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"Gheorghe Asachi" Technical University of Iasi, Romania

HYDROPOWER IMPACT ON WATER QUALITY: A CASE STUDY ON THE MICHALICE RESERVOIR, POLAND

Paweł Tomczyk[1*], Mirosław Wiatkowski[1], Łukasz Gruss[1], Bogna Buta[1], Robert Kasperek[1], Robert Głowski[1], Kamil Rembielak[2]

[1]*Institute of Environmental Engineering, Wrocław University of Environmental and Life Sciences, Plac Grunwaldzki 24, 50-363 Wrocław, Poland*
[2]*Marshal's Office of the Lower Silesia, wybrzeże Juliusza Słowackiego 12/14, 50-411 Wrocław, Poland*

Abstract

In this article, we discuss the impact of hydropower plants (HPPs) on water quality (WQ), as this issue is of growing interest among researchers in the world. The article analyzes the impact of a small HPP on the Michalice Reservoir on the Widawa River (Poland) on selected physicochemical properties of water. A comparative analysis of the results of our research and those obtained in HPP studies in Lithuania and Malaysia was also carried out. It has been shown that the concentrations of $P\text{-}PO_4$, $N\text{-}NH_4$ and turbidity increase below the Michalice HPP (by 39.3%, 430% and 130%, respectively, compared to the median value at the measuring point above the HPP), while the concentrations of $N\text{-}NO_3$ directly below the dam increase (by 95.4% compared to the median above the HPP). The results obtained for the Michalice Reservoir are similar to those from Lithuania and Malaysia – at some distance from HPPs, the turbidity of water increases. In contrast, the concentrations of $N\text{-}NO_3$, $P\text{-}PO_4$ and $N\text{-}NH_4$ below the HPPs decrease. Moreover, it was found that the main WQ problem in the Michalice Reservoir is the high pollution of the Widawa River catchment, which results from its agricultural use, its geological structure, the high share of endorheic (drainage) areas and the uncontrolled sewage discharge. Our assessment of WQ in the reservoir HPP may be the starting point for further research on rational, sustainable water management at hydropower facilities.

Key words: dam reservoir, ecological status, environmental effects, hydropower, water quality

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1. Introduction

Hydropower is an increasingly popular renewable energy source (RES). In the EU, the share of hydropower in the total gross energy consumption from RES is 14.3% and ranks second behind wood and other solid biofuels (Eurostat, 2019). Currently, the target of the climate and energy package is 20% by 2020 (i.e. we aim to cut the greenhouse gas emissions by 20% compared to the 1990 level, we want to produce 20% of the total energy consumption from RES and we undertake to increase our energy efficiency also by 20%) (EC 2020; Eurostat, 2019). The environmental goals set out by individual member states were achieved by 11 out of 28 countries (as of 2017 end; Fig. 1)(EC, 2020; Eurostat, 2019).

On a global scale, the installed capacity of hydropower plants (HPPs) is continually growing. This capacity was 778.62 GW back in 2000 but rose to 1290.56 GW in 2018. This is an increase of nearly 40%. In terms of individual countries, the most massive capacity increase as recorded in Cambodia: from 10 MW in 2000 to 1280 MW in 2018. However, there are some exceptions, i.e. countries where the HPP capacity has decreased –for example, as in Australia, where the capacity in 2000 was 9201 MW compared to 8271 MW in 2018 (IRENA, 2019). As mentioned earlier, the environmental goals set out in

* Author to whom all correspondence should be addressed: e-mail: pawel.tomczyk@upwr.edu.pl; Phone: +48 713205518; Fax: 71 320 5579

the climate and energy package are to be achieved by the end of 2020 (EC, 2020). Apart from these, there are also specific targets in terms of good water quality – WQ (also quantity) in water bodies set out in the Water Framework Directive – WFD (EPC, 2000; Kuriqi et al., 2019a). To meet legal requirements for the rational management of HPPs, certain environmental flows should be maintained. They are defined as the amount of water used in such an amount as not to destroy aquatic ecosystems and dependent waters (Młyński et al., 2020), with simultaneous support of cultural and economic benefits, people's well-being and sustainable livelihoods (Kuriqi et al., 2019b).

Hence, this article analyzes the impact of HPPs on environmental conditions in watercourses, with particular focus on the impact on physicochemical elements of WQ (the biological and hydro-morphological elements are also assessed as part of monitoring under the WFD, but these will be omitted in further analysis). In order to discuss the issue, we need to distinguish different types of HPPs, depending on the way they obtain energy. There are three types: run-of-river, impoundment and pumped-storage (Igliński, 2019; Wiatkowski et al., 2018). The impact of HPPs on the status of physicochemical elements (such as the dissolved oxygen (DO), the temperature and turbidity) is recorded below these structures, but has not been studied in detail yet (Bunea et al., 2010; von Sperling, 2012; Wiatkowski and Tomczyk, 2018).

The most noticeable effect is the increase in the concentration of DO below the dam. However, this impact is only local and mainly depends on the damming height of the HPP, although its size is also a factor. This impact is due to the vertical drop in water columns that are directed to turbines or weirs. At the bottom station of the HPP, the phenomenon of hydraulic jump is observed, i.e. the formation of a vortex movement of significant speed. This water is strongly saturated with oxygen: water masses are being strongly mixed here and it can improve the conditions for macrophyte development, but also causes bubble disease of fish as a result of a sharp increase in water pressure. The impact of this phenomenon ranges from a few meters to dozens of kilometers, depending on the size and location of the HPP (Bakken et al., 2015; Tomczyk et al., 2019; Wu and Ma, 2018).

The second phenomenon is the change in water temperature – in this case the HPPs increase it in the cold season and decrease it in the warm season. Warming is visible when the temperature of the water entering an HPP is lower than that of the mechanisms in this HPP, while cooling can be seen when the temperature at the entrance is higher. As a result of the increase in temperature in winter, the ice cover may be weakened. It may last shorter, which can disturb the stratification of reservoirs and, consequently, disturb the living conditions of the organisms, because the abiotic conditions will change (Fantin-Cruz et al., 2016; Florentina et al., 2010; Valero, 2012).

The turbidity of water below HPPs increases due to the intense mixing of water masses and the creation of a whirling movement. This increase in turbidity has a significant impact on the living conditions of aquatic organisms, which may have different ecological tolerances. Those that prefer clean water and low turbidity will be replaced below the HPPs by aquatic organisms whose ecological optimum is in high turbidity (Bogen and Bønsnes, 2001; Finger et al., 2006; Puzdrowska and Heese, 2019). Moreover, sometimes eutrophication is also observed below the HPPs. It can be seen in stagnant and enrichment with nutrients water zones, which offer good conditions for algae. This occurs when the HPP is misused or if specific hydropower units are not used. Algae bloom harm the aerobic conditions of the water. Their appearance is usually not directly related to the operation of the HPP. However, it is the consequence of the use of water reservoirs located next to them – depending on the phase of the water reservoir operation (da Costa Lobato et al., 2014; Kobus et al., 2016; Schneider et al., 2012; Smith et al., 1999; Zhang et al., 2010).

