Reducing water quality impacts from abandoned mines in Saxony – Challenges and benefits for passive treatment options

Eberhard Janneck[1], Mirko Martin[1], Christine Stevens[2], Axel Hiller[3]

[1]G.E.O.S. Ingenieurgesellschaft mbH, POB 1162, 09581 Freiberg, Germany; e.janneck@geosfreiberg.de; m.martin@geosfreiberg.de

[2]Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, Zur Wetterwarte 11, 01109 Dresden, Germany; Christine.Stevens@smekul.sachsen.de

[3]Wismut GmbH, Jagdschänkenstr. 29, 09117 Chemnitz, Germany; a.hiller@wismut.de

Abstract

Recent studies have investigated metal contamination in rivers and streams from abandoned mines in Saxony, Germany. Many of the pollutant sources are suitable for passive treatment systems in terms of metal load and composition. They are also one of the few affordable measures, which can improve the ecological and chemical status of the receiving water bodies. Reviewing a full-scale passive system for the treatment of the effluent from an abandoned uranium mine and pilot tests for the treatment of mine water containing iron, arsenic and zinc are presented in this paper. The performance of the test systems qualifies for a successful application of passive treatment schemes in Saxony's mining regions. Benefits not only include the improvement of water quality but also the enhancement of biodiversity, resilience to climate change, water retention and landscape aesthetic value.

Keywords: Passive treatment, abandoned metal & hard coal mines, vertical flow reactor, ferrous iron oxidation and sedimentation reactor

Introduction

Water authorities in Saxony, Germany, are facing challenges with effluents from numerous abandoned metal and hard coal mines. Many rivers and streams in the region suffer from pollution with arsenic, copper, zinc, cadmium or nickel from these historic mines. Pollution from mining represents one of five major water management issues and breaches the environmental objectives of the European Water Framework Directive in the transboundary River Elbe basin.

Characteristic element composition of the mined mineral deposits lead to typical element associations in the related mine waters. In Saxony, the main contaminant families consist of

- Arsenic and iron from tin-tungsten mines
- Zinc, cadmium, arsenic and in some cases aluminium from silver-lead-zinc mines
- Arsenic, iron, uranium and radium from uranium mines
- Zinc, cadmium, nickel and sulfate from hard coal mine dumps

During the last 25 years, mine water remediation in Saxony has focused on large point sources of polluted mine effluents where active treatment is necessary to meet discharge limits. The runoff from many abandoned mines, where no legal successor exists, has so far remained untreated, and thereby, it prevents streams in Saxony from achieving a good chemical and ecological status.

In contrast to most metal and hard coal mines in Saxony without a legal successor, Wismut GmbH is responsible for the remediation of legacies from uranium mining. Besides the construction and operation of six active water treatment plants, Wismut started working on passive systems as early as the late 1990s. Pilot plants for the passive treatment of leachate from waste rock dumps were tested at several sites. As a result, one plant was built and operated at full-scale with a flow rate of 3.1–4.2 L/s. This passive biological plant was located at the Pöhla site in the Saxon Ore Mountains at an altitude of 550 to 575 m above sea level. The challenge was

Table 1 Annual average values of selected parameters of the mine water compared to the discharge values

Parameter	Unit	Mine Water		Discharge limit	Treated discharge (avg. 2005–2013)
		2001	2013		
Fe	mg/L	8.0	4.6	2.0	0.02
As	mg/L	2.3	1.9	0.1	0.041
Ra-226	Bq/L	4.3	4.1	0.3	0.014
U	mg/L	< 0.1	< 0.1	0.2	0.017

to treat the mine water from the Pöhla-Tellerhäuser underground mine drained by the main adit. Although pollutant levels showed a declining trend over time, a comparison with the discharge limits identified a necessity for treatment (Tab. 1).

The following process steps were implemented in the two-line plant (line A and B):

- Aeration cascade for enrichment of the mine effluent with dissolved oxygen,
- Basins 1A and 1B for precipitation/settling of iron hydroxides (FeOOH),
- Basins 2A and 2B for precipitation of suspended solids and fine iron hydroxide flocs,
- Basins 3A to 4B with Characeae: Radium-226 separation by incorporation into the cytoskeleton structure of stonewort (Characeae),
- Filters 5A and 5B with adsorbents to control radium-226,
- Filters 6A and 6B with adsorbents to control arsenic.

