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## HYDROCHEMICAL DIFFERENTIATION OF SELECTED RESERVOIRS IN CARPATHIAN MTS. AND EASTERN EUROPEAN LOWLAND

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### Abstract

The aim of the analysis was to compare physicochemical parameters and chemical composition of two groups of artificial reservoirs, mountain and lowland ones, characterised by different parameters and functions. Three mountain artificial reservoirs (Klimkówka, Dobczyce, Czorsztyn) located in the Upper Vistula basin (Carpathian Mountains in Poland) and three lowland reservoirs (Ivankovo, Verhnevolzhskoye, Vyshnevolotzkoye) located in the Upper Volga basin (Eastern European Lowland in Russia) were selected for the study. Data for the summer season in 2009-2013 were used in the analysis. Mountain reservoirs display high water concentrations of sulphates, chlorides and biogenic nitrates, and lower concentrations of ammonium and oxygen indicator in relation to lowland reservoirs. Similar concentrations of phosphates were noticed in both the mountain and the lowland reservoirs. The hydrochemical differentiation between the individual mountain reservoirs was small, and statistically significant differences only occurred for SEC. Greater differentiation of the hydrochemical parameters was found among the lowland reservoirs. Statistically significant differences were demonstrated with regard to SEC, Cl and NO<sub>3</sub><sup>-</sup>.

### Key words

water chemistry • lowland reservoirs • mountain reservoirs • Upper Volga basin • Vistula basin

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## Introduction

Reservoirs play an important role in the geochemical cycle of elements and influence the chemical composition of surface water (Hannan, 1979; Palmer & O'Keefe, 1990; Ceron et al., 2014; Van Cappellen & Maavara, 2016). Dam reservoirs are the receivers of water and sediments as well as pollutants from the upstream catchment and they constitute the ecosystems that are especially exposed to the negative effects of anthropogenic pressure (Thornton, Kimmel, & Payne, 1990; Mihailova, Traykov, Tosheva, & Nachev, 2013). Chemical composition of water in reservoirs comes from the feeding river system, precipitation, weathering and geochemical processes in the catchments and reservoirs as well as anthropogenic sources (Hannan, 1979; Palmer & O'Keefe, 1990).

The concentration dynamics of water chemical elements in reservoir changes on a daily (Jekatierynczuk-Rudczyk, Gorniak, Zielinski, & Dziemian, 2002) and an annual basis (Li, Ye, & Zhang, 2017; Pawar & Shembekar, 2012) and depends on the hydrometeorological conditions (Major & Cieśliński, 2017). Analysis of the chemistry of reservoir water is mainly aimed at discerning the temporal and spatial dynamics of concentrations of the individual chemical constituents and of the physicochemical parameters (Kennedy & Walker, 1990; Kijowska-Strugała, Wiejaczka, & Kozłowski, 2016; Wiejaczka, Prokop, Kozłowski, & Sarkar, 2018). Several studies concerned factors affecting the chemical composition of reservoir water and determined its quality for the habitat conditions of aquatic organisms (Hou et al., 2016; Savichev & Matveenko, 2013). Investigation of water chemistry in reservoirs with various functions demonstrated great chemical elements differentiation between the reservoirs (Obeidat, Alomary, Sekhaneh, Al-momani, & Hamid, 2011). This causes difficulties in formulating general conclusions regarding hydrochemical similarities and differences between the studied objects. Especially mountain and lowland areas are characterized by a different

dynamics of the natural environment. In particular, hydrological processes are characterized by greater variability in mountainous areas than lowland ones (Viviroli & Weingartner, 2004). For this reason, can be expected the differences between mountain and lowland reservoirs in the water chemistry should be distinct.

In the scientific literature there is a gap of the analysis which compare the water chemistry (and based on it water quality) between reservoirs located in contrasted – mountain and lowland regions. Such comparison in relation to different environmental areas is difficult because the chemical composition of water is conditioned by many overlapping natural and anthropogenic factors. An additional difficulty is the large variety of functions that water reservoirs fulfill. The importance of comparative research of water chemistry in reservoirs results from the possibility of using such analyses to assess and forecast global changes in the aquatic environment.

The aim of the study is to compare water physicochemical properties between artificial reservoirs with different parameters and functions located in the same – Carpathian Mountains and Eastern European Lowland regions as well as between these regions. The analysis was focussed on discerning the differences in concentrations of selected chemical constituents and physicochemical parameters that determine the quality of water. It was hypothesized that mountain and lowland reservoirs are characterized by a distinct diversity of chemical properties of water. The analysis was conducted for the summer season. In the temperate climate, the physicochemical and chemico-biological processes in the aquatic environment of artificial reservoirs are most intensive in the summer.

