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Impact of Coal-Fired Power Plant Activities on the Ecological Status of River Ecosystems: Case Study of Sokolitsa River, Bulgaria

Vanina Mitseva [1,*], Tsvetelina Isheva [2], Mila Ihtimanska [2] and Emilia Varadinova [1,2]

[1] Department of Geography, Ecology and Environmental Protection, Faculty of Natural Sciences and Mathematics, South-West University "Neofit Rilski", 66 Ivan Mihailov Street, 2700 Blagoevgrad, Bulgaria; emily.varadinova@gmail.com
[2] Department of Aquatic Ecosystems, Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria; tsvetelina.isheva@abv.bg (T.I.); mila.ihtimanska@gmail.com (M.I.)
* Correspondence: vanim@abv.bg

Abstract

Coal-fired power plants can adversely affect aquatic ecosystems through wastewater discharge, waste landfills, and the atmospheric deposition of toxic substances released during coal combustion. These processes degrade the water quality of nearby surface and underground water bodies. The study presents the impact of the coal-fired power plant Contour Global Maritza East 3 on the ecological status of the Sokolitsa River, reflected by changes in the composition and structure of the sensitive phytobenthos and macrozoobenthos communities and supporting environmental variables, including water temperature, pH, dissolved oxygen, conductivity, nutrients, sulfates, calcium, and calcium carbonate hardness. Methods for monitoring and assessing the ecological status of surface water bodies compliant with European and national legislation were applied to the studied biological quality elements and key physicochemical variables. Historical monitoring data from a ten-year period, 2013–2022, together with data collected during the study in 2023 and 2024 were analyzed and evaluated. The results indicated a significant increase in most physicochemical variables downstream of the CFPP compared with the upstream site, including water temperature, conductivity, calcium carbonate hardness, calcium, sulfates and nitrogen (N) nutrients (ammonium N, nitrite N, nitrate N, total N). The ecological status of the river deteriorated, as indicated by the negatively affected aquatic habitats and the changes in the taxonomic richness and abundance of the studied organism groups.

Keywords: coal-fired power plant; surface water pollutants; benthic communities; ecological status

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1. Introduction

In the late 19th century, the construction of coal-fired power plants (CFPPs) played an important role in the development of the industrial society. The world's first CFPP was built and commissioned in 1882 on the Holborn Viaduct in London, United Kingdom, where the famous inventor Thomas Edison played a key role in the development of electricity generation for household lighting. In the same year, the second CFPP was commissioned in the United States at Pearl Street Station in New York City [1,2]. In the early 20th century, coal became the dominant energy source for production in many major industrial countries. After World War II, economic recovery and growing electricity demand led to the

construction of CFPPs with much larger generating capacities in Europe, the United States, Japan, the Soviet Union, and China [3]. By the end of the 20th century, CFPP electricity generation had been identified as one of the largest anthropogenic sources of greenhouse gas emissions and toxic substances released into the atmosphere worldwide [4–6]. The link between fossil fuel combustion and global warming has been firmly established. At the same time, CFPPs are recognized as a major source of air pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO_2), ash, soot, and fine particulate matter (PM10 and PM2.5), causing acid rain, industrial smog and biodiversity loss [7,8]. In the early 21st century, the most pronounced increase in CFPP use was registered in the rapidly developing economies of East and Southeast Asia, particularly China, India, and Indonesia, where coal deposits are either abundant or easily supplied by sea [9]. In 2019, CFPPs accounted for approximately 38% of the global electricity production [5,10,11]. In Bulgaria, CFPPs supplied 8,372,886 MWh of electricity in 2024, with a combined installed capacity of 3601 MW. For the same year, the total electricity generation in the country amounted to 34,335,588 MWh, of which more than 24 million MWh was produced by the baseload capacity of nuclear and coal-fired power plants. According to the Global Energy Monitor, more than 6500 CFPPs were in operation worldwide at the beginning of 2026. The highest numbers were reported in China (1207), India (292), the United States (192), Indonesia (95), Japan (87), Russia (63), Germany (40), Poland (40), and Turkey (34), while Bulgaria has 11 operating CFPPs [12]. In 2024, only Germany, Poland and the Czech Republic had larger shares of CFPPs in the EU electricity generation mix than Bulgaria [13]. This highlights the continuing importance of these plants for the security of the national electricity system [14].

Under the European Green Deal, EU member states are expected to terminate coal use in electricity production by 2030, in order to achieve a 55% reduction in net carbon emissions relative to 1990 levels [15]. In the National Recovery and Resilience Plan, Bulgaria committed to reducing carbon emissions by 40% by 2026 [16]. In 2023, Bulgaria was among the European countries with the highest carbon intensity of electricity generation due to its reliance on solid fossil fuels, the relatively low share of renewable energy sources, and limited nuclear capacity in its national electricity mix [17].

The environmental impact of CFPPs is mostly associated with air pollution, particularly emissions of greenhouse gases, soot, and fine dust particles. However, their adverse effects on water are equally significant and may result in severe and potentially irreversible consequences for aquatic ecosystems. CFPPs are recognized as the largest industrial consumers of water worldwide as large amounts are deployed in CFPPs for technological processes, including boiler exploitation, steam generation and cleaning of the purification facilities [18–21]. Lots of water is also used for the turbine cooling in CFPPs which significantly increases wastewater temperature. If discharged without sufficient cooling, this wastewater can cause thermal pollution, reduce dissolved oxygen levels, and adversely affect aquatic organisms by inducing stress, altering their metabolism, reducing fertility, and increasing mortality [22].

Coal combustion produces large amounts of ash, containing toxic metals and other pollutants, which can contaminate nearby surface and groundwater, especially when stored outdoors. It also emits sulfur dioxide (SO_2) and nitrogen oxides (NOx), which react in the atmosphere to form acid rain. Water acidification disrupts aquatic ecosystems, and potentially causes mortality of the biota [8,23].

Recent prolonged droughts in Bulgaria have caused serious water shortages in many regions, leading to crisis situations due to insufficient water supply for households and businesses. These conditions also threaten freshwater ecosystems and biodiversity by reducing ecological river flow [24]. In the context of the rising water demand and ongoing climate change, the operation of CFPPs should be reconsidered in regard to Bulgaria's

obligations under the European environmental legislation and its wider ethical, social, and economic implications [25]. In recent years, the public debate in Bulgaria on the closure of CFPPs and the identification of alternative sources for sustainable energy supply has intensified in the context of climate change, insecurities associated with the ongoing war in Ukraine and the natural gas crisis, and rising energy consumption. In September 2024, the 50th Parliament of Bulgaria failed to adopt the proposed Law on the Closure of CFPPs. The results of this study may inform management decisions concerning the uncertain closure of the operating CFPPs in Bulgaria and the transition to sustainable energy production, with significant environmental, social, and economic implications for the ecosystems and the communities in the regions concerned.

The impacts of CFPPs are multifactorial and often combine thermal alteration, nutrient enrichment, hydrological modification and metal contamination, among others. Diatom and macroinvertebrate communities respond to the cumulative pressure gradients, making them particularly suitable for detecting multiple stressors [26,27]. Hence, studying the benthic communities downstream of the coal plant can detect eutrophication, metal and ion stress and degradation in the ecological status (ES).

The present study aims to assess the changes in the ecological status of the affected Sokolitsa River under the pressure of the operating CFPP Contour Global Maritsa East 3 over a period of more than ten years. To address this question, we tried to track the quantitative changes in the lotic ecosystem associated with this anthropogenic pressure and focus on the sensitive benthic communities phytobenthos and macrozoobenthos, which detect changes in key physicochemical variables and are the main biological quality elements (BQEs) for the ecological status assessment of rivers.

2. Materials and Methods

2.1. Study Area

According to Global Energy Monitor, CFPP Contour Global Maritsa East 3 is part of Maritsa East Complex, the largest energy complex in Southeastern Europe, consisting of three lignite-fired power plants. The complex is located in Stara Zagora Province, near the village of Mednikarovo, in south-central Bulgaria, within an extensive lignite coal basin comprising several mines, enrichment plants, a briquette plant and its own internal railway system. It has an installed capacity of 908 megawatts (MW), distributed across four generating units, and is the second largest CFPP in Bulgaria, which plays an important role in the security of the country's electricity supply and energy independence [28]. CFPP Contour Global Maritsa East 3 is located within the catchment of the Sokolitsa River, a left tributary of the Sazlijka River in the Maritsa River basin, within the East Aegean River Basin District (EARBD) (Figure 1). Sokolitsa River begins at an altitude of 713 m in the Sakar Mountains, in southeastern Bulgaria. In its upper reaches, the river flows north through a deeply cut valley, then turns west and continues in a wide valley. The length of the river is 60.5 km, with a catchment area of 343 km. Its hydrological regime is characterized by a pronounced spring high-flow period from January to May and a low-flow period from July to October. Below 150 m altitude, the lowland part of the river is characterized by slow flow and a fine substrate dominated by sand, fine gravel, and organic sediments. The precipitation regime is influenced by the Mediterranean climate, with a mean annual air temperature above 12 °C, and relative humidity of about 70% [29].

