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Groundwater Management in Mining: The Drainage and Reinjection System in Cobre Las Cruces, Spain

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Abstract: Cobre Las Cruces (CLC) is an open-pit copper mine located in SW Spain. The ore body is embedded in a low permeability Paleozoic basement covered by a Cenozoic sandstone formation known as the Niebla-Posadas aquifer. At the mine site, this aquifer is confined under a 120-150 m thickness marl formation. Under natural conditions, groundwater in the confined area at the CLC site shows a north to south natural quality degradation due to high As, NH_4 and B contents. This groundwater is neither appropriate for human consumption nor for irrigation in the confined area and is almost no renewable based on ^{3}H, ^{14}C and ^{36}Cl results. The mine pit intersects and discharges the Niebla-Posadas aquifer. In order to allow the mine drainage and preserve the groundwater resources in the surroundings, CLC has set up a complex Drainage and Re-injection System (DRS) consisting in a ring of 32 peripheral drainage wells, which is connected to a second ring of 28 re-injection wells. This system manages about 3.2 hm^3/year. Prior to be injected, the drained water must be treated by reverse osmosis to remove metals and undesirable dissolved substances, with 91% water recovery.

Key words: aquifer management, mine drainage, re-injection, recharge water treatment, reverse osmosis

1. Introduction

Cobre Las Cruces S.A.U. (hereinafter CLC), is a mining complex that exploits a metallic sulphide deposit formed by an open pit mine from which a copper-rich ore is extracted and a hydro-metallurgic plant in which the mineral is converted into high purity (99.999%) copper cathodes.

The CLC mining operation site is located in SW peninsular Spain, in the province of Seville, between the towns of Gerena and Guillena, in the south-eastern most foothills of the Iberian Pyrite Belt (Fig. 1).

The Paleozoic basement acts as a host rock for the mineralization process. The ore body consists essentially of chalcocite (high-grade copper).

The study area is located in south-western Spain, in the Guadalquivir river basin, which is one of the largest basins in the Iberian Peninsula. Its water resources are fundamental to the development of agricultural and industrial activity in the area and thus it plays a significant role in the livelihood of the surrounding rural areas. The mining activities need to pre-drain the mine site. Operation permits make mandatory that mining do not affect other groundwater users in the surroundings and preserve the water balance of the NP aquifer. To accomplish this, a novel drainage method was devised, which has not been applied in any other mining operation before. It consists in separating the groundwater coming from the Paleozoic rock from the NP aquifer drainage in order to treat the drained aquifer water afterward, to be re-injected again through a newly devised drainage and re-injection system. This creates a peripheral negative barrier around the mine

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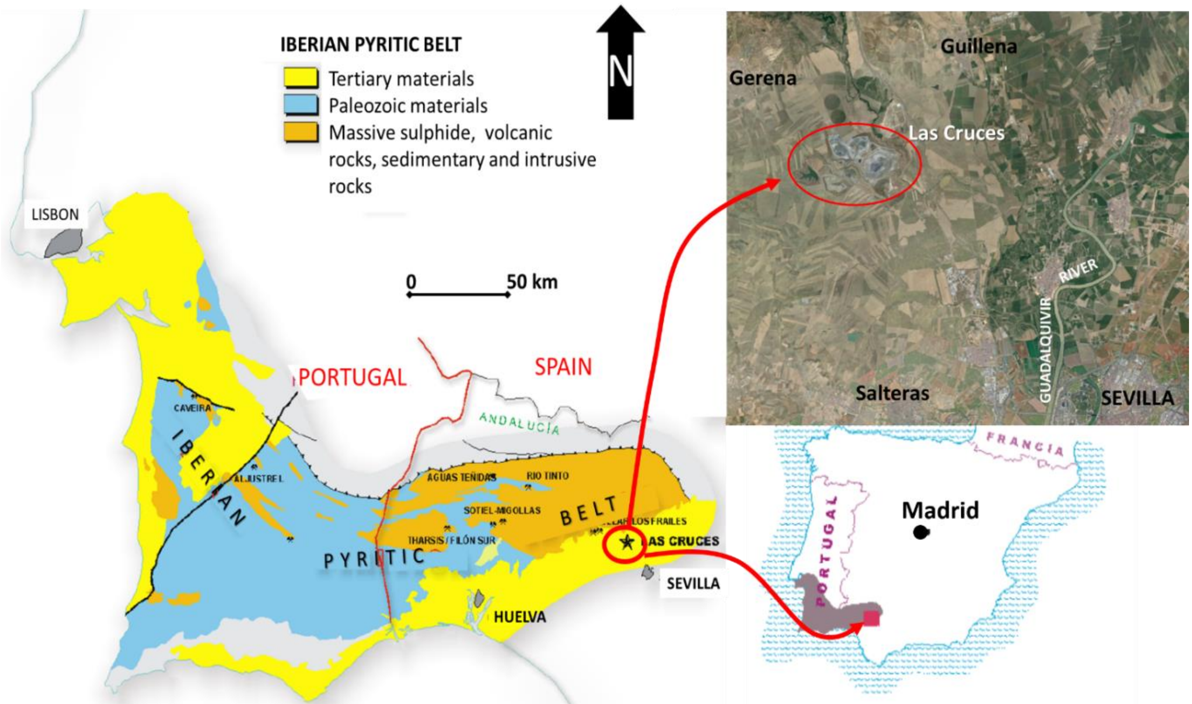

Fig. 1 Iberian Pyrite Belt and CLC location.

together with a re-injection positive barrier that cuts off the drainage drawdown cone and keeps piezometric levels outside the mining area to be close to those before mine operation. Besides, the water injected into the aquifer is purified.

As neither, the water drained from the Paleozoic rocks nor the return flows generated in the treatment of aquifer water can be disposed into the local streams, all this water is consumed in the Hydrometallurgical Plant. Therefore, self-supply is reinforced and the requirement of external water is minimized. At the same time, the generation of mine acid water is avoided.

The goal of this paper is to introduce the characteristics of this Drainage and Re-injection System (DRS) and comment on the interaction with natural water quality. About 3.2 hm^3/year of water are managed through the DRS, of which. 1 hm^3/year comes from the open-pit bottom.

2. Hydrogeological Setting

2.1 Hydrogeological Characteristics

Part of the area under study is covered by loamy Quaternary materials associated with watercourses. They cover the "Gibraleón Clays" formation, consisting on marine marls. The Gibraleón formation thickness increases towards the SE, from the south of Gerena, where the Palaeozoic unconformity crops out. It reaches around 110 m at the mine and 800 m approximately 20 km south of the mine. Near Gibraleón crops out the base of the formation, consisting on the Cenozoic sands formation known as the "Transgressive Miocene base", which makes up the Niebla-Posadas (NP) aquifer. The NP formation consists in a marine transgressive level of sands and gravels of some 20 m thickness, outcropping at the northern margin, which is the recharge area. To the SE the NP aquifer becomes confined beneath the marl. The Paleozoic bedrock below, mainly formed by the Culm formation, presents a varied lithology of shale, granite and volcanogenic massive sulphide deposits. It is affected by a system of major faults oriented SW-NE and a secondary system with a NW-SE direction. The Paleozoic materials are intensely fractured and altered at the top, forming a somewhat permeable upper layer in contact with the NP aquifer (Fig. 2).

