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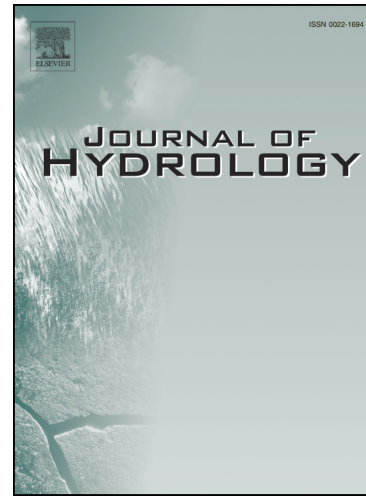

Research papers

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Conceptualization and finite element groundwater flow modeling of a flooded underground mine reservoir in the Asturian Coal Basin, Spain.

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Highlights:

- Conceptualization and numerical model of two flooded coal mines in Spain.
- A methodological approach to incorporate mine information in the numerical models.
- Flow is computed using a coupled-continuum pipe-flow approach.
- Computational efficiency allows calibration using Monte Carlo method.
- Flow regimes, directions and critical velocities in the mine are evaluated.

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Abstract

Secure workings in underground coal mines usually require the lowering of water levels via pumping. After mine closure, pump systems are stopped and the water level recovers in a process known as groundwater rebound. In the Asturian Coal Basin, Spain, the closure and flooding of underground coal mines carries associated environmental impacts that ought to be assessed. Among them, those related with groundwater flow and pollutant transport are of main interest. To evaluate the environmental risks during and after mine closure the construction of numerical flow models is suggested, which rely on an appropriate conceptualization of the mine-hydrogeological system. Underground mines of this region are characterized by very steep coal seams due to a folded and faulted geological structure. The resulting geometry translates into a complex network of hundreds of kilometers of mine tunnels and galleries. This is a challenge for the construction of numerical models in issues like geometrical problems, assignation of hydraulic parameters, coupling of physical laws and high computational cost. This paper presents the conceptual and numerical model of two linked mines of the region, Mosquitera and Pumarabule, that recently ended the flooding stage, to be used in assessment of post-closure environmental risks. To implement the geometry of the underground mine, a methodological approach to translate the mining information to the numerical simulator has been developed, that retains the hydraulic behavior of the key underground mine elements. A methodological approach for coupled simulation of mine conduits and porous media flow has been explicitly adapted. The results, in terms of the velocity distribution field inside the mine and possible outflow sites, are useful to provide a basis for later extension of transport models and assessment of hydro chemical impacts on the area.

Keywords: *Mine closure; Underground coal mining; Asturian Coal Basin; Environmental risks; Conceptual model; Numerical modeling*

1 Introduction

Managing of environmental risks during and after coal mine closure is an important matter of concern in a scenario in which many exploitations have closed, or will do soon, in Europe (Didier 2009; Klinger et al. 2011; Bondaruk et al. 2013; Younger 2016). Such is the case of numerous mines in Asturias, Spain (Moreno and López 2008; Jardón et al. 2013).

Within this context, it has been urged by the European Comission (2013) to undertake actions to mitigate the negative environmental impacts of the European raw materials sector. Recently, Krzemien et al. (2016) proposed a methodology for environmental risk management with the objective of achieving a sustainable mine closure, and within this framework, a fundamental stage is the evaluation of water related risks (Klinger et al. 2012).

A well-known strategy within the hydrogeological community to evaluate and predict water related impacts is the construction of groundwater flow (and transport) numerical models (e.g. Anderson et al. 2015). Computational models include relevant information related to hydrological parameters and detailed geometry to solve the governing equations of the processes occurring in the system. The outcomes, in terms of distribution of state variables over time and space, are useful to provide estimations (e.g. of pollutants and discharges) or take actions to avoid water-related environmental impacts.

Modeling groundwater flow in underground mine systems is a difficult task due to the complexity of simulating water flow processes in the mine voids that differ from those encountered in classical porous aquifers where Darcy's laminar flow law is applicable (Wolkersdorfer 2008). However, flow through the aquifers in which the mine is embedded should not be disregarded, as happens with some processes like recharge (e.g. Ordóñez et al. 2012). A strategy that combines both flow regimes is therefore needed, that assures mass continuity. This should be done in a computationally efficient way to support further developments such as transport of contaminants or heat for geothermal applications.

Previous works have undertaken the simulation of water flow in underground mines. The modelling solutions adopted vary but can be classified in two main groups: a) semi-distributed box type and, b) physically based models. Box type models have been satisfactorily utilized in water rebound studies, that is, to predict the flooding after mine closure. These models use the concept of interconnected "ponds" where the water budget is computed (Younger et al., 2002). Some examples are GRAM (Sherwood and Younger, 1997) or MIFIM (Banks, 2001). Physically-based models usually take advantage of existing groundwater numerical codes, such as the VSS-NET component of SHETRAN (Ewen et al., 2000), which was added in order to simulate turbulent flow in mine studies (Adams and Younger, 2001), or the well-known MODFLOW (Harbaugh, 2005) and FEFLOW (Diersch, 2013).

The modelling of underground mine reservoirs, especially in the Asturian basin, is a complex task derived from the intricate geometry and layout of the underground voids that are embedded into, and should be hydraulically coupled to, the porous media. For example, the steep coal panels linked by galleries at different levels would be extremely difficult (or almost impossible) to accommodate using finite difference codes with prismatic elements, such as MODFLOW. Additionally, the hundreds of kilometres of galleries are not feasible to be implemented as three-dimensional elements and the hundreds of interconnected branches would cause numerical instabilities in the calculation of water flow in the conduits.

This work presents the conceptual and numerical groundwater flow model of the flooded underground coal mine reservoir of Mosquitera and Pumarabule, in Asturias, Northern Spain. As a novelty, a methodological approach to incorporate mining information into a groundwater model, that addresses some peculiarities found in the Asturian coal region derived from the characteristic geological settings, is explained. The results provide information about groundwater flow and distribution of pressures in the mine and in the surrounding massif, water velocities and flow regimes in the mine conduits and risks of groundwater flooding after mine water rebound and discharge of contaminated mine waters. The model constitutes the basis for further studies encompassing water rebound, reactive transport and geothermal models.

2 Background and site description

2.1 Coal mining in Asturias

First testimonials of coal exploitation in Asturias, Spain, come from the second half of 18th century. In the 19th century starts a more intensive and industrialized stage of activities due to a flourishing metallurgic industry (Anes and Ojeda 1983). Asturian mines have been characterized by difficulties of extracting coal due to the very complex geological settings (commonly with existence of very steep coal seams of low thickness and limited spatial continuity, highly fractured), requiring very intensive manpower. In 1967 the national company HUNOSA (Hulleras del Norte SA) was established with the objective to cluster all the mines and exploitation of the Asturian Carboniferous Central Coal region, including those not making profits. In the 1990s underground coal mines started to close in Asturias, a process within an industrial reconversion that led to closure of all non-profitable mines in the region by the end of 2018 (European Commission 2010).

2.2 Geological and hydrogeological settings

2.2.1 Structure

The Carboniferous Central Asturian Coal Basin (CCB) lies in the center of the Principality of Asturias with a total area of approx. 1400 km^2 (see **Fig. 1**). From a geological point of view, it belongs to the Cantabrian Zone of the Iberian Massif (Julivert et al. 1971). The geological limits of the CCB are the Mesozoic-Tertiary basin to the North, the Ponga-Nappe regions to the East, the Leon fault to the South and the Aramo Unit whose limit is the Aramo thrust, to the West.

The zone of study is placed at the North of the Central Coal Basin, on a highly folded and faulted area. The main structures respond to the historical (Variscan and Alpine) main stresses with directions West-East and North-South (Fuente-Alonso and Sáenz de Santa María Benedict 1999). The mines of Mosquitera and Pumarabule are located to the eastern flank of the Sama Syncline (see **Fig. 1**). This syncline fold has a hinge line direction approx. N – S and plunges smoothly to the South. The axial surface dips to the East with an angle of around 70º. To the East of the Sama syncline, two other folds have importance in the underground distribution of the mine exploitation areas: The Magdalena anticline is a tight fold with axial surface dipping to the East, as well as El Entrego syncline, both with axis direction N – S. The general structure in a W – E cross-section is shown in **Fig. 1**.

