

Abandoned Mines as Pumped Hydro Storage Power Plants – A Strategy for Geochemical Characterisation of Mine Water Before Operation

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Abstract

Pumped hydro storage (PHS) is a suitable method for storing energy, and abandoned mines are often suitable due to the large elevational differences between potential upper and lower storage reservoirs. Several geochemically related issues have been identified regarding the selection of abandoned mines: (i) initial lowering of the mine water level to obtain a suitable elevational difference, (ii) discharge of excess water during operation, and (iii) water quality during operation.

It is suggested that detailed chemical profiles and underground water volumes be determined. It is also important to determine the water quality and water flows in the recipient in order to avoid breaching environmental quality standards during both the initial and the operational discharge of excess water.

Keywords: Mine water, geochemical evolution, sampling, acid rock drainage

Introduction

Abandoned mining sites are common around the world. Underground mine infrastructure can, however, continue to deliver value after active mining has ceased. As intermittent electricity production increases, the need for energy storage and energy balancing services increases as well. Pumped hydro storage (PHS) is a suitable method for energy storage, as it requires fewer finite resources and provides substantially longer lifecycles compared to battery storage systems. Pumped hydro storage also contributes to grid stability and security through, e.g., inertia and black start capabilities. Several studies have been published regarding issues surrounding pumped hydro storage (Morabito *et al.*, 2020; Lyu *et al.*, 2022; Colas *et al.*, 2023), but few have focused on issues related to the geochemical composition of the mine water and the resulting effect on potential projects.

The elevational difference in some underground mines is well suited for pumped hydro storage. With an elevational difference

of 100–150 m or more, even small volumes of water (0.5 Mm³) can be used to produce electricity and provide balancing services for an extended period (several hours).

In Sweden, there are several abandoned mining sites with deep underground infrastructure suitable as the lower reservoir, in combination with a suitable upper reservoir either above or below ground. The upper reservoir can, for instance, be an adjacent open pit, an aggregate quarry, or a large cavity in the upper parts of the underground mine.

There are, however, several geochemical challenges when repurposing an abandoned underground mine. The geochemical issues are at least threefold: (i) discharge of existing mine water in an abandoned mine, (ii) discharge of excess water during operation, and (iii) quality of water during operation.

Abandoned underground mines are often water-filled, and water needs to be discharged to obtain a sufficient elevational difference between the upper and lower reservoirs. Depending on the mineralisation (base



metals or iron ore), the initial water quality might be an issue (ARD in sulfide base metal mines and, for instance, molybdenum or uranium in iron ore mines). Lowering the water level by 100–150 m may require draining several Mm^3 of mine water into a suitable recipient.

During injection from the upper reservoir to the lower reservoir in the mine, large amounts of dissolved oxygen will also be introduced into the underground mine system. Increased oxygen saturation might lead to increased oxidation of any sulfide minerals present and of dissolved ferrous iron, resulting in lower water quality (Pujades *et al.*, 2018; Pujades *et al.*, 2019). The groundwater cone of depression will draw additional drainage water into the mine, requiring continuous discharge and potentially treatment if the water quality is poor. Moreover, injection and pumping activities during operation can alter groundwater levels in the surrounding area (Pujades *et al.*, 2016), potentially enhancing the leaching of trace elements from remaining mineralisation.

Water quality during operation may also affect scaling or corrosion of the turbine and pumping equipment (Roy *et al.*, 2016).

We have developed a strategy, from a geochemical perspective, for determining whether a mine site can be developed into a pumped hydro storage facility. The strategy will be illustrated using a water-filled abandoned iron ore mine in Norberg, Sweden, where minor parts were also mined for silver and lead.

Methods

It is important to properly sample and characterise the underground mine water through depth profiles in several parts of the mine in order to determine the likely quality of the entire water volume and, based on this, to determine proper management and suitable discharge points into the recipient. It is important to understand both the underground and the surface water quality in order to avoid breaching any environmental water quality standards in the recipient during discharge.

Norberg field site

The municipality of Norberg, in the historical mining district of Bergslagen, Sweden, has had active mining for around 1 500 years. Mining started around 500 AD and stopped in the early 1980s. Iron ore has been the major product, while small amounts of silver ore have been produced in one of the oldest parts, around Silvergruvan (Fig. 1). One of the largest underground mines in Norberg is today water-filled and contains, in total, around 10 Mm^3 of water. The natural discharge point is currently located somewhere south of Centralschaktet (C), in an abandoned area with several open or poorly covered shafts and building remains. The current natural discharge from the underground mine is estimated to be around 10–20 L/s.

