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Groundwater Quality in the Vicinity of an Abandoned Mining Site – The M'fis Mine, Southeast of Morocco

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ABSTRACT

The diagnosis of the current state of the environment (groundwater quality and tailings composition) was carried out in the vicinity of the M'fis mine (Southeast of Morocco) in order to evaluate the impact of mine tailings on groundwater. Water samples from the well in the center of the mine site and from other nearby wells were collected and analyzed. In addition, the characterization of the tailings shows the presence of sulfides and other chemical elements, constituting the main source of pollution. In turn, the results of geochemical analyses show that groundwater is characterized by low levels of metals, despite the presence of these pollutants in the tailings and in the waste rock piles. The concentrations of metallic trace elements in well groundwater, slightly exceeding the standards of potability (the WHO standard), remain acceptable for irrigation and for livestock. These results can be explained by the carbonate geological formation, constituting the transfer medium of the pollutants towards the aquifer and also by the weak circulation of the metal ions under the desert climate which prevent dissolution and infiltration.

Keywords: Eastern Anti-Atlas; M'fis; abandoned mines; mining discharges; groundwater quality.

INTRODUCTION

Throughout the world, mining is considered essential for socio-economic development. However, it accelerates natural processes and increases the probability of release of toxic elements, with high doses in adjacent areas (Yuan et al., 2023, Qi et al., 2023, Chen et al., 2022). Indeed, the generation of large quantities of solid waste and effluents from mining activities represents a potential source of pollution of soil and groundwater resources as well as surface water. The trace metals they contain can be dispersed by natural factors (wind and/or rain) or accidentally (Wu et al., 2023, Cánovas et al., 2023). For these reasons, mining is considered one of the activities with the greatest impact on the environment (Paraguassú et al., 2019), even those abandoned. In fact, the problem of depleted mines that have been abandoned without rehabilitation remains a topical issue (Balan et al., 2021, Cornelissen et al., 2019). These constitute a potential source of pollution generated by the storage of waste from mineral extraction and chemicals used in industrial processing (Ahmedat et al., 2018). Tailings stored on site are exposed to ongoing weathering (Schudel et al., 2023, Wen et al., 2021, Khalidy et al., 2021). The release of metals comes from dissolution of mineral species in disequilibrium with the conditions of the environment containing them. This is the case for the dissolution of a sulfide (Ferrer et al., 2021; Sinche-Gonzalez et al., 2021; Pattanaik et al., 2020).

In Morocco, the Anti-Atlas region, especially the Eastern part, of which the Tafilalet basin is a part, contains important mineral resources; mining is thus the fundamental activity carried out in these regions. Indeed, the great metallogenic diversity of the Pericratonic domains of the Moroccan Anti-Atlas reflects its complex geodynamic history at the northern edge of the West African Craton (WAC), which spans more than 2 billion

years, according to four major geodynamic and metallogenic events (Aabi et al., 2022, Kouyaté et al., 2013). However, several mines have been abandoned without rehabilitation.

The M'fis mine located 11 km northeast of Taous (Figure 1), Errachidia province, represents a special position in this polymetallic district of Tafilalet, comprising sulfide veins of different mineral paragenesis, mainly lead-bearing, hosted in carbonates and shales attributed to the Upper Devonian; the mineralization is oriented E-W and ENE-WSE (Ait Daoud et al., 2020). Mining began in 1951 and reached its peak between 1951 and 1958 (14,200 T/year at 65% Pb) (Makkodi, 1995). Thus, industrial-scale activity gave way to artisanal mining, which nevertheless allowed a large population to subsist in an otherwise very disadvantaged region (Makkodi, 1995).

The objective of this work was to study the impact of the abandoned M'fis mine on the aquifer. Firstly, the study focused on the diagnosis of the current state of the mine and its surroundings; secondly, it considered evaluation of the potential risk of groundwater contamination by metal trace elements (MTE) from the processing residues in the vicinity of the mining center.

