Screening-Level Economic Evaluation of Critical and Strategic Raw Materials stored in Iberian Pyrite Belt Pit Lakes, Spain

Devin Castendyk[1], Skyler Sorsby[2], Javier Sánchez-España[3]

[1]WSP USA Inc., 7245 West Alaska Drive, Suite 200, Lakewood, Colorado, 80226, USA, devin.castendyk@wsp.com, ORCID 0000-0002-8150-5566

[2]WSP USA Inc., 10 Lake Center Drive, Suite 205, Marlton, New Jersey, 08053, USA, skyler.sorsby@wsp.com, ORCID 0000-0003-4612-3199

[3]Centro de Astrobiología, Spanish National Research Council (CSIC), Carretera de Ajalvir, Km 4, Torrejón de Ardoz, 28850 Madrid, Spain, jsanchez@cab.inta-csic.es, ORCID 0000-0001-6295-1459

Abstract

The recovery of metals from pit lakes can potentially generate circular economies, improve water quality, provide critical materials, and demonstrate corporate investments in Environmental-Social-Governance objectives. A screening-level assessment of copper recovery from thirteen pit lakes in the Iberian Pyrite Belt, Spain, using copper cementation, solvent extraction-electrowinning and sulfide precipitation extraction methods, found copper cementation from Corta Atalaya could generate approximately €14.9 million over 5.8 years after a combined expenditure of €12.5 million. The approach used a novel, artificial intelligence, Pit Lake Decision Tool to calculate returns. The Tool can be used to prospect for metal recover from pit lakes.

Keywords: Pit lakes, copper recovery, return on investment, AI, Iberian Pyrite Belt stratification, lessons learned

Introduction

Pit lakes that store large volumes of acid rock drainage and metal leachate may provide unique opportunities for the recovery of critical raw materials (CRMs) and strategic raw materials (SRMs). Researchers in Spain have been exploring opportunities to recover CRMs and SRMs from historic mine tailings, waste rock, and mine water to prompt domestic production, clean up abandoned mine sites, build circular economies and reduce national supply chain risks (Rosario-Beltré *et al* 2023). This work includes acidic pit lakes of the Iberian Pyrite Belt (IPB), Spain (Fig. 1) which have been studied for potential metal recovery for nearly two decades (Sánchez España *et al* 2008), notably, Corta Atalaya Pit Lake (Santofimia *et al* 2023), which has high concentrations of dissolved cobalt, copper, nickel and zinc (Table 1). The European Union identifies cobalt as a CRM and copper and nickel as SRMs.

Conceptually, the extraction of CRMs and SRMs from pit lake water may be less energy intensive and have a lower carbon footprint than extraction from tailings or waste rock which require mechanical excavation, haulage, and potentially, regrinding. Instead, lake water with high dissolved concentrations of metals can be pumped to a dedicated metal recovery facility. Recovery options for copper include: cementation, ion exchange, electrowinning, solvent extraction-electrowinning and sulfide precipitation. The operational life of the metal recovery facility is proportional to the volume stored in the lake plus the volume stored in flooded historic workings that are hydrogeologically connected to the pit lake.

Montana Resources (MR) used copper cementation to recover copper from the Berkeley Pit Lake in Montana, USA, from 1998 to 2013 (Gammons and Icopini 2020). This process lowered the average concentration of dissolved copper from approximately 180 mg/L to 50 mg/L and may be the first reported example of metal recovery from pit lake water. Over the tenyear period from 2003 to 2013, MR recovered 15 million kg of copper using this process, worth an estimated €126 million today. Sánchez-España *et al* (2022) demonstrated copper cementation to be the most efficient Cu-recovery method for acid mine waters in the IPB. Other recovery operations for zinc, copper and rare earth elements are currently being investigated at two pit lakes in former open pit copper mines in the western United States (Castendyk *et al* 2025).