## Study area

Three mountain artificial reservoirs located in the Upper Vistula basin (Carpathian Mts. in Poland) and three lowland reservoirs

in the Upper Volga basin (Eastern European Lowland in Russia) were selected for the study. In the Upper Vistula basin, the analysis comprised the Klimkówka reservoir on the Ropa River, Dobczyce reservoir on the Raba River and the Czorsztyn reservoir on the Dunajec River. In the Upper Volga basin, the Ivankovo reservoir, the Verhnevolzhskoye reservoir on the Volga River and the Vyshnevolotzkoye reservoir on the tributary of the Volga River (Cna and Szlina Rivers) (Tab.1, Fig.1) were selected for the analysis. The primary criterion for the selection of the reservoirs was the differentiation of functions and parameters as well as the availability of hydrochemical data allowing the analysis of the chemical composition over a long-term period.

The study reservoirs in the Upper Vistula basin are located within the Outer Western Carpathians. Geologically, this area comprises several overlapping nappes made of sandstones, conglomerates and Paleogene and Upper Cretaceous shales (Carpathian Flysch). According to the Köppen (1931) climate classification the reservoirs in the Carpathians are in a zone of humid continental climate with warm summer and

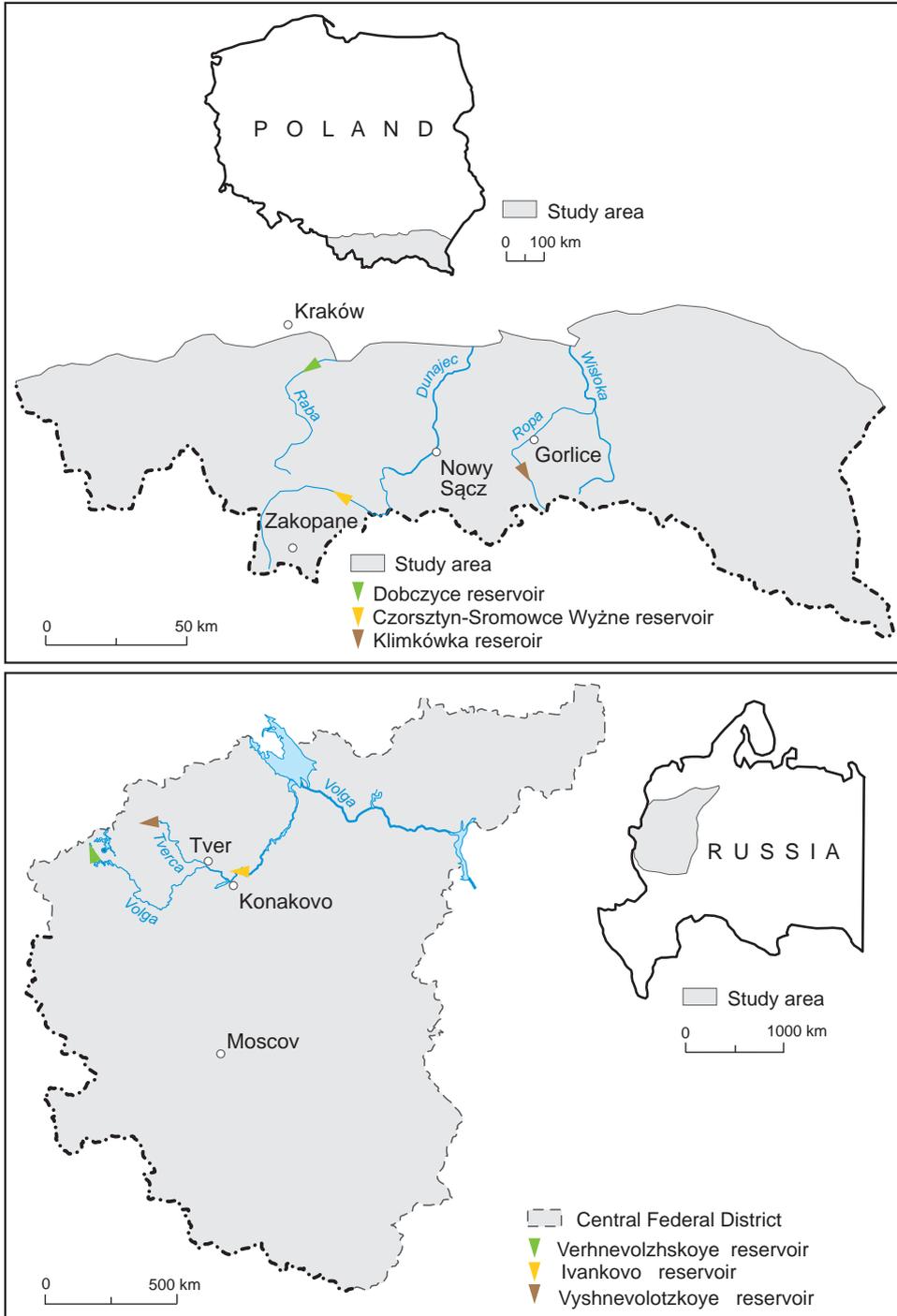
no precipitation difference between seasons (Cfb). The average annual temperature range between 7-8.5°C, and annual precipitation varies between 600 and 1100 mm (Cebulska & Twardosz, 2014).

