INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE
ISSN: 2067-533X Volume 16, Issue 4, 2025: 1865-1876 www.ijcs.ro
DOI: 10. 36868/IJCS.2025.04.18

CONSERVATION, MANAGEMENT STRATEGIES AND FUTURE PROSPECTS IN A MODEL "HOTSPOT", BULGARIA

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Abstract

Industrial and mining activities are major sources of heavy metal pollution, leading to the formation of "hotspots" in regions with concentrated industrialization and mineral extraction. Areas with heavy industrial activity, such as mining, metalworking, and manufacturing, often experience elevated levels of heavy metals in environmental components, especially water, soil, and sediments, due to emissions, wastewater, and waste disposal. The waters of the Topolnitsa River are subjected to continuous and complex anthropogenic impact. The present study aims to determine the concentrations of eight heavy metal parameters (As, Cd, Cu, Fe, Mn, Ni, Pb, and Zn) in the waters of the Topolnitsa River, Bulgaria, for the period 2018–2023 in the context of the developed ore-mining and processing industry in the region. In this study, the data set was analyzed and evaluated following the requirements of the Water Framework Directive 2000/60/EU and its equivalent criteria, transposed into Ordinance N-4 on surface water characterization from 2012 and the Ordinance on environmental quality standards for priority substances and some other pollutants from 2010. The Canadian Council Water Quality Index (CCME WQI) was applied, through which a complex water quality assessment was carried out. Statistical and graphical methods were also used. The results show a constant exceedance of reference standards in terms of the content of Cu, Mn, and Zn. The CCME WQI values indicate a predominantly "poor" water quality during the investigated period. Achieving "good" surface water quality in the studied river basin requires timely management decisions to change existing practices and a well-founded approach to limiting and preventing their pollution by defining appropriate measures.

Keywords: *Conservation; Hotspot; Water quality; Heavy metals; Mining activity*

Introduction

Global hotspots represent significant environmental challenges that require urgent action to mitigate pollution, protect human health, and preserve ecosystems. Heavy metal pollution is a widespread environmental problem with significant consequences for human health and ecosystem integrity. Although heavy metals occur naturally in the Earth's crust, human activities such as industrialization, mining, and agriculture have increased their release into the environment, leading to the formation of global pollution "hotspots" [1, 2].

The mining and processing industries are significant sources of technogenic pollutants emitted into the environment, including water. One of the leading groups of contaminants are the heavy metals, which are released from rocks during the extractive metallurgy (mining and

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smelting of metals) and, given their toxicity, persistence, and high concentrations, can cause significant damage to the environment [3-5]. The non-degradable nature, the bioaccumulation in plants and animals, and the long biological half-life of heavy metals can increase the level of their toxicity on both aquatic and terrestrial ecosystems [6-7].

The biomagnification of concentrations exposes flora and fauna to life-threatening risks, and passing through the different trophic levels, there is a danger for human health [8-10]. In this sense, the presence of heavy metals in water is a global environmental issue and a subject of management and public concern at the local level.

Today, in the European Union's (EU) states, including the Republic of Bulgaria, based on policies related to the water sector, a wide range of problems are being discussed, finding their solution in the preparation and implementation of legislative acts, programs, and projects. A key element of the EU water legislation is the Water Framework Directive (WFD) 2000/60/EC of the European Parliament and of the Council of 23 October 2000 [11]. At the national level, the main document related to its implementation in the Republic of Bulgaria is the Water Act of 28 January 2000 [12].

Regardless of the policies implemented, many water bodies remain loaded with heavy metals, metalloids, and other toxic substances as a result of the discharge of wastewater from open-pit mines, tailing impoundments, industrial lagoons, ferrous and non-ferrous metallurgy enterprises, etc. Studying the content of heavy metals in the mining-affected areas is needed to prepare objective analyses and assessments and define possible measures for the sustainable protection and management of water resources.