The plant was operated from October 2004 to March 2014, treating up to 131,000 m^3 of mine water per year (a total of 1.1 million m^3) in continuous operation. It was possible to meet the required discharge limits continually by active management of the Characeae stocks and the use of control filters (Tab. 1).

During the operation of the plant, the biological treatment step never achieved the predicted degree of separation. Despite various optimization measures, the pollutants were predominantly separated by the reactive materials, which had originally been planned as control filters. As a result, operating costs increased substantially due to the frequent need to replace the filter materials. Due to these problems, the operation of the passive plant was terminated ahead of schedule, although the basic suitability of the process had been confirmed. Despite this decision, Wismut GmbH is still interested in the further development of passive water treatment processes. In the long term, with declining pollutant levels and suitable boundary conditions, passive treatment plants are an effective option for the treatment of mine and seepage waters.

Methods

Determining the effects of abandoned mines on streams and rivers in Saxony

In Saxony, emissions from abandoned mines and their associated spoil heaps and tailings are responsible for the pollution of more than 1,300 km of river systems. Results of a recently completed study, commissioned by the Saxon State Office for Environment, Agriculture and Geology (LfULG), allow for a detailed breakdown of overall river pollution loads to specific sub-sources including abandoned mines, spoil heaps and tailings. Pollution loads were calculated for relevant point sources. Metal load contributions from diffuse and geogenic sources for specified reaches were estimated by means of load balancing. Geogenic sources could only be derived for reaches where no historic or recent mining had taken place. Tab. 2 summarises point sources from mining including pollution from adits as well as discharges from spoil heaps and tailing management facilities (TMF) for the River Zwickauer Mulde sub-basin of the Elbe River basin. More details of these investigations were recently published by Stevens et al. (2023).

The smaller-scale sources (with discharges up to 25 L/s) shown in Tab. 2 are in principle suitable for passive treatment facilities to improve the ecological and chemical status of their receiving water bodies. For the successful application and engineering of such treatment schemes, small

Table 2 Important point sources from mining for waterbodies of the Zwickauer Mulde sub-basin

#	Water body	Source of metal pollution	Load contribution (%)$^{1)}$					Q
			As	Cu	Zn	Cd	Ni	L/s
1	Schwarzwasser-2	Treue Freundschaft Adit		37	44		11	30–70
2	Oswaldbach	Frisch Glück Adit			21			4–5
3	Kleine Pyra	Leachates from TMF Gottesberg	87	46				7–10
4	Kleine Pyra	Leachates from TMF Schneckenstein	41	82	45	38		35
5	Kleine Pyra	Wolfram Adit	10					0,1–0,6
6	Reinsdorfer Bach	Spoil heap leachate Morgenstern shaft #II			23	48		3
7	Reinsdorfer Bach	Spoil heap leachate Brückenberg shaft #IV			50	56		3*
8	Mulde-4	Markus Semmler Adit	41					140–170
9	Hegebach	Spoil heap leachate Kaiserin Augusta and Vertrauen shaft			16	23	16	10–12
10	Hegebach	Spoil heap leachate Merkur, Pluto shaft, Spoil heap leachate Kaisergrube, Ida and Helene shaft			31	25	16	10–50
11	Schwarzwasser-1	St. Christoph Adit			29			4–6*
12	Schwarzwasser-1	Adit #146			21			5*

1) The percentages of the loads refer to the total load in the respective river section. *estimated value

scale pilot tests are necessary to determine the appropriate design parameters. These will enable gradual scaling up to full-flow treatment and provide the necessary data for obtaining the mandatory approvals.

Study sites

Study sites presented in this paper include mine waters from the Zwickauer Mulde sub-basin (Tab. 2) as well as the Freiberger Mulde sub-basin. Tab. 3 provides hydrochemical data of Saxon metal and hard coal mine discharges suitable for passive treatment options. Contaminant characteristics differ considerably ranging from arsenic as the sole contaminant (Ehrenfriedersdorf #1) to a more complex contaminant composition at the Breitenbrunn site and for the leachate discharges. Effluents #2 to #5 were selected for further lab, pilot and field tests as these are most suitable for passive treatment. Tests at the sites #2 and #3 are currently ongoing while tests at sites #4 and #5 are planned for the near future.

