Deep Physico-Chemical Profiling in a Flooded Mine Shaft: Understanding Water Dynamics in Gardanne Lignite Mine (France)

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Abstract

Neutral Mine Drainage (NMD) in the flooded Gardanne lignite mine (Southern France) remains poorly understood, with persistently high Fe (30 mg/L) and SO_4 (2000 mg/L) concentrations. In 2024, a field campaign conducted in the Gérard shaft, using in-situ profiling and water sampling, reveals a deep stratification. Comparisons with 2011 data indicate a shift from a predominantly static regime with diffusive processes in the deeper part to a more dynamic system, characterized by convective loops and forced convection driven by pumping. Persistent inflows seem to influence the water column structure, shaping its stratification and internal dynamics.

Keywords: Gardanne, lignite, post-mining water management, physico-chemical log, stratification, shaft

Introduction

Acid mine drainage (AMD) is widely recognized for its environmental impact. However, in carbonate-rich systems, neutral mine drainage (NMD) can also occur, posing distinct risks to water quality despite its neutral pH. Long-term management of post-mining sites requires a deep understanding of the hydrogeochemical processes controlling water chemistry. Therefore, extensive localized studies are essential to identify key water-rock interactions, sources of dissolved elements, and the role of bacterial populations in the geochemical cycles of each abandoned mine.

Gardanne underground lignite mine, located near Marseille (Southern France), operates in an NMD context. The flooding of the mine in 2003 led to a deterioration of water quality, characterized by persistent high iron and sulfate concentrations. Hydrogeochemical studies conducted at the time of the mine closure predicted a fast decline in these concentrations over time. More than two decades later, iron and sulfate levels measured at the pumping outlet remain unexpectedly high (Fe: 30 mg/L; SO_4: 2000 mg/L), suggesting the persistence of unaccounted geochemical processes, additional mineralized water inputs within the mine reservoir, and/or insufficient knowledge of the hydrogeological system.

This work investigates the evolution of water quality in the Gardanne mine water reservoir through the analysis of vertical variations in physico-chemical parameters. These variations help understand water-rock interactions, groundwater flow dynamics, and mixing processes within the reservoir. To achieve this, in-situ profiling was conducted along the water column, complemented by chemical analyses of water samples collected at different depths in the Gérard shaft, the only remaining access to the mine water reservoir.

Site description

The Arc Basin is a large east-west syncline, located about ten kilometers north of Marseille (Fig. 1(a)). It extends 75 km east-west and 20 km north-south. It consists of fluvio-lacustrine deposits, including the Upper Cretaceous sub-stages: Valdonnien, Fuvélien, Bégudien, Rognacien (oldest to youngest), and Eocene formations. This structure lies on a substratum of Jurassic and Cretaceous formations. The eastern part of the Arc Basin, known as the Gardanne Basin (Ancel *et al.* 2004), was a coal mining area from the early 19th century until 2003. Although this basin is only slightly affected by major tectonic faults, it is structurally bounded to the north by the Sainte-Victoire mountain, resulting from a thrust system, and to the south by the Étoile massif, also formed by thrust tectonics (Fig. 1).

The Fuvélien formation, which was exploited during mining operations, is a local term referring to the Upper Campanian (about 74 Ma). This formation is present in the autochthonous part of the Gardanne Basin, where it dips north-northwest. It is also found in the southern part of the basin, within a tectonic slice known as the "Lambeau charrié" (thrust sheet), which is bounded by the Diote fault to the north and the Safre fault to the south. This thrusted structure, formed simultaneously with that of the Étoile massif, induced a southward dip of the Fuvélien layers in this area (Fig. 1(b)). The Fuvélien is an approximately 300 m thick formation composed of 96% limestone, divided into five distinct types, and 4% lignite (Gaviglio 1985). The lignite layers are mainly concentrated in its basal part, where they form seven distinct horizons with specific petrographic and sedimentological characteristics (Gonzalez