The Topolnitsa River is one of these "ecological hotspots" in the Republic of Bulgaria, impacted by various anthropogenic practices, including mining activity. The largest copper ore mines and processing enterprises in the country are located and operate in the river basin. Past studies on surface water quality [13-22] showed continuous pollution with toxic substances like heavy metals, metalloids, and hazardous waste materials. Therefore, achieving sustainable development in the study region requires implementing an integrated approach that addresses all aspects of society.

This article examines a key “hotspot” of heavy metal pollution, addressing causes, impacts, challenges, and potential solutions. The main aim is to assess the content of eight heavy metals in the waters of the Topolnitsa River for six years, from 2018 to 2023. Implementing the set objective will update the previous studies with recent information. The results of this work may be useful to local authorities for more adequate control of unregulated discharges.

Experimental part

Study Area

The Topolnitsa River is formed and flows in the Sashtinska Sredna Gora Mountain and the Upper Thracian Lowland (Pazardzhik Field). The river rises at the eastern foothills of the Bunaya Peak at 1413m a.s.l. and empties as a left tributary in the Maritsa River about 1.5km west of Pazardzhik at 205m a.s.l. The river's length is 154km, and its drainage basin is 1789km^2 [23] (Fig. 1).

The Topolnitsa River Basin is impacted by active and diverse anthropogenic practices. Some of the largest copper mines, industrial lagoons, and non-ferrous metal processing plants in the country have operated or are currently operating in the study area. Given the copper ore reserves in the Sashtinska Sredna Gora Mountain, in the 1950s, underground mining activities were launched at Chelopech and open-pit copper mining from the Asarel and Medet mines. A Copper Mining Plant between the towns of Zlatitsa and Pirdop was constructed. After digging a tunnel between the Elatsite mine and the village of Mirkovo, a flotation plant was built. For the functioning of these mining sites, landfills for waste materials and tailing impounds were built [19]. The Medetska River, a left tributary in the upper reaches of the Topolnitsa River, drains the largest mining sites. In the vicinity are constructed and currently operated the "Aurubis Copper Mining Plant" AD (between the towns of Zlatitsa and Pirdop), "Dundee Precious Metal" Inc. (Canadian-based international gold mining enterprises) for the extraction and processing of copper near Pirdop, the Chelopech copper mine near the village of Chelopech with the Chavdar tailings dam, and the Flotation Complex mine in the village of Mirkovo with the Benkovski-2 tailings dam (Fig. 1). The Elshishka River, a left tributary in the lower reaches of the Topolnitsa River, drains the Elshitsa open-pit mine, where copper was extracted from 1936 to 1998 [19]. The existing ore-mining and processing facilities, as well as the closed ones, release hazardous waste materials and saturate the surface waters with heavy metals [22]. An additional factor for the deteriorated quality of surface waters is the relatively small size of the rivers and their low self-purification capability. To assess the self-purification ability in our country, collective research has been carried out on the conditioning of river waters through ion exchange methods and technologies [24].

In this context, the assessment of heavy metal contamination of the waters of the Topolnitsa River is a basis for preparing and implementing well-grounded decisions for sustainable water management.

