Impacts of Extreme Precipitation Events on Abandoned Mines: A Case Study from North Rhine-Westphalia, Germany

B.M.A. Teichert[1], S.E. Nikutta[1], H. Strauss[2], S. Weinand[3], S. Westermann[1]

[1]*Research Center of Post-Mining (FZN), Georg Agricola University of Applied Sciences (THGA), Herner Str. 45, Bochum, Germany*

[2]*Institute for Geology and Paleontology, University Münster, Corrensstr. 24, Münster, Germany*

[3]*RAG Aktiengesellschaft, Im Welterbe 10, 45141 Essen, Germany*

Abstract

An exceptional precipitation period from October 2023 to March 2024 in North Rhine-Westphalia, Germany, caused pronounced changes in mine water chemistry at abandoned hard coal mines. Bimonthly monitoring at pumping stations of 'Robert Müser' (RM) and 'Friedlicher Nachbar' (FN) revealed that sulfate concentrations increased by up to 160 % (RM) and 60 % (FN), peaking between September and November 2024. The sulfur isotopic composition ($\delta^{34}S$) of dissolved sulfate in the mine water initially indicated ongoing microbial sulfate reduction, but subsequently decreased by up to 10 ‰ reflecting the input of sulfate from pyrite oxidation in the hard coal and possibly surrounding rocks. The inverse relationship between $\delta^{34}S$ and sulfate concentration highlights dynamic biogeochemical and hydrological responses to extreme infiltration of surface waters within the upper, unsaturated zones of the mine workings. These results demonstrate that extreme winter precipitation can mobilize significant amounts of sulfate and other soluble compounds in shallow, partially flooded abandoned mines. Understanding such processes is critical for predicting the impacts of future extreme climatic events on post-mining environments.

Keywords: Mine water, precipitation, climate, sulfate, sulfur isotopes

Introduction

In North Rhine-Westphalia, Germany, a very remarkable and unprecedented precipitation period occurred between October 2023 and the end of March 2024. The region recorded its highest rainfalls since meteorological observations began in 1881. As part of an ongoing hydrochemical monitoring program, mine water from abandoned hard coal mines was sampled at least every two months from standpipes through which it is pumped to the surface and analysed for its geochemical composition. To identify ongoing processes in the inaccessible underground mine workings, sulfur isotopes of the dissolved sulfate was measured.

Study Area

Hard coal, formed from extensive Carboniferous swamps, defines the geology of the Ruhr Area, having been buried and tectonically deformed over geological time. This sequence was later covered by younger Permian, Mesozoic, and Cenozoic sediments, marking a complex history of geological uplift and subsidence. Today, these Carboniferous rocks mostly lie beneath thick overburden, dipping towards the northwest, with exposures limited to the southern part of the region.

Methods

Water samples were collected every 2 months and at higher resolution starting April 2023. The samples represent mine water that is being pumped from two water provinces (Robert Müser (RM), Friedlicher Nachbar (FN)) in the southern Ruhr Area in the city of Bochum, Germany (Figure 1). Precipitation data obtained from the German Weather

Service (DWD) station in Bochum were used to compare with mine water geochemistry (Deutscher Wetterdienst, 2026).

Sulfate was measured with ion chromatography. For sulfate sulfur isotope measurements, dissolved sulfate was first filtered (cellulose nitrate filter, 0.45 µm pore diameter) and subsequently precipitated as $BaSO_4$ at subboiling temperature (80 °C) and pH 2 using an 8.5% $BaCl_2$ solution following Dogramaci *et al.* (2001). Sulfur isotopic measurements ($\delta^{34}S$) were performed using Flash EA IsoLink CN Elemental Analyzer interfaced to a ThermoScientific Delta V Advantage (EA-IRMS). For this, approximately 200 µg of BaSO4 precipitate was mixed with an equal amount of V_2O_5 and placed in a tin cup. Results are reported in the standard delta notation as permil difference to the Vienna Canon Diablo Troilite (V-CDT). Reproducibility (1σ) as determined from replicate measurements was generally better than ±0.3 ‰. Accuracy was monitored with internal lab standards and international reference materials (IAEA S1, S2, S3, and NBS127).

Results and Conclusions

Precipitation

Following a rather wet summer in 2023, precipitation showed a remarkable period between October 2023 and March 2024 in Bochum, North Rhine-Westphalia. Daily precipitation was as high as 26.6 Lm^{2-} at the end of December 2023. The monthly precipitation values also reflect the high precipitation values during winter 2023/2024. The sum of the monthly mean precipitation values between October 2023 and March 2024 in Bochum was 669.6 Lm^{2-} (Deutscher Wetterdienst, 2026). In comparison, the sum of the monthly mean values for the same time period (October – March) was 378.7 Lm^{2-} from 1991 to 2020 and 363.5 Lm^{2-} from 1961 to 1990. Therefore, precipitation during the winter of 2023/24 was approximately 177 % to 184 % of the long-term average recorded between 1961 and 2020 for the same period.