Two main families of faults, which approximately follow the same directions of the folding structures (E – W and N – S) are observed in the area. The most important have N – S (or NNE – SSW) direction. Remarkable in this group is La Carrera fault, a reverse fault not well-known because it is developed in clay non-productive materials (Fuente-Alonso and Sáenz de Santa María Benedict 1999). The second fault system is approximately orthogonal to the main one but are generally minor structures with less continuity. The delineation of these faults is in many cases only possible through underground information and is revealed by changes in the position of the coal seams.

2.2.2 Stratigraphy

The coal bearing sequence of the Basin has been divided into two main units (**Fig. 2**): (a) a lower, unproductive unit, called Lena Group (Westphalian A – C), 3500 m of deltaic and marine sediments mainly composed by limestones with sporadic, thin and discontinuous coal seams, mostly in its upper part; and (b) an upper, productive unit, called Sama group (Westphalian D), that has a thickness of more than 2000 m and contains exploitable coal seams within an important sandy sequence with sporadic limestones. Within each unit, a grouping was done into smaller entities called "packs" (Adaro 1929; García Loygorri et al. 1970), an informal mining term utilized to identify in the sequence the position of the exploitable coal seams in the area (**Fig. 2**). Only coal seams from the Sama group were exploited in the mines of Mosquitera and Pumarabule. The most recent (in the stratigraphic sequence) were those from the Sorriego mining pack, in Mosquitera, and the oldest from the Generalas mining pack (see **Fig. 1** and **Fig. 2**).

2.2.3 Hydrogeological properties

The hydrogeological properties of the carboniferous materials in the area are generally poor in terms of permeability and storage properties. Previous authors (Ordóñez et al. 2012; Álvarez et al. 2016) have classified them into three hydrogeological groups: a) Shales and siltstones with very low hydraulic conductivities of $10^{-7} – 10^{-8}$ m·s^{-1}; b) Carboniferous sandstones and conglomerates, which show conductivities of around 10^{-6} m·s^{-1}; c) Carboniferous limestones and dolostones, whose permeability vary according to the extent of the karstification. These materials may have changed their natural properties in exploited zones, according to the stresses, extension and compression, caused by the mine works (see for example Younger and Adams 1999).

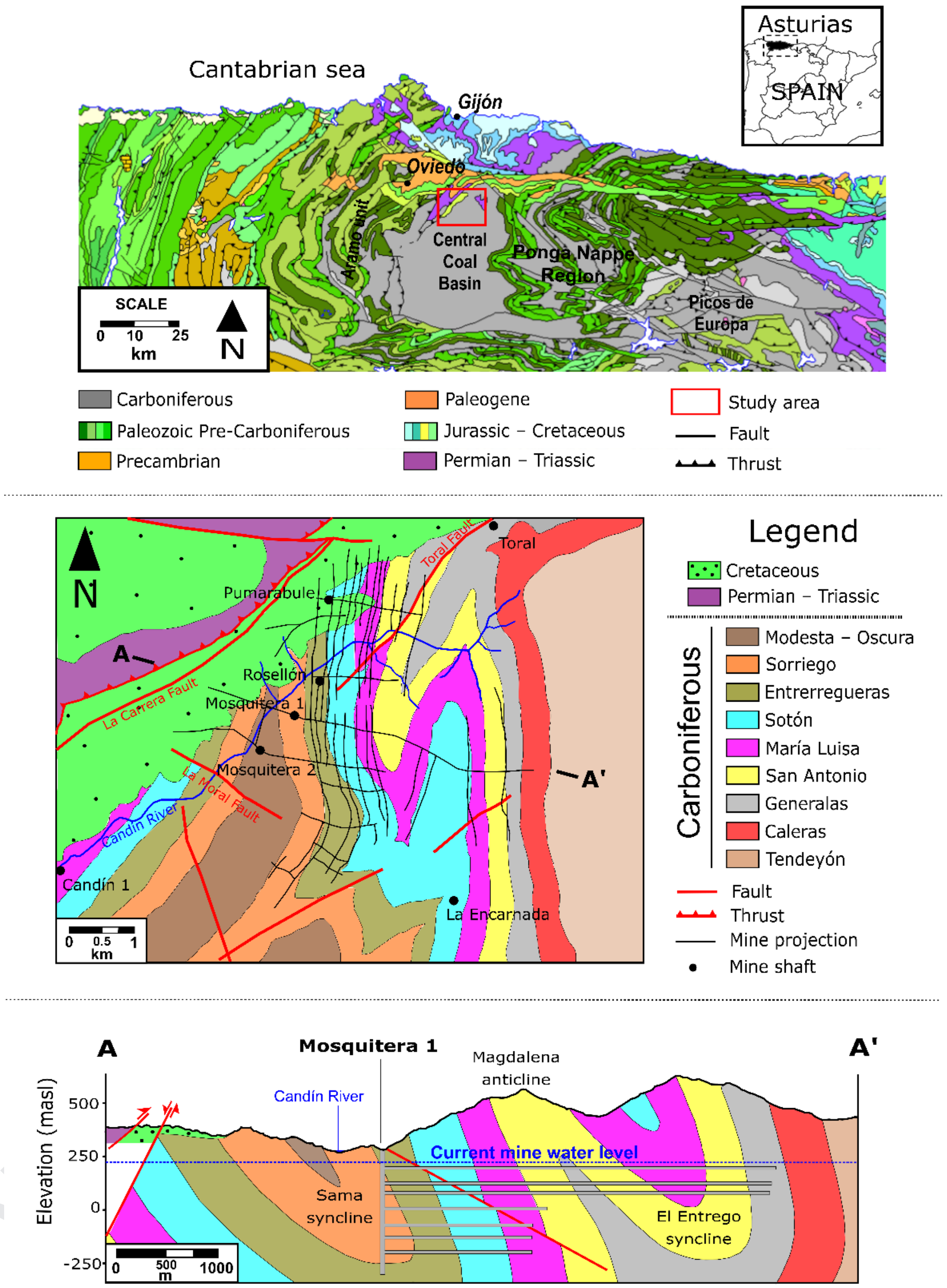

***Fig. 1. Up**: General location of the study area in the Central Coal Basin in Asturias; **Middle:** Detailed geological map including main geological characteristics and location of shafts. Pumarabule mines are nearby so are considered at the same location in the map; **Bottom:** Cross section showing the geological structure and a schematic projection of the mine. Vertical scale is exaggerated. Elevation in meters above mean sea level (masl).*

