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An estimation of water resources in flooded, connected underground mines

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ABSTRACT

When studying discharges in closed mines with relevant environmental impact, the first step is to undertake a complete hydrogeological study of the mining system. In this study, some inactive and flooded coal mines in NW Spain were characterized. The water resources (recharge) of each mine were evaluated considering the infiltration of effective rainfall over mined areas, the groundwater contribution, and the losses from surface watercourses. The studied mine drainage corresponds to a mining reservoir of 5 connected mines. The resources of this reservoir were estimated in 54 L s^{-1} for an average year, coming mainly from rainfall as well as losses from irrigation systems during the summer. The volume of voids of the reservoir was estimated by using different approaches: the calculation of the void left by the mining activity and the volume of infiltrated water during the mine flooding. In this particular case, the volume of voids below the discharge level (water reserves) are estimated to be around 1 Mm^3, which makes them useful for storage and regulation of water, as well as for the production of energy. The acid mine water discharge is of poor quality, and affects the receiving watercourses. Strategies, such as the reduction of the mine's water flow, avoiding water level fluctuations, and passive treatment systems could be applied to diminish these negative effects. The methodology explained here is believed to be suitable for application in closed mines where there is not much information available.

1. Introduction

As one on the main global economic contributors, coal has been intensively exploited in the north-western Spain (Wolde-Rufael, 2009). Coal mining is reported to have a serious environmental impact, particularly on water systems (Bell et al., 2006; Younger et al., 2002). The intensive mining activity in the coal basins of Spain, which lasted several decades, has altered the natural groundwater flow. When the mines are active, pumping is absolutely necessary in order to keep dry the area for the mine workings. If the pumping is stopped when the mines close, the water level will raise, thus leading to the so-called 'groundwater rebound' (Gandy and Younger, 2007). The mine voids, together with the rock pores and the fractures caused by the mining activities will be flooded gradually until the hydrodynamic equilibrium is reached; this situation will continue until the pumping is resumed or water is discharged at the surface (Younger et al., 2002). The water rebound depends on the rate of discharge, the hydraulic conductivity of the system and surrounding rocks (Andrés et al., 2017), and the volume of voids to fill. Therefore, it will slow down when it has reached the height of the mine levels, where a higher void volume concentrates (galleries), and it will rise faster in the space between them (Ordóñez et al., 2012). During the mine flooding, the water level raises through each mine channel. The faster this happens, the larger the hydraulic conductivity will be, moving quickly through free mine voids and progressively leading to a progressive saturation (Younger et al., 2002). In the area affected by mining, fissures constitute preferential flow paths for recharge. Even when the sediments of the coal basin have low permeability, flooded mines form underground or 'mining reservoirs', assimilable to created karst-type aquifers (Ordóñez et al., 2012) with triple-porosity (primary porosity of the rock, anthropogenic voids generated by mining, and secondary porosity caused by mining-induced fracturing). The water in these mines is a potential significant resource. Mining reservoirs can be regulated and used as water supply, for geothermal and hydraulic energy applications, to strengthen the flow of nearby rivers, etc. (Jardón et al., 2013; Peralta et al., 2015; Watzlaf and Ackman, 2006). In order to use mine water as a resource, it is necessary to characterize the reservoir containing it as best as possible. This is not as easy as it might seem, especially in old, abandoned mines and taking into account that there is not much published information about it. There are some recent works on the use of mining voids in abandoned coal mines and the water management in flooded mines. That is the case of geothermal use of mine water (an excellent summary is presented in (Preene and Younger, 2014); see also (Banks et al., 2017)) or the underground pumped storage hydropower (UPSH, see (Boudeux et al., 2017) and references therein, and (Menéndez et al., 2017), among others). Nevertheless, the approach proposed in this work, that

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is, the methodology to characterize mining reservoirs and their water resources, has not received much attention yet (Dinger et al., 2006; Hobba, 1987; Ordóñez et al., 2012; Wolkersdorfer, 2008).

The pumping process is usually not performed in abandoned, flooded mines, so they release the previously recharged water through the lowest mine adit or through a permeable lithology connected to the mining network (Andrés et al., 2017). This uncontrolled mine water discharge is often unwanted, since it might affect nearby populated areas, compromise the receiving watercourse water quality or affect the surrounding environment. Contaminant mine waters constitute a major geochemical problem, especially when they are acidic, sulphate, heavy-metal-containing waters derived from sulphide oxidation and when they are discharged at the surface (Banks et al., 1997). Mining reservoirs should be characterized both hydrogeologically and geochemically in order to use them, as well as to avoid environmental problems. The mine waters drained from the mining reservoirs have variable flow and quality, depending on the size and the characteristics of the mining exploitation they come from, and the geological materials involved.

The main objective of this work is to evaluate the resources of the reservoir constituted by the flooded coal mines developed near to Torre del Bierzo (León, north-western Spain), taking into account the mine connections, the groundwater rebound and the relationship between recharge and discharge of each system. Additionally, the mine water discharge is characterized according to its origin, quantity, upwelling and duration in time, as well as its effect on receiving watercourses.

2. Study area

The coal mining activity in the Carboniferous basin of El Bierzo (León, Spain) has been intensely developed since the middle of the 19th century, but most of the mines are now abandoned. El Bierzo is consists of 38 municipalities, one of which is Torre del Bierzo (Fig. 1).

From a geological point of view, the Torre del Bierzo-Bembibre unit is located in the South-Central part of the El Bierzo coal basin, within the West Asturian-Leonese Zone (Lotze, 1945) (Fig. 2). Stratigraphically, there are three different sequences. The oldest (pre-orogenic) sequence is constituted by Lower Palaeozoic (Cambrian and Ordovician) rocks such as limestones, slates and quartzites. The second sequence, which overlays the previous one, was deposited during the Upper Carboniferous (Stephanian B–C); it contains up to 2000 m of conglomerates, sandstones, coal seams and siltstones. This sequence has been partially divided, following the distribution of economic coal seams, into non-formal units about 50–150 m thick known as “mining packs”. They are called (from bottom to top): Ancho (4 coal seams), Estrecho (3 coal seams), Chuchú (6 coal seams, called 1st to 6th), Navaleo (3 coal seams), Torre (3 coal seams), Delias (2 coal seams) and Sarita (2 coal seams). The mines considered in this work exploited the Chuchú mining pack. Detailed information about formal stratigraphy and other features can be found in specific publications of the Spanish Geological Survey (IGME), such as IGME (IGME, 1980). The Carboniferous sequence is partially covered by a maximum of 180 m of red/orange non-consolidated Tertiary sediments with gravel, sand and clay textures (not deformed, but partially eroded; further details in (Heredia et al., 2015)). Finally, the Quaternary materials in this area are mainly alluvial deposits, constituted by gravels in a sandy-clayly matrix, disposed sub-horizontally with metric thicknesses. Anthropogenic surficial deposits include mining spoil heaps (Ribeiro et al., 2016b; Ribeiro et al., 2016a).