Prior to the installation of equipment (turbines and pumps) in the underground mine, the current water level needs to be lowered to around 100 m, requiring an estimated 3 Mm^3 of water to be pumped and discharged into the recipient. It is planned to be discharged into the recipient over 1 year at an average rate of 100 L/s.

A disused aggregate quarry will be used as the upper reservoir, and the entire underground mine will act as the lower reservoir. A penstock will transfer water between the quarry (upper reservoir) and Skakelbergsschaktet (Sk in Fig. 1) (lower reservoir). The upper reservoir will have a maximum capacity of around 0.5 Mm^3 , allowing for 5–6 hours of continuous electricity production at $25 \text{ m}^3/\text{s}$.

Sampling

Sampling has been performed in the accessible shafts: Silvergruvan, Skakelbergsschaktet, and Centralschaktet (see Fig. 1 for a map and Fig. 2 for the depth profiles). Depth profile sampling was performed using both a depth sampler and a continuously logging diver for temperature and electrical conductivity. Surface water was sampled at selected recipient points around the old mine (Fig. 1). The surface water sampling points were selected both to generate a water quality baseline prior to operation and to determine the most suitable discharge points

Table 1 Surface water sampling points.

Description	
N1	Present outlet from the quarry, the upper reservoir.
N3	Into lake Bålsjön. Between N1 and N3 the creek is affected by historical sulfidic mining waste. Potential recipient for discharge of excess water during operation (10-20 L/s).
N15	Outlet lake Bålsjön.
N11	Inlet lake Dammsjön. Potential recipient for discharge of excess water during operation (10-20 L/s).
N14	Outlet lake Dammsjön. Lake Dammsjön also affected by a reprocessed stainless steel slag deposit.
N5	Potential current discharge from the underground mine.
N18	Potential current discharge from the underground mine.
N16	Downstream N18. Between N18 and N16 the water passes through another underground mine. Potential recipient for discharge of excess water during operation (10-20 L/s).
N8	Outlet lake Noren (major recipient in Norberg). Potential recipient for the initial draining of the underground mine (100 L/s).

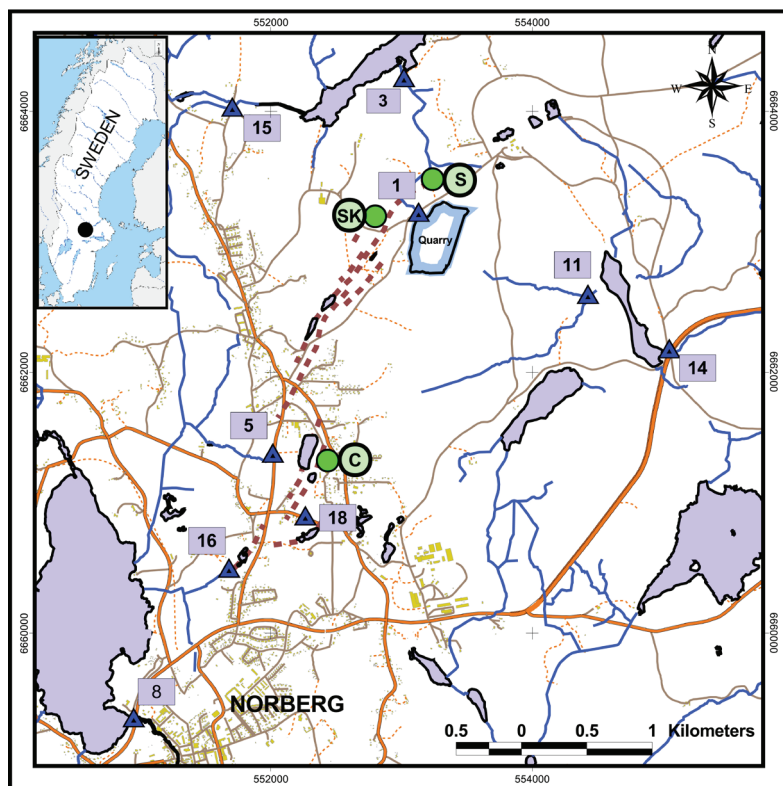


Figure 1 Illustration of the Norberg underground mining system. Silvergruvan (S), Skakelbergsschaktet (Sk), the upper reservoir (Quarry) and Centralschaktet (C). Skakelbergsschaktet (C) is the shaft planned to be used for turbines and pumps. Surface water sampling points 1, 3, 5, 8, 11, 14, 15, 16 and 18. Red dotted line indicates the extension of the underground mine between shaft Silvergruvan (S) and Centralschaktet (C).



for emptying the underground mine and for the discharge of excess water (rain on the upper reservoir and groundwater seepage into the lower reservoir) during operation. During water sampling, the water flow was also estimated at each point. The surface water sampling points are described in more detail in Tab. 1.