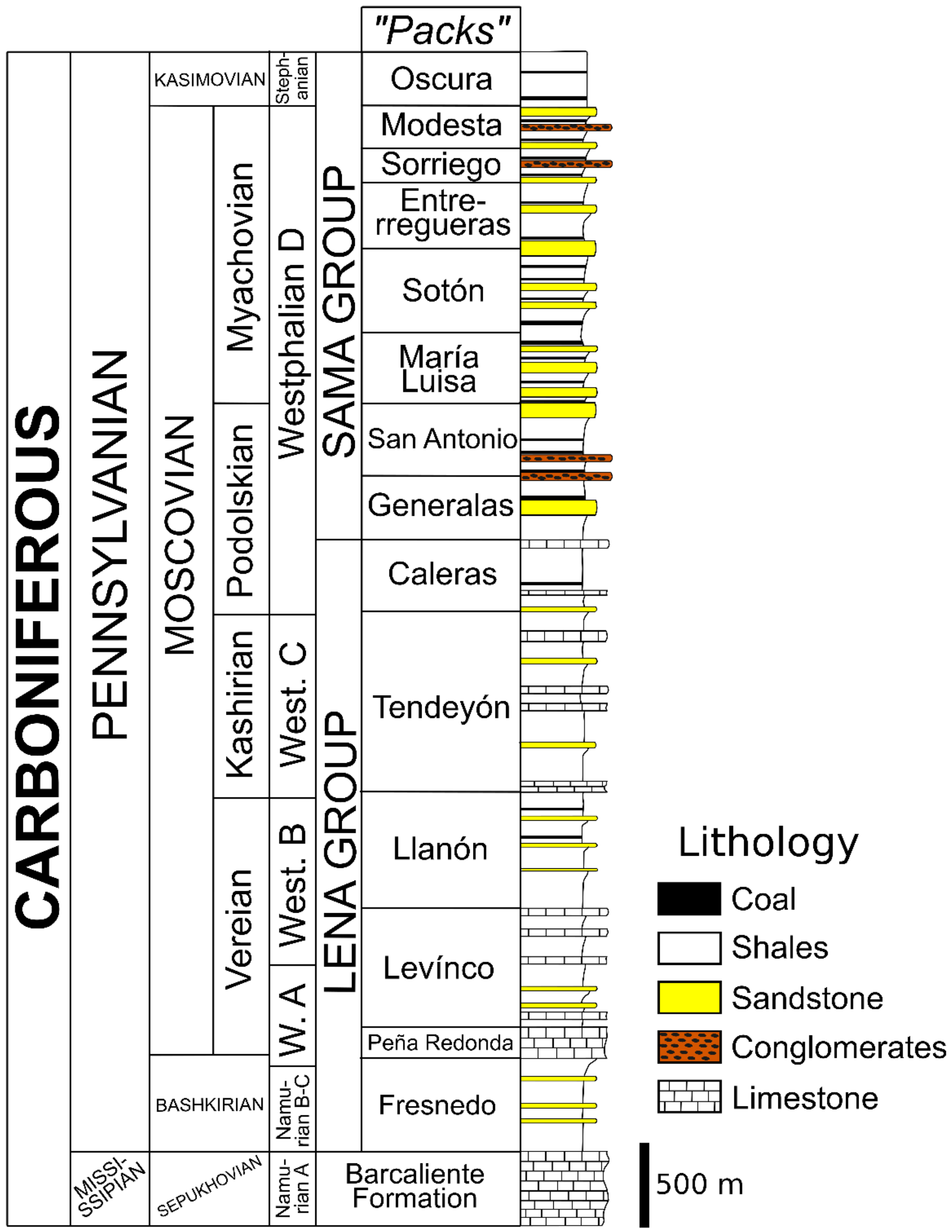

Fig. 2. *Stratigraphic column of the Carboniferous sequence in the Asturias Coal Basin, Nalón-Aller sector. (Modified from Piedad-Sánchez et al. 2004 after Sáenz de Santa-María Benedict et al. 1985; Águeda et al. 1991; Fernández 1995).*

2.3 Mosquitera-Pumarabule mines

2.3.1 General characteristics

The mine system under study includes the mines of Pumarabule (1 and 2), Mosquitera 1, Mosquitera 2 and Rosellón (see shaft locations in **Fig. 1**). In total, the underground workings extend over an area of more than 20 km^2 and reach a depth of almost 600 m below the ground surface.

The first shaft of the Pumarabule mine, Marta or Pumarabule 1, was excavated in 1916 and operations began in 1917. The second shaft, Pumarabule 2, was excavated in 1957 less than 40 m away from the first shaft. Pumarabule 1 has a total depth of 242 m and Pumarabule 2 reaches a depth of 578 m (-292 masl). Pumarabule underground workings are distributed in 13 levels or floors with main transverse roadways of W – E direction. The main transverses connect the shaft with the galleries that allowed access to the exploitation areas and are approximately aligned with the strike direction (N – S) of the coal layers. The galleries extend to the North of transverses with a length between 400 and 800 m. To the South the galleries reach further, with lengths up to 1500 m. In the exploitation zones coal panels of high dips (around 70º) were exploited using manual methods with backfilling.

Mosquitera 1 was concluded in 1929 and Mosquitera 2 started its production in 1946. Mosquitera 1 has a maximum depth of 566 m (-296 masl) and Mosquitera 2 reaches a maximum depth of 477 m (-204 masl). In December 1989, a fire in the 7th level of Mosquitera 1 caused the death of seven miners and the shaft was closed. From that date, Pumarabule was used to continue the exploitation of coal until its closure in 2005. The underground distribution of Mosquitera's mine workings is more complex than that of Pumarabule's. Instead of a unique main transverse roadway per level, in Mosquitera there is one main transverse per shaft. The main transverses of Mosquitera 1 are longer than 2 km. The shafts allow access to different underground levels, 11 in Mosquitera 1 and 7 in Mosquitera 2. Pumarabule and Mosquitera mines are connected at 2nd, 4th, 7th and 8th floors. This proprietary information, gathered from different sources —mainly data provided by the mining company (HUNOSA), historical records in the regional mining archives and the Spanish Geological Survey (IGME)— and processed by the authors, is fundamental to build the modelling geometry.

2.3.2 Water discharge and rebound in Pumarabule-Mosquitera

With the deepening of the underground workings to extract coal, water pumping keeps areas dry and secure. The depressed water level is later reverted after closure of the mine, but the natural system has by then been largely affected and modified by the anthropic activity.

Historical data for the Pumarabule exploitation shows that for each ton of coal extracted between 15 and 25 tons of water was pumped. For example, in the period 1995 – 2001 the total production of coal was $\approx 8 \cdot 10^5$ t (tonnes) —in the selected mines $\approx 1.85 \pm 0.2$ t of raw materials to obtain 1 t of coal after washing— and the water extracted in the same period was $\approx 1.6 \cdot 10^7$ m^3. This is $\approx 2.1 \cdot 10^5$ $t \cdot a^{-1}$ of raw material extracted and $\approx 2.3 \cdot 10^6$ $m^3 \cdot a^{-1}$ water pumped, a factor of approximately 11:1 of water to raw material, which is in the middle range of other coalfields in Europe and in the World (see Fig. 29 in Wolkersdorfer, 2008). Residence times have not been estimated, but previous studies (e.g. Jardón 2010) suggest delay times between 15 and 45 days since water is infiltrated until it is pumped out of the shafts.

Extraction of coal in Pumarabule-Mosquitera ended in 2004. Dewatering pumps were stopped the 26th of October 2010. Natural flooding of the mine occurred until a previously defined security level of 230 masl. was reached in December 2014. It is a water elevation defined by the mining company to avoid unwanted discharges of contaminated mine water to the surface. This level is maintained using five pumps—three located in Mosquitera 1 and two in Pumarabule—each one with a theoretical pumping capacity of 225 – 240 $m^3 \cdot h^{-1}$. By April 2016, after permission, the company let the level risen to the current 235 masl. **Fig. 3** shows historical data of monthly pumping rates in both mines and the water rebound curve for the Mosquitera mine. Pumarabule rebound curve is not shown as it perfectly matches Mosquitera levels, confirming the very good hydraulic connection between the two mines.

Monthly water pumped in both shafts is shown in **Fig. 3a**. The main pumping station is located in Mosquitera 1 whereas additional pumps in Pumarabule are utilized as backup for high rain periods. Pumping rate in Mosquitera is higher during the wet season, usually between November and May, which shows the relation with precipitation patterns, with highest pumping accumulated values of 0.2 – 0.3 $hm^3 \cdot month^{-1}$. All this information shows the structure of the geometry and dynamic relationships among the interlinked shafts.

