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# HYDROCHEMICAL CONDITIONS FOR LOCALIZATION OF SMALL WATER RESERVOIRS ON THE EXAMPLE OF KLUCZBORK RESERVOIR

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**Keywords:** Water reservoir, water quality, water protection, pre-dam.

**Abstract**: The paper presents an analysis of hydrochemical conditions of the Stobrawa River – the right tributary of the Odra River. The aim of the analysis was to assess the possibility of storing the Stobrawa water in Kluczbork storage reservoir. A preliminary assessment of the reservoir water quality and its usability was made. The quality of water in the reservoir is particularly important as the main functions of the reservoir are flood protection, agricultural irrigation and recreation. The following physicochemical parameters of the Stobrawa River were analyzed: $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $BOD_5$, COD, dissolved oxygen (DO), water temperature, pH, electrolytic conductivity and total suspended solids (TSS). Main descriptive statistical data were presented for the analyzed water quality indicators and loads. A statistical analysis of the correlations among all investigated water quality indicators and water flow was performed. The analysis showed that some of the indicators were mutually correlated with water flow at a significance level of $p < 0.05$. The carried out research showed significant contamination of the Stobrawa River in the cross-section of the planned reservoir, which indicates that the Stobrawa water