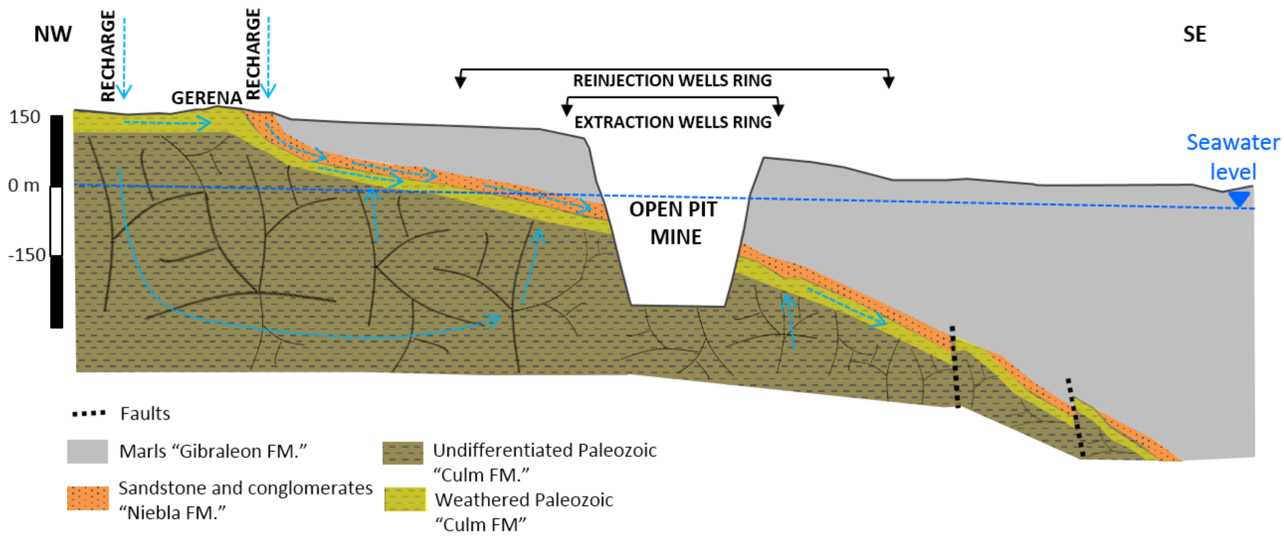

Fig. 2 Simplified geological-hydrogeological cross-section of the Niebla-Posadas aquifer in the area of the CLC mine.

According to data published by the Guadalquivir Basin water Authority (CHG, 2015), most of aquifer recharge occurs by infiltration of both rainwater in the northern fringe where the aquifer crops out and through the local streams and ravines. Aquifer discharge is produced mainly by agricultural abstractions at a rate of 13 hm^3/year. This abstraction rate equals the recharge rate computed for the area.

2.2 Groundwater Dynamics

In order to assess the impact of CLC mining operations on groundwater, a water head-monitoring network was created. It consists of 13 control points distributed around the mining complex that comply with the control network for monitoring the water quality, as defined in the Surveillance Plan. This group of wells is referred to as “third party wells”, as they are not owned by CLC but by other users in the area. Monthly physical and chemical analyses are performed in them. In addition, CLC also has a groundwater head-monitoring network consisting on more than 50 points.

Prior to the start of the CLC mining operations, the highest piezometric levels were observed in the north-western sector. The general flow direction was to the southeast.

There was a piezometric level positive anomaly (higher levels) corresponding to the sands and conglomerates that form part of the NP aquifer where in practice the aquifer disappears due to faulting. There is a positive topography, so the marls rest directly on the bedrock containing the mineralization (Fig. 3), thus redirecting groundwater flow around.

2.3 Hydrochemical Background

The groundwater water characteristics of the NP aquifer near CLC show its progress along the flow lines from the recharge zone (NW) to the deepest zone (SE). The temperature of these waters varies between 14.7 ℃ in the recharge zone and 37.5 ℃ in the deepest exploited parts. The pH values range between 6.8 and 10.6. The positive values of the redox potential (Eh) in the recharge zone tend towards negative values (-300 mV) down flow, showing the reducing conditions in the confined zone of the NPaquifer. The groundwater in the recharge zone is of the Ca-HCO_3 type, evolving through intermediate types, such as Na-Ca-HCO_3 and Na-HCO_3, to the Na-Cl type in the deepest parts. Water salinity increases due to mixing between meteoric water and relict or connate marine water trapped in the pores of the sediments during the Tortonian sea transgression. The mixture between these two end-members (Table) can be clearly seen from the chloride-bromide relationship. The meteoric waters may have a Cl/Br molar ratio of about 200 while the relict marine water has a molar ratio of 665 coinciding with that in current seawater. Based on the chloride and bromide contents a maximum of 8% of seawater in the deep zone of the NP aquifer has been calculated (Fig. 4A). Moreover, the decrease in calcium concentration and the increase in sodium in groundwater are related to a Na-Ca exchange process that takes place in the clays of marine origin interspersed in the material forming the aquifer and the closest confining layers when freshwater is diluting the more saline water (Fig. 4B and Fig. 4C). This shows that the system is far away from flushing due to a very long transit time.

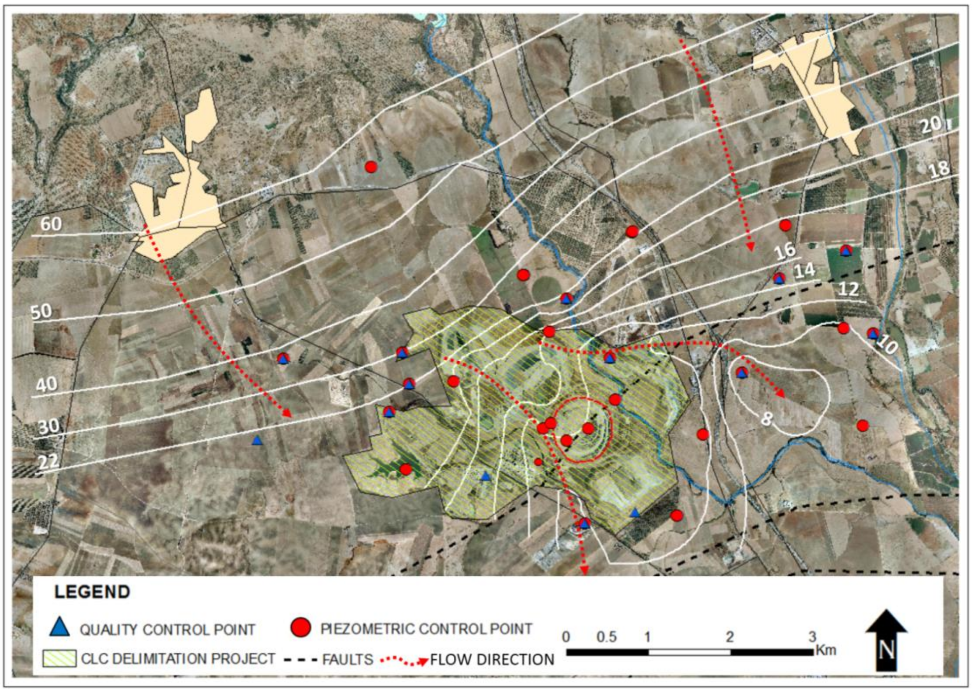

Fig. 3 Piezometric map in m amsl showing the state before the start of mining. The aquifer is not in steady state but under exploitation by farmers and for human supply. Distribution of points in the network control: hydraulic head (red circles) and groundwater quality (blue triangles). This piezometric map is based on the control points represented and a series of additional points alien to the mining activity.

Table 1 Chemical composition of meteoric and saline end-members: Values in mg/L if otherwise not indicated.

WATER	pH	C.E. (μS/cm)	T (℃)	Cl- (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	NH_4 (mg/L)	I (mg/L)	Br (mg/L)
Meteoric end-member	7.1	903	18.6	19.1	48.1	13.1	268.5	102.7	0.1	2.8	14.6	0.10	0.01	0.09
Saline end-member	7.3	5940	37.5	1581.3	16.7	12.5	390.2	95.1	15.0	30.1	1061.8	7.49	0.67	4.95

High nitrate concentrations related to agricultural practices are found, particularly in the aquifer recharge zone. Nitrate disappears where the aquifer becomes confined.

The water of the recharge zone is also characterized by its relative high sulphate concentration (up to 70 mg/L) relative to the chloride content. It is of atmospheric origin and corresponds to a continental environment with human and mining activities. The sulphate concentration decreases along the flow lines. The $\delta^{34}S$-$\delta^{18}O$ plot of the dissolved sulphate show light $\delta^{34}S$ values at the recharge area, which reflects the origin of sulphate. These values tend towards heavier $\delta^{18}O$, and $\delta^{34}S$ agrees with a sulphate reduction depletion process (Fig. 4D).