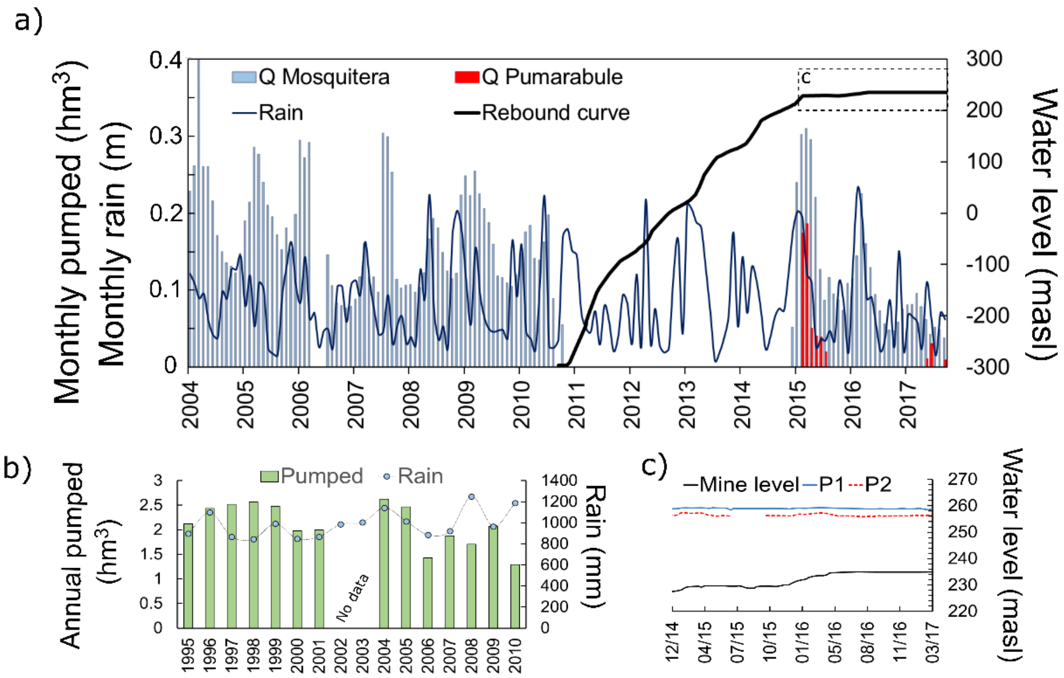

__Fig. 3. a)__ Bar chart showing monthly pumped volumes in Mosquitera (blue) and Pumarabule (red). Blue line is monthly accumulated rain in mm. The black line represents water levels in the mine. Rebound started (pumps stopped) in October 2010. Current level is in 235 masl. __b)__ Annual volume pumped and rain in the 15 years before flooding. __c)__ Water levels after rebound in the mine and the two piezometers.

3 Conceptual model development

3.1 Objectives

The groundwater model presented in this work aims to provide insights about water flow dynamics in the reservoir after the mines have been flooded and the pumps are reactivated to maintain the security level. The objectives of the numerical groundwater model are to analyze the hydrodynamic characteristics —e.g. water velocity in the galleries, flow regime, discharge volumes— in different scenarios to provide a context for evaluation and further extension to include contaminant transport models that constitute the basis for environmental risk assessment after mine closure.

To proceed with the numerical evaluation is it necessary to define first the conceptual model, which includes all what is known and relevant about the system and can be defined as "an assembly of simplifications about a complex, real system, which achieves a valid representation of that system, including all major features, whilst avoiding unnecessary detail" (Younger and Adams 1999).

3.2 General assumptions

Mine workings act as preferential pathways for groundwater akin to that of a karst aquifer (Wolkersdorfer 2008). The hydraulic properties of the geological medium surrounding the mine are also modified to an extent as consequence of the mining activity, showing a higher increasing of permeability and porosity near the voids (e.g. Younger and Adams, 1999). The general flow behavior of the system can be conceptualized as a connected network of mine voids, of different dimensionality, that act as a large drainage system embedded in a massif, partially altered after mining. The main recharge is caused by rain. The water that infiltrates through the porous media aquifer flow through the massif until percolates into the mine voids. Water is then conducted to discharge points located in the shafts, where pumping is active to maintain a fixed security level.

3.3 Model extension and definition of boundary conditions

The conceptual model has been given an extent of approximately 25.5 km^2 (**Fig. 4**). The limits have been defined using the geological information that assigns a very low permeability of the existent unaltered massifs that separates the studied mines from nearby workings. To the East, a no-flow boundary is represented by the Tendeyón mining pack (**Fig. 2**), a thick sequence of shale materials of more than 500 m, considered impervious. The same formation provides the no-flow boundary at the bottom of the model, following the syncline structure, at depths ranging between 2000 and 3000 m. The Northwest boundary is represented by La Carrera fault, a reverse fault or thrust, not well-known, but considered impervious because it is developed in clay non-productive materials (Fuente-Alonso and Sáenz de Santa María Benedict, 1999). Two closed mines are located further to the North of the study area, Toral-Aramil and, at a larger distance, a more important one named Lieres (**Fig. 4**). To the South, a large mined zone exists, with two closed mines, Candín (SW) and Venturo (SE). An unaltered protection massif acts as a separation boundary with all these exploitations. Analysis of historical records of pumping rates from these mines show no apparent connection, and therefore it is assumed that no flow occurs between these mines and the reservoir under study.

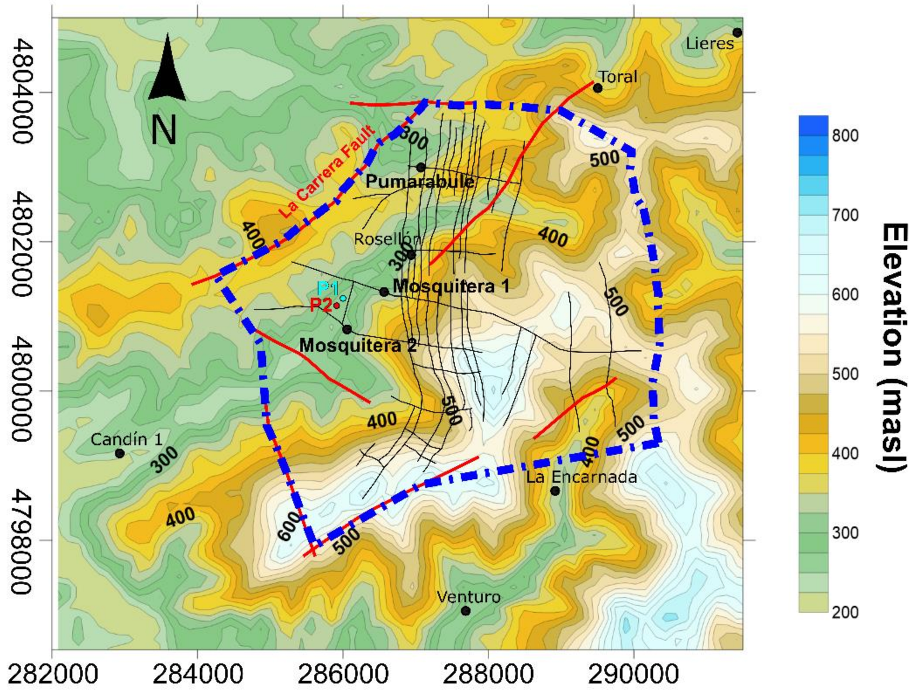

__Fig. 4.__ Limits of the conceptual model represented as a no-flow boundary condition in the numerical model (in blue). Projection of 1st floor of mine galleries under study are shown with dark grey lines and position of shafts with black dots. P1 and P2 are two piezometers. Coordinate system UTM WGS84 Zone 30 T.

The upper (surface) boundary is defined with detailed topography of the area. Recharge has been estimated using precipitation data from Oviedo meteorological station (located about 15 km from the study area) and works from previous authors, who estimated infiltration values for aquifers on the area of 104 (Álvarez et al., 2016) and 110 mm·year^{-1} (Muñoz de Fraga, 2015). These values represent around 22 – 26% of the average effective rainfall, estimated in 450 mm·year^{-1} by Álvarez et al. (2016) for the area of Candín, just Southwest of the study area (**Fig. 1**). Finally, the Candín River (see **Fig. 1**), the main river in the area, is represented in the model as a line segment in the valley.

The main dewatering points of the system are the pumps located in the mine shafts. These pumping facilities aim to keep the water level below the security height of 235 masl and are intermittently active when water level raises above the predefined level, with higher pumping rates during wet season. Total annual pumping rates have ranged, before flooding, between 1.4 and 2.6 hm^3·year^{-1}, with a mean value of 2.091 hm^3·year^{-1} (**Fig. 3b**). After flooding, in 2015, the annual discharged volume was 2.06 hm^3 in Mosquitera, supported by pumping of 0.5 hm^3 in Pumarabule, that is, 2.56 hm^3 in total; while in 2016 the total pumped was much lower, 1.23 hm^3, but the pumps stopped for some months to let the level rise from 230 to the current 235 masl. **Fig. 3** shows monthly pumping rates in Mosquitera (blue) and Pumarabule (red).