MATERIALS AND METHODS

Study area and choice of wells

The present study was carried out in the vicinity of the former mine of M'fis. The landscape of the mine area has been largely modified, the current state of the mine shows the negative effect of mining on its physiognomy (Essalhi et al., 2016), which is added to the large amounts of stored tailings, resulting from processing, as well as spoil piles that cover a fairly large area, in the vicinity. These spoil piles appear to be due to artisanal mining after the official closure of the mine in 1958. These tailings are rich in galena and iron oxide (Essalhi et al., 2016).

To meet the objectives of this study, and given the lack of access to the water table and the limited number of wells in the vicinity of the mine, four wells were monitored for water quality. These were Pt, (control station located 30 km upstream of the mine), P1 downstream, P2 downstream, and P3 upstream. Groundwater sampling points were selected based on their location upstream and downstream of the tailings. These treatment tailings were also sampled from the dam; these sampling missions were conducted during the years 2019 and 2022 in dry (August) and wet (September) periods.

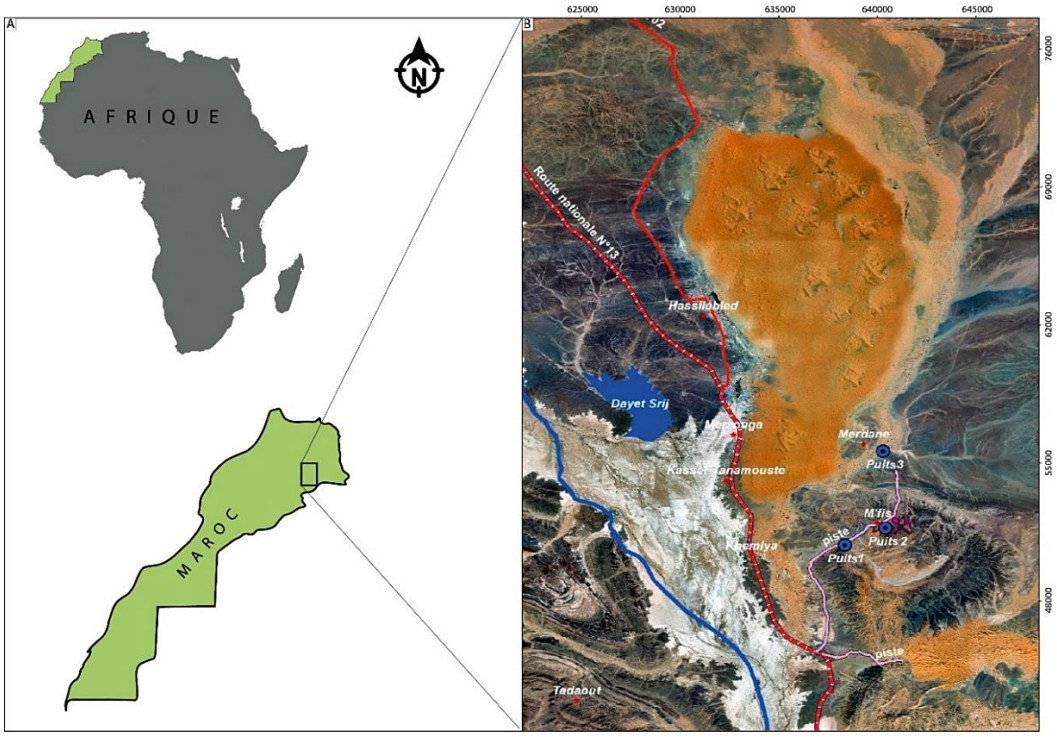

Fig. 1. Geographic location of the study area and sampling wells

Geological context

The area covered by this study constitutes the eastern part of the Anti-Atlasic chain and forms what is called the Tafilalt-Maïder region (Figure 2), the paleozoic series outcrops in synclines of major E-W and NW-SE direction, slightly deformed, is surmounted by undeformed deposits of the upper cretaceous Kem-Kem to the south and by tertiary deposits of the Hamada of Guir to the east (Wendt et al., 2021; Ibrahim et al., 2020).