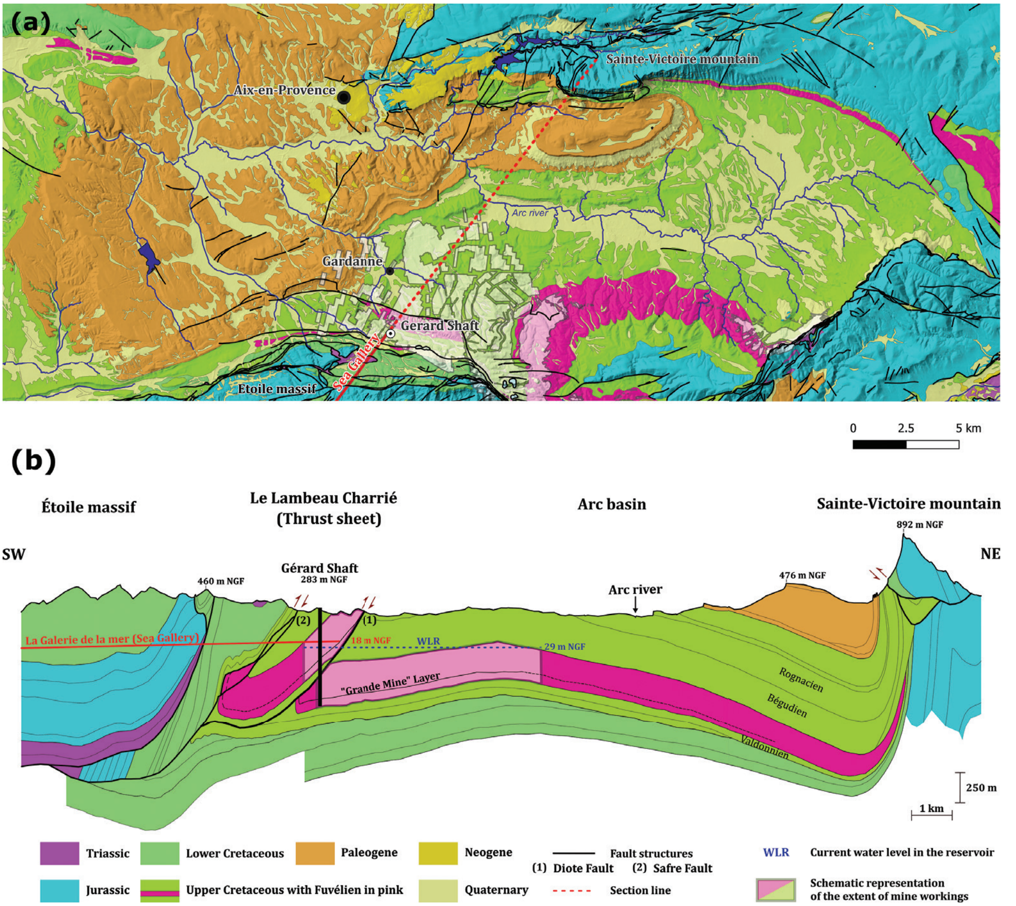

Figure 1 Simplified geological map (a) and cross-section (b) of the Gardanne basin, illustrating the main lithological units and structural features; (b) adapted from J-P Durand (1980, Houillères du Bassin de Centre-Midi) (NGF: French altimetric reference based on the mean Mediterranean Sea level).

1981). These layers were exploited to varying degrees depending on their thickness. The most intensively mined was the 'Grande Mine' lignite layer, which is 2.5 m thick in the autochthonous deposit and 4 m in the thrust sheet.

The Gardanne basin has a complex hydrogeological setting, with multiple superimposed aquifers compartmentalized by low-permeability formations. The most important and deepest aquifer is the Upper Jurassic unit, composed of karstified limestones, with a recharge occurring in the Sainte-Victoire Mountain (Fig. 1). In some areas (mainly in the north), the localized absence of Lower Cretaceous formations results in a direct contact between Jurassic and Upper Cretaceous units (Ancel *et al.* 2004). The Fuvélien, the main karstic aquifer of the Upper Cretaceous, is separated from the Jurassic by the Valdonnien, a marl formation acting as an aquitard. No natural outlet of the Fuvélien has been identified. Above it, the Bégudien forms the second Upper Cretaceous aquifer unit.