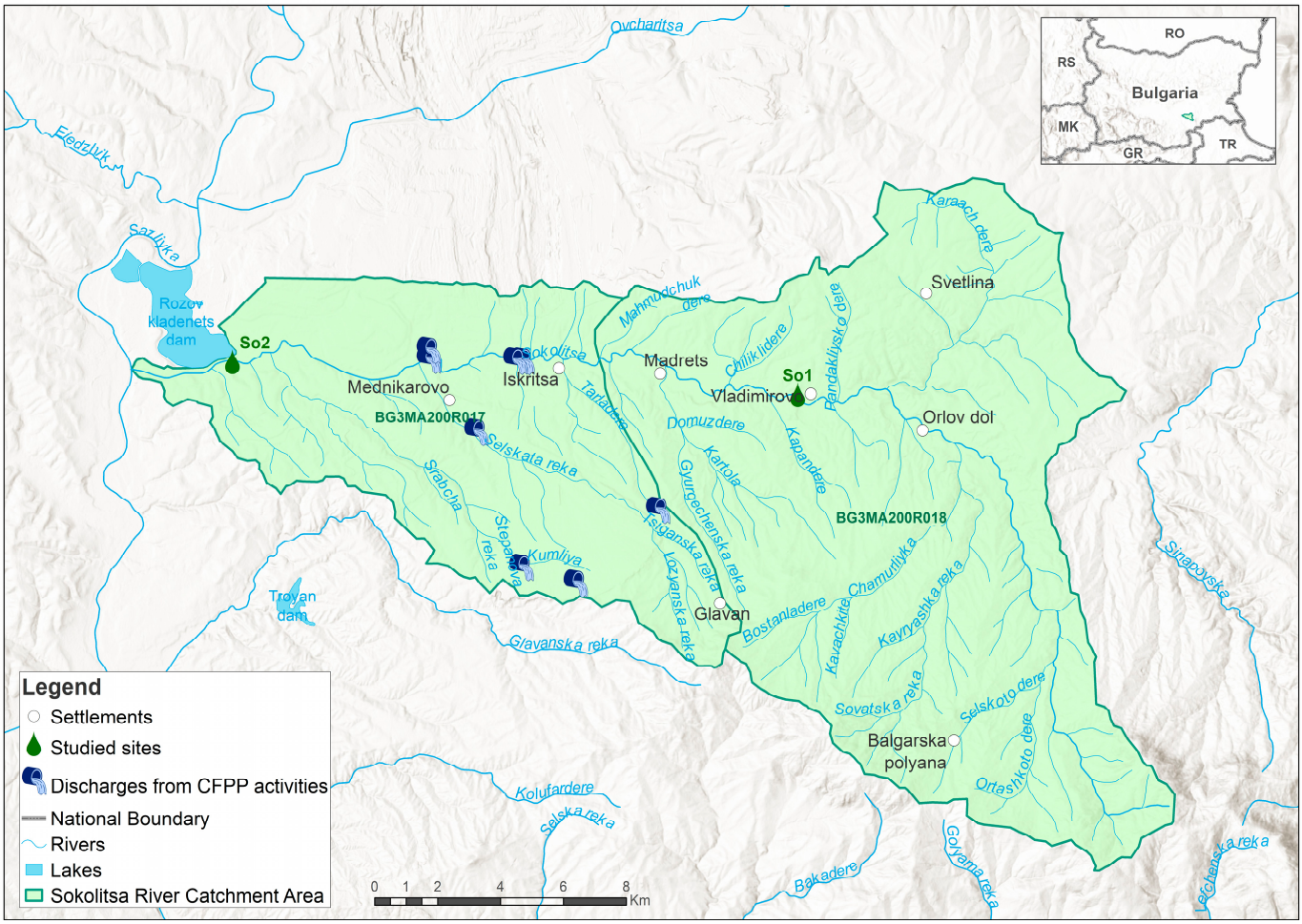


Figure 1. Location of wastewater discharges from coal-fired power plant activities and the studied sites within the Sokolitsa River catchment area. Inset map: location of the Sokolitsa River catchment in the Bulgarian territory. Legend of the inset map on Figure 1: RO—Romania; TR—Turkey; GR—Greece; MK—North Macedonia; RS—Serbia.

The Sokolitsa River catchment includes the protected area BG0000440 "Sokolitsa River," under the Habitats Directive 92/43/EEC and included in the European ecological network Natura 2000 [30,31].

According to the current River Basin Management Plan (RBMP) 2022–2027 of the East Aegean River Basin District (EARBD) [32], two surface water bodies (SWBs) have been identified within the Sokolitsa River catchment (Figure 1): SWB BG3MA200R018, Sokolitsa River, upper course; and SWB BG3MA200R017, Sokolitsa River, middle course to Rozov Kladenets Dam.

According to the European Water Framework Directive, both surface water bodies belong to Bulgarian river type R13, defined as "Small- and medium-sized lowland rivers in the Eastern—Balkans ecoregion" [33]. The rivers of this type are characterized by great variability in the growth of higher aquatic plants—macrophytes. They vary from typical macrophyte river sections (with a dominance of helophytes) to the absence of macrophytes in some sections. The seasonal flooding characteristic in spring is absent (seasonal spills) from this type of river, which does not particularly affect the phytobenthic communities as it affects the other BQEs (fish, macrophytes and macrozoobenthos). The dominant fish species in R13 rivers are *Barbus cyclolepis*, *Squalius orpheus*, and *Rhodeus amarus*.

The fuel facility of CFPP Contour Global Maritsa East 3 and "Embankment Mednikarovo", the landfill for non-hazardous waste of "Mines Maritsa East" with a total of

eight points of wastewater discharge, are located within SWB BG3MA200R017, Sokolitsa River middle reaches to Rozov Kladenets Dam (Figure 1).

For the assessment of the CFPP's impacts, two sampling sites were selected along the Sokolitsa River (Figure 1):

- Site So1: Sokolitsa River near Vladimirovo village, upstream of the discharges from the facilities of CFPP "Contour Global Maritsa East 3", located within SWB BG3MA200R018 (reference site, not affected by CFPP activities);
- Site So2: Sokolitsa River near Obruchishte village, downstream of the discharges of the CFPP "Contour Global Maritsa East 3" facilities, located within SWB BG3MA200R017 (impacted site, affected by CFPP activities).

The selected sites are consistent with the aims of the study. Site So1, located upstream of all CFPP facilities, represents unaffected, reference conditions, whereas Site So2, located downstream of all facilities and wastewater discharge points, represents impacted conditions. Long-term monitoring data are available for both sites for phytobenthos, macrozoobenthos, and the supporting physicochemical variables.

2.2. Data Collection and Analysis

To address the research question, the study combined the national surface water monitoring data for the Sokolitsa River for the period 2013–2022 and recent data from 2023 and 2024 by analyzing physicochemical variables, along with the phytobenthic and macrozoobenthic communities. Field measurements and sampling were conducted in the summer and autumn, during the low-flow period in 2023 and 2024, upstream and downstream of the wastewater discharge points from the fuel facilities and waste landfills of CFPP Contour Global Maritsa East 3 (Table 1).

Table 1. Site characteristics, studied biological quality elements and environmental variables.

№	Name of the Studied Site	Coordinates	Code and Name of the Water Body	Environmental Variables and BQEs
1	So1: Sokolitsa River near Vladimirovo village, upstream of discharges from CFPP Contour Global Maritsa East 3 facilities and the landfill "Embankment Mednikarovo"	26°8′11.76″ E, 42°7′38.64″ N	BG3MA200R018, Sokolitsa River upper stream	t° C, pH, dissolved oxygen (mg/L), conductivity (μS/cm), ammonium nitrogen (mg/L), nitrite nitrogen (mg/L), nitrate nitrogen (mg/L), total nitrogen (mg/L), orthophosphates as phosphorus (mg/L), total phosphorus (mg/L), calcium carbonate hardness (mg/L), calcium (mg/L), sulfates (mg/L), BQE phytobenthos, BQE macrozoobenthos.
2	So2: Sokolitsa River near Obruchishte village, downstream of discharges from CFPP Contour Global Maritsa East 3 facilities and the landfill "Embankment Mednikarovo"	25°55′8.4″ E, 42°8′5.64″ N	BG3MA200R017, Sokolitsa River middle reaches to the Rozov Kladenets Dam	

Natural and anthropogenic changes in the Sokolitsa River ecosystem, particularly downstream, were identified. Natural and anthropogenic changes in the studied river ecosystem, particularly downstream, were identified through long-term monitoring data, statistical modeling, and comparative analysis of the upstream (control) and downstream (impact) site.

The field sampling followed EN ISO 5667-3:2018 "*Water quality—Sampling—Part 3: Preservation and handling of water samples*", as amended by ISO 5667-3:2024 [34]. The standard specifies the general requirements for the sampling, preservation, handling, transport and storage of water samples including those for biological analyses.

Water samples for physicochemical analysis were collected from mid-channel sections, at 20–30 cm depth, avoiding stagnant water and immediately after wastewater mixing zones. Samples were stored in glass or plastic bottles, depending on the variable, con-

taining the required preservatives; transported at 5 ± 3 °C; and delivered to the regional laboratories of the Executive Environmental Agency (EEA) on the same day—no later than 12 h after sampling. Temperature, pH, dissolved oxygen, and conductivity were measured in situ using a CX-461 multifunctional meter.

Sampling data were recorded in an official protocol, including: site coordinates and site/river name; hydrometeorological conditions, e.g., water level (runoff); precipitation; and air temperature.

Ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, total nitrogen, orthophosphates as phosphorus, total phosphorus, calcium carbonate hardness, calcium and sulfates were measured and analyzed in the laboratory using national and international methods (Table 2).

Table 2. Physicochemical variables and applied standards.

Variable	Units	Limit of Quantification (LoQ)	Measurement/Analytical Standards
pH		0.02	BDS EN ISO 10523:2012 [35]
Water temperature	°C		BDS 17.1.4.01:1977 [36]
Conductivity	µS/cm	1.3	BDS EN 27888:2000 [37]
Dissolved oxygen	mg/L	0.3	BDS EN ISO 5814:2012 [38]
Total phosphorus	mg/L	0.008	BDS EN ISO 6878:2005 [39]
Ammonium nitrogen	mg/L	0.01	BDS ISO 7150-1:2002[40]
Nitrite nitrogen	mg/L	0.015	BDS EN ISO 10304-1:2009 [41]
Nitrate nitrogen	mg/L	0.02	BDS EN ISO 10304-1:2009 [41]
Total nitrogen	mg/L	0.2	BDS EN ISO 20236:2021, point. 5.3 (amended with BDS EN ISO 20236:2025) [42]
Orthophosphates (as phosphorus)	mg/L	0.006	BDS EN ISO 6878:2005 [39]
Sulfates	mg/L	1	BDS EN ISO 10304-1:2009 [41]
Calcium	mg/L	1	BDS EN ISO 14911:2002 [43]
Calcium carbonate hardness	mg $CaCO_3$/L	20	BDS ISO 6059:2002 [44]

