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SEASONAL ASSESSMENT OF HYDROCHEMICAL CHARACTERISTICS OF RIVERS IN THE BOR MINING AREA

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Abstract

This study evaluates the current hydrochemical status of rivers in the Bor mining area through seasonal monitoring conducted from summer 2025 to spring 2026. Twelve sampling sites were analyzed for pH, electrical conductivity (EC), and sulfate concentrations. Background waters were characterized by the Ca–Mg–HCO_3 hydrochemical facies, whereas mining-affected rivers were dominated by the Ca–Mg–SO_4 facies. Elevated EC and sulfate concentrations downstream of the mining area confirmed the persistent influence of mining activities. Comparison with historical data revealed substantial improvement in water quality following mine wastewater treatment, although sulfate remains a reliable indicator of residual contamination.

***Keywords**: river water, sulfate, seasonal monitoring, Bor mining area*

1. INTRODUCTION

Mining and metallurgical activities are among the major anthropogenic sources of surface water contamination. Long-term discharge of untreated mine wastewater alters river hydrochemistry by increasing dissolved ion concentrations, particularly sulfate, thereby elevating electrical conductivity and altering hydrochemical facies [1]. Following the introduction of mine wastewater treatment, improvements in water quality are expected; however, long-term monitoring is required to evaluate the effectiveness of remediation measures and to identify any remaining environmental impacts [2].

The Bor mining area in eastern Serbia has been affected by intensive copper mining and smelting for more than a century. Although mine wastewater treatment was introduced in 2022, the extent to which river water quality has recovered remains insufficiently documented. Therefore, this study aimed to assess the current hydrochemical status of rivers in the Bor mining area through seasonal monitoring conducted during 2025–2026. Particular emphasis was placed on pH, electrical conductivity, sulfate concentrations, and hydrochemical facies, as well as on comparison

with historical data collected before wastewater treatment to evaluate long-term changes in surface water quality.

2. EXPERIMENTAL

During the four-season campaign (summer 2025 to spring 2026), river water was collected from 12 sampling sites each season. The sampling locations were classified into three groups: (i) upstream rivers unaffected by mining activities (W1–W3), representing background conditions; (ii) the Timok River downstream of the mining area (W4–W5), which receives the waters of the Bela River; and (iii) rivers directly influenced by mining activities (W6–W12) (Figure 1).

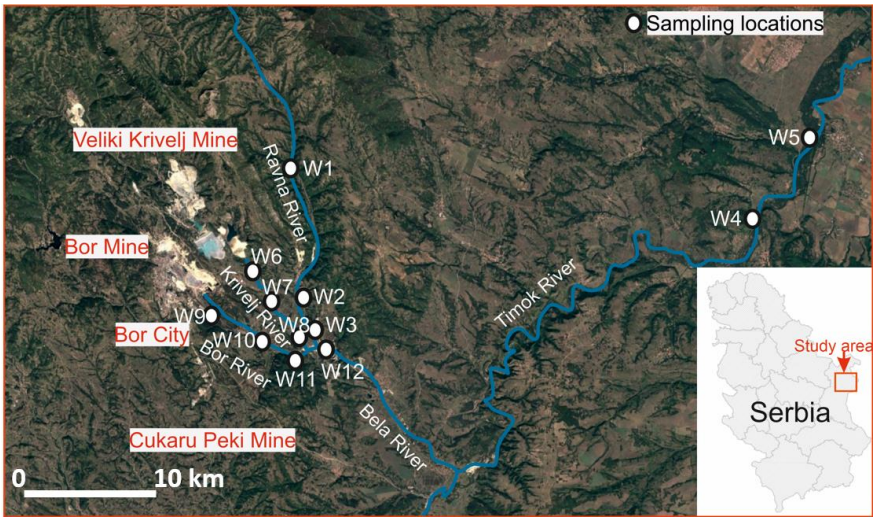


Figure 1. *Study area showing rivers, sampling locations, mines, and Bor City*

During the field survey, in situ measurements of pH and electrical conductivity were conducted. Field parameters were measured using a hand-held pH/EC meter. Chemical analyses, including Ion Chromatography (IC) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), were performed in the SRPS ISO/IEC 17025-accredited laboratory of the Mining and Metallurgy Institute Bor, Serbia [3]. Non-acidified water samples were analyzed for anions (SO_4^{2-}, Cl^-, NO_3^-) using Ion Chromatography. The samples used for the determination of major elements (Na, K, Mg, Ca) were acidified by adding concentrated ultrapure nitric acid and then analyzed by Inductively Coupled Plasma Optical Emission Spectrometry.