Table 3 Typical water quality data from abandoned mines in Saxony

	Unit	Adit „Tiefer Sauberger Stolln“, Ehren-friedersdorf$^{2)}$	Spoil heap leachate Ehrenfrieders-dorf$^{2)}$	St. Christoph adit, Breiten-brunn$^{1)}$ (#11 in Tab. 2)	Spoil heap leachate, Kaiser-grube, Gersdorf (Hard coal)$^{1)}$ (included in #10, Tab. 2)	Leachates from TMF Hammer-berg, Freiberg$^{2)}$
#		1	2	3	4	5
Q	L/s	24	4	4-6	6	4
pH	-	7.5	7.1	7.1	6.8	5.5-6.5
SO4	mg/L	72	1050	40	320	1500
Al	mg/L	0.1	0.2	0.066	n.a.	**14**
Mn	mg/L	n.a.	7.5	0.013	n.a.	17
Zn	mg/L	0.08	**4.5**	**2.4**	**4.31**	45
As	µg/L	**290**	**1500**	**41.1**	2.9	5.1
Cd	µg/L	0,35	8.3.	**16.2**	**15.5**	**560**
Cu	µg/L	<2	2.6.	6	2.42	**860**
Fe	µg/L	630	**9000**	<0.03	302	15
Ni	µg/L	5.4	**270**	3.1	**50.5**	**130**
Pb	µg/L	<0.2	<0.5	<0.5	2.3	14

1) Zwickauer Mulde sub-basin, 2) Freiberger Mulde sub-basin, most relevant contaminants in **bold** letters.

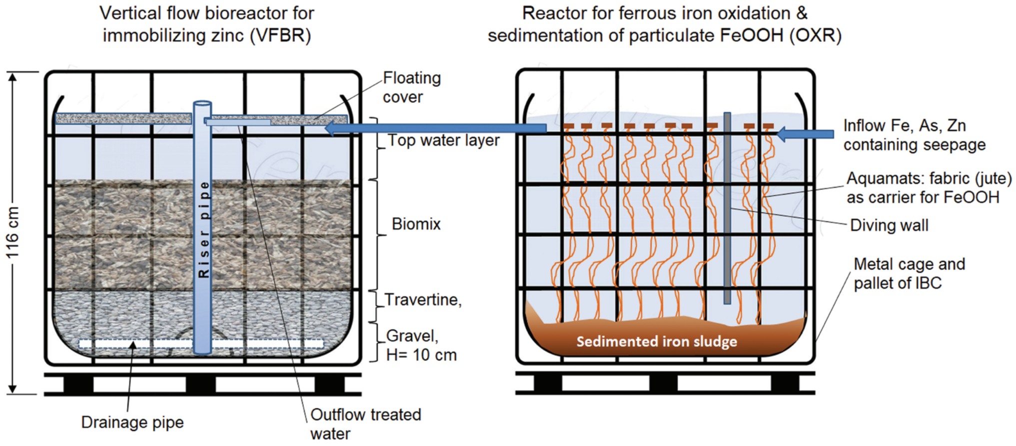

Figure 1 Pilot reactors for passive treatment at mine sites #2 and#3

Intermediate bulk containers (IBC) were used as reactors for the on-site pilot tests (Fig. 1). At site #3 a vertical flow bioreactor (VFBR) without the floating cover was utilized for the anaerobic treatment of the mine effluent. The reactive substrate (Biomix) in the VFBR is a mixture of travertine, wood chips (22% by volume each), chopped straw (45%) and commercial compost (11%).