The original permeability of the Lower Palaeozoic materials is very low (impermeable), although it can increase locally in areas with fractures and joints, where some groundwater flow might penetrate. Only the Tertiary detrital aquifer, linked occasionally to Quaternary alluvial deposits, could have a relative hydrogeological significance in the area. Its permeability is variable due to intergranular porosity, and it depends on its position in the basin. However, it is generally low, since the permeable materials are arranged in discontinuous lenses within an impermeable matrix. When present, the Quaternary materials allow the water to pass through them to the underlying Tertiary, and this combined aquifer behaves as unconfined and it is geometrically limited by the Palaeozoic materials (IGME, 1993). The aquifer recharge comes from rainfall (and to a lesser extent from agricultural irrigation) but not from the Palaeozoic materials in the studied area. The infiltration is vertical at the surface and the water flow continues sub-horizontally through the Tertiary/Quaternary materials from the topographical divide to the discharge zones, which are mainly watercourses and very scarce wells. These wells are generally drilled into the Quaternary, so they are shallow (5–8 m deep) with very low flow rates ($< 0.2\ L\,s^{-1}$). Low flow rates (ca. $1\ L\,s^{-1}$) are also found in rare deep wells (> 100 m) and the springs, which are used for water supply (IGME, 1993).

Mean values of 10 °C and 900 mm $year^{-1}$ of temperature and precipitation, respectively, are observed in the studied area in the last 30 years. An average value of Turc evapotranspiration is calculated to be 507 mm $year^{-1}$, so the effective rainfall is 393 mm per year. These values correspond to an average year; the effective rainfall is estimated in 590 mm $year^{-1}$ in a wet year, and 216 mm $year^{-1}$ in a dry year.

As to hydrology, the main watercourse in the area is the Tremor River, followed by its tributaries, the streams called Rial and La Silva (Fig. 1), whose waters are demanded for urban, industrial and agricultural use. The Tremor River, whose flow is measured daily, has an average flow –upstream of the Rial Stream- of $900\ L\,s^{-1}$. The Rial Stream is only gauged occasionally; a mean flow of $800\ L\,s^{-1}$ is estimated for this stream in an average year, considering the available data, the contribution to a dam downstream of these rivers and the effective rainfall on its watershed surface (58 km^2). The drainages from the mine adits and the spoil heaps leachates are major sources of river contamination. Acid mine drainage (AMD) is generated by the oxidation of the sulphides (mainly pyrite) associated to the coal. The mine adits release AMD and it can also be generated from infiltration of rainwater in spoil heaps where sulphidic materials, often with high surface of reaction, are stored. These acid drainages have a high capacity for dissolution and affect the quality of the receiving streams, increasing their acidity, sulphate and metal contents, and generating Fe and Al oxy-hydroxides precipitates (Banks et al., 1997; Younger et al., 2002). There are cases of groundwater with low pH (ca. 5) and high contents of Fe and Mn and nitrate, due to overuse of fertilizers, although they are not as affected as surface water (IGME, 2008). Waters from Upper Palaeozoic (Stephanian) and Tertiary materials generally show $Ca\text{-}SO_4$ (and $Ca\text{-}HCO_3$) facies. In general, these are short-haul waters of fast transit, with reduced mineralization and electrical conductivity (IGME, 2008). The low maturity of these waters and their variable composition indicate that they come from a vulnerable system, with low residence time and heterogeneous structure; therefore, they should be protected from pollution, especially that derived from spoil heaps leachates or direct discharges.

Fig. 1 shows the mines in the area of study, which are now closed (they were intermittently active from the middle of the 19th century to 2014, adding up a total of 30 year of activity). Although it is not always explicit in the work plans, these mines are supposedly interconnected, which was believed to facilitate the drainage through the lowest mine workings. The mining reservoir constituted by the flooded mine network is not a homogeneous and isotropic aquifer, but areas with different hydraulic conductivity and transmissivity overlap, so that the flow is very complex. The water will move quickly through the open holes, but collapses in the mines' networks limit connections and hinder the flow in certain directions. This fact has already been proven in other flooded coal mining reservoirs, where the rise of water level curves in connected shafts are parallel but spaced by some meters in height, due to low transmissivity (Ordóñez et al., 2012). Previous works have focused on the environmental effects on the La Silva Stream and the Tremor River. However, none has focused on the effect on the Rial