3. RESULTS AND DISCUSSION

3.1. pH, electrical conductivity, and sulfate concentrations in river water

The pH values ranged from 7.13 to 9.19 in summer, 6.37 to 8.07 in autumn, 6.90 to 8.29 in winter, and 7.62 to 8.46 in spring (Figure 2a). The highest pH values were recorded in the Bor River (W10 and W11) during summer, exceeding the regulatory

threshold of 8.5, while the lowest value (6.37) was measured in the Krivelj River (W6) during autumn. In winter and spring, all measured pH values were within the prescribed limits in the Regulation on Limit Values of Pollutants in Surface Waters [4].

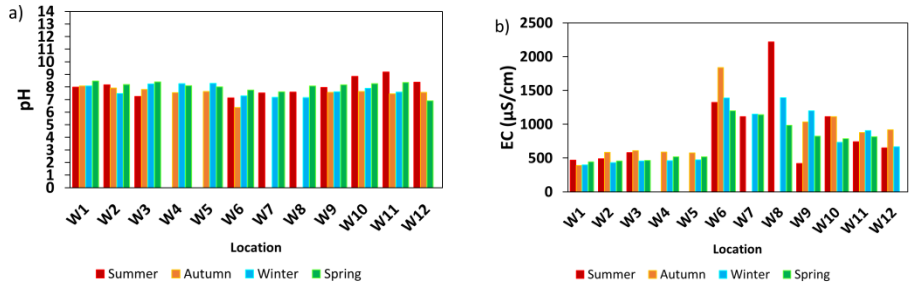


Figure 2. *Seasonal variation of (a) pH and (b) electrical conductivity (EC) in river water at the investigated sampling sites*

Electrical conductivity (EC) ranged from 418–2219 µS/cm in summer, 392–1836 µS/cm in autumn, 399–1393 µS/cm in winter, and from 422-1200 µS/cm in spring (Figure 2b), indicating moderate to high mineralization of surface waters, particularly at sites affected by mining activities.

Sulfate (SO_4^{2-}) concentrations were considerably lower in rivers unaffected by mining activities, ranging from 32–47 mg/L in summer, 72–102 mg/L in autumn, 36–62 mg/L in winter, and 43-73 mg/L in spring (Figure 3a). In contrast, rivers directly affected by mine wastewater showed substantially higher concentrations, ranging from 65–1272 mg/L in summer, 418–1504 mg/L in autumn, 194–881 mg/L in winter, and 360-830 mg/L in spring (Figure 3b), reflecting the strong influence of mining activities on surface water quality.

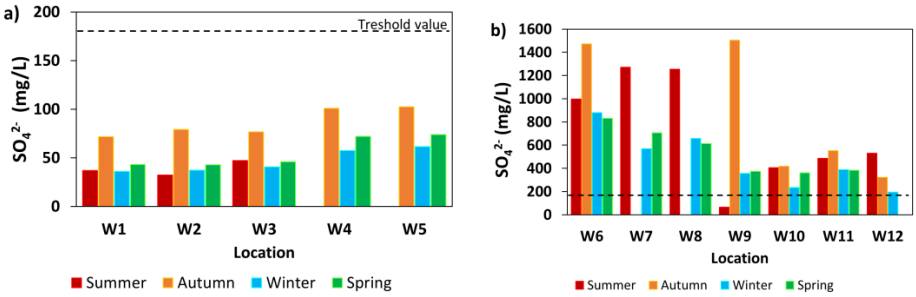


Figure 3. *Seasonal variation of sulfate concentrations in a) unpolluted river water, and b) polluted river water. The dashed line represents the region-specific geochemical threshold value for sulfates in the river water of the study area*