The geological series constituting the essential of the grounds of this sector is situated between the average Devonian characterized by blue limestones with schistose past and lumpy limestones as well as the upper Devonian represented by black marls with goniatites. The series presents calcareous intercalations but it is clayey on its greatest thickness and outcrops with an average power of about 150 m. This series is intruded in its great mass by sills of magmatic rocks of basaltic type with a doleritic texture (Makkoudi, 1995).

The M'fis mine containing the vein deposits hosted in this Middle and Upper Devonian stratigraphic series has a main E-W vein (called "contamine"), essentially with galena, chalcopyrite, pyrite and barite as well as satellite nickel and wulfenite veins (lead molybdate $PbMoO_4$) (Makkoudi, 1995).

The structural analysis shows that the mineralization was emplaced in a strike-slip fault system where the contaminated vein corresponds to the major shear direction while the satellite veins correspond to the R and T fractures of the Riedel system (Makkoudi, 1995).

Tools and analysis

MTE concentration in the tailings dam residue

The tailings were collected in clean plastic bags, to avoid contamination of the samples, from the top of the tailings dam and then crushed and stored until mineralization. The sampling method used is by quartering, while the method used for the geochemical analyses is Atomic Absorption Spectroscopy and graphite furnace.

Concentration of MTEs in groundwater

At each station, the collected water samples were immediately filtered through clean filters mounted on a NalgeneR apparatus. The filtrates were divided into polyethylene vials for the various analyses and stored in 5% HNO_3 at 4°C. Chemical analyses were performed by ICP-MS in the laboratory for several elements, namely Pb, Zn, Cu, As, Ni, Co, Mo and Fe. The pH, EC,

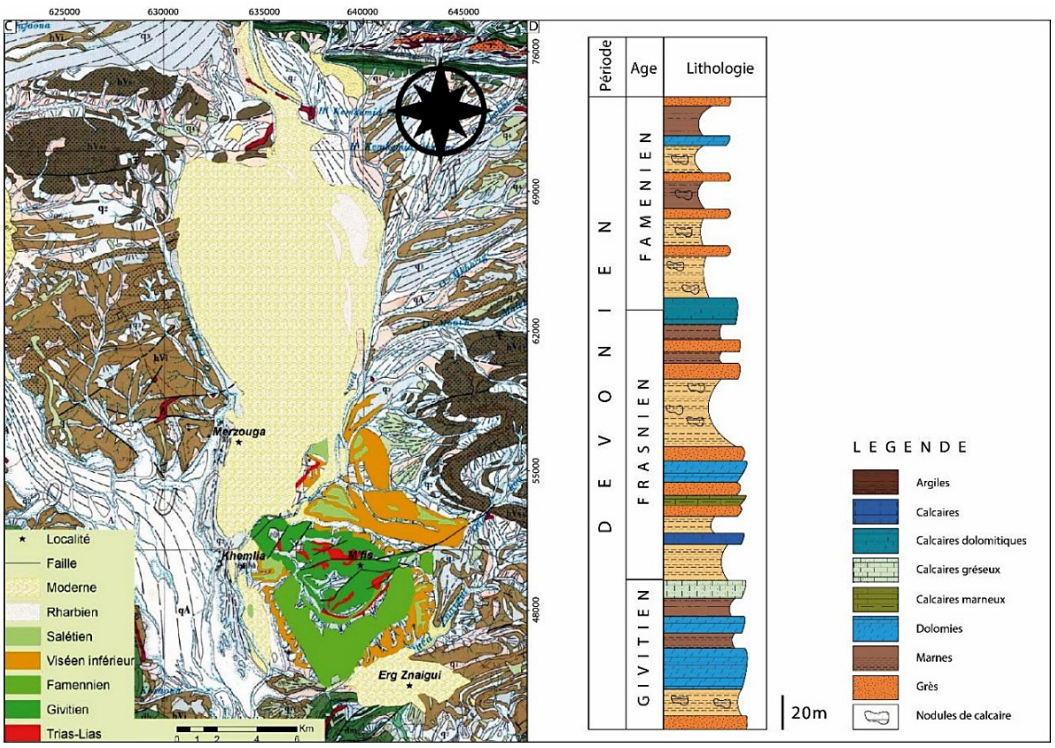

Fig. 2. Left, geological map of the study area (extracted from the geological map Tafilalet-Taouz 1/200000). On the right, stratigraphic log of M'fis sector (Makkoudi, 1995)

dissolved oxygen parameters of the waters were measured during the sampling, using WTW portable measuring devices.