3.4 Conceptualization of mine elements affecting groundwater flow

Mine voids, including galleries, roadways, access works and shafts constitute the main pathways for rapid water flow in the model. The large system of underground tunnels is there conceptualized as a large interconnected pipe system that conducts water to the discharge points, in this case the pump systems located in the shafts. Galleries in Asturian mines have an average cross-section of 9 m^2, although values range from those of less-important secondary galleries (sections of 6 m^2 were identified in old mine plans) to main roadways and landing areas located near the shaft, which have sections of 20 m^2. Convergence due to overburden has been estimated to cause a reduction in section of galleries of about 5 – 10% (Ordóñez et al. 2012). The average cross-section of shafts is bigger and depends on the diameter of each shaft ranging between 4.3 m and 5.65 m.

Exploitation zones (coal panels) suffer a transformation of their characteristics once coal has been extracted. Hydraulic properties vary depending on the method of exploitation. Compaction and subsidence reduce the original net volume once the exploitation is abandoned. As coarse practical approximation, values of porosity of 20% can be employed for filled exploitation zones and of 30% for collapsed ones (Jardón, 2010). In compacted backfill material porosity can be reduced to less than 10% whereas collapsed sandstone can show porosities of 40% (Ordóñez et al. 2010). In the study area, values lower than 20% have been chosen after having analyzed exploitation methods. For the altered massif, the values of hydraulic conductivity are based on previous works in the area (Díaz Noriega, 2017) and values estimated in the literature (e.g. Younger and Adams, 1999; Younger, 2011). The unaltered massif is considered to have very low permeability, with hydraulic conductivity values generally lower than 10^{-7} m·s^{-1}, reaching $5 \cdot 10^{-6}$ m·s^{-1} in fractured zones (Álvarez et al. 2016). A summary of values utilized are shown in **Table 1**.

Table 1. *Elements in the model with values of their main hydraulic properties. Properties for the massif are only for carboniferous materials. Also shown their dimensionality in the numerical model.*

Element	Model Representation	Process	Property	Value(s)
Galleries	1D	Conduit flow	Section	6 – 9 m^2
Landing areas	1D	Conduit flow	Section	20 m^2
Shaft	1D	Conduit flow	Diameter	4.3 – 5.65 m
Panels	2D	Porous media flow/ Fracture flow	Transmissivity	10^{-3} – 10^{-5} m^2·s^{-1}
Altered massif	3D	Porous media flow	Hydraulic conductivity	10^{-4} – 10^{-6} m·s^{-1}

Unaltered massif	3D	Porous media flow	Hydraulic conductivity	$10^{-6} – 10^{-8}$ m·s^{-1}

4 Groundwater numerical model development

4.1 Modeling objectives

Available data are very scarce: the only available information are water levels measured in the shafts, monthly discharge rates (necessary to keep levels at the 235 masl security height) and piezometric heads measured in two piezometers located in the Candín valley in the proximity of Mosquitera (**Fig. 4**). The boreholes have total depths of 20 m (P1) and 40 m (P2) and are excavated in the unaltered massif without reaching the mine workings. Yearly head fluctuations in these piezometers are low (**Fig. 3c**) and show no apparent direct hydraulic connection with the mine workings.

Due to this scarcity of data, the objectives of the numerical models are, first, to develop a methodological approach to integrate the mining geometry in the numerical simulator able to simulate the main processes in the system; and, second, to improve, through evaluation and simulation of likely scenarios, the understanding on the groundwater dynamics both in the mine and in the massif. The final objective is to provide information of principal flows and pathways, velocities, flow regime and risk scenarios for a later extension and application to contaminant transport models, which will be the next stage in the post-closure study.

4.2 Implementation of geometry and numerical model

To include all the available information of Pumarabule-Mosquitera in a numerical model, is neither realistic nor achievable in terms of the computational power available in the research group, even more if transient or transport models were to be run in the future. To produce useful models, the main features of the elements in the mine have been conceptualized and simplified in a way that aims to maintain the characteristics and influence in the process to be modeled. The steps taken to translate mine plans into the model were the following: 1) coal seams were grouped according to relative positions, thickness and continuity of the layers. The representative coal seam of each group is taken as reference and a code is assigned; 2) underground galleries are geometrically simplified, reducing segments and grouping those within each “coal seam group”. This stage is conducted using CAD software checking for joining errors that would lead to problems in the numerical calculations; 3) coal seams in form of planar surfaces between galleries of different levels are drawn using information from the mine and coal seam plans, if available; and 4) the geometry of the mine is then imported from the CAD software into the numerical simulator and embedded in the volume representing the massif constructed using the topography and geological information.

The physically based numerical model is built using the finite element commercial code COMSOL Multiphysics®. A coupled continuum pipe flow (CCPF) model (e.g. Liedl et al., 2003) was developed using the capabilities of the equation-based PDE (Partial Derivative Equations) interface, following a conceptualization of the system like the one proposed by Adams and Younger (2001), where mine workings are modeled as a discrete network of conduits embedded in a Darcian surrounding medium.

The massif is modeled using Darcy’s law for flow in porous media.

$$q = -K\nabla h_m \tag{1}$$

q [L·T^{-1}] is the specific discharge or Darcy velocity, h_m [L] is the hydraulic head at the massif and K [L·T^{-1}] is the hydraulic conductivity. In the exploitation zones (panels), defined as two dimensional planes, the above expression is integrated with the thickness of the panel.

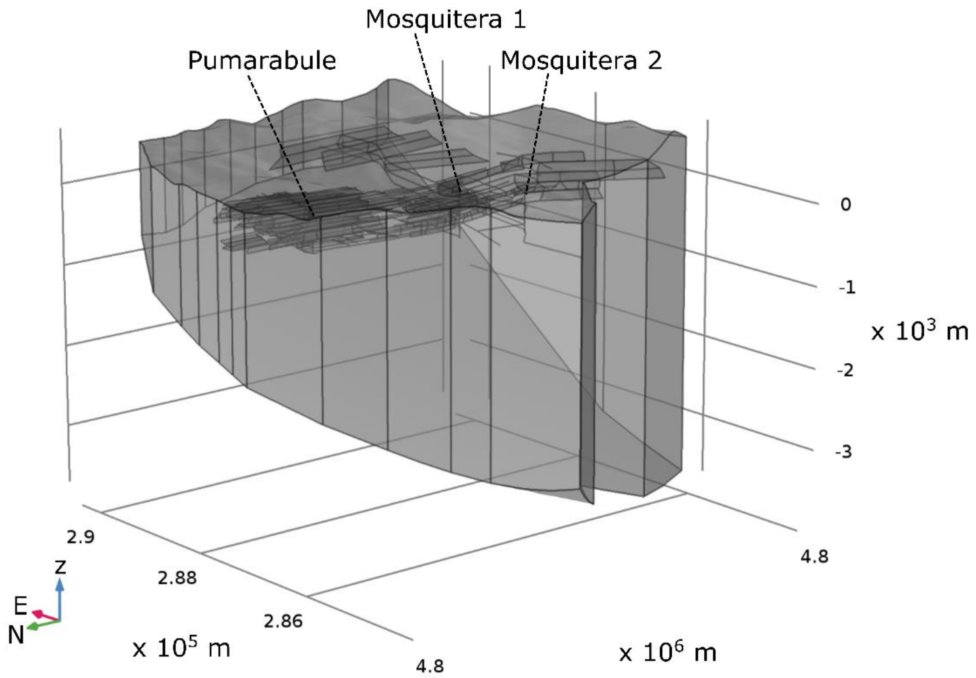

Fig. 5. *Final geometrical view of the complete model including the mine workings embedded in the porous media domain built using geological information and detailed topography.*

Mine galleries are modeled as discrete 1D elements using the Hagen-Poiseuille equation

$$Q = \frac{\pi d^4 \rho g}{128\mu}\frac{\Delta h_c}{l} \quad (2)$$

Q [$L^3 \cdot T^{-1}$] is the volumetric flow rate in the conduit, d [L] is the pipe diameter, ρ [$M \cdot L^{-3}$] is the water density, μ [$M \cdot L^{-1} \cdot T^{-1}$] the dynamic viscosity, g [$L \cdot T^{-2}$] is gravity acceleration, h_c [L] is the head in the conduit and l [L] its length.