3.2. Current status of contamination in a mining-affected river system

A Piper diagram was used to identify the hydrochemical facies of the investigated waters, i.e., the dominant ionic composition controlling water chemistry (Figure 4). Background waters were classified as the Ca–Mg–HCO_3 facies, while downstream waters were predominantly of the Ca–Mg–SO_4 facies, indicating a strong influence of mining activities

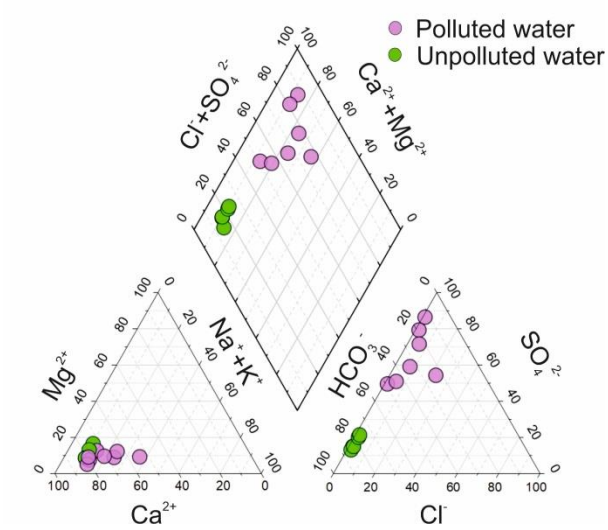


Figure 4. *Piper diagram showing the hydrochemical facies of river waters from the Bor mining area*

pH and electrical conductivity (EC) are widely used indicators of surface water quality and are particularly useful for assessing the impact of mining activities. In the present study, pH values generally remained within the expected range and did not indicate significant acidification of the investigated rivers. In contrast, EC values were considerably higher at sites affected by mining activities than at background locations, reflecting elevated concentrations of dissolved ions.

Sulfate concentrations in background waters remained below the regional geochemical threshold values established for the study area, whereas rivers influenced by mining activities showed pronounced exceedances, indicating a strong anthropogenic impact (Figure 3) [4]. The highest sulfate concentrations were recorded downstream of the mining area, and these waters were classified as having poor ecological status according to Serbian surface water quality regulations [4]. The combined evaluation of pH, EC, sulfate concentrations, and hydrochemical facies proved effective in distinguishing natural background conditions from mining-related contamination.

3.3. Long-Term Changes in pH, Electrical Conductivity, and Sulfate Concentrations

Mine wastewater treatment was introduced in 2022, whereas untreated wastewater had previously been discharged directly into the Bor River for decades, causing severe deterioration of surface water quality. Historical data indicate that river water was highly acidic (pH ≈ 2) and that contamination extended downstream to the Danube River [5].

Comparison of the 2025–2026 monitoring results with historical data from 2015 indicates a substantial improvement in surface water quality following the implementation of wastewater treatment. Present-day river water exhibits near-neutral pH values, whereas sulfate concentrations have decreased considerably. However, sulfate concentrations downstream of the mining area remain well above regional threshold values, indicating that mining-related contamination is still present. Together with elevated electrical conductivity in mining-affected rivers, sulfate remains a reliable indicator of the long-term impact of mining activities on surface water quality.

4. CONCLUSION

Seasonal monitoring showed that rivers affected by mining activities remain characterized by elevated electrical conductivity and sulfate concentrations compared with background waters. Although river water quality has improved substantially following the introduction of mine wastewater treatment, sulfate concentrations downstream of the mining area still exceed regional threshold values, indicating the persistence of mining-related impacts. The observed shift from the natural Ca–Mg–HCO_3 to the Ca–Mg–SO_4 water type further confirms the influence of mining activities on river hydrochemistry. These findings demonstrate the importance of continued seasonal monitoring for assessing long-term trends and the effectiveness of remediation measures.

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