Mining operations revealed heterogeneous permeability in the Fuvélien: behaving as an active aquifer in the east near outcrops, but drier in the deeper western part (Chalumeau 2000). During the 1970s and 1980s, major groundwater inflows (sources "90" and "Sainte-Victoire") were encountered in the eastern part of the mine, temporarily disrupting operations. These inflows likely originate from the Jurassic karst aquifer, and reach the mine through localized connections (fractures or karst conduits) between the Fuvélien and Jurassic formations (Chalumeau 2000; Dewandel *et al.* 2017). These exchanges, still active today, influence the flow dynamics within the mine water reservoir. When mining operations ceased in 2003, pumping was stopped, initiating a gradual rise of the water table within the underground workings. This process resulted in the progressive flooding of the mine, substantially altering the hydrogeochemical conditions within the system. As expected, iron and sulfate concentrations increased due to water-rock interactions, with peak values reaching 55 mg/L for iron and 3000 mg/L for sulfate. During active mining, various water inflows were mainly drained by gravity through the Galerie de la Mer, a historical drainage gallery that discharged directly into the port of Marseille. Once the mine was flooded, the risk of mine water overflowing into this pathway became problematic, as the iron-rich water could oxidize and precipitate, potentially causing visible staining in the port. To prevent this uncontrolled discharge, a pumping system was established in 2010 at the Gérard shaft, located upstream of the gallery, to transport the pumped water to the sea via a pressurized pipeline under anoxic conditions, preventing any risk of iron oxidation. The Gérard shaft is the only access point to the entire mine water reservoir and intersects both the autochthonous and thrust sheet sections of the Fuvélien formation. It features multiple gallery levels along its 700 m depth, providing a unique opportunity to investigate the hydrogeochemical processes within the flooded mine. A field campaign was conducted at this site to identify the sources of mineralized water, characterize mixing processes, and assess ongoing water-rock interactions within the mine system.

Methods

To investigate the hydrogeochemical conditions in the flooded Gardanne lignite mine, a field campaign was conducted in October 2024 at the Gérard shaft, the only access point to the mine water reservoir. Based on the framework proposed by Mugova and Wolkersdorfer (2022) for studying flooded shafts and stratification, a specialized mobile setup was deployed. This system consisted of a 1.5 km winch mounted on a field truck and equipped with an electrified cable for data transmission and real-time monitoring. This setup allowed for precise depth control, ensuring accurate in-situ measurements and water sample collection.

To avoid some undesirable interactions between the equipment and the pumps, the water extraction system was shut down 92 hours before the field measurements. A multiparameter probe (Idronaut 303, GeoVista) was then deployed to perform a detailed continuous physico-chemical log along the water column. The recorded parameters included pH, temperature and conductivity. The probe was calibrated beforehand and deployed at a speed of approximately 5 m/min. The probe provides high-resolution (±0.005 °C, ±1 µS/cm, ±0.05 for pH). A similar logging approach was conducted in several shafts of the Lorraine coal basin (Reichart 2013).

Based on physico-chemical profiling, water samples were collected at specific depths corresponding to major transitions (Fig. 2). Sampling was performed using remotely operated, pre-vacuumed stainless-steel bottles, which were opened at depth via a solenoid valve. This ensured passive filling with minimal air contact, preserving redox-sensitive species such as dissolved ferrous iron. The collected samples were analyzed for dissolved gases (free gases, CFCs, SF_6), carbon species (TOC, TIC, DOC, DIC), alkalinity (CO_3^{2-}, HCO_3^-), major anions (Cl^-, F^-, NO_3^-, NO_2^-, SO_4^{2-}, PO_4^{3-}), major cations (Ca^{2+}, Fe^{2+}/Fe^{3+}, K^+, Mg^{2+}, Na^+, NH_4^+, Si), trace elements (Ag, Al, As, B, Ba, Be, Br, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, Sr, Zn), isotopic ratios (δ^2H/δ^1H, $\delta^{18}O/\delta^{16}O$ in water; $\delta^{13}C/\delta^{12}C$ in DIC; $\delta^{34}S$, $\delta^{18}O$ in SO_4^{2-}; $\delta^{34}S$ in dissolved sulfides; $^{87}Sr/^{86}Sr$, $^7Li/^6Li$, $\delta^{11}B/\delta^{10}B$), and microbiological parameters (bacterial biodiversity via DNA sequencing, microflora abundance). Only dissolved iron concentrations will be discussed in this paper.