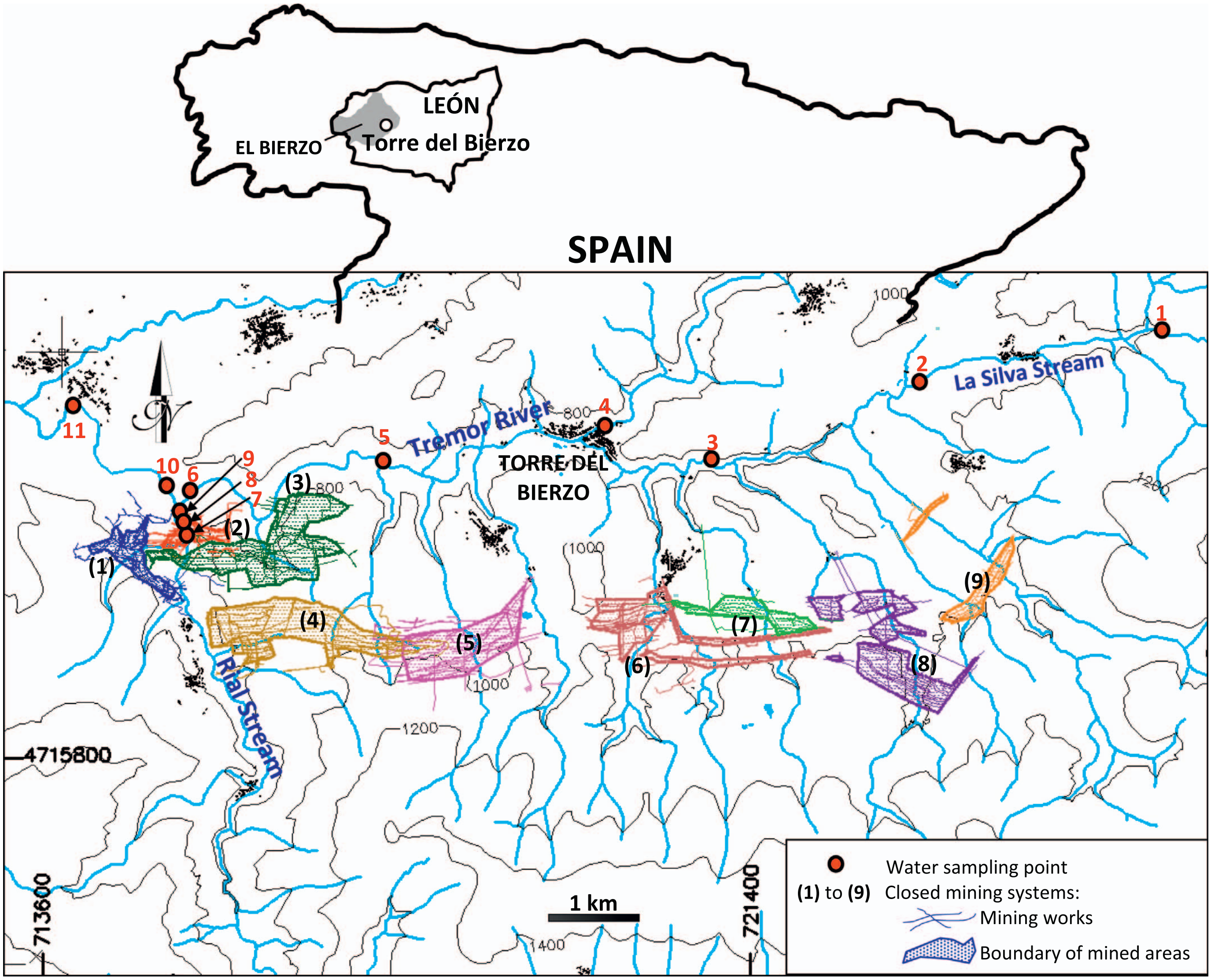

Fig. 1. Location of the study area (UTM Zone 29). Closed mines: (1) Navaleo; (2) Antracitas San Antonio S.L.; (3) Carbones San Antonio S.L.; (4) Unión Minera del Norte S.A. (Minex); (5) Virgilio Riesco S.A.; (6) Campomanes Hermanos, S.A.; (7) Antracitas de Caunedo-Salgueiro; (8) Antracitas de Brañuelas; (9) Andrés Calvo Martínez. Water sampling points: 1, 2 and 3 in the La Silva Stream; 4, 5 and 6 in the Tremor River, upstream of the Rial Stream; 7 and 9 in the Rial Stream, upstream and downstream of Navaleo discharge (8), respectively; 10 and 11 in the Tremor River, downstream of the Rial Stream.

Stream -and the watercourses downstream of it- caused by the discharge from the Navaleo mine.

3. Materials and methods

3.1. Groundwater rebound

According to information provided by the technical staff of the mining company, the mines located at a greater height, such as Minex and Virgilio Riesco, S.A. (identified as No. (4) and (5) in Fig. 1, respectively) practically did not need to be pumped in the past. This is due to their communication with the Carbones de San Antonio S.L. (mine (3) in Fig. 1), which is located at a lower level, and where pumping were still taking place. This centralized pumping continued until 2003 when it was interrupted, which caused the water level to reach almost 640 m a.s.l. In June 2004, the whole interconnected mining system was drained by pumping from the mine located at the lowest level (Navaleo; (1) in Fig. 1). The pumped flow was approximately 150–200 $m^3 h^{-1}$ (42–56 $L s^{-1}$) in the rainy season and about 100 $m^3 h^{-1}$ (28 $L s^{-1}$) during the summer, to keep a stable water level at the aforementioned height. In January 2009, the pumping at Navaleo was stopped, the groundwater rebound was resumed, and all the mine workings were flooded between 640 and 675 m a.s.l. At that height (675 m a.s.l.) there was an upwelling of mine drainage at the Navaleo mine, seven months later (according to the technical staff of the mining company). The evolution of the water level during this period is shown in Fig. 3. Not including the period of time when pumping activities were happening, it took a total of 17.3 months (249 + 269 days) for the water level to rise between the levels 560 and 675 m a.s.l. The rise of the water level during the rebound depends on the volume of infiltration, and therefore on the precipitation. It is higher between the mine plants and it slows down when reaching the sections with a greater volume of voids. Although the water level was not frequently monitored below the 660 m a.s.l., a reduced slope in the curve is shown above 620 m a.s.l. despite the registered rainfall, probably due to the conjunction of mine workings (voids) at these heights.

The fact that there is only centralized pumping in one single mine and discharge only happens at a single point (at the lowest level –Navaleo adit-) suggests that all the mines, from (1) to (5), are interconnected. Nevertheless, it should be noted that in some old mountain

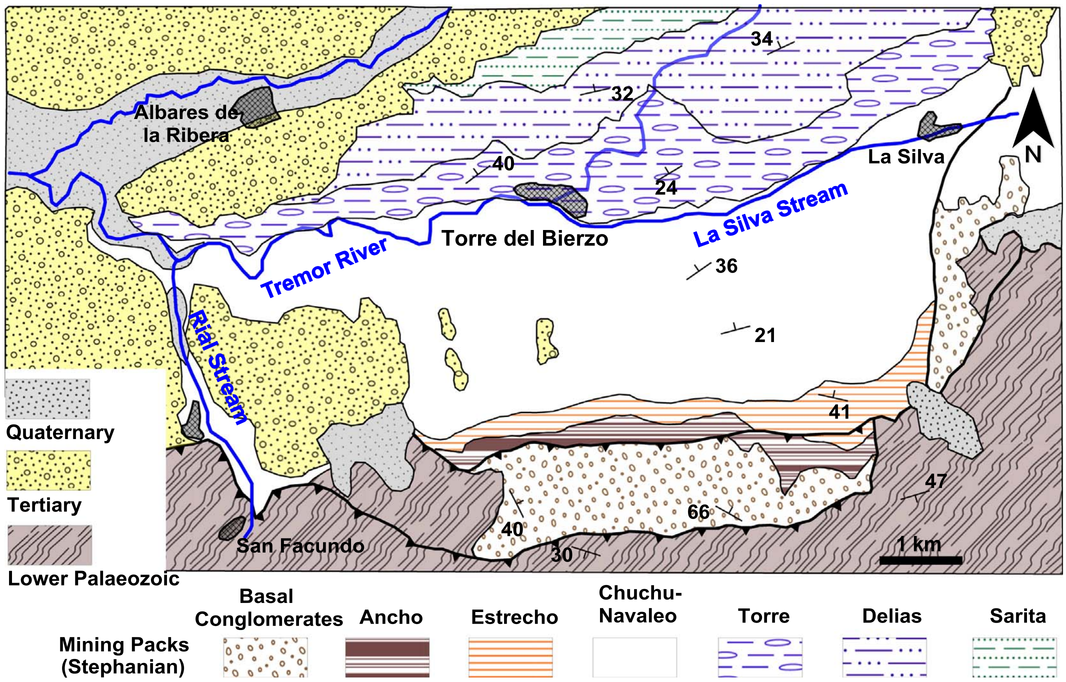

Fig. 2. Geological map of the study area.