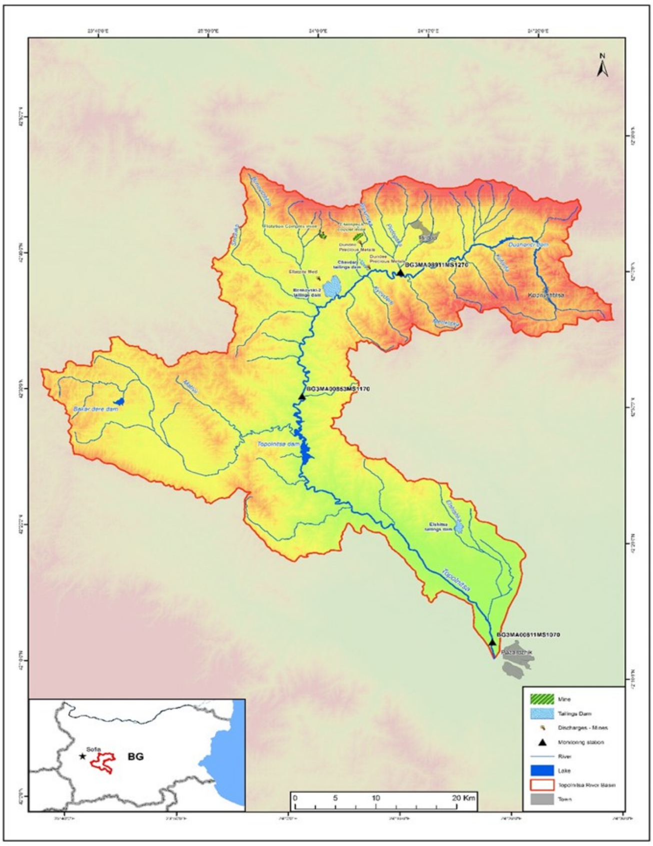

Fig. 1. Map of the study area

Materials

The article examines the values of eight chemical parameters – arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn). Data is provided by the Executive Environment Agency (EEA) for six years between 2018 and 2023. It is necessary to clarify that for 2022 only the value of Fe was measured.

This study is based on statistical information processed following the current Bulgarian legislation, namely Ordinance N-4 on the characterization of surface waters of 14 September 2012 and the Environmental Quality Standards (EQS) [25] for priority substances and some other pollutants of Directive 2008/105/EC of 16 December 2008 (later transposed into the Ordinance on Environmental Quality Standards for priority substances and certain other pollutants from 2010) [26] (Table 1). The analysis is based on the Highest Permissible Limit (HPL). When a given HPL indicator is marked as "not applicable," the assessment is based on the Annual Average Value (AAV). The values not exceeding the relevant HPL and AAV are considered to meet the requirements for "good" chemical status. Concentrations that deviate from the reference standards are considered to be indicative of "bad" status (Table 1).

Table 1. Description of the Environmental Quality Standards (EQS) as stated in Ordinance N-4 of 14 September 2012 and Regulation on Environmental quality standards from 2010

Chemical parameter	*Annual average value (µg/l)*	*Highest permissible limit (µg/l)*
As	10.00	25.00
Cu	1.00	not applicable
Zn	8.00	not applicable
Fe	100.00	not applicable
Mn	50.00	not applicable
Pb	1.20	14.00
Cd	0.08	0.45
Ni	4.00	34.00

The measurements are conducted at three water monitoring points, covering the upper, middle, and lower reaches of the Topolnitsa River (Fig. 1, Table 2).

Table 2. Information about the water monitoring points

Code of the water monitoring point	*Location of the water monitoring point*		
	Description	**Geographic coordinates**	
		X (°E)	**Y (°N)**
BG3MA08911MS1270	Topolnitsa River at the bridge between the towns of Panagyurishte and Pirdop	24.13799	42.65831
BG3MA00853MS1170	Topolnitsa River at the village of Poibrene, before the "Topolnitsa" Dam	23.99647	42.50230
BG3MA00811MS1070	Topolnitsa River at the town of Pazardzhik, before its mouth	24.29583	42.20750

Comparing the measured concentrations with the normatively defined standards (HPL and AAV), the degree of the exceedance in times (up to 10, between 10 and 25, and over 25) for each of the chemical parameters and each of the sampling sites was established, which represents the differentiated assessment of water quality in the studied river basin.

Methods

The diversity of pollutants entering the surface water bodies requires not only obtaining a differentiated assessment of their conditions but also performing a complex analysis of the anthropogenic impact. The differentiated assessment shows information about the water body by individual parameters, while the complex allows a comprehensive study of the qualitative status. The complex approach uses a universal and widely applicable water quality index in the hydro-ecological practice (Canadian Council of the Ministers of the Environment – CCME WQI, 2001) [27]. This index has proven its simplicity of use and informativeness of the results in many countries around the world, including Canada [28], Spain [29], Chile [30], Iran [31], and Bulgaria [20-21]. An advantage of its use is that the intermediate results are a basis not only for obtaining a final integral assessment but also for analyzing and assessing changes in individual water quality parameters in time and space (CCME WQI, 2001). The index includes three components, representing the scope (F_1), frequency (F_2), and amplitude (F_3) of the anthropogenic impact on surface water quality. The water quality index was computed according to the formula (1):

$$WQI = 100 - \left(\frac{\sqrt{F_1^2+F_2^2+F_3^2}}{1.732}\right) \qquad (1)$$

The divisor 1.732 normalizes the obtained value in the interval from 0 to 100, where 0 means the worst and 100 shows the best water quality. The index ratings are classified into five categories, using a special scale (Table 3).

