problem, particularly when they are acidic, heavy-metal-containing, sulphate waters derived from pyrite oxidation and are discharged at the surface (Banks et al., 1997). Mining activities, along with the population explosion and the extensive exploitation of the natural resources in a region can contribute significantly to the impact on groundwater (Karan and Samadder, 2016). However, mine waters are not merely to be perceived as a problem, they can be regarded as energy, industrial or drinking water sources.

For more than two centuries, up to 70% of all Spanish production of coal came from the Asturian Central Coal Basin (CCB). From late 1980s, mining has resulted in the closure of most coal mines (Moreno and López, 2008; Jardón et al., 2013). Historically in the CCB, a first phase of *mountain mining* was undertaken from valley level to the highest outcrops of the coal seams. Exploitation would then continue through vertical shafts to access lower heights, opening galleries on rock and exploiting coal up to depths of 700 m below the valley. Since mining left a fractured rock mass, the infiltration of rainwater was facilitated and an intense pumping drainage had to be maintained when the mine was active (Ordóñez et al., 2012). A correlation between precipitation and water percolating to the mine workings to be subsequently pumped out, has been found in several cases in the CCB (Arquer et al., 2006; Ordóñez et al., 2012). These studies also proved that there is a total independence between the drainage and the depth of the mine workings, as the latter does not affect significantly the recharge area; this shows that there are no relevant inputs from potential permeable levels intercepted by such works and the average flow pumped from the mine can be assimilated to the recharge provided by rain. However, the *period of delay* (time spanning from the infiltration of rainwater on the surface until it is pumped out again from the mine workings) varies depending on the mining reservoir.

This pumping is usually interrupted when the mine is closed, proceeding to the gradual flooding of the mine voids or the so-called *groundwater rebound* (Gandy and Younger, 2007). During this flooding, water level raises through each channel, the faster the larger the hydraulic conductivity, moving fast through free mine voids and leading to a progressive saturation, until hydrodynamic equilibrium is reached (Younger et al., 2002; Arquer et al., 2006; Delgado et al., 2008). The rebound depends on infiltration flow (and therefore on the season) and on void volume, so it will slow down when reaching the height of the mine levels, where a higher void volume concentrates (galleries) and rise faster in between them (Ordóñez et al., 2012). In the area affected by mining, fissures constitute preferential flow paths for recharge. Thus, the successive

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positions of the piezometric level during the groundwater rebound are approximations, since leaks between the recharge level and the water level are common in a fissured medium. Moreover, zones with different hydraulic conductivity and transmissivity overlap so that the flow is very complex (González and Rebollar, 1986). The reservoir is not a homogeneous and isotropic aquifer. The water will move quickly through the open holes, but the collapse of the networks limits connections and hinders the flow through certain directions. This has been proven in other flooded reservoirs, where water level rise in connected shafts in parallel form but spaced some m in height, due to low transmissivity (Ordóñez et al., 2012; Dep. Explotación y Prospección de Minas, 2012).

If pumping is not resumed, eventually a water upwelling (spring) will occur at the surface through the lowest mine adit or through any permeable lithology connected with the flooded mining system. Frequently, this uncontrolled mine water discharge is not desired, so pumping is re-established and graded so the discharge equals the recharge in order to keep a permanent flood level in this created *mining reservoir*. This underground reservoir can be regulated and used for water supply, strengthening of flow of nearby rivers, and particularly for geothermal applications (the usually high temperature and volume allows for district heating use, etc.), among others (Hall et al., 2011; Jardón et al., 2013; Peralta et al., 2015).

The storage capacity of a mining reservoir has to be estimated in order to predict its flooding and to define future uses. For this purpose, the mining voids have to be assessed, considering the local mining history and the interconnections with adjacent mine workings, as very often a mining shaft does not constitute an isolated system. Also, an estimation of the recharge that the system is receiving is required (Ordóñez et al., 2012). This study aims to characterize the mining reservoir Candín-Fondón, consisting of the voids likely to be saturated when pumping is interrupted in these two connected coal mines. The geological framework and the hydrogeological behaviour of the materials, once they have been affected by mining activity, are defined. The recharge by infiltration of this underground reservoir, as well as the implications of flooding it, are estimated in this paper.

2. Area of study

The studied area is located in the Nalón River valley, in the municipality of Langreo (CCB, Asturias, NW Spain). Nalón River crosses the study area in SE-NW, and the towns of Sama and La Felguera settle on the left and right river banks, respectively (Fig. 1). In particular, the urban district of La Felguera, partly included in the study area, is the most populous one in Langreo, with 19,550 inhabitants (SADEI, 2015). Coal mining started in this area in the 18th century and together with the steel industry, led to a major industrial development and a large increase in population during the 19th and 20th centuries, which reduced gradually from its peak in the 1960s. Nowadays, almost all the mines in the studied area are inactive.