mines, there might be an occasional low-flow drainage during the rainy season, when the precipitation intensity exceeds the ability for infiltration in the underground workings. In Fig. 1 the 'mined area' of each mine is delimited considering the area with higher density of mine workings; these areas constitute the sections where the infiltration of rainwater will recharge the mining reservoirs. These sub-systems are supposed to act as connected 'ponds' that receive and distribute the water thanks to gravity. This recharge comes from rainwater which infiltrates from the surface, and from irrigation losses; however, lateral contribution of groundwater is not to be expected, due to the very low permeability of the involved geological formations.

3.2. Discharge rate

The discharge rate at the Navaleo adit was measured approximately fortnightly during a hydrological year. Flow measurements were done in order to determine the 'period of delay' (the lag time between a rainfall episode and the flow rate increase, i.e. the amount of time it takes for water to infiltrate the mine workings). It is possible to deduce the volume of water that the reservoir can release if there is no precipitation, by assimilating it to a spring that drains an unconfined aquifer. Sometime after the rain ceases, the overflow rate will decrease, as so does the volume of water stored in the reservoir does. This decrease (physical emptying) obeys a law of the type:

$$Q = \frac{Q_0}{(1 + \alpha t)^2} \tag{1}$$

where Q is the flow at time t, Q_0 is the initial flow at the start of the depletion, α is a constant known as the depletion coefficient [T^{-1}], which is characteristic of each aquifer and determined experimentally (Fetter, 2013). The volume of water drained by the reservoir between two instants is:

$$V = \int_{t_1}^{t_2} Q \cdot dt = \int_{t_1}^{t_2} \frac{Q_0}{(1 + \alpha t)^2} \cdot dt = \frac{Q_{t_1}(1 + \alpha t_1) - Q_{t_2}(1 + \alpha t_2)}{\alpha} \tag{2}$$

3.3. Resources of the mining reservoir

As it was previously described, Lower Palaeozoic materials can be considered as impermeable, and the permeability caused by fractures

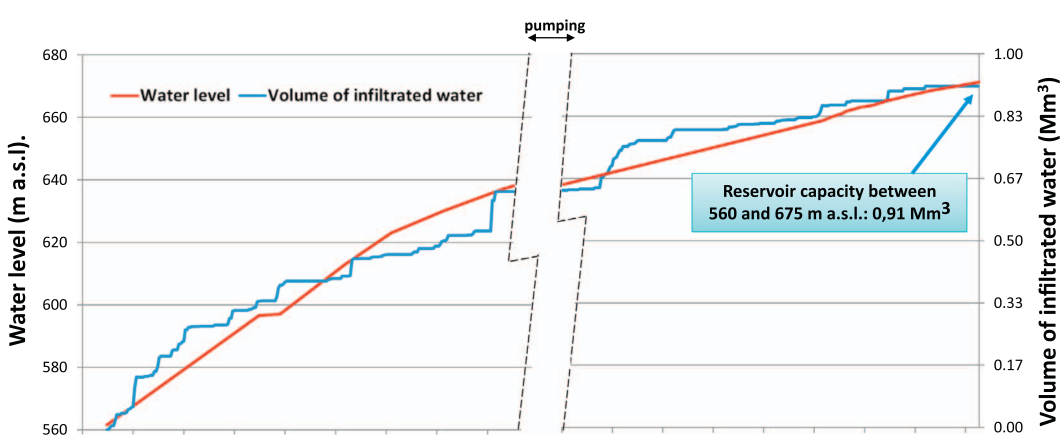

Fig. 3. Groundwater rebound and volume of infiltrated water during the flooding of the mines.

