Preliminary Analysis of Stable Water Isotope Patterns in the Lusatian Lignite Mining District (Germany)

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Abstract

This study presents preliminary findings from a large-scale survey comprising over 1,000 samples of precipitation, surface water, groundwater, and post-mining lakes in the Lusatian lignite mining district (Germany). All samples were analyzed for stable water isotopes (δ^2H, $\delta^{18}O$) to refine our understanding of hydrological connectivity among surface and groundwater as well as evaporation loss from post-mining lakes. Our results show distinct isotopic differences among water sources, identifying post-mining lakes primarily recharged by groundwater and areas where groundwater is influenced by surface water. These insights highlight the potential of isotope analysis as a valuable tool for adaptive water resource management.

Keywords: Stable water isotopes, Lusatian lignite mining district, post-mining lakes, surface-groundwater interactions, lake evaporation

Introduction

The EU aims to have a net-zero greenhouse gas (GHG) economy by 2050, with 55% reduction on 1990 levels by 2030. At present, heating and cooling represent over 50% of the nd cooling supply, two conceivable well locations were derived based on the mine layouts.

Conclusions

The lignite-mining region of Lusatia is characterized by i) low precipitation (less than 600 mm a-1, compared to the German average (820 mm a-1), 1981–2010, National Meteorological Service), ii) a negative climatic water balance in most years (MLUL 2018), iii) predominantly sandy soils with a low water storage capacity covered by highly managed ecosystems (forest and agricultural monocultures), and iv) long-term, large-scale open cast lignite mining activities. The lignite mining activities have significantly affected the water resources, both in terms of water quantity and quality, in the Lusatian river basins of the rivers Spree, Schwarze Elster and Lusatian Neiße (Grünewald 2001). Recent extreme heatwaves, coupled with low precipitation, have exacerbated water management challenges in this already water-scarce region (Creutzfeldt *et al*. 2021; MLUK 2021).

Stable water isotopes (δ^2H, $\delta^{18}O$), can serve as environmental tracers for investigating groundwater-surface water interactions and evaporation loss in (post-mining) lakes (Baskaran *et al*. 2009). The isotopic composition of precipitation, groundwater, and surface water can be used to trace the movement and mixing as well as the residence times of these water sources. This analysis potentially enables the identification of groundwater discharge pathways into surface water bodies and vice versa (Gat 1996). In addition, stable isotopes can support the quantification of evaporation loss from surface water and lakes (Koeniger *et al.* 2021), as the isotopic signature of the water sources (surface and groundwater, precipitation) differ. Evaporation is causing enrichment of heavier isotopes in source water, thus creating distinct gradients. These gradients provide insights into the rate of evaporation, the influence of climate variability, and the dynamics of the water balance within lake ecosystems. Stable isotopes thus offer a non-invasive method to better understanding hydrological processes.

The aim is this study is to refine our understanding of hydrological processes in mining-affected watersheds by using stable water (δ18O, δ2H) isotopic signatures of precipitation, surface water, groundwater, and post-mining lakes. The (long-term) aim is to assess the groundwater-surface water interaction and evaporation loss of the post-mining lakes. Our analysis focuses on the Lusatian mining district, located in northeastern Germany.

Study Area

The Lusatian mining district is located approximately 100 km southeast of the German capital Berlin, extending across the federal states of Brandenburg and Saxony and three watersheds: Spree, Schwarze Elster and Lusatian Neiße (Fig. 1 a) covering together an area of approximately 20,000 km². Lusatia experiences a temperate climate with both maritime and continental influences. Since the 1960s, significant air temperature increases were observed, while total annual precipitation remained unchanged (Gädeke *et al.* 2017). Industrial-scale open-cast lignite mining has been ongoing since the early 20th century in the Lusatian mining district. The open-cast lignite mining has had a profound impact on watersheds, resulting in extensive groundwater depletion, modified river courses, and changes in discharge patterns (Grünewald 2001; Schoenheinz *et al.* 2011; Pohle *et al.* 2019). To safely extract the lignite in the open-cast mines, groundwater is lowered below the coal seams, often reaching depths of up to 100 m below the ground surface. Part of the groundwater pumped has been used to augment surface water discharge over decades, especially of the Spree River. At the peak of mining, the groundwater drawdown cone extended across 2,100 km² and the total water deficit was about 9 × 109 m³. After the German reunification (1990), 12 out of 17 mines were closed resulting, among others, in a considerable reduction in the mine drainage water. Currently, the average proportion of mine drainage water in the Spree River at Cottbus is ~ 50%, increasing to ~75% during dry summer months (Uhlmann *et al.* 2023). The mass deficit following lignite extraction results in open pits, which are generally transformed into post-mining lakes in Lusatia. Once flooded, these lakes will collectively cover an area of approximately 350 km². The three still active open-cast mines will have to be shut down by 2038. Several water management challenges are overlapping in the Lusatian mining district, including, among others: further reduction of mine drainage waters to augment surface water flow, mitigation of the remaining mining-related water deficit, mining-related water quality problems, climate change, socioeconomic impacts.