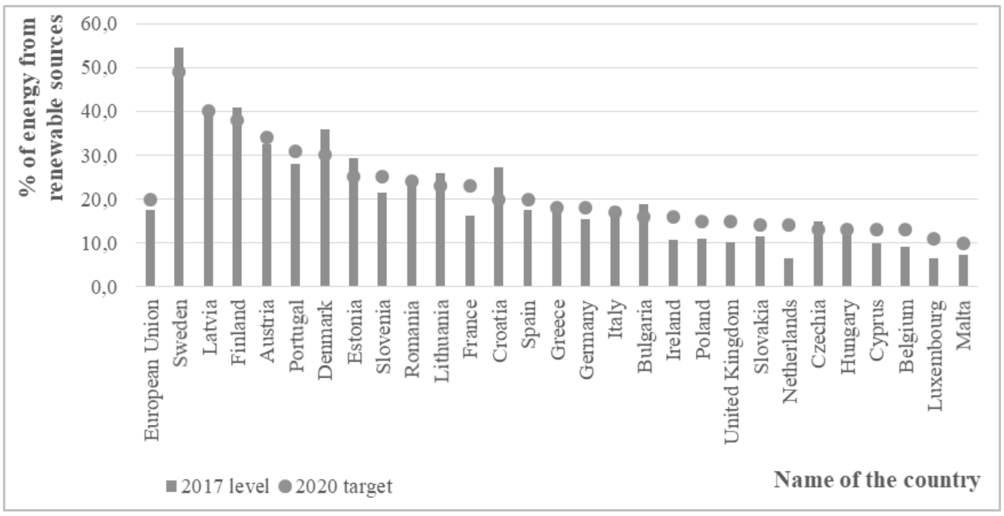

Fig. 1. Share of energy from renewable sources in the EU Member States in 2017 (% of gross final energy consumption; based on Eurostat, 2019)

Over the years, several studies have been carried out regarding the impact of HPPs on various elements of WQ, including physicochemical elements. Extensive research was conducted in Lithuania by a scientific team consisting of Vaiksas, Bastiene and Pliuraite (2015), who examined 17 reservoir HPPs on the selected rivers. The team designated water sampling stations in reference sections, on a cascade of reservoirs (between HPPs) and below water storages. They divided the HPPs into groups with low dam height ($H < 5$ m) and medium dam height ($H = 5 – 15$ m). All the HPPs under this study are small, with installed capacity below 5 MW. Their research covered: fine particles (FP), total suspended solids (TSS), total nitrogen (TN) both in water and in sediment, total phosphorus (TP) both in water and in sediment. Conclusions from this research are listed in Fig. 2.

A study of the Impact of HPPs on physicochemical elements was also carried out by a team of scientists from Malaysia (Ling et al., 2016). This research was carried out in 2013-2014 below the HPP Bakun on the Balui River. Researchers identified research sections located at different distances from the dam (4.3, 9.9, 17.5, 24.9 and 32.1 km).

They carried out their research at various stages of the water reservoir operation (the emptying phase when the HPP was active, and reservoir filling phase when water was not stored). Unlike the Lithuanian research, the HPP selected by the Malaysian team has a high capacity, 2400 MW, and the dam itself is the third tallest concrete structure of this type in the world (205 m high). The scope of this research included *in situ* and *ex situ* determination of the following parameters: total sulphide (TS), chemical oxygen demand (COD), BOD_5, TP, turbidity and total ammonia nitrogen (TAN – the sum of the concentration of non-ionized (NH_3) and ionized (NH_4^+) ammonia), pH and DO. Conclusions from this study are summarized in Fig. 3.

Our article focuses on reservoir HPPs. Our research on selected physicochemical parameters was carried out on the Michalice Reservoir on the Widawa River (Poland) in the period from May 2016 to April 2017 (Rembielak, 2017). Results will be presented and compared with those from other parts of the world – from Malaysia (the Bakun HPP on the Balui river) (Ling et al., 2016) and Lithuania (17 HPPs on the rivers Virvytė, Varduva, Venta, Obelis and Šušve) (Vaikasas et al., 2015).

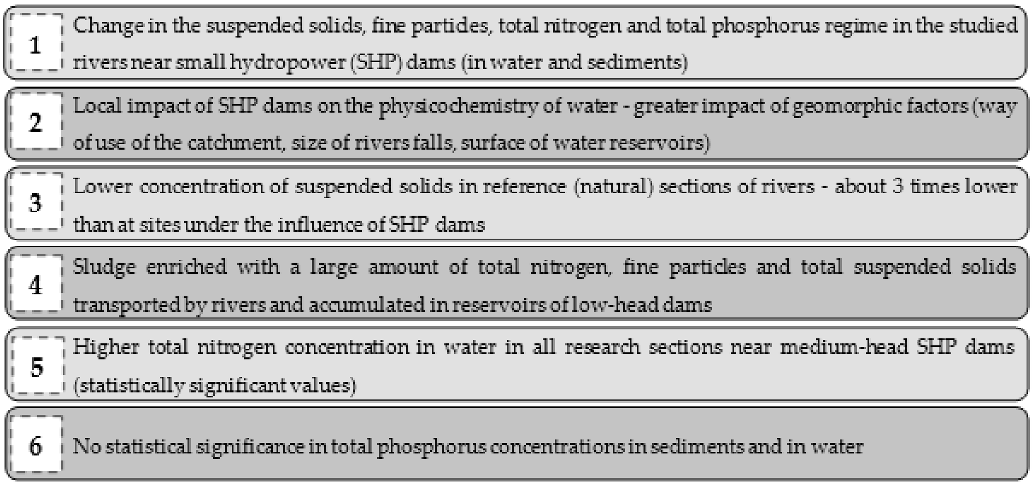

Fig. 2. Conclusions from the research carried out on hydropower plants on the Virvytė, Varduva, Venta, Obelis and Šušve rivers in Lithuania (based on Vaiksas et al., 2015)

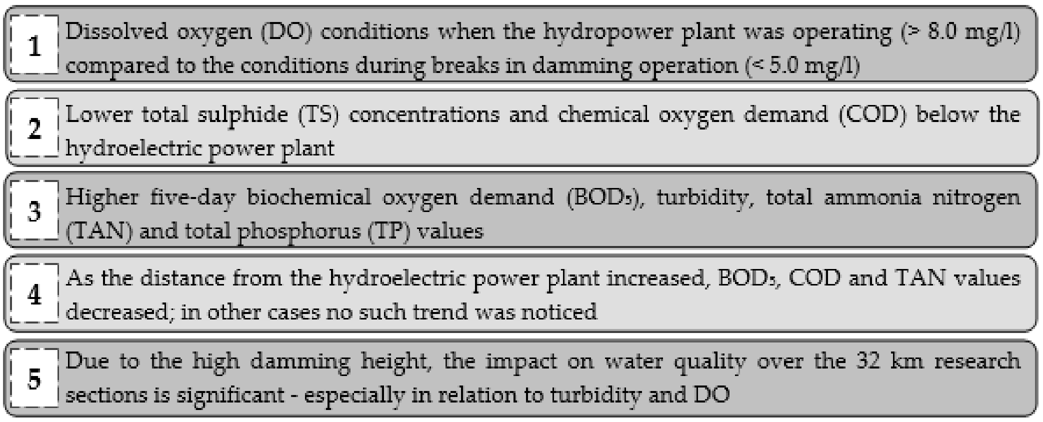

Fig. 3. Conclusions from the research carried out below the Bakun hydropower plant on the Balui River, Malaysia (based on Ling et al., 2016)

The article analyzes the impact of HPP operation on selected physicochemical parameters of water and compares the obtained results with the results on different HPPs. The goal is also to identify other potential sources of pollution affecting the physicochemistry in the Michalice Reservoir. In the future, it is planned to research other facilities which would make it possible to build a much larger base for creating the most accurate model of WQ. As a result, it will be possible to determine the potential impact of HPPs on the aquatic environment, which may allow such facilities to operate in accordance with the principles of sustainable development. It should be added that so far there has been no focus on the issue of the impact of small reservoir HPPs on physicochemical conditions of water. If such tests were conducted, they concerned run-of-river HPPs or focused on several parameters.