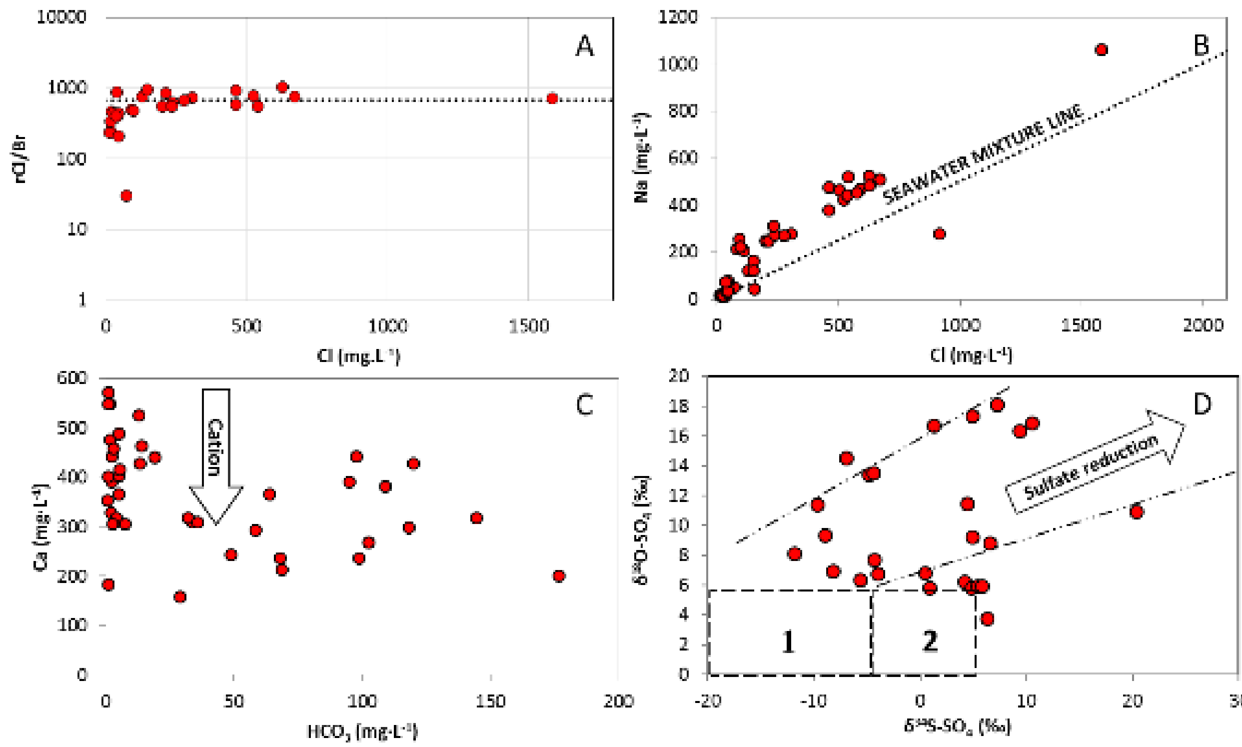

Fig. 4 (A) Relationship between Cl- and Br- ions (the broken line corresponds to the CL/Br molar ratio in seawater. (B): Ionic relationship between Na^+ and Cl. (C) ion relationship between Ca^{2+} and HCO_3^-. (D) Change in $\delta^{34}S$ / $\delta^{18}O$ in the sulfate molecule in groundwater. (1) Sulfate derived from sedimentary oxidation sulfides; (2) Sulfate derived from magmatic sulfide oxidation.

2.4 Groundwater Dating

The age of groundwater around CLC was calculated by Scheiber et al. (2015) to determine the origin of the groundwater and the renewal time. The environmental radioactive isotopes ^3H, ^{14}C and ^{36}Cl have been used. ^3H (12.54 years half-life) was used to date waters considered as modern, that is, water recharged after the 1960s and affected by nuclear tests in the atmosphere. For dating older water, the longer half-life ^{14}C and ^{36}Cl radioactive isotopes of atmospheric origin have been used. ^{14}C (5 730 years half-life) is incorporated into organic matter by plant photosynthesis of atmospheric CO_2 and transferred to dissolved inorganic carbon (DIC) in groundwater by root respiration and decomposition of organic matter in the soil. The dissolution of carbonate materials is also a source of C that interferes with the concentration of ^{14}C. Carbonates are found in the NP calcarenites and in the marl. In fact, the DIC increases down flow. A correction is needed, such as the Tamers and the Pearson methods. ^{36}Cl (301 ky half-life) allows dating transit times between 40 ky and 3 000 ky (thousand years). Based on the results obtained, four zones with different transit times were defined: Recharge (< 0.06 ky); Intermediate (0.06 to 20 ky); Deep 1 (20 to 30 ky) and Deep 2 (> 30 ky) (Fig. 5).

2.5 Groundwater Quality

The water quality of the Niebla-Posadas aquifer near CLC degrades down flow from the recharge zone (NW) to the deeper areas (SE). This degradation is related mainly to the presence and increasing concentration of certain compounds such as ammonium (max = 12.8 mg/L), arsenic (max = 180 μg/L) and boron (max = 3.48 mg/L), and by increasing salinity (EC_{max} = 5 940 μS/cm) caused by higher concentration of sodium and chloride. In the area where the aquifer becomes confined, the