The chemical composition of river water in the catchments of the studied reservoirs is determined by the geology, land cover and use, development of the sanitary infrastructure as well as the hydrometeorological conditions (Kopacz & Twardy, 2012). In the Ropa catchment, with the Klimkówka reservoir, the chemistry of the river water is affected by both natural factors and pollutants of agricultural origin. Agricultural land covers about 54% of the area, including 25% of arable land while forests occupy 43% of the catchment (CLC, 2014). There is also an unsolved problem of insufficient treatment of wastewater in this region. The Raba catchment, with the Dobczyce reservoir, is of an agricultural and recreational character. Above the reservoir, there are three urban centres, Myślenice, Mszana Dolna and Rabka. Despite sewage treatment plants being in place, there are deficiencies in the sewer network, especially in the rural areas. Furthermore, there are

**Table 1.** Basic characteristics of the studied mountain and lowland reservoirs

Characteristics	Mountain reservoirs			Lowland reservoirs		
	Klimkówka	Dobczyce	Czorsztyn	Ivankovo	Verhnevolzhskoye	Vyshnevolotzkoye
River	Ropa	Raba	Dunajec	Volga	Volga	Cna and Szlina
Year of construction	1994	1986	1997	1937	1843	1719
Dam location in the river course (km)	54	60	173	2,970	3,425	188
Catchment area (km <sup>2</sup> )	210	768	1,147	41,000	3,500	4,710,188
Total capacity (mln m <sup>3</sup> )	43	127	234	1120	524	322
Maximum depth (m)	30	28	50	19	16	12
Average water exchange rate (per a year)	3	4	4	10	2	3
Reservoir functions*	F, L, E, R	F, W	E, F, W, R	E, F, W, R, N, FF	L, W, R, N,	E, L, W, R, N

\*E – energy production, F – flood protection, L – low flow increasing, W – drinking water providing, R – recreation, N – navigation, FF – fish-farming



**Figure 1.** Location of the studied reservoirs in the Carpathian Mts. (Poland) and the Eastern European Lowland (Russia)

holiday houses located within the catchment. Sewage from these facilities ends up in a river flowing into the reservoir. Increased ion supply to the reservoir water is also caused by a considerable percentage of arable land (up to 64%) and the relatively steep gradient of the slopes contributing to the processes of soil erosion (Kopacz, Drzewiecki, & Twardy, 2011). The Dobczyce reservoir is the main source of drinking water for the urban agglomeration of Kraków. The Czorsztyn reservoir closes the catchment of the Upper Dunajec. The major sources of ions concentration are municipal and industrial sewage (including tanning waste) and non-point source of agricultural origin. The area of arable land in the upper course of the Dunajec has decreased by approx. 17% since the early 1990s. Concurrently, an increase in the area of wasteland as well as urban areas is observed – on average by 4% (Kopacz & Twardy, 2012).

The lowland reservoirs catchments are situated in the central part of the crystalline substrate of the Eastern European Lowland within the Moscow Depression that is filled with Permian and Jurassic deposits of 1,500-3,000 m thick. Tertiary sediments are exposed in river channels while the interfluvies are covered with Quaternary deposits. The area was covered by glaciers during the Moscow and Valdai glaciations. The post-glacial deposits have a thickness of several tens of meters and consist of boulders, clays and sands. This area rises to an altitude of 120-178 m a.s.l. and has a warm humid continental climate (Cfb), like the Carpathian reservoirs in Poland. The average annual temperature is 3.8°C, and the daily temperatures during summer reach from 15°C to 25°C. The warmest month is July, and the coldest ones are January and February (mean temperature: -9 to -17°C). Annual precipitation varies between 500 and 800 mm (Gravenhorst et al., 2000).