The results for the basic physicochemical variables pH, dissolved oxygen (DO), conductivity (Cond.), ammonium nitrogen (N-NH_4), nitrite nitrogen (N-NO_2), nitrate nitrogen (N-NO_3), total nitrogen (N-total), orthophosphates as phosphorus (P-PO_4), and total phosphorus (P-tot) were compared with the values corresponding to "Good ecological status" for Bulgarian river type R13. When a result was below the limit of quantification (LoQ) of the analytical method, a value of 1/2 of LoQ was applied, in accordance with Ordinance N-4/2012 for the characterization of surface waters in Bulgaria [33]. Variables without good ecological status standards under Ordinance No. 4/2012, such as calcium carbonate hardness ($CaCO_3$), calcium (Ca), and sulfates (SO_4^{2-}), were evaluated by comparing the results from the sites unaffected and affected by CFPP wastewater discharges. BQE phytobenthos was sampled at two sites in order to evaluate the spatial differences in the assemblages upstream and downstream of the coal-fired power plant. The upstream site (So1) served as reference and is unaffected by the CFPP, whereas the downstream site (So2) reflected the impacts associated with the discharges from the CFPP. At each site, phytobenthos were collected from representative substrates under comparable hydrological conditions to ensure consistency. Species composition, relative abundance, and ecological status metrics were then compared between sites to determine whether the power plant operations influenced the community structure and the ecological status. The Bulgarian method for

the assessment of a river's ecological status based on BQE phytobenthos uses benthic diatoms as proxies, where taxonomic composition and species relative abundance are taken into consideration [33]. Sampling procedures, processing, and taxa identification were performed in accordance with European standards EN 13946:2014 *Water quality—Guidance for the identification and enumeration of benthic diatom samples from rivers and lakes* (amended with EN 13946:2024) [45] and EN 14407:2014 *Water quality—Guidance for the identification and enumeration of benthic diatom samples from rivers and lakes* (amended with EN 14407:2024) [46]. Diatom samples were collected from submerged stones by carefully scraping the upper surface area to obtain a representative assemblage of the epilithic community. In the laboratory, samples were digested with oxidizing agents to remove organic matter and carbonates. The cleaned material was mounted on permanent slides using a high-refractive medium. Diatoms were identified to species level under light microscopy (1000×); relative abundances were determined by counting a minimum of 400 valves per sample. The nationally approved diatom metric IPS—Indice de polluo-sensibilité [47]—was applied, calculated with OMNIDIA software ver. 5.5 [48], and expressed as nEQR (normalized Ecological Quality Ratio (EQR = observed/reference value). nEQR is rescaled EQR during the intercalibration between EU countries. The ecological status was determined based on a validated type-specific scale for the assessment of national river type R13 [34]. A total of 6 diatom samples were analyzed for the period 2019–2024, as the data for two of the samples (2019 for site So1 and 2022 for site So2) were provided by the Bulgarian Executive Environment Agency. The diatom ecological indicator values follow Mertens et al. [49].

Macroinvertebrate samples were collected in order to assess the changes in the taxonomic diversity and abundance between the two studied sites and in relation to the measured environmental variables. BQE macrozoobenthos were sampled using the multi-habitat approach with a hydrobiological hand-held kick-net (mesh size 500 µm) and a set of hydrobiological sieves for sandy and silt substrates [50]. This approach is in accordance with the national standards [51,52], applied by the Bulgarian Executive Environment Agency. At each site, the sampled area was 0.9 m^2 equivalent to the bottom projection of 10 hand nets with a frame size of 0.30 × 0.30 cm as specified in the applied standard. The bottom substrate at the two sampling sites included small and middle-sized stones, gravel and sand. The velocity of the current was comparably equal with a lack of submerged and floating aquatic vegetation. The abundance of macroinvertebrates was recalculated to a number of individuals per square meter (ind./m^2) which was used in the statistical analyses. The samples were collected once per year during the low-flow period (August–September), as conducted for national monitoring by the authorities.

The laboratory processing of the samples included separation and determination of the macroinvertebrates. Macroinvertebrate taxa were determined at the lowest possible taxonomic level using [53–59]. The taxonomic level of determination followed the requirements for the calculation of the adapted biotic index (BI) [60–62]—family and genus level. It is used for an assessment of the ecological state of water bodies in Bulgaria, is implemented in the national legislation [33] and follows the requirements of the WFD. The index can have values between 1 and 5 which are equated to the values of normalized Ecological Quality Ratio (nEQR). The nEQR is a measure used to assess the ecological status of water bodies by comparing a specific parameter value to its reference values for good and bad conditions. The nEQR values range from 0 (indicating poor ecological quality) to 1 (indicating high ecological quality). The values are presented on a five-point scale—very bad, bad, moderate, good and high.

The Shannon–Wiener diversity index was used for the study of the structure of the macroinvertebrate community [63]. It is a metric used in ecology to quantify the diversity of species in a community. It takes into account both the number of species (richness)

and their relative abundances (evenness) to provide a single value that reflects overall biodiversity. Higher values of the index indicate a community which is well balanced without pronounced dominant species.

Data for 15 macrozoobenthic samples were used for the analyses in the present study. It included number of taxa (i.e., taxa richness) and taxa abundance (ind./m^2). The data from site So1 in the years 2013, 2017, 2018 and 2019 and from site So2 in the years 2012, 2014, 2015, 2016, 2017, 2020 and 2022 were sampled as part of the national monitoring program.

The national monitoring of BQE phytobenthos and macrozoobenthos corresponds with the requirements of Ordinance No. N-4 for the characterization of surface waters, where all the above sampling and proceeding standards are included [33]. The samples are taken once per year during the late spring or early autumn. Processing of the data obtained from the official monitoring (2013–2022) and those obtained in 2023–2024, as well as the assessment of the ecological status, followed the same methodological approach. Thus, the obtained results for the ecological status during the two periods are fully comparable.

Both sampling sites So1 and So2 fall into surface water bodies of the Bulgarian river type R13, i.e., the assessments of the obtained results will be carried out according to the same type-specific classification system of ecological status, i.e., the results are comparable with the same ecological status standards for the same river type R13.

2.3. Statistical Analyses

Statistical Box-and-Whisker plots in Excel were used to visualize the distribution of numerical monitoring data for the physicochemical variables. These plots enable easy and clear visual comparison among data groups and facilitate the simultaneous assessment of multiple variables. They clearly reveal anomalies, data errors, and extreme values, including pollution peaks, which are typical of sites downstream of CFPP discharges (accidental and volley pollution). It is also compact and remains clear with large datasets. Box-and-Whisker plots are also compact and remain clear with large datasets. The analyzed samples cover monitoring data over a 10-year period; as for each physicochemical variable, the results are presented and analyzed by year and by sampling site.

The abundance of the main macroinvertebrates' taxonomic groups by sampling sites was visualized using Past software v.4.03 [64].

The RELATE test (REsemblance and LAtent TEmporal Analysis) was used to assess the relationship between two sets of multivariate data by comparing their resemblance matrices. It helps to determine how closely related the data sets are by calculating a rank correlation coefficient between them. The RELATE test was used to examine if the distribution pattern of phyto- and macrozoobenthic communities can be explained by the values of the environmental variables.

The BEST analysis was used to identify the combination of environmental variables that best explained multivariate patterns in the biological assemblages. It determines which environmental factors most closely correspond to the observed variation in the taxa distribution. Distance-based ReDundancy Analysis (dbRDA or db-RDA) [65] was applied to examine the dissimilarities between the taxa composition and abundance of macroinvertebrates at the studied sites (So1 and So2) in relation to the environmental variables.

The biological data were square-root transformed and the environmental data were log-transformed and normalized before the analyses.

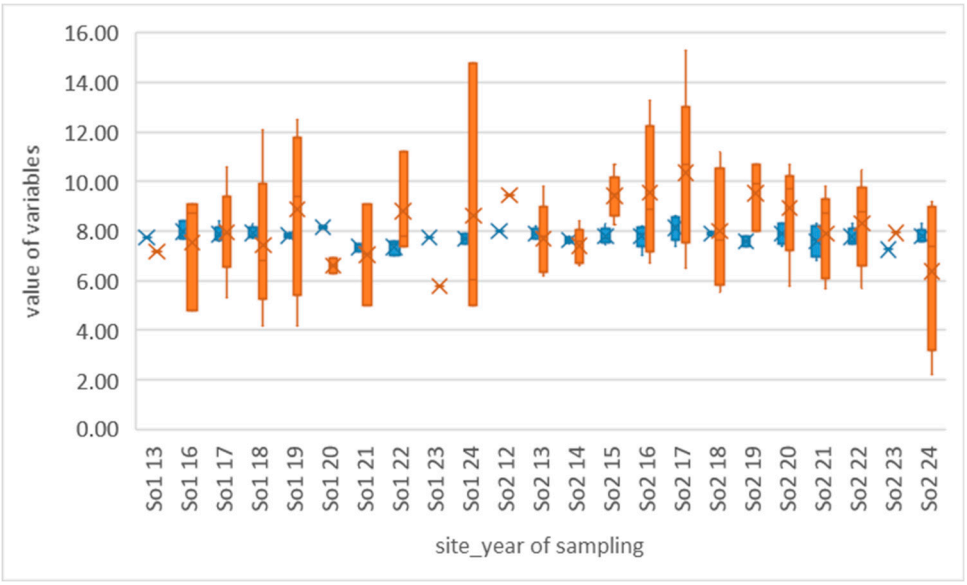
All analyses were performed using software Primer v6 [66], which is a software tool for visualizing and testing multivariate data, especially species-by-samples data from community ecology.

3. Results

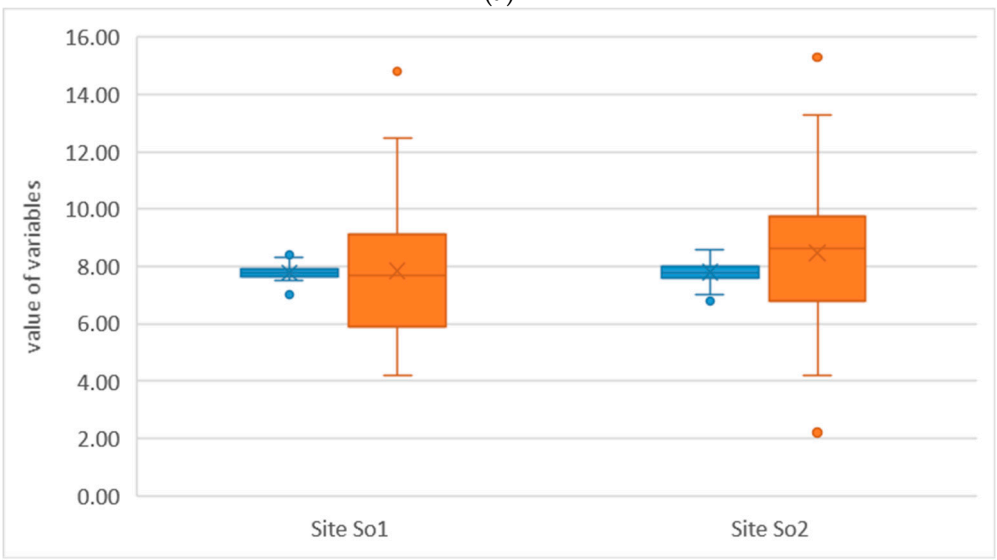
3.1. Physicochemical Variables

Physicochemical variables measured at sites So1 (unaffected by the CFPP) and So2 (affected by the CFPP) in the Sokolitsa River correspond to high, good and moderate ecological status (Table 3).