Sulfate concentration in mine water

Sulfate concentration at the pumping stations 'Robert Müser' (RM) and 'Friedlicher Nachbar' (FN) has been monitored every 2 months since the end of 2021. The mean sulfate concentration at RM until the end of 2023 was about 88 mgL^{-1} (Figure 2). In January 2024, the sulfate concentration was significantly elevated by about 50 mgL-1 and continued to rise until September 2024 (Figure 2). The mean sulfate concentration at FN until the end of 2023 was about 224 mgL^{-1}. In April 2024, the sulfate concentration was significantly elevated by about 49 mgL^{-1} and continued to rise until November 2024

Figure 1 *Map showing the mine water sampling locations 'Friedlicher Nachbar' and 'Robert Müser'.*

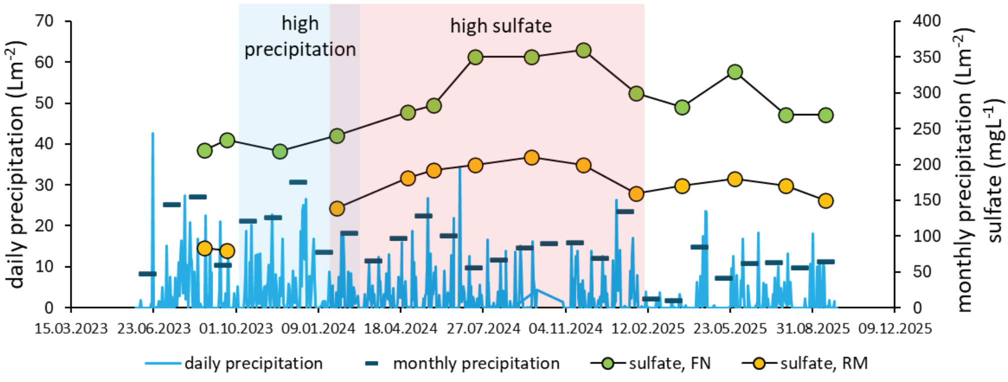

Figure 2 Graph showing the daily and monthly precipitation at Bochum (Deutscher Wetterdienst, 2026) together with sulfate concentration at the pumping stations 'Friedlicher Nachbar' (FN) and 'Robert Müser' (RM) from June 2023 to September 2025. The blue box indicates the high precipitation period in winter 2023/24. The red box indicates the time interval of high sulfate concentration in the mine water.

(Figure 2). At both pumping stations, sulfate concentrations slowly decreased afterwards but did not return to pre-winter 2023/24 values until September 2025.

Sulfur isotopic composition of sulfate in mine water

The sulfur isotopic composition of sulfate in the mine water at 'Robert Müser' (RM) shows rather high values between 20 ‰ V-CDT and 25 ‰ V-CDT at the end of 2023 (Figure 3). Such high $\delta^{34}S$ values are typical for ongoing sulfate reduction (Kaplan & Rittenberg 1964). Within the monitored time interval, sulfate sulfur isotopic composition and sulfate concentration exhibit an inverse relationship (Figure 3). The $\delta^{34}S$ values decrease by about 10 ‰.

A similar observation can be made at 'Friedlicher Nachbar' (FN). At the end of 2023, the sulfur isotopic composition of sulfate in the mine water at FN shows values between 15 ‰ V-CDT and 20 ‰ V-CDT (Figure 4). The $\delta^{34}S$ values decrease quickly by about 7 ‰ and start rising again in May 2024 which is four months earlier than at RM (Figure 4). Thus, the inverse relationship is less pronounced at FN compared to RM.