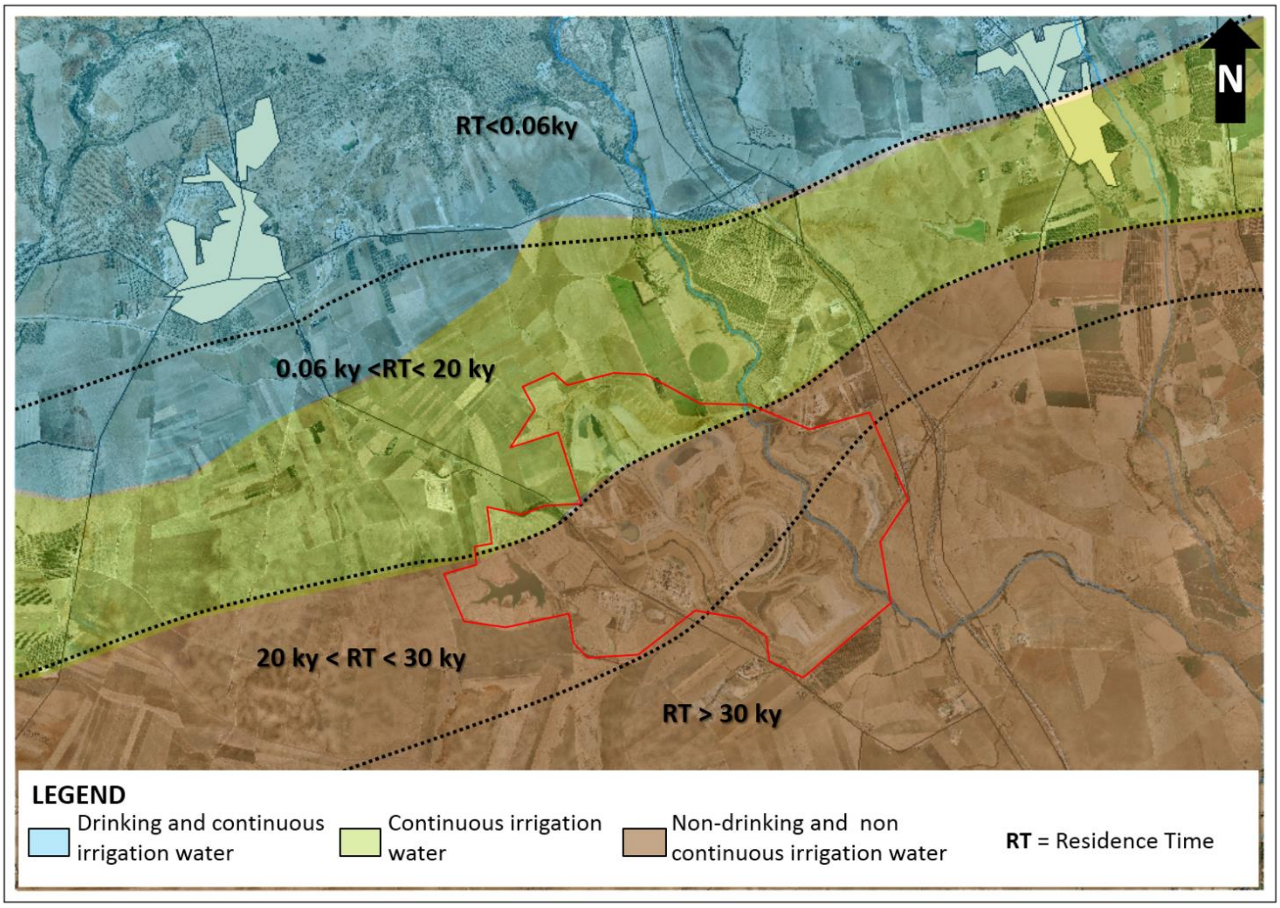

Fig. 5 Zoning of groundwater obtained according with the residence time, also showing water quality based on the As, NH_4, and B concentration and salinity.

concentration of these compounds increases down flow as it becomes deeper. In some cases, the contents exceed the drinking water limits and the limits recommended for continual irrigation. The anthropogenic origin of these compounds was ruled out because the aquifer is confined by a thick layer of low permeability marls.

In addition, the high transit time of groundwater rejects the presence of these compounds being related to pollution in the recharge zone. Furthermore, the presence of these compounds in the aquifer was identified in studies done before the beginning of the mining operations. The concentration of ammonium and boron correlate with the concentration of iodide and chloride. This suggests that these elements could have a marine origin, although the waters contain higher concentration of ammonium, iodide and boron than those corresponding to a simple mixture of fresh water with seawater. This may be related to anaerobic degradation of the organic matter (R1) present in the marls and the aquifer, which is accompanied by sulphide production from sulphate reduction.

$$CH_2O + 4FeOOH + 7H^+ \rightarrow 4Fe^{+2} + HCO_3^- + 6H_2O \quad \text{(R1)}$$

The iron hydroxide present is able to absorb metals, such as arsenic in this case. When the organic matter-rich reducing groundwater contacts the mineralization, iron hydroxides dissolve and consequently arsenic and the absorbed metals are released to groundwater.

Three groundwater quality zones were defined with respect to NH_4, As, B and salinity: (1) water suitable for consumption and continued irrigation; (2) water safe for continued irrigation; and (3) water unfit for drinking and continued irrigation. The CLC mining complex affects Zone 2 and Zone 3.

3. Drainage and Re-injection System (DRS) and water treatment

3.1 DRS and Treatment Description

In order to balance the needs of mine water drainage while maintaining the equilibrium of the water in the Niebla-Posadas aquifer, CLC developed the Drainage and Re-injection System (DRS). This system allows the advanced drainage of the pit with a peripheral ring of 45 wells grouped into 9 sectors, of which 32 wells are currently operating. These wells intercept the water flowing through the aquifer and prevent it from falling along the sidewalls of the mine pit. After being treated, the water is re-routed to a second ring re-injection system composed of 37 wells grouped into 8 sectors, of which 28 wells are currently operating. This second ring surrounds the mine area at a distance of 0.7 to 2.5 km from the mine pit. This allows returning the captured groundwater to its source aquifer (Fig. 6).

The sectors that divide drainage and re-injection correspond to land-use management and planning barriers existing in the area, which must be maintained. Therefore, they do not respond to specific hydrogeological and hydrochemical conditions.

The main objectives of the DRS are:

- Minimize water filtration through the aquifer outcrop on the sidewalls of the mine open-pit.
- Maintain the water balance in the aquifer.
- Reduce the extent of the drainage drawdown cone to minimize the effect to third parties.
- To ensure the stability of the sidewalls of the open-pit and consequently the effective and safe operation of the mine.

In this way, through the DRS, the ring of drainage wells creates a negative drainage barrier while the ring of re-injection wells produces a positive barrier that stops the expansion of the drainage drawdown cone.

All data concerning the operation of the DRS is collected in real time via a remote control system (*Supervisory Control And Data Acquisition*, SCADA). All data is accessible to Management.

This ensures that both the parameters of water quality re-injection (flow, pH, electrical conductivity and water temperature) and the operating parameters of each of the wells (flow, groundwater level, speed and intensity of the pump, etc.) are known at any time. The water pressure in each re-injection well should not exceed 12 bars, which is an Administrative condition to avoid hydro-fracturing. The DRS requires a complex network of high-density polyethylene (PN16) pipelines of over 14 km in length to collect the water of all the drainage wells and send it to the Water Treatment Permanent Plant (WTPP) and afterwards to the re-injection wells.

The natural quality of the aquifer water in the immediate area of the site (Table 2) is conditioned by the long period of time that the groundwater has been in contact with the mineral mass. Therefore, after drainage it requires treatment prior to being re-injected. This ensures that the injection of water meets the quality standards required by Water Administration. To do this, CLC built a Permanent Water Treatment Plant (WTPP-DRS) which purifies the water passing through the DRS by reverse osmosis. Thus, it is contributing to improve groundwater conditions to the benefit of all users (Fig. 7).

The WTPP-DRS integrates pre-filtration, microfiltration, reverse osmosis, settling, filtration and forced evaporation. They are combined at different stages in what refers to the addition of different reagents (Fig. 8), in order to minimize rejections. The water treatment capacity in the WTPP-DRS is 576 m^3/h (160 L/s), through three lines of reverse osmosis with physicochemical pre-treatment and a forced evaporation plant as a final step. However, it has never been necessary to treat more than 140 L/s, with an average of 100-110 L/s. This flow is send to the DRS.

Within each treatment line, after the initial stage of pre-filtration through 75 μm pores, the water passes through the microfiltration module composed of 36 units of 2 m height (Fig. 9A). Each unit is composed of 1500 hollow fibres of 0.6-1.2 mm diameter, through which water is filtered from inside to outside, thus retaining any particle or microorganism sized more than 0.1 μm.

Table 2 Natural quality of the aquifer water collected through the DRS (average values of major components).

HCO_3 (mg/L)	Cl (mg/L)	SO_3 (mg/L)	NO_3 (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	As (mg/L)	Ba (mg/L)	B (mg/L)	EC (μS/cm)	pH	TSD (mg/L)	S í (mg/L)	Cu (mg/L)
358	871	14	2.1	31	722	10	12	10	5.7	1.8	3413	8.2	1744	14.3	0.0025

Fig. 7 Water treatment permanent plant.