Data and Methods

In 2024, more than 1,000 water samples, consisting of ~400 groundwater, ~260 surface water and ~450 post-mining lake samples, were collected in the Lusatian mining district (Fig. 1) as part of the standard montane hydrological monitoring of the LMBV (Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH). The survey covers an area of approximately 4,000 km². In addition, the Federal Institute for Geosciences and Natural Resources operates a weekly precipitation sampling since 2023 in the city of Cottbus (Fig. 1 a).

A total of approximately 75 post-mining lakes were sampled using boats, helicopters, or onshore techniques (Fig. 1 b). Within each lake, samples were systematically collected from multiple locations and depths. Sampling followed the lakes' seasonal circulation patterns, including spring turnover, the start and end of summer stagnation, and autumn circulation, to capture temporal variations in water composition. Surface water sampling includes 68 streams, with sampling intervals ranging from biweekly to quarterly (Fig. 1 c). Groundwater samples were obtained from depths between 2.5 and 114 meters below the surface, representing different aquifer systems: aquifers formed in mining dumps and natural systems surrounding the post-mining lakes (Fig. 1 d).

All samples were analysed in the isotope laboratory of the German Federal Institute for Geosciences and Natural Resources (BGR), utilizing a Picarro L2130-i laser spectrometer. Results are expressed as parts per thousand deviations from the VSMOW (Vienna Standard Mean Ocean Water) with analytical precisions of 0.2‰ and 0.8‰ for $\delta^{18}O$ and $\delta^{2}H$ values, respectively.

Here, we present a subset of the samples (886 samples) as sample processing and data analysis are still ongoing (groundwater: 253 (~63% of collected samples), surface water: 217 (~84%), post-mining lakes: 363 (~81%), precipitation (53 weekly samples (January 2023 – April 2024), sampling ongoing)).

Mean precipitation of Cottbus presents the precipitation amount-weighted average of weekly isotope values ($\bar{\delta}$) from the total