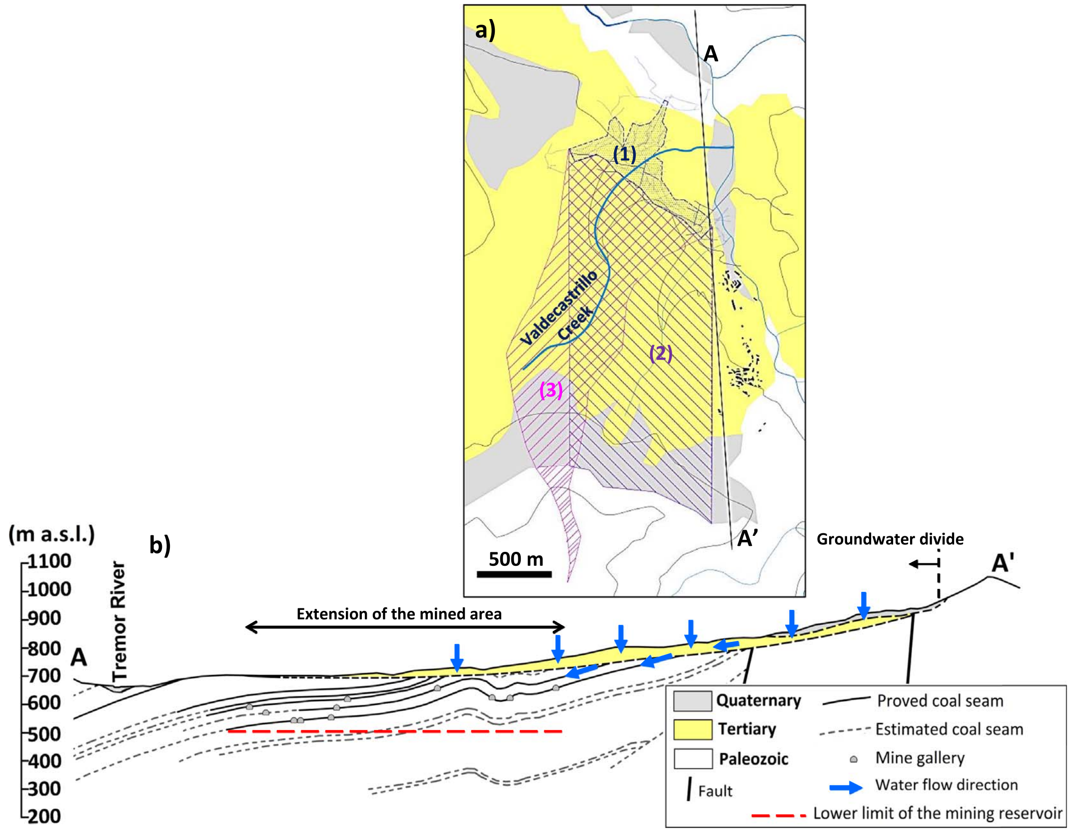

Fig. 4. a) Geological map showing the plant view of the Navaleo mining reservoir (mined area) (1) and its recharge areas (2) & (3); b) Geological cross section AA′, where the exploited seams and the potential water flow directions are indicated.

does not reach significant values either. Therefore, infiltration through these materials will not be considered. Tertiary materials are semi-permeable, and Quaternary materials constitute a detrital aquifer whose permeability varies according to its lithological composition and grain size; nevertheless in both cases their permeability is generally considered as low. 5% and 10–25% of the effective rainfall is thought to infiltrate through the Tertiary and the Quaternary, respectively (IGME, 1993). Taking this into account, the flow of water that each mine can receive has been estimated as follows (Fig. 4a shows the recharge areas defined for Navaleo mine):

i) Direct infiltration of effective rainfall in the fractured mined areas: underground mining can affect the surface, causing the ground to sag and crack (Unlu et al., 2013); it causes fracturing in the overlying materials, which increases its permeability and facilitates infiltration from the surface. An infiltration of 90% of the effective rainfall on the mined areas has been considered, which coincides with data from previous studies of nearby mines. This will be the biggest contribution of water to the reservoirs. The recharge area is indicated as (1) in Fig. 4a.

ii) Contribution of groundwater to the reservoir: The effective rainfall on the non-fractured Palaeozoic materials will generate runoff but not infiltration. However, the effective rainfall on the Tertiary will both infiltrate (5%), and generate runoff (95%). Likewise, the effective rainfall on the Quaternary will be distributed between 10 and 25% of infiltration and 75–90% of runoff. As the Quaternary rests on the Tertiary, the water which infiltrates the Quaternary will feed vertically the Tertiary, which will infiltrate only up to a 5%; the rest will circulate horizontally through the contact between both until it finally reaches the surface, where it becomes runoff. Therefore, the contact between the Quaternary-Tertiary and the Palaeozoic is considered as a groundwater divide. In the areas with Quaternary-Tertiary deposits, the effective rainfall is divided in 5% infiltration and 95% runoff. On the other hand, the water which infiltrated the Tertiary, which is disposed discordantly over the Palaeozoic, will circulate horizontally until it reaches the surface, since it is not able to infiltrate the Palaeozoic, except when mine workings allow infiltration. Given the dip of the Palaeozoic materials to the N, the infiltration area on the Tertiary will be a N−S band bounded by the groundwater divide (contact with the Palaeozoic to the S) and by the mined area to the N. The mine workings will intercept this volume of infiltration. This area is indicated as (2) in Fig. 4a. If there is no outcrop of Quaternary-Tertiary materials but only Palaeozoic, neither infiltration nor underground contribution is considered.

iii) Contribution of surface water to the reservoir: The part of the basin of the rivers which cross the mined areas and may contribute to the reservoir is considered (indicated as (3) in Fig. 4a). The flow of the river upstream of the mined area is calculated from the effective rainfall on this basin (subtracting, if necessary, the part of the infiltrated effective rainfall, as it was described above). Obviously not all the flow of these streams infiltrates in the workings. Previous studies carried out in coal mines in a close region, proved that the volume of infiltration into the mine workings from perennial rivers does not depend on their flow; on the contrary, it is an almost constant contribution, through the fractures that connect the mine with the river (Ordóñez et al., 2016; Ordóñez et al., 2012). It is because of this quasi-constant contribution that pumping activities continued in these mines during dry periods, when they were active. The rate of infiltration is variable, as it depends on the depth of the workings and the permeability of the overlying terrain. In the cited study, it was observed an infiltration of 0.02 $L\,s^{-1}$ per meter of river flowing over mined areas. Since the infiltrated flows in this case are too low to be determined in differential gauges, and given the analogies between both mining basins, the aforementioned value will be applied here. Nevertheless, this infiltration value was obtained in an area where intensive mountain and underground mining took place, so the induced fracturing could be slightly higher than in El Bierzo.

The excess of irrigation water in some parts of the studied area should also be taken into account. In particular, the Rial Stream has abstractions for the purpose of distributing water to numerous ditches that cross some mined areas. In these intensively mined areas, subsidence caused the water of some ditches to infiltrate the ground, preventing their use for irrigation and increasing the reservoir recharge. For that reason, the mining company installed a pipe that leads the water from the stream into the fields (allowing some flow to infiltrate again the mine workings). It is impossible to accurately find the extent to which surface water contributes to the reservoir, because the irrigation is discontinuous, the flows derived to the ditches are variable, and it is not easy to estimate the losses of the irrigation devices through the mined areas.

The resources of each of the mines were calculated using the methodology described above, based on geological maps and cross sections, such as Fig. 4. It should be noted that these calculations are only approximate estimates, calculated for average conditions. The error made in estimating the infiltration in the different materials, mined areas, and the involved flows (also subject to high variability) restricts the accuracy of the estimated resources.

3.4. Reserves of the mining reservoir

An approximate estimate of the volume of voids in the mining reservoir, equivalent to its reserves of water once it is flooded, was made using different methods.

i) In the absence of detailed work plans where the tonnage of the coal extracted in each mine could be consulted, the volume of the extracted coal was calculated geometrically. From the geological sections (such as Fig. 4b), where the mining galleries are shown, the length of the exploited coal seams (Chuchú mining pack) were estimated. This length was multiplied by the average thickness of each seam, which varies between 0.4 (1st) and 0.9 m (3rd; (IGME, 1980)); thus, the total exploited area in each of the geological sections was calculated. Considering the distance between the geological sections, the volume of exploited coal was estimated using the cross-sectional method (Gandhi and Sarkar, 2016). According to technical staff with experience in the studied mines, the residual void after filling is a 25–40% of the initial one; in this case, we used 30% of it, since this is a value is suggested by Younger et al. (Younger et al., 2002). Regarding the mining galleries, their total length in the reservoir was estimated and multiplied by their section. The original midsection of the galleries was generally 7 m^2, but according to the technical staff of the mine, the final section, after convergence, is estimated in 5 m^2.

ii) On the other hand, the production of coal of the 5 considered mines together during the period of time between 1974 and 1979 was fairly constant, with an average of 230,000 t $year^{-1}$ (IGME, 1980). Assuming a similar production for 30 years and an anthracite density of 1.7 t m^{-3}, it was possible to estimate the volume of the void left by the extracted coal.