Both models are coupled in the contact between the discrete features (mine workings) and the massif using an exchange term (for example Cao et al. 2011)

$$N = \alpha_{ex}(h_c - h_m) \quad (3)$$

α_{ex} [$L^2 \cdot T^{-1}$] is the exchange coefficient and h_c [L] and h_m [L] the heads at the conduit and the massif respectively. The exchange coefficient is computed with conduit diameter and a representative hydraulic conductivity.

Hydraulic parameters have been assigned according to mine information for galleries and shafts (section) and exploitation zones (thickness and estimated porosity derived from mining method and filling material) as explained in section 3.

The numerical models have been defined using a (point) constant head of 235 masl in Mosquitera 1 and Pumarabule shafts and the boundary conditions defined in section 3.5. The boundary conditions in the shafts allow for calculation of the pumping rates necessary to keep the water below the security level. A constant recharge is implemented on the ground surface with homogeneous distribution. The Candín River is implemented using a mixed boundary condition with the form of equation (3), computed with the differences between the river levels and massif head and an estimated conductance.

The final geometry shown in **Fig. 5** was meshed with a total of 877,746 nodes. The numerical models were run assuming steady-state conditions. To solve the stationary model it has been utilized an iterative "Generalized minimal residual method" (GMRES) solver with a multigrid preconditioner. Total computational time using a standard desktop computer with a processor Intel® Core i7-2600 CPU and 16 GB RAM is less than 2 minutes for a steady-state model.

Because scarce data, which makes it more difficult to proceed with an appropriate calibration of the model, an exploratory strategy based on extensive multi-parametric runs has allowed to explore possible scenarios. The objective is to explore the effect of variations in the main parameters of the model (shown in Table 1), including: hydraulic conductivities in the altered and unaltered massif, recharge values, conduit section variations (such as caused by convergence or collapse of the mine voids), hydraulic conductivity and thickness of exploitation zones (panels) and river conductance.

5 Results and Discussion

450 model runs of the model in steady state conditions with parametric variations (Monte Carlo analysis) were computed. From them, a total of 441 were solved and considered in the

analysis of the results presented below, while 9 models did not reach convergence. As a first measure for quality control, net balance was computed using the expression: $R = N = Q$. R is the total recharge at the top layer, N is the total integrated flow rate between the porous media and the mine and Q is the pumped water in the shafts. As the models are in steady-state and no other inflows/outflows exist in the model the resulting balance must be zero —plus ins/outs from/to the river. The mean balance error in all the 441 models was 0.167 %. Among them, 20 models showed errors higher than 1% and only 2 above 5%.

Fig. 6 shows some of the relevant results of accepted models for variations in hydraulic conductivities for unaltered and altered massif and recharge. Results are compared with piezometric heads measured at the two piezometers in the proximities of Mosquitera mines in which mean values were calculated from annual data (P1 = 258.9 m and P2 = 256.4 m). Variations through the year in both piezometers are lower than 2 m.

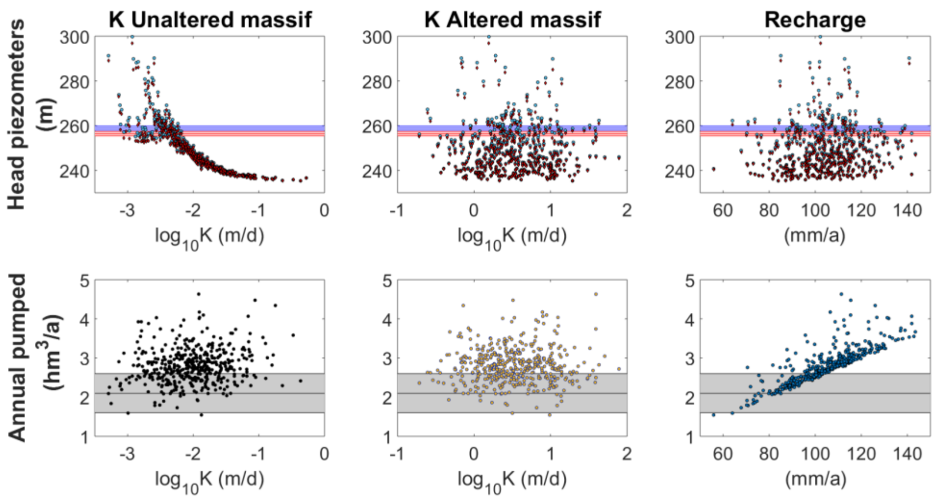

__Fig. 6.__ Summary of some model results. From left to right: K of unaltered massif, K Altered massif and Recharge. Above: comparative with measured heads at Mosquitera piezometers (P1 = 258.9±1 m, in blue; and P2 = 256.4±1 m, in red). Below: Annual pumped volume (Q = 2.1±0.5 hm^3/year).

The results show a strong dependence on the values of hydraulic conductivity in the unaltered massif and measured head in both piezometers. The best correspondence was found for hydraulic conductivity values of 7 – 9·10^{-8} m·s^{-1}, which agree with the values provided by other authors that ranged between 3·10^{-8} m·s^{-1} and 1·10^{-7} m·s^{-1} (Ordóñez et al., 2010; IGME, 2011).

Fig. 6 also shows calculated annual pumped volume to keep the security level below 235 masl. Recharge values, as expected, show a strong correlation with total pumped discharged. The results indicate that initial estimations (105 – 110 mm a^{-1}; see section 3.3) would be on the upper range of validity and be acceptable for a year of high precipitation (annual discharges around 2.5 hm^3). The lower estimated infiltration might be result of the drain effects and the prevention of infiltration in the main system caused by ancient mines —many from the XIX century— in the mountainsides, which capture a fraction of infiltrated water at higher elevations that later outflows at old adits.

The altered massif, because of its high hydraulic conductivity, which agrees with values proposed for the altered zone, shows no high influence neither in the piezometers nor in the pumped discharge (for steady-state models). This is shown in the distribution of heads in the model. **Fig. 7** shows a general plain view of hydraulic heads at -50 masl, above 3rd floor of Mosquitera and Pumarabule mines, in one of the accepted models. Flow directions in the mine voids are shown with red arrows heading to the Mosquitera 1 shaft, where the main pumping facility is located. The influence of the mine is shown in the depression of hydraulic heads near the workings, as pressure/head variations are more easily transmitted through the open voids and in the altered massif.

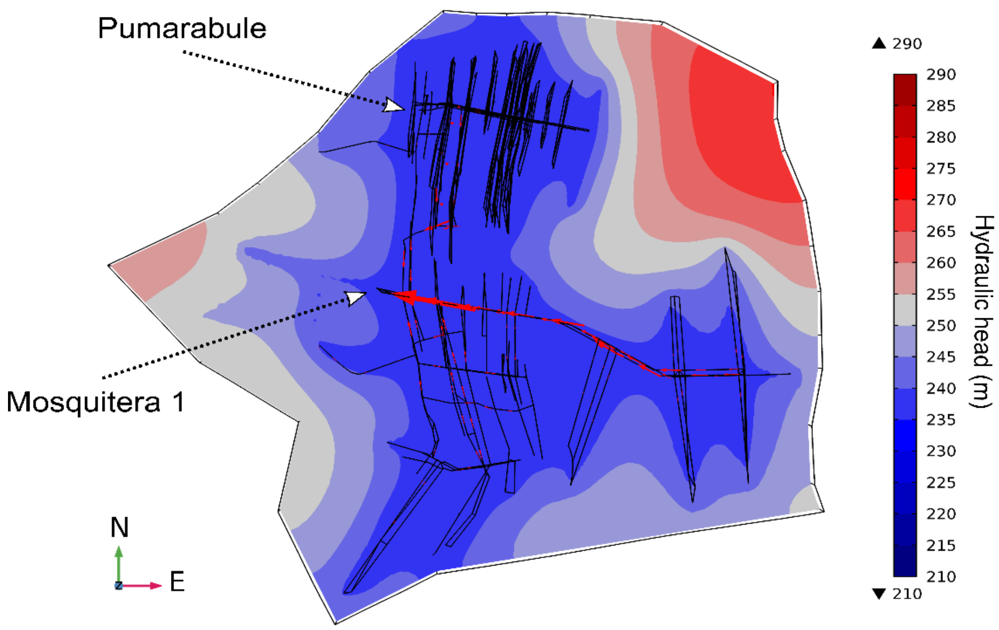

Fig. 7. *Plan view of hydraulic head (m) distribution at -50 masl. A high recharge model has been selected to illustrate the effect of the mine in the depression of levels.*

A further general objective is to implement a contaminant transport model to assess the environmental risks related to the closure of the mine. As open voids constitute the preferential pathways for transported species and suspended solids, groundwater velocities and flow regime in the mine voids have been evaluated to estimate the possible residence times of contaminant species in the galleries. **Fig. 8** shows example results of calculated dimensionless Reynolds numbers that characterize the flow regime in the open voids for the reference model. Turbulent regimes are more likely to occur in the shafts, the end of long transverses and the communication galleries between both mines. The latter is important when pumping is only active in Mosquitera, as all the water from Pumarabule is redirected to the nearby mine through the only four connections located at the 2nd, 4th, 7th and 8th floors. Results indicate that further research is necessary to study the effect of turbulent flows, especially to study water circulation in the shafts, where some flooded mines in the area are or will be utilized for geothermal energy use (Díaz Noriega 2017).