The two reactors in series (Fig. 1) were used at site #2. The first reactor (OXR) for ferrous iron oxidation contains Aquamats (jute fabric). Due to the lack of electrical infrastructure at site #2, the pilot system had to be operated off-grid. The OXR inflow uses a siphon line with a hydraulic height difference of 2.5 m. Adjusting the planned flow rate of 0.007 L/s (25 L/h) was problematic due to deposits of FeOOH inside the flexible tube. A vertical tube next to the reactor (Fig. 2) as a feeding device for the OXR solved the issue. By varying the height Δh between

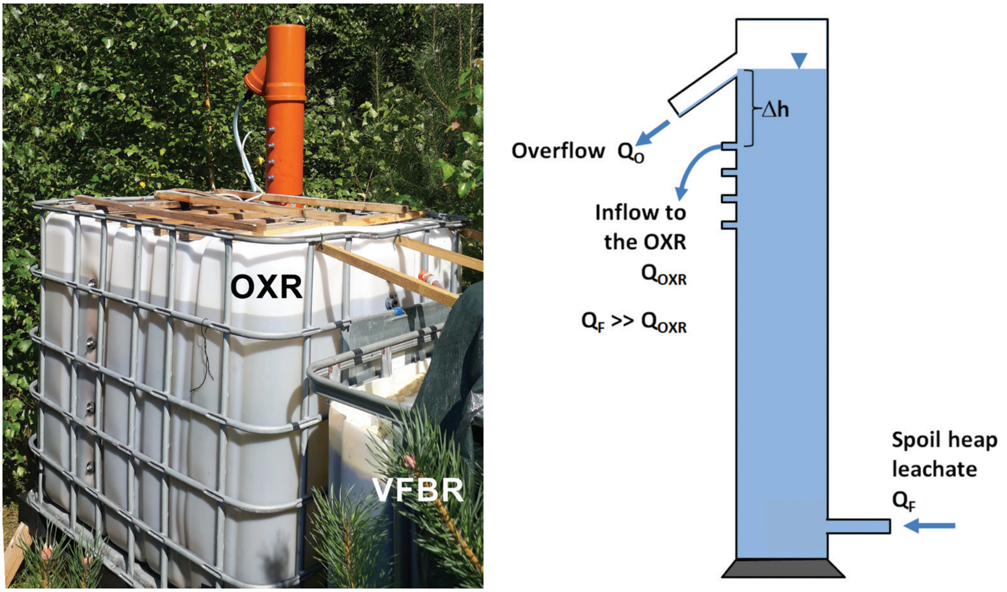

Figure 2 Arrangement of OXR and VFBR in the field (left) and a sketch of the vertical tube principle according to Torricelli's theorem for adjusting the flow of the OXR feed

the overflow and the outlet to the OXR, the discharge flow could be adjusted according to Torricelli's theorem.

Results

Results of the pilot test at the adit St. Christoph (#3) were recently reported by Martin et al. (2023). In the warm season (Jun.-Oct.) a stable efficiency (Zn) > 90% was achieved. Only after the water temperature fell below 5°C, the efficiency decreased to 75%. A volumetric Zn removal rate of 2.43 g/(m^3 × d) with an efficiency of 90% could be determined by the pilot test data. These results are in the same range as for other Sulfate Reducing Bioreactor systems (SRB) (Barley et al. 2016).

The leachate from the spoil heaps at the Ehrenfriedersdorf tin mine (#2) contains As (1–3 mg/L, 33–50% as As(III)), Fe (2–13 mg/L, 5–80% as ferrous iron) and Zn (3.5–6 mg/L). The water is circumneutral (pH 6.9–7.4) and net-alkaline. The oxygen saturation varies in the range of 60–90%. The OXR has to be designed for the following reactions: oxidation of Fe^{2+} and subsequent hydrolysis of Fe^{3+}, precipitation of iron as FeOOH and its settling. At the same time, As adsorption is to be expected on the very fine FeOOH particles formed by Fe^{3+} hydrolysis. At a pH ~ 7, Fe^{2+} oxidation is dominated by abiotic mechanisms (Hedin 2008):

1) Spontaneous chemical oxidation of ferrous iron only with dissolved reactants.
(2) Adsorption-oxidation mechanism with oxidation of Fe^{2+} adsorbed on the surface of FeOOH particles.

The rate of abiotic oxidation depends on the concentration of protons, dissolved oxygen, ferrous iron, temperature and on the concentration of FeOOH solids for the second mechanism.