2. Material and methods

The research area includes the Michalice Reservoir on the Widawa River along with a short section of the Widawa River above and below the water reservoir, as well as a left reservoir tributary – the Studnica River. The Michalice Reservoir is an artificial retention reservoir formed on the Widawa River in its middle reaches. The reservoir is located in south-western Poland, in the Opolskie Voivodeship. It was commissioned in 2001. Its surface area is 92 ha. On the dam of the Michalice Reservoir (located at 70.232 km of the Widawa River, catchment area from the source to the reservoir – 520.07 km^2), in its end part, there is a small HPP with an installed capacity of 62.4 kW, damming height 3.3 m and outflow with a discharge of 2.04 m^3/s along with a fish pass enabling free migration of aquatic organisms (Rembielak, 2017).

Agricultural areas constitute 74.1% of the land used in the Widawa River catchment (seminatural areas – 21.1%, artificial surfaces – 4.5%, water bodies – 0.3%). The average annual temperature is 8.5°C and average annual rainfall – 595 mm. Six measurement points were selected for the research: above and below the water reservoir (on the Widawa River), in the middle of the reservoir, on the Studnica River, above and below the HPP dam (bottom drain below the dam). The distances between the water sampling points and the HPP dam are as follows: point 1 – 2750 m, point 2 – 1300 m, point 3 – 5 m, point 4 – 10 m, point 5 – 270 m, point 6 – 2400 m. The choice of points was selected on the basis of the characteristics of the reservoir, the location of its tributaries, and especially the location of the HPP in such a way as to determine the degree of its impact on the WQ in the reservoir (Bajkiewicz-Grabowska, 2002; Rembielak, 2017; Statistics Poland, 2019).

The Michalice Reservoir is classified as category III of water reservoir resistance to degradation, i.e. it is not very resistant to the impact of its catchment (according to Bajkiewicz-Grabowska (2002), its indicator value is 2.0). When assessing its susceptibility to degradation, the density of the river network (0.51 km/km^2) and the average slope of the catchment (2.14%) were also taken into account. These catchment parameters increase the resistance of the Michalice Reservoir to degradation, unlike the ones mentioned earlier.

The measurements were carried out once a month from May 2016 to April 2017 (in February, water samples were not taken due to freezing of the water reservoir). Samples were taken with a scoop into sealed bottles, after which they were transported to the laboratory, where they were marked. As part of the research, the following physicochemical parameters were determined: pH, electrolytic conductivity (EC), turbidity, ammonium nitrogen ($N\text{-}NH_4$), nitrate-nitrogen ($N\text{-}NO_3$), nitrite nitrogen ($N\text{-}NO_2$), phosphate phosphorus ($P\text{-}PO_4$), BOD_5 (Rembielak, 2017).

The limitation of laboratory measurements results from field measurements and location of the selected points. Local anomalies may appear that do not reflect the WQ of the point location (e.g. temporary point pollution). In addition, each laboratory device measures in a limited range and measurement of parameters is burdened with a certain error, mainly due to the characteristics of the apparatus. The research area is shown in Fig. 4.

The classification of results was based on the provisions in force in Poland regarding surface water monitoring (MMEIN, 2019). The measuring points located on the Widawa River (1, 5) were classified as lowland river points, with a catchment area of fewer than 5000 km^2, the point on the Studnica River (6) – as representing a sandy lowland stream, while the other points (2, 3, 4) – as located in a limestone lake with low Schindler's value (<2,0), stratified. In the case of the measuring points 2, 3 and 4, the EC values in the collected water samples were classified, while in other points, apart from EC, also the concentrations of $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$ and $P\text{-}PO_4$ were assessed. These values were compared with the limits specified in the regulation. The assessment is carried out on a 3-point scale, i.e. class I – very good condition, class II – good condition and NMS – condition below good, exceeding the limit values (standards). It should be added that points 1, 5 and 6 are located on natural surface water bodies (ecological status is assessed), while numbers 2, 3 and 4 – on profoundly transformed and artificial water bodies (potential ecological assessment).

For comparison, we selected the studies mentioned above from Lithuania and Malaysia. This choice was dictated by the comprehensiveness of these tests, the detailed analysis of the results obtained and the fact that they are structures of different types – with varying dam heights and various technological solutions (impoundment HPPs, run-of-river HPPs, HPPs on cascade reservoirs). Moreover, the terrain conditions were different (slopes in the catchment, land use, geological structure etc.). All these factors affect the results of physicochemical tests of water.

OriginPro 2016 (OriginLab Corporation), SAS University Edition (Proc Mixed Model) and Canoco 4.5 (Principal Component Analysis – PCA) were used to make the charts and to perform the statistical analysis. For the comparison of the results the mixed model (Proc Mixed) was used, with date as the repeated factor.

Additionally, the environmental data were correlated with each other using the PCA. Fig. 5 schematically illustrates the research methodology.

3. Results and discussion

3.1. This study – the hydropower plant Michalice on the Widawa River, Poland

When analyzing the results of our research carried out in the Michalice Reservoir on the Widawa River in Poland (averaged measurements of physicochemical parameters and the corresponding standard deviation, as in Table 1), we conclude that the physicochemical parameters being considered reached different values. Some of the parameters being tested differed between the sampling points. This was the case of pH, turbidity and BOD_5 (Table 1). The pH was significantly higher at point 4 compared to point 3. The turbidity was the lowest at point 1 and the highest at point 5 ($p < 0.001$). The BOD_5 value was significantly higher at sampling points 2, 3, 4, 5, compared to sampling points 1 and 6 ($p = 0.009$).

Water temperature. Seasonal variability of results is visible, i.e. the lowest values were recorded in winter (December-January, the minimum value of 0 ℃ at points 2, 3, 6), and higher values in summer (the maximum temperatures from May to August, with maximum 19.7 ℃ at point 3 in August). Intermediate values were recorded in autumn and spring. Due to this diversity, the reservoir can be classified as being stratified in the annual cycle. The average temperature was lower in the inflowing river and the river above the water reservoir than that in the reservoir itself and the immediate vicinity below the water reservoir (Table 2).