The comparison of the results for pH (Figure 2a,b) showed no clear differences between sites So1 and So2. In contrast, DO demonstrated higher maximum and mean values for the period 2013–2022, and higher values in 2023 and 2024 at site So2, in comparison to So1.



(**a**)



(**b**)

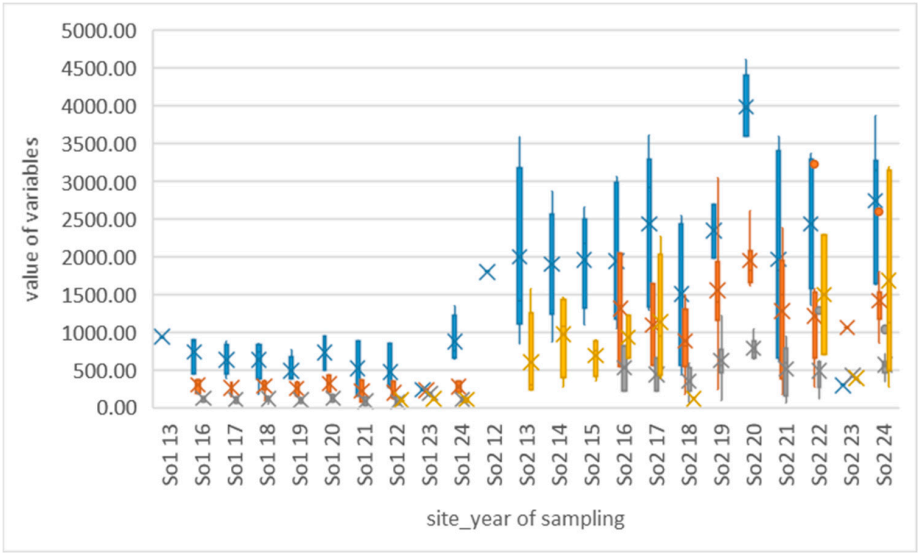
Figure 2. (**a**) Results for the basic physicochemical variables pH and dissolved oxygen (DO) at sites So1 and So2 for the monitoring period (2013–2022) and for the last period 2023–2024. Legend: So1 13—results for site So1 in 2013; So2 24—results for site So2 in 2024; Blue boxes—pH value; Red boxes—Dissolved oxygen, mg/L. (**b**) Summary of pH and dissolved oxygen (DO) results at sites So1 and So2 for the period 2013–2022 and 2023–2024. Legend: Blue boxes—pH value; Red boxes—Dissolved oxygen, mg/L.

Table 3. Ecological status assessment of basic physicochemical variables at sites So1 and So2, according to Ordinance N-4/2012.

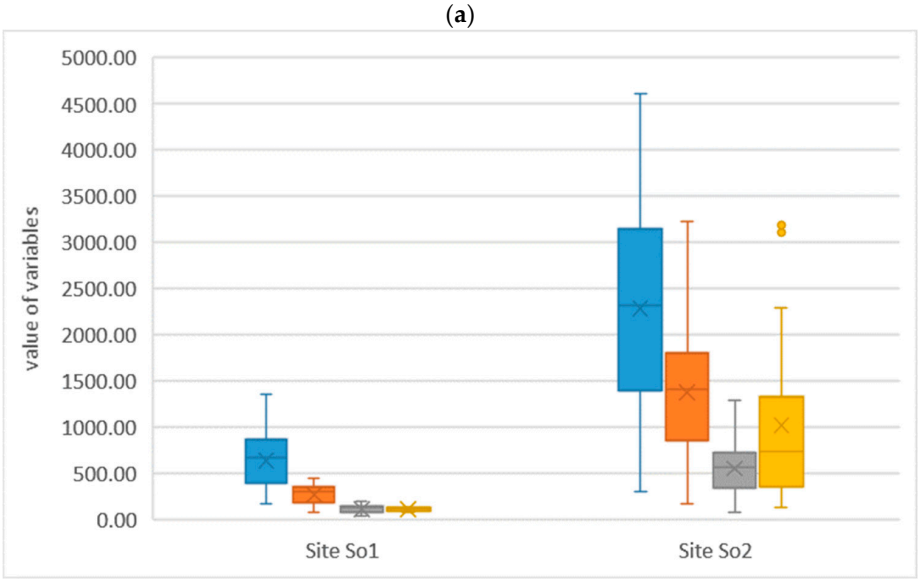
Monitoring Site	-	pH	Conductivity	Dissolved Oxygen	Ammonium Nitrogen $N\text{-}NH_4$	Nitrite Nitrogen $N\text{-}NO_2$	Nitrate Nitrogen $N\text{-}NO_3$	Total Nitrogen—N-tot	Orthophosphates (as P)—PO_4-P	Total Phosphorus (as P)—P-tot
	-	-	µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Monitoring site So1	min for the period 2013–2022	7	160	4.2	0.005 *	0.003 *	0.26	0.5 *	0.0165 *	0.097
	max for the period 2013–2022	8.4	1354	14.8	0.46	0.057	2.7	3.5	0.05	0.21
	mean for the period 2013–2022	7.79	637	7.84	0.1	0.0176	1.06	1.72	0.06	0.092
	measured in 2023	7.74	237	5.79	0.13	0.053	1.6	2.15	0.0276	0.0417
	measured in 2024	7.51	824	6.03	0.06	0.006	1.2	1.8	0.068	0.1
Monitoring site So2	min for the period 2013–2022	6.8	297	2.2	0.005 *	0.005	0.204	0.6	0.003 *	0.004 *
	max for the period 2013–2022	8.6	4610	15.3	0.81	0.52	3.8	7.4	0.112	0.24
	mean for the period 2013–2022	7.8	2282	8.47	0.21	0.095	1.84	2.65	0.0324	0.0725
	measured in 2023	7.26	297	7.93	0.2	0.128	3.4	3.72	0.0947	0.103
	measured in 2024	7.61	1636	7.4	0.005	0.005	1.52	2.21	0.091	0.14

Notes: *—the obtained monitoring result is below LoQ, so the applied value is calculated as 1/2 of LoQ; blue—high ecological status; green—good ecological status; yellow—moderate ecological status.

Conductivity at site So2 was consistently several times higher than at So1 throughout the studied period. The greatest difference (3.58 times higher in So2) in the mean conductivity between the two sites was observed for the period 2013–2022,. Similarly, the concentrations of SO_4^{2-}, $CaCO_3$ and Ca at site So2 exceeded several times those at site So1 across all periods and years of the study (Figure 3a,b). Significant difference in the concentration of SO_4^{2-} was observed between the maximum (25.3 times) and mean values (9.63 times) at site So2 compared to So1. The same pattern was for $CaCO_3$ and Ca, with values at So2 7.34 times higher than at So1. between the specified periods. Comparison of SO_4^{2-}, $CaCO_3$, and Ca in 2023 and 2024 showed the same trend, although at lower concentrations (Figure 3a,b).



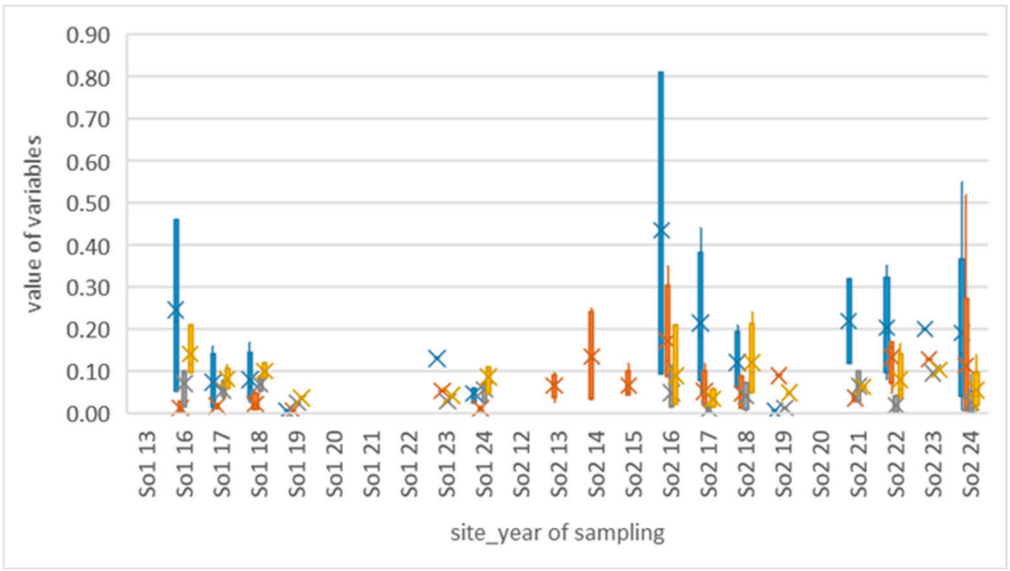
(**a**)



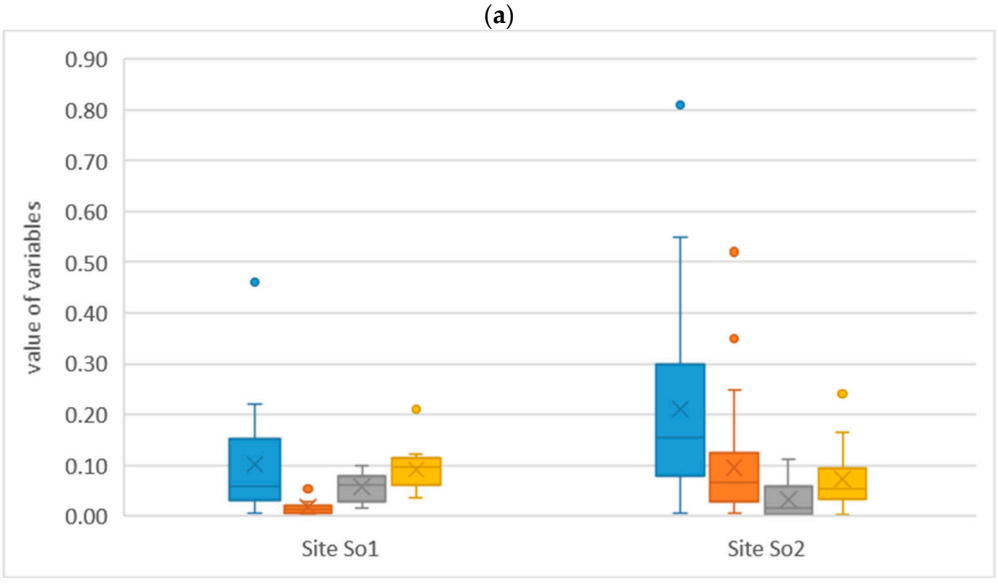
(**b**)

Figure 3. (**a**) Results for conductivity, calcium carbonate hardness ($CaCO_3$), calcium (Ca), and sulfates (SO_4^{2-}) at sites So1 and So2 for the period 2013–2022 and sampling from 2023 to 2024. Legend: So1 13—results for site So1 in 2013; So2 24—results for site So2 in 2024; blue boxes—conductivity, µS/cm; red boxes—calcium carbonate hardness, mg $CaCO_3$/L; gray boxes—calcium, mg/L; yellow boxes—sulfates, mg/L. (**b**) Summarized results for conductivity, calcium carbonate hardness $CaCO_3$, calcium Ca and sulfates SO_4^{2-} at sites So1 and So2 for the period 2013–2022 and the sampling from 2023 to 2024. Legend: Blue boxes—conductivity, µS/cm; red boxes—calcium carbonate hardness, mg $CaCO_3$/L; gray boxes—calcium, mg/L; yellow boxes—sulfates, mg/L.

