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The Effects of Hydropower Plants on the Physicochemical Parameters of the Bystrzyca River in Poland

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Abstract: Currently, the literature lacks comprehensive studies on the impact of hydropower plants (HPs) on the environment, including studies focused on the physicochemical parameters of water. The aim of the article is to verify the current state of knowledge on the impact of run-of-river HPs on 17 physicochemical parameters of water. The article is in line with the recommendations of the European Union that the member states, under the common energy policy, should increase the share of renewable energy sources in the energy and perform environmental impact assessments of such facilities. As a result of the analysis carried out on three HPs (Sadowice, Skałka and Marszowice) located on the Bystrzyca River (a tributary of the Odra River in Poland), it was found that HPs affect the selected physicochemical parameters of the water, i.e., ($p < 0.05$): electrolytic conductivity (EC; Skałka, Marszowice HPs), pH (Skałka, Marszowice HPs); nitrate nitrogen (NO_3-N; Marszowice HP), dissolved oxygen (DO; Marszowice HP) and ammonium nitrogen (NH_4-N; Marszowice HP). The largest (>5%), statistically significant mean cumulative effect below Marszowice HP concerned NH_4-N (−27.83%), DO (+14.04%) and NO_3-N (+5.50%). In addition, it was observed that the effect of HPs increases in direct proportion to the damming height, and that run-of-river HPs have a lesser impact on the physicochemical parameters' values than in storage HPs. Our results were in accordance with those of other scientists in terms of the increase in DO, the decrease in EC, and the decrease in total phosphorus concentrations below HPs.

Keywords: hydropower plants; physicochemical parameters; water quality; renewable energy sources; environmental impacts; sustainable development; energy policy

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Citation: Tomczyk, P.; Wiatkowski, M. The Effects of Hydropower Plants on the Physicochemical Parameters of the Bystrzyca River in Poland. *Energies* **2021**, *14*, 2075. https://doi.org/10.3390/en14082075

Academic Editor: Nikolaos P. Theodossiou

Received: 12 February 2021
Accepted: 5 April 2021
Published: 8 April 2021

1. Introduction

The demand for hydropower will increase due to the search for renewable energy sources. It is estimated that, within 40 years, the share of hydropower will increase to 50% (currently being 15.6% of installed capacity) [1]. The current hydropower potential is 51.677 TWh per year, 48% of which is in Asia (South America—19%, Africa—15%, North America—13%, Europe—4%, Australia and Oceania—1%) [2]. In 2019, the most electricity from hydropower plants (HPs) per person was used by Iceland (40.087 kWh), Norway (24.411 kWh), Canada (10.088 kWh), Bhutan (9.991 kWh), and Paraguay (8.482 kWh), respectively [3]. In addition, there was an increase in installed capacity of HPs by 1.2% compared to the previous year, with the newest installed capacity corresponding to Brazil (4919 MW), China (4170 MW), and Laos (1892 MW) [4]. The development of hydropower is influenced by natural, social, and economic factors, as well as the hydropower potential of various regions (economic profitability and technical feasibility) and climate change [5–7].

Research on the influence of HPs on individual elements of the environment has been carried out by several scientists. The main focus was on impacts on aquatic organisms (mainly ichthyofauna and invertebrates) and the functioning of water-related ecosystems [8–13], hydrological conditions below damming structures [14–17], transport and composition of bottom sediments, accumulation and erosion processes [18–21], hydromorphological conditions [22–26], water quality [27–30], and social and economic issues [31–36].

When locating new projects in the field of hydropower, it is important to remember to minimize potential impacts [37]. Such methods are, for example, fish ladders to keep rivers open for aquatic organisms [38,39], but also to take into account environmental flows related to the quality, quantity and timing of freshwater flows necessary to maintain the balance of aquatic ecosystems, which in turn provide important ecosystem services [16,40–42]. Including such solutions is important both in documents regulating the operation of HPs, as well as in international environmental policies [5,43,44]. This is for the rational use of environmental resources, in accordance with the principles of sustainable development [11,45,46].

The main emphasis in this article is on the study of physicochemical elements that make up water quality. Previous analyses by scientists in this area, however, usually concerned HPs established on water reservoirs, and not run-of-the-river power plants (e.g., [47–50]) or dams only, without HPs (e.g., [51–55]). The influence of run-of-river HPs on the physicochemical parameters of water was investigated, for example, in Spain [56,57] and Brazil [58]. Therefore, it is a still undiscovered topic that allows for the performance of a series of new analyses and the determination of trends in changes in these parameters.

So far, in terms of changes in the physicochemical parameters of water within HPs, regardless of their type, the following phenomena have been distinguished: supersaturation, changes in thermal conditions, oxygenation and turbidity, phosphorus remobilization, reductions in some minerals, and trophic changes [30,59].

As a result of research conducted so far on the operation of HPs, below the structure, the phenomenon of hydraulic recoil is noticeable, i.e., the formation of rotary motion as a result of a significant increase in the flow velocity (caused by the difference in the damming height) [60]. This phenomenon causes the mixing of water masses and changes in water stratification, which is intensified especially in the case of the location of HPs in front of water reservoirs or in water reservoirs located in a cascade [61,62]. The phenomenon of hydraulic jump, combined with the discharge of water from turbines, is responsible for changes in thermal conditions, oxygenation, phosphorus remobilization, and reductions in mineral compounds [59]. Changes in thermal conditions concern reductions in temperature amplitudes in rivers below the HP and in reservoirs, where there is usually a lower temperature and disturbance of thermal stratification (especially in tropical zones) [63–65]. In stratified reservoirs, anaerobic, lower layers of water are activated, which deteriorates the aerobic conditions; such a phenomenon is not noted in rivers, where, due to the vortex movement, oxygenation may be even higher than above HPs [66]. Additionally, in reservoirs, there is the release of phosphorus from the lower layers of waters, responsible for the phenomenon of eutrophication, as well as the release of toxic hydrogen sulphide [67]. The combination of lower temperature, lower oxygen content, and the activation of phosphorus and hydrogen sulphide causes deterioration of habitat conditions for organisms found in reservoirs below HPs [68,69]. It can be concluded that, so far, in the case of rivers, this impact is ambiguous.

The second phenomenon influencing the changes in the physicochemical parameters of water is the accumulation of bottom sediments on dams and above HPs [70]. This is due to the slowing down of the water flow velocity and, consequently, a reduction in the rivers' ability to transport sediment. As a result of this phenomenon, there are changes in water turbidity and trophic changes within hydropower structures. For example, it is estimated that about 15% of the river phosphorus load is above dams [71], which causes large changes in the conditions for aquatic life and the functioning of water-related ecosystems, as well as the processes of accumulation and erosion of the river below hydropower [72,73].

A separate issue is the phenomenon of supersaturation, occurring mainly in HPs located in a cascade of water reservoirs. This happens when flood waters circulate and large amounts of water are discharged between reservoirs, which causes a rapid increase in thehydrodynamic pressure (higher than atmospheric) and the saturation of water with oxygen up to the limit of solubility [74]. As a result of these changes, caused by the pursuit of pressure equilibrium between the centres, air bubbles appear. This has a major impact on aquatic organisms, which can die off massively due to the rapid change in blood pressure caused by escaping bubbles, blocking blood vessels (bubble disease, barotrauma) [75]. With regard to the physical chemistry of water, the phenomenon of supersaturation may be accompanied by an increase in the concentration of dissolved elements, mainly aluminium, iron, cobalt, and titanium [76].

The aim of this article is to verify the current state of knowledge on the impact of run-of-river HPs located on the Bystrzyca River (a tributary of the Odra River located in southwestern Poland) on the physicochemical parameters (oxygen conditions, nutrients and minerals, physical parameters) of the waters. The relationships between individual water quality parameters, types, and specificity of HPs (depending on their damming height and whether they are run-of-river or storage) were also analysed in detail. Another variable which took into account in this case is the location of hydropower structures in natural or human-transformed areas. So far, no comprehensive research has been conducted on the impact of run-of-river HPs on the physicochemical conditions of water. In addition, such analyzes did not take into account other factors that may have a potential impact on the variability of physicochemical parameters (e.g., socio-economic issues or other environmental impacts).

2. Materials and Methods

2.1. Field Studies

The research was carried out on the Bystrzyca River, located in Central Europe, in south-western Poland (Dolnośląskie Voivodeship). The Bystrzyca River is a tributary of the Odra River; it is 101.5 km long, and its catchment area is 1768 km^2. It has a lowland character. The field studies took into account the lower course of the river from the town of Kamionna to the mouth of the river in the city of Wrocław (the total length of the research section is over 32 kilometres), diversified in terms of land use (forests, meadows, fields, and urbanized areas). In part of the studied area, there are areas of nature protection, i.e., from point 1 to 10 the research area is located in the Bystrzyca Valley ("Dolina Bystrzycy") Landscape Park, from point 2 to 10 in the Natura 2000 area "Łęgi nad Bystrzycą" (PLH020103), and in point 1 in the Natura 2000 area "Przeplatki nad Bystrzycą" (PLH020055) [11,26,77,78]. The locations of the measurement and control points are shown in Figure 1, and a detailed summary is given in Table 1.

Laboratory field tests of water quality were carried out over a three-year period, with a monthly frequency, at 12 measuring points within three barrages with HPs. The criterion for selecting the points was the location in relation to the tested HPs—about 50 m above and 50 m below hydropower facilities, as well as in areas remote from the power plant, treated as reference points (the frequency and placement of points was based on the subject literature and various legal acts, e.g., the Water Framework Directive) [28,38,79,80]. The analyses also used five research points at which analyses were performed as part of the national water quality monitoring (1970–2018; the frequency of tests differed at various points; data obtained from the Provincial Inspectorate for Environmental Protection in Wrocław and the State Archives in Wrocław from the archives of the Environmental Research and Control in Wrocław) [81]. Technical data on HPs come from documents obtained from the State Water Management Polish Waters Regional Water Management Authority in Wrocław [82].

Three research objects were selected for the analyses, i.e., the Marszowice, Skałka, and Sadowice HPs on the Bystrzyca River. All of them are located in the riverbed (run-of-river HPs), including two in the created artificial derivative canals (Marszowice and Skałka HPs). All of them are low power (less than 5 MW), low damming (less than 5 m) hydroelectric plants with no fish passes. All of them were built about 100 years ago. Technical details of the described hydropower facilities are presented in Table 2, and photos of the facilities are shown in Figure 2.

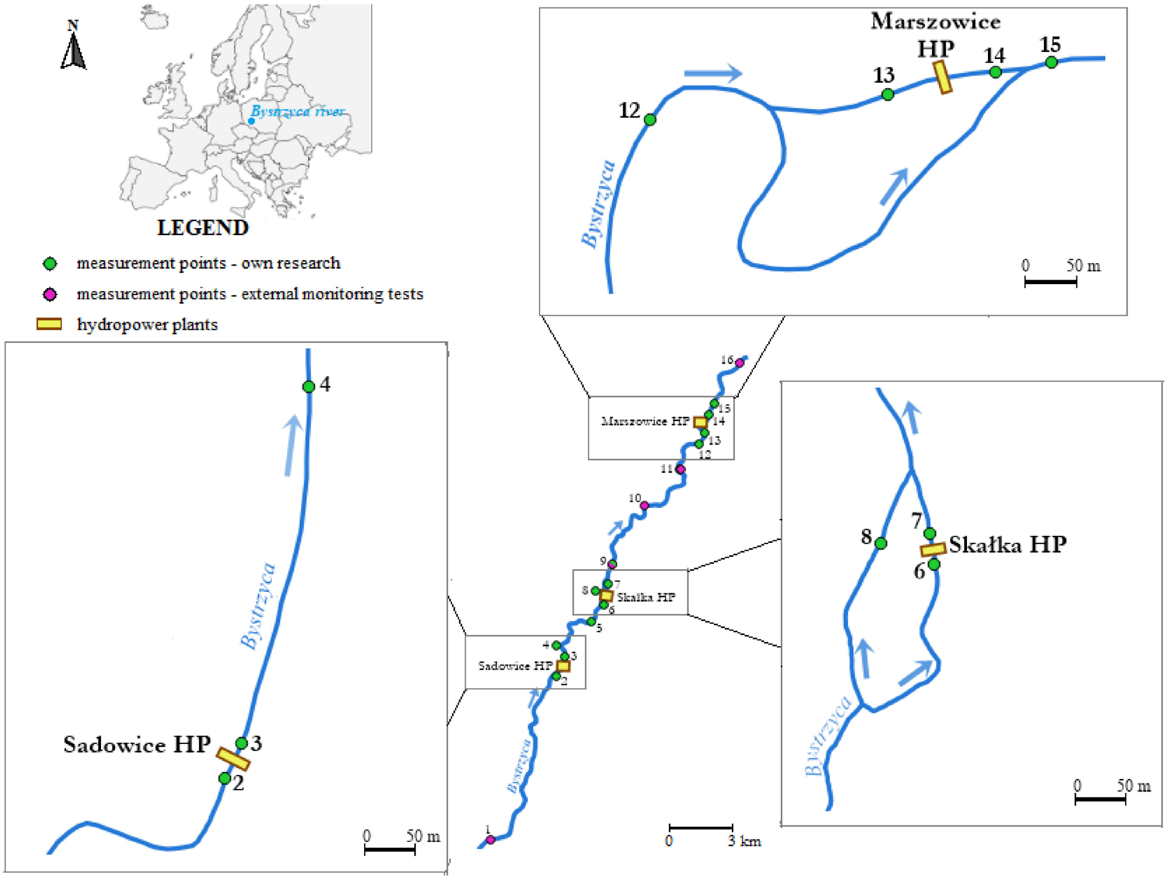

Figure 1. Location of research points and facilities, Bystrzyca River, Poland.