Not all this volume of voids represents a useful volume of reservoir. The voids above the discharge level (Navaleo) will not be suitable to store water (although they can receive water and transmit it - slowly - to the lower workings). The flooded voids (reserves of the reservoir) have been calculated not taking into account the voids of the higher mines (Minex and Virgilio Riesco S.A.), as they are above the discharge level (675 m a.s.l.).

iii) The most accurate method of calculating the volume of the reservoir is to estimate the amount of water it required to be full during the flood period.

3.5. Geochemistry and characterization of water properties

In the proximity of the studied area, the construction of a highway crossing Palaeozoic pyrite-rich slates, which are now exposed to oxidation, lead to the generation of acid rock drainage (ARD) (Vadillo et al., 2009). This geological material was found to be in an advanced state of oxidation. Two samples were taken, pulverized and analyzed by X-Ray fluorescence (XRF) by means of a portable NITON analyser.

The drainage from Navaleo mine (point No. 8 in Fig. 1) and its receiving watercourses (the Rial Stream and the Tremor River) were monitored regularly since 2006, but more intensely in 2011 and 2012. A total of 24 samples were taken in the Navaleo drainage during this period. Watercourses receiving this discharge -Rial Stream (Points 7 & 9, upstream and downstream of 8, respectively) and Tremor River (Points 6 & 10, upstream and downstream of the mouth of the Rial Stream, respectively)- were also monitored, adding up to a total of 19 samples. Field parameters such as pH and electrical conductivity were measured in situ by means of a HANNA portable multiprobe. Sulphate and nitrate were determined by AAS, and metal concentrations were analyzed by ICP-MS, at the CARBOMINSA laboratory (León, Spain). Acidity (mg L^{-1} $CaCO_3$) was calculated according to Hedin et al. (Hedin et al., 1994). Water flows were measured using a digital flowmeter mod. PROBE. In addition, the sediments deposited in the pipe of the Navaleo mine discharge were sampled and analyzed by XRF.

4. Results and discussion

4.1. Discharge rate

The discharge rate at the Navaleo adit ranges between 140 and 150 $m^3\ h^{-1}$ (39–42 L s^{-1}) from December to May and it is about 90 $m^3\ h^{-1}$ (25 L s^{-1}) from June to November. These values coincide with the pumping rates maintained during the period of mining activity (Section 3), although they are slightly lower, possibly due to the fact that the period of gauging was abnormally dry. Punctual very high flows (up to 83 L s^{-1}) have been measured during the summer irrigation period; in the surroundings of the Navaleo mine, water is taken away from the river for irrigation, thus recharging artificially the mining system so that the discharge flow rate increases. Frequent measurements were done in a month to determine the 'period of delay', which was estimated in 8 days, which coincides with the estimate of the technical staff with professional experience in these mines (personal communication). An approximate coefficient of depletion $\alpha = 0.013\ day^{-1}$ was estimated [Eq. (1)]; this means that it would take 380 days in complete absence of rainfall for the discharge flow to be 1 L s^{-1}, and the maximum volume that could be released by the reservoir without recharging, until exhaustion, is about 2.5 $10^5\ m^3$ [Eq. (2)]. Given the uncertainty associated to the flow data (scarcity, dry period), the previous value is probably lower than the real one.

4.2. Resources of the mining reservoir

According to the previously exposed methodology, the resources of the Navaleo mine are indicated in Table 1. Total resources of this system (considered in isolation) for an average hydrological year are 8.5 L s^{-1}. If Navaleo is connected to other mines, it will receive water contributions from them, since Navaleo is located at the lowest level. This must be the case, as the average drainage flow from this mine is almost 5 times greater.

The resources of the rest of the mines have been calculated analogously. For the sake of brevity, the calculations are not detailed here, but the results (resources in an average year) are included in Table 2. The resources for dry and wet years, considering the corresponding effective rainfall, are also included. Taking into account the measured discharge rate (25–42 L s^{-1}), it can be deduced from Table 2 that the first 5 mines constitute a sole reservoir, so the drainage that comes out from the Navaleo adit is the sum of the resources of all of them. The resources of this combined mining reservoir, constituted by connected 'ponds', vary from 33 L s^{-1} in a dry year to 71 L s^{-1} in a wet year.

Table 1
Resources estimated for the Navaleo mine in an average year.

Component			Explanation
i) Direct infiltration of rainfall	Mined area (km^2)	0.2	(1) in Fig. 4a
	Resources (L s^{-1})	2.5	90% eff. rainfall
ii) Groundwater contribution	Area (km^2)	1.9	(2) in Fig. 4a
	Resources (L s^{-1})	1.2	5% eff. rainfall
iii) Surface water contribution	Valdecastrillo Creek basin (km^2)	1.3	(3) in Fig. 4a
	Average flow of the Creek upstream mined area (L s^{-1})	15.3	100% eff. rainfall on Palaeozoic + 95% eff. rainfall on Q-Tertiary
	Length of the Creek over mined area (m)	240	
	Resources (L s^{-1})	4.8	0.02 L s^{-1}/m
Total resources (L s^{-1})		8.5	i + ii + iii

Assuming that these 5 sub-systems are hydraulically connected, the drainage of the system will occur at the lowest adit (Navaleo). The resources of the mining reservoir in an average year were calculated to be about 54 L s^{-1}, which makes them slightly higher than the flow measured at the Navaleo drainage and the flow pumped when the mines were active (28–56 L s^{-1}). This can be due to: i) having measured the drainage flow in a dry year; ii) an slight overestimation of the resources might have been slightly overestimated, when considering the maximum contributions; iii) the fact that the two systems located at a higher height (Minex and Virgilio Riesco S.A.) are not so well connected with the other three, so the low transmissivity makes the water flow slow down; this is why in stormy weather, some water is drained from the Minex mine (overflow) directly to the Rial Stream. Moreover, it is ruled out that the remaining four mines located to the East of the five considered mines (Fig. 1) have a relevant influence on the discharge flow from Navaleo.