The maximum and mean values of N-NH_4 registered at site So2 exceeded those at So1 for the period 2013–2022 and in 2023 (Figure 4a,b), with the largest ratio between the mean values in both sites recorded for the period 2013–2022 (2.1 times). The maximum and the mean N-NO_2 values for the period 2013–2022 and the one measured in 2023 at site So2 were several times the values at site So1 (Figure 5). In 2024, however, N-NO_2 at So1 was slightly higher, although the values at the two sites were nearly equal. During 2013–2022, the minimum, maximum, and mean P-tot values, together with the minimum and mean PO_4-P values, were markedly higher at So1 than at So2 (Figure 4a,b).

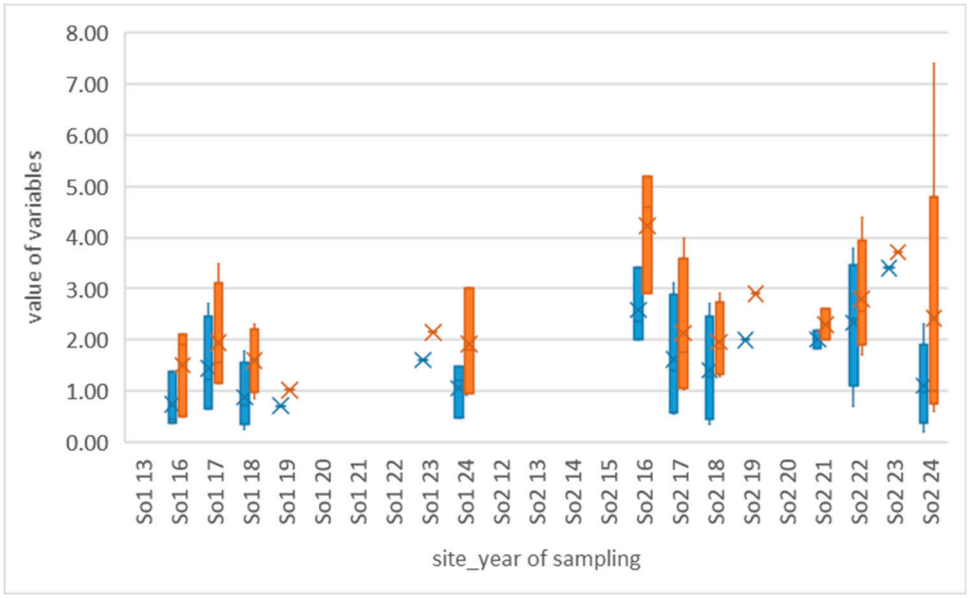


(**a**)

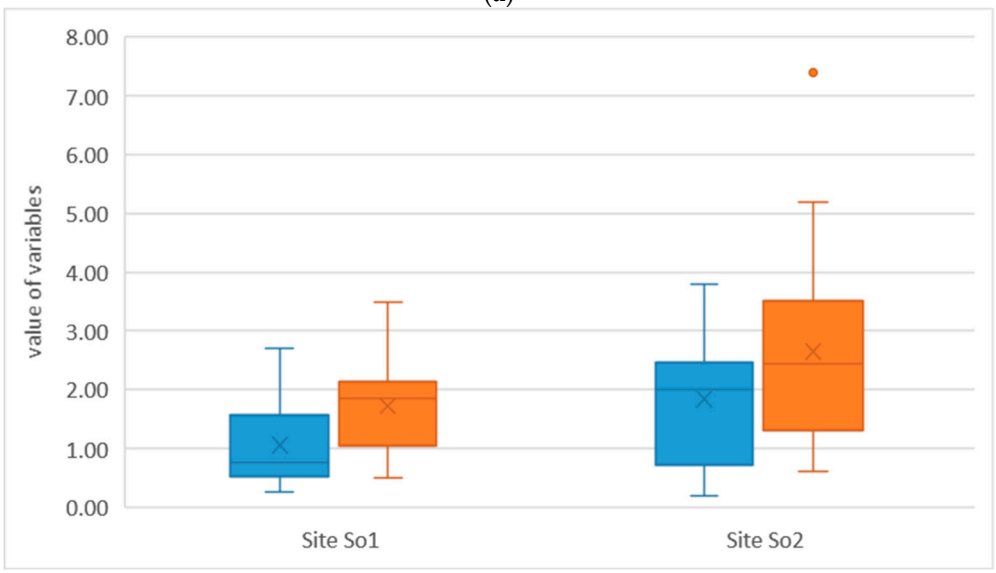


(**b**)

Figure 4. (**a**) Results for ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, orthophosphates (as P), total phosphorus (as P) at sites So1 and So2 for the period 2013–2022 and the sampling from 2023 to 2024. Legend: So1 13—results for site So1 in 2013; So2 24—results for site So2 in 2024; blue boxes—ammonium nitrogen, mg/L; red boxes—nitrite nitrogen, mg/L; gray boxes—orthophosphates (as P), mg/L; yellow boxes—total phosphorus (as P), mg/L. (**b**) Summarized results for ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, orthophosphates (as P), total phosphorus (as P) at sites So1 and So2 for the period 2013–2022 and the sampling from 2023 to 2024. Legend: Blue boxes—ammonium nitrogen, mg/L; red boxes—nitrite nitrogen, mg/L; gray boxes—orthophosphates (as P), mg/L; yellow boxes—total phosphorus (as P), mg/L.



(**a**)



(**b**)

Figure 5. (**a**) Results for nitrate nitrogen and total nitrogen at sites So1 and So2 for the period 2013–2022 and the sampling from 2023 to 2024. Legend: So1 13—results for site So1 in 2013; So2 24—results for site So2 in 2024; blue boxes—nitrate nitrogen, mg/L; red boxes—total nitrogen, mg/L. (**b**) Summarized results for nitrate nitrogen and total nitrogen at sites So1 and So2 for the period 2013–2022 and the sampling from 2023 to 2024. Legend: Blue boxes—nitrate nitrogen, mg/L; red boxes—total nitrogen, mg/L.

The values of N-NO_3 and N-tot at site So2 were consistently higher than at So1 throughout all the periods of the study (Figure 5a,b). The largest difference (2.13 times) in N-NO_3 between sites So2 and So1 was recorded in 2023, followed by the period 2013–2022 (1.74 times). The most significant discrepancy (2.11 times) of N-tot values between sites So2 and So1 was registered with the maximum values for the period 2013–2022, followed by 2023 (1.73 times) (Figure 5a,b).

3.2. Results for BQE Phytobenthos

A total of 136 diatom taxa were identified, 52 of which were above 1% relative abundance in at least one of the samples. Both sites showed a predominance of tolerant and

halophilic species, e.g., *Nanofrustulum* cf. *neoellipticum*, *Diadesmis confervacea*, *Planothidium delicatulum*, *Bacillaria paxillifera*, *Tabularia fasciculata*, *Nitzscia amphibia* and others, most evident in the samples from 2024.

The RELATE test showed that the distribution of the diatom taxa could not be explained by the values of environmental variables measured at the two sites (Rho = −0.771, significance level = 0.956) (Table 4).

Table 4. Values of the diatom index IPS, normalized ecological quality ratio nEQR and the class ecological status for BQE phytobenthos.

Monitoring Site	So1 2019	So1 2023	So1 2024	So2 2022	So2 2023	So2 2024
IPS/20	12.8	12.6	7.9	10.8	9.7	3.9
nEQR	0.64	0.63	0.395	0.54	0.485	0.195
Ecological status (R13):	Moderate	Moderate	Poor	Moderate	Moderate	Bad

The diatom metric IPS ranged from Moderate to Bad ecological status, worsening during the studied years at both sites. At the unaffected site (So1), the status in 2019 and 2023 falls within the upper range of the Moderate ES; however, in 2024, it reaches Poor ES. In contrast, the affected site (So2) exhibits a consistent downward trend. Although it maintained a Moderate ES (in the lower range) in 2022 and 2023, a significant deterioration is observed in 2024, when the status falls to the worst category—Bad ES (Table 4, Figure 6). The mean species richness at So1 (65 taxa) was substantially higher than at So2 (35), representing an approximate 46% reduction at the site downstream. Similarly, Shannon diversity was higher at So1 (=3.6) compared to So 2 (=3.1), indicating greater taxonomic richness and more even distribution of the present taxa upstream.