Chemical analysis

Water samples were analysed for pH, electrical conductivity, alkalinity, sulfate, chloride, fluoride, nitrate and ammonia as well as base cations (Na, K, Mg, Ca, Fe and Mn) and trace elements including molybdenum and uranium.

Results and discussion

The results from the water sampling in the mining shafts are presented in Tab. 2. The mine water in the Silvergruvan (S) shaft is affected by the sulfide mineralisation in that part of the underground mine. Sulfate,

lead, copper and zinc concentrations are elevated. In the more modern parts of the mine, represented by the Skakelbergsschaktet (Sk) and Centralschaktet (C) shafts, concentrations of molybdenum and uranium are elevated instead. Both molybdenum and uranium concentrations increase with depth, along with increasing dissolved iron concentrations, while decreasing sulfate concentrations indicate slightly more reducing conditions with depth. To avoid drawing water from Silvergruvan (S) during the emptying of the underground mine, the most likely draw point for the initial lowering of the water level is Centralschaktet (C). Since the exact water volumes in the underground mine as a function of depth are not fully understood, it is not possible to determine exactly the average water quality during the initial pumping. The large mined-out voids underground are not accessible, and the water quality for a large fraction of the underground mine water is thus not known. At this stage, it

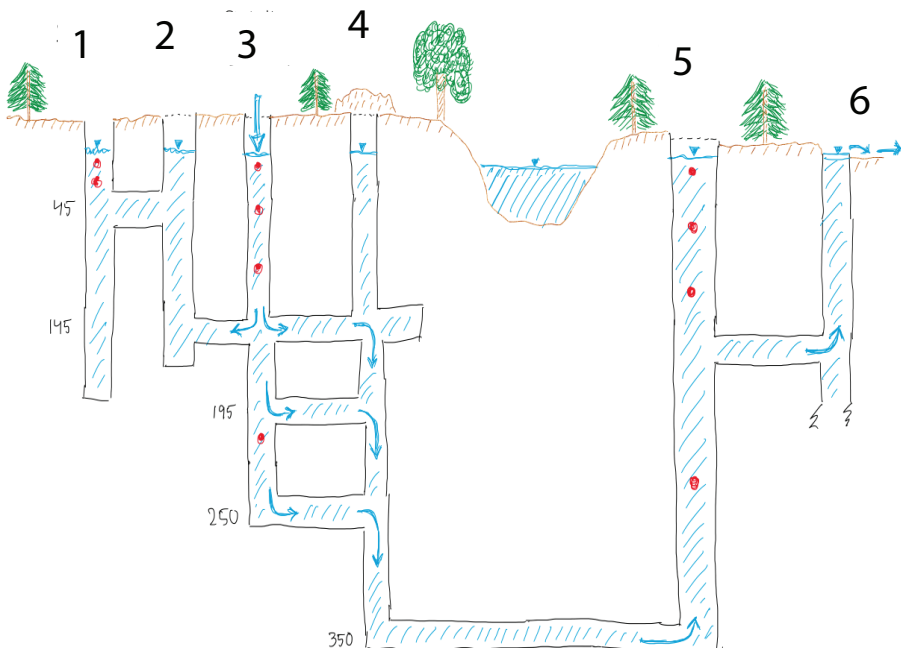


Figure 2 Illustration of the Norberg underground mining system. Shafts are numbered; Silvergruvan (1), Nya Mångsgruvan (2), Skakelbergsschaktet (3), Gustaf Adolfsschaktet (4), Centralschaktet (5) and discharge area (6). Red dots illustrate sampling points and numbers in black are depth below the surface. Skakelbergsschaktet (3) is the shaft planned to be used for installation of turbines and pumps. Blue arrows indicate possible waterways for injected water during operation. Also note that the actual stopping chambers (larger voids) are not included in the illustration.



Table 2 Concentrations in the mine shafts. All concentrations in µg/L except for sulfate and fluoride (mg/L). S, Silvergruvan; Sk, Skakelbergsschaktet and C, Centralschaktet (shaft numbers 1, 3 and 5 in Fig. 2). Numbers indicate depth (m) below water surface.