RESULTS AND DISCUSSION

Mine tailings

The results of the analyses carried out on the samples of mine tailings in the M'fis sector show that they are very rich in MTE (Table 1). Indeed, these tailings are highly contaminated with lead and zinc and relatively in copper; thus, lead represents a content of 2.36% and 2.97%, followed by zinc of 1.4%, copper does not exceed 0.38% in the analyzed samples. These results corroborate with those obtained in the mine residue of Zeïda (Moulouya, Morocco) the lead content of which was 5547 ppm (El Azhari et 2016) and in the residue of the mine of Drâa Lesfar (Marrakech, Morocco) the lead and zinc content of which is 127 ppm and 414 ppm, respectively (El-Fadeli et al., 2015).

The analysis of these results shows that the mine tailings constitute a potential effect on the surrounding environment, especially on groundwater and surface water. This is the case of the Kettara mine (Marrakech, Morocco), where mine tailings contain metallic elements and are considered dangerous for human health (Zouhri et al., 2019, El Amari et al., 2014).

Groundwater

Physico-chemical quality

The pH values found in the waters (Table 2) reveal that the pH is slightly neutral to alkaline in all the wells measured (7<pH<8.2), both in rainy and dry periods.

This is due to the presence of carbonates that buffer surface water flowing to the aquifer by runoff and infiltration into the carbonate cover, as well as into the bare sulfide mineral rich process tailings deposited in the vicinity. These results are similar to those measured in the Aouli, Mibladen, and Zaida mining district waters of the upper Moulouya (Makhoukh, 2011).

Conductivity measurement is a good indicator of the degree of water mineralization. The average values measured, show variations from one well to another; they vary between 1500 µs/cm in Pt and P1 to 9040 µs/cm and 4560 µs/cm in P2 and P3, respectively. This corroborates with the results obtained in the measurements carried out on the waters of the Moulouya talweg which exceed the WHO standard (2700 µs/cm), indicating strong mineralization due to the leaching and infiltration of metallic pollutants from the mining residue.

The increase in conductivity downstream was probably due to SO_4-Mg-Ca enrichment. Sulfates can also come from the dissolution in water of sulfide minerals (Chedadi et al., 2023). This could be the result of the drainage of processing residues and carbonates containing sulfide minerals. It can also be due to the geochemical background.

Dissolved oxygen (O_2) is very important factor because it conditions the state of several mineral salts, the degradation of organic matter and the life of aquatic animals (Cai et al., 2023; Yan et al., 2022). It plays a vital role in maintaining aquatic life and cleaning itself. Its occurrence in natural water bodies mainly depends on the respiration of organisms, the photosynthetic activity of

Table 1. Results of physico-chemical analyses of the mine tailings

Designation	Sample 1	Sample 2	Sample 3	Average crustal grade (g/t)
Ag (ppm)	22.2	189	11.4	0.08
Au (ppm)	<0.05	<0.05	<0.05	0.0031
Cu (%)	0.17	0.38	<0.01	62.5
Ni (%)	<0.01	<0.01	<0.01	84
Pb (%)	2.97	2.36	0.82	16
Zn (%)	1.4	0.0194	0.0203	101

Table 2. Results of physico-chemical analyses of groundwater

Parameter	Control (Pt)	Road (P1)	Mine (P2)	Gazelle (P3)
pH (–)	8.2	8.1	7	7.73
CE (ms)	1.5	1.5	9.04	4.56
Dissolved O_2 (mg/l)	3.6	1.45	1.36	4.21