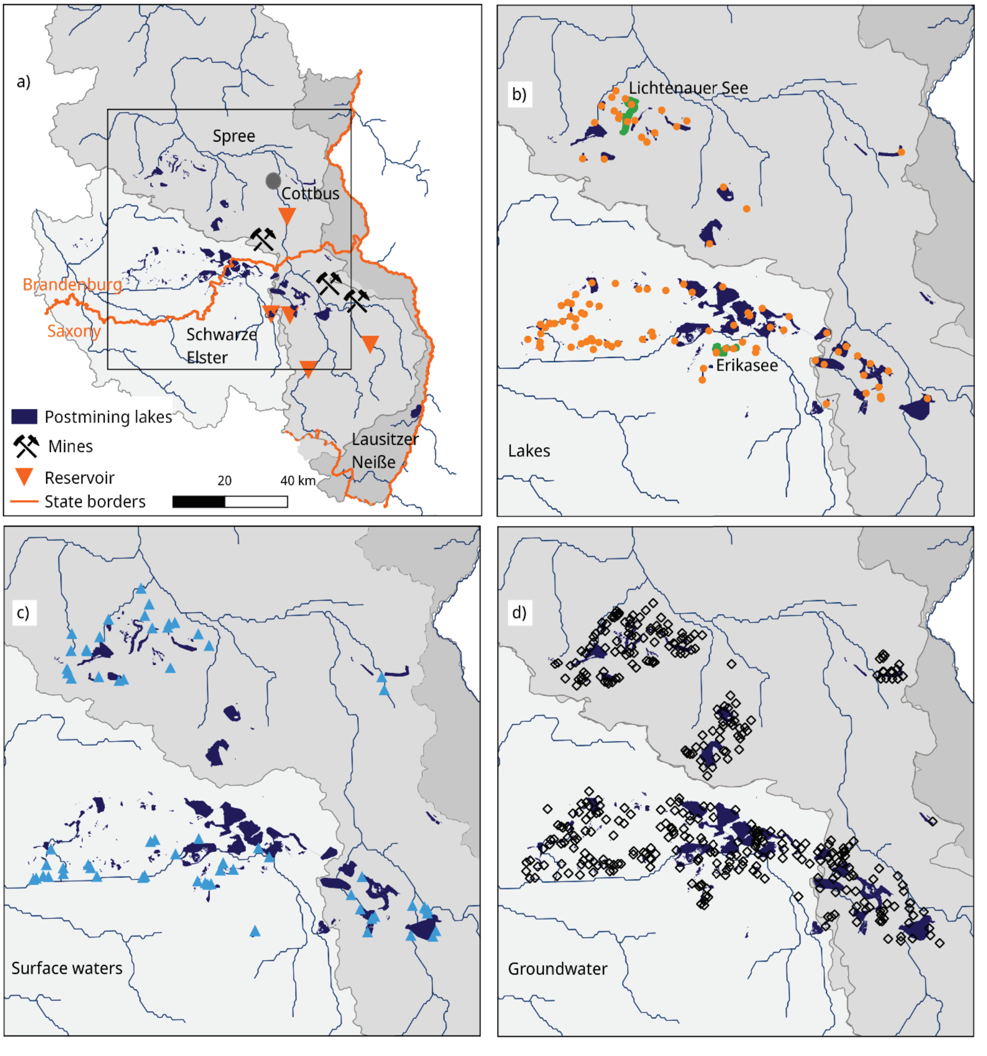

Figure 1 Overview of the study area a) and the sampling locations for post-mining lakes b), surface c) and groundwater d). The black box in a) presents the section that is zoomed into in b), c) and d). In b) the lakes shown in green colour present the Erikasee and the Lichtenauer See.

Table 1 *Statistical properties of the samples (886 in total).*

	Precipitation		Lakes		Surface waters		Groundwater	
	$\bar{\delta}$18O	$\bar{\delta}$2H	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$
Minimum	-19.5	-147	-8.6	-62	-9.4	-66	-9.9	-69
25. Percentile	-9.8	-71	-5.1	-43	-7.7	-57	-9.1	-65
Median	-8.0	-57	-4.0	-37	-6.5	-51	-8.8	-63
Mean	-8.0	-57	-4.0	-38	-6.3	-50	-8.2	-60
75. Percentile	-5.8	-36	-3.0	-31	-4.8	-41	-8.1	-59
Maximum	1.3	-9	0.8	-17	-2.1	-28	-3.0	-30

weekly precipitation (P) and isotope values (δ) as follows:

$$\bar{\delta}[‰] = \frac{\sum_{i=1}^{N} \delta_i \times P_i}{\sum_{i=1}^{N} P_i} \qquad (1)$$

Results and Discussion

Table 1 provides an overview of the statistical properties of the isotopic signatures of precipitation, post-mining lakes, surface and groundwater. Overall, post-mining lakes have the most enriched (less negative) isotopic signature, followed by surface waters. Groundwater and precipitation isotopic signatures are most depleted (more negative). In addition, precipitation isotopes show a distinct variability characteristic for stations in a continental-influenced climate in the Northern Hemisphere: More positive δ-values occur during summer compared to the winter.

The dual-isotope plot, which includes all samples, reveals that there are distinct isotopic signatures depending on the water source (Fig. 2).

- The majority of surface, and especially the post-mining lakes water samples deviate from the meteoric water lines (MWL) due to evaporative enrichment (lower slope compared to the Global MWL and Local MWL)
- Groundwater samples, and also surface water samples, that plot near the GMWL and LMWL present locations where no

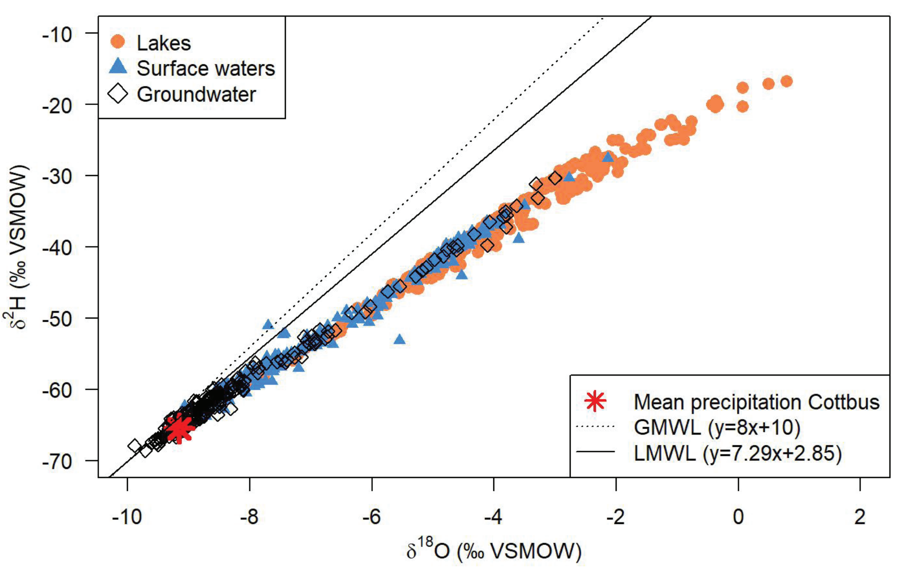

Figure 2 *Dual isotope plot ($\delta^{18}O$ vs. $\delta^{2}H$) showing the post-mining lake, surface and groundwater samples, the Global (GMWL) and Local (LMWL) Meteorological Water Line, and the mean weighted precipitation of Cottbus (01/2023-04/2024). Precipitation is <600 mm a^{-1}.*

mixing with surface/post-mining lake water has occurred (minimal evaporative losses)