The Upper Volga basin is mainly overgrown by spruce forests. In the Verhnevolszhskoye and the Ivankovo catchments, forest covered 66% and 39% of the area respectively.

Agricultural land occupied 31% while settlement 5% (The national report..., 2013). Among the anthropogenic factors, of the greatest significance with regard to ions concentration of surface water is industrial, agricultural and municipal sewage. The greatest amount of pollutants comes to the Ivankovo reservoir from the Tver town (Lantsova, Grigor'eva, & Tikhomirov, 2005).

## Material and methods

The study presents the differentiation of the water chemical composition from the selected mountain reservoirs (the Upper Vistula) as well as the lowland ones (the Upper Volga) in the summer season in 2009-2013. It was assumed that the summer season is represented by a measurement taken in one of the summer months (July or August). The choice of a five-year period was dictated by the availability of data. Data used for the analysis of water chemistry in the Carpathian reservoirs were collected from the monitoring conducted by the Regional Inspectorate for Environmental Protection in Kraków. The data from the Ivankovo Research Station of the Water Problems Institute, Russian Academy of Sciences were used for the water chemical composition analysis in the lowland reservoirs (in the Upper Volga basin). Water samples were taken from the water surface in the lower parts (near dams) of the studied reservoirs.

The following physicochemical parameters of the waters were analysed:

- general physicochemical properties of the water: pH, specific electrical conductance (SEC);
- water salt composition: sulphates ( $\text{SO}_4^{2-}$ ), chlorides ( $\text{Cl}^-$ );
- biogenic element concentrations: phosphates ( $\text{PO}_4^{3-}$ ), ammonium ( $\text{NH}_4^+$ ), nitrate ( $\text{NO}_3^-$ );
- oxygen indicator: Biochemical Oxygen Demand ( $\text{BOD}_5$ ).

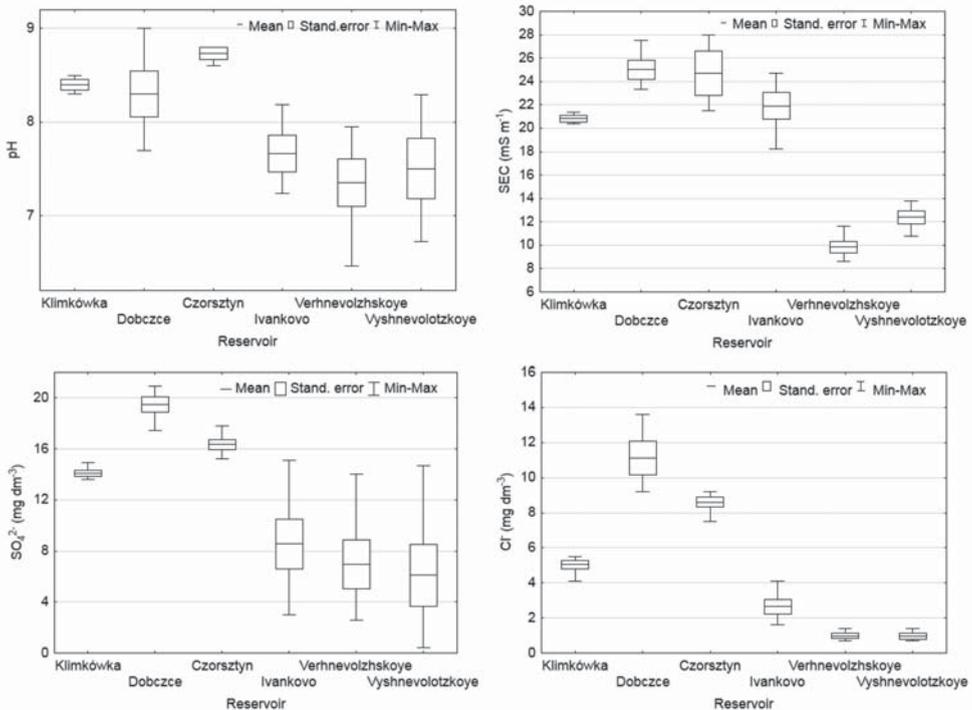
The non-parametric Mann-Whitney U Test was used for checking statistically significant differences ( $p < 0.05$ ) of variables.