Extremely fine particles are formed in the process of ferrous iron oxidation especially at low salinity and Fe^{2+} concentrations <10 mg/L. This leads to very long settling times. To avoid this problem and to accelerate the heterogeneous oxidation of Fe^{2+}, the OXR was equipped with several strips of jute fabric.

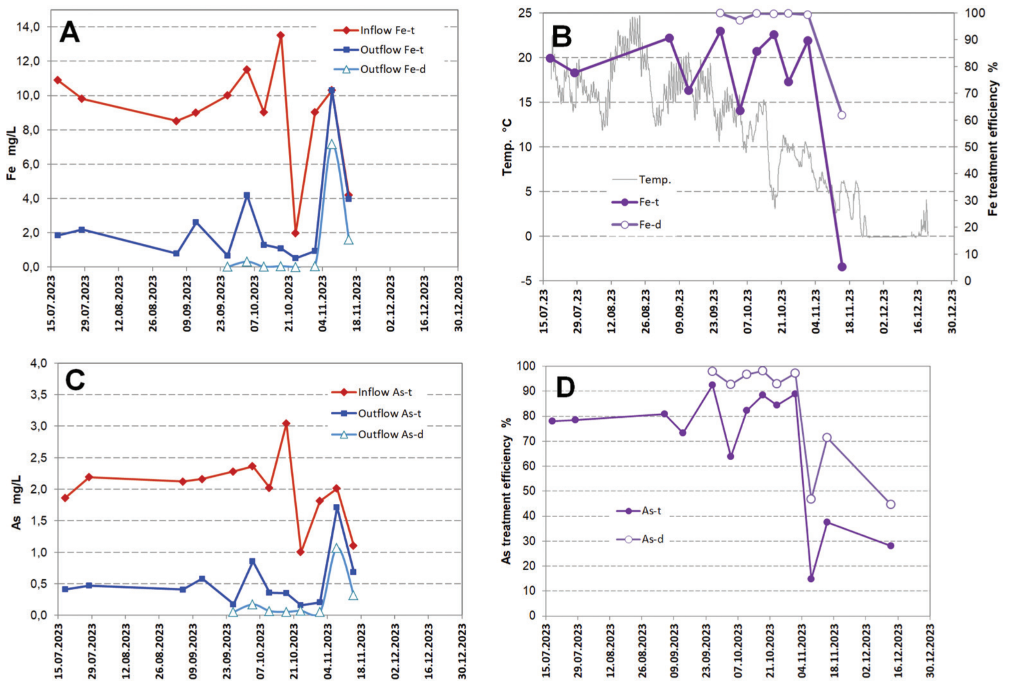

Figure 3 *Fe and As concentrations at the OXR (A, C) and treatment efficiency for Fe (B) and As (D). Fe-t: total, Fe-d: dissolved*

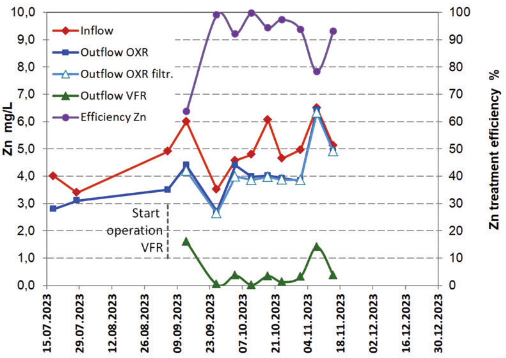

Figure 4 *Zn concentrations at the first (OXR) and second reactor (VFBR) and overall Zn treatment efficiency*

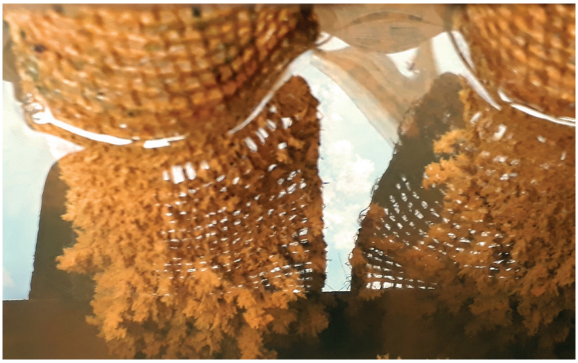

Figure 5 *FeOOH flocs growing on the jute fabric*

The fine particles stick to the jute and slowly grow into larger flocs. At the same time, a large surface area of FeOOH solids is thereby available, utilising the entire volume of the reactor (Fig. 5), which has a positive effect on the heterogeneous iron oxidation.