- Groundwater samples that plot away from the GMWL and LMWL indicate that mixing processes with surface/post-mining lake water have occurred (intermediate isotopic signatures)

To evaluate a subset of the post-mining lakes in more detail, we preselected 24 lakes. Out of these 24 lakes, the "Erikasee" samples plot nearest to the LMWL. This observation supports the fact that the Erikasee was primarily flooded by groundwater instead of surface water. A total of 11 samples were collected from the "Erikasee" at three different locations (shore, southwestern part, lake center (close to an inlet of a trench)) and different periods (March, May, June, August, September). The analysis reveals the following: samples collected close to the lake surface become more enriched during summer compared to winter. At the sampling point in the center of the post-mining lake for example, an increase in δ18O (δ2H) of 40% (28%) was identified between March and September. Furthermore, sampling points near the lake's surface are more enriched compared to those at greater depths. Opposite to the enrichment process taking place close to the lake surface, the samples collected at depths greater 10 m become more depleted during summer (Fig. 3). For the most enriched lakes, e.g. "Lichtenauer See", two possibilities and their combined effect exist: large evaporation demand and surface water input/flooding of lake with surface water to keep water levels as well as to ensure a satisfactory water quality. Based on 16 samples collected between March and September, the spatio-temporally analysis reveals the same patterns as for lake "Erikasee": more enriched (depleted) values closer to the lake surface (bottom) and as the year advances. In terms of morphology, the "Erikasee" and "Lichtenauer See" are similar, though they differ in size ("Erikasee" ~40% of the size of "Lichtenauer See") and the "Erikasee" is characterised by a large internal in-pit dump. Both lakes are fully flooded. The other most enriched lakes, present the larger post-mining lakes of Lusatia, some of which, are still actively flooded by surface water and/or are characterised by channels connecting different lakes. In addition, due to their size, large evaporation loss is expected.

Conclusions

Our study shows the potential of using stable water isotope tracers to investigate the spatial and temporal variability of the dominant

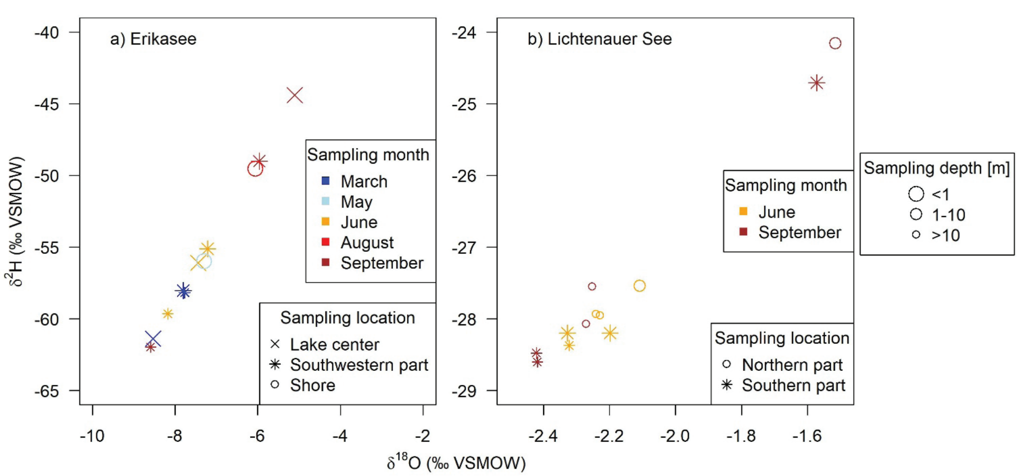

Figure 3 Dual isotope scatter plot for the Erikasee (a) and Lichtenauer See (b) showing differences based on sampling month, location and depth.

hydrological processes in watersheds affected by large-scale lignite mining. The simultaneous sampling of precipitation, lake, surface and groundwater allows the identification of isotopically distinct regions: effluent (groundwater infiltration into surface water) and influent (surface water infiltration into groundwater) systems, reflecting the state of flooding the post-mining lakes and rising groundwater levels in the groundwater depression cone (ongoing, completed). Our preliminary results also reveal that isotopic signatures of post-mining lakes, surface and groundwater samples differ considerably: clear enrichment of heavier isotopes and more thus more positive δ-values indicate progressive enrichment due to evaporation of water, especially close to the postmining lake surfaces. This approach enables a more detailed characterisation and interpretation of the current status of post-mining lakes in the Lusatian lignite mining district.

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