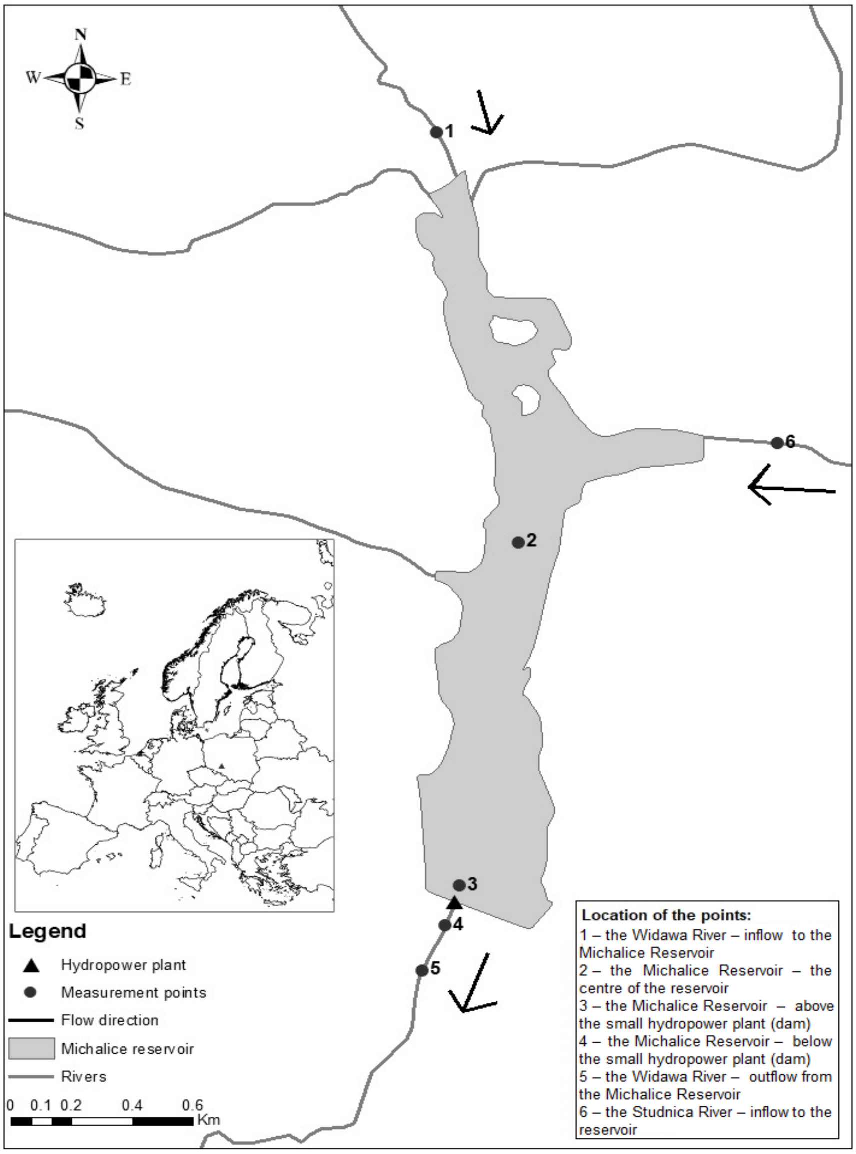

Fig. 4. Location of the research area and location of water sampling points for the physicochemical tests

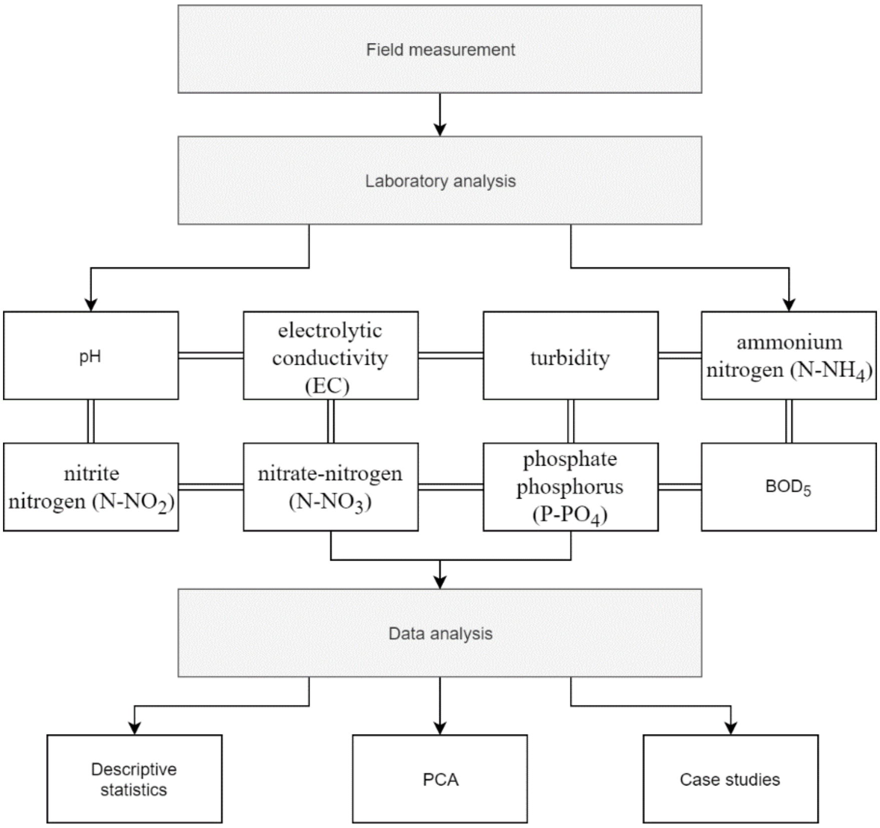

Fig. 5. Diagram of the methodology of scientific research

pH. The pH values showed a slight variation and ranged from pH 6.6 to 8.3 with a median ranging from 7.3 to 7.7 (Table 1).

Electrolytic conductivity EC. The situation with the EC is similar to that of pH, whose median does not differ significantly between points (ranging from 608 to 625.5 µS/cm; Table 1).

Turbidity (turb). Compared to the values obtained for the river reach above the reservoir and the Studnica River, turbidity is noticeably higher at points located in the water reservoir and below it. The highest values were recorded on the Widawa river below the reservoir (median 5.64 NTU; Table 2) and the lowest – on the Widawa river above the reservoir and the Studnica River (median 1.55 and 2.56 NTU, respectively). The turbidity values were the highest in summer (June – September; Fig. 6-8), and the lowest – in autumn and winter (November to January and March). In this situation, one may conclude that the HPP does not have a significant effect on turbidity. In this case, the impact of the water reservoir is more pronounced (although the measuring points 2, 3, 4 and 5 are located below the Studnica River, the turbidity values there are higher than those at point 6 located on this river and these concentrations increase with the course of the river, reaching their maximum at point 5, below the Michalice Reservoir, rather than directly below the HPP; at point 4; below the HPP these concentrations are lower than those above the plant).

Table 1. Averaged physicochemical parameters at points in the Michalice Reservoir

Parameters	***Sampling point***						***F, p***
	1	***2***	***3***	***4***	***5***	***6***	
Temp, ℃	8.9±6.9	9.8±7.4	10.4±7.3	10.3±7.0	10.7±6.9	9.8±6.6	0.10; 0.99
pH	7.3±0.3	7.4±0.4	7.4±0.6**b**	7.7±0.5**a**	7.5±0.5	7.5±0.4	2.38; 0.05
EC, µS/cm	593±66	623±68	607±56	609±59	619±43	614±50	0.62; 0.70
Turb, NTU	2.5±3.0b	4.7±3.5ad	6.7±6.7ad	6.4±5.5ad	7.5±5.6ac	4.0±3.2d	12.35; <0.001
$N\text{-}NH_4$, mg/L	0.071±0.059	0.061±0.088	0.059±0.061	0.057±0.058	0.235±0.208	0.084±0.069	2.33; 0.18
$N\text{-}NO_3$, mg/L	7.8±6.6	6.8±7.4	5.9±8.3	6.2±7.7	5.2±6.7	5.4±4.7	1.88; 0.11
$N\text{-}NO_2$, mg/L	0.028±0.022	0.045±0.022	0.058±0.033	0.052±0.022	0.047±0.017	0.059±0.041	1.43; 0.12
$P\text{-}PO_4$, mg/L	0.061±0.029	0.132±0.263	0.083±0.156	0.050±0.038	0.081±0.044	0.071±0.034	0.54; 0.74
BOD_5, mg/L	1.6±0.8bd	2.8±1.3a	2.8±1.0a	2.6±0.8a	2.8±1.0a	2.1±1.0bc	3.39; 0.009

Mean ± confidence interval at the significance level α = 0.05; F, p = results of mixed model (ProcMixed model); a, b, c, d = significant differences between means in rows.