Results and Discussions

Physico-chemical profiles from 2024 can be compared with a 2011 log, recorded about a year after mine flooding ended and pumping started (Fig. 2). Temperature, conductivity and pH of both datasets are presented in Fig. 2. The Fe^{2+} concentrations in different zones of the Gérard shaft (precise depths shown in Fig. 2) are presented in Table 1. Dissolved iron, analysed by ICP-AES within one month after sampling, was measured on samples filtered on-site at 0.45 µm and acidified to pH <2 with ultrapure nitric acid immediately after collection.

The 2024 log reveals five distinct zones (Fig. 2), which will structure our following discussion. These zones appear to be strongly related to different mining levels, corresponding to former access galleries in the shaft. In 2011, Zone 1 (above pumps) has a uniform temperature of 21.73°C with a low temperature gradient (0.2 °C/100 m). Zone 2 (between the pumps and level 250) is stable at 22.45°C down to -183 m NGF, then decreases irregularly to 21.8°C at -250 m NGF. Zone 3 (level 250 to -315 m NGF) displays a nearly linear but unstable gradient (2.57°C/100 m) extending to -276 m NGF, followed by a temperature jump and another gradient (1.87°C/100 m) to -309 m NGF, before rising abruptly to 24.1°C at -314 m NGF. Zone 4 (-315 to -335 m NGF) shows a uniform temperature (24.15°C) with a low gradient (0.04°C/100 m). Finally, in Zone 5 (-335 to -421 m NGF), temperature increases irregularly with depth (0.74°C/100 m), reaching 24.79°C at -421 m NGF. The 2024 log shows notable changes. Zone 1 remains uniform, with a temperature of 20.77°C and a low gradient (0.2°C/100 m). Zone 2 is stable at 21.3°C (0.028°C/100 m). In Zone 3, temperature is stable but slightly noisy (~21.76°C) with a gradient of 0.06°C/100 m. Zone 4 reveals a staircase-like structure: the upper part has two large steps (~3.5 m), followed by four smaller ones (~1.5 m) with a gradient of 11.8°C/100 m. At -329.5 m NGF, the gradient steepens (24.2°C/100 m) with smaller steps (~50 cm). In Zone 5, temperature remains stable at 25.02°C (0.09°C/100 m). Conductivity and pH follow a similar trend to

Table 1 *Fe^{2+} Concentration evolution in different Gérard shaft zones (2011 & 2024).*

			Fe^{2+} (mg/L)	
Zone n°	**Sampling Depth 2011**	**Sampling Depth 2024**	**2011**	**2024**
1	-17 m NGF	-35 m NGF	< 0.05	< 0.02
2	-247 m NGF	-247 m NGF	43	32.9
3	–	-310 m NGF	–	29.7
4	-317 m NGF	–	27.8	–
5	-417 m NGF	-419 m NGF	2.2	13.0

temperature, except in Zone 1, where the pH is higher (6.76 in 2011 and 7.35 in 2024) than in the rest of the shaft and slightly decreases from top to bottom in 2024. Additionally, a 2 m-thick intermediate layer (Wolkersdorfer 2008, Mugova and Wolkersdorfer 2022) appears between Zones 1 and 2, and a 1.5 m-thick one between Zones 2 and 3. Between the two periods, a general cooling and decrease in conductivity are observed throughout the water column, except in Zone 5, along with an overall increase in pH. The dissolved iron concentration in the shaft (Table 1) is very low in Zone 1, reaches a maximum in Zone 2, then tends to decrease with depth. It is contrary to what is generally observed (Nuttall *et al.* 2004), stating that dissolved iron concentrations typically increase with depth.