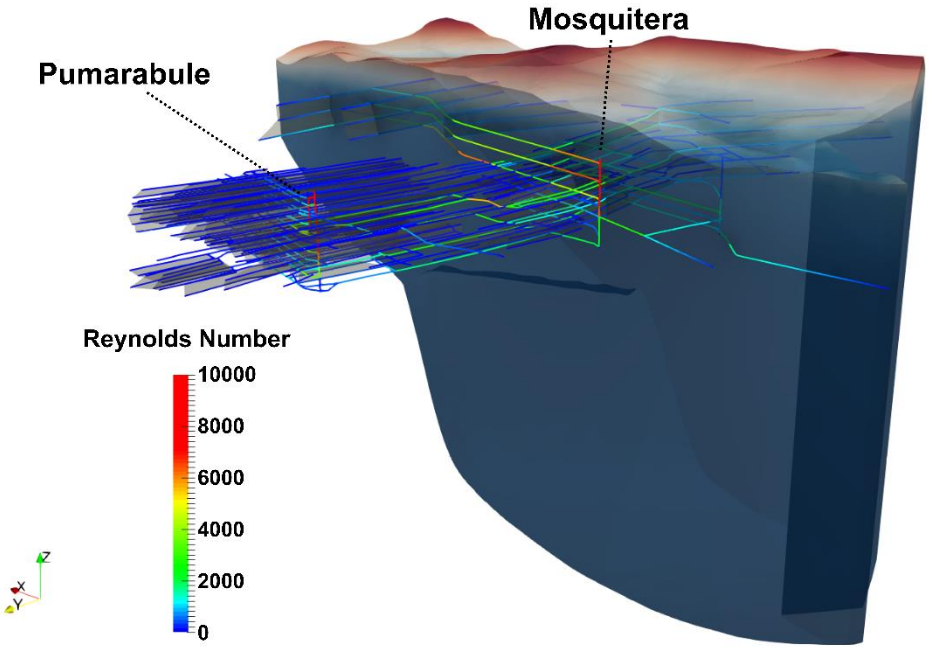

Fig. 8. *Reynolds number in the mine galleries for the reference model. Maximum (turbulent flow) are located in and near the shafts where pumping facilities are active (Mosquitera 1 and Pumarabule).*

The calculated velocities have a large variability depending on the location. In secondary and poorly connected galleries located far from the main shaft and transverses, velocities are very low, ranging from 10^{-3} to 10^{-1} m·d^{-1}. These velocities increase near main transverses, up to values of 1 m·d^{-1} (≈0.1 L·s^{-1} for a gallery with cross-section of 9 m^{2}). In the four documented direct underground connections between Pumarabule and Mosquitera, there have been calculated velocities of 50 – 100 m·d^{-1}, and up to 125 m·d^{-1} for scenarios where the only pumping is produced in Mosquitera (as it is in the normal set up). In the transverses, that collect the water from the galleries and communicate with the shafts, velocities range from values of 10 m·d^{-1} far from the discharging points to maximums of 300 – 500 m·d^{-1} near the shaft. In the shaft maximum velocities have been computed near the pumping facilities, ranging between 500 and 800 m·d^{-1}. A summary of calculated velocities and a representative view is shown in **Fig 9**.

Calculated velocities agree with the lower range of velocities from tracer tests and measurements from other authors (e.g. Wolkersdorfer 2005, 2008). However, caution must be taken on using these calculated values as reference figures because, although obtained from exploration from a broad variety of conditions and parameter ranges, stationary models and average rates are used. Using intermittent pumping rates, with short-term increase, and after heavy rainfall periods, higher velocities might be expected.

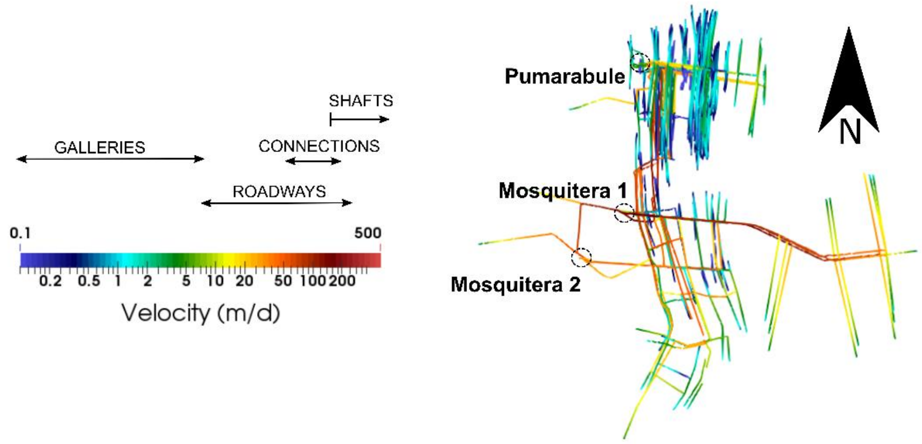

Fig. 9. (Left) *Ranges of calculated velocities in some parts of the mine and,* ***(right)*** *distribution of velocities for the reference model in the mine conduits.*

Candín River has been included to analyse and evaluate the possibility of water loss (from the river to the mine) or discharge (from the mine to the river). A potential zone of river loss has been identified on a stretch where the river flows above the mine workings (in green in **Fig. 10**). The calculated percentage of the total water infiltrated from the river is very small (approx. 3%) compared with the total pumped in Mosquitera. From that 3%, around 1% has been computed that would discharges back to the River at the Southwest of the study area (in red in **Fig.10**). The river flows above the workings and subsidence on nearby areas have been detected, however no inflows from the river into the mine workings have been detected. The identification of infiltration from the river in the mines will require further investigation, including differential gauging in the river.

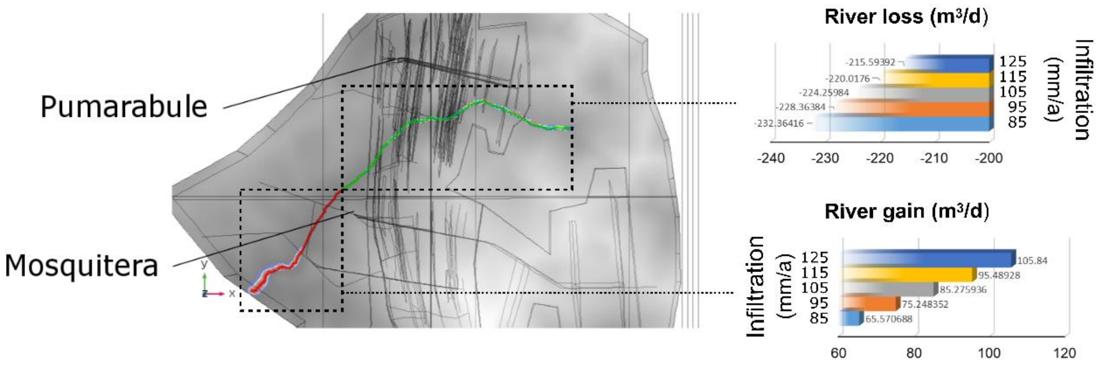

Fig. 10. *Candín River course above the mines. Green for river loss (surface water into the ground) and red for river gain (water discharged out of the model to the river). Gains and losses (in $m^3 \cdot d^{-1}$) for five different recharge scenarios are shown in the right boxes.*

The capacity of pumping facilities to remove the necessary volumes has proven satisfactory until now. However, the potential risk of sudden water discharges to the surface that would have negative environmental impacts because of the presence of associated chemical species have been recognized and evaluated. A potential area of discharge has been identified after modeling in the Valley of Candín River (**Fig. 11**), southbound of Mosquitera 2, which is the topographically lower zone (below 240 masl). **Fig. 11** shows a distribution of calculated heads in the massif for the set of models run. Heads above overflow elevation of the mine (shaft entrance) were computed in less than 10% of the models. However, it has been identified that more than 50% of models show elevations above 240 masl the lower topographic point, at the southwest of the model.