The resources of the reservoir depend directly on the effective rainfall, and there is also a quasi-constant contribution from the streams that flow over the mined areas. For an average year, the resources derived from the infiltration from the rivers are estimated at 19 L s^{-1}, while the remaining resources constitute about 99% of the effective rainfall which infiltrated the mined area (90% of effective rainfall plus the groundwater contribution). This can be simplified as follows:

$$\text{Reservoir resources (L s}^{-1}) = 99\%\text{effective rainfall over total mined area (L s}^{-1}) + 19\text{ (L s}^{-1}) \quad (3)$$

Before receiving the Navaleo drainage, the Rial Stream is used for field irrigation in one of the most mined areas. A complex gauging campaign allowed the estimation of the water loss from this stream and the irrigation ditches, together with the water that leaks from the pipe installed by the mining company. The total loss was calculated to be 41 L s^{-1}, whereas the mine drainage flow at that time was 45 L s^{-1}. Therefore, the joint water losses from the stream and the irrigation canals, by infiltration on intensely mined areas, practically maintain the discharge flow of the mining system in dry periods. The Rial Stream crosses 425 m of mined areas and there are about 1400 m of ditches, so the measured loss coincides with the value of 0.02 L s^{-1} per meter of river/canal flowing over mined areas that was applied here.

4.3. Reserves of the mining reservoir

i) A total volume of the exploited coal was estimated to be 4.23 10^6 m^3 using the cross-sectional method. Thus, the residual void left due to the extraction of coal is 30% of this value (1.27 10^6 m^3). A ratio of approximately 33 km of gallery/km^2 of mined area was calculated in this case. This results in a total of 92.1 km of gallery for the 5 mines constituting the reservoir, which coincides with the value of 90 km estimated by the technical staff (personal communication). Considering a 5 m^2 section, the void due to the mining galleries is estimated in 0.46 10^6 m^3. Finally, the total volume of voids corresponding to the 5 mines is estimated at 1.73 10^6 m^3. This figure is not considered to be very accurate because of the error in the estimation of the coal exploited using the cross-sectional method, the residual void volume, and the length of galleries from old mine workings plans.

ii) Taking into account the production of coal over 30 years and the density of the coal, the void left by the extracted coal can be estimated at 4.06 10^6 m^3. The residual void (30%) is in this case: 1.22 10^6 m^3, which does not differ much from the previously calculated. If this volume is added to that of the galleries, there is a final volume of voids of 1.68 10^6 m^3. This is a rough estimation, since it was assumed that there was constant production during an average period of activity. The volume of voids above the discharge level (675 m a.s.l.) has been estimated using the first method in 1.04 10^6 m^3. This volume includes the voids of the mines Navaleo, Antracitas de San Antonio S.L. and Carbones de San Antonio S.L. The other two mines connected with these feed the reservoir, but they do not store water.

iii) As it was stated, the groundwater rebound (from 560 to 675 m a.s.l.) lasted 17.3 months, which were divided into two periods: from October 2003 to June 2004, and from January 2008 to September 2009 (Fig. 3). Considering the precipitation registered during these two periods (taking into account a period of delay of 8 days) and the evapotranspiration, the effective rainfall was calculated. The eq. 3 can be applied considering the total mined area of the reservoir (2.79 km^2, Table 2), so a total volume of 0.91 10^6 m^3 of water infiltrated the reservoir during the flood period. This value is lower than the one previously calculated, because it only considers the water infiltrated between 560 and 675 m a.s.l. (monitored period) and some workings (voids) existing below 560 m a.s.l. Fig. 3 shows the volume of infiltrated

Table 2
Resources estimated for the mine sub-systems. The references of the mines are those indicated in Fig. 1.

Mine	Mined area (km^2)	Resources in an average year (L s^{-1})				Resources in a wet year (L s^{-1})	Resources in a dry year (L s^{-1})
		Direct infiltration effective rainfall	Groundwater contribution	Surface water contribution	Total resources		
1	0.22	2.5	1.2	4.8	8.5	10.3	4.0
3	0.12	1.3	0.0	5.2	6.6	7.2	6.0
2	0.92	10.3	0.8	3.3	14.4	19.9	9.4
4	0.89	10.0	1.3	2.0	13.2	18.9	6.2
5	0.64	7.2	0.2	4.1	11.5	15.2	7.6
Total resources of mining reservoir (L s^{-1}):	2.79				54.1	71.5	33.2
6	0.55	6.2	0.0	14.8	20.9	24.0	18.2
7	0.22	2.5	0.0	2.1	4.7	5.9	3.5
8	0.70	7.8	0.0	6.2	14.0	17.9	10.5
9	0.20	2.2	0.0	3.3	5.5	6.6	3.9

Table 3
Summary of analytical water results. Water sampling points shown in Fig. 1.

Point	N		pH	El. Cond.	Acidity	SO_4	Fe	Al	Mn	Zn	Cu	Ref.
1	7	Min	2.8	3305	395	1459	10.6	43.1	1.05	0.67		[1] & [2]
		Max	3.0	5460	3174	3360	244	504	2.22	0.77		
		Mean	2.9	4091	1203	2410	121	164	1.63	0.72		
2	1		4.6	868	276	560	3.10	48.4				[1]
3	7	Min	4.5	561	16.6	296	0.71	1.97	0.81	0.33		[1] & [2]
		Max	5.5	676	56.2	368	2.00	8.55	3.47	0.77		
		Mean	4.9	621	36.7	332	1.35	5.66	2.14	0.55		
4	6	Min	7.6	3.3	0.24	129	0.04	0.02	0.03	0.01		[1] & [2]
		Max	7.9	463	0.45	129	0.08	0.05	0.06	0.10		
		Mean	7.8	276	0.34	129	0.06	0.03	0.04	0.06		
5	7	Min	6.5	307	0.39	153	0.01	0.05	0.43	0.05		[1] & [2]
		Max	7.6	415	1.40	163	0.10	0.11	0.55	0.09		
		Mean	7.1	372	0.98	158	0.05	0.08	0.49	0.07		
6	4	Min	6.9	357	1.02	120	0.26	0.06	0.30	< 0.01		This work
		Max	7.9	581	13.0	274	5.60	0.06	1.64	0.02		
		Mean	7.3	438	4.43	208	1.63	0.06	0.79	0.01		
7	5	Min	5.6	56.0	0.62	12.0	0.09	0.03	0.04	0.02	< 0.0001	This work
		Max	6.6	259	1.96	120	0.62	0.07	0.70	0.08	0.002	
		Mean	6.2	138	1.37	47.2	0.31	0.06	0.28	0.05	0.001	
8	24	Min	5.0	598	29.1	330	9.00	0.10	7.15	< 0.01	< 0.0001	This work
		Max	7.0	3000	330	2800	144	3.20	30.0	1.16	1.610	
		Mean	5.9	2070	202	1764	92.8	1.65	19.4	0.18	0.338	
9	6	Min	5.7	60.0	0.65	12.0	0.09	0.03	0.04	0.02	< 0.0001	This work
		Max	6.7	1827	151	1000	69.0	0.07	15.0	0.04	0.003	
		Mean	6.3	746	59.4	319	27.1	0.05	5.86	0.03	0.001	
10	4	Min	6.3	446	7.04	220	0.71	0.06	1.50	0.01	< 0.0001	This work
		Max	6.9	595	29.6	410	10.7	4.31	2.87	0.02	< 0.0001	
		Mean	6.5	531	19.8	301	5.43	2.19	2.20	0.02	< 0.0001	
11	6	Min	6.8	263	0.31	219	0.07	0.03	0.35	0.03		[1] & [2]
		Max	7.3	556	6.79	219	2.20	0.06	1.47	0.10		
		Mean	7.1	445	2.73	219	0.78	0.04	0.91	0.06		