Table 3. Ranking system and interpretation of water quality (CCME WQI, 2001)

Status	***WQI values***	***Interpretation***
Excellent	95–100	Water quality is protected with a virtual absence of threat or impairment; conditions are very close to natural or pristine levels. Unpolluted water.
Good	80–94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels. Almost unpolluted water.
Fair	65–79	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels. Slightly polluted water.
Marginal	45–64	Water quality is frequently threatened or impaired; conditions usually depart from natural or desirable levels. Polluted water.
Poor	0–44	Water quality is almost always threatened or impaired; conditions very often depart from natural or desirable levels. Heavily polluted water.

Results and discussion

Conservation challenges

The remediation of areas contaminated with heavy metals and subsequently becoming hotspots is associated with numerous limitations that may hinder the effectiveness of efforts to remediate them. These limitations arise from the complex nature of the causes of the entry and behavior of heavy metals in or between components of the natural environment. The consequences of heavy metal pollution are wide-ranging and affect human health, ecosystems, and socio-economic well-being. For example, the development of heavy industrial activities and heavy metals can also enter agricultural ecosystems through the application of fertilizers, pesticides, and sewage sludge, as well as through irrigation with contaminated water sources [2]. In addition, livestock farming also plays a role in the cycle of heavy metal pollution through various routes. Over time, they can accumulate in soil, crops, and groundwater, posing a risk to food safety, human health, and environmental quality. Prolonged exposure to heavy metals can cause a number of adverse health effects, including neurological disorders, respiratory diseases, cardiovascular problems, and developmental abnormalities. In addition, heavy metals can bioaccumulate and migrate, posing a risk to humans and ecosystems [32].

In order to achieve long-term protection of ecosystem health, biodiversity, and human well-being in the so-called hotspots, it is necessary to develop and implement appropriate management strategies. Effective management strategies aimed at preventing, remediating, and restoring pollution are essential to mitigate the adverse effects of heavy metal pollution and preserve the ecological integrity of areas with degraded ecosystem quality [33]. Effective management requires a comprehensive approach that encompasses efforts to prevent, remediate, and restore pollution. Today, the key strategies are the following: pollution control regulations; best management practices; restoration techniques; phytoremediation; monitoring and adaptive management; and stakeholder engagement and education [32].

Current state of the model "hotspot" in Bulgaria

The results show that the waters of the ***Topolnitsa River at the monitoring point bridge between Panagyurishte and Pirdop*** (***BG3MA08911MS1270***) are polluted with Cu, Ni, Cd, Mn, and Zn. During the study period, the excess in the average annual values of Zn, Mn, and Cu was most often up to 25 times above the reference norm (Fig. 2, Table 4). The calculated average annual values for 2020 reached 4729µg/l (Cu), 906µg/l (Zn), and 1938µg/l (Mn). The river waters at this monitoring point are also contaminated with Cd and Ni. The highest measured concentrations were recorded on 09.10.2019 – 5µg/l and 06.02.2020 – 139µg/l, respectively. Only the Fe and Pb values remain within the normatively determined standards. The calculated Water Quality Index (WQI) ratings show that surface waters maintain "poor quality" during the period – the index scores vary between 21.9 (2019) and 31.8 (2018) (Fig. 3). These results do not differ significantly from those reported by Varbanov et al. (2015) for 1981–2009, which means that river waters did not improve their quality and remained heavily polluted between 2018 and 2023 [34]. The water quality of the Topolnitsa River in this section is seriously impaired due to the discharge of untreated wastewater from the Zlatishka, Pirdopska, and Medetska tributaries, draining the largest mining and processing enterprises.