	S1	S20	Sk5	Sk43	Sk100	Sk208	C5	C48	C96	C228
pH	6.20	6.60	6.70	6.60	6.70	7.20	7.40	7.40	7.40	7.40
Pb	1 300	180	7.3	7.5	7.1	4.4	0.12	0.38	0.49	1.6
Cd	0.62	0.11	0.019	0.011	0.011	0.013	0.013	0.014	0.016	<0.01
Cu	150	12	24	15	13	4.5	8.4	9.1	6.9	4.1
Mo	-	-	1.6	1.3	1.6	6.9	7.0	6.8	7.1	8.6
U	0.10	0.48	0.88	1.0	1.4	8.9	3.6	3.6	4.8	8.1
Zn	88	19	25	5.6	7.2	9.5	24	25	22	12
Fe	680	7 300	11 000	12 000	11 000	5 000	65	380	700	2 800
Sulfate	99	130	56	56	54	31	15	15	19	20
Fluoride	4.0	3.2	3.5	3.4	3.4	2.5	0.75	0.74	1.5	1.6

Table 3 Average concentrations of trace elements in selected recipient sampling points. All concentrations in µg/L except for sulfate and fluoride (mg/L). Average flow calculated from the size of the drainage area and an annual runoff of 260 mm.

	N1	N3	N15	N11	N14	N5	N18	N16	N8
Av flow (L/s)	0.2	13	48	13	35	1.2	-	15	1 390
pH	7.15	7.43	7.27	6.27	7.60	7.73	7.70	7.90	6.93
Pb	2.89	15.9	0.57	0.34	0.39	0.09	0.31	<0.02	0.27
Cd	0.02	0.02	<0.01	0.02	0.02	<0.01	0.01	<0.01	<0.01
Cu	2.75	12.8	3.93	1.01	4.57	1.90	7.80	3.77	1.20
Mo	10.5	4.90	2.50	<1	26.0	<1	6.30	18.0	<1
U	41.0	4.07	0.87	0.29	1.93	0.48	7.0	11.0	0.40
Zn	<1	2.80	1.25	2.67	1.73	<1	2.90	<1	1.87
Fe	71.3	3 000	427	1 250	800	60.0	1 300	60.0	407
Sulfate	35.0	10.6	6.60	3.37	53.7	7.13	19.0	30.0	3.93
Fluoride	2.18	1.90	0.89	0.26	0.99	0.85	2.10	1.90	0.19

is therefore assumed that the water quality in the large voids is similar to the water quality in the closest shaft at a similar depth.

The results for concentrations in selected surface waters are presented in Tab. 3. Elevated concentrations of molybdenum and uranium indicate a major influence from mine water (N16 and N18). The local granite is also a likely source of molybdenum and

uranium, as the discharge from the disused aggregate quarry (N1) contains the highest concentrations. Leaching from the remaining crushed aggregate in the disused quarry might thus also be a problem during operation. It is also likely that the surface water at N18 originates from the discharge of underground mine water close to Centralschaktet. After passing through another underground mine,



sample N16 has even higher concentrations of molybdenum and uranium, confirming the fact that the iron ore in the area contributes these trace elements to the leachates.

The relatively small water volumes in the Silvergruvan (S) shaft (Fig. 2) indicate that the sulfide-affected water will not create an issue, as it will most likely drain into the Skakelbergsschakt (Sk) shaft, where the reduced iron will precipitate. The major issue when it comes to discharging the initial volume of water (around 5 Mm³) is the effect on the recipient, given a flow of 100 L/s over a full calendar year and the elevated concentrations of molybdenum and uranium. A high discharge flow from the underground mine requires a recipient with a decent water flow, where the concentrations of the relevant trace elements will not be significantly affected by the discharged water. If a suitable discharge point cannot be found, water treatment or a lower pumping rate might be required to decrease the amount of trace elements being discharged and thus avoid breaching the environmental quality standards.

Conclusions

The initial lowering of the water level in the underground mine, prior to the installation of turbines and pumps, requires detailed knowledge of the water chemistry as well as of the water volume in the mine as a function of depth, in order to determine the actual concentrations during pumping and to select a suitable draw point in one of the shafts. Knowledge of the water flow and concentrations in the recipient is required, in combination with the quality of the underground mine water, in order to select a suitable discharge point into the recipient.

Leaching from the upper reservoir also needs to be investigated, as frequent repeated cycles of pumping and discharge might create conditions leading to increased leaching of naturally occurring trace elements.

The water quality during operation is a function of the original mine water quality, the leachability of the surrounding rock, and the injection of oxygen, as well as of potential leaching from the upper reservoir.

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