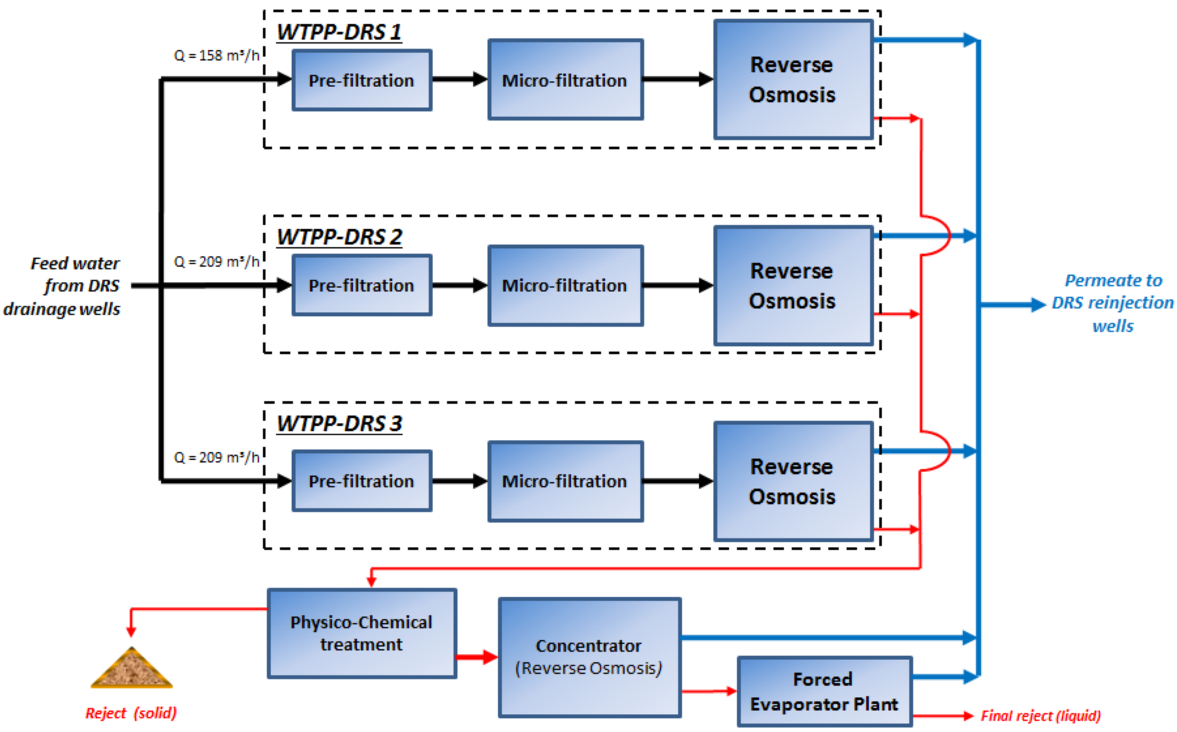

Fig. 8 Water flow diagram of the WTPP-DRS.

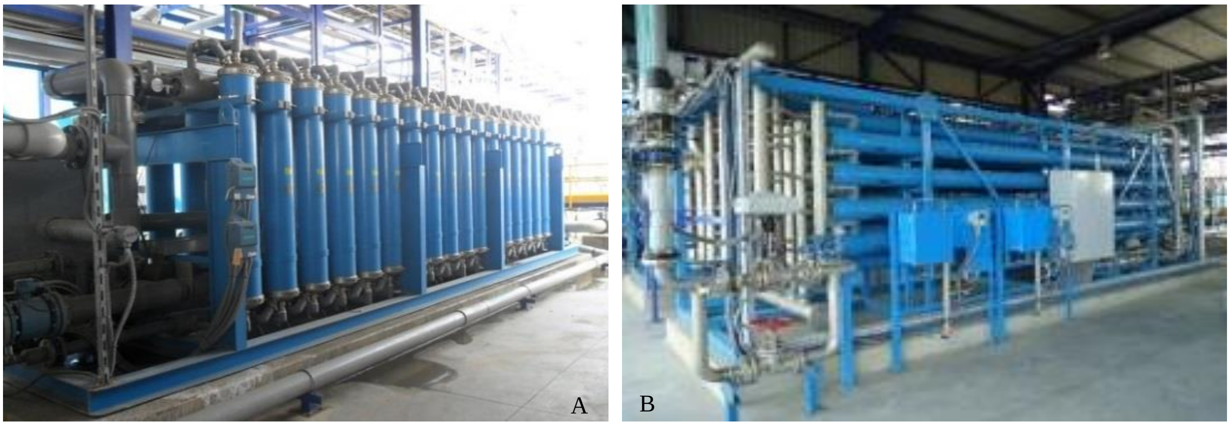

Fig. 9 (A) Micro-filtration units, (B) Reverse osmosis units.

The clarified water is sent to a buffer tank where it enters the first of the three stages. Each stage has a high-pressure pump (15-30 bar) to feed the reverse osmosis unit. The rejection from the first stage feeds the second one and the rejection from the second is sent to the third one by means of a second pressure pump. This process reduces the volume at each stage and at the final rejection stage (Fig. 9B). Each osmosis stage is formed by a number of cylinders, each with 6 spiral membranes, combining sea-water type with brackish-water type, depending on the position and stage. Each one has a filter area of 37-41 m^2/unit. Membranes are specific for boron removal.

The total rejection from the three lines of reverse osmosis is combined in a common physico-chemical treatment (Fig. 10A). It consists of a number of mixing chambers in cascade. With the addition of various reagents and a settler as the final stage, this enables the removal of most of the existing encrusted salts by precipitation and filtration, so that the clarified residue may again be treated by reverse osmosis. This reduces the liquid rejection by 50%. The final product is sent to a forced six-effect evaporation plant with condensate recovery capacity of 13.5 m^3/h and 80% recovery rate (Fig. 10B).

The water management in the WTPP-DRS aims to obtain permeate of excellent quality that meets the re-injection limits defined by the Water Administration. In turn, the final rejection is around 9%. Therefore, the flow decrease due to water treatment is small and easily compensated.

3.2 Results of DRS Implementation

The DRS manages a total volume of approximately 3.2 hm^3/year of drainage water from 37 wells at an average rate of 93 L/s (Table 3). In Fig. 11 the location of these wells is identified, showing for each one the average and maximum drainage rate.

After being treated in the WTPP, the water is re-injected through wells to create a positive recharge barrier at an average rate of 83 L/s, and capacity of at least 272 L/s (Table 4). Fig. 12 shows the location of the re-injection wells and the average and maximum re-injection rate for each one.

As a result of the water treatment through the WWTP, it is possible to obtain a permeate suitable for re-injection, in accordance with the quality standards defined by the Administration (Table 5).

The piezometric map near CLC (Fig. 13) with the DRS in operation shows that in the area to the north of the mine the groundwater flow is from NW to SE and is not affected by the operation of the DRS. This is confirmed by studying the evolution of piezometric wells located in this area, where the water table has not undergone major changes (Fig. 14). This is the case of wells ACG005 and ACG030 located outside the mine complex, north of CLC. The small oscillations associated with rainfall are due to the high storage capacity of the unconfined area.

Fig. 2 (A) Physico-chemical treatment of rejection from reverse osmosis units (HiRec), (B) Forced evaporation plant.

Table 1 Average and maximum distribution flows in the drainage of DRS.

Drainage	X_UTM29	Y_UTM29	Average	Maximum	Drainage	X_UTM29	Y_UTM29	Average	Maximum
EXT102	756716	4154048	1.13	2.52	EXT306	757018	4154969	0.40	1.67
EXT103	756634	4154145	3.78	5.29	EXT308	757029	4154546	20.88	30.65
EXT104	756586	4154223	0.19	2.09	EXT501	757372	4154540	3.77	18.12
EXT105	756558	4154334	0.39	0.66	EXT502A	757675	4154586	0.52	22.36
EXT106	756799	4153982	1.24	2.10	EXT505	757552	4154552	0.14	2.37
EXT107	756566	4154283	1.58	1.96	EXT602	757304	4154086	0.80	1.11
EXT108	756674	4154078	0.64	1.89	EXT603	757316	4154545	1.44	4.22
EXT201	756401	4154421	0.67	1.52	EXT702	757094	4153975	0.04	0.23
EXT202	756539	4154460	0.12	0.59	EXT801	756923	4153948	0.00	0.70
EXT203	756485	4154527	0.36	0.55	EXT901	756928	4155065	0.52	5.46
EXT204	756551	4154620	0.27	0.99	EXT902	757076	4155085	0.67	2.30
EXT205	756504	4154574	1.73	3.60	EXT907	757639	4154990	0.14	0.35
EXT206	756526	4154395	3.99	4.97	EXT909	757739	4154988	19.50	32.01
EXT207	756577	4154683	1.15	1.86	EXT910	757861	4154984	15.19	26.24
EXT301A	756753	4154789	3.44	6.21	EXT911	757947	4154932	1.11	3.20
EXT302A	756923	4154825	1.05	5.13	EXT913	758090	4154749	0.48	1.43
EXT303	756622	4154766	0.86	4.87	EXT919	757849	4154233	0.59	1.77
EXT304	756718	4154842	0.46	3.86	EXT923	757471	4154147	2.97	7.52
EXT305	756853	4154942	1.12	2.10					

Table 2 Average and maximum flows in the re-injection of DRS.