Table 1. List of test points for physicochemical elements on the Bystrzyca River [81].

Point No.	Name of the Point	River km *	This Research	External Tests	Research Period
1 W	Bystrzyca River above Czarna Woda River (Kamionna)	33.5		X	1975, 1981–1983, 2012, 2015
2	Sadowice hydropower plant (point above HP)	26.15	X		06.2018 –05.2020
3	Sadowice hydropower plant (point below HP)	26.05	X		
4	Sadowice hydropower plant (reference point)	25.95	X		
5	Małkowice—reference point	22.2	X		
6	Skałka hydropower plant (point above HP)	20.05	X		
7	Skałka hydropower plant (point below HP)	19.95	X		
8	Bystrzyca river next to Skałka HP—a natural bed	20.0	X		
9	Bystrzyca above Strzegomka River (Samotwór)				
9 W	Bystrzyca above Strzegomka River (Samotwór)	17.9	X	X	1975–2003 **, 2018
10 W	Bystrzyca below Strzegomka River (Jarnołtów)	14.8		X	1975–2006 **
11 W	Bystrzyca below Leśnica	7.7		X	1975–1989
12	Bystrzyca above the division into a HP canal and a natural bed	4.15	X		06.2018 –05.2020
13	Marszowice hydropower plant (point above HP)	4.05	X		06.2017 –05.2020
14	Marszowice hydropower plant (point below HP)	3.95	X		
15	Marszowice hydropower plant (reference point)	3.85	X		
16 W	Bystrzyca—estuary to the Odra River (Janówek)	1.2		X	1975–2008 **, 2013, 2018

* counted from the mouth to the spring of the river; ** without 1990 and 1991.

Table 2. Characteristics of research facilities described in the article [82].

Name of the HP	River	River Length (km)	Type of HP	Generation (MW)	Type of Turbine	Year of Construction	Fish Ladder	Damming Height (m)
Marszowice (in Wrocław)	Bystrzyca	4400	run-of-river *	0.385	Francis	1912	N	3.75
Skałka	Bystrzyca	19,982	run-of-river *	0.07	Kaplan	before 1939	N	2.2
Sadowice	Bystrzyca	26,050	run-of-river	0.06	Francis	1921	N	1.8

* located in the diversion channel.

Figure 2. Research facilities (from left): Marszowice, Skałka, and Sadowice hydropower plants.

2.2. Laboratory Tests

Water samples for field water quality tests were collected with scoops, which were then transferred to plastic bottles and transported in refrigerators to the Environmental Research Laboratory of the University of Life Sciences in Wrocław (Poland). Laboratory analyses were performed up to 24 h after water sampling, using the standard methods listed in Table 3. In the authors' own research, 10 physicochemical parameters determining the state of chemical, physical, biogenic, and oxygen conditions were determined, and we performed 16 monitoring tests. The methods used are in accordance with ISO standards and documents and legal acts adopted for the monitoring of surface water quality (in the European Union, water quality consists of the ecological state/potential—biological, hydromorphological, and physicochemical elements—and the chemical status of surface waters in surface water bodies) [79,83,84]. Depending on the method used, the measurement error ranged from 0.5% to 5% (DO and EC determinations—0.5%, pH, temperature, turbidity—2.0%, other physicochemical parameters—5%).

Table 3. List of tested physicochemical parameters with methods of their determination.

No.	Parameter	This Research	External Tests	Name of the Method	Measurement Range
1.	pH	X	X	Potentiometric method	0.00–14.00
2.	Electrolytic conductivity (EC)	X	X	Conductometric method	0.1–2000 mS/cm
3.	Temperature of water	X	X	Temperature sensor	−50.0–199.9 °C
4.	Turbidity	X		Nephelometric method	0.1–1000 NTU
5.	Total suspended solids (TSS)		X	Filtration though glass-fibre filters	0.01–4000 mg/L
6.	Total dissolved solids (TDS)		X		0–2000 mg/L
7.	Ammonium nitrogen (NH_4-N)	X	X	Spectrophotometric method	0.001–1000
8.	Nitrate nitrogen (NO_3-N)	X	X		0.1–7.0
9.	Nitrite nitrogen (NO_2-N)	X	X		0.001–1.2
10.	Kjeldahl nitrogen (KN)		X	Method after mineralization with Se	-
11.	Total nitrogen (TN)		X	Spectrophotometric method	-
12.	Total phosphorus (TP)	X	X		0.001–0.5 PO_4-P

Table 3. *Cont.*

No.	Parameter	This Research	External Tests	Name of the Method	Measurement Range
13.	Dissolved oxygen (DO)	X	X	Electrochemical sensor	0.00–20.00
14.	Biochemical oxygen demand (BOD_5)	X	X	Dilution method	0.1–2000
15.	Chemical oxygen demand (COD)		X	Permanganate method	0.1–1000
16.	Sulphates (SO_4)		X	Gravimetric method using BaCl	10–1000
17.	Chlorides (Cl)		X	Mohr’s method	5–400

2.3. Statistical Analysis

Statistica 13 (Dell, Round Rock, TX, USA), Origin Pro 2021 (OriginLab Corporation, Northampton, MA, USA), SPSS Statistics 26 (IBM, Armonk, NY, USA) were used to compile the results and statistical analyses. We also used Office 2013 (Excel 2013 and Word 2013; Microsoft, Richmond, WA, USA), and, for map creation, QGIS 2.8.4 (QGIS Development Team, Open Source Geospatial Foundation Project).

The article presents statistical analyses (for the significance level $p < 0.05$):

- related to basic statistics (Statistica software);
- boxplots with minimum, maximum, mean, median, 25th and 75th percentiles and outliers (Origin software);
- Hierarchical cluster analysis (HCA) and principal component analysis (PCA) in the following variants: relationships between research points within the tested physicochemical parameters, physicochemical parameters at each research point, observations within each parameter (Origin software);
- general linear model (nonparametric): intragroup analysis of variance (ANOVA) for repeated measurements in the following variants: analysis for each parameter separately between eigenvalues on the Bystrzyca river, without point 8 (points 2–7, 9, and 12–15; joint research performed for 24 months; omission of point 8 results from the location in the canal parallel to the main tested watercourse—points 6 and 7; taking this point into account would cause erroneous analysis results), analysis of each HP separately above and below each hydropower facility (points 2 and 3, 6 and 7, 13 and 14; for the Marszowice HP a 36-month period) and taking into account the reference points (points 2, 3 and 4; 6, 7; 12–15—2 years and 13–15—3 years); such a model was chosen due to the number of repeated measurements less than 100, and the fact that in such an analysis the results can be compared in the most reliable way, taking into account their temporal and spatial variability, as well as the impact of each parameter on the results; within the model, the significance for the Mauchly sphericity test was checked and in the case of significance $p < 0.05$ (sphericity was found), the significance for the Greenhouse-Geisser test (selected due to its conservativeness) was checked, and then, if the result was significant, a comparison in pairs between points above and below HPs (2 and 3, 6 and 7, and 13 and 14); if the test was found to be aspherical ($p > 0.05$), the significance for the assumed sphericity was checked, and the subsequent steps were analogous to the above (SPSS software).

2.4. Interpretation and Discussion of the Results

The analysis of the size effects of HPs within the parameters was also analysed. The results from the points above and below hydropower facilities were taken into account (for Skałka and Sadowice HPs, two years; and for Marszowice HP, three years) and the percentage change of a given parameter below HPs for each month was designated by calculating the difference between the points above and below HPs, and then dividing that difference by the result above hydropower. Then a variability plot was plotted, with the minimum, average, and highest values plotted on it. The final result was a table illustrating this variability; it took into account the statistical significance determined from the ANOVA test and the changes were considered significant results if higher than the assumed statistical error, i.e., $p = 0.05$.

In order to check whether HPs have a positive or negative impact on the state of physicochemical elements, an analysis of water quality was carried out at our own sampling points and points obtained from an institution dealing with environmental monitoring in Poland [81]. In accordance with the classification in force, the parameters were assessed on a three-point scale, i.e., class I (very good condition), class II (good condition), and the condition not corresponding to the standards (NMS) for the 95th percentile of results (including a 5% measurement error). The assessment was carried out for the abiotic type 20 (gravel lowland river), to which the Bystrzyca River belongs in the studied section. The overall assessment of the physicochemical elements takes into account the weakest result achieved. The legal basis is the regulation appropriate in Poland, implementing the assumptions of the Water Framework Directive [79,83].

Within the Sadowice, Skałka, and Marszowice HPs, an analysis was also made of whether the conditions for the life of salmonids and cyprinids were met, based on the relevant legal act specifying the acceptable levels of selected physicochemical parameters [85], and also on the basis of the literature [86–97].

An additional analysis, verifying possible factors influencing the physicochemical condition of the Bystrzyca River waters, was taking into account the results of multiyear monitoring studies for selected physicochemical parameters. In this way, the variability of parameter sizes over time was obtained, thanks to which it was possible to draw more detailed conclusions from the analyses performed.

Figure 3 summarizes the research procedure followed in the article.

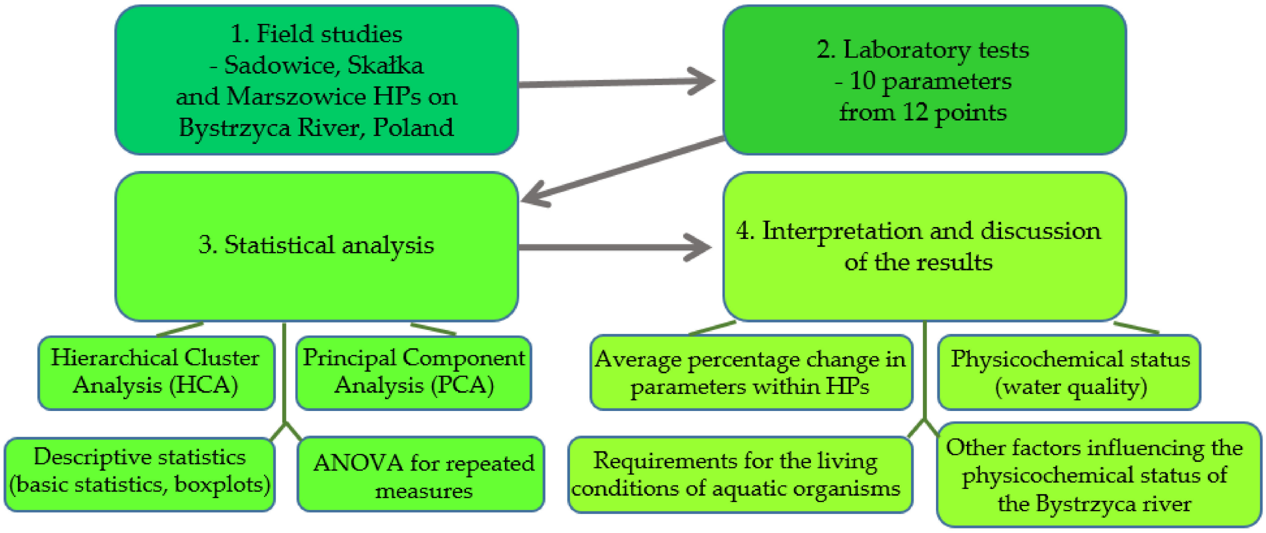

Figure 3. Research procedure followed in the article.

3. Results and Discussion

3.1. Cumulative Results for Points above HPs, below HPs, and Reference Points

Table 4 presents the results of our research. The points were divided into groups according to their location within hydropower facilities, i.e., above HPs (2, 6, and 13), below HPs (3, 7, and 14), and other points/reference points (4, 5, 8, 9, 12, and 15).

Table 4. Basic statistics for tested physicochemical parameters at reference points, points above HPs and below HPs (this research).