## Results and discussion

The analysis of the basic physicochemical parameters in the summer season (2009-2013) in the Polish Carpathian reservoirs: Klimkówka, Dobczyce, and Czorsztyn, demonstrated slight differences between them (Tab. 2, Fig. 2). The highest average pH of 8.73 was recorded in the Czorsztyn reservoir. This value was higher than in the Klimkówka and Dobczyce reservoirs by 0.33 and 0.43, respectively. Thus, water stored in the mountain reservoirs was slightly alkaline. Values of pH noted in summer season are higher than the annual values noted in other Carpathian reservoirs (Romanescu, Miftode, Pintilie, Stoleriu, & Sandu, 2016; Jachniak, Jaguś, Młyński, & Nycz, 2019). It could be related to the intensive photosynthesis in the summer season, when the strong development of phytoplankton and increased photosynthesis

may lead to alkalization and increased pH of water (Puczyńska & Skrzypski, 2009).

The highest values of specific electrical conductance (SEC) were observed in the Dobczyce and Czorsztyn reservoirs, on average 25.0 and 24.7  $\text{mS}\cdot\text{m}^{-1}$  (Fig. 2, Tab. 2). The main indicators of water salinity, beside electrical conductivity, are chlorides and sulphates. They may be supplied to water inter alia through sewage discharges or as a result of improper soil fertilisation (Müller & Gächter, 2012; Leslie & Lyons, 2018). The average concentration of chlorides and sulphates was highest in the Dobczyce reservoir, 11.1 and 19.5  $\text{mg}\cdot\text{dm}^{-3}$ , respectively. In the Klimkówka and Czorsztyn reservoirs, the average values of these ions were lower by 6.1  $\text{mgCl}\cdot\text{dm}^{-3}$  and 5.4  $\text{mgSO}_4\cdot\text{dm}^{-3}$  (Klimkówka), 2.5  $\text{mgCl}\cdot\text{dm}^{-3}$  and 3.2  $\text{mgSO}_4\cdot\text{dm}^{-3}$  (Czorsztyn). According to Leslie and Lyon (2018) the concentration of chlorides may also depend on precipitation amounts in summer season.



**Figure 2.** Physicochemical parameters and water salt composition in the studied mountain and lowland reservoirs in the summer season (2009-2013)

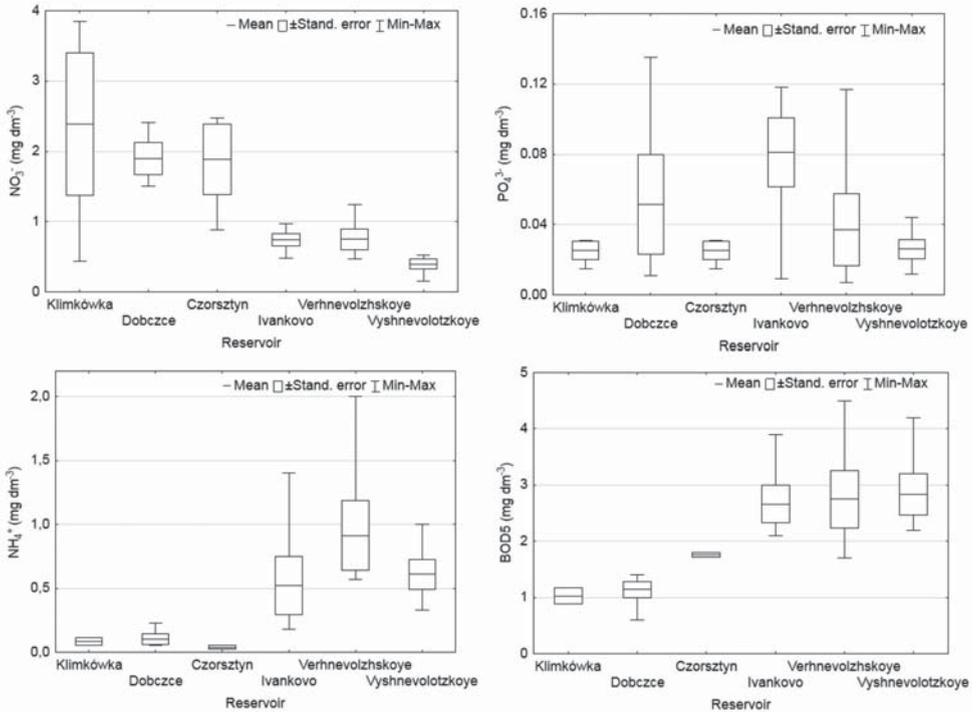
**Table 2.** Mean summer characteristics of water chemistry in the mountain and lowland selected reservoirs in the period (2009-2013)