Table 3. Results of the groundwater chemical analyses

Station	Fe (ppm)	Cu (ppm)	Zn (ppm)	As (ppb)	Pb (ppb)	Mo (ppm)	Co (ppm)	Ni (ppm)
well t	<0.01	<0.01	<0.01	<50	<50	<0.01	<0.01	<0.01
well 1	<0.01	<0.01	<0.01	<50	<50	<0.01	<0.01	<0.01
well 2	<0.01	<0.01	1.74	<50	<50	<0.01	<0.01	<0.01
well 3	<0.01	<0.01	<0.01	<50	<50	<0.01	<0.01	<0.01
WHO standards	0.02	0.02	0.02	50	50	0.02	0.02	0.02

flora, the oxidation and degradation of pollutants, and finally the exchange process at the air-water interface (Yona et al., 2022, Zhu et al., 2021).

In the study area, the dissolved oxygen presents many variations between the water points, it varies from 1.36 mg/l recorded at the level of well P2 to 4.21 mg/l recorded at the level of well P3, the results obtained show that the wells are generally less oxygenated, these results characterizing the month of September.

The witness well and the well 3 are oxygenated compared to the wells 1 and 2, these two last ones are deeper compared to the first ones, the witness well and the well 3 have an average quality whereas the two other wells have a bad quality.

MTE in water

The monitoring of the spatio-temporal evolution of metallic pollution of water samples, taken at the level of the different wells, upstream and downstream of the mine tailings concern the metallic trace elements (Fe, Pb, Zn, Cu, Mo, Co, As and Ni), can be considered as a general indication of the state of the waters in the whole area. Thus, the results of the groundwater chemical analyses are presented in Table 3.

Analytical results reveal that the concentrations of these elements in groundwater in the M'fis area, although slightly variable from one well to another, they are generally similar to the concentrations measured at well *t* (reference well) located 30 km upstream from the mining center on the Derkaoua valley.

Thus, the MTE concentrations in groundwater in the vicinity of the M'fis mining center do not exceed the average concentrations of uncontaminated natural freshwater (0.2 µg/l) (Rajaram et al., 2023), nor do they exceed the average concentrations of natural freshwater (3 µg/l) (Panda et al., 2023; Bawa-Allah, 2023).

These results show that the aquifer does not seem to be affected by this metallic pollution, this can be explained by the weak circulation of ions due to the desert climate of the region, and the carbonate geological context that constitutes the non-negligible transfer medium in this process. This results in the groundwater of the M'fis mine being devoid of metals. This corroborates with the results obtained from the chemical analysis of the waters of the Kettara mine (Marrakech, Morocco) where the desert climate and the low rate of annual precipitation constitute a limiting factor (El Amari et al., 2014).

The relatively high zinc concentration in the mine shaft (P2) can be explained by the geochemical background. Indeed, the aquifer can be enriched by zinc through the mineralized seams.

Although zinc is essential for the enhancement of health and the functioning of many enzymes (Prasad et al., 2022) as well as in strengthening the human body's immune system and protecting against infections and various diseases (Alfawaz et al., 2023), the potential damage of zinc to human health and the surrounding environment through the combination of zinc with other heavy metals may cause multiple cancers (stomach, brain, liver and colon cancers) (Jia et al., 2022). The health risk of excess zinc in groundwater remains the order of the day, in a desertic region where groundwater is the only source of drinking waters.

CONCLUSIONS

The results of chemical analyses show that the groundwater of the M'fis mine, constituted by sulfide metals, is not contaminated by MTE from mining, despite the abandonment of tailings in the mine without rehabilitation.

In fact, the solid waste composed of the treatment tailings and slag heaps, constitutes a source of pollution that can disturb the landscape and degrade the soil, the biological environment (fauna and flora) and the neighboring human settlement; the deflation and the transport of the tailing particles can be carried out by the wind.

However, the aquifer does not seem to be affected by this pollution, the desert climate of the region, as well as the transfer medium (carbonate) of the metallic pollutants towards it, is added the relative depth of the water table what constitute limiting factors. As a result, the groundwater in vicinity of the M'fis mine remains protected.

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