Physicochemical Parameter	**Group of Points**	**Statistical Parameter**				
		Min.	**Max.**	**Avg.**	**Mdn.**	**SD**
pH (-)	Reference points	6.60	8.70	7.99	8.10	0.47
	Points above HPs	6.60	8.70	7.92	8.10	0.49
	Points below HPs	6.60	8.60	7.98	8.10	0.46
EC (µS/cm)	Reference points	312.0	931.0	526.6	491.5	134.1
	Points above HPs	318.0	961.0	537.1	493.0	136.9
	Points below HPs	318.0	933.0	531.4	489.5	136.2
Temperature of water (°C)	Reference points	0.10	22.70	11.10	9.80	6.62
	Points above HPs	0.50	21.50	11.09	9.70	6.53
	Points below HPs	0.10	22.60	11.37	10.00	6.49
Turbidity (NTU)	Reference points	1.20	190.00	11.39	5.50	23.95
	Points above HPs	1.50	160.00	10.40	5.80	18.64
	Points below HPs	1.20	115.00	9.69	5.50	16.33
NH_4-N (mg/L)	Reference points	0.000	1.102	0.154	0.109	0.168
	Points above HPs	0.000	1.180	0.169	0.129	0.170
	Points below HPs	0.000	1.094	0.156	0.109	0.169
NO_3-N (mg/L)	Reference points	0.111	5.312	1.591	1.430	1.051
	Points above HPs	0.314	5.849	1.535	1.323	1.072
	Points below HPs	0.289	4.621	1.555	1.381	0.995
NO_2-N (mg/L)	Reference points	0.0030	0.1368	0.0289	0.0213	0.0240
	Points above HPs	0.0000	0.1337	0.0290	0.0213	0.0248
	Points below HPs	0.0000	0.1368	0.0281	0.0213	0.0252
TP (mg/L)	Reference points	0.020	0.290	0.112	0.100	0.054
	Points above HPs	0.030	0.290	0.116	0.100	0.059
	Points below HPs	0.010	1.015	0.131	0.100	0.136
DO (mg/L)	Reference points	3.50	12.80	9.33	9.20	2.29
	Points above HPs	2.70	13.20	8.67	8.40	2.63
	Points below HPs	3.60	12.70	9.09	9.30	2.54
BOD_5 (mg/L)	Reference points	0.3	9.0	3.8	3.6	1.8
	Points above HPs	0.4	9.1	3.7	3.4	1.7
	Points below HPs	0.6	10.1	3.9	3.6	1.8

As can be seen in Table 4, the overall results of the individual parameters, divided into the above groups, achieve similar values. The greatest differences, taking into account the median, were recorded for dissolved oxygen (the lowest values above HPs, the highest—below 8.4 and 9.3 mg/L, respectively), NO_3-N (the highest value at reference points, the lowest above HPs—1.430 and 1.323 mg/L), NH_4-N, turbidity (maximum values above HPs for both parameters), and BOD_5 (minimum values above HPs). For pH, conductivity, water temperature, NO_2-N, and TP, the median value did not differ or the difference was small between the groups of points.

3.2. *Within-Group Analysis of Variance for Repeated Measures—ANOVA*

Due to the fact that the baseline analyses do not clearly indicate specific relationships between points, a within-group analysis of variance for repeated measures (ANOVA) was performed. We checked whether the results obtained for individual parameters were statistically significant at the scale of the river under consideration. Table 5 summarizes the results of the conducted analysis. They show that the greatest impact force, and thus spatial variability, was recorded for electrolytic conductivity (0.924 on a scale from 0 to 1), NO_3-N (0.541), dissolved oxygen (0.322), pH (0.310), and TP (0.178). For BOD_5, NO_2-N, ammonium nitrogen, turbidity, and temperature, no statistically significant variability was noted, which means that they do not change along the river course and will not be subject to further analysis.

Table 5. Summary of the results of the within-group analysis of variance for repeated parameters (ANOVA)—a variant for all research points (this research).

Parameter	***df***	**Error *df***	**F**	***p* (< 0.05)**	η_p^2
EC	*1.620*	*37.259*	*279.916*	*0.000 * (points 6/7)*	*0.924*
NO_3-N	*2.455*	*56.463*	*27.144*	*0.000 * (13/14)*	*0.541*
DO	*4.939*	*113.607*	*10.902*	*0.000 * (13/14)*	*0.322*
pH	*3.941*	*90.649*	*10.314*	*0.000 * (6/7, 13/14)*	*0.310*
TP	*1.356*	*31.199*	*4.970*	*0.024 **	*0.178*
BOD_5	5.580	128.341	2.082	0.064	0.083
NO_2-N	1.572	36.147	1.525	0.232	0.062
NH_4-N	1.360	31.289	1.467	0.243	0.060
Turbidity	1.204	27.686	1.190	0.296	0.049
Temperature	1.681	31.930	0.517	0.570	0.026

Designations in the table: * = statistically significant value ($p < 0.05$); italics = parameters subject to further analysis.

In the context of HPs (on the catchment scale, taking into account all eigenvalues except 8), statistical significance was noted for the conductivity and pH in the Skałka HP (points 6 and 7 in the pairwise comparison analysis), as well as for NO_3-N, dissolved oxygen, and pH for the Marszowice HP (points 13 and 14). No dependencies were found for the Sadowice HP (points 2 and 3). Detailed ANOVA results are summarized in Table 5.

An ANOVA was also performed within the HPs on a local scale, comparing only the points above and above the hydropower facilities. For the Marszowice HP, the significance was noted for: NH_4-N (effect strength 0.442), dissolved oxygen (0.408), pH (0.405), and NO_3-N (0.408). Conductivity (0.623) and pH (0.338) were statistically significant for the Skałka HP. In the case of the Sadowice HP, no statistically significant variation was noted.

3.3. *Analysis of the Variability of Results for Statistically Significant Parameters*

The section presents the results of the following analyzes: boxplots, hierarchical cluster analysis (HCA) and principal component analysis (PCA). Additionally, Annex 1 contains graphs of spatial and temporal variability of the parameters under consideration (EC, NO3-N, DO, pH, and TP), taking into account the state of physicochemical elements (water quality) and the statistical significance of the results on the Bystrzyca river scale.

3.3.1. Electrolytic Conductivity (EC)

As can be seen in Figure 4A, between points 9 and 12, the conductivity values vary significantly. Taking into account the 1 W, 9 W, 10 W, and 16 W points from multiyear measurements, it can be seen that at the 10 W point the conductivity median increases significantly compared to the previous points (761 µS/cm; in the previous: 416–540 µS/cm) and remains at a similar horizontal up to the 16 W point (665–728 µS/cm). Point 10W is the first one located in the city of Wrocław, as well as further points on the Bystrzyca River. Therefore, it can be said that the HPs themselves do not have as much of an impact on the conductivity values as the urbanization process and the related impacts (e.g., sewage discharge, leakage of septic tanks, waste disposal or storage, etc.) [26,84,98]. Our HCA and PCA analyses (Figure 4B,C) confirm these relationships: the points at the Marszowice HP clearly differ from the rest (these are two different groups of points). As for the time variability of our analyses (June 2018-May 2020), it can be seen that in the initial series of measurements the conductivity values were the highest; they decreased over time and in the last months of the research they began to return to the values from the beginning of the research period (at the beginning of the period of conductivity they exceeded the quality standards, and in half and at the end of the study they usually belonged to class II, i.e., good condition, especially at points 2–9). Additionally, between points 6 and 7 (above and below Skałka HP), statistical significance was found—absolute values are higher above the HP. The spatial and temporal variability, including statistical significance for ECs, is included in Figure A1.

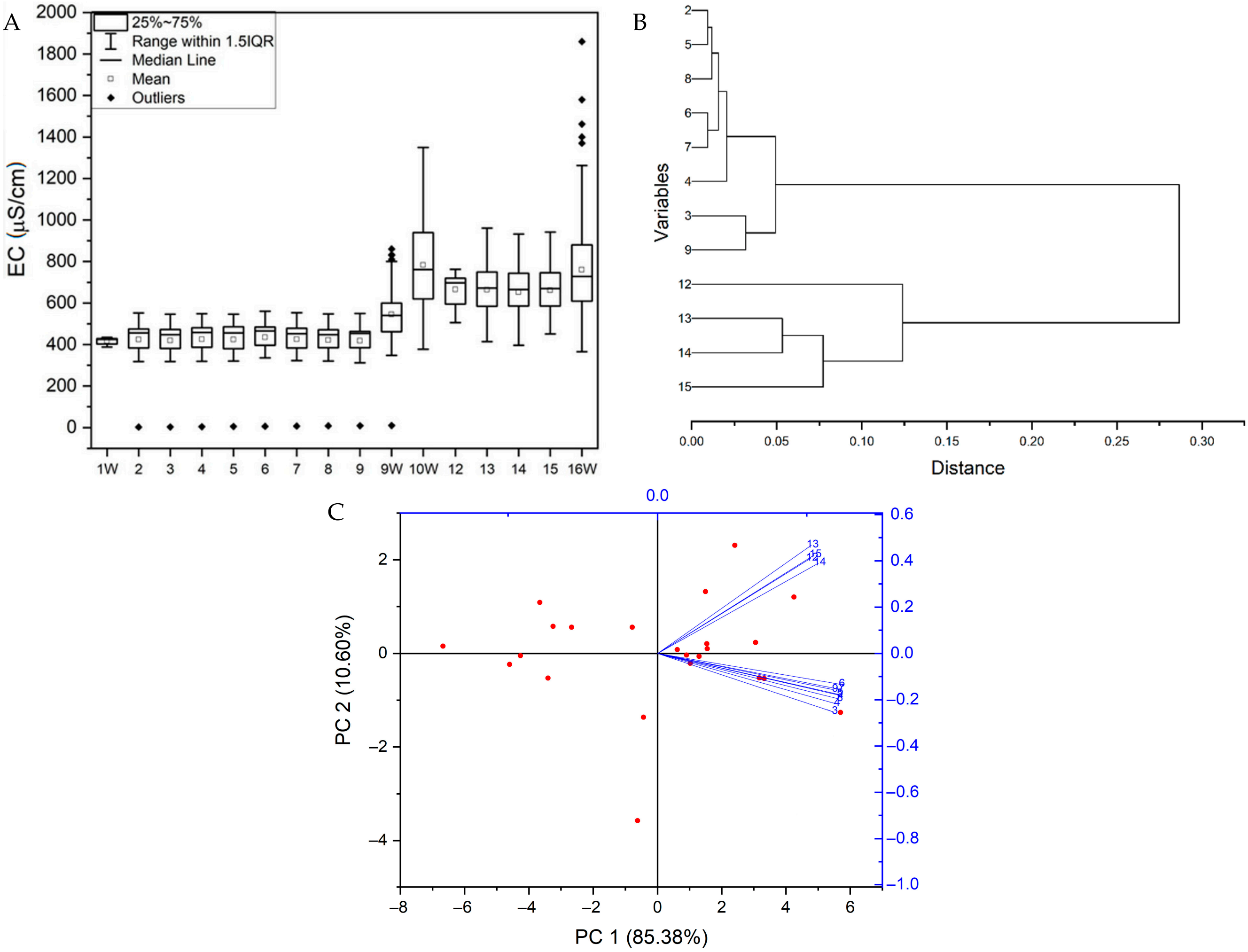

Figure 4. Statistical analyses of electrolytic conductivity (EC): boxplots (**A**; this research and WIOŚ), HCA (**B**; this research), and PCA (**C**; this research).

3.3.2. Nitrate Nitrogen (NO_3-N)

In the case of NO_3-N, the greatest differences in the course of the river are between points 2 to 9 and points 12 to 15. This is visible for both HCA and PCA (Figure 5): points at the Marszowice HP (12–15) differ significantly away from other points, especially above the derivative canal (point 12). The median values range from 1.135 to 1.410 mg/L for points 2–9 and from 1.924 to 2.056 mg/L for points 12–15. Taking into account the data from many years, the highest values are recorded, respectively, in points 16 W, 10 W, and 11 W (median 2.97, 2.94, and 2.40 mg/L). Analysing Figure A2, it can also be seen that the physicochemical state of NO_3-N changed over time: the highest values were recorded in the first months of the study, then they decreased and at the end of the study period the results tended to return to those from the first measurements. In the classification of the physicochemical condition of this element, the good condition (class II) was recorded for most months, but there were also months with a very good condition (class I) exceeding the accepted standards. Additionally, for points 13 and 14 (above and below the Marszowice HP), the results were statistically significant. The reason for the increase in NO_3-N content is pollution in urbanized areas, mainly from fertilizer runoff from intensively used arable land (for example, grazing and plantations of industrial plants near the Marszowice HP) [26]; this suggests a separate point 12 compared to the others in the HCA analysis and the greatest distance from the other points in the PCA analysis. However, the HP also influences the NO_3-N concentration levels in this case.