Parameter	Mountain reservoirs			Lowland reservoirs		
	Klimkówka	Dobczyce	Czorsztyn	Ivankovo	Verhnevolzhskoye	Vyshnevolotzkoye
Average						
pH (-)	8.40	8.10	8.73	7.67	7.35	7.50
SEC (mS m <sup>-1</sup> )	20.80	25.00	31.40	21.92	9.84	12.40
BOD <sub>5</sub> (mg dm <sup>-3</sup> )	1.03	1.14	1.76	2.66	2.75	2.83
SO <sub>4</sub> <sup>2-</sup> (mg dm <sup>-3</sup> )	14.10	19.49	16.30	8.56	6.94	6.10
Cl <sup>-</sup> (mg dm <sup>-3</sup> )	5.00	11.12	8.64	2.64	0.98	0.78
PO <sub>4</sub> <sup>3-</sup> (mg dm <sup>-3</sup> )	0.03	0.05	0.03	0.08	0.04	0.03
NH <sub>4</sub> <sup>+</sup> (mg dm <sup>-3</sup> )	0.08	0.10	0.04	0.52	0.91	0.61
NO <sub>3</sub> <sup>-</sup> (mg dm <sup>-3</sup> )	2.39	1.90	1.89	0.74	0.75	0.40
Coefficient of variation (%)						
pH	1.2	6.5	1.3	5.1	7.7	8.6
SEC	2.5	7.4	13.2	11.5	11.3	10.0
BOD <sub>5</sub>	20.0	28.2	3.2	28.0	42.0	28.8
SO <sub>4</sub> <sup>2-</sup>	3.5	7.0	5.7	51.1	61.7	88.7
Cl <sup>-</sup>	11.1	19.1	7.7	36.2	34.9	34.9
PO <sub>4</sub> <sup>3-</sup>	35.4	109.5	35.4	54.0	122.8	47.7
NH <sub>4</sub> <sup>+</sup>	53.4	82.5	47.1	97.0	66.7	42.3
NO <sub>3</sub> <sup>-</sup>	73.7	24.5	46.2	27.7	44.4	38.6

One of the basic nutrients of surface water are nitrates (NO<sub>3</sub><sup>-</sup>). Their sources are sewage, fertilised soils runoff, precipitation and biochemical decomposition of organic nitrogen compounds (Zhao, Zheng, Jia, Chen, & Zhao, 2019). The analysis demonstrated that the average content of NO<sub>3</sub><sup>-</sup> in the Klimkówka reservoir was the highest, 2.39 mg·dm<sup>-3</sup> (0.54 mgN·NO<sub>3</sub><sup>-</sup>·dm<sup>-3</sup>). This value was higher by 0.50 mg·dm<sup>-3</sup> (0.11 mgN·NO<sub>3</sub><sup>-</sup>·dm<sup>-3</sup>) than in the Czorsztyn and Dobczyce reservoirs (Fig. 3, Tab. 2). These values are similar to those recorded in other mountain areas (Stuchlík, Hořícká, Prchalová, Křeček, & Barica, 1997; Romanescu et al., 2016). It should be noted that in the Polish Carpathians the annual nitrate content in reservoirs decrease in the last years mainly due to increase

of grassland area at the expense of cultivated land and dynamic development of sanitary infrastructure (Kijowska-Strugała et al., 2016).

Other major biogenic substances, beside nitrates, affecting the quality of surface water are phosphates (PO<sub>4</sub><sup>3-</sup>). In the Dobczyce reservoir, the average phosphate content was 0.05 mg·dm<sup>-3</sup>. This value was higher than in other two analyzed mountain reservoirs (average 0.03 mg·dm<sup>-3</sup>). An additional biogenic ion considered in the context of water chemistry was NH<sub>4</sub><sup>+</sup>. The highest average concentrations of ammonia were recorded in the Dobczyce reservoir, 0.10 mg·dm<sup>-3</sup> while the lowest in the Czorsztyn reservoir, 0.04 mg·dm<sup>-3</sup> (Fig. 3). The main anthropogenic sources of ammonia are industrial wastewater or domestic sewage (Fu, Zheng,



**Figure 3.** Biogenic element concentrations ( $\text{NO}_3^-$ ,  $\text{PO}_4^{3+}$ ,  $\text{NH}_4^+$ ) and oxygen indicator ( $\text{BOD}_5$ ) in the studied mountain and lowland reservoirs in the summer season (2009-2013)

Zhao, Wang, & Liu, 2012). In mountain reservoir in Romania (Eastern Carpathians) the concentration of  $\text{NH}_4^+$  was higher (0.21-0.75  $\text{mg}\cdot\text{dm}^{-3}$ ) than in analyzed reservoirs in Polish Carpathians.

In the Czorsztyń reservoir, the value of the  $\text{BOD}_5$ , specifying the amount of oxygen used by the microorganisms in the process of oxidising organic substances, was the highest, 1.80  $\text{mg}\cdot\text{dm}^{-3}$  (Fig. 3). This value indicated a small load of organic contaminants.