In 2011, an inflow of cold, fresh water clearly appeared at -250 m NGF, cooling both the upper and lower parts of the shaft. Since the Gérard shaft is cased and supposed

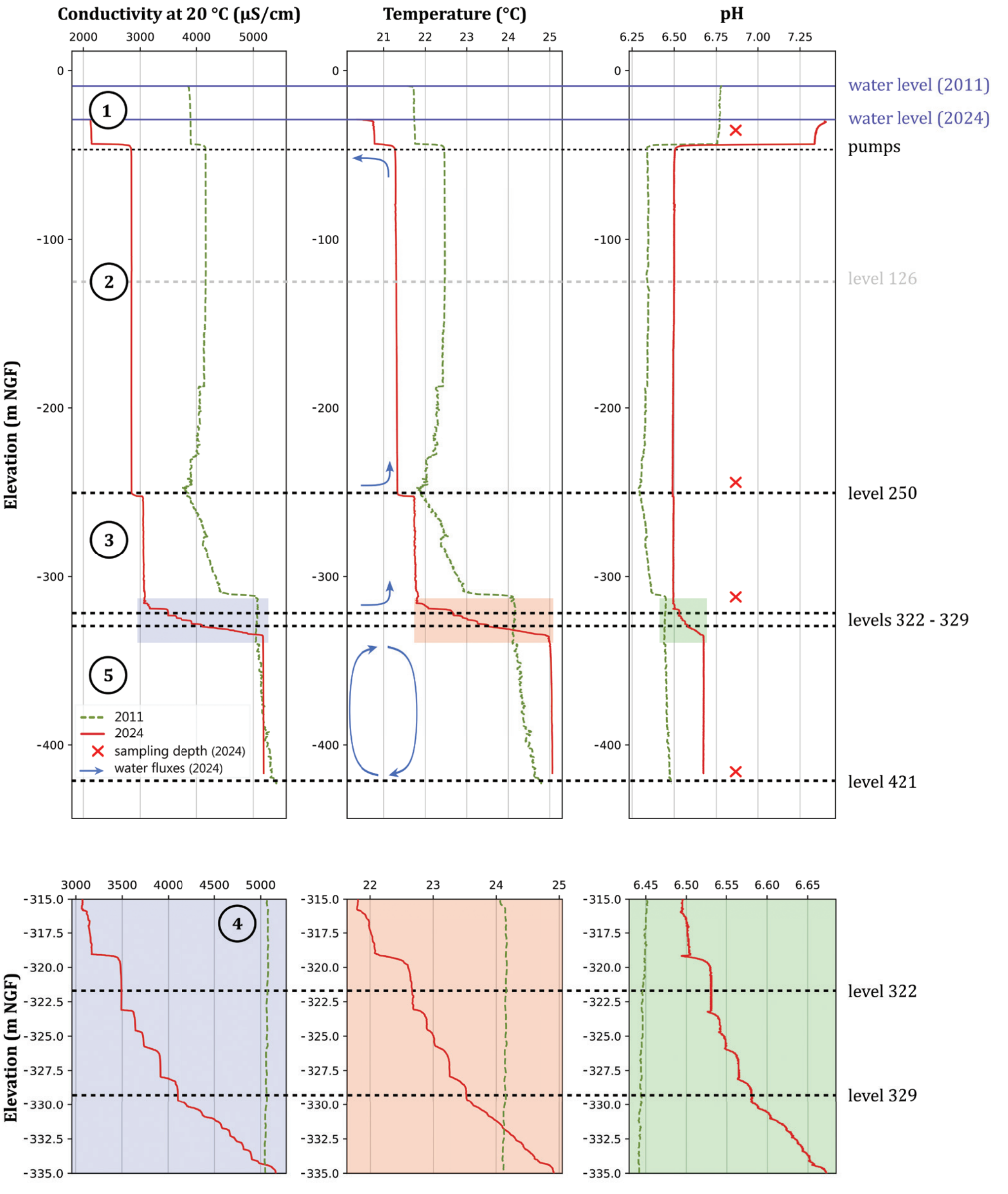

Figure 2 Comparison of pH, Conductivity and Temperature logs in the Gérard Shaft (2011 & 2024).