For stakeholders to consider metal recovery options, at a minimum, the expected return on investment (ROI) must be positive, meaning the revenue generated must exceed the combined capital expenses (CAPEX) and operational expenses (OPEX) over the duration of the project. Whereas several studies identify CRMs and SRMs in mine wastes, few studies report the expected ROI from these operations, which can generate unrealistic expectations.

This study presents a screening-level approach to estimate the stored value of CRMs and SRMs in pit lakes and to estimate the ROI for copper recovery. The approach uses a novel, artificial intelligence (AI) application, called the Pit Lake Decision Tool (PLDT), to estimate ROI. We demonstrate the approach for thirteen acidic (pH<5) IPB pit lakes, provide an analysis for Corta Atalaya Pit Lake, and recommend "next steps" for pit lakes passing the screen tool.

Method

The screening approach has three steps: (1) Estimate the mass and current value stored in the pit lake. If the metal value is ≥ €10 million, proceed to Step 2; (2) Compare the stored metal mass in the pit lake to the mass stored in an equivalent volume of Earth's crust. If the mass stored is ≥ 2× crustal mass, proceed to Step 3; and (3) Estimate the ROI over time. Lakes that generate a positive ROI and cross the break-event point within a reasonable period (e.g., 2 years) pass the screening process and should be further investigated (see Discussion). Thirteen pit lakes in the IPB listed in Table 1 were screened for potential copper recovery using these steps.

The first step uses available pit lake volumes (m^3) and published dissolved metal concentrations (mg/L) (Table 1) to calculate the mass (kg) stored in pit lake water. Lake volume is best derived from a high-resolution stage-storage relationship produced from a recent bathymetric survey of the pit lake or from the mine plan at the time of closure

Figure 1 Map of Southwest Spain showing 20 pit lakes (colored circles) in the Iberian Pyrite Belt.

(provided no pit wall failures or mine waste deposition has occurred over time). In the absence of these data, an approximate volume can be generated using the surface area and maximum depth assuming the pit lake has the geometry of a right-circular cone.

If published metal concentrations are not available, concentrations (specifically, copper) can be estimated via the PLDT using a tree-based ensemble machine-learning method (XGboost) applied to the International Network for Acid Prevention (INAP), Pit Lakes Database (Richards and Castendyk 2024) and other data sources. The Database contains chemical analyses from >2,600 water samples collected from over 270 pit lakes located in 25 different ore deposit types. These data are used to predict dissolved copper concentrations in surface waters around the world. The fitted machine-learning model predicts low, best-fit, and optimistic copper concentrations for a user-selected pit lake which informs the initial stored metal mass estimate for the ROI calculations. The current commodity price (€/kg) is multiplied by the stored mass and a recovery efficiency factor (assumed to be 95%) to estimate the present-day stored value.

In Step 2, the mass of each metal stored in pit lake water is compared against the mass stored in an equivalent volume of rock at a concentration equal to the average crustal abundance on Earth. We assumed a bulk rock density of 2,600 kg/m^3 and a copper concentration of 68 ppm (https://periodictable.com/Properties/A/CrustAbundance.al.html; March 31, 2025).

In Step 3, the PLDT is used to estimate the ROI for various copper recovery methods using the machine-learning derived estimates of low, best-fit, and optimistic concentrations as initial estimates. To calculate the ROI over time, the user selects the predicted copper concentrations or provides an observed concentration. The user also provides the lake volume, a realistic influent flow rate to the recovery system (e.g., 750 gal/min or 0.047 m^3/sec), and a realistic recovery period (e.g., ≈10 years) for operations. Finally, the user selects the copper recovery method from a drop-down list which currently includes: cementation (C), solvent extraction-electro-winning (SX-EW), chemical sulfide precipitation (CSP), and biological sulfide