Water stored in the lowland reservoirs was characterised by lower values of pH and SEC than in the mountain reservoirs. The pH was range between 6.46 and 8.29 in the lowland reservoirs and the SEC between 8.6 and 24.7  $\text{mS}\cdot\text{m}^{-1}$ . The lowest values of pH and SEC were recorded in the Vyshnevolotzkoye and Verhnevolzhskoye reservoirs mainly due

to the position of these reservoirs on the boundary of the catchment, which received significant rainwater with low salt concentrations and pH, as well as supply of marsh water. The differences between lowland and mountain reservoirs were also associated with environmental factors, such as catchment geology and vegetation cover. Therefore, the influence of land use on water quality varies between areas with different environmental features (Baker, 2003; Lee S.W., Hwang, Lee S.B., Hwang, & Sung, 2009). According to Dumont (1999), the greatest SEC values are usually found in areas with high anthropopression. Many studies documented that areas with less urbanization and more forests have better water quality (Ding et al., 2015; Lee et al., 2009), and extent of the negative impact of agricultural land depends on the

agricultural practices (Baker, 2003; Jeon, Yoon, Ham, & Jun, 2004).

With regard to sulphate salinity of the water, the difference between the average values in the individual lowland reservoir reach a maximum of  $2.46 \text{ mg}\cdot\text{dm}^{-3}$ . In the mountain reservoirs the differences was higher ( $5.39 \text{ mg}\cdot\text{dm}^{-3}$ ). Similar observations were found for chloride concentrations. High concentrations of sulphates and chlorides impair or prevent freshwater fish life (Georgieva, Yaneva, & Dospatliev, 2010). In the lowland reservoirs, the maximum difference between chloride concentrations was  $1.66 \text{ mg}\cdot\text{dm}^{-3}$ . This value was 73% lower than in the mountain reservoirs. In general, salinity in the lowland reservoirs was lower than in the mountain ones. The concentration of sulphates in the lowland reservoirs was in the range between 0.4 and  $15.1 \text{ mg}\cdot\text{dm}^{-3}$  ( $14.1$  and  $20.9 \text{ mg}\cdot\text{dm}^{-3}$  in mountain reservoirs) while the concentration of chlorides was between 0.7 and  $4.1 \text{ mg}\cdot\text{dm}^{-3}$  ( $5.0$  and  $13.6 \text{ mg}\cdot\text{dm}^{-3}$  in mountain reservoirs). Low concentrations of sulfates and chlorides were associated with a little human impact, especially in the Vyshnevolotzkoye reservoir, where there are only a few settlements, which do not supply a large amount of wastewater. Leslie and Lyons (2018) showed that higher concentration of chloride in river and reservoir are associated with increased usage of se-icing salt on roads. The values obtained for sulphates in water stored in the mountain and lowland reservoirs in this study did not exceed the limit of  $250 \text{ mg}\cdot\text{dm}^{-3}$  given in the guidelines for drinking water prescribed by the World Health Organization (WHO, 2011). Additionally, no health-based guideline value has been established by the WHO for chloride in drinking water.

In the lowland reservoirs, the differences between the average concentrations of phosphates were  $0.06 \text{ mg}\cdot\text{dm}^{-3}$  while ammonia  $0.39 \text{ mg}\cdot\text{dm}^{-3}$  and nitrates  $0.35 \text{ mg}\cdot\text{dm}^{-3}$ . The average concentration of nitrates in the Vyshnevolotzkoye reservoir was lower by  $0.35 \text{ mg}\cdot\text{dm}^{-3}$  than in the other two lowland reservoirs. The average concentration