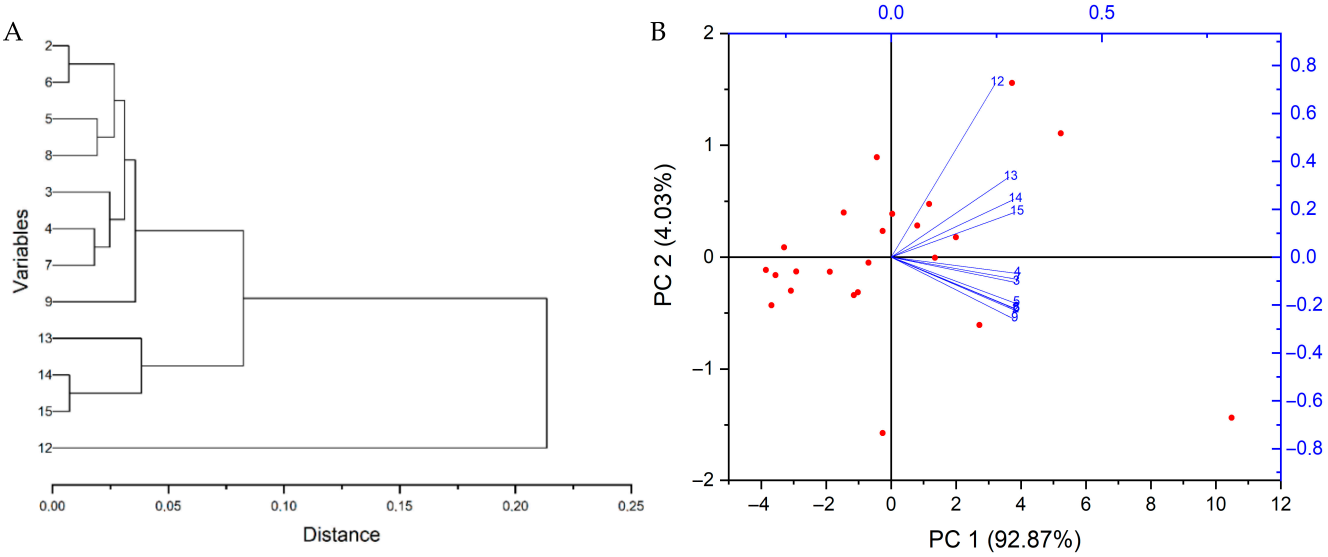

Figure 5. Statistical analyses for nitrate nitrogen (NO_3-N): HCA (**A**) and PCA (**B**; this research).

3.3.3. Dissolved Oxygen (DO)

In the case of dissolved oxygen, the difference can be seen in point 13, in front of the Marszowice HP, where the concentrations are much lower than at the other points. This is reflected both in the PCA analysis, where points 13 and 14 are furthest from the other points, and the closest to them is point 15 (reference, below the Marszowice HP); as well as in box graphs, where you can see a greater range of values for point 13 (minimum 4.1, maximum 12.6 mg/L; for other points usually 6.2–12.8 mg/L). It should be mentioned that, for the PCA analysis, these are not large differences—the vertical axis is responsible for 2.77% of the translation factors, and the horizontal axis for 91.14%, for which the distances between the points are negligible. Additionally, a statistical significance was noted between points 13 and 14 (Marszowice HP); usually the oxygenation below the HP increases. In most months, the standards for this parameter were not exceeded or were class II (good condition). The results are shown in Figure 6A,B and Figure A3.

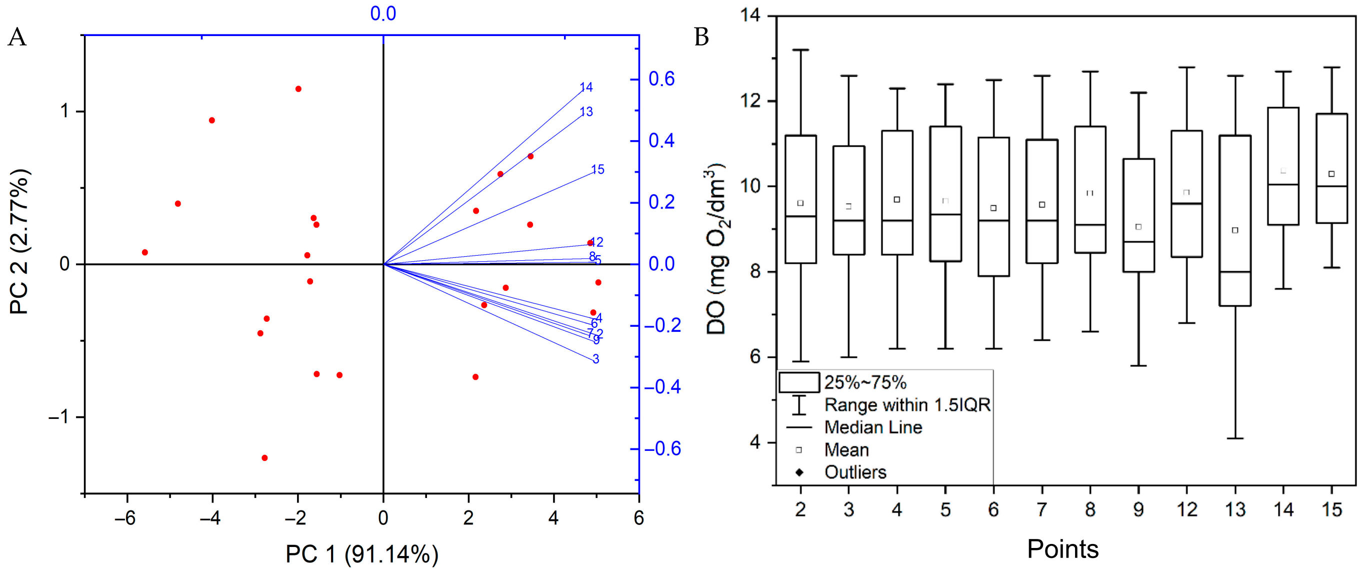

Figure 6. Statistical analyses for dissolved oxygen (DO): PCA (**A**) and boxplots (**B**; this research).

3.3.4. pH

Fluctuations in the pH on the scale of the Bystrzyca River during the research period were quite large, but they did not differ between most points. The exceptions are points 13–15 near the Marszowice HP, which can be seen in the PCA (Figure 7). In addition, for the Marszowice and Skałka HPs, statistical significance was noted in terms of the difference in the results (Figure A4). The physicochemical state of the pH deviated from the norms in about two out of three months; it reached the second class in only one month, and the first in six months. The pH was slightly higher at the test endpoints, but usually these differences were small (median pH 7.95–8.3; pH ranged from 6.5 to 8.7). Due to the different use of the catchment area and different types of pollutants, the pH fluctuations sometimes amounted to 1 pH unit (agricultural, forest, residential, industrial, etc.) [26]. The impact of HPs is local in nature.

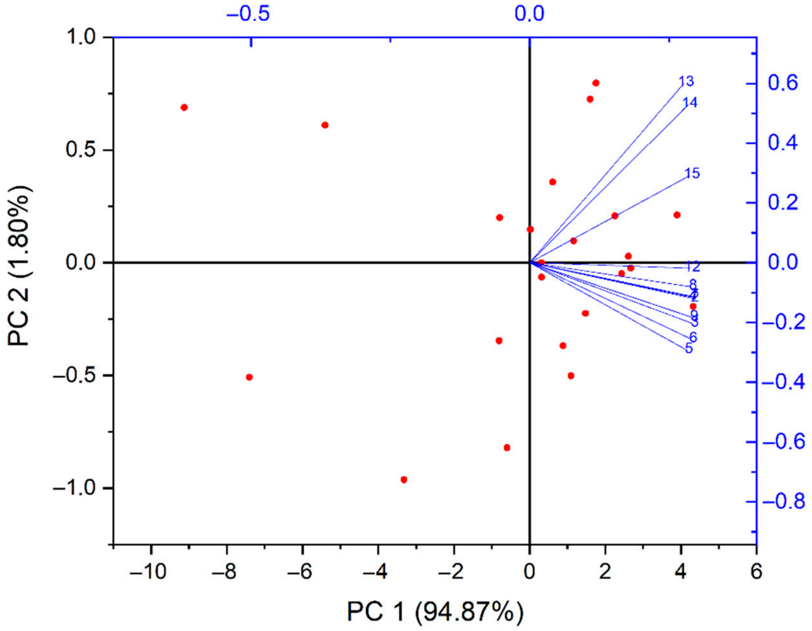

Figure 7. Statistical analyses for pH—PCA (this research).

3.3.5. Total Phosphorus (TP)

TP has the lowest interaction force among the considered parameters, so its values on the Bystrzyca River scale do not differ significantly. The biggest differences can be seen in points near the Marszowice HP (12–15) compared to the other points (median 0.12–0.14 mg/L and 0.08–0.09 mg/L, respectively), but it is not related to the operation of the HPs (no statistical significance). This distinctness of the points can be seen in both the HCA and PCA (Figure 8). In most cases (about 18 out of 24 months), the norms of TP were not exceeded, and in only one month, these norms were exceeded by marginal values in only one month (Figure A5). Low values of TP indicate a low probability of eutrophication on the scale of the Bystrzyca River (phosphorus compounds have the greatest potential to cause water blooms) and low pollution with sewage (industrial and domestic) and phosphorus fertilizers from agriculture [26,99].

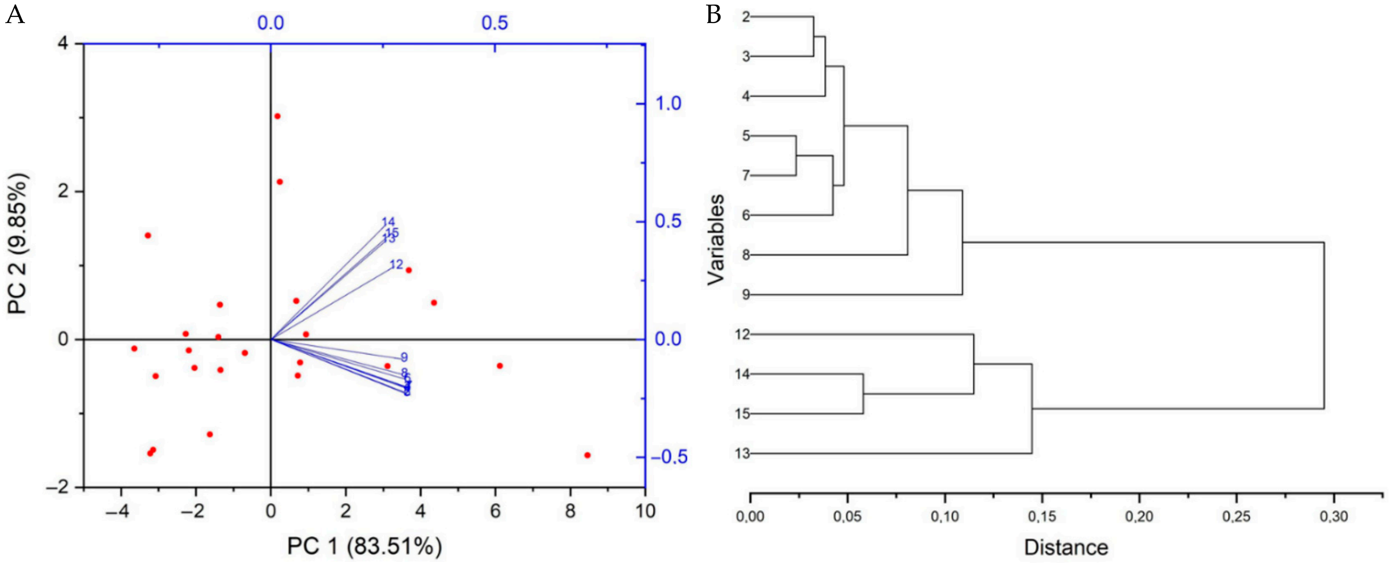

Figure 8. Statistical analyses for total phosphorus (TP): PCA (**A**) and HCA (**B**; this research).

3.4. Cumulative Effect of Hydropower Plants on the Tested Physicochemical Parameters

Statistically significant changes between the points above and below the HPs were recorded for the following parameters: conductivity (Skałka HP), NO_3-N (Marszowice HP), dissolved oxygen (Marszowice HP), pH (Skałka and Marszowice HPs). and ammonium nitrogen (Marszowice HP).

However, taking into account the absolute values of the percentage effect of changes below the analysed hydropower facilities, the following parameters should be taken into account (with an effect higher than 5%): NO_3-N (Marszowice HP = 5.50%), DO (Marszowice HP = 14.04%), TP (Skałka HP = −7.22%), BOD_5 (Sadowice HP = 20.16%, Skałka HP = 14.78%, Marszowice HP = 7.80%), NO_2-N (Marszowice HP = −9.77%), NH_4N (Marszowice HP = −27.83%), turbidity (Sadowice HP = 5.75%, Skałka HP = 5.95%, Marszowice HP = −7.14%). The described effects for all parameters within each HP are presented in Table 6.

Based on the above analyses, it can be concluded that statistically significant parameters with an effect below HPs greater than 5% were recorded for the Marszowice HP with regard to the following parameters: NH_4-N (−27.83%), DO (14.04%), and NO_3-N (5.50%). For these parameters, graphs were drawn showing the variability of the percentage effects of individual parameters over time (Figure 9).

Table 6. Average percentage change in physicochemical parameters below the Sadowice, Skałka, and Marszowice hydropower plants.

Mean Change below HPs Parameter	Sadowice HP (Points 2 and 3)	Skałka HP (Points 6 and 7)	Marszowice HP (Points 13 and 14)
EC	−1.17%	−2.02% *	−1.51%
NO_3-N	2.40%	−4.97%	**5.50%** *
DO	0.56%	1.50%	**14.04%** *
pH	0.37%	−0.93% *	2.16%*
TP	−2.58%	**−7.22%**	−0.19%
BOD_5	**20.16%**	**14.78%**	**7.80%**
NO_2-N	1.26%	4.66%	**−9.77%**
NH_4-N	2.50%	2.32%	**−27.83%** *
Turbidity	**5.75%**	**5.95%**	**−7.14%**
Temperature	2.14%	1.58%	−0.10%

Designations in the table: * = statistically significant value ($p < 0.05$), bold = value considered significant for analysis.

Analysing the results from the highest effects, a decrease in content was found for NH_4-N below the Marszowice HP. This means that, according to the literature review, some of the nutrients remain above the hydropower facility and accumulate in bottom sediments above the damming thresholds. This effect is clear and applies to 29 out of 36 analysed research months (minimum value of the effect = −100%, average = −27.8%, maximum = 41.7%).

In the case of dissolved oxygen, the effect of HPs is smaller, mainly due to the phenomenon of hydraulic jump. Downstream of the hydropower structure, the water is usually oxygenated as a result of a vortex motion. Such a relationship was visible in 28 out of 36 analysed months, with the maximum effect being 102.4%, the average effect 14.0%, and the lowest −17.0%.

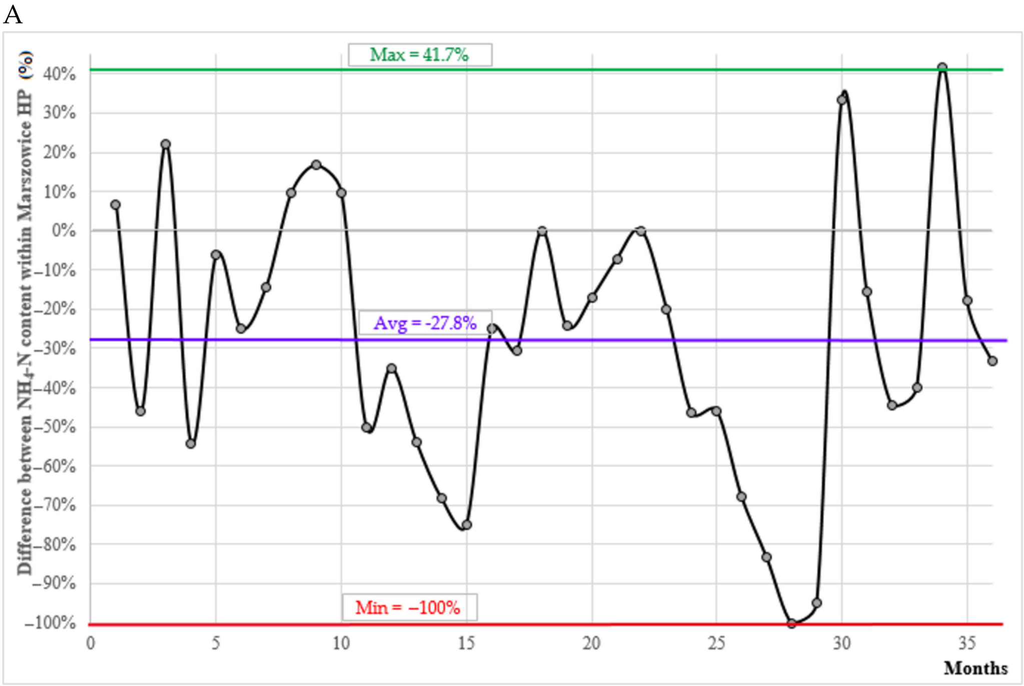

Figure 9. *Cont.*

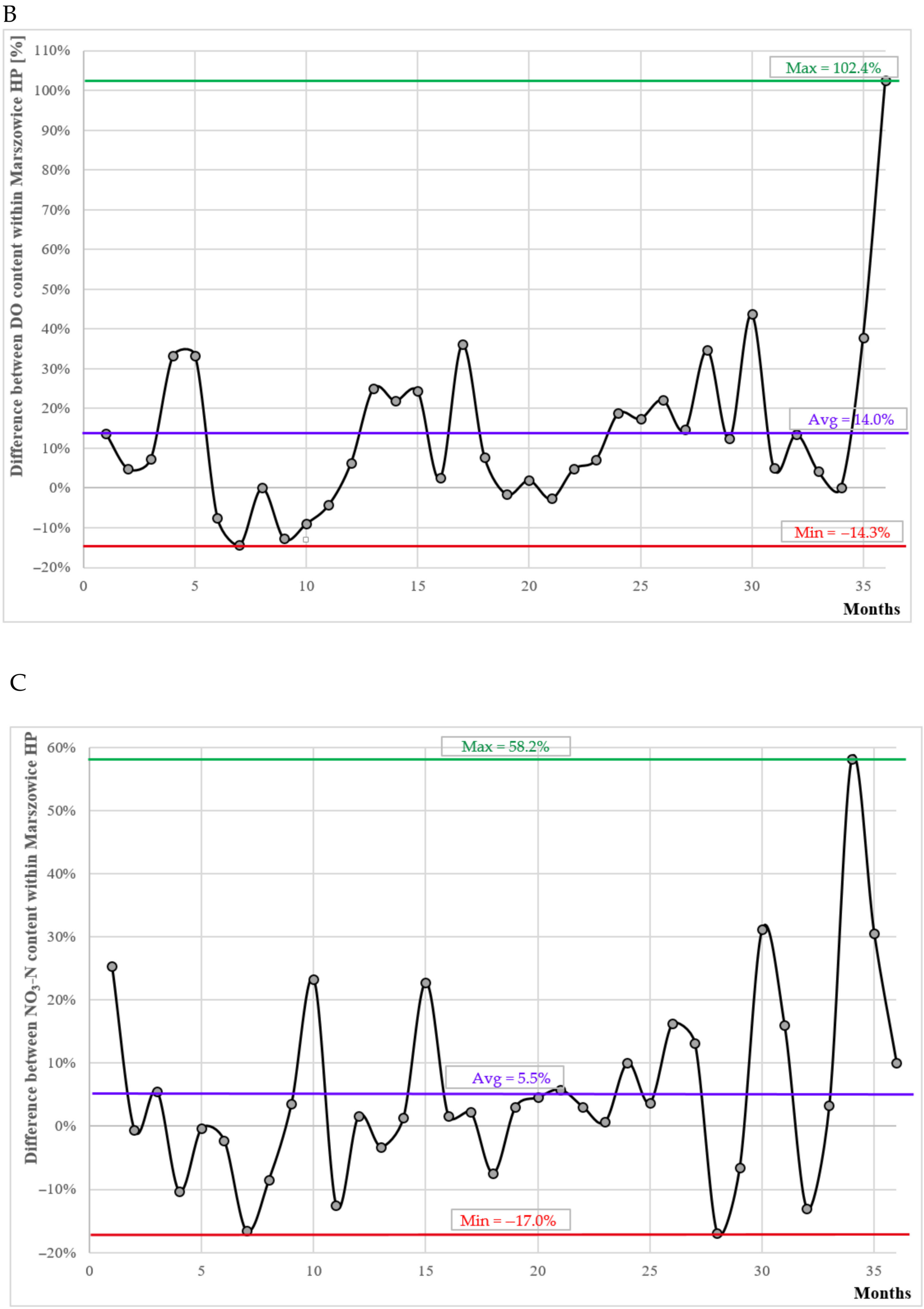

Figure 9. Percentage change in selected statistically significant physicochemical parameters with an average change greater than 5%: (**A**) ammonium nitrogen (NH_4-N), (**B**) dissolved oxygen (DO), and (**C**) nitrate nitrogen (NO_3-N) below the Marszowice hydropower plant, June 2017–May 2020.

The smallest effect of the statistically significant parameters that was simultaneously higher than the standard statistical error was for NO_3-N. In this case, there was an increase below the HP, which is contrary to the decrease in content usually assumed in the literature below the HP. The reason may be the agricultural use of the catchment area and surface runoff from the surrounding meadows and pastures where plant protection products are applied [11,26]. The NO_3-N increase effect was recorded in 24 out of 36 months (the minimum achieved effect value was −17.0%, the average was −5.5%, and the maximum was −58.2%).

Other effects greater than 5% were for TP (Skalka HP) and NO_2-N (Marszowice HP), indicating a decrease in nutrient concentrations below HPs. The results for BOD_5 are also convergent, which proves the greater amount of oxygen necessary for the oxidation of organic compounds by organisms, and thus a higher content of organic substances below HPs. However, it is difficult to say what kind of organic substances they are. The only heterogeneous results, with an effect higher than 5%, were for turbidity for the Sadowice and Skałka HPs; these values are higher below the damming, while for the Marszowice HP they were lower. The field observations show that the decrease in turbidity in the Marszowice HP may be caused by the stagnation of sediments suspended in the derivative canal, deteriorating the oxygen conditions there (which is reflected in the results of NH_4-N, NO_2-N, and DO). In the case of the Sadowice and Skałka HPs, some of the bottom sediments are passed through the damming thresholds and, due to the vortex movement caused by water discharges, mixed in the water column, causing greater turbidity of the water. This may result from the construction of HPs: in the first case, water is taken from the left bank of the river, and in the second and third from the entire bed [26,82].

Looking at the number of statistically significant impacts (for the Sadowice HP, 0; for Skałka, two; and for Marszowice, five), it can be concluded that a higher damming height causes a greater number of impacts (Sadowice = 1.8 m, Skałka = 2.2 m, Marszowice = 3.75 m) [82]. The power of HPs also correlates in this case with the damming height and may have an impact on the number and magnitude of impacts.

Compared to other hydropower studies, there is an increase in dissolved oxygen content below hydropower facilities (San Xusto Flow Hydroelectric Power Station in Spain [56] of 7.12%, vs. in this study from 0.56% to 14.04%), a decrease in TP content (storage HPs in Lithuania with average head [38] by 26.97%, run-of-river large HP in Brazil by 28%, this study from 7.22% to 0.19%). According to other studies, there are drops among other nutrients: NO_3 by 14%, TN by 2.08–15.49%; in the case of this study, there was a decrease of 5.06% for TN in one power plant, while in the others there was an increase of almost 0% and 3.15% (this results from taking into account only NH_4-N, NO_3-N, and NO_2-N, without other forms of it, which may give different results; NO_3-N takes higher values than NO_2-N and NH_4-N, so the final results could be different). The same relationship applies to NO_3-N, i.e., the change in the value between about −5% and +5% (the reason is most likely the agricultural use of the areas near the Marszowice HP) [26].

The results summarized in Table 7 show that, the higher the slope of a HP, the greater the impact, and that the type of HP influences the magnitude of the impact (although the HPs in Lithuania [48] have a much lower damming height than the HP in Brazil [61], the change for TP is comparable and the percentage change for TN compared to the results in this article is three times higher). The differences in the magnitude of the effects of hydropower facilities indicate that the type of HP is much more important than the damming height: the greatest impact is therefore caused by reservoir HPs with a high damming height, while the smallest is caused by flow power plants with a low damming height.

Table 7. Summary of the average percentage changes in the values of physicochemical parameters below selected hydropower plants.

Reference Parameter	Vaikasas et al. 2015 [48]		Valero 2012 [56]	Fantin-Cruz et al. 2015 [61]	This Research
pH			0.17%		from −0.93%* to 2.16% *
Temperature			2.73%		from −0.10% to 2.14%
DO			**7.12%**		from 0.56% to **14.04%** *
EC			**−7.50%**		from −2.02%* to −1.17%
Turbidity				**−38.00%** *	from **−7.14%** to **5.95%**
TP	0%	**−26.97%**		**−28.00%** *	from **−7.22%** to −0.19%
NO_3				**−14.00%** *	from −4.97% to **5.50%** *[1]
TN	−2.08%	**−15.49%**			from −**5.06%** to 3.15% [2]
Type of hydropower	storage (reservoir)		run-of-river		
Damming height	<5 m	5–15 m	70 m	243 m	1.8–3.75 m
Location	Lithuania		Spain	Brazil	Poland

Designations: [1] NO_3-N, [2] TN = NH_4-N + NO_3-N + NO_2-N, * -statistically significant value ($p < 0.05$), bold = value considered significant for analysis.

3.5. The State of Physicochemical Elements at the Tested Measuring Points (Water Quality)

The general physicochemical condition of the considered parameters exceeds the assumed water quality standards [83] at each of the measuring points (taking into account the worst results). Exceedances concern the following parameters: NO_2-N, NO_3-N (without the 1 W point), BOD_5, pH (without the 1W point), DO (without the 8 point), conductivity (9–16 W points), NH_4-N, and TP (1W, 9W, 10W, 11W, and 16W). The standard was met for most or all of the points for temperature (class I), NH_4-N, and TP (class II). The results show strong pollution in the lower reaches of the Bystrzyca River with substances of organic origin, deteriorating the oxygen and physical properties of the water. In addition, in the case of conductivity, the deterioration takes place at points within the city limits of Wrocław. HPs do not have an effect or have an insignificant effect on the considered parameters in the context of their classification to a specific class of physicochemical conditions (points 2/3, 6/7, and 13/14). As a supplement to the analyses, confirming the pollution of the Bystrzyca River with organic compounds, the standards for TSS, TDS, COD-Mn, SO_4, and Cl were exceeded at all points, as well as for KN and TN at points 9W, 10W, 11W, and 16W. The greatest exceedances were for TSS and KN (approximately 10-fold greater than the limits). Due to the difficulty of comparing the results for monitoring points from several to several dozen years with our own results from 2–3 years, the issue of time variability of parameters and factors affecting them is described in more detail in Section 3.7. Tables 8 and 9 show the physicochemical condition of the considered parameters in all analysed points on the Bystrzyca River.

Designations in the table: blue = very good status of parameter (first class), green = good status of parameter (second class), red = does not meet the standards, n/d = no data, italics = points above and below HPs.

Table 8. The state of physicochemical elements at own points and points tested by WIOŚ [81,83].

Point	**Parameter**								
	Temp	**EC**	**pH**	**NH_4-N**	**NO_3-N**	**NO_2-N**	**TP**	**DO**	**BOD_5**
1 W	20.0	432	7.4–8.1	11.9	2.00	0.294	2.79	3.4	132
2	*20.0*	*505*	*7.0–8.4*	*0.549*	*2.76*	*0.069*	*0.19*	*6.6*	*6.2*
3	*19.8*	*502*	*7.0–8.4*	*0.530*	*2.72*	*0.069*	*0.21*	*6.3*	*6.0*
4	20.0	505	7.0–8.4	0.530	2.77	0.081	0.26	6.7	7.2
5	19.8	499	7.0–8.5	0.374	2.83	0.067	0.21	6.3	7.0
6	*19.8*	*511*	*7.0–8.5*	*0.425*	*2.78*	*0.066*	*0.19*	*6.5*	*5.6*
7	*19.7*	*502*	*7.0–8.5*	*0.432*	*2.80*	*0.066*	*0.19*	*6.8*	*6.1*
8	19.9	503	7.0–8.4	0.453	2.82	0.066	0.20	8.0	7.3
9	20.1	506	*6.9–8.4*	0.348	3.22	0.063	0.17	6.0	5.8
9 W	19.1	755	6.8–8.3	9.825	4.71	0.370	3.05	6.5	27.8
10 W	19.5	1188	6.8–8.2	10.475	5.20	0.582	3.23	5.9	64.9
11 W	20.0	n/d	6.4–8.0	14.45	5.66	0.638	5.11	6.6	52.0
12	20.6	747	7.2–8.5	0.489	3.64	0.068	0.21	7.3	7.4
13	*21.0*	*817*	*6.9–8.5*	*0.436*	*3.60*	*0.064*	*0.26*	*3.8*	*7.2*
14	*21.3*	*804*	*7.1–8.5*	*0.377*	*3.73*	*0.070*	*0.22*	*3.7*	*8.5*
15	21.3	815	7.0–8.6	0.346	3.78	0.067	0.21	3.6	7.5
16W	20.3	1098	6.9-.8.2	10.50	5.20	0.420	2.87	6.0	36.0
Norms (I and II class)	I: $\leq$ 22.0 II: $\leq$ 24.0	I: $\leq$ 352 II: $\leq$ 518	I: 7.7–8.1 II: 7.3–8.1	I: $\leq$ 0.13 II: $\leq$ 0.563	I: $\leq$ 1.0 II: $\leq$ 2.4	I: $\leq$ 0.01 II: $\leq$ 0.03	I: $\leq$ 0.15 II: $\leq$ 0.27	I: $\geq$ 8.4 II: $\geq$ 7.6	I: $\leq$ 2.1 II: $\leq$ 3.3

Table 9. The state of physicochemical elements at points tested by WIOŚ [81,83].

	Parameter						
Point	**TSS**	**TDS**	**KN**	**TN**	**COD-Mn**	**SO_4**	**Cl**
1 W	88.0	578	1.068	2.94	99.5	106.9	79.7
9 W	143.8	738	3.59	7.42	124.9	222.0	86.0
10 W	128.0	812	12.4	15.0	34.35	272.8	90.0
11 W	207.5	850	n/d	n/d	251.7	205.4	114.5
16 W	111.8	792	9.49	11.5	27.9	260.0	97.3
Norms (I and II class)	I: $\leq$ 11.0 II: $\leq$ 15.0	I: $\leq$ 266 II: $\leq$ 383	I: $\leq$ 1.0 II: $\leq$ 1.3	I: $\leq$ 2.0 II: $\leq$ 4.1	I: $\leq$ 7.8 II: $\leq$ 9.2	I: $\leq$ 28.4 II: $\leq$ 74.5	I: $\leq$ 13.0 II: $\leq$ 29.8

Designations in the table: blue = very good status of parameter (first class), green = good status of parameter (second class), red = does not meet the standards, n/d = no data.

3.6. *Requirements for the Living Conditions of Aquatic Organisms*

The river is the habitat of aquatic organisms. An important element of the functioning of water-related ecosystems is the fulfilment of certain requirements regarding the physicochemical properties of the water. For this reason, due to natural conditions but also aquaculture purposes, these criteria are defined. For the purposes of the assessment, salmonids and cyprinids are most often distinguished due to their different ecological tolerances [100].

The most important factor determining the living conditions of aquatic organisms is the content of dissolved oxygen. In the case of the considered HPs, the conditions for the life of salmonids were not met, in accordance with the Polish requirements [75] (Table 10)—the concentration of dissolved oxygen was lower than 7 mg/L at the Sadowice and Skałka HPs and above at the Marszowice HP (in 23 out of 24 months). For cyprinids, the assumed requirements were met at each point, i.e., dissolved oxygen concentration higher than 5 mg/L. Taking into account other studies, above the Marszowice HP, carp and other aquatic organisms well adapted to difficult conditions, such as water fleas, would survive. In other cases, most organisms would survive, with the exception of, for example, juvenile forms of salmonids (Table 11). Typically, most aquatic organisms survive at oxygen concentrations higher than 5 mg/L and are resistant to drops in this level for a short time, and therefore all HPs would meet this condition (values lower than 5 mg/L were recorded only once in the whole research period).

With regard to the other parameters, the temperature criterion for salmonids within the Marszowice HP was not met; it was 0.5–0.6 degrees higher than the norm, but its fluctuations do not exclude the existence of this group of organisms. The amplitude of the pH at the points above and below this HP was also a bit too high for cyprinids and salmonids—0.6 degrees or 0.5. Exceedances of the BOD_5 standard for salmonids were found for all HPs—in this case, they are exceeded by about 2-fold, which indicates too much pollution with organic compounds (for cyprinids, these exceedances were insignificant; they were recorded above the Sadowice HP, below the Skałka HP, and above and below the Marszowice HP). Salmonid standards for nitrite were not met; concentrations were double the norm. The TP values for salmonids were slightly exceeded, and this applies to the point below the Sadowice HP and within the Marszowice HP. Standards were met at all points for pH, NH_4-N (salmonids and cyprinids), TP, and dissolved oxygen and nitrite (cyprinids), as well as for temperature fluctuations. The overall results show that, within the considered HPs, the assumed standards for salmonids and for cyprinids in relation to points 2, 7, 13, and 14 (above Sadowice HP, below Skałka HP, and within Marszowice HP) were not met, although in the light of the results, it can be seen that the HPs themselves on the Bystrzyca River scale have little impact on this condition, especially looking at the data from many years (see Sections 3.5 and 3.7); other factors play a major role. The worst conditions for fish are in the Marszowice HP, the only one located in a highly urbanized area (Wrocław) [26]. It should be added that no HP has a fish ladder, which significantly prevents the migration of aquatic organisms that are unable to overcome this transverse barrier and are injured or die after attempting to pass through it [82,101–104].

Table 10. List of physicochemical parameters within Sadowice, Skałka, Marszowice HPs (points 2/3, 6/7, 13/14) in terms of meeting the requirements for the existence of salmonids and cyprinids [85].

Parameter	Point Requirement	2	3	6	7	13	14
Temperature (98% compliance)	≤21.5 °C (salmonids S)	+	+	+	+	- (22.0)	- (22.1)
	≤28.0 °C (cyprinids C)	+	+	+	+	+	+
	max Δ 1.5 °C (S)	+		+		+	
	max Δ 3.0 °C (C)	+		+		+	
DO (100%)	≥7 mg/L (S)	- (5.9)	- (6.0)	- (6.2)	- (6.4)	- (4.1)	+
	≥5 mg/L (C)	+	+	+	+	+	+
pH (95%)	6–9 (S/C)	+	+	+	+	+	+
	max Δ 0.5 (S/C)	+		+		- (0.6)	
BOD_5 (95%)	≤3 mg/L (S)	- (6.2)	- (6.0)	- (5.6)	- (6.1)	- (7.2)	- (8.5)
	≤6 mg/L (C)	-	+	+	-	-	-
TP (95%)	≤0.2 mg/L (S)	+	- (0.21)	+	+	- (0.26)	- (0.22)
	≤0.4 mg/L (C)	+	+	+	+	+	+
NO_2 (95%)	≤0.01 mg/L (S)	- (0.021)	- (0.021)	- (0.020)	- (0.020)	- (0.019)	- (0.021)
	≤0.03 mg/L (C)	+	+	+	+	+	+
NH_4-N (95%)	≤0.78 mg/L (S/C)	+	+	+	+	+	+

Designations in the table: blue = compliance with requirements, red = noncompliance with requirements, numeric values = physicochemical parameter values for the specified compliance percentile.

Table 11. Examples of dissolved oxygen concentrations necessary for the life of various groups of aquatic organisms.

Species	Criterion	Reference(s)
Salmonids	>5.0	Lloyd 1992 [76], Bergheim et al. 1978 [87]
	>5.5 (fish), >7.0 (eggs)	Roberts and Shepherd 1974 [88]
	>7.0 (100%), >9.0 (50%)	Stiff et al. 1992 [89]
	>6.0 (early life stages), >3.0	Chapman 1986 [90]
	>6.0 (juveniles)	JRB Associates 1984 [91]
	>4.8	EIFAC 1987 [92]
Cyprinids	>5.0 (100%), >7.0 (50%)	Stiff et al. 1992 [89]
	>2.9 (carp)	Beamish 2011 [93]
Freshwater fish	>5.0	Coble 1982 [94], Winton et al. 2019 [99]
	>6.0 (100%)	Lawson 1995 [95]
Daphnia magna	>3.7 (100%)	Homer and Waller 1983 [96]
Well-adapted organisms (e.g., cyanobacteria)	>2.0	Spoor 1990 [97]

3.7. Other Factors Influencing the Physicochemical Status of the Bystrzyca River

The state of the physicochemical elements in the Bystrzyca River has changed over the years. As can be seen in Figure 10, there are distinct periods when the condition has gradually started to improve. The most spectacular cause of this state of affairs was June 4, 1989, when the first democratic elections were held in Poland [105]. Since then, the system has changed from communist to democratic, which means a thorough overhaul of the existing political and economic system [106]. In the context of the parameters mentioned below (NH_4-N, DO, BOD_5, and TP), it is associated in particular with the abandonment of Poland's economic development attitude towards heavy industry and switching to services, precision industry, and more environmentally friendly agriculture, not using a highly toxic large-scale plant [107]. The systemic change was also associated with wider international cooperation, e.g., in the field of environmental protection (including the ratification in 1996 of the provisions contained in the 1992 UN Earth Summit on climate change, sustainable development, biodiversity, and forest protection) [108].

Another important event for Poland, which resulted in the tightening of regulations related to the monitoring of the aquatic environment, was Poland's accession to the European Union on May 1, 2004 [109]. Along with joining the ranks of this institution, the country gained access to a number of facilities, such as EU subsidies, but in return was obliged to implement EU law [110]. The most important legal act in the field of water protection is the Water Framework Directive [79], thanks to which new procedures and institutions related to the issues of rational use of water resources, as well as ensuring their appropriate quantitative and qualitative status, were created. The first such commitment in Poland was to achieve at least good ecological status in surface water bodies (JCWP) by 2015, and in the event of noncompliance with the standards by 2021 [79,111]. There is also a new water quality assessment system that takes into account the chemical and ecological status of JCWP (along with the new assessment system, more restrictive water quality standards have been implemented, distinguished for various types of abiotic waters) [112]. In the context of renewable energy sources, Poland takes into account the assumptions of the EU Directive related to RES [113–115], implementing them in its own energy policy and assuming, inter alia, achieving appropriate levels of the use of renewable energy sources in the country's energy balance (21% in 2030) [116].

To confirm the above statements, the results for selected physicochemical parameters, presented in Figure 10, will be compared. In the case of NH_4-N, the median value until 1989 was 5.9 mg/L, in 1990–2003 1.36 mg/L, and from 2004 0.40 mg/L. Thus, it has decreased almost 15-fold since the change of the political system. In the case of DO, the values were, respectively, 7.04, 9.49, and 10.07 mg/L (increase by 43%), for TP, 1.44, 0.66, and 0.28 mg/L (decrease by 80.6%), and for BOD_5, 14.09, 6.18, and 3.31 mg/L (decrease by 76.5%). Other examples include TSS (decrease 64.5%), COD-Mn (decrease 82.9%), and NO_2-N (decrease 77.5%).

In all research periods, regardless of the location of the research points, the Marszowice, Skałka, and Sadowice HPs operated, and looking, for example, at the median of mean NH_4-N concentrations at points above and below Marszowice HP (statistically significant results for this parameter), for the common years the river studies did not differ significantly (at point 10 W the value was 0.174 mg/L, while at 16 W it was 0.1795 mg/L; common study period: 1977–1988, 1992–1996, and 1998–2006).

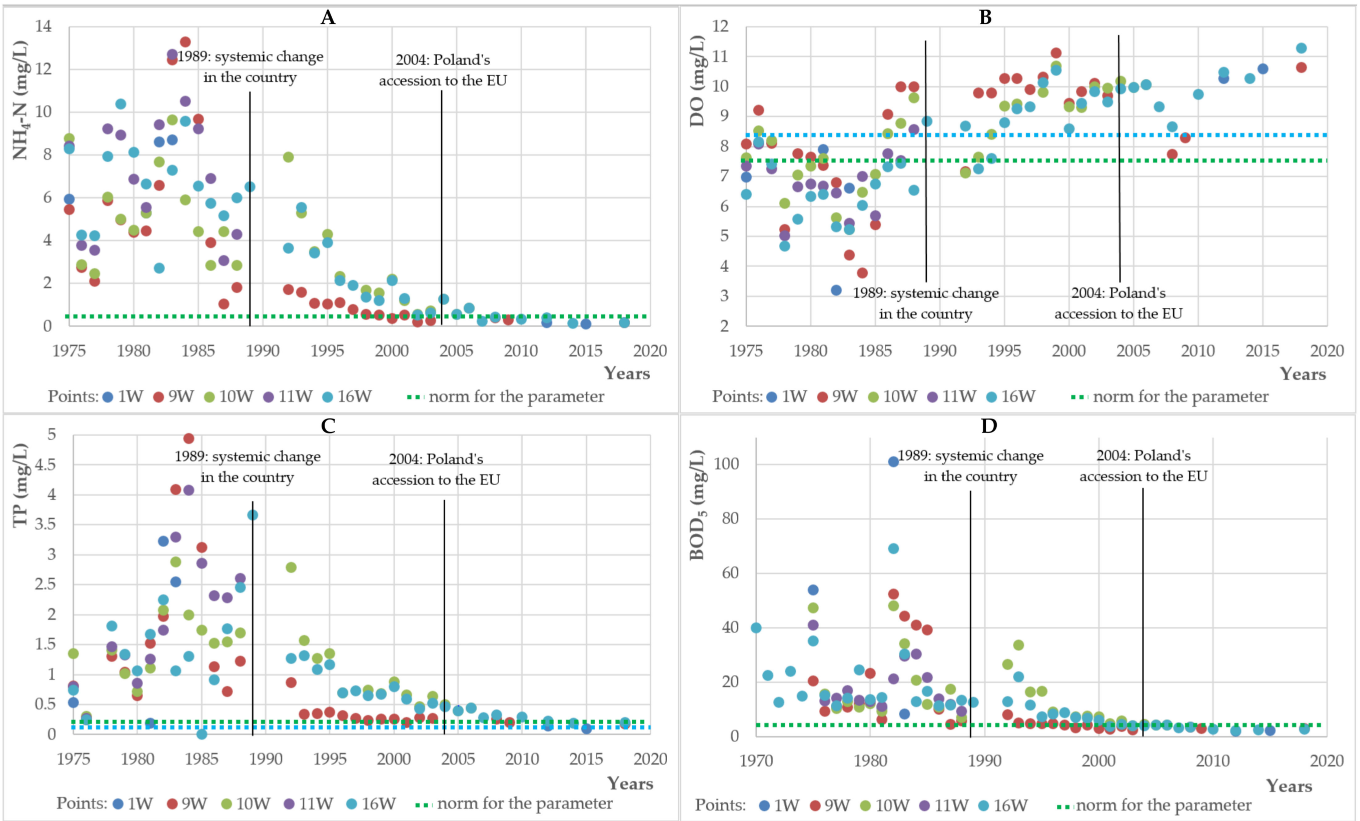

Figure 10. Temporal variability of selected physicochemical parameters (from the top left (**A**–**D**): NH_4-N, DO, TP, and BOD_5) at monitoring points on the Bystrzyca River, taking into account important events in Poland's history.

4. Conclusions

The conclusions of the research are as follows:

(1) The investigated HPs influence the selected physicochemical parameters of water (Sections 3.1 and 3.2).

(2) On the scale of the studied section of the Bystrzyca River, the following parameters changed statistically significantly: EC (effect size 0.924), NO_3-N (0.541), DO (0.322), pH (0.310), and TP (0.179) (Table 5).

(3) A statistically significant effect ($p < 0.05$) was found for the Skałka HP (EC and pH) and Marszowice (EC, NO_3-N, DO, pH, and NH_4-N) (Section 3.2).

(4) Statistically significant and higher than 5% impact within the Marszowice HP on the following parameters: NH_4-N (decrease below the HP by 27.83%), DO (increase by 14.0%), and NO_3-N (increase by 5.5%) (Table 6).

(5) Taking into account our results and those from the literature review, we see that the scale of the impact of HPs is influenced by their type and water level. The higher the damming height, the greater the impact on the values of physicochemical parameters (the damming heights of the Marszowice, Skałka, and Sadowice HPs are, respectively,

3.75, 2.2, and 1.8 m; five, two, and zero parameters changed significantly within the HPs) (Tables 6 and 7).

(6) It was found that run-of-river HPs have less impact on physicochemical parameters than reservoir ones and this is more important than the damming height (e.g., change of TP below HPs: reservoir HP, with a damming height of 5–15 m = −26.97%, run-of-river HP, damming height 243 m = −28.0%, run-of-river HPs below 5 m = −7.22 to −0.19%) (Table 7).

(7) Our results corroborate the results of other scientists in terms of an increase in dissolved oxygen below hydropower facilities, a decrease in conductivity, and a decrease in TP concentrations. The results for turbidity, NO_3-N, and TN are partially different (decreases in other tests, negative and positive values in our own tests, but usually they are not statistically significant) (Section 3.4).

(8) HPs should be tested each time within the barrages on which they are located. Research has shown that HPs have little impact on the shaping of water quality over a larger time and spatial scale (longitudinal profile of the watercourse) (Section 3.3 and Appendix A), where a greater role may be played by the use of the river basin, the applicable political system, and environmental requirements (e.g., in agriculture and water protection) (Section 3.7).

(9) There were no significant differences in the impact of HPs on physicochemical parameters in the context of the assessment of their condition (water quality classification) and in terms of meeting the requirements for the life of aquatic organisms. The results were similar above and below hydropower facilities (Section 3.5).

Author Contributions: Author Contributions: Conceptualization, P.T. and M.W.; methodology, P.T. and M.W.; software, P.T.; validation, P.T.; formal analysis, P.T.; investigation, P.T. and M.W.; resources, P.T. and M.W.; data curation, P.T.; writing—original draft preparation, P.T.; writing—review and editing, M.W.; visualization, P.T.; supervision, M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figures showing the temporal and spatial variability of statistically significant parameters on the scale of the Bystrzyca River, Poland.

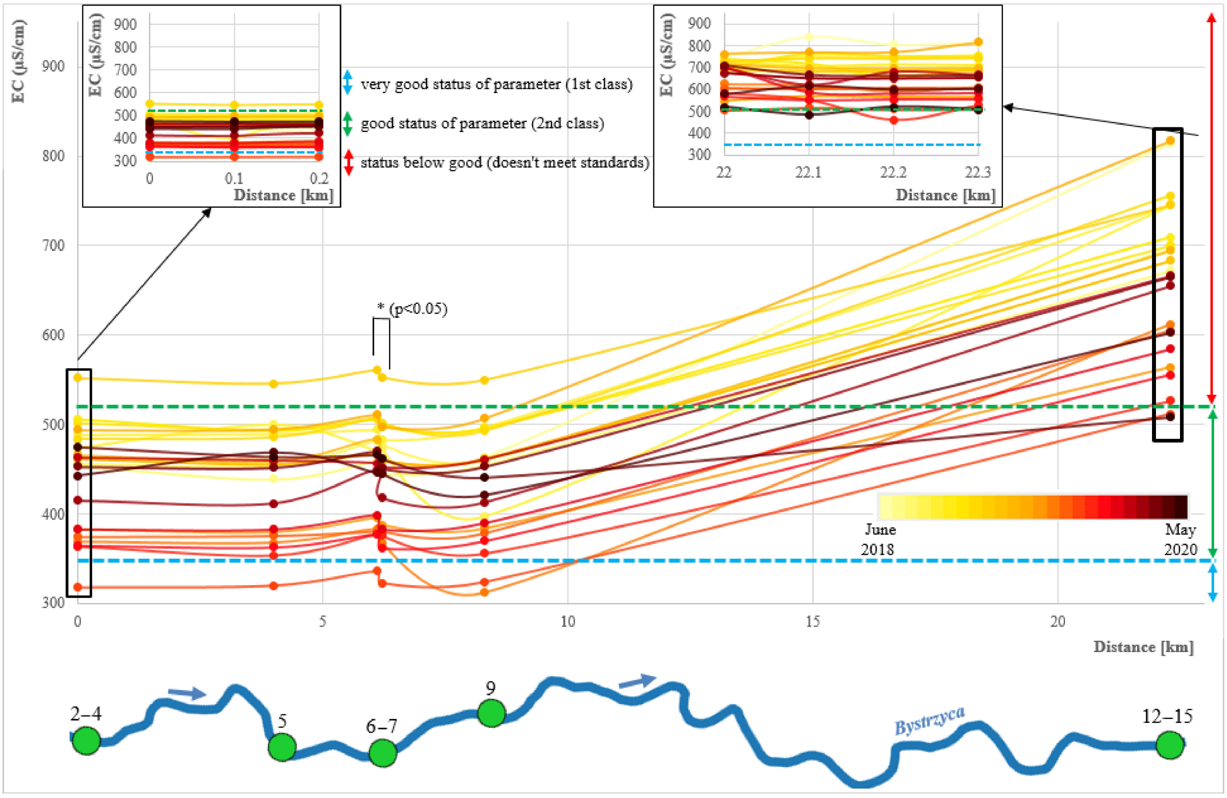

Figure A1. Temporal and spatial variability of EC at the tested measurement points, including the physicochemical condition of the parameter and statistical significance within the Sadowice, Skałka, and Marszowice HPs ($p < 0.05$).

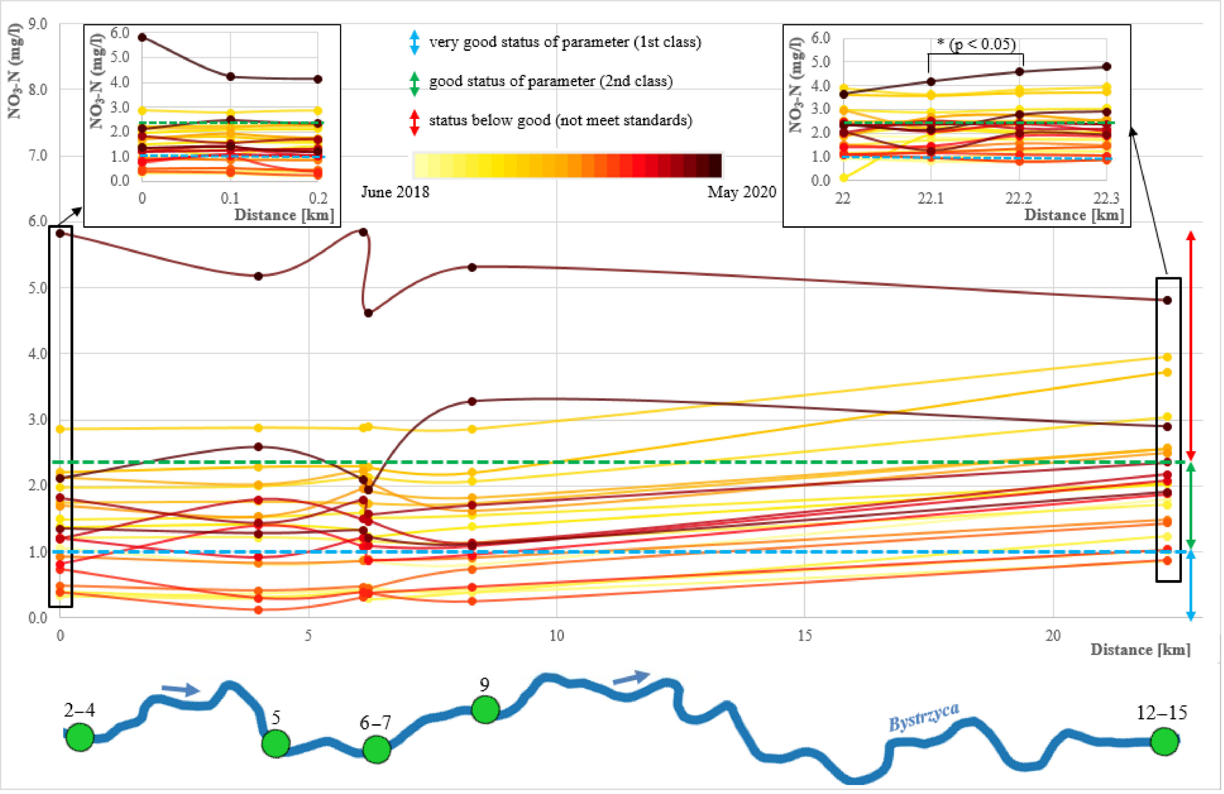

Figure A2. Temporal and spatial variability of NO_3-N at the tested measurement points, including the physicochemical condition of the parameter and statistical significance within the Sadowice, Skałka, and Marszowice HPs ($p < 0.05$).

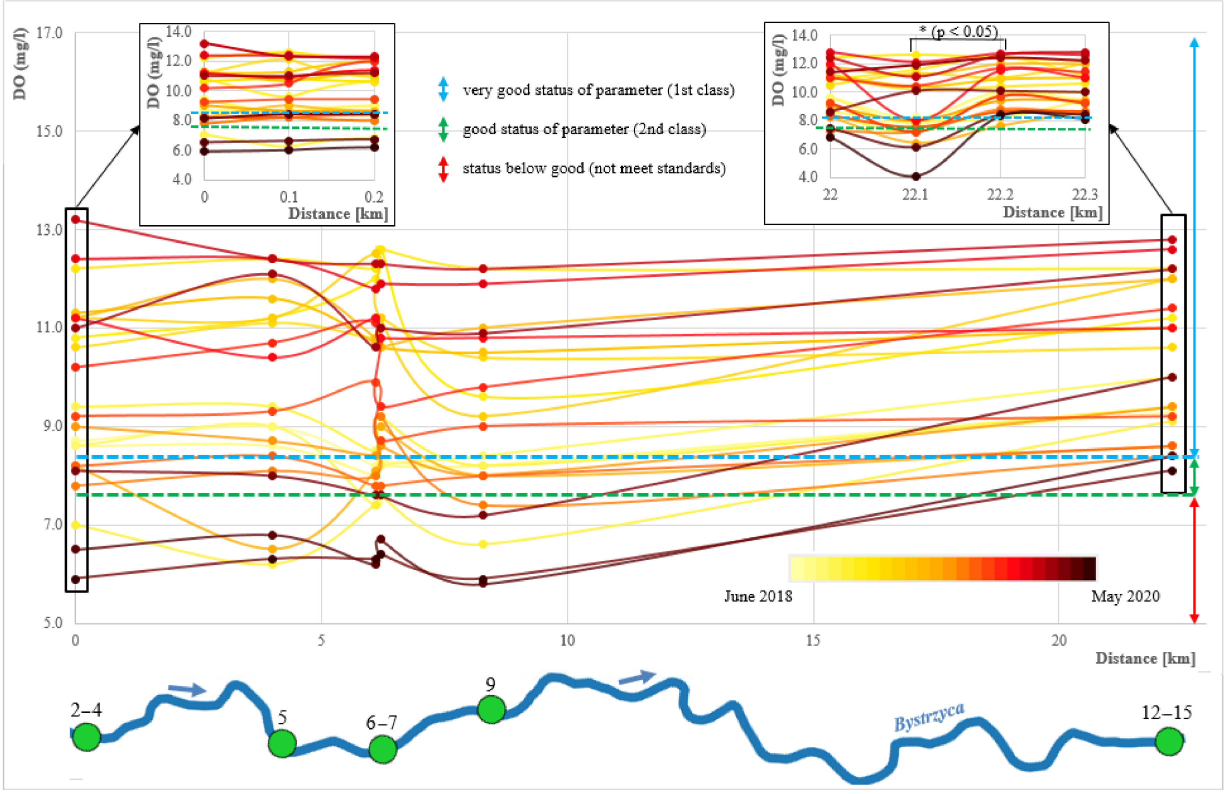

Figure A3. Temporal and spatial variability of DO at the tested measurement points, including the physicochemical condition of the parameter and statistical significance within the Sadowice, Skałka, and Marszowice HPs ($p < 0.05$).

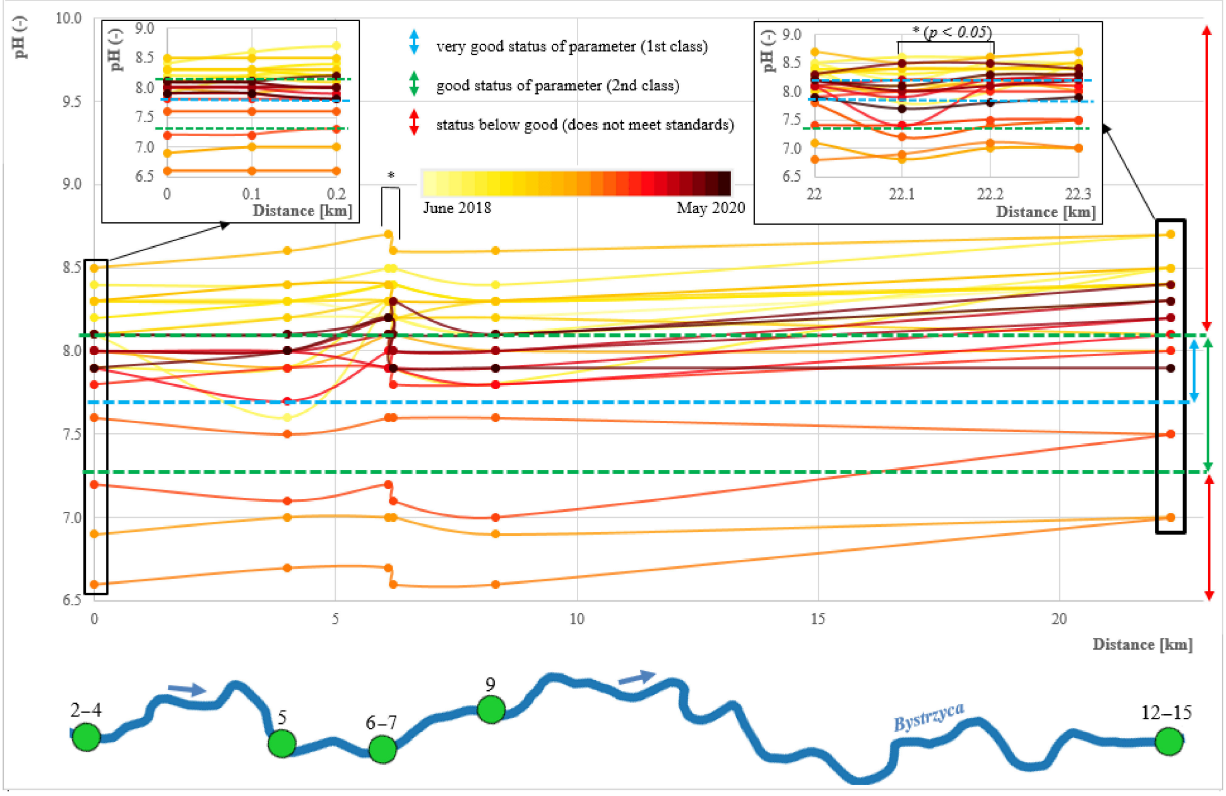

Figure A4. Temporal and spatial variability of pH at the tested measurement points, including the physicochemical condition of the parameter and statistical significance within the Sadowice, Skałka, and Marszowice HPs ($p < 0.05$).

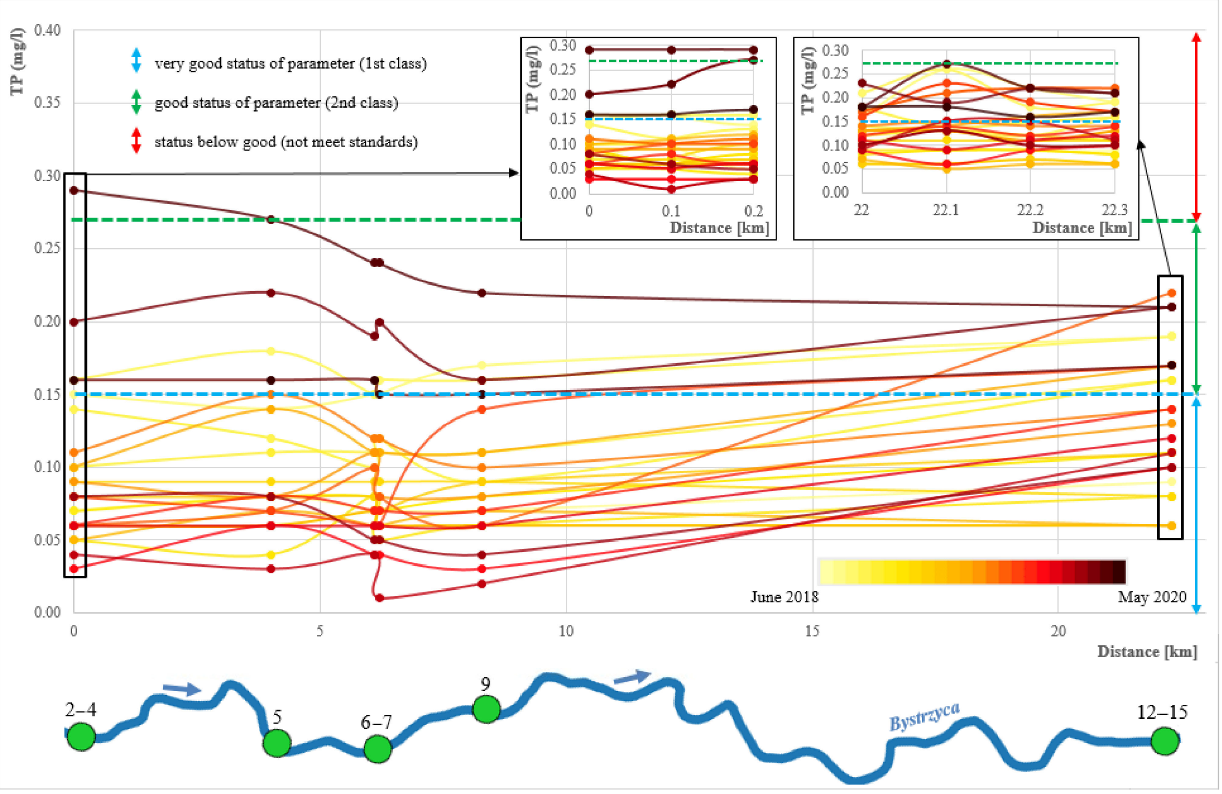

Figure A5. Temporal and spatial variability of TP at the tested measurement points, including the physicochemical condition of the parameter and statistical significance within the Sadowice, Skałka, and Marszowice HPs ($p < 0.05$).

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