Table 2. Essential statistical data on the physicochemical results at the sampling points in the Michalice Reservoir, May 2016 – April 2017

Parameter	***Sampling point***	x_{av}	***Mdn***	x_{min}	x_{max}	***SD***	***CV***
Temp, ℃	1	8.93	7	0.5	18.4	6.584	77.35
	2	9.77	8	0	19.1	7.068	75.855
	3	10.39	8	0	19.7	6.993	70.582
	4	10.29	9	1	19.1	6.661	67.884
	5	10.65	10	1	19.2	6.578	64.806
	6	9.75	9	0	18.2	6.249	67.247
Turb, NTU	1	2.49	1.55	0.87	11.5	2.896	122.131
	2	4.74	3.805	0.88	11.8	3.29	73.215
	3	6.68	4.05	1.76	25.1	6.426	100.906
	4	6.41	4.28	1.51	20.6	5.278	86.299
	5	7.54	5.64	1.73	21.4	5.327	74.127
	6	3.69	2.56	1.5	13.1	3.085	81.736
$N\text{-}NH_4$, mg/L	1	0.07	0.05	0.02	0.22	0.056	83.063
	2	0.06	0.025	0.01	0.25	0.083	143.634
	3	0.06	0.03	0.01	0.21	0.058	102.787
	4	0.06	0.03	0.01	0.2	0.055	101.538
	5	0.023	0.16	0.01	0.63	0.199	88.767
	6	0.08	0.06	0.01	0.21	0.066	82.191
$N\text{-}NO_3$, mg/L	1	7.77	5.67	0.35	21.71	6.307	85.139
	2	6.81	4.165	0.71	24.98	7.058	109.221
	3	5.88	1.95	0.35	26.84	7.923	141.314
	4	6.15	3.81	0.22	25.28	7.379	125.766
	5	5.24	1.55	0.31	21.17	6.337	126.788
	6	5.43	4.045	0.44	14.49	4.77	92.684
$N\text{-}NO_2$, mg/L	1	0.03	0.02	0.01	0.07	0.021	79.055
	2	0.05	0.055	0.01	0.07	0.021	48.29
	3	0.06	0.06	0.01	0.14	0.032	56.91
	4	0.05	0.05	0.01	0.09	0.021	42.995
	5	0.05	0.05	0.01	0.06	0.016	35.512
	6	0.06	0.05	0.02	0.16	0.039	68.723
$P\text{-}PO_4$, mg/L	1	0.06	0.04	0.03	0.11	0.028	48.401
	2	0.13	0.05	0.02	0.88	0.25	199.536
	3	0.08	0.03	0.01	0.55	0.149	188.516
	4	0.05	0.04	0.01	0.14	0.036	75.895
	5	0.08	0.07	0.03	0.15	0.042	54.566
	6	0.07	0.06	0.02	0.14	0.033	48.219
BOD_5, mg/L	1	1.64	1.9	0.6	2.6	0.719	46.079
	2	2.82	2.9	0.6	4.6	1.215	45.406
	3	2.84	2.9	0.7	4.3	0.974	35.999
	4	2.62	2.4	1.1	4	0.789	31.626
	5	2.75	2.8	0.9	4.8	0.952	36.244
	6	2.07	2.2	0.6	3.4	0.923	46.681

It can be assumed that the bottom sediments are retained on the section below the accumulation and that they are accumulated in the river at a certain distance from the dam, outside of the area of the hydraulic rebound. Therefore, additional research on the physicochemical composition of bottom sediment would be required. The monthly values of the selected measured physicochemical parameters (turbidity, $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$, $P\text{-}PO_4$, BOD_5) at the sampling stations near the Michalice Reservoir are shown in Fig. 6 below and the boxplots of the measured values of the physicochemical parameters at the sampling stations – in Fig. 7.

Ammonium nitrogen ($N\text{-}NH_4$). A slightly different situation is observed in the case of $N\text{-}NH_4$. The highest values of this parameter occur at a point below the water reservoir, on the Widawa River (median 0.16 mg/L; Table 2).

The lowest concentrations of $N\text{-}NH_4$ are in the water reservoir and just behind it (median at points 2, 3 and 4, respectively: 0.025, 0.03 and 0.03 mg/L). Compared to the reservoir, these values are twice as high above the water reservoir and in the Studnica River, but three times lower than at point 5. In this case, the HPP acts similarly as in the case of turbidity – provided that immediately below the HPP (point 4) the concentrations of this parameter are similar to those at the point above it (point 3). At a slightly further distance (at point 5), $N\text{-}NH_4$ is present in much more massive amounts (for example 0.63 mg/L in October and 0.54 mg/L in March – Fig. 6-8; at other points the values during these months ranged from 0.02 to 0.03 mg/L and from 0.01 to 0.17 mg/L, so the differences are significant). Presumably, N-NH_4 occurs in the accumulated bottom sediments and debris that remain in contact with water.

There was no apparent seasonal variability in values – only in May and in January the values were outliers – the median was then 0.20 mg/L and 0.13 mg/L at all points. Throughout the series of measurements, the median was 0.05 mg/L.

Nitrate nitrogen (N-NO_3). Significant exceedance of the WQ standards was recorded for N-NO_3: the maximum values reached the measuring points were above 20 mg/L (with a single exception of the Studnica River, where the maximum value was 14.49 mg/L; Fig. 6) whereas the limit value is 2.0 mg/L.