of phosphates in the Ivankovo reservoir was the highest (in compare to other analyzed reservoirs) and reached  $0.08 \text{ mg}\cdot\text{dm}^{-3}$ . The highest average ammonia concentrations in the summer period were recorded in the Verhnevolzhskoye reservoir,  $0.91 \text{ mg}\cdot\text{dm}^{-3}$  ( $0.71 \text{ mgN}\cdot\text{NH}_4^+\cdot\text{dm}^{-3}$ ). These differences were slightly lower in the mountain reservoirs with the exception of nitrogen. In addition, the concentrations of ammonia in the lowland reservoirs were higher ( $0.18$ - $2.00 \text{ mg}\cdot\text{dm}^{-3}$ ) than in the mountain reservoirs ( $0.03$ - $0.23 \text{ mg}\cdot\text{dm}^{-3}$ ). Ammonia in surface water comes from the biochemical decomposition of organic nitrogen compounds of plant and animal origin as well as from industrial or domestic sewage (Varol, Gokot, Bekleyen, & Sen, 2012). High concentrations of ammonia in the Upper Volga reservoirs, especially in its near-dam part, appear to be due to the influence of marshy water and small tributaries of reservoirs, which are characterized by high concentrations of ammonia. In the case of nitrate, higher concentrations were recorded in the mountain reservoirs ( $0.44$ - $3.85 \text{ mg}\cdot\text{dm}^{-3}$ ) than in the lowland reservoirs ( $0.15$ - $1.24 \text{ mg}\cdot\text{dm}^{-3}$ ). High contents of nitrates and phosphates in reservoirs lead to overgrowing (eutrophication) and the excessive quantity of organic matter leads in turn to excessive oxygen consumption (Wiatkowski, 2011). According to the WHO (2011), the permissible limit of nitrate concentration in drinking water, which is  $44 \text{ mgNO}_3^-\cdot\text{dm}^{-3}$  ( $10 \text{ mgN}\cdot\text{NO}_3^-\cdot\text{dm}^{-3}$ ), was not exceeded in any of the artificial reservoirs. Concentrations of phosphorus were similar in the five-year period. In the lowland reservoirs, the  $\text{PO}_4^{3-}$  ranged between 0.01 and  $0.12 \text{ mg}\cdot\text{dm}^{-3}$  and in the mountains between 0.01 and  $0.14 \text{ mg}\cdot\text{dm}^{-3}$ . The source of phosphorus in water is decomposition of organic compounds of plant or animal origin as well as agriculture, mainly through phosphorus fertilisers, and pollutants from industrial sewage (Varol et al., 2012).

In the lowland reservoirs the average values of  $\text{BOD}_5$  were similar. In the Vyshnevolotzkoye reservoir the average  $\text{BOD}_5$  reached

2.83 mgO·dm<sup>-3</sup> (Fig. 3). The reservoirs located in the Upper Volga basin noticed the higher values of BOD<sub>5</sub> compared to the Carpathian reservoirs (0.60-1.80 mgO·dm<sup>-3</sup>). The lower BOD<sub>5</sub> values indicated that the loading of water with organic compounds affecting oxygen consumption in the process of self-purification was at a lower level in the mountain reservoirs. According to Wei et al. (2009), reservoirs reduce BOD<sub>5</sub> mainly in effect of longer water residence time and slower flow velocity.

The non-parametric Mann-Whitney U-Test, revealed a statistically significant difference ( $p < 0.05$ ) of SEC between all of the lowland reservoirs. In the mountains, statistically significant difference of SEC was only between the Dobczyce and Klimkówka reservoirs. In the case of Cl<sup>-</sup> concentrations, a statistically significant difference was found between the Ivankovo and the other two lowland reservoirs. Statistically significant differences were also demonstrated for NO<sub>3</sub><sup>-</sup> concentrations between the Ivankovo and Vyshnevoltzkoye reservoirs, as well as between Verhnevolzhskoye and Vyshnevoltzkoye reservoirs.

## Conclusions

The analysis of the chemical composition of water in mountain (the Upper Vistula) and lowland (the Upper Volga basin) reservoirs in the five years summer season (2009-2013) has demonstrated a hydrochemical differentiation between them. The results justify the following conclusions:

1. The mountain reservoirs display higher water concentrations of sulphates, chlorides and biogenic nitrates, and lower

concentrations of ammonium and oxygen indicator (BOD<sub>5</sub>) in relation to lowland reservoirs. High concentrations of ammonium in the water of the Upper Volga reservoirs result mainly from the influence of marshy water, which are characterized by high concentrations of this ion. Similar concentrations of phosphates were noticed in both the mountain and the lowland reservoirs.

2. The hydrochemical differentiation between the individual mountain reservoirs is small, and statistically significant differences only occur in the SEC. Greater differentiation of the hydrochemical parameters was found among the lowland reservoirs (several to over a dozen times greater than the mountain reservoirs). Statistically significant differences were demonstrated with regard to SEC, Cl<sup>-</sup> and NO<sub>3</sub><sup>-</sup>. It results from high amounts of precipitation with low pH and low salt concentration, as well as inflow of marsh water and low anthropopressure especially in the Vyshnevoltzkoye basin.
3. Concentrations of the particular ions in the mountain and lowland reservoirs do not exceed the WHO guide values.

It would be interesting to perform an analysis of the dynamics of the hydrochemical parameters in the studied reservoirs in the annual cycle in order to expand the above conclusions. However, the analysis requires gathering an extensive database.

Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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