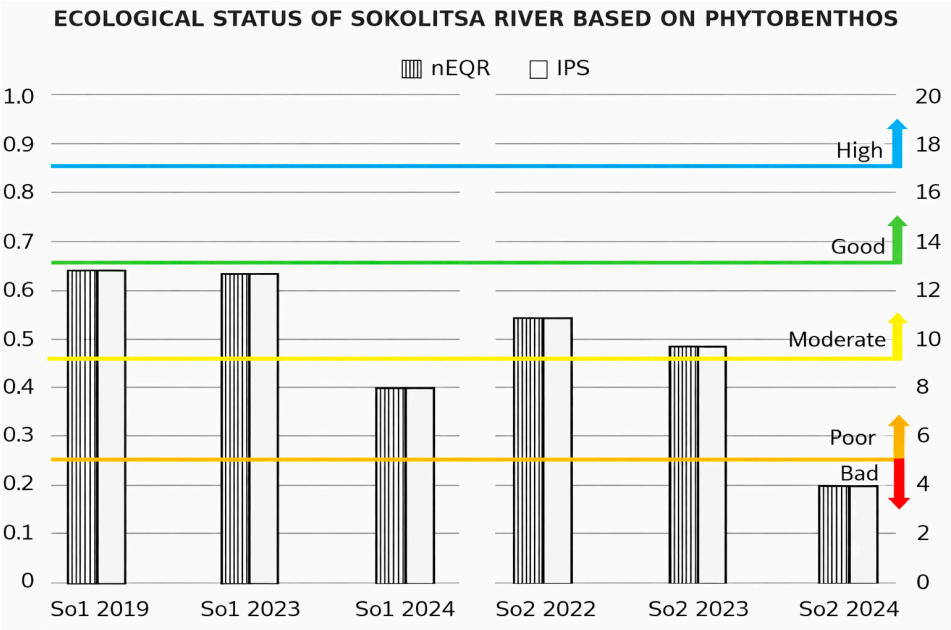


Figure 6. Ecological status based on BQE phytobenthos for sites So1 and So2.

3.3. Results for BQE Macrozoobenthos

A total of 55 macroinvertebrate taxa of the main taxonomic groups Oligochaeta, Gastropoda, Bivalvia, Hydracarina, Crustacea, Ephemeroptera, Odonata, Coleoptera, Hemiptera, Trichoptera, Megaloptera, Chironomidae and Diptera varia (Diptera families except Chironomidae) were found in the samples from the two sites—So1 and So2 within the period between the years 2013 and 2024. The total number of taxa found at So1 for all sampling years was 45 and at So2—41.

The values on the Shannon–Wiener Index at So1 varied between 2.016 and 1.374 and at So2 between 1.676 and 0.595 (Figure 7). Most of the samples at So2 had considerably lower values on the index than those at So1, indicating a more disturbed structure of the community.

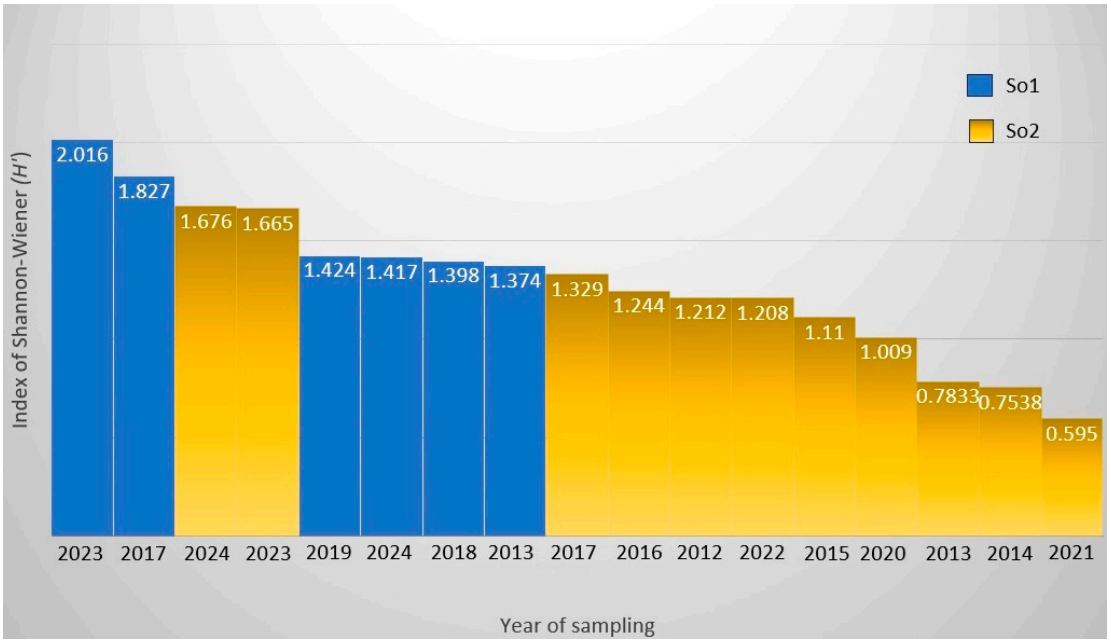


Figure 7. Shannon–Wiener Diversity Index of macrozoobenthic samples at sites So1 and So2 during all studied years.

The comparison of the abundance of the main taxonomic groups which belong to the primary aquatic invertebrates for the whole studied period showed that crustaceans had a higher abundance at So1, while oligochaetes and gastropods had a higher abundance at So2 (Figure 8a). Macrozoobenthos of the secondary aquatic invertebrates are characterized by a higher abundance of mayflies, true water bugs, caddis flies and the larvae of non-biting midges (Chironomidae) at So1, while at So2 dragonflies, water beetles, megalopterans and the larvae of insects other than Chironomidae dipterans prevailed (Figure 8b).

The distribution of macroinvertebrate communities at the two sampling sites during the studied years was influenced by the physical and chemical variables water temperature, pH, conductivity and dissolved oxygen concentrations as shown by the RELATE test with a level of significance $p = 0.002$ and rank correlation coefficient Rho = 0.225. The most important prove to be pH and oxygen content, followed by conductivity (BEST analysis, $p = 0.01$). Nevertheless, the correlation was considerably lower (Rho = 0.461) and the percentage of data explained by the values of the environmental variables was also low (0.381).

The taxa composition and abundance differed between the two sampling sites (So1 and So2) in relation to the environmental variables, forming two clusters (Figure 9). As noted above, the values of water temperature, oxygen concentration and conductivity (Figures 2 and 3) were higher at So2 compared to So1, while those for pH did not differ significantly between the studied sites (Figure 2).

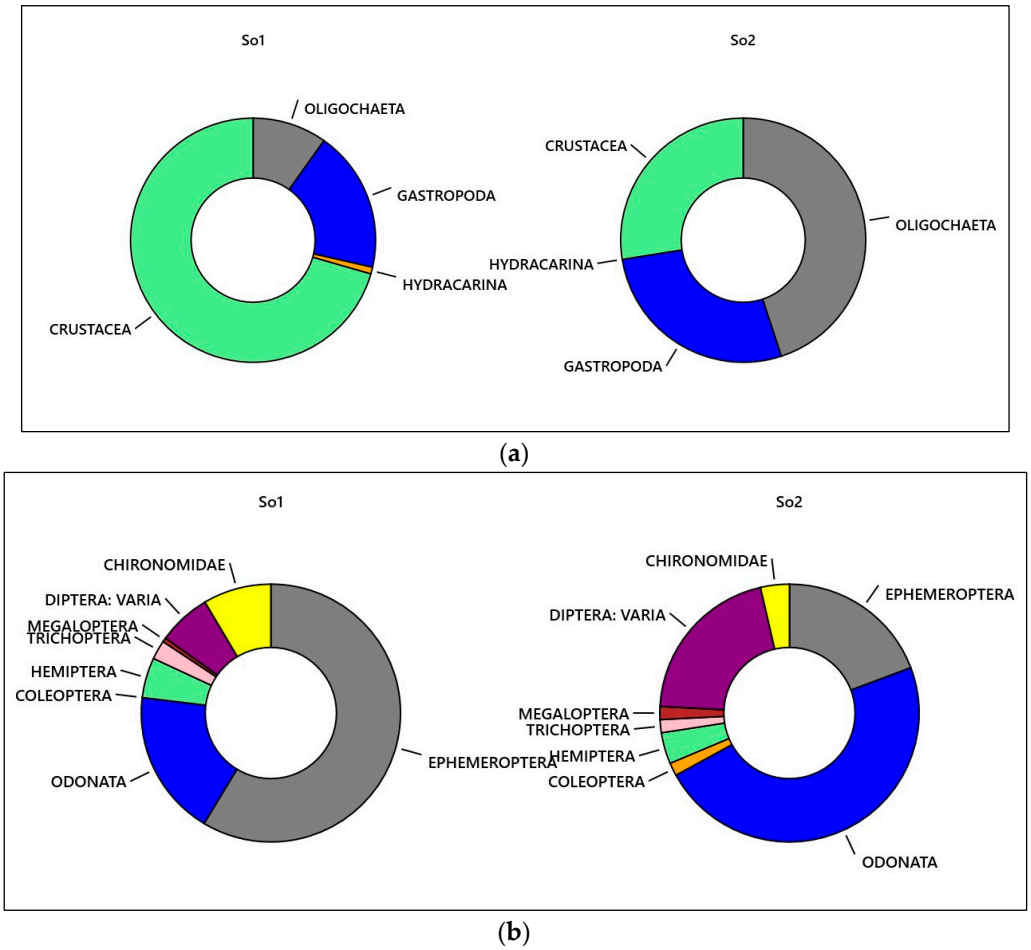


Figure 8. (**a**) Abundance of the main taxonomic groups of primary aquatic invertebrates for the whole studied period at sampling sites So1 and So2. (**b**) Abundance of the main taxonomic groups of secondary aquatic invertebrates for the whole studied period at sampling sites So1 and So2.

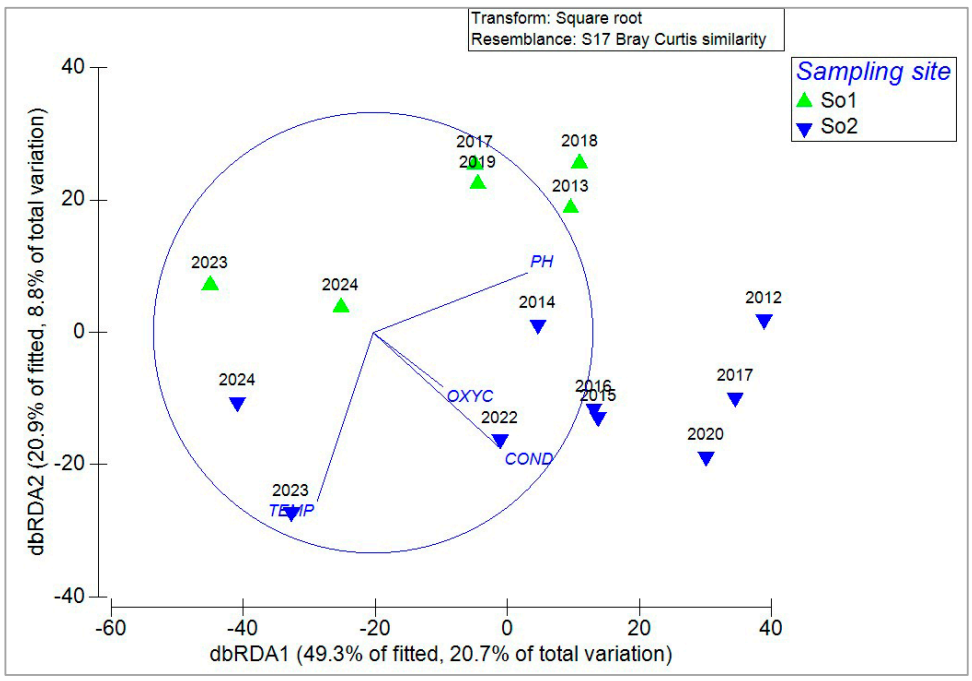


Figure 9. dbRDA plot of the composition and abundance of macroinvertebrates at So1 and So2 and measured environmental variables during the studied years.