Table 1 *Properties of thirteen acidic pit lakes in the Iberian Pyrite Belt.*

Name	Area	Depth	Volume	pH	Co	Cu	Ni	Zn
	Ha	m	m^3		mg/L	mg/L	mg/L	mg/L
Corta Atalaya[1]	16	106	5.8E + 06	2.2-2.8	27	405	6	5,500
Filon Centro[2]	3.8	40	6E + 05	2.4	1.4	17	0.8	33
Confesionarios[2]	2.48	80	1E + 06	2.5	2.7	2	0.1	7
Pena del Hierro[2]	1.87	>50	*3.1E + 05*	2.5	0.7	5	0.0	22
Ntra. Sra. Del Carmen[2]	0.7	32	1E + 05	2.5	1.0	19	0.4	5
La Zarza-W[2]	1.77	>40	*2.4E + 05*	2.6	6.0	151	5.0	207
Cueva de la Mora[2]	1.78	40	3E + 05	2.6	1.1	8	0.5	17
La Zarza-E[2]	0.7	>40	*9.3E + 04*	2.6	2.5	80	2.5	102
Herrerias I[2]	0.81	50	2E + 05	2.8	2.2	25	1.8	101
San Telmo[2]	14.36	107	7E + 06	2.9	0.9	21	0.5	89
Concepcion[2]	1.2	15	4E + 5	3.0	0.9	10	0.1	28
Aznalcollar[2]	28.4	38	6E + 06	3.6	6.7	35	2.6	834
Hererias II[2]	1.42	15	1E + 5	4.7	1.1	8	0.9	27

[1] Volume and monimolimnion chemistry from Santofimia *et al* (2023)

[2] Volumes from Sánchez España *et al* (2009); surface water chemistry from Sánchez España *et al* (2008)

Italicized volumes were estimated assuming a circular surface area and geometry of a right-circular cone precipitation (BSP). The PLDT stores default scalable CAPEX (linked to pump rate) and fixed and variable OPEX for each method based on costs for similar projects in the western United States (Table 2).

The PLDT calculates the daily ROI in US dollars (USD) over time using the market value of the commodity in today's prices minus the CAPEX and cumulative OPEX. Of importance, the Tool identifies the break-even point (ROI = \$0; ignoring inflation) and the net gain/loss over the duration of recovery. Pit lakes worth further investigation will exceed the break-even point within the first few years and show an initial increase in ROI with time.

Results

Table 3 lists IPB pit lakes (from Table 1) that store over €1 million in cobalt, copper, nickel and zinc. Consistent with work by Santofimia *et al* (2023), this study finds that Corta Atalaya Pit Lake has the most potential for metal recovery among IPB pit lakes, storing approximately €20 million in copper and over €118 million in combined metals. Although not listed as a CRM or SRM, zinc makes up 80% of the stored value in Corta Atalaya Pit Lake. The second and third most valuable IPB pit lakes are Aznalcollar Pit Lake, which stores €18 million in combined metals, and San Telmo Pit Lake, which stores €3 million in combined metals. Corta Atalaya Pit Lake was the only pit lake in Table 1 to store over €10 million in copper and was advanced to Step 2.

With a volume of 5.8 million m^3, Corta Atalaya Pit Lake stores approximately 2.3 million kg of copper. An equivalent volume of average Earth's crust with a copper concentration of 68 mg/kg would store approximately 1 million kg of copper. With 2.3 times more copper mass stored compared to an equal volume of average crustal rock, Corta Atalaya was advanced to Step 3.

Fig. 2 compares the estimated ROI (in \$US millions) over a fifteen-year period for Corta Atalaya Pit Lake using four methods generated by the PLDT: C, SX-EW, CSP and BSP. Design criteria assumed an initial copper concentration of 405 mg/L (Table 1) and a pump rate of 0.047 m^3/sec. Copper-depleted effluent from the recovery process is assumed to return to the pit lake, resulting in an overall decrease in stored copper concentration (and value) with time.

This analysis shows that copper cementation is likely to generate a profit for 5.8 years. The CAPEX for plant startup would be \$4.1 million USD (Table 2). The value of copper produced would exceed the CAPEX plus cumulative annual OPEX over the first 5.8 years, increasing the net ROI over time. After approximately two years of operation, the value of copper recovered would equal the combined value of CAPEX plus cumulative OPEX, called the "break-even point." At 5.8 years of operations, the value generated from

Table 2 *Costs in \$USD millions for copper recovery at 750 gallons/minute (Castendyk et al 2025).*

Cost	C	SX-EW	CSP	BSP
CAPEX	\$4.1	\$28.5	\$4.3	\$7.8
OPEX (annual)	\$1.6	\$3.1	\$8.5	\$3.7

Table 3 *IPB pit lakes storing over €1 million in CRMs, SRMs and zinc, assuming 95% recovery.*

Name	Co (€21.87/kg)[1] € million	Cu (€8.87/kg)[1] € million	Ni (€14.99/kg)[1] € million	Zn (€3.14/kg)[1] € million
Corta Atalaya	3.3	20	0.5	95
San Telmo	0.1	1	-	2
Aznalcollar	0.8	2	0.2	15

[1] Commodity prices from London Stock Exchange Global (LSEG), September 9, 2024

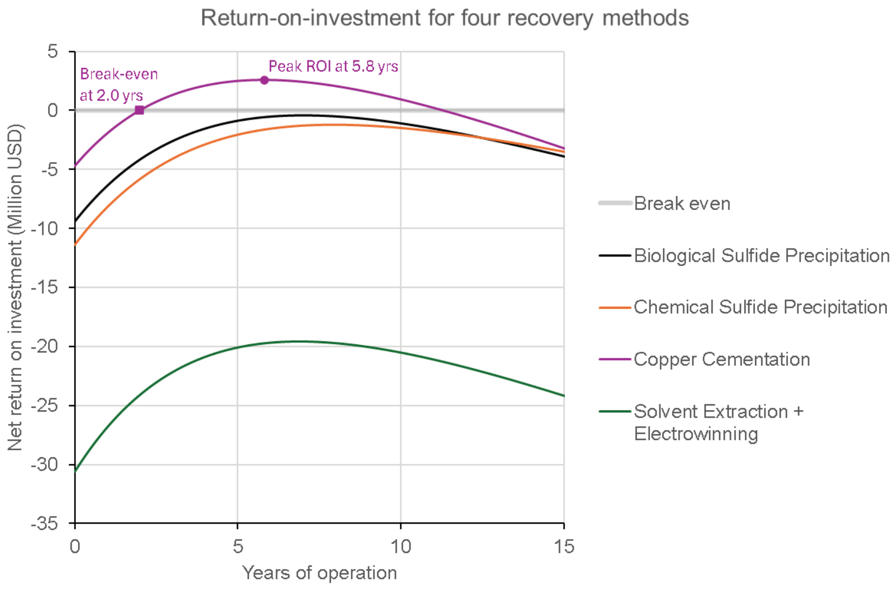

Figure 2 *Estimated net ROI using four different copper recovery methods at Corta Atalaya Pit Lake.*

copper recover would peak at approximately \$16.0 million USD (€14.9 million) after an expense (CAPEX and cumulative OPEX) of \$13.4 million USD (€12.5 million) for a peak ROI of \$2.6 million USD (€2.4 million). Beyond 5.8 years, the ongoing OPEX costs would exceed the value generated by continued copper recovery, eroding the net ROI over time. After 12 years of operations, the net ROI would reduce to zero.

The value of copper recovered using other methods also exceeds the annual OPEX over the first five to seven years. However, the initial CAPEX is significantly higher for these methods (Table 2) resulting in a large, negative ROI at time zero. As a result, the net ROI from these methods did not pass the break-even point, suggesting these methods may not be profitable at present time.

Discussion

When applied to thirteen pit lakes in the IPB, the screening tool found that one pit lake, Corta Atalaya (the biggest and most metal-rich pit lake in this mining district) has the potential to generate a positive ROI using copper cementation methods. For ESG benefits, circular economy development, and resource resiliency, some stakeholders may be willing to invest in copper recovery even if the net ROI is low. For other methods (SX-EW, CSP, BSP), the ROI produced from metal recover did not pass the break-even point, which makes metal recovery less interesting for stakeholders.

In addition to costs, there are two important differences between the copper recovery methods considered: the form of the final product and effluent pH. Although initially more expensive, SX-EW produces a salable product of nearly 99.5% pure copper, whereas copper cementation and sulfide precipitation produce concentrates that must be sent to a smelter for refinement. Smelter costs decrease the ROI of both cementation and sulfide precipitation methods. The sulfide precipitation process decreases the pH of the process effluent, whereas SX-EW and copper cementation have little impact on pH. Treatment of acidic effluent can increase the cost of sulfide precipitation unless effluent is directly discharged back to the pit lake.

For stratified, meromictic pit lakes like Corta Atalaya, copper-rich water stored in the deep layer (monimolimnion) could be pumped to the copper recovery plant and copper-depleted water could be returned to the shallow layer (mixolimnion). This could ensure a (more or less) constant copper concentration in influent to the recovery plant over the first few years of operation.

It may be possible to combine copper recovery with the recovery of additional metals to increase the value obtained from a pit lake. Castendyk *et al* (2025) discuss a plan for a pit lake in the United States where copper will be recovered by cementation, followed by the precipitation of aluminum hydroxide by titration, followed by the recovery of zinc by ion exchange and sulfide precipitation. A similar process at Corta Atalaya could increase value by recovering zinc.

The volume of a pit lake is a critical factor influencing ROI. For Corta Atalaya Pit Lake, the analysis used copper concentrations for water in the monimolimnion, the deepest part of the pit lake (Santofima *et al* 2023). Because pit lakes have a cone-shaped bathymetry, where stored volume decreases with depth, the use of the monimolimnion concentration overestimates the stored mass and economic value of copper in Corta Atalaya Pit Lake. That said, most pit lakes in the IPB intersect historic workings which may store additional mass, such that lake volume alone may underestimate the value of the resource. Inclusion of the mass stored in connected mine workings, if applicable, would increase the estimated ROI.

The PLDT is shown to be a useful tool for rapid estimation of ROI from pit lakes, allowing the prospecting of metal recovery from pit lakes on a global scale. However, the CAPEX and OPEX used in the Tool are based on a similar pit lake in the western United States (Castendyk *et al* 2025) and require additional refinement to ensure applicability to Spain. Key factors include: electricity costs, distance from mine site to a smelter for the processing of concentrate, reagent costs, and environmental permitting. A detailed review of potential environmental effects, carbon footprint (from transportation), etc, would be needed as part of an advanced analysis. Future updates to the PLDT will include (1) provide CAPEX and OPEX for additional CRMs, SRMs and economic metals such as zinc, (2) factor inflation on initial CAPEX into ROI, and (3) add more copper recovery methods such as electrowinning and ion exchange.

For pit lakes that pass the three-step screening process presented here, the following "next steps" should be completed: (4) Collect a new water quality profile to verify concentrations and update the screening level estimate. Water samples should be collected at a high resolution (e.g., one sample per five meters depth) and/or a high-resolution profile of specific conductance should be collected and correlated to available metal concentrations to plot the metal concentration as a function of depth for the entire water column; (5) Define a high resolution stage-storage relationship for the pit lake using a recent bathymetric survey or mine plans; (6) Plot the incremental mass stored as a function of depth and sum to obtain the true stored value; (7) Conduct a desk-top study on available recovery methods to estimate site-specific costs; and (8) collect new samples and submit to a laboratory for a bench-scale study of copper recover using the most economical recovery method. This work would then lead to an advanced analysis and conceptual design for a copper recovery system. The authors hope this approach will facilitate more utilization of existing pit lake resources leading to improved ESG practices.

Conclusions:

A three-step screening method using a novel, AI-based, PLDT found that copper recovery from Corta Atalaya Pit Lake using copper cementation could potentially generate a positive ROI, leading to a circular economy and beneficial use for mine impacted water. The PLDT can be rapidly applied to other pit lakes to prospect for other metal recovery opportunities.

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