hydraulically sealed, water exchanges are only possible through intersecting galleries. This inflow corresponds to one such gallery, likely fed by groundwater from the Jurassic karst aquifer (sources 90 and Sainte-Victoire), through the former main drainage gallery (Travers Banc 250). Between 2011 and 2024, temperature, conductivity, and pH have homogenized up to the pumps level (Zone 2), indicating an upward forced convection regime in this water column (Reichart 2015, Bao *et al.* 2019a). The progressive deepening of this forced convection suggests that pumping has extended its influence over time, creating a homogeneous layer as a balance between the inflow at level 250 and the outflow at the pump. Stratification occurs when water layers form due to density contrasts from temperature, salinity, or turbidity variations (Wolkersdorfer 2008). The 2011 data indicate a predominantly diffusive regime in Zone 3, characterized by the absence of vertical water fluxes, as evidenced by the observed temperature gradient. The sharp transition between Zones 3 and 4 at -315 m NGF, followed by a uniform temperature in Zone 4, suggests the influence of a warmer inflow through the gallery at level 322 interacting with the gallery at level 329 to form a localized convection loop (similar to the Ronneburg Uranium mine; Wolkersdorfer 2008). Zone 5 was primarily governed by a diffusive regime. Between 2011 and 2024, important changes occurred in these deeper zones. Zone 3 has now stabilized into a homogeneous layer, possibly due to the influence of pumping extending to level 322, which would now direct its inflow upward. This shift has disrupted the dynamic exchanges between levels 322 and 329, giving rise to a thermohaline staircase structure in Zone 4. This type of stratification typically results from local opposing temperature and salinity gradients, triggering double-diffusive convection, which generates a sequence of oscillatory convection cells (Reichart 2015, Bao *et al.* 2019a, Bao *et al.* 2019b). The stable conditions observed in Zone 5 in 2024 now suggest the presence of a large convection loop between levels 421 and 329, or inter-level connections at the mine scale. The staircase structure in Zone 4 effectively isolates Zone 5 from the upper part of the shaft (Wolkersdorfer 2008, Reichart 2015, Bao *et al.* 2019b). The two identified inflows at levels 250 and 322 potentially share a similar origin due to their comparable iron concentrations. In its upper part (above level 322), the mine appears to be supplied by recharge zones and major inflows encountered during mining operations, likely originating from the Jurassic karst aquifer. Water circulates through the gallery network before reaching the shaft openings at levels 250 and 322, where it is pumped out. Lower concentrations in the deepest part may indicate other water sources and/or specific biogeochemical processes.

Conclusions

The comparative analysis of physico-chemical profiles between 2011 and 2024 highlights changes in the organization of water masses within the Gérard shaft. For thirteen years of pumping, the water column has evolved towards a stable stratification. This structuring appears to reflect a differentiated convection regime depending on the shaft zones, with the upper part being primarily influenced by anthropogenic pumping, while the deeper section results from natural stratification processes. Two inflows at levels 250 and 322, seemingly originating from similar sources, have been identified. Additionally, the deepest zone appears to be isolated from the rest of the shaft, potentially influenced by distinct biogeochemical processes or different water inputs. These preliminary interpretations, although supported by the literature, concern complex systems that remain challenging to understand. The forthcoming interpretation of chemical, isotopic, and bacteriological analysis results, coupled with their modeling, should help refine the understanding of flow dynamics within the shaft and its exchanges with the rest of the mining network.

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