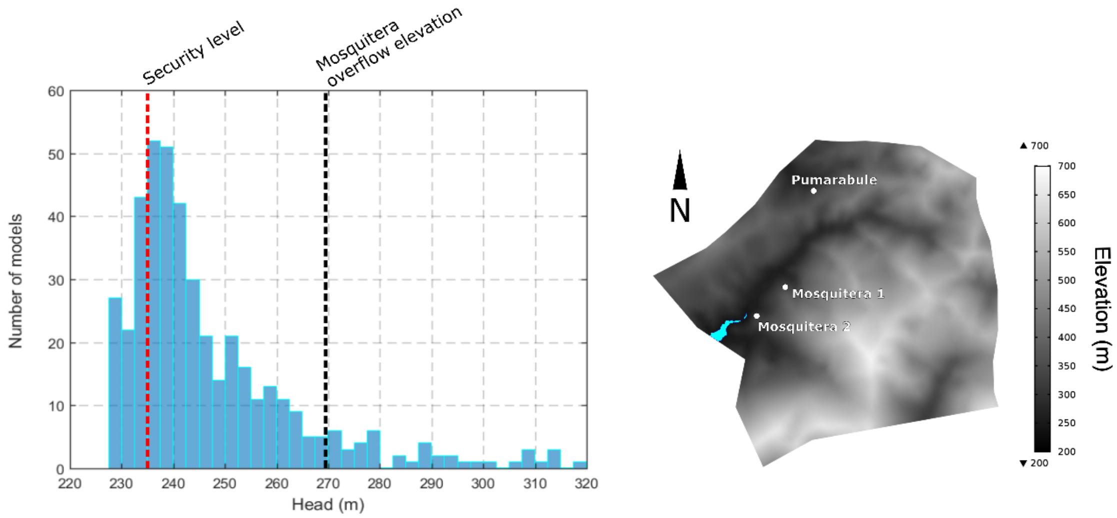

Fig. 11. Left) *Histogram distribution of calculated elevations from accepted models in the vicinity of Mosquitera 2.* ***Right)*** *Potential risk discharge zones (blue) have been identified in the most depressed zones of the area, southbound of Mosquitera 2.*

6 Conclusions

This paper has shown a strategy to conceptualize a complex underground mine system and to develop a numerically efficient water flow model. Using a finite element commercial software, we have adapted a continuum and coupled conduit/porous media formulation that has proved to be very satisfactory in term of computational times and mass balances. This strategy allowed hundreds of models to be explored using Monte Carlo methods that allowed to identify and assess the sensitivity of the solutions to variations in the hydraulic parameters.

The results obtained provided an improvement in the understanding of groundwater flow in an underground mine system in the Asturian Coal Basin. Hydraulic parameters of the massif have been estimated and agree with previous studies in the area. In the mine voids, it has been computed that water velocities can range from less than 0.001 m·d^{-1} in secondary galleries, far from the discharge points to hundreds of m·d^{-1} near the shafts. These velocities provide reference to evaluate the flow regime, to assess the applicability of physical laws —such as laminar flow approach— in some zones of the mine and to develop further efficient formulations adaptable to these systems. The models also constitute the base for later extension to more complex transient, water rebound and transport models.

Finally, this work has shown that groundwater flow numerical models of very complex coal mine systems are feasible with up to date computational tools, but require detailed mine information, a proper previous analysis of the data and an adequate strategy of conceptualization of the elements and processes under study. The definition of the conceptual model is a critical stage and should be explored in future models in the Asturian Central Basin where other mines are under closure and at different flooding stages, which strongly may affect regional groundwater gradients. As so, the presented methodology can be easily adapted to these mines, especially because the geological framework, exploitation methods and geometrical characteristics are very similar, and expanded to include transport models for other applications, such as to study their geothermal potential. Also type and origin of information is analogous in formats and datasets as all the mines in the area have been under operation by the same company. In this sense, the construction of a regional numerical model and a complete centralized database of all the mines in the Asturian Coal region should be a medium-term objective with great utility for stakeholders, academics and authorities to conduct further analysis of environmental impacts in the area.

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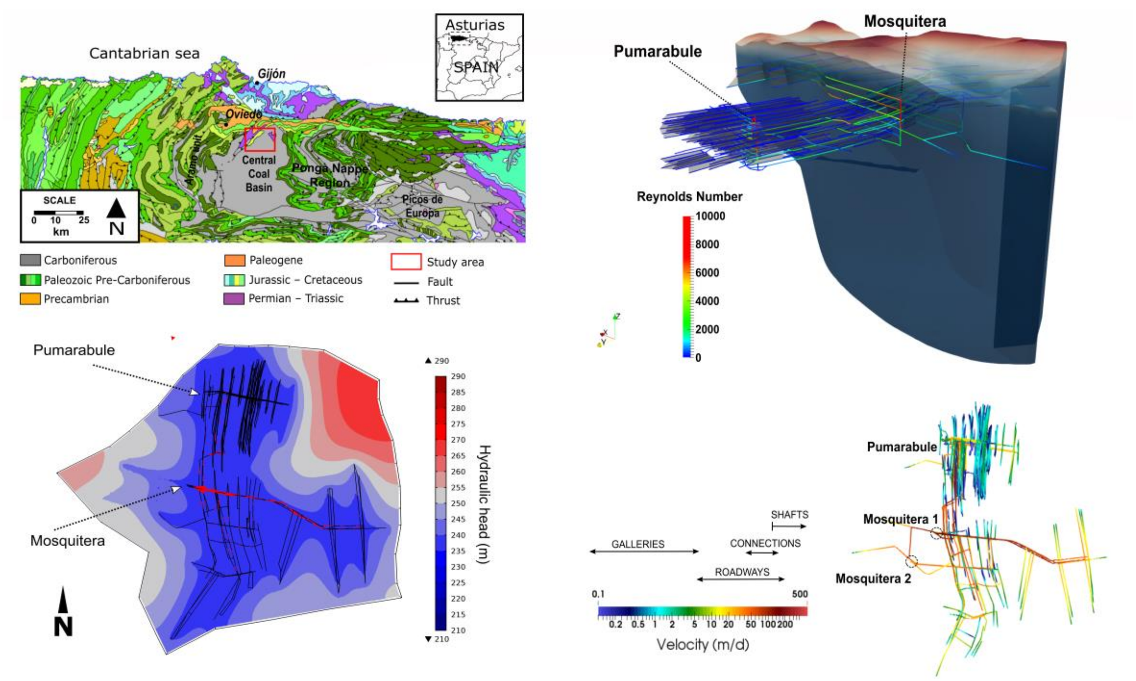
- A methodological approach to incorporate mine information in the numerical models.
- Flow is computed using a coupled-continuum pipe-flow approach.
- Computational efficiency allows calibration using Monte Carlo method.
- Flow regimes, directions and critical velocities in the mine are evaluated.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Cantabrian sea
Gijón
Oviedo
Central Coal Basin
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Picos de Europa
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Paleogene
Jurassic – Cretaceous
Permian – Triassic
Study area
Fault
Thrust
Pumarabule
Mosquitera
Hydraulic head (m)
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10000
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4000
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SHAFTS
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ROADWAYS
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Mosquitera 2

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: