Bull Eng Geol Environ
DOI 10.1007/s10064-017-1037-0

ORIGINAL PAPER

Resource recovery as a sustainable perspective for the remediation of mining wastes: rehabilitation of the CMC mining waste site in Northern Cyprus

S. Sözen[1,2] · D. Orhon[1,3] · H. Dinçer[4] · G. Ateşok[4] · H. Baştürkçü[4] · T. Yalçın[5] · H. Öznesil[6] · C. Karaca[1] · B. Allı[1] · H. Dulkadiroğlu[7] · N. Yağcı[2]

Received: 13 April 2016 / Accepted: 20 March 2017

Abstract This paper highlights resource recovery and stabilization as the novel approach adopted in the rehabilitation strategy of the abandoned copper mine site (CMC mine) located in Northern Cyprus, recognized as a source of chronic pollution problems. The site holds 9.5 million tons of tailings stored in poorly equipped ponds. The waste contains pyrite and chalcopyrite undergoing slow oxidation; this way, sulfide has been partly converted to sulfuric acid causing severe acid mine drainage problems. The rehabilitation strategy adopted the EU's key principle of resource recovery, where all tailings would be processed for copper recovery and stabilized to further prevent the chemical mobility of heavy metals before final landfilling. A leaching-cementation process, with no chemical usage, except for lime stabilization after recovery, was designed for this purpose. The corresponding action plan entailed that all the waste material be processed in situ, in a zero waste environment. Accordingly, the remediation will be carried out in a sequential process involving emptying the ponds for resource recovery, preparing the necessary number of emptied ponds with sufficient holding capacity, as selected landfill sites in a way to secure and provide all necessary measures imposed by international regulations for containing and controlling hazardous wastes. Finally closure plans will be implemented for the rehabilitation of the mining site to reclaim full attributes of natural characteristics.

Keywords Copper mining waste · Acid mine drainage · Resource recovery · Sustainable rehabilitation · Hazardous waste landfill

Introduction

The abandoned copper mine site located in the Lefke (Lefka) area of Northern Cyprus has been one of the most significant sources of a wide array of chronic pollution problems in the world. It was always identified as the cause for all the consequences of environmental degradation in the area, due to water and soil contamination typically associated with mining activities (Bhattacharya et al. 2006). Today's Zaman (Oruç 2007) refers to a report for the pollution problem where the region of the CMC mine was described as a "death valley", arguing that "the problem posed a serious treat for the entire Aegean region".

There are many studies that were undertaken to determine mine drainage (Frempang and Yanful 2006; Yesilnacar and Kadiragagil 2013). Copper mining has been

✉ S. Sözen
sozens@itu.edu.tr

1 ENVIS Energy and Environmental Systems R and D Ltd, ITU Arı Teknokent, Arı-1 Building No.16, Maslak, 34469 Istanbul, Turkey

2 Faculty of Civil Engineering, Environmental Engineering Department, Istanbul Technical University, Maslak, 34469 Istanbul, Turkey

3 The Science Academy, Beşiktaş, 34353 Istanbul, Turkey

4 Mineral Processing Department, Faculty of Mines, Istanbul Technical University, Maslak, 34469 Istanbul, Turkey

5 Geological Engineering Department, Faculty of Mines, Istanbul Technical University, Maslak, 34469 Istanbul, Turkey

6 PortİSBİ-Cyprus Free Zone and Marine Logistics Services Limited, Famagusta Free Port and Zone, Famagusta, Turkish Republic of Northern Cyprus

7 Environmental Engineering Department, Faculty of Civil Engineering, Nevşehir Hacı Bektaş University, 50300 Nevşehir, Turkey

practiced in the Lefke area of Northern Cyprus, for more than 3000 years (Cohen 2002). It is also believed that the name of the island "Cyprus" was derived from the word copper—"cuprous". The modern mining of sulfide ores in the area was started by the Cyprus Mines Corporation (CMC) around 1930, processing pyrite ores for the production of copper concentrate and cement copper. Later, CMC also focused on producing gold and silver, which continued until 1942. The expanding activities of CMC stopped in 1974 and CMC abandoned the mine, leaving behind 9.5 million tons of tailings stored in primitive ponds with no protective measures. Different companies undertook similar mining activities between 1979 and 1987. All installations were gradually dismantled between 1994 and 2002 and the site was abandoned and remained unattended, basically overlooking the major pollution potential involved.

Public concern and related observations started when pollution escalated to visual dimensions. Altinbas et al. (2002) provided a pictorial account of the pollution showing transportation of mining wastes by means of acid mine drainage causing colored deposits—reddish color from iron and yellowish color from sulfur—in the frontal area outside the ponds along the shoreline. They also indicated color condensation in the seawater by the coastline, presumably due to copper containing drainage and deposits.

Related investigations were mostly sporadic and patchy; they failed to provide an overall picture of the problem. Cohen (2002) summarized previous environmental studies, mostly inconclusive, conducted since 1970 and reported the results of analyses on 19 different samples he collected from the tailing ponds and groundwater; sample analyses of three monitoring wells within the site only reflected high iron concentrations in the range of 0.2–12.9 mg/l. Groundwater quality in ten different locations including the Lefke water supply indicated no signs of pollution from seepage and/or drainage. Tailing samples taken from four different ponds contained the expected mineral and heavy metal composition including 0.4–0.7% copper together with very high iron and sulfate levels. Atımtay and Sarıçiçek (2001) and Gücel et al. (2009) reported adverse effects of mine dust precipitation on vegetation causing changes in taste, color and other properties. Baycu et al. (2015) investigated the possibility of growing metal tolerant species in and around the polluted site. Gökçekuş et al. (2003) assessed the characteristics of acid mine drainage; they confirmed that acid mine drainage was the diluted version of the water retained in the tailing ponds, with pH below 2.0, high sulfate and iron concentrations exceeding 2,000 and 100 mg/l, respectively, and basically the same mineral composition as the mining waste. Pebble samples collected from the shoreline were found to be coated by the precipitations of the main heavy metal components of acid main drainage. Later, Gökcekus et al. (2007), reported the impact on ground water based on analyses from five different monitoring wells in the impoundment area, two located along the shoreline. Results indicated high levels of iron up to 82 mg/l; copper up to 8.4 mg/l; aluminum up to 13.8 mg/l and sulfate up to 1066 mg/l in different wells, but offered no possible correlations between different wells. Nevertheless, the authors concluded that pollutant accumulated in ponds and transferred into acid mine drainage were all toxic, and caused significant damage on soil as well as on water resources. Recently, an interesting study was carried out on the awareness of the public in Lefke about the CMC mine (Gündüz et al. 2016). This study indicated that, although the percentage of participants with cancer related health problems was high (40.7%); these incidents could not be directly correlated with pollution problems caused by CMC mines.

Overview of available observations show that while indicative to a certain extent, they are far from providing a reliable scientific basis for a sustainable remediation of abandoned mining wastes in a way to solve the existing pollution problems. Therefore, the site urgently needs a comprehensive project for a sustainable rehabilitation. The objective of this paper is to report the basic components of the action plan for the rehabilitation project in a way to also serve as a workable example for similar polluted sites. The project obviously involves environmental and engineered components to contain the movement of contaminants. In this context, the essential features of the rehabilitation plan are presented with all relevant characteristics, emphasizing how contaminants in the waste, leachate and/or drainage water are to be contained or controlled to prevent mixing with surface and ground waters and transport to the atmosphere in a way to suppress possible risks to the community and environment.

Methodology

The study first involved assessment of essential properties of the tailings and environmental characteristics of the site for the purpose of establishing the necessary scientific basis of the rehabilitation strategy and action plan to be adopted.

Site description

The site containing the abandoned tailing ponds covers an area of around 1.5 km^2. It is located in the coastal plain of the Trodos-Karlıdağ (Troodos Mountains) in Northern

Cyprus; it is located a few kilometers north of the Skouriotissa mine, which resumed its activity in 1996. It now produces high purity copper mainly by processing waste material from previous mining operations, using high technology, i.e., leaching and solvent extraction- electrowinning methods (Johansson et al. 2005; U.S. Department of Interior 2014). The topography of the area extends from the coastal plain where the site is located to approximately to 300 m around the former mine area in the north. The Lefke town is located at 200 m. Further north is the Denizli (Xeros) reservoir created by an earthen dam on the Xeros River, and is currently used to supply irrigation water. Two streams set the boundaries of the site, the Xeros River to the west and the Lefke River to the east, both ephemeral in nature, drying during the summer period (Fig. 1). Aside from Lefke (Lefka) town and Gemikonağı (Karavostasi) town in the west, the land use is mainly agricultural.

The area reflects the typical semi-arid character of Cyprus with hot, dry summers and cool, wet winters, with a yearly average temperature of around 20 °C. The precipitation fluctuated in the range of 185–517 mm/year between 2010 and 2014, yielding an average value of 330 mm/year. During the same period the average evaporation rate was 2080 mm/year, largely exceeding the precipitation as expected for this area.

The site includes 12 ponds covering a total area of 790,000 m^2 holding around 9.5 million tons of copper and pyrite tailings. Typical characteristics of the ponds are summarized in Table 1. There are indications that they were built before 1955 (Lavender 1962). Eight ponds located on the northeast and east sides of the site (ponds 10, 11A, 11B, 11C, 16, 17, 19 and 21) are designated as copper tailing ponds; four ponds situated on the south and southeast side of the site contain pyrite tailings.

As shown in Fig. 1, these ponds retain rainwater during the wet season, which remain and evaporate throughout the dry period, leaving behind a hard crust of sulfur, iron and copper bearing compounds. The moisture content of the material in the upper zones does not drop below 40% by weight, and the crust forms an effective barrier against dispersal of dust particles to the environment.

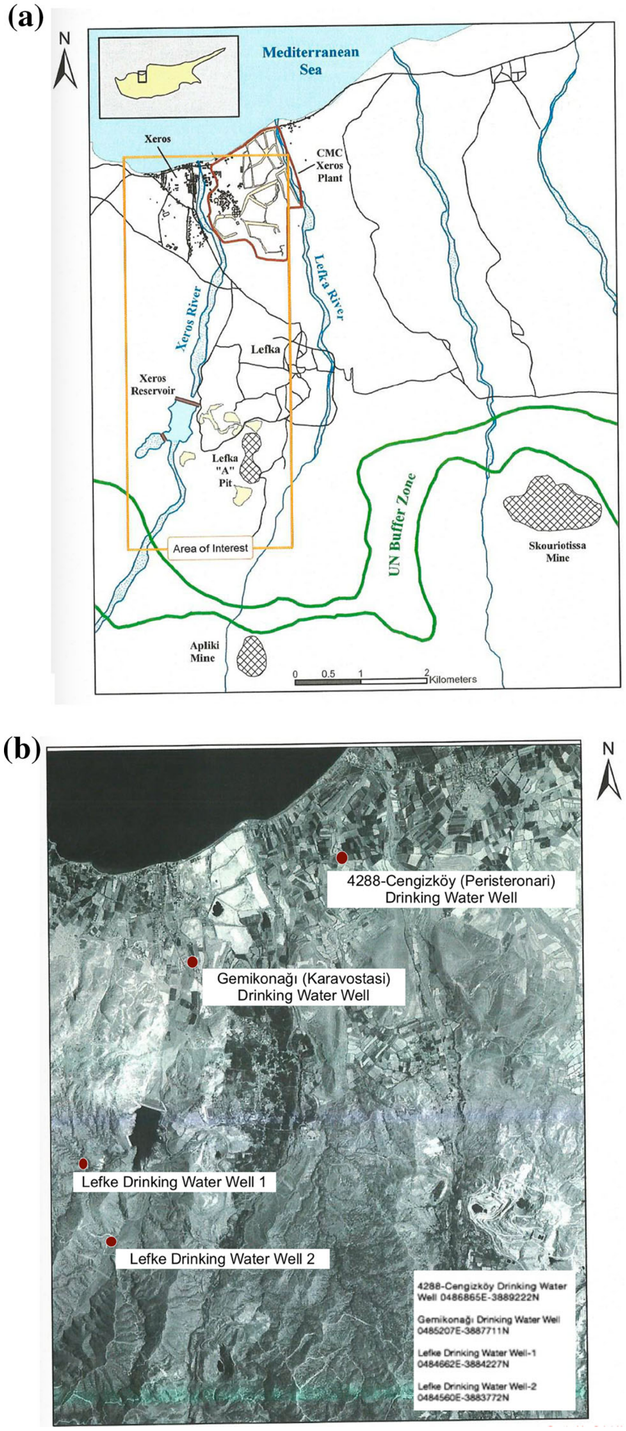


Fig. 1 **a** Schematic line diagram and **b** Satellite image with location of water supply wells of the Greater Lefke (Lefka)—Xeros Area (Cohen 2002)

Chemical characteristics of tailings

The color and composition of the tailings were basically the same: They were mostly fine-grained material dark in color, highly acidic in nature with pH below 2.0, and containing significant amounts of iron, copper and sulfur as well as other heavy metals. For chemical analyses outlined in Tables 2 and 3, tailing samples were taken from each pond using boreholes 1.5 meters apart through the depth of the pond. The samples were then mixed and homogenized for analyses that would characterize the average characteristics of each pond. The average mineralogical composition of the tailings outlined in Table 2, reflects the typical character of the ore with 23.8% of pyrite (FeS_2) and 1.2%

Table 1 Basic characteristics of tailing ponds

Pond no.	Area (m^2)	Stored wastes		Clearance volume (m^3)
		Volume (m^3)	Mass (total) (ton)	
13	74,800	300,000	750,000	300,000
12	106,100	409,000	1,000,000	200,000
17	58,000	270,000	676,000	–
11C	60,800	395,000	1,000,000	–
21	81,600	635,000	1,600,000	–
15	118,000	1,100,000	2,750,000	–
11A	47,490	123,000	307,000	–
19	41,453	130,000	322,000	–
11B	30,055	107,600	269,000	–
16	32,800	210,000	523,000	60,000
10	40,000	70,700	177,000	70,700
14	102,804	65,924	165,055	535,000
Total	793,902	3,816,224	9,539,055	

of chalcopyrite ($CuFeS_2$). The interesting feature of the chemical structure is that it also contains 14.3% of ionized $FeSO_4$. This is basically the result of slow oxidation of sulfide during a long exposure time to oxygen and water in the ponds. Stumm and Morgan (1996) explained the oxidation mechanism of pyrite with the following reactions, where: (1) oxidation of sulfide to sulfate releases ferrous iron, sulfate and acidity; (2) ferrous iron is oxidized to ferric ion, and (3) ferric ion hydrolyzes to ferric hydroxide. The formation of ferric hydroxide can be associated with the reddish-brown color of acid mine drainage as also observed on the site.

$$FeS_2(s) + 7/2\ O_2 + H_2O\ \text{- - -}\ Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad (1)$$

$$Fe^{2+} + 1/4O_2 + H^+\ \text{- - -}\ Fe^{3+} + 1/2H_2O \qquad (2)$$

$$Fe^{3+}3H_2O\ \text{- - -}\ Fe(OH)_3(s) + 3H^+ \qquad (3)$$

Chalcopyrite ($CuFeS_2$), which is the primary copper ore mineral, undergoes an oxidation process similar to pyrite. The oxidation mechanism not only produces acidity sulfate, iron and copper, but the resulting low pH level also releases into solution other metals in both pyrite and chalcopyrite, and creates a potential for passage of pollutants into surface and ground waters.

In this study, a detailed survey was also conducted on the precious metal contents of the ponds, and the results are summarized in Table 3, together with average values. Accordingly, the copper content varies in the range of 0.17–0.78% corresponding to an average value of 0.38%; the current assessment agrees well with similar measurements conducted in 2002 (Cohen 2002). The analyses also indicated that the tailings contained gold in the range of 0.03–1.03 g/ton.

Lithology, hydrogeology and groundwater characteristics

This part should first recognize two excellent recent reviews on Cyprus geology (Cohen et al. 2012; Hakyemez 2014). They complement each other, as Cohen et al. (2012) mostly covered the southern part of Cyprus and Hakyemez (2014), the northern part. The study additionally included the micro-scale geology and hydrogeology, which was directly related to the rehabilitation work, mainly focusing on (1) geological and permeability characteristics of the site; (2) the location of the ground water table; and (3) direction of the ground water flow. In this context,

Table 2 Mineralogical composition of tailings

Components	Mineral composition (%)	Distribution of iron (%)	Distribution of calcium (%)	Distribution of sulfur (%)
Pyrite	23.8	48.9	–	68.9
Chalcopyrite	1.2	1.6	–	2.2
Galena	0.0	–	–	0.0
Gypsum	8.1	–	63.3	8.2
Calcite	1.2	–	16.9	–
Alunite	7.1	–	–	6.0
Fe-sulfate	14.3	20.8	–	14.7
Goethite	10.3	28.7	–	–
Silicates	13.0	–	19.8	–
Quartz	16.1	–	–	–
Others	4.9	–	–	–
Total	100.0	100.0	100.0	100.0

Table 3 Chemical composition of the tailings in the storage ponds

Pond no.	Cu (%)	Co (g/ton)	Au (g/ton)	Ni (g/ton)	Pb (g/ton)	Zn (g/ton)	Pt (g/ton)	V (g/ton)	Mo (g/ton)
13	0.78	446	1.03	24	136	750	0.02	226	124
12	0.44	354	0.68	37	108	1020	0.03	266	120
17	0.50	270	0.67	18	120	357	0.02	134	119
11C	0.58	457	0.69	57	118	751	0.01	345	108
21	0.46	213	0.43	26	64	478	0.03	240	88
15	0.20	291	0.70	16	120	431	0.03	233	112
11A	0.27	150	0.16	18	23	232	0.01	188	59
19	0.20	82	0.19	17	44	388	0.01	165	47
11B	0.17	110	0.15	20	25	317	0.01	140	46
16	0.19	117	0.27	20	42	215	0.02	205	46
10	0.24	63	0.03	38	8	175	0.02	292	19
14	0.20	205	0.48	21	66	271	0.03	219	84
Average	0.38	230	0.46	26	73	449	0.02	221	81

geotechnical investigations in the ponds, geomorphological and hydrogeological surveys and measurements in the region were conducted in order to serve as a basis for remediation and renovation process.

The studied area is located at the border of Troodos Massif and Mesarya Plain, on the Güzelyurt (Morfou) Plain subbasin, which covers a surface area of 415 km^2 and drainage area of 900 km^{2,} where the elevation in the basin changes between 5 and 50 m. Consequently, the land is more undulated compared to other parts of the plain.

Güzelyurt Plain is made up of four main rock types: Troodos Ophiolites in the basement, Middle Miocene Koronea formation comprising reef limestone-gypsum; Pliocene Potami formation comprising conglomerate-sand-silt; Plio-Quaternary Athalassa formation comprising talus deposits, sand, calcarenite; Pleistocene Fanglomerate of Wilson and Ingham (1959) named as Bostancı Conglomerate by Hakyemez (2014) consisting of gravel and sand; and Quaternary alluvium. All these formations are observed in and around the investigation area.

Examination of existing borehole logs shows that the aquifer is mainly Bostancı Conglomerate and alluvium (Geology and Mining Department of North Cyprus-GMD 2009). The 40 m deep PSK 14 borehole (pond borehole) encountered sandy silty clay, sand-gravel and sandy clay between 0 and 13 m and only clay between 13–40.5 m (Geosurvey 2015). These data reveal that the land is more clayey around the waste ponds (Fig. 2). Pumping tests, lab and field measurements of permeability for this investigation, and the previous tests in and around the investigation area yielded that transmissibility and permeability of the aquifer were quite heterogeneous (Table 4). The locations of the wells are given in Fig. 3. The earlier pumping tests done by GMD yielded transmissivities of 850 m^2/day for CMG1 and 20 m^2/day for CMG2; other wells CMG3 through CMG9 are evaluated as unproductive wells. It is not clear whether the unproductivity should be attributed to the aquifer or clogged screens. Boronina (2003) indicated a maximum transmissibility value for this aquifer to be 250 m^2/day; however, Gökmenoglu et al. (2002) reported a hydraulic conductivity value (K) of 0.18 m/day, which supports the heterogeneity of the aquifer.

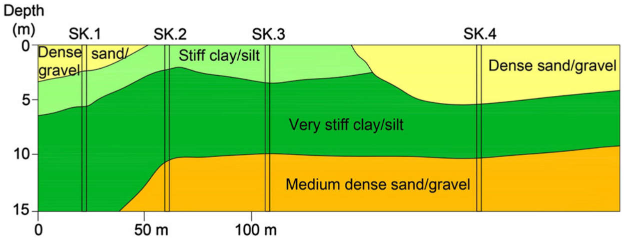


Fig. 2 Geological cross-section drawn using SK exploration boreholes

The permeability tests conducted on tailings material stored in pond no. 14 and the formation underlying the tailings pond resulted in permeability values of 9.56×10^{-8} and 6.1×10^{-6} m/s in samples taken at the surface and at 3.0–3.5 m depth, respectively, under laboratory conditions. In situ permeability tests yielded permeability levels of 2.1×10^{-6}–2.3×10^{-7} m/s between 0 and 13 m in 40.5 m-deep PSK 14 borehole. They showed that water tightness ($K < 10^{-9}$ m/s) could only be obtained in the PSK 14 borehole between 13 and 40.5 m inside the clay layer. The ground water level was at 16 m deep below pond 14, inside the impermeable formation. Additional consolidation tests conducted at the interface between tailings material and natural soil yielded permeability values significantly lower than the threshold level of $K = 10^{-9}$ m/s as will be outlined in the following sections.

Table 4 Pumping tests

Well	Distance to pumping well (m)	Discharge rate (m^3/day)	Transmissivity (m^2/day)	Storativity	Coordinates UTM (m)
4329	41	–	600	0.0098	0486333 3888991
ZN	96	–	976	0.0011	04866375 3888943
YK	47	–	878	0.0062	0486364 3888993
5250[a]	0	1,440	–	–	0486337 3889032

[a] Well no. 5250 is a pumping well, others used as observation wells

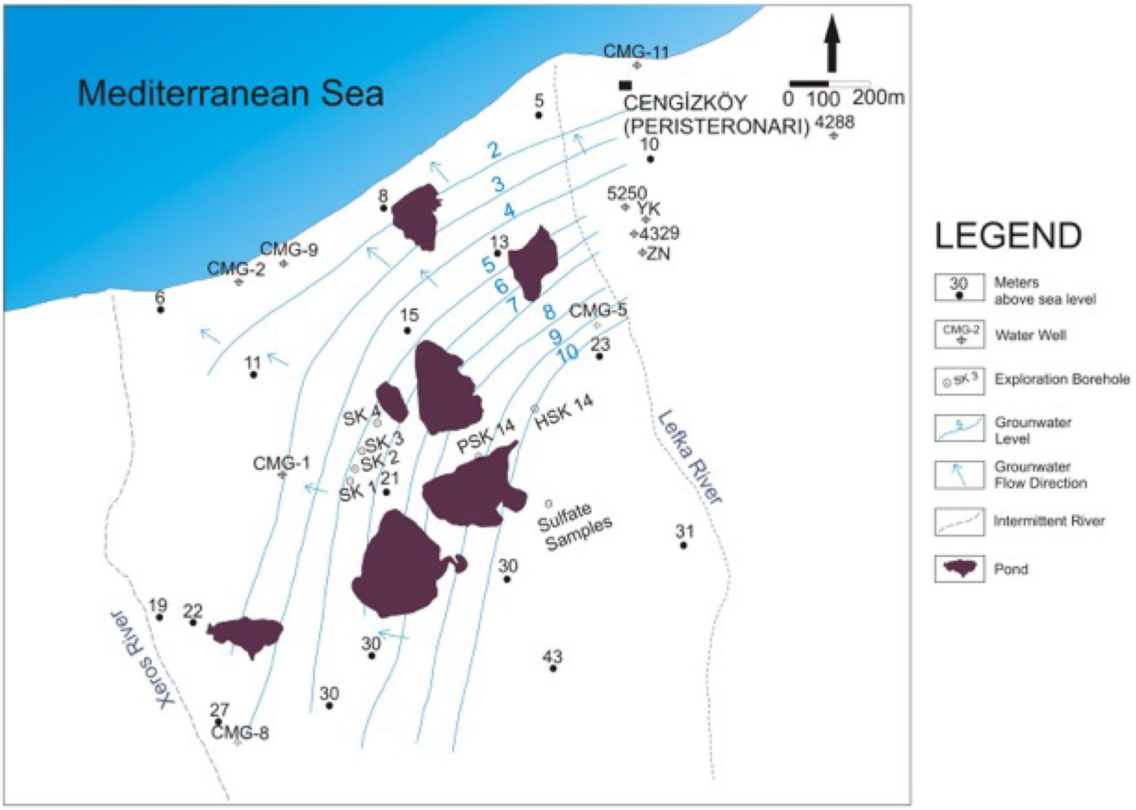


Fig. 3 Water table map, borehole and well locations (this study)

In order to obtain the groundwater water levels, hydraulic gradient and groundwater flow direction, water level measurements carried out in May 7 2015 using the data obtained from six wells (CMG1, CMG2, CMG5, CMG8, CMG9, CMG11) together with well no. 4329 (Fig. 3). They indicated that groundwater flow direction is towards the northwest and Mediterranean Sea, in agreement with similar results reported by MTA (Gökmenoğlu et al. 2002); groundwater flow remains confined mostly within the boundaries of the site towards the seashore, and involves interference and risk of contamination for adjacent water supply wells. As shown in Fig. 1, all water supply wells, namely, Lefke (Lefka) wells 1 and 2, Gemikonağı (Karavostasi) well and Cengizköy (Peristeronari) well, providing water supply to the neighboring towns that are all situated upstream and/or outside the borders of the site, with respect to contaminated surface and groundwater flow in the site.

The water type is $CaMgSO_4HCO_3$ in the samples collected from CMG_2 and CMG_6 boreholes, where sulfate is more dominant than bicarbonates. However, the water type for the 4288 borehole is $MgCaHCO_3$. The existing data show that seawater encroachment (intrusion) is not yet actually seen in the area. Analyses of water samples taken from wells utilized for groundwater level measurements indicated excessive levels of heavy metals including Fe, Al, Zn, Mn and Cu, presumably transmitted from contaminated soil deposits in and around the area.

Legislative framework of the adopted approach

It should be noted that European directives and related technical documents were reviewed, not because of legal inferences to the case study, but because of the quest in the study for exploring the state of the art technology for the solution of the problems explored. In the context, other pertinent international documents were also given serious consideration. In essence, regardless of the status of related legal enforcement and restrictions for a country or localities, it is believed that the solution of a significant pollution problem such as the one tacked in this study should always aim at the best available and/or economically achievable technologies. European legislation is one of the sources that always provide this information.

Mining wastes

Mine wastes necessitate a careful management to sustain the long-term stability of storage and disposal facilities. The major environmental impacts at mine sites can be first considered as the loss of productive land transferred into a waste storage area, and, secondly, as the contamination of surrounding surface and groundwater from water running over chemically reactive wastes.

Guidelines on mine waste management have been developed at the European Union level and provide an advisory framework for best practices. The Mining Waste Directive (Directive 2006/21/EC) on the management of waste from the extractive industries sets up the framework for managing wastes from the extractive industry with the aim of ensuring long-term stability of disposal facilities and preventing or minimizing water and soil pollution.

The most common methods for managing tailings of metal mining operations are defined in “Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities-BREF Document” (European Commission 2009). BREF defines “best available techniques” mainly addressing the first recycle-reuse-reduce (3R) approach for the management of tailings in the copper mining activities. The 3R approach serves both for the reduction of the large volumes and the land requirement and also for the decrease of polluting parameters. The methods mainly depend on backfilling tailings into ponds or underground mines or using them for the construction of tailings dams. The BREF was developed following the Communication from the European Commission COM (2000) 664 on the ‘Safe Operation of Mining Activities’ and is not a part of the information exchange under the IED/IPPC Directive.

Depending on the need for developing technical guidelines for inspections as one of the implementing measures of the Mining Waste Directive, the European Commission has commissioned a study to assess the “Establishment of guidelines for the inspection of mining waste facilities, inventory and rehabilitation of abandoned facilities and review of the BREF document”, still standing as a final draft under discussion.

Hazardous wastes

The main directives that regulate the environmental impacts of mining are mainly identified in directives addressing the “waste” concept. The so-called umbrella directive, Directive on Waste (2008/98/EC) establishes a legal framework for treating waste within the borders of the European Union (EU). This directive is designed to protect the environment and human health by emphasizing the importance of proper waste management, recovery and recycling techniques to reduce pressure on resources and improve their use (The European Parliament and The Council of the European Union 2008).

All the measures that have to be taken for the management of waste from extractive industries have been defined in the Directive (2006/21/EC) covering the whole period starting from the facility building to facility closure, land rehabilitation and the after-closure phase. The directive also includes the aspects for waste characterization and classification criteria for waste facilities (The European Parliament and The Council of the European Union 2006).

Here, one of the waste characterization aspects is the classification of the waste according to the relevant entry in Decision 2000/532/EC, with particular regard to its hazardous characteristics. The waste list given in the Annex of this Decision describes Tailings in the frame of 01 Wastes Resulting from Exploration, Mining, Dressing and Further Treatment of Minerals and Quarry as non-hazardous waste (The Council of the European Communities 2000).

But wastes, which are considered to display one or more of the properties listed in the Annex of the Directive 91/689/EEC on hazardous waste are classified as hazardous. The aforementioned waste consisting of “liquids or sludges containing metal or metal compounds” is subject to being tested due to its “inorganic sulphides” content regarding Annex III—Properties of wastes which render them hazardous, to prove its hazardous characteristics. In this legal framework, the CMC tailings need to be considered and processed as hazardous wastes after the resource recovery operations (The Council of the European Communities 1991).

Sustainable rehabilitation strategy

In accordance with the principles outlined by Morelli (2013), environmental sustainability of the mining site after rehabilitation would mean a balance and resilience between intended beneficial uses of current and future generations and newly acquired ecological characteristics of the site. In fact, the location of the site offers a close interaction with urban life and the wide array of related beneficial uses such as public health, water usage, agriculture, marine life, recreation, etc. The pollution created by the stored mine tailings severely impaired and inhibited almost all possible beneficial uses. The adopted rehabilitation process with pollution abatement and resource recovery primarily intended to restore the human-ecosystem equilibrium. This should be considered as the main message of the paper.

First of all, collected information outlined in the preceding sections clearly indicated that all previous observations did not explore nor had access to this information package and related evaluations were speculative at best. Highlights of generated data are outlined below: (1) Containment and isolation properties of the ponds are still unknown but certainly not reliable especially with current stringent regulations related to hazardous landfills. (2) The copper level of the tailings is generally suitable for recovery. High sulfate content indicate slow oxidation of the sulfurous material—transition from sulfides to sulfates—in the ore during a long storage period in the ponds. The low pH together with high sulfate levels implies the increased potential for solubility and mobility of pollutants. This is a major risk for the migration of heavy metals through soil, ground water or surface water. (3) Tailings are currently classified as hazardous wastes with respect to their sulfur contents. (4) The hydrogeological properties of the site show that the direction of the ground water flow is quite restricted towards the seashore, mostly within the site and poses no risk for the contamination of water supply sources in the neighborhood.

Relevant data generated during the study should be considered accounting for the fact that landfilling is still prescribed as a preferred disposal approach for mining wastes. It requires a sound design involving environmental as well as engineered components to contain and control the movement of contaminants. This is the best achieved by minimizing or eliminating hazardous properties and/or components, stabilizing the waste and/or reducing its volume. In this context, a landfill facility represents the final stage in the treatment and/or handling processes to provide the safest long-term confinement.

Reusing and recycling of material complies with EU's new waste management policy, which regards waste not as an unwanted burden of no value to be disposed of, but as a resource. Accordingly, the new "waste hierarchy" introduces "The 3R's—reduce; reuse; recycle", basically referring to five steps in article 4 of the Waste Framework Directive (2008/98/EC). The aim of the waste hierarchy is to extract the maximum practical benefit and to generate the minimum amount of waste (The European Parliament and The Council of the European Union 2008).

In this context, recovery of copper in the tailings was adopted as the first essential step in the sustainable rehabilitation of the CMC mining site. Another key principle was to create a "zero waste" environment, eliminating all discharges to land, water or air that may cause a threat to environmental health. The major steps of the adopted rehabilitation strategy may be outlined as follows:

1. The rehabilitation strategy did not contemplate relocation of the mining waste as a viable option, for the following reasons: The quest for an alternative site would create a more severe public concern and objection for Cyprus—an island where tourism is the main activity and focus of attraction. A preliminary survey could locate no alternative/candidate site that could be assigned for this purpose; transfer of 9.5 million tons of mining wastes elsewhere would create major environmental risks of containment and exposure problems. This approach would further require comprehensive environmental surveys to ensure suitability of the site. The environmental conditions of the present location, i.e., hydrogeological and geological characteristics, show that an appropriate remediation program can eliminate risks for environmental health and pollution problems.

   The area has suffered from severe environmental pollution problems, not because the wastes were there, but mainly because they were stored under very poor/primitive conditions, with no scientific information regarding the environmental characteristics, i.e., geology, hydrogeology etc., that would indicate and lead to appropriate corrective measures.

2. The rehabilitation strategy relied upon handling and processing of the collected wastes within the site involving (1) emptying all ponds and this way (2) subjecting the stored material to a resource recovery process, reclaiming the available copper in the tailings. This step will also have an auxiliary but equally important task of stabilizing the pollutant content of the waste before final disposal into the landfills.
3. The third phase of the action plan that would be carried out concurrently with the copper recovery process consisted of preparing the necessary number of

emptied ponds with sufficient holding capacity, as selected landfill sites could be used in a way to secure and provide all necessary measures imposed by international regulations for containing and controlling hazardous wastes.

4. The next phase entailed storing all secondary waste material generated by the copper recovery and stabilization processes into the ponds prepared and reclaimed as hazardous waste landfill sites.
5. The final phase of the action plan would be to implement closure and a post closure plan for the rehabilitation of the mining site.

Copper recovery technology from tailings

Recently, Anawar (2015) published an excellent review on different factors affecting sustainable rehabilitation of mining waste and provided a comprehensive evaluation of different remediation options. For this purpose, leaching-cementation technology was adopted owing to its simplicity in implementation and control.

Usually, leaching in mining refers to dissolution, extraction and recovery of metals by means of appropriate chemical agents. As the striking feature of the study, the leaching technology was modified to omit the use of chemicals, mainly for two reasons: (1) The magnitude and handling of chemicals to process 9.5 million tons of mining waste in situ would involve a level of environmental risks too objectionable in view of the sensitive nature of the site. (2) As previously mentioned, sulfur was partly oxidized due to long exposure of tailings to atmospheric conditions, i.e., contact with air and water lead so that 14.3% of the total tailings were identified as iron sulfate; similarly, 60% of the total copper was in the sulfate form. Therefore, the leaching process will be limited with the ionic copper (Cu^{2+}) fraction in solution.

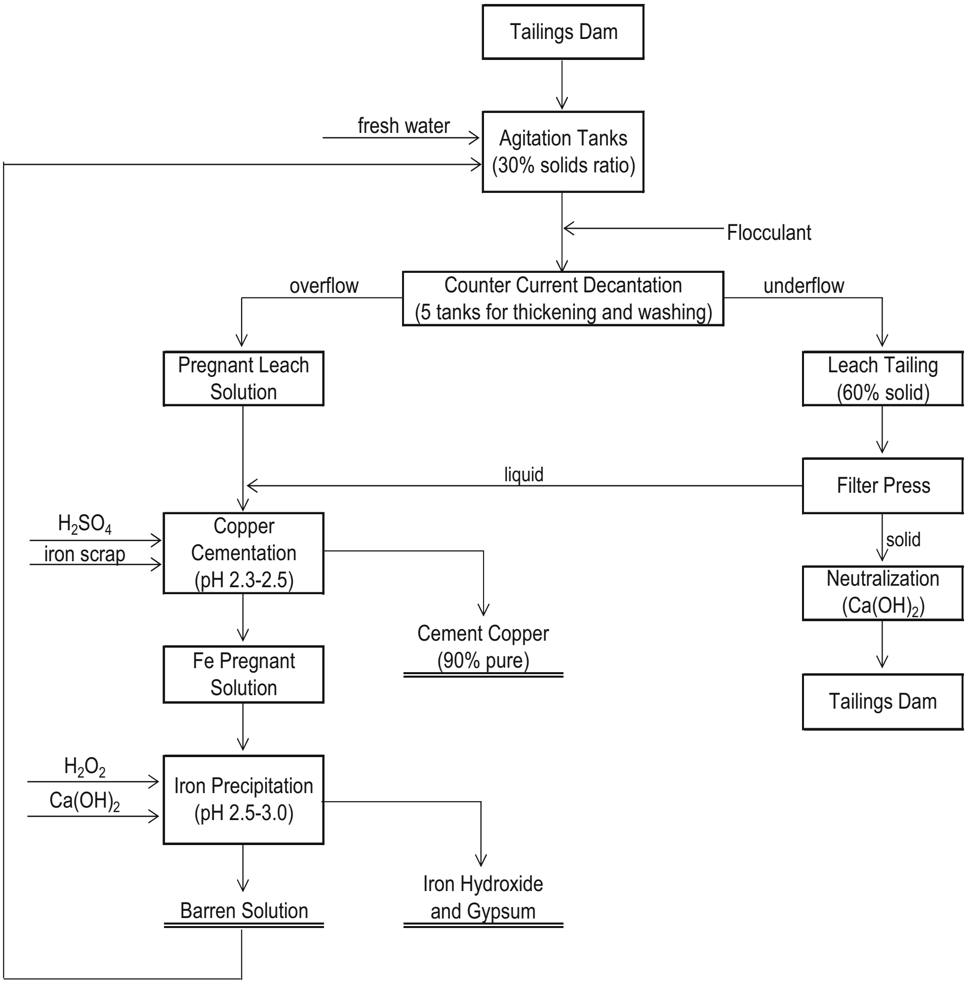
In this context, the pregnant (copper bearing) leach solution, which is obtained after leaching, will be subject to cementation. The cementation method is essentially based upon an oxidation–reduction reaction occurring between the metal ions (Cu^{2+}) in the leach solution and a more active metal source (scrap iron) introduced into the solution. As a result of these reactions, the reduced metal cements on the more active metal; Cu^{2+} will be transformed into Cu^0 by the electrons of iron scraps, while Fe^{2+} ions transfer to aqueous phase from the iron scraps. Accordingly, the basic steps of the copper recovery will proceed as schematically outlined in Fig. 4:

> The tailings are scrubbed with water in the continuously mixed leaching tanks. The leaching is carried at the natural pH level 2.75–2.80, without any acid and/or reagent addition, at a solid/liquid ratio of 1.0–2.5 in the tanks.
>
> After leaching, the pulp is pumped to the counter current decantation (CCD) units consisting of five tanks, in which the leach tailing can be washed with the pregnant leach solution to prevent copper loss. When the solid is totally washed, the pregnant leach solution is taken from the first tank and sent to the cementation unit. The remaining tailing material (the processes waste) at the bottom of the last tank is collected and sent to the filter press unit for dewatering, to reach a final moisture content of 25%. The process waste is then stabilized with $Ca(OH)_2$ on a conveyor to a pH level of 8.0 before final storage in landfill sites.
>
> Cementation is applied on the pregnant leach solution with iron scraps. The nature of the chemical reactions likely to occur requires that pH needs to be adjusted and maintained in the proper range for effective cementation. Iron precipitates above pH 2.5; on the other hand, if the cementation medium is more acidic than pH 2.3, then the dissolution of the iron scraps increases. For this reason, optimum cementation occurs in the narrow pH range of 2.3–2.5. This range is secured and sustained using small doses of H_2SO_4, when necessary.
>
> When the cementation process is terminated with an efficiency of more than 98%, yielding around 88% Cu, the remaining copper barren solution is essentially left with Fe^{2+}. This solution is recycled in the process until the Fe^{2+} concentration reaches an upper limit of around 17 g Fe/l. At this stage, iron should be removed first to proceed with the recirculation process.
>
> Iron in solution should be first oxidized from Fe^{2+} to Fe^{3+} for removal by precipitation. The oxidation is best performed using H_2O_2 and precipitation is carried out at a pH range of 2.5–3.0 just. At this stage, pH adjustment is secured by $Ca(OH)_2$ dosage. Experimental results indicated that around 95% of the iron may be precipitated, allowing recirculation and reuse of the barren solution.
>
> The entire process is conducted as a closed circuit operation, discharging no pollutants and polluted water outside the operation area.

Action plan for the rehabilitation process

The first phase of the action plan was to provide total collection and containment of storm water drainage. In this past, free-flowing rainwater exhibited itself as acid mine drainage, which was the major source of public concern in the area as the visible indicator for the pollution impact of

Fig. 4 Schematic description of the copper recovery process



tailing ponds. For this purpose, all storm water of the site was captured in a collector system constructed along the shoreline border of the site and pumped into pond no. 16 assigned for this purpose (Fig. 5). This pond has approximately a surface area of 33,000 m^2 and a clearance volume of around 55,000–60,000 m^3 on the surface for storage, evaporation and subsequent reuse of the rainwater. This capacity is quite sufficient to store around 30,000–35,000 m^3/year of storm water drainage generated in the area based on practical assessments in the last few years. This system will ensure a zero-waste concept for surface waters.

The essential feature of the operation is the sequential nature of the copper recovery process, imposing a similar stepwise approach for the storage of processed wastes. In order to be implemented without interruption, especially at the initial phase, the action plan necessitates a temporary waste protection/storage area, introduced as a novel approach in the rehabilitation process. As shown in Fig. 5, pond no. 14 was selected to provide temporary waste protection; despite its relatively large surface area of 102,800 m^2, it stores only 66,000 m^3 of mining wastes and offers a clearance volume of 535,000 m^3 to be allocated and used for this purpose.

Selection of the two ponds–ponds no. 14 and no.16—for water and temporary waste storage was tested on the basis of permeability tests to justify that they do not involve any appreciable risk of pollutant leakage during the operation. For this purpose, three soil samples were taken from the interface between natural soil at the bottom and the stored material from three different locations in pond no. 14; one soil sample was analyzed the same way from pond no. 16. The sampling holes used for this purpose revealed no sign of a clay layer originally used as a protective measure. The moisture content of the stored material at sampling points varied around 40–50%, while it was reduced to 5–10% in the adjacent natural soil. As outlined in Table 5, the permeability coefficients determined on the basis of consolidation tests remained in the range of 1.1×10^{-10}–5.2×10^{-10} m/s and below the threshold level of 10^{-9} m/s commonly associated with protective liners securing impervious pond design.

The operation was planned in two phases; the first phase included around 5 million tons (2 million m^3) of tailings with relative higher copper and pollutants content stored in

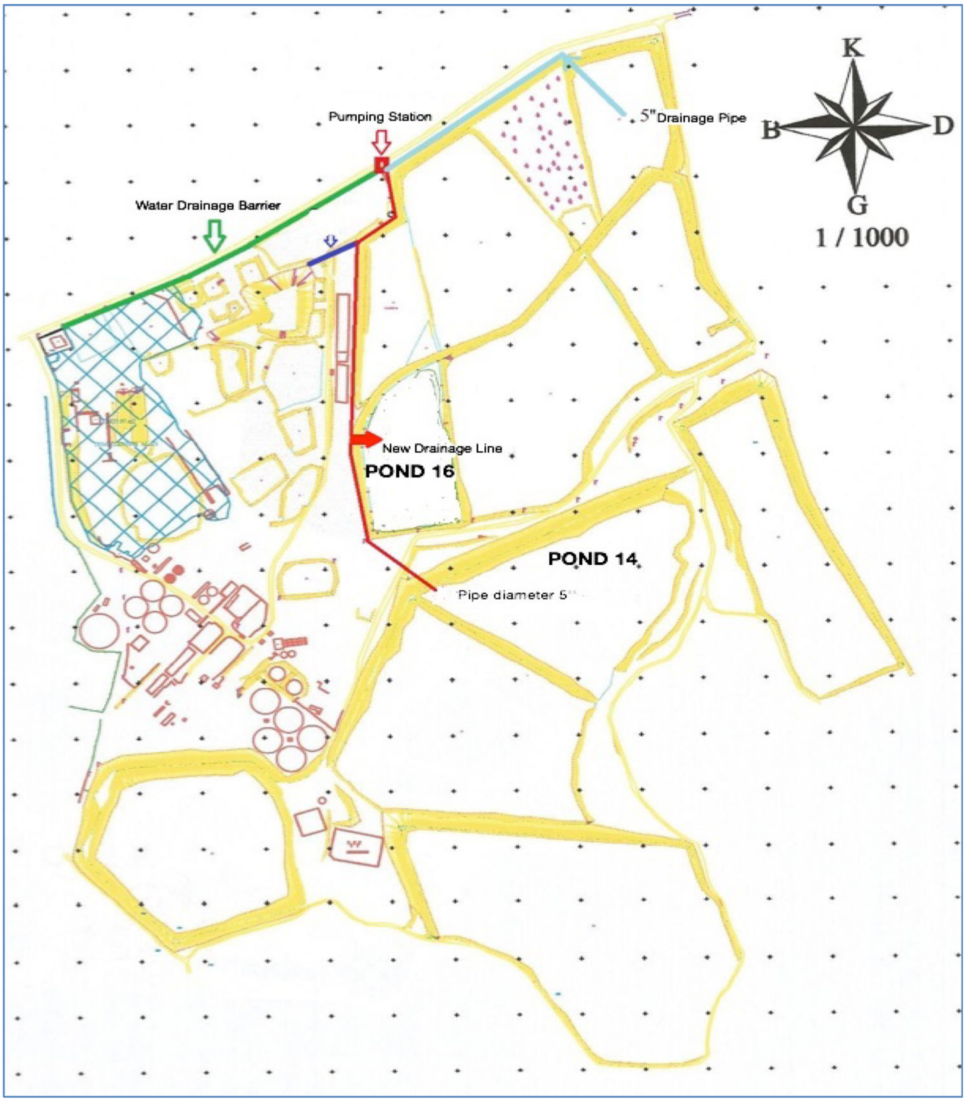


Fig. 5 Storage of storm water drainage and temporary waste protection and storage ponds in the area

Table 5 Permeability coefficients

Sample	Depth (m)	γ (kN/m^3)	w (%)	Kv (m/s)
14-1	1.05	20.70	22	1.1×10^{-10}
14-2	3.07	18.30	33	2.7×10^{-10}
14-3	1.84	18.50	38	5.2×10^{-10}
16-1	1.50	18.80	35	3.3×10^{-10}

five different ponds–ponds no. 13, 12, 17, 11C and 21) to reduce the risk of pollution and contamination of the environment to the extent possible. Details of the operation are outlined in Table 1, and its sequential aspect is schematically illustrated in Fig. 6. As shown in Fig. 6, it will start with the recovery of 300,000 m^3 of tailings stored in pond no. 13; 240,000 m^3 of processed waste after copper recovery and stabilization will be transferred to pond no.14 for temporary storage. The operation will continue with the tailings in pond no.12, while pond no.13 is prepared and equipped as one of the final waste landfill sites. When the capacity provided in pond no.14 is fully used, the remaining portion of the material from pond no.12 will be conveyed directly to its final storage location in pond no.13. At the end of the first phase, more than 1.6 million tons of processed and stabilized waste, still containing a significant level of sulfur, will be properly stored in three final landfills—ponds no. 13, 12 and 11C—renovated to include all the necessary protective measures prescribed by related regulations. During the entire process, rainwater collected on the surface of all ponds under operation will be drained and diverted into water storage pond no.16.

In the second phase, the remaining 4.1 million tons (1.65 million m^3) of tailings will be processed the same way, in the sequence indicated in Fig. 6; the resulting 1.3 million m^3 of stabilized waste generated by the copper recovery process will be conveyed and stored in two additional final

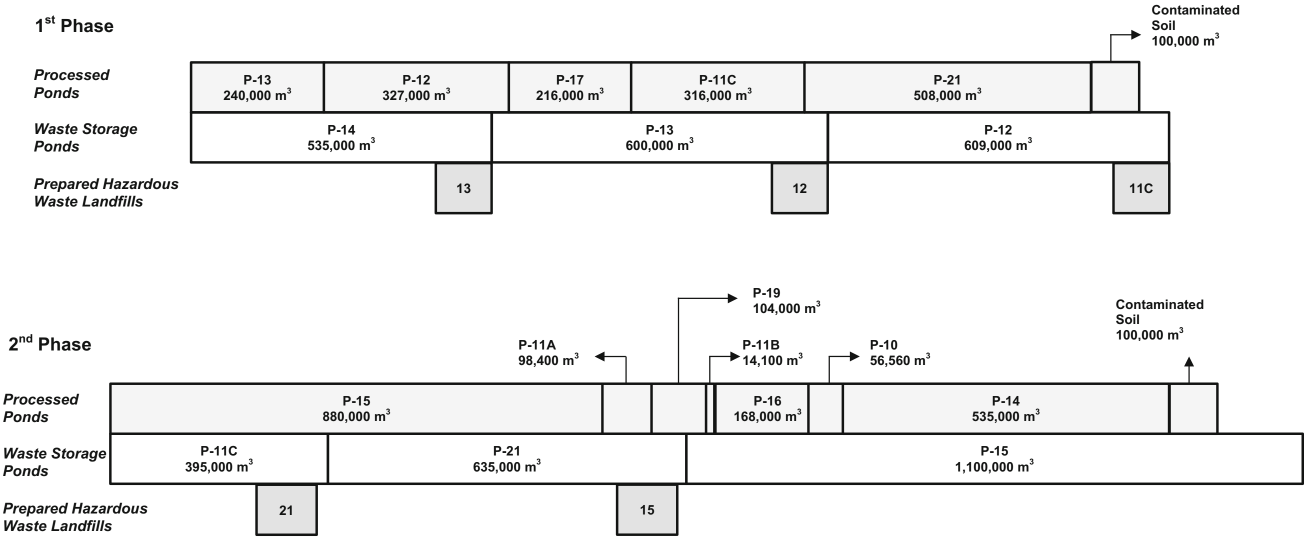


Fig. 6 Schematic illustration of operation

landfill sites. This way, the rehabilitation process will utilize only five of the existing ponds with appropriate total capacity converted into individual landfill facilities. The last landfill site (pond no. 15) will also receive the 535,000 m^3 of processed waste temporarily accumulated in pond no.14 at the beginning of the operation together with 66,000 m^3 of tailings originally stored in the same pond.

Furthermore, the northwestern section of the site beyond the ponds shows strong indications of soil contamination and discoloration with yellow and red staining. This is obviously the result of uncontrolled acid mine drainage during wet seasons, carrying fine-grained hazardous materials released from the tailing ponds and forming metal bearing sediment layers on the surrounding environment. These sediments presumably act as the source of chronic pollution problems in the groundwater. Engineering evaluations have estimated that around 100,000 m^3 of contaminated soil need to be scraped from this area and replaced with natural soil. This operation will be carried out within the first phase of the operation and contaminated soil will also be stored in the landfilling facility with available capacity at the end of the phase. This is hoped to provide a noticeable improvement in the groundwater quality.

After closure of landfill facilities, the rehabilitation process will be completed with a reclamation project involving a multipurpose activity and land use plan that will restore and bring back the natural features of the site.