Injection Well	X_UTM29 (ETRS89)	Y_UTM29 (ETRS89)	Average flow (L/s)	Maximum flow (L/s)	Injection Well	X_UTM29 (ETRS89)	Y_UTM29 (ETRS89)	Average flow (L/s)	Maximum flow (L/s)
INY102	755329	4153223	0.57	1.64	INY304	755656	4156527	0.81	8.79
INY103	755176	4153247	0.51	2.57	INY401	759400	4156908	10.29	25.91
INY104	755025	4153473	3.68	6,81	INY402	759087	4156945	0.57	11.91
INY105	754952	4153654	0.18	2.14	INY403	758820	4156961	5.57	29.10
INY106	754905	4153874	0.09	1.08	INY502	759882	4156661	5.71	14.62
INY107	755155	4153904	0.75	7.80	INY503	760514	4155718	4.78	10.41
INY108	755283	4154121	7.67	11.67	INY504	760621	4155218	6.12	21.48
INY201	755182	4154546	1.71	3.23	INY506	760721	4154557	1.94	13.88
INY202	755236	4154672	0.39	4.11	INY601	760765	4154305	1.39	3.34
INY203	755055	4155036	0.32	4.95	INY602	760794	4154158	0.24	1.23
INY204	754978	4155340	0.79	5,70	INY702	757479	4153139	1,96	4,54
INY205	754907	4155673	4.34	13.72	INY703	757663	4153274	0.94	3.90
INY301	756492	4155740	12.35	32.16	INY801	755505	4153004	3.52	6.53
INY303	755763	4156288	5.57	18.34	INY802	755348	4152789	0.22	0.70

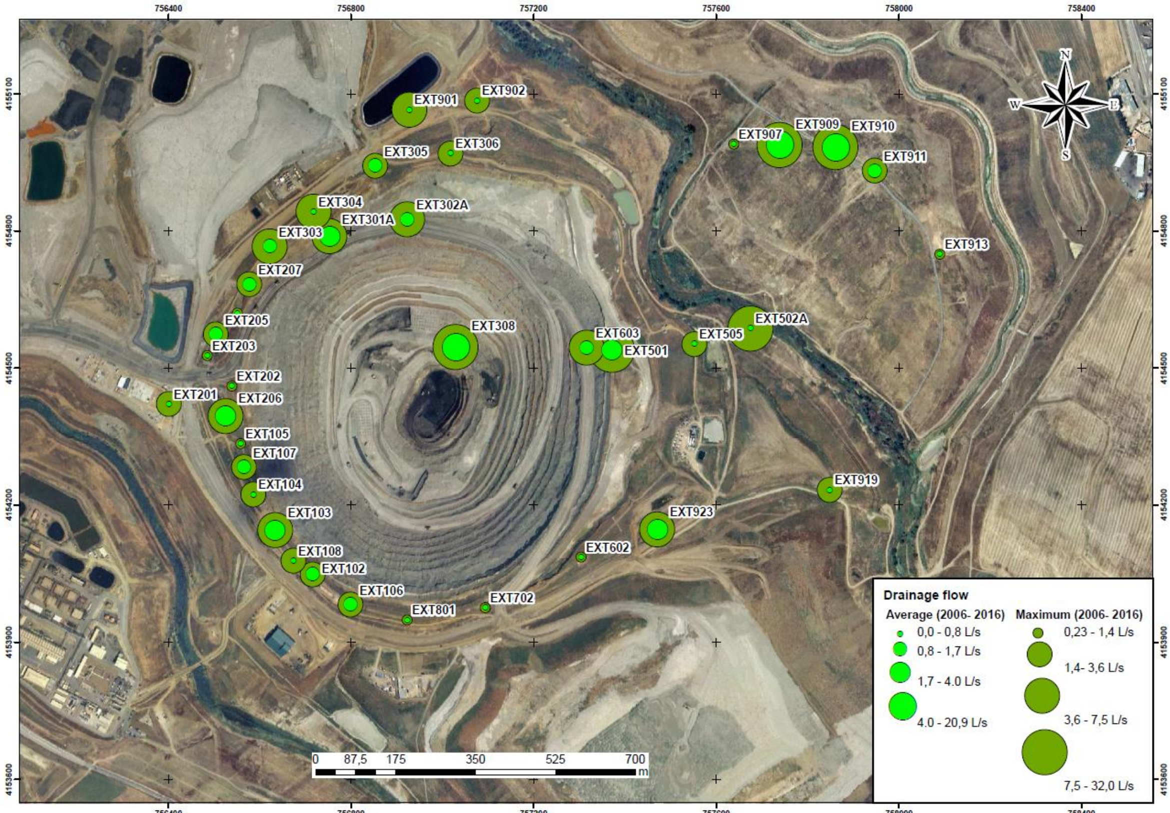

Fig. 11 Distribution of average and maximum flows in the drainage of DRS.

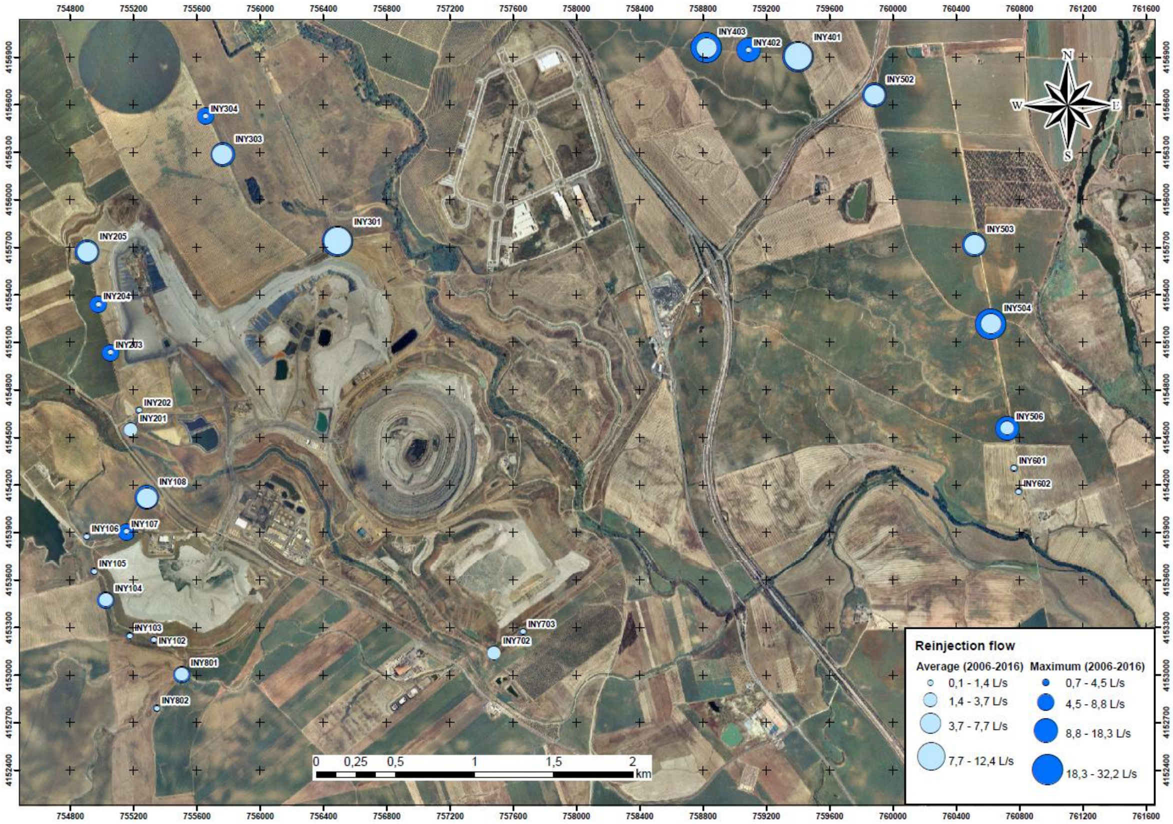

Fig. 12 Distribution of average and maximum flows in the re-injection of DRS.