There were a number of mountain mines (La Nalona, La Moral, Respinedo and Rufina), but more significantly, two deep mines: Fondón and Candín. The coal extraction started in 1840 at La Nalona, whose main mine entrance is still preserved, at an altitude of 216 m a.s.l. Some years later, the Fondón shaft was the second of Asturias to be deepened, reaching eventually up to 667 m of depth, from 218 m a.s.l. at the surface; this mine was active until 1995 and now it houses the historical archive of the mining company HUNOSA and the mining rescue brigade of the company. Candín includes 2 shafts: Santa Eulalia or Candín I and Lláscaras or Candín II, whose entrances are at 235 and 224 m.a.s.l, being 694 and 717 m deep, respectively. Candín I (situated on the outskirts of La Felguera) is now preserved as part of an industrial museum; it was used to extract the coal from Candín II (located by the river Candín) and to facilitate the ventilation until the extractive activity ceased. Candín I and II are clearly connected through galleries at −149, -258 and −455 m a.s.l. and Candín II is also connected to Fondón at −175 and −258 m a.s.l. (HUNOSA, 2011). Potential connections with other close mines are discarded, so the set of voids associated with Fondón and Candín mine workings constitutes an isolated mining reservoir.

The CCB is located in the south-central part of the so-called Cantabrian Zone (Lotze, 1945), the foreland of the NW Iberia variscan chain. It is constituted by a 6000 m thick terrigenous synorogenic Carboniferous succession; these series have been traditionally divided into Productive (Upper Westphalian lutites, sandstones, conglomerates and coal beds) and Unproductive (Lower Westphalian lutites, limestones and sandstones) Groups (Aller and Gallastegui, 1995; Piedad-Sánchez et al., 2004). The assembly of coal beds and enclosing rocks in these Groups is usually subdivided into associations (about 300 m thick) locally known as "*mining packs*". The mines studied in this work exploited the packs: Generalas, San Antonio, María Luisa, Sotón, Sorriego (Productive Group) and Caleras (Unproductive Group). The carboniferous sequences are strongly deformed and fractured in the area. Cretaceous cover and Quaternary deposits have very moderate sizes and low thickness.

From the hydrogeological point of view, the CCB and the studied area in particular, are mostly formed by Carboniferous materials of low permeability which do not give rise to major aquifer systems (Castillejo et al., 2010). The virgin massif behaves as being practically impermeable and only some sandstones (litharenites) can act as small aquifers, confined by the abundant mudstones and shales. Because of this, the preferred routes of circulation of groundwater are mining voids, open fractures and decompression areas associated with them, so the hydraulic behaviour is more associated to fracturing than to lithology. Therefore, mine workings acquire an important role in the management of water resources in the area, creating artificial pseudo-karstic aquifers, characterized by their complexity and unpredictability (Ordóñez et al., 2012; Jardón et al., 2013). Water stored in the undisturbed massif is negligible compared to that stored in the voids caused by mining (Jardón, 2010). Also, the hydrogeological parameters of the scarce materials of low permeability (sandstones) affected by mining increase significantly from their initial values (porosity, permeability, storage coefficient and transmissivity increase up to 1, 3, 3 and 2 orders of magnitude, respectively) (García-Fuente, 1996; Andrés et al., 2015).

The materials existing in the studied area can be classified according to their permeability (HUNOSA, 2011; Ordóñez et al., 2012; Loredo et al., 2013): i) Carboniferous shales or siltstones with very low permeability ($<10^{-7}$ m s^{-1} in natural conditions and around 10^{-6} m s^{-1} in exploited areas; Fandos et al., 2004; Arquer et al., 2006); ii) Carboniferous siliceous sandstones and conglomerates with low permeability due to fissuring (10^{-6} m s^{-1}) and very low original values (Arquer et al., 2006); iii) Carboniferous thin limestone and dolostone levels sandwiched between series of shale and siltstone, with variable (medium to low) permeability due to fissuring and karstification; iv) Cretaceous clays, sands, sandstones (with low permeability related to intergranular porosity) and marl and limestone levels (with variable permeability by fissuring/karstification), with little relevance in the study area; and v) Quaternary alluvial deposits of intergranular porosity and variable permeability (10^{-5} - 10^{-6} m s^{-1} for clayey sands and ca. 10^{-4} m s^{-1} for gravel) widely represented in the studied area, with low thickness and which can be hydraulically connected with the mining voids. The materials intersected by the mines studied in this