Results of the pilot tests at the spoil heaps of the Ehrenfriedersdorf tin mine are shown in Fig. 3 and Fig. 4. A good treatment efficiency was achieved in the OXR for Fe and As, which is particularly true for the filtered samples. The solids retention was not complete (70–90%). However, the outflow showed neither Fe nor As in dissolved form, but as particles. A drop in water temperature to <5 °C correlated with a sharp reduction of treatment efficiency for Fe as well as for As. This is attributed to a decline in iron oxidation. For the retention of Zn in the VFBR, an efficiency >90% was nearly always achieved following a start-up phase. A strong decrease in treatment efficiency as for Fe & As at low temperatures was not observed for Zn.

Conclusions and outlook for further work

At the Breitenbrunn site (#3), results for the retention of Zn in the VFBR show good efficiency. Neither Fe nor Al is present in relevant concentrations which promotes anaerobic treatment. Discharge volumes and hydrochemistry at the adit in Breitenbrunn are almost similar to the conditions at the Force Craig Mine where the first full-scale passive treatment scheme for metal mine drainage in the UK was commissioned in 2014 (Jarvis et al. 2015). The next step in the project development for Breitenbrunn will be a larger scale field test (upscaling by a factor of 100 in comparison to the pilot) for 10% of the adit discharge which can then be expanded into a full scale system. The main challenges here are finding a suitable location and meeting all permit requirements.

Further investigations are required for the Ehrenfriedersdorf leachate from the spoil heaps (#2) in order to verify results and to obtain data to implement further upscaling. A potential treatment scheme for the site consists of a sequence of an aeration cascade, oxidation/settling pond, aerobic wetland, vertical flow pond and polishing reed bed. The site morphology would allow for a facility containing all these treatment steps. The main challenge for future work is to ensure a stable system operation during the winter season in the mountainous regions of Saxony.

Acknowledgements

The authors are grateful to Adam Jarvis for a very fruitful online discussion about experiences with the Force Craig passive treatment system. The research at the Breitenbrunn site was financed by the Saxon State Office for Environment, Agriculture and Geology and the investigations at the Ehrenfriedersdorf site are supported by the German Federal Ministry of Education and Research under contract no. FKZ 03WIR1906B (Project TERZinn).

References

Bailey MT, Gandy CJ, Jarvis AP (2016) Reducing life-cycle costs of passive mine water treatment by recovery of metals from treatment wastes. Proceedings IMWA 2016, Germany, p 1255–1262

Hedin, RS (2008) Iron Removal by a Passive System Treating Alkaline Coal Mine Drainage. Mine Water Environ 27:200–209, doi:10.1007/s10230-008-0041-9

Jarvis A, Gandy C, Bailey M, Davis J, Orme P, Malley J, Potter H, Moorhouse A (2015) Metal Removal and Secondary Contamination in a Passive Metal Mine Drainage Treatment System, ICARD-IMWA2015, Conference Proceedings, p 1311-1319

Martin M, Janneck E, Stevens C, Meyer J, Hiller A (2023): Re-thinking passive treatment options as sustainable solution for reducing surface water quality impacts from abandoned mines in Saxony. Extended Abstracts WISSYM2023, p 245-248, https://www.wismut.de/de/wissym-2023-Kopie.php Accessed: 2023-12-21

Stevens C, Martin M, Janneck E, Greif A (2023) Reducing water quality impacts from abandoned mines on streams and rivers in Saxony – Challenges and benefits for the River Elbe Basin. Proceedings Magdeburger Gewaesserschutzseminar 2023, p 113-116, https://www.ikse-mkol.org/en/themen/magdeburger-gewaesserschutzseminar/mgs-2023 Accessed 2023-12-21