Table 5 Quality of permeate produced in the WTPP for re-injection (average of major components).

HCO_3 (mg/L)	Cl (mg/L)	SO_3 (mg/L)	NO_3 (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	As (mg/L)	Ba (mg/L)	B (mg/L)	EC (µS/cm)	pH	TSD (mg/L)	S í (mg/L)	Cu (mg/L)
106	138	< 5	2.0	< 2.5	122	< 2	< 3.7	1	0.4	1.4	400	7.8	362	2.4	0.001

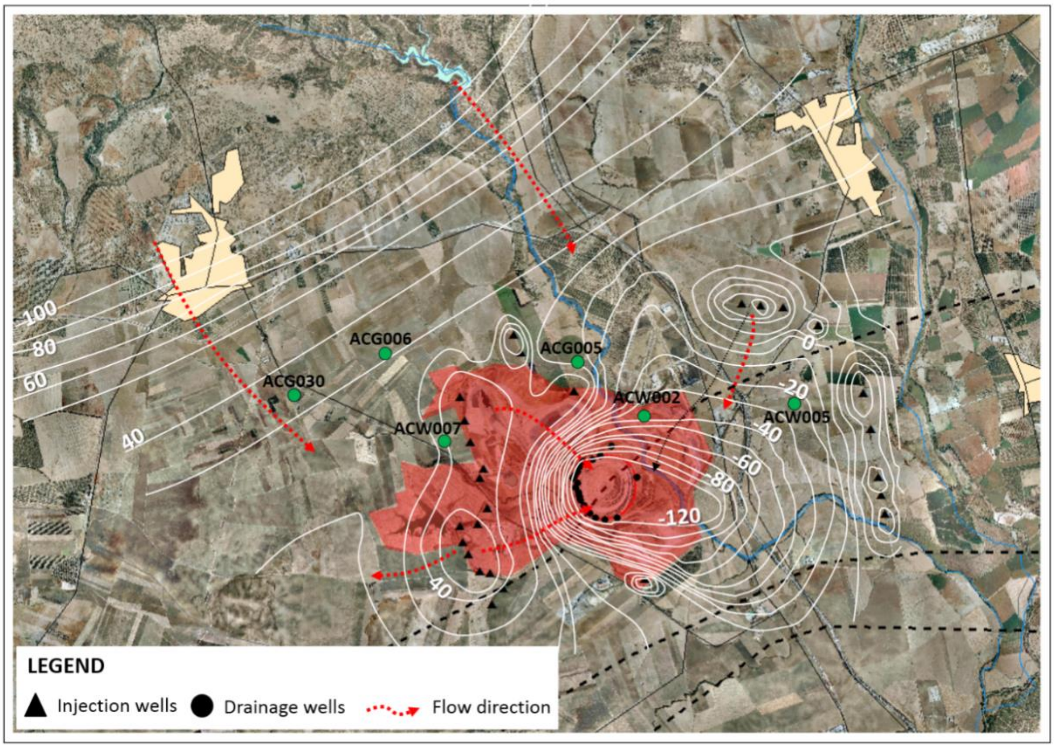

Fig. 13 Piezometric map in m amsl of the area of study area integrating the effect of DRS and location of the selected wells to study the evolution of groundwater level and quality.

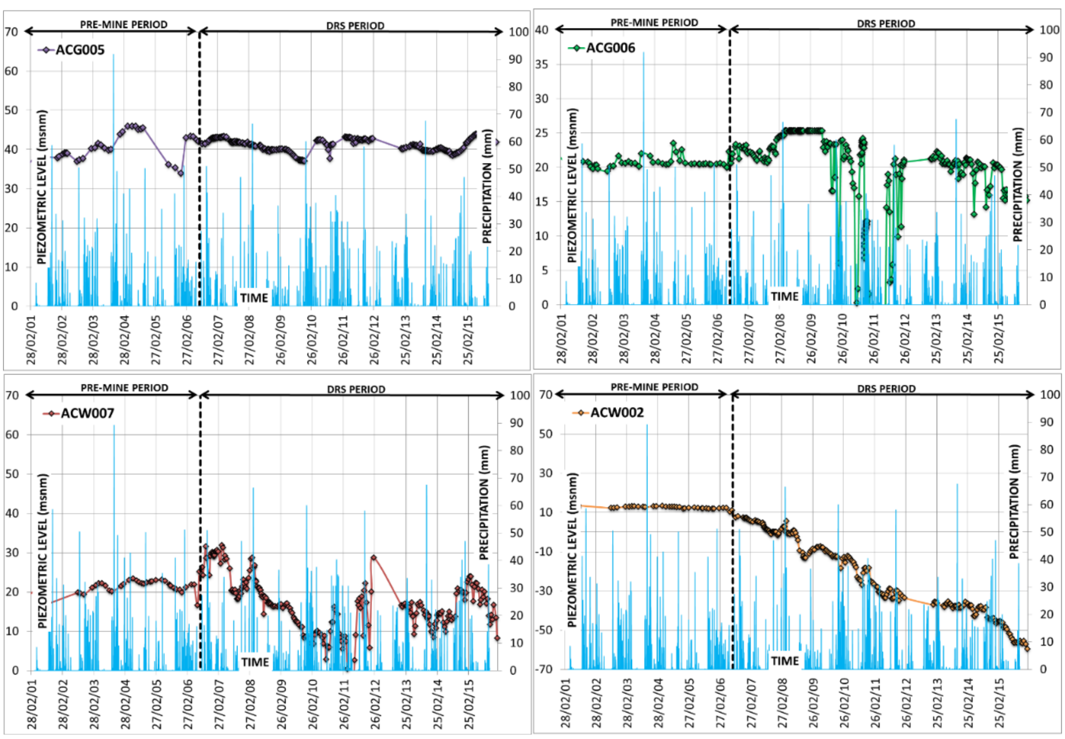

Fig. 14 Piezometric evolution of the wells: ACG005, ACG006, ACW007 and ACW002.

The filtration produced in the reverse osmosis plant, allows the microbiological purification of the water while eliminating colloids that could cause clogging of well filters and decrease re-injection. After 10 years of operation, it has been only necessary to clean 3 of the re-injection wells after being out of service for a considerable period of time.

The cleaning process of wells was performed by combining several techniques: mechanical cleaning of filters by brushing, bactericidal treatment and descaling by combining the use of a weak acid and polyphosphate, and pistoning.

As a result of the activity of the drainage wells, a drawdown cone has been produced where the groundwater level can be more than 120 m below sea level. On the other hand, the re-injection wells create a positive hydraulic barrier that blocks the flow from the northwest side (NW) from reaching the area of mining operations and limits the extent of the drawdown cone. While a percentage of re-injected water is returned to the drainage system, a fraction of the re-injection water escapes to outside the system.

This effect is detected in the wells/piezometers closer to the re-injection ring where the piezometric level variations depend on the actual re-injection flow in the area (ACW007, Fig. 14). The hydraulic gradient is less in the eastern half than in the western half. This may be due to the presence of geological structures such as faults, variations in the hydraulic parameters and/or the distribution of wells of the DRS. The points that are located between the drainage ring and the re-injection ring experience a drawdown of more than 50 m (ACW002, Fig. 14).

In order to assess the impact of CLC mining operations on the quality of groundwater, the evolution of certain chemical species in a number of the wells within the monitoring network were studied. Four wells were chosen based on their location relative to DRS (Fig. 15):

- ACG030 located in the west and outside of the injection ring.
- ACW007 located on the west side but close to the injection zone.
- ACW002 and ACW005, located between the extraction and injection rings; the first one is in the central sector and the second one in the eastern sector.

Two distinct periods can be differentiated. The first corresponds to the pre-mine time and the second to the implementation of the DRS. The initiation of the reverse osmosis treatment can be differentiated within the second period.

To study the evolution of the quality of groundwater, ammonium, boron, arsenic and chloride were chosen as they have the main effect on the quality of these waters.