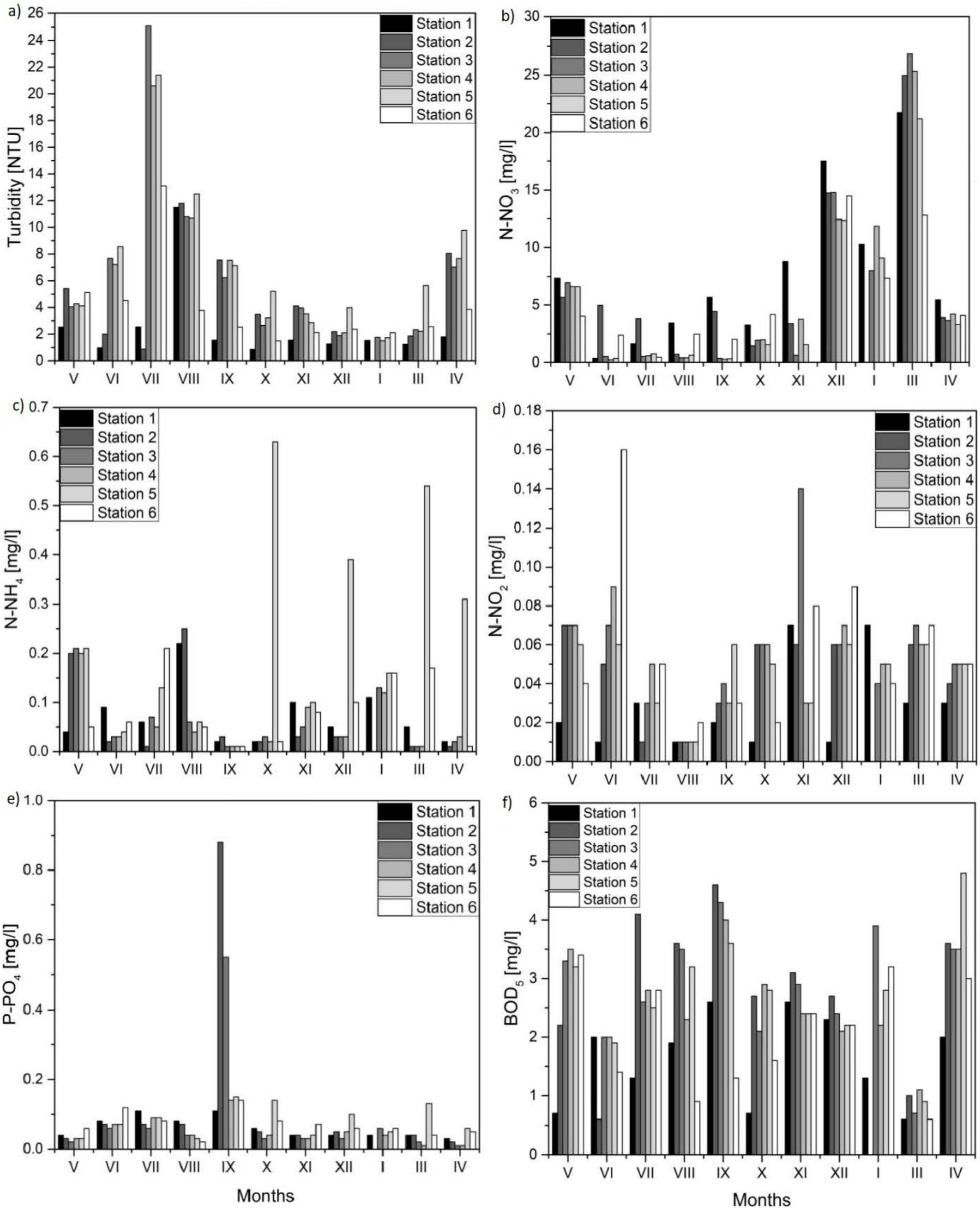

Fig. 6. (a)-(f) Monthly values of selected physicochemical parameters at the sampling stations in the Michalice Reservoir, May 2016 – April 2017

The month with the highest $N\text{-}NO_3$ concentrations is March – a possible reason for this was spring melt – at points on the Widawa River the results were 1.5 times higher than those on the Studnica that flows into it. Throughout the year, the median values differed significantly (Table 2) and the lowest concentrations were recorded at the measuring points 3 and 5 (1.95 and 1.55 mg/L). The highest values were at point 1 (5.67 mg/L). In this case, directly below the HPP, the $N\text{-}NO_3$ concentration was much higher than that above the hydrotechnical building – 3.81 mg/L compared to 1.95 mg/L below the HPP. At a certain distance from the dam (on the Widawa River), this value decreases to 1.55 mg/L. In terms of months, the lowest $N\text{-}NO_3$ concentrations were recorded from June to August (median from 0.44 to 0.67 mg/L with 3.88 mg/L for the year).

Nitrite nitrogen ($N\text{-}NO_2$). The only conclusion that can be drawn is that water above the water reservoir (point 1) is much less enriched in this biogen than for all other sampling points – in this case, the median for the entire year was 0.02 mg/L; Table 2), while at other points it varied from 0.05 to 0.06 mg/L. In terms of seasonal variation, the lowest $N\text{-}NO_2$ values were recorded in August (0.01 mg/L; Fig. 6) and in July and September (0.03 mg/L). In the remaining months these values were even (from 0.05 to 0.07 mg/L). As shown in Fig. 7, the outliers are 0.16 mg/L and 0.14 mg/L – in June at point 6 and in November at point 3, respectively.

Phosphate phosphorus ($P\text{-}PO_4$). $P\text{-}PO_4$ showed some variation (Fig. 6-8) – in September the concentration values were much higher than in other months – ranged from 0.11 (point 1) to 0.88 mg/L (point 2) with a median of 0.15 mg/L. The annual median for this parameter was 0.05 mg/L (Table 2). In terms of comparison between the sampling points, the highest $P\text{-}PO_4$ concentrations were recorded below the water reservoir (point 5; 0.07 mg/L) and in the Studnica River (point 6; 0.06 mg/L), while the lowest was above the HPP dam (point 3; 0.03 mg/L). Therefore, the relationships are similar to those of ammonium and turbidity.

Five-day biochemical oxygen demand (BOD_5). BOD_5 was lowest at point 1 and 6 (median 1.9 mg/L at point 1 and 2.2 mg/L at point 6; Table 2). The BOD_5 values increase significantly when the river enters the water reservoir (Fig. 6-8), temporarily decrease directly below the HPP and increase again on the Widawa River below the reservoir, however, the values are not as low as in the water flowing into the reservoir (median at points 2 and 3 – 2.9 mg/L, at point 4 – 2.4 mg/L, at point 5 – 2.8 mg/L). Although the Studnica River was more enriched with oxygen (which showed by the lower BOD_5; point 6), its higher oxygenation did not change the BOD_5 value in the Michalice Reservoir (point 2). The BOD_5 values in March (0.80 mg/L) with an annual median of 2.4 mg/L were noticeable outliers. The most extreme months in this respect were scattered over time – September (3.8 mg/L), April (3.5 mg/L) and May (3.25 mg/L).

The high values of BOD_5, NO_2 and NH_4 are mainly caused by the following factors: the agricultural use of the catchment (the area from the source to the dam at the end of the Michalice Reservoir; 74.1% in 2018; excessive use of fertilizers and plant protection products), the geological structure (sandy loam), the high share of endorheic (drainage) areas in the catchment (4%), the balance type of the water reservoir (flow type) and the high value of the Ohle index (the ratio of the sum of the catchment area and the reservoir surface to the reservoir surface, which is 664). Rural areas are an additional source of pollution – the sewage system in the communes through which the Studnica River flows along with its tributaries is not well developed and covers only from 23.8% to 72.1% of the area (GDEP, 2020; Bajkiewicz-Grabowska, 2002; Statistics Poland, 2020).

Designations in the table: x_{av} – mean value of the parameter at a given point, *Mdn* – median, x_{min} – minimum value of the parameter, x_{max} – maximum value, *SD* – standard deviation, *CV* – coefficient of variation.

The results of the physicochemical tests indicate that none of the measuring points complied with the standards set by law concerning the assessed physicochemical parameters. The exceptions are some of the parameters evaluated at points located on rivers, at the inflow to the reservoir (point 1) and on the Studnica River flowing into the Michalice Reservoir (point 6) – the concentrations of $N\text{-}NO_3$ and BOD_5 reached values falling within the second class limit of ES, i.e. good condition. Additionally, at point 1, the values of electrolytic conductivity can also be classified as class II. This situation is shown in Table 3.

Table 3. Classification of the physicochemical results in the Michalice Reservoir into selected ecological status/potential classes (classification based on MMEIN, 2019)

Parameters	***Sampling point***					
	1	**2**	**3**	**4**	**5**	**6**
EC, mg/L	II	NMS	NMS	NMS	NMS	NMS
$N\text{-}NH_4$, mg/L	II	-	-	-	NMS	II
$N\text{-}NO_3$, mg/L	NMS	-	-	-	NMS	NMS
$P\text{-}PO_4$, mg/L	NMS	-	-	-	NMS	NMS
BOD_5, mg/L	II	-	-	-	NMS	II

Designations in the table: II – second class of ecological status/potential (good status), NMS – ecological status/potential below good (more than the limit values), - – parameter not included in the regulation.

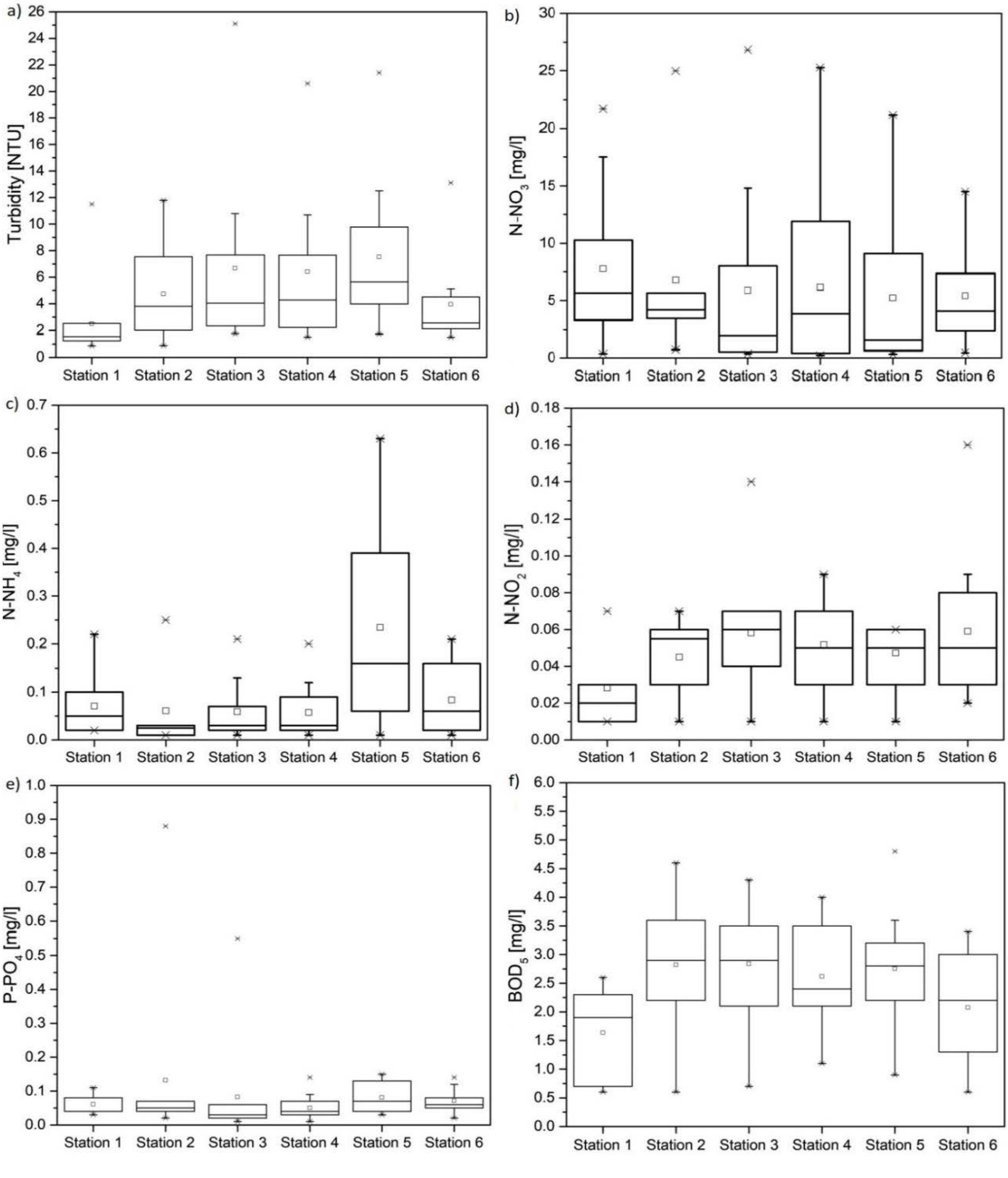

Fig. 7. (a)-(f) Boxplots of selected physicochemical parameters at the sampling stations in the Michalice Reservoir, May 2016 – April 2017

The sum of eigenvalues of the first two PCA axes (PCA 1 and PCA 2) was 0.793 (Table 4). As shown in the PCA plot (Fig. 8A), the main differences between the samples chemical characteristics are for the sampling points 1 and 3. The second plot (Fig. 8B) shows the vectors of specific chemical properties. Turbulence and temperature were highly correlated with each other. The PCA 1 was significantly correlated with N-NH_4 (p=0.0002) and P-PO_4 (0.007), while the PCA 2 was correlated with pH (0.05), EC (0.007) and BOD_5 (0.008) (Table 4, Fig. 8).

In the tests carried out within the HPP on the river in north-eastern Spain, no significant statistical differences were found between most of the parameters tested (temperature, DO, EC), the exception is only pH - these results coincide with those presented (except for EC), they result from similar the methodology adopted (above and below the HPP), field conditions (lowland areas, temperate climate) and HPP capacity (<5 MW) (Álvarez et al., 2020). Similar results in a reservoir HPP in Brazil, with no significant impact of the HPP on physicochemical conditions (analysis based on the Water Quality Index; the biggest change were the increasing turbidity values below the damming - the same results were obtained by Bogen and Bønsnes (2012) in Norway, and also water temperature variability - as Valero showed in Spain (2012), despite the large installed capacity (130 MW) (Pimenta et al., 2012). As it can be seen, most of the research results of other scientists coincide with the results presented in the article.

3.2. Case study I – the hydropower plants in Lithuania, rivers Virvytė, Varduva, Venta, Obelis and Šušve

In terms of $P\text{-}PO_4$ and the various forms of nitrogen, the conclusions of the research carried out by the Lithuanian scientists are consistent with the results obtained in the research on the Michalice Reservoir (Table 5). Changes in parameter values after passing through the HPPs were as follows: Lithuania – TN = 18.3%, TP = 36.9%; Poland – TN = 5.1% (after adding up the nitrogen forms), TP = 66%.

In connection with the results obtained in Lithuania, it is worth considering the physicochemical tests for different heights of the HPPs, landform, as well as testing not only water but also the bottom sediments. The scope of future research should also be broader, enriched with TSS, FP, TN and TP.

3.3. Case study II – the hydropower plant Bakun on the Balui River, Malaysia

When analyzing the research results for Michalice and those for Bakun (Table 6), we found that the values of $N\text{-}NH_4$ and TAN below the HPPs were falling. In both cases, the trends for BOD_5 coincided and were consistent for turbidity (greater turbidity at some distance from the HPP). The maximum differences between the average values (the point closest to the HPP and the point with the most extreme value) were as follows: Bakun – TAN = 45,8%, turb = 46.1%, BOD_5 = 22.9%; Michalice – TAN = 61.8% ($N\text{-}NH_4$ values calculated using a calculator (FDEP, 2019)), turb = 15.0%, BOD_5 = 4.7% (downward trend for BOD_5 in Bakun, upward in Michalice).

Further research should take into account a wider range of measurements, especially DO. Moreover, the operation phases of the Michalice Reservoir should be taken into account due to their possible impact on the final results.

Table 4. Summary statistics from the PCA the physicochemical parameters in the Michalice Reservoir.

Eigenvalues	***PCA 1***			***PCA 2***		***PCA 3*** / ***PCA 4***
	0.476			0.317		0.117 / 0.063
Parameters	***Significance of the axes***					
	PCA 1			***PCA 2***		
	F	***p***	***T-value***	***F***	***P***	***T-value***
Temp, ℃	1.91	0.17	12.04	124.41	0.10	20.35
pH	108.14	0.10	94.92	3.94	**0.05**	59.62
EC, µS/cm	252.30	0.10	115.26	0.008	**0.007**	51.85
Turbidity, NTU	0.104	0.25	8.49	72.66	0.10	12.40
$N\text{-}NO_2$, mg/L	2.40	0.12	6.43	0.013	0.09	6.31
$N\text{-}NH_4$, mg/L	16.22	0.0002	8.02	65.73	0.10	10.20
$N\text{-}NO_3$, mg/L	2.75	0.10	13.61	0.39	0.47	13.37
$P\text{-}PO_4$, mg/L	0.008	0.007	5.12	2.04	0.16	5.20
BOD_5, mg/L	0.86	0.86	18.09	7.43	0.008	18.99

Note: The significance of axes (PCA 1 and PCA 2) was determined using the General Linear Model (GLM).

Table 5. Comparison of selected physicochemical results in our study and in that of Vaikasas et al. (2015) (Lithuania), the mean value of the physicochemical parameters with deviation

Location of point	***Vaikasas et al. study (Lithuania)***		***This study (Michalice, Poland)***			
	Parameters		***Parameters***			
	TN, mg/L	***TP, mg/L***	***$N\text{-}NH_4$, mg/L***	***$N\text{-}NO_3$, mg/L***	***$N\text{-}NO_2$, mg/L***	***$P\text{-}PO_4$,mg/L***
above SHP	7.1±1.6	0.089±0.044	0.059±0.061	6.2±8.3	0.058±0.033	0.083±0.156
below SHP	6.0±2.2	0.065±0.036	0.057±0.058	5.9±7.7	0.052±0.022	0.050±0.038

Table 6. Comparison of selected physicochemical results below the Bakun and Michalice hydropower plants (average values of physicochemical parameters)

Distance below Bakun dam, km	***Parameters***			***Distance below Michalice dam, km***	***Parameters***		
	TAN, mg/L	**Turb, NTU**	**BOD_5, mg/L**		**TAN, mg/L**	**Turb, NTU**	**BOD_5, mg/L**
4.3	0.24	41	4.3	**0.01**	0.078	6.41	2.62
9.9	0.16	43	4.1	**0.27**	0.0298	7.54	2.75
17.5	0.13	76	4.0				
24.9	0.14	61	3.8				
32.1	0.15	62	3.5				

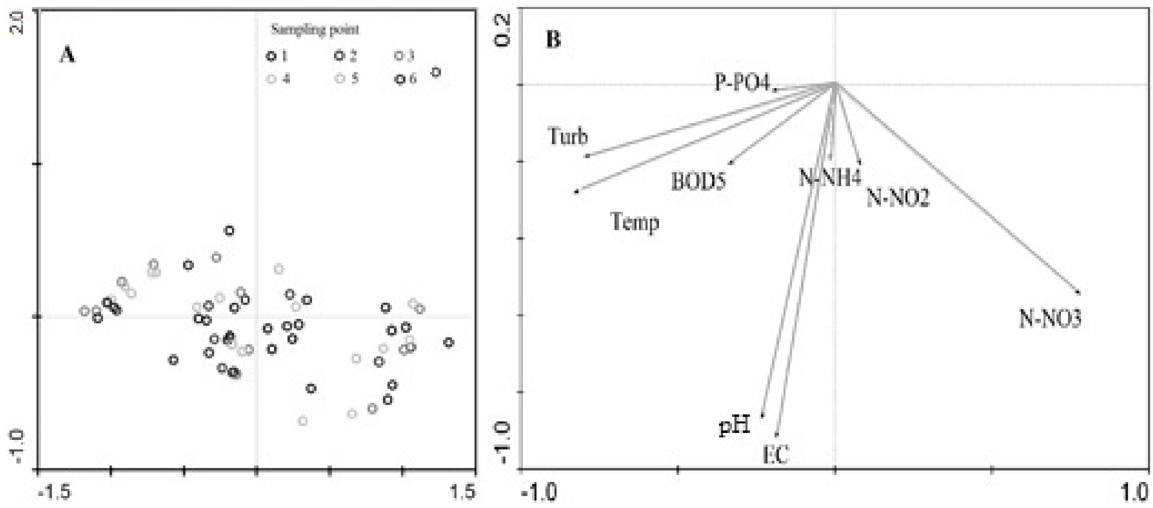

Fig. 8. PCA plots presented as samples (A) in correlation with physicochemical parameters (B)

4. Conclusions

An analysis of the data presented in this article leads us to several conclusions and suggestions for further work:

1) The test results obtained at six measurement points at the Michalice Reservoir and its HPP indicate a high level of water pollution. High values of BOD_5, NO_2 and NH_4 are caused mainly by the agricultural use of the catchment, the geological structure, the high share of endorheic (drainage) areas in the catchment, the balance type of the reservoir (flow type), the high value of the Ohle index and the uncontrolled sewage discharge (low sewerage index in communes within the catchment area). To reduce the values of the given parameters, it is necessary to reduce pollution from agricultural sources (e.g. the use of fertilizers), increase the level of sewerage of the area or use biological methods of water purification (e.g. by using zooplankton that consumes cyanobacteria causing eutrophication), etc.

2) Turbidity and N-NH_4 reached the highest values in the reach below the Michalice Reservoir, at a certain distance from the HPP (median value: 5.64 NTU and 0.06 mg/L, respectively). The lowest turbidity values were recorded at the inflow to the water reservoir (median value: 1.55 NTU). The N-NH_4 concentrations were the lowest at the beginning of the water reservoir and increased gradually along the course of the river (median value: 0.025 mg/L; the Studnica River is a source of N-NH_4 supply to the Michalice Reservoir). The water temperature changed cyclically throughout the year, reaching minimum values in winter (minimum 0°C in January) and maximum values in summer (maximum 19.7°C in August).

3) The results obtained in the Michalice Reservoir indicate that in general the physicochemical parameters exceeded the limits set by the applicable regulation (EC, BOD_5, P-PO_4, N-NO_3 and N-NH_4).

4) When analyzing the Impact of the Michalice Reservoir HPP on the Widawa River on WQ, it was found that the concentrations of P-PO_4, N-NH_4 and turbidity increase below the Michalice HPP – point 3 (by 39.3%, 430% and 130%, respectively, compared to the median value at the measuring point above the HPP – point 4), while the concentrations of N-NO_3 directly below the dam increase (an increase of 95.4% compared to the median above the HPP).

5) The measured parameters differed between sampling stations in the case of pH, turbidity and BOD_5. Compared to point 3, the value of pH at point 4 was significantly higher. The turbidity was the lowest at point 1 and the highest at point 5 ($p < 0.001$). The BOD_5 value was significantly higher at points 2, 3, 4, 5, compared to points 1 and 6 ($p = 0.009$).

6) The results obtained for the Michalice Reservoir and those of the tests carried out in Lithuania and Malaysia are similar – at some distance from the HPPs, the turbidity of water increases while the concentrations of N-NO_3, P-PO_4 and N-NH_4 decrease below the HPPs. Changes in the average parameter values after passing through the HPPs were as follows: Lithuania – TN = 18.3%, TP = 36.9%; Malaysia – TAN = 45,8%, turbidity = 46.1%; Poland – TN = 5.1%, TP = 66%, turbidity = 15.0%.

7) The presented WQ assessments within the reservoir HPP form the basis for further research on rational, sustainable water management at hydropower facilities.

List of abbreviations

BOD_5	five-day biochemical oxygen demand
COD	chemical oxygen demand
DO	dissolved oxygen
EC	electrolytic conductivity
EU	European Union
FP	fine particles
HPP(s)	hydropower plant(s)
N-NO_2	nitrite nitrogen
N-NO_3	nitrate nitrogen
PCA	Principal Component Analysis
P-PO_4	phosphate phosphorus
RES	renewable energy sources
TAN	total ammonia nitrogen
TN	total nitrogen

TP	total phosphorus
WFD	Water Framework Directive
WQ	water quality

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