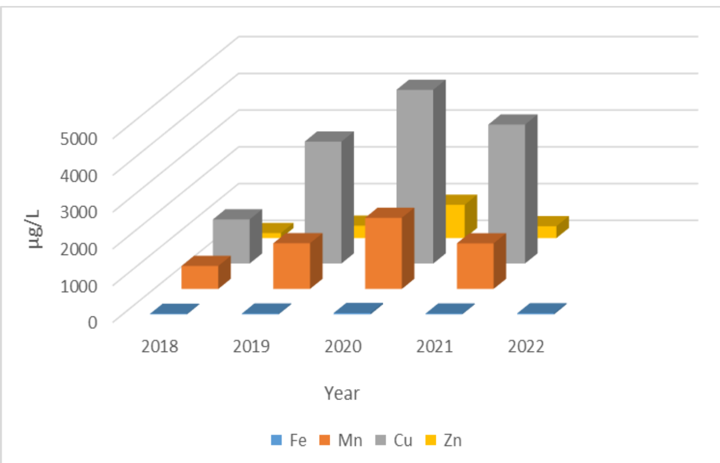

Fig. 2. Change of AAV (µg/l) of Fe, Mn, Cu, and Zn for the Topolnitsa River at the monitoring point bridge between the towns of Panagyurishte and Pirdop (BG3MA08911MS1270)

Table 4. Chemical elements with exceedances above the reference norms

Water monitoring point	*Degree of the exceedance*		
	up to 10 times	**from 10 to 25 times**	**over 25 times**
Topolnitsa River at the bridge between the towns of Panagyurishte and Pirdop	Cd, Ni, Cu, Mn, Zn	Cu, Mn, Zn	Cu, Mn, Zn
Topolnitsa River at the village of Poibrene, before the "Topolnitsa" Dam	Cu, Mn, Zn, Cd, Ni	Mn, Cu	Cu
Topolnitsa River at the town of Pazardzhik, before its mouth	Cu, Mn, Zn, Cd, Ni	Cu, Mn, Zn	Cu, Mn, Zn