It can be seen that in the pre-mine period, ammonium was already present in high concentrations, greater than 0.5 mg/L.

Although pre-mine boron concentration data is not available, this species did not present high concentration levels at the time of implementing the DRS.

As for the arsenic concentration, pre-mine data in the four wells is not available. It has generally been observed that the arsenic concentration level varies between 0 and 0.005 mg/L, except in well ACW005, which has higher concentrations of between 5 and 10 μg/L.

Wells located in the western sector show a concentration lower than that of the other sectors, with less than 200 mg/L of chloride.

No changes between the mine pre-period and the implementation of the DRS are observed, nor in the quality of groundwater in the vicinity of the mining site. The chemical characteristics of the water makes it unfit for both human consumption and continued irrigation, both before and after the start of mining operations. In fact, the water abstracted from the NP aquifer was declares unfit for human consumption.

The reinjection system pressure is exerted through several booster pumps installed in line at the outlet of WTPP. The pressure is regulated in each re-injection wells with a group of valve and manometer existing in the head of each well, such that varies between 1-5 bar (12 bar is the safety limit), depending on the availability of water flow and groundwater level desired.

The water re-injected do not have any air thanks to the combination of existing deposits and the feed points of the reinjection pumps, with automatic air purge and vent valves.

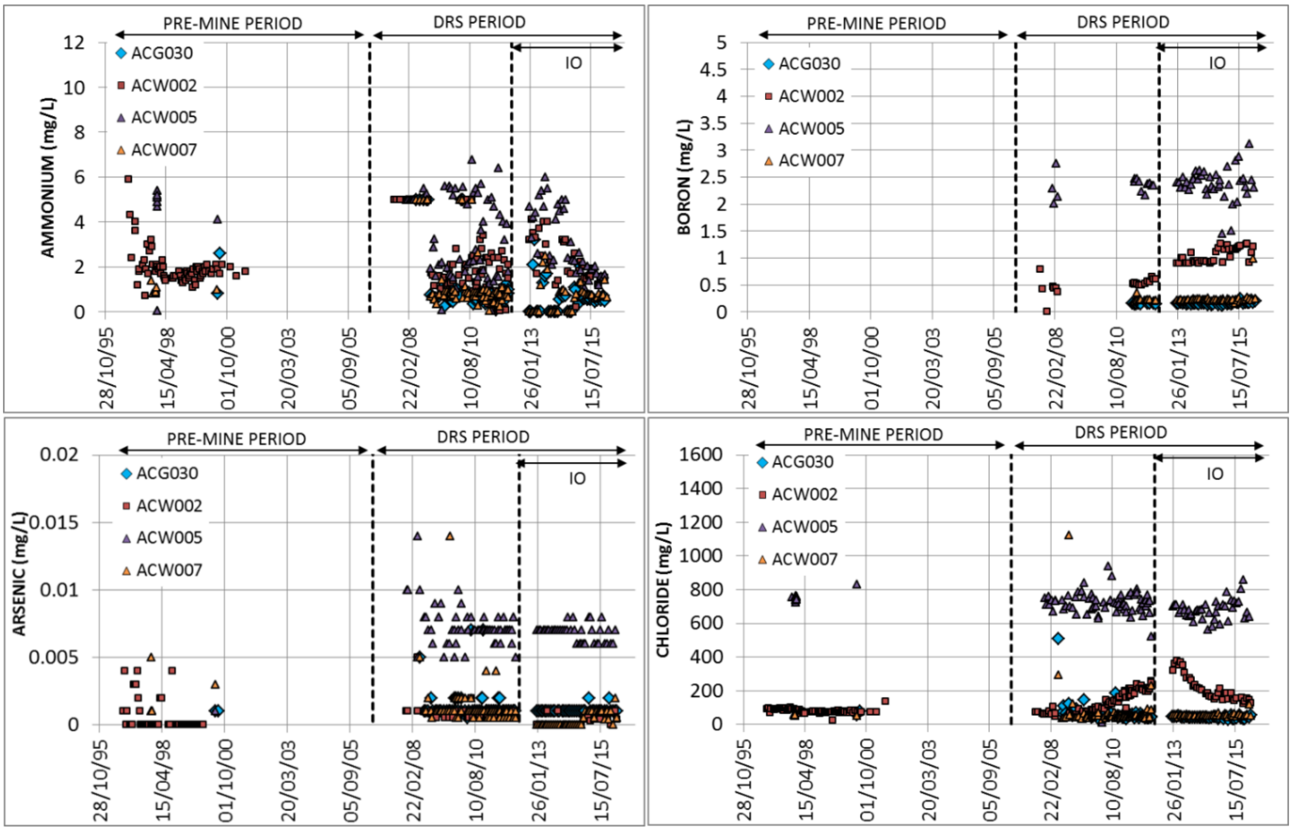

Fig. 15 Evolution of the concentration of NH_4, B, As and Cl in wells ACG030, ACW002, ACW005 and ACW007.

4. Conclusion

Groundwater flow is north to south and show a progressive increase in certain dissolved compounds. Once groundwater flow arrives at the mine area, the natural groundwater quality is definitively not appropriate for human consumption and even partly unsuitable for irrigation purposes due to high As, NH_4 and B contents.

Groundwater in the proximity of the mine site is old water because dating results in more than 20 thousand years of transit time under natural conditions.

In order to allow the mine drainage and at the same time preserve the groundwater resources in the surroundings of the mining area, CLC has set up a complex Drainage-Reinjection System (DRS).

CLC's objectives in conducting this water management system are:

- Improving the geotechnical conditions and security of the mining operations through an intensive peripheral drainage.
- Protecting the Niebla-Posadas aquifer by intercepting the flow of water via the DRS, by preventing the entry of water into the open-pit and being reinjected back into the aquifer 700-2500 m away, after being purified.
- Supplying only the wastewater to the hydrometallurgical plant, either from the open-pit mine (which cannot be re-injected into the aquifer)

or from the wastewater treatment plant of San Jerónimo (14 km away), where domestic and industrial wastewater from around the city of Sevilla is treated.

A Monitoring and Control Program was developed to measure the space-temporal evolution of the groundwater levels as well as the water quality and water balance. In parallel, CLC has developed a Contingency Plan based on a prior risk analysis, in order to ensure stability of the built system. This ensures that if any change occurs by accident or incident, both the quality and the amount of the surface and groundwater resources, which could undergo significant change can be corrected before causing any damage.

The continual operation of the DRS is carried out semi-automatically to perform drainage, treatment and re-injection under continuous supervision of a highly qualified team. It minimizes the water deficit produced in the aquifer due to water treatment DRS and improves substantially the quality of re-injected water respect to the water originally present in the aquifer.

The DRS has been running almost without interruption since 2006 (10 years). During this time, the DRS has enabled to manage about 28.1 hm^3 of water from the aquifer before entering the open-pit mine and contacting the ore, thus reducing many underground water losses.

At same time, the WTPP has been operating since 2009-2010, although in 2008 began operating a mobile unit 60 m^3/h, a third of the current capacity. During these 7 years of operation of the WTPP, about 17.4 hm^3 of water have been treated, making purification of the DRS water and reinjecting it afterwards, to renew the waters of the aquifer and improve its overall quality, so that the aquifer has now better conditions to the benefit of consumers around the mine area.

Acknowledgments

Credit must be given to CLC in recognition of their contribution to the knowledge of the Niebla-Posadas aquifer and the implementation of high standards of quality compatible to the whole of the mining sector.

Abbreviations

The following abbreviations are used in this manuscript:

amsl: above mean sea level.
CLC: Cobre Las Cruces S.A.U. mining company.
CSIC: High Council for Scientific Research (Consejo Superior de Investigaciones Científicas)
DRS: Drainage and Re-injection System.
EC: Electrical conductivity.
ky: Thousand years.
NE: Northeast.
NP aquifer: Niebla-Posadas aquifer.
NW: Northwest.
SE: Southeast.
SW: Southwest.
UPC: Technical University of Cataluña.
WTPP: Water Treatment Permanent Plant.

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