The assessments of the ecological status by BQE macrozoobenthos at sites So1 (unaffected by the CFPP) and So2 (affected by the CFPP) (Figures 10 and 11) showed that most of the samples from the studied sites during all observed years fall into Moderate ES. Site So1 falls into Poor ES in 2019 and High ES in 2023. Site So2 falls into Poor ES in 2020, 2021 and 2023. When comparing the samples in Moderate ES at the two sites (So1 and So2), the nEQR of samples at So1 in most of the cases exceeds the lower boundary of the class, while at So2 it falls toward the very lower limit. Additionally, the only sample in High ES was found to be from So1 and from the three samples in Bad ES, two are found to be from So2.

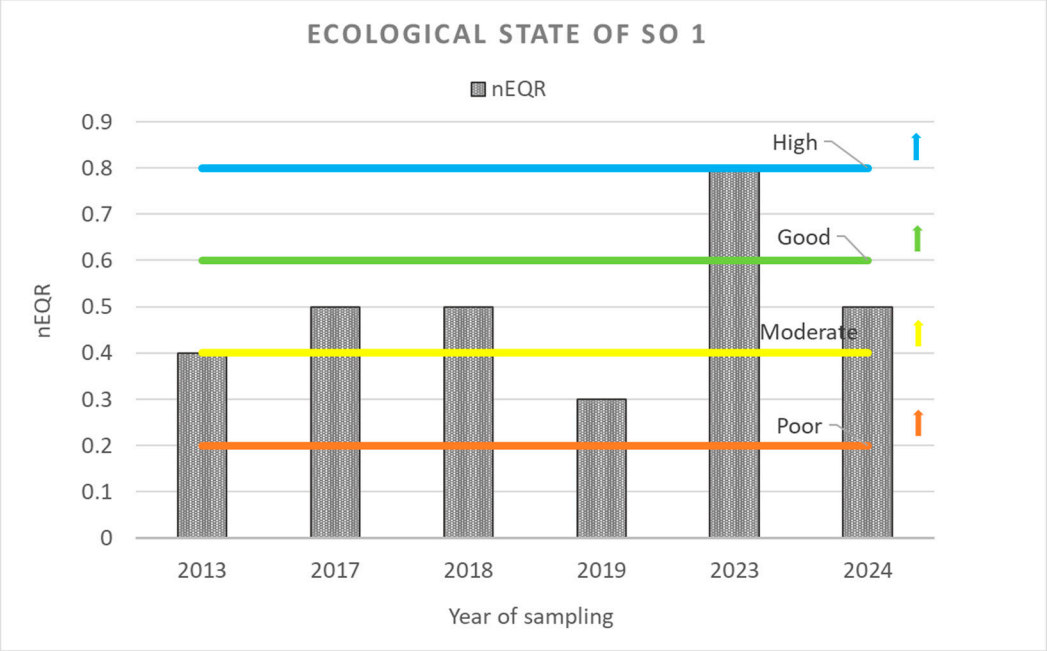


Figure 10. Assessment of the ecological status based on BQE macrozoobenthos in the studied site So1 (unaffected by CFPP).

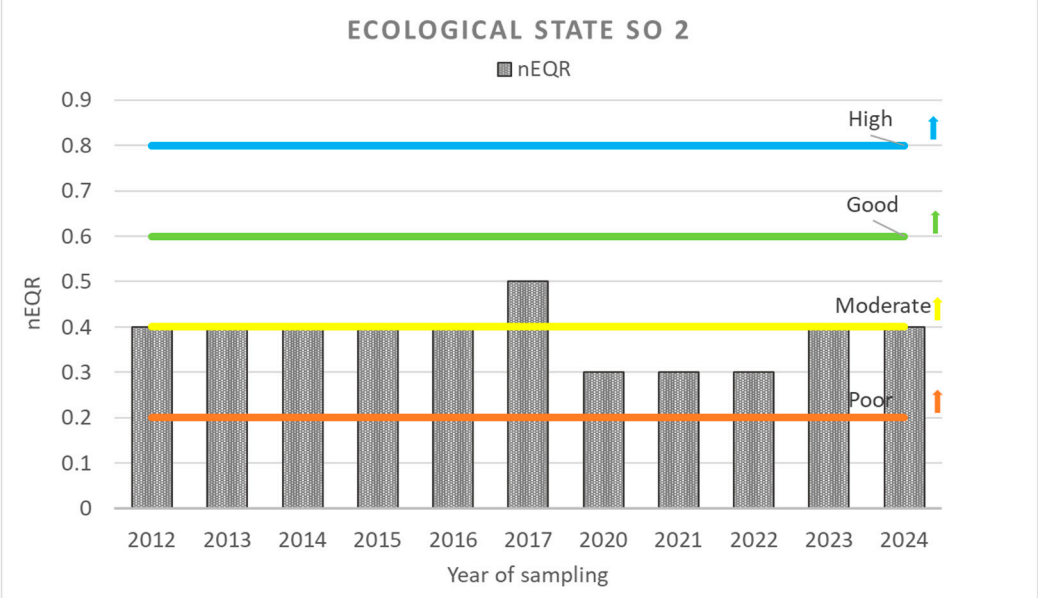


Figure 11. Assessment of the ecological status based on BQE macrozoobenthos in the studied site So2 (affected by CFPP).

4. Discussion

The CFPP's activities substantially increased the values of the studied physicochemical variables in the site So2, located downstream of the CFPP facilities in the Sokolitsa River catchment. The suitability of the aquatic habitat at this site is markedly altered, causing adverse effects on the growth and reproduction of aquatic organisms and on the structure and composition of the phytobenthic and macrozoobenthic communities.

4.1. Environmental Variables

The observed higher values of most physicochemical variables at the CFPP-affected site, including conductivity, N-NH_4 (except for 2024), N-NO_2 (except for 2024), N-tot, SO_4^{2-}, $CaCO_3$ and Ca, indicate degradation of the aquatic ecosystem structure and function relative to the unaffected site. The elevated conductivity reflects an influx of dissolved salts (common in CFPP fly ash and wastewater). It generates osmotic stress on aquatic organisms, potentially leading to the loss of sensitive species and reduced biodiversity [67,68]. The significantly elevated $CaCO_3$ values in the So2 site may alter the ionic balance and alkalinity of the water, disrupt the physiological processes of aquatic organisms, and modify the habitat structure through mineral precipitation, potentially changing the composition of the bottom substrate inhabited by the benthic communities. Water hardness, expressed as $CaCO_3$ (mg/L), is an important limiting factor in the aquatic environment. Calcium, a major component of water hardness, plays a key role in the physiological function and shell formation of aquatic organisms, although excessive concentrations can harm them. Calcium also affects membrane permeability, which is essential for the successful embryonic development of fish [69,70]. Wastewater discharged from CFPPs into rivers may contain high amounts of sulfates, which are a by-product of the flue gas cleaning processes during coal combustion (flue gas desulfurization (FGD) effluents). The impact of elevated sulfate concentrations on the structure and functioning of river ecosystems has not yet been sufficiently studied. The available scientific research demonstrates that sulfate pollution may have toxic effects on aquatic plants and animals, including fish, invertebrates and amphibians [71,72]. Among the most sensitive species reported to date is the cladoceran *Ceriodaphnia dubia*, with the effective concentration (EC10) of 137 mg/L [73]. Sulfates may cause osmotic stress and ion-specific toxicity in aquatic organisms, particularly in soft waters with low Ca^{2+} and Mg^{2+} concentrations [73–75]. The limited evidence on their ecological effects may partly explain why sulfates have not yet been widely regulated as river basin-specific pollutants (RBSPs) in most EU Member States [76–78]. Similar quality standards have not been established in Bulgaria either [33]. Data on the adverse effects of CFPPs on water quality have been reported by other authors [79,80]. The most pronounced increases in the physicochemical variables at the impacted site, So2, relative to So1 were observed during 2013–2022. Results for SO_4^{2-}, $CaCO_3$, and Ca in 2023 and 2024 demonstrated a similar pattern, although at lower concentrations, possibly reflecting the reduced operating capacity of the CFPP in recent years. During the study period, several exceptions were observed in which values at site So1 exceeded those at So2. For example, PO_4-P and total phosphorus were higher at So1, possibly due to more intensive soil erosion and associated phosphorus input in the higher-altitude catchment area of this site [81,82].

The higher N-NH_4 value at site So1 in 2024, compared with So2, may be explained by the nearly dry conditions of the Sokolitsa River at So1 during sampling, characterized by low flow and the formation of intermittently drying pools due to prolonged summer drought. In contrast, permanent flow was observed at site So2. The slightly higher N-NO_2 concentration at So1 could be explained by the same conditions, as elevated nutrient levels likely reflect the critical low flow, which shifts the river from lotic to lentic conditions and reduces its self-purification capacity [83,84].

The elevated nutrient concentrations at the CFPP-affected site could be attributed to several anthropogenic pressures, including wastewater discharge, diffuse atmospheric deposition of CFPP-related pollutants, and untreated wastewater from the village of Obruchishte.