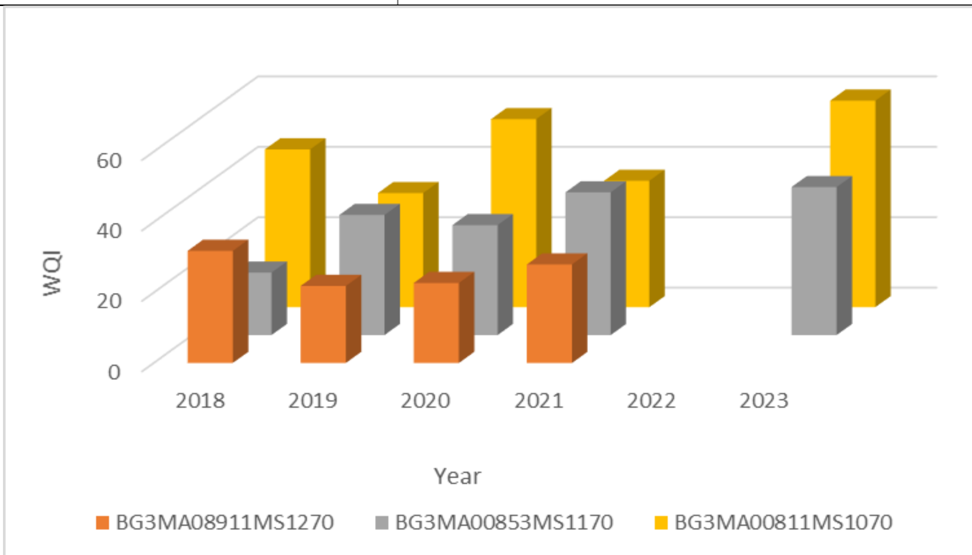

Fig. 3. Change of the CCME WQI values for the Topolnitsa River

The results show that the waters of the ***Topolnitsa River at the monitoring point in the village of Poibrene*** (***BG3MA00853MS1170***) are loaded with Mn, Zn, Cu, Cd, and Ni. The average values for the study period, as well as the registered maximum concentrations, exceed the highest permissible limits tenfold. The content of Mn and Zn is most often characterized by a tenfold excess, with deviations between 10 and 25 times being established in some years (Fig. 4, Table 4). For example, in 2023, the calculated average concentration of Mn was 391µg/l, and in 2019, the Zn content reached 37µg/l. The highest registered concentrations of Cd were 1µg/l in 2018, 2020, and 2023; the Ni content reached 38µg/l in 2018; and the Cu value was 119µg/l in 2019. All of these values do not meet the reference norms. The resulting WQI scores classify the river water quality into the "poor" category. The lowest index rating (17.7) was established in 2018, while the highest one (42.0) was reported in 2023 (Fig. 3). The obtained in previous study [34] partially similar estimates for 1981–2009, which shows that water quality continues to be seriously impaired from 2018 to 2023. The deteriorated qualitative status of the waters in this section is due to the effect of untreated wastewater released from the Chelopech copper mine near Chelopech with the Chavdar tailings dam and the Flotation Complex mine at Mirkovo with the Benkovski-2 tailings dam. The exploitation of these mining sites also has a negative impact on the villages of Poibrene, Muhovo, Lesichovo, and the other settlements around the "Topolnitsa" Dam.

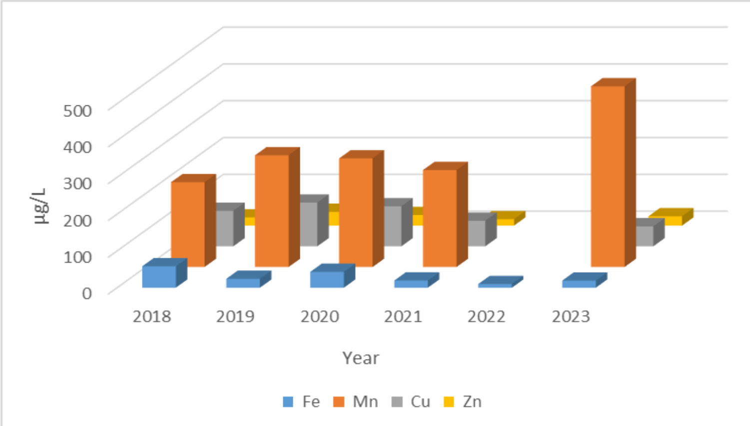

Fig. 4. Change of AAV (µg/l) of Fe, Mn, Cu, and Zn for the Topolnitsa River at the monitoring point in the village of Poibrene, before the "Topolnitsa" Dam (BG3MA00853MS1170)

The waters of the ***Topolnitsa River at the monitoring point in the town of Pazardzhik, before its mouth (BG3MA00811MS1070)***, are contaminated with Cu, Mn, Zn, Cd, and Ni, most often exceeding the reference standards tenfold, except the registered values of Cu, Mn, and Zn, which overtop the norms between 10 and 25 times, as well as over 25 times (Fig. 5, Table 4). The highest deviation from the normatively determined standards is for the annual average value of Mn in 2019: 3836µg/l. The WQI scores range from 32.4 (2019) to 58.6 (2023), which classify water quality into the "poor" and "marginal" categories (Fig. 3). This result confirms the conclusion from previous study for 1990–2009 [34] and suggests that the technogenic impact of mining activities on the river system goes on. In this section, the Topolnitsa River feels the adverse effect of the tributary Elshishka River, which flows the untreated effluents from the Elshitsa mine.