The sulfur cycle in the mine waters of the Ruhr Area is largely governed by the presence of iron sulfide minerals in the hard coal deposits. Iron sulfide, predominantly

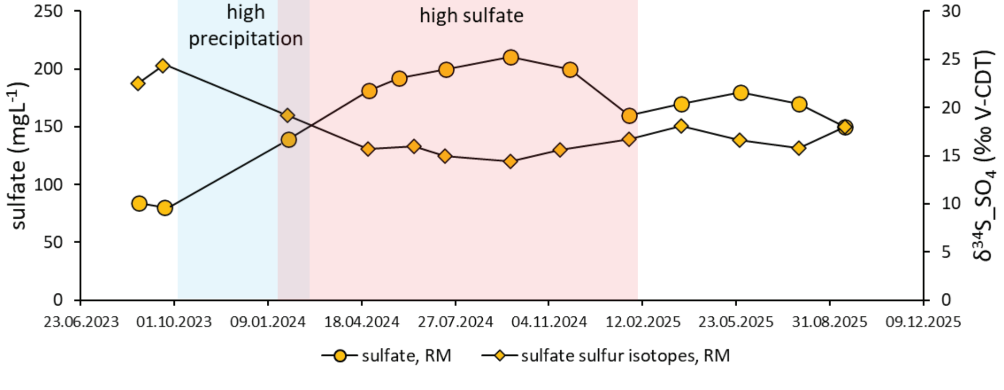

Figure 3 Sulfate concentration (circles) and sulfur isotopic composition of dissolved sulfate (diamonds) at 'Robert Müser' (RM). The blue and red boxes correspond to those shown in Figure 2.

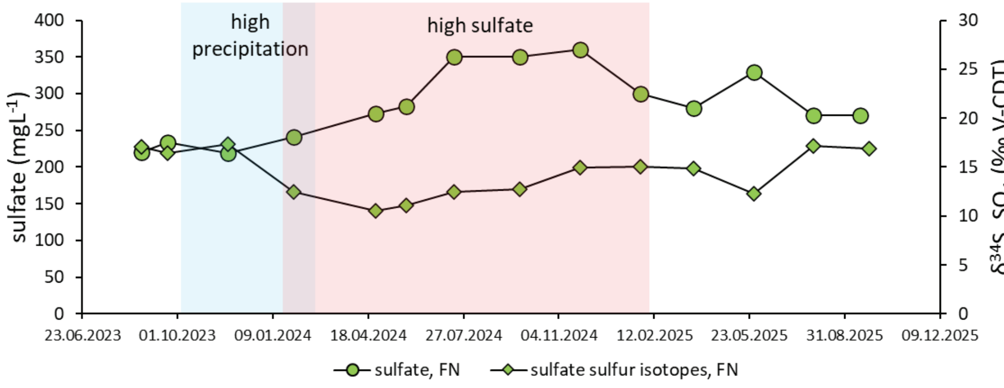

Figure 4 Sulfate concentration (circles) and sulfur isotopic composition of dissolved sulfate (diamonds) at 'Friedlicher Nachbar' (FN). The blue and red boxes correspond to those shown in Figure 2.

occuring as pyrite, is oxidized under aerobic conditions through a complex biogeochemical process (Singer & Stumm 1970). The sulfate formed during iron sulfide oxidation exhibits a characteristic isotopic fingerprint as negligible fractionation occurs during the oxidation. Consequently, the sulfur isotopic composition of the resulting dissolved sulfate reflects the original iron sulfide source. Sulfur isotopic values around 10 ‰ V-CDT are typical for pyrite (Puchelt & Nielsen 1967). Such low $\delta^{34}S$ values are observed at FN and nearly at RM, indicating that substantial quantities of sulfur derived from pyrite oxidation were released into the mine water following the precipitation anomaly of 2023/24.

Conclusion and Outlook

The precipitation anomaly 2023/24 led to a distinct change in mine water chemistry at the former hard coal mines 'Friedlicher Nachbar' and 'Robert Müser'. Sulfate concentrations showed the most prominent changes. Starting in January 2024, these increased by about 60 % (FN) to 160 % (RM), reaching a maximum between September and November 2024, before subsequently decreasing. The sulfur isotopic composition of sulfate in the mine water provides evidence for the origin of the sulfate. Both former mining sites are characterized by a thin or absent Cretaceous overburden allowing precipitation water to directly infiltrate the mine workings. Within the upper, unsaturated zones of the mine workings, sulfate from oxidized pyrite in the hard coal and possibly also the wall rock was dissolved during the extensive infiltration of surface water and transferred into the deeper, flooded part of the ancient mine workings. This process is reflected by a distinct decrease in δ34S values of the dissolved sulfate by up to 10 ‰ resulting from the release of lighter sulfur isotopes during pyrite oxidation.

The precipitation anomaly 2023/24 in western Germany provides a unique opportunity to assess the potential consequences of extreme climatic conditions on post-mining environments. Mine waters from shallow, abandoned underground mines that are only partially flooded and receive infiltration from precipitation may contain substantial amounts of soluble compounds originating from the upper mine levels or the overburden. As climate models predict more extreme weather events in the future with increasing precipitation during winter and prolonged dry periods in summer it is crucial to understand the potential consequences for such abandoned mining systems.

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