Conclusions

The paper's contribution lies in a novel perspective about a poorly documented site of Cyprus—a case study that presents current understanding of the scale and nature of the environmental geology and severe pollution challenges with a sustainable perspective for some future efforts to resolve those challenges. The adopted approach involves all the essential indicators of a sustainable operation since the rehabilitation process with resource recovery was essentially designed to restore the severely damaged the human-ecosystem equilibrium in the area. This should be considered as the main message of the paper.

It is true that the study primarily addresses a local pollution problem created by the tailings of an abandoned mine site. However, it defines a sustainable road map for pollution abatement of numerous similar sites in the world. It should be noted that the majority of copper mining activities in the world are placed in countries where environmental issues are not regarded as a priority concern. The overall management scheme presented in the study would be a rational waste management concept that could be adopted in many similar sites around the world. Especially, the novel concept of considering mining waste as a resource and considering copper recovery as an integral part of the operation would make the presented waste management concept an attractive approach from an economic standpoint.

The highlight of the study may be outlined as follows: (1) the copper recovery technology adopted on the basis of EU's key principle of waste recovery and reuse also defined the required prerequisite for the rehabilitation strategy stabilizing the highly reactive nature of the tailings before final disposal into landfills. (2) Processing of all tailings carried out in situ ensured a zero waste environment eliminating all discharges to land, water or air that may cause a threat to environmental health. (3) The zero waste approach required all tailing materials to be recirculated in a sequential process and stored in a temporary waste protection area within the site, while the necessary storage capacity in emptied ponds were prepared to secure and provide all required measures imposed by international standards for containing and controlling the entire volume of processed wastes.

References

Altinbas U, Erdem U, Veryeri NO (2002) Pollutions of Cyprus Mine Company (CMC) wastes on soil, water and the Mediterranean in Cyprus. In: Camarda D, Grassini L (eds) Coastal zone management in the Mediterranean region. Bari:CIHEAM, 3-13 **(Options Mediterraneennes: Serie A. Seminaires Mediterraneens; n.53:3-13)**

Anawar HM (2015) Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge. J Environ Manage 158:111–121

Atımtay AT, Sarıçiçek VE (2001) Environmental effects of the copper mining activities in Lefke and Karadag Region of Nothern Cyprus: Present Status. In: Proceeding of the International Conference on European Environmental Policy and the Case of Cyprus Mines, Lefke European University

Baycu G, Tolunay D, Ozden H, Csatari I, Karadag S, Agba T, Rognes SE (2015) An abandoned copper mining site in Cyprus and assessment of metal concentrations in plants and soil. Int J Phytoremediation 17(7):622–631

Bhattacharya A, Routh J, Jacks G, Bhattacharya P, Morth M (2006) Environmental assessment of abandoned mine tailings in Adak, Vasterbotten district (northern Sweden). Appl Geochem 21:1760–1780

Boronina AV (2003) Application of Numerical Modelling, Isotope Studies and Streamflows Observations for Quantitative Description of Hydrogeology of the Kouris Catchment (Cyprus). Ph.D Thesis, Eidgenössische Technische Hochschule (ETH) Zürich

Cohen AH (2002) Preliminary Report for Environmental Assessment of the Lefka-Xeros Area of Northern Cyprus. United Nation Office for Project Services Program Management Unit, Cyprus

Cohen DR, Rutherford NF, Morisseau E, Zissimos AM (2012) Geochemical patterns in the soils of Cyprus. Sci Total Environ 420:250–262

European Commission (2009) Reference document on best available techniques for management of tailing and waste rock in mining activities http://eippcb.jrc.ec.europa.eu/reference/BREF/mmr_adopted_0109.pdf. Accessed 11 April 2016

Frempang EM, Yanful EK (2006) Chemical and mineralogical transformation in three tropical soils due to permeation with acid mine drainage. B Eng Geol Env 65:253–271

Geology and Mining Department, Ministry of Agricultural and Natural Resources, Turkish Republic of Northern Cyprus (2009) Technical report of water quality studies in Gemikonagi-CMC mining site existing water wells. pp 7, Northern Cyprus (In Turkish)

Geosurvey (2015) Gemikonağı/Lefke Port İSBİ Soil Survey Report of Port ISBI Waste Ponds, Lefkoşa KKTC. pp 8 (In Turkish)

Gökcekuş H, Turker U, Gokcekush H, Rızza T, Sıdal M (2007) The management of polluted coastal mining activities at Morphou Bay, Northern Cyprus. Natural Cataclysms and Global Problems of the Modern Civilization. Special edition of Transaction of the International Academy of Science. H and E. ICSD/IAS, Baku-Innsbruck, pp 179–186

Gökçekuş H, Kabdaşlı S, Kabdaşlı I, Türker U, Tünay O, Ölmez T (2003) Pollution of coastal region impacted by acid mine drainage in Morphou Bay. North Cyprus Enviro Sci Health-A 38:1445–1457

Gökmenoğlu O, Erduran B, Özgür C, Tamgaç ÖF (2002) Hydrogeology Report of Turkish Republic of Northern Cyprus, MTA (In Turkish- unpublished report)

Gücel S, Öztürk M, Yücel E, Kadis C, Güvensen A (2009) Studies on trace metals in soils and plants growing in the vicinity of copper mining area-Lefke, Cyprus. Fresenius Environ Bull 18:360–368

Gündüz Ş, Erbulut C, Öznacar B, Baştaş M (2016) Determination of consciousness and awareness of the public in Lefka about the Cyprus Mining Corporation (CMC). Eurasia J Math, Sci Technol Educ 12(4):783–792

Hakyemez YH (2014) Main Geological Characterisitics of Northern Cyprus (In turkish: Kuzey Kıbrıs'ın Temel Jeolojik Özellikleri). TAPG Bull 26(2):7–46

Johansson L, Xydas C, Messios N, Stotz E, Greger M (2005) Growth and Cu accumulation by plants grown on Cu containing mine tailings in Cyprus. Appl Geochem 20:101–107

Lavender D (1962) The story of Cyprus Mines Corporation. In: Henry E (ed) Huntington Library and Art Gallery, San Marino

Morelli J (2013) Environmental sustainability: a definition for environmental professionals. J Environ Sustain 1(1):2

Oruç O (2007) US company's toxic waste under scrutiny in Cyprus. Today's Zaman. Accessed 11 April 2016 **(May 2007)**

Stumm W, Morgan JJ (1996) Aquatic chemistry: chemical equilibria and rates in natural waters, 3rd edn. Wiley, New York, p 1024

The Council of the European Communities (1991) Council Directive 91/689/EEC of 12 December 1991 on hazardous waste. Off J Eur Communities No:L 377/20, pp. 8

The Council of the European Communities (2000) Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste. Off J Eur Communities No:L 226/3, pp. 22

The European Parliament and The Council of the European Union (2006) Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC—Statement by the European Parliament, the Council and the Commission. Off J Eur Communities No:L 102/15, pp. 19

The European Parliament and The Council of the European Union (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Off J Eur Communities No:L 312/3, pp. 28

U.S. Department of Interior (2014) U.S. Geological Survey, 2012 Minerals Yearbook: Cyprus. (Advanced Release), March

Wilson RAM, Ingham FT (1959) The Geology of the Xeros-Troodos Area. Cyprus Geological Survey Department Memoir 1

Yesilnacar MI, Kadiragagil Z (2013) Effects of acid mine drainage on groundwater quality: a case study from an open-pit copper mine in eastern Turkey. B Eng Geol Env 72:485–493