The discharged wastewater from CFPP scrubbers, machine washing, and bottom ash effluents contain nutrients, alongside other pollutants like heavy metals, which enter the receiving river. To some extent, part of the nutrient pollution at site So2 is due to the diffuse input of CFPP pollutants (NOx, products of coal combustion) into the river's catchment from the atmosphere [85,86]. The US Department of Energy [87], Russell et al. [88] and Crawford et al. [89] have mentioned that atmospheric pollutants deposited in water bodies may potentially have a negative effect on water quality, and subsequently aquatic flora and fauna. In support of this, the modeling of diffuse atmospheric pressure on the surface water body BG3MA200R017, where the CFPP Contour Global Maritsa East 3 facilities are located, presented in the RBMP of EARBD (2022–2027), identified one of the highest NOx loads in the whole Maritsa River Basin (133,900 kg/a) [33]. In addition to the two identified sources of nutrient pollution from the CFPP Contour Global Maritsa East 3, untreated wastewater from the village of Obruchishte is also discharged in the area of site So2, further contributing to the elevated nutrient concentrations. As a result, site So2 is subject to the cumulative effects of three anthropogenic pressure sources. The significant increases in conductivity, calcium carbonate hardness, calcium and sulfates at the site So2 are, likewise, undoubtedly caused by the activity of the CFPP Contour Global Maritsa East 3 facilities.

4.2. BQEs

The effects of the water stress (increased conductivity), reflected on the diatom assemblages in the Sokolitsa River during the studied years, caused changes from freshwater towards mesohalophilic and halotolerant taxa, indicating salinity-driven community shifts under low-water-flow conditions. The diatom community's structure, comprising ion-tolerant taxa, is an indicator of increased levels of electrical conductivity and habitats under water stress. The species composition reflects sustained unfavorable conditions, associated with the industrial discharge and higher ion concentration in critical low flow, especially evident in 2024. The observed taxa tolerate moderate salinity, which suggests a response linked to increased concentrations of dissolved salts and ions in the water, indicating salinization and elevated conductivity-related degradation, which is a key stressor affecting the ecological status. A higher relative abundance of mesohalophilic and halotolerant taxa in the studied communities has also been reported as being indicative of increased salinity in multiple studies [90], which identified a conductivity threshold of approximately 1200 µS/cm, above which the diatom community composition shifts toward ion-tolerant assemblages. Potapova & Charles [91] demonstrated that high values along the $SO_4^{2-}/(HCO_3^- + CO_3^{2-})$ gradient correspond to assemblages dominated by halophilous taxa. Smucker & Vis Charles [92] and Bąk et al. [93] highlighted that coal mining activities can elevate water salinity to marine levels, enabling the colonization by typical halobiont species. Such taxa were not dominant in the Sokolitsa River; however, their presence may reflect episodic pulses of higher salinity associated with industrial discharge, especially during the low-flow season.

According to the updated list of diatom ecological indicator values applied to the taxa above 1% relative abundance, the moisture preferences show that 25% are strictly aquatic, 28% occur mainly in water but occasionally on wet substrates, 33% are regularly found on moist or wet habitats, and 5% typically inhabit moist areas that may dry out temporarily. Regarding pH, 14% of the taxa are circumneutral, while the majority—71%—are alkaliphilous, and 15% are alkalibiontic. Salinity preferences indicate that 64% are freshwater–brackish,

20% brackish–freshwater, 10% brackish, and 6% brackish–marine. In terms of the trophic state, 25% are mesoeutraphentic, 53% eutraphentic, and 12% hypereutraphentic. Based on BQE phytobenthos, both sites were in Moderate ecological status during the studied years, which declined to Poor (So1) and Bad (So2) in 2024. The year 2024 was characterized by significantly lower water levels, which led to reduced dilution capacity and consequently higher concentrations of dissolved salts, ions and other pollutants in the water. This is consistent with other studies in lotic systems, where decreased water flow intensifies the salinization processes [94,95]. The negative trend in 2024 at site So1 is likely due to the increasing environmental pressure of drought and extremely low-water levels, which reduce the river's ability to dilute contaminants, leading to higher concentrations of ions and nutrients; extreme water temperature; low oxygen levels, resulting in processes of ammonification; and other types of local pollution, e.g., wastewater discharge from nearby settlements, which could explain the increased phosphorus levels. All of the above results in low self-purification capacity in the river ecosystem. The concentrations of SO_4^{2-}, $CaCO_3$, and Ca were several times higher at So2 in comparison to So1, which coincides with the degraded ecological conditions downstream, as reflected by the diatom metric IPS. The decline in species richness and diversity at So2 suggests a shift toward less complex and more stress-tolerant assemblages, pointing to environmental disturbance and reduced ecological quality. At site So2 in 2024, the pressures are the strongest, which is most likely linked to the high sulphate and carbonate loading from CFPP activities, the effects of which are amplified by low-flow conditions. Physicochemical conditions and aquatic communities change naturally along the river continuum, as differences registered downstream should not automatically be attributed to coal-related impacts. In our study, the significantly higher conductivity, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^{+}, and Cl^{-} at the impacted site, together with a shift in benthic communities toward dominant ion-tolerant biological assemblages, revealed ecological situations which are not typical for the natural uninfluenced river stretches [93].

The diatom community structure serves as a robust biological indicator of conductivity-related degradation, as reported in other European river systems impacted by industrial activities and reduced flow [93–95], underlining the role of elevated ion content as a key stressor influencing the ecological status.

The development of macroinvertebrate communities under stressful environmental conditions caused by mining activities has been studied in countries across all continents [96–100]. In the territory of Bulgaria there are several operating mining companies and CFPPs, and water bodies affected by their drainage and cooling waters. Nevertheless, their impact on the composition/structure of the macroinvertebrate communities is poorly studied.

The present study showed that the environmental variables, measured at the two sampling sites, shaped the distribution of the macroinvertebrate community. The abundance of Oligochaeta, Gastropoda, Odonata and Diptera varia was higher at site So2, while Crustacea, Ephemeroptera, Hemiptera, Trichoptera and Chironomidae prevailed at site So1. It is noteworthy that the more pollution-tolerant groups Oligochaeta and Diptera varia were found to be more abundant at So2, while those considered as more sensitive—Ephemeroptera and Trichoptera—had a higher abundance at So1.

The representatives of the more sensitive taxa groups, Ephemeroptera and Trichoptera, were negatively influenced by the higher values of water temperature and conductivity at sampling site So2, especially mayflies. Previous studies revealed that increased water temperatures could reduce the number of rarer invertebrate taxa [101] and the diversity of specific functional groups such as 'shredders' [102], as some of the representatives of Ephemeroptera and Trichoptera are. The impact of water temperature can cause significant differences in taxa richness and diversity between heated and unheated sections of the

rivers, as those in the heated section are significantly lower [103]. In such heated sections a striking decrease in Ephemeroptera, Plecoptera, and Trichoptera abundance, taxon richness and diversity could be observed along with a decline in the abundance of grazers and shredders [103].

The elevated conductivity, as a result of mining activities, reflects the presence of a large number of ions in the water, which alters the environmental conditions in an unfavorable way for the development of macroinvertebrates [104–108], resulting in a loss of Ephemeroptera [109] and Trichoptera taxa [92,103]. Additionally, increased salinization especially affects insects by preventing them for completing their life cycles [108].

On the other hand, a high salinity level can favor predators [110] such as the larvae of Odonata, whose abundance is higher at sampling site So2. The tolerance of some families which belong to the orders Diptera, Coleoptera and Odonata [111] to high salinity has also been confirmed by our results, as these orders have higher abundances at sampling site So2. The increased abundance of freshwater snails at sampling site So2 is in accordance with previous studies in which it has been reported that molluscs reach the highest densities in brackish waters [111–113]. Higher quantities of gastropods and bivalves, along with the death and loss of function of other freshwater species in such streams with deteriorated conditions, could also be the cause of an increase in the abundance of more tolerant oligochaete species due to the concentration of large amounts of nutrients in the bottom sediment by molluscs and weak competition for resources [111,114].

Despite elevated values of water temperature and conductivity at So2, pH and oxygen content were found to have higher significance for the development of the community. In our study, pH ranged between 7.26 and 8.1 during the whole studied period. The values of pH in a similar range are found to be a significant factor for the distribution of mayflies and caddis flies [115] and one of the factors explaining a higher species diversity [116]. The oxygen content is essential for the development and distribution of aquatic invertebrates and its low values can be a limiting factor. The concentration of dissolved oxygen at the two sampling sites ranges between the values of 5.79 and 11.22 mg/L; on only two occasions were the values measured as low as 5.79 and 6.03 mg/L. Most of the measured concentrations varied between 7.17 and 11.22 mg/L, which are considered as favorable stream conditions for macroinvertebrates. Even though the importance of elevated water temperatures was discussed already, the oxygen content could have a more direct effect on the development and distribution of macroinvertebrates [117].

Therefore, we suggest that the values for pH and oxygen concentration might act as a stabilizing and structure-determining factor for the development of macroinvertebrates in deteriorated stream conditions.

The ecological assessment of both sampling sites in most cases during different years fall in the “Moderate” class. Nevertheless, the reasons might be different. For example, during the years 2023 and 2024, the water level at So1 was registered as being extremely low, forming an almost lentic ecosystem, while at So2 the water current was continuous. It should be noted, however, that site So1 has slightly higher values of nEQR during all years. With an intermediate level of salinization, other additional environmental factors of an anthropogenic origin could be masked by the salinity, or might interact with it [118–120]. This suggests that other factors—mainly the waters from the operating CFPP—also contribute to the deteriorated stream conditions.

5. Conclusions

The present study highlights the adverse effects of CFPPs on aquatic ecosystems and ecological status. Wastewater discharge from the CFPP Contour Global Maritsa East 3 into the Sokolitsa River adversely altered the characteristics of the aquatic habitat and

affected the structure and taxonomic abundance of the phytobenthos and macrozoobenthos communities. These changes resulted in the ecological deterioration of the lotic ecosystem. The effects were particularly pronounced during the low-flow periods and prolonged drought, when reduced river levels increased the impact of the CFPP-discharged pollutants.

Our study covered a limited number of basic physicochemical variables and biological quality elements. A more comprehensive assessment of CFPP impacts on the river ecosystem requires further long-term investigation, including additional variables, other biological quality elements, and specific pollutants and priority substances in the matrices water, biota, and sediments.

This document presents preliminary results that reveal the absence of regulated permissible values of pollutants from CFPP operations entering surface and groundwater. There is a need to review and expand the regulated pollutants in the IPPS (Integrated Pollution Prevention and Control) permits of CFPPs, for which individual emission limits in discharged wastewater are set as an administrative tool for monitoring and control. Further research on the impacts of mining activities on adjacent water bodies is also needed in the context of the challenges associated with the sustainable transition to clean energy, while taking into account the country's economic and social realities in determining the timeline and approach for CFPP closure.

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