All values in mg L^{-1} excepting pH and electrical conductivity (µS cm^{-1}). Acidity calculated according to Hedin et al. (Hedin et al., 1994). Refs.: [1] Rodríguez et al., 2008; [2] Rodríguez et al., 2010.

water during the groundwater rebound.

Therefore, the reservoir has a capacity of about 1 Mm^3, up to the current level of the Navaleo discharge, which can be used for storage and regulation of mine water.

4.4. Geochemistry and water properties

The XRF analysis of the slates reveals very high iron concentrations (9–10%), due to their pyrite content. Concentrations up to 6650, 615, 129 and 35 mg kg^{-1} of Pb, Mn, Zn and Cu, respectively, were found, whereas Ca content is only at a 0.3%. The La Silva Stream receives ARD generated by the oxidation of these materials, which seriously affects its quality (Table 3).

Table 3 summarizes the analytical data of the sampled surface waters (the Navaleo mine drainage, the Rial Stream and the Tremor River), together with data from other sampling points indicated in Fig. 1, which have been compiled from previous works. The La Silva Stream has very low pH (< 3) and elevated electrical conductivity (> 3000 µS cm^{-1}), sulphate and metal concentrations when receiving ARD (Point 1), but there is a natural attenuation as the distance from the source grows (Points 2 & 3). The Tremor River shows a better quality despite of receiving the waters of La Silva Stream (Points 4, 5 & 6), but it gets worse when receiving the Rial Stream (Point 10) to be again attenuated downstream (Point 11). The electrical conductivity and the sulphate and metal contents of the Rial Stream increase due to the influence of the Navaleo mine drainage (Point 8), whose electrical conductivity reaches up to 3000 µS cm^{-1}, and whose maximum concentrations of sulphate, Fe, Al and Mn are 2800, 144, 3 and 30 mg L^{-1}, respectively. The original quality of the Rial Stream is similar to that of the Tremor River before receiving it. However, since the Navaleo has a 90% higher content of sulphate and metal contents, the quality of the Rial Stream worsens, despite of the dilution in its flow. This effect is diminished when this stream flows into the Tremor River. Considering the average flow of the Navaleo drainage and the average concentrations, the required values for watercourses receiving discharges (e.g. 250 and 2 mg L^{-1} of sulphate and iron, respectively) imposed by the Spanish laws, cannot be generally achieved with the relatively low flows of the receiving rivers (Rial and Tremor), particularly in the low-flow season. Nitrate concentrations were only detectable in the Rial Stream, reaching up to 8 mg L^{-1}.

The sediments deposited in the mine discharge pipe, which come from the precipitation after the oxidation of dissolved ions, show high contents in Fe (55%), Mn (1280 mg kg^{-1}) and other elements (5 and 81 mg kg^{-1} of Se and As, respectively). This demonstrates that if aeration and oxidation of this effluent were artificially promoted by waterfalls, ponds and other passive systems, the concentrations in the drainage could be greatly reduced.

5. Conclusions

The resources of 9 inactive and supposedly connected coal mines have been evaluated independently,. It is inferred that there is a connection between the Navaleo mine and other 4 nearby mines, because it receives water contributions from them. The water resources of the mine reservoir made up of the 5 connected mines result in approximately 54 L s^{-1} for an average year. The water enters through this complex system and it is drained by gravity to the lower parts of it, to finally overflow at the lowest adit. This discharge will be permanently maintained over time, and its flow will depend on the volume of precipitation, as well as losses from surface watercourses and irrigation systems.

The total volume of voids of the reservoir is estimated to be 1.7 10^6 Mm^3. The useful volume of reservoir (voids below the discharge level) is believed to be around 1 Mm^3. The two mines located at a higher level would not be suitable to store water, but appropriate for capturing it and transmitting it. The reserves of the mining reservoir could be used for storage and regulation of mine water, among other uses (energy, industrial, etc.).

The discharge of mine water enters the Rial Stream shortly before it flows into the Tremor River. The quality of the stream deteriorates downstream of the discharge, which has high concentrations of sulphate, Fe and Mn, although this effect is attenuated when the stream enters the Tremor River. Since agricultural activity in the area has decreased significantly, it would be better to avoid losses from the irrigation systems by making a waterproofed by-pass of the stream over the most mined areas, of ca. 1 km. This would reduce the rate of mine discharge, as well as improve its quality by avoiding fluctuations in the filling level of the reservoir, which causes the water to "wash" the walls, which were previously exposed to oxidation, above the saturated zone. Conventional passive treatments could be applied to this mine water, especially if its flow could be reduced. On the other hand, it would be advisable to check the hydraulic connections by controlling the water level with pressure sensors inside the abandoned workings. Likewise, it would be beneficial to monitor the discharge rate continuously and to undertake a complete hydrochemical characterization.

A considerable amount of data has been published on the generation of AMD and its consequences on aquatic environments. However, the characterization of mining reservoirs has not been the focus of many studies, especially regarding the transformation of mine water from a waste into a resource. The annual water resources are investigated in this case through several methods in order to understand better how to approach this estimate. Taking into account the management of flooded mines due to environmental/industrial motivations, the applicability of the findings of this study increases significantly.

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