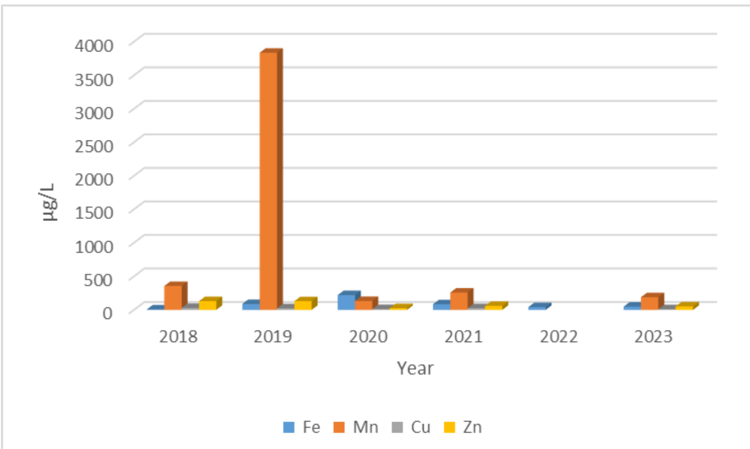

Fig. 5. Change of AAV (µg/l) of Fe, Mn, Cu, and Zn for the Topolnitsa River at the monitoring point in the town of Pazardzhik, before its mouth (BG3MA00811MS1070)

Recommendations and future needs of research

In order to address the challenges facing the problem, advances in understanding and integrating interdisciplinary research are of paramount importance. The development of predictive models that include the behavior of heavy metals, ecosystem services, and socio-economic factors are among the main ways to protect and restore ecologically disturbed areas. The effectiveness of pollution control regulations, as well as their enforcement mechanisms and real-time monitoring technologies, should be a key focus of cooperation between stakeholders - policymakers, researchers, and local communities [32]. Ultimately, the protection of so-called hotspots with severely disturbed ecological balance resulting from aggressive heavy metal pollution requires a comprehensive and adaptive management framework. Future efforts should focus on identifying gaps in current knowledge and areas for future research, some of which are mentioned below:

- Long-term monitoring and assessment;
- Multi-sector integration;
- Good understanding of remediation processes;
- Assessment of ecological risks and ecosystem services;
- Development of technologies for sustainable management;
- Stakeholder engagement and knowledge exchange;
- Increased capacity to mitigate the long-term impacts of heavy metal pollution on critical ecosystems [33].

Conclusions

The water quality of the Topolnitsa River is deteriorating as a result of pollution from both point and diffuse sources, related to mining activities, processing industrial enterprises, and tailings storage facilities. Given the results of the study at three monitoring points located in the upper, middle, and lower reaches of the river, it can be summarized that the impact of mine wastewater on surface water quality is present throughout the river's course, including at the mouth. This is confirmed by the elevated concentrations of Cu, Mn, Zn, and Cd, and the corresponding failure to achieve the regulatory standard for "good" physicochemical status of river waters in all years during the study period. The applied WQI classifies water quality into the "poor" and "marginal" categories due to the considerable anthropogenic pressure.

The sustainable development of the pilot area, given the presence of some of the largest mines and processing enterprises in the country, requires the implementation of an integrated approach, considering the economic, social, and ecological aspects of society. In line with the results of this study and the response to the Water Framework Directive 2000/60/EU (WFD) requirements for maintaining the "good" status (qualitative and quantitative) of water bodies is the development of an adequate program of measures. Specifically for the pilot basin of the Topolnitsa River, the following activities can be proposed: prevention of the generation of acidic mine waters; construction of wetlands for the purification of mine waters; improvement of the operation and management of the wastewater treatment plants for the purification of mine waters; semi-passive treatment of mine waters; restoration of damaged components of compromised industrial waste landfills; construction of collection and drainage systems in mining waste landfills; introduction of water recycling cycles in the management of tailings ponds; implementation of a program for conducting own monitoring of surface wastewater in mining-affected areas, tailings ponds, and tailings pipelines within the scope of the concession territories; reclamation of contaminated sites from mining activities; collection and mapping of information on mine water leakage.

Implementing the above measures will inevitably limit and prevent pollution with heavy metals, metalloids, and other substances, but expanding and upgrading scientific research in this direction will be important for the overall approach and sustainable water management.

Acknowledgments

This study was supported by Contract No. D01-321/30.11.2023 (Project "National Geoinformation Center (NGIC)" financed by the Ministry of Education and Sciences of Bulgaria through the National Roadmap for Scientific Infrastructure 2020-2027).

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Received: March 10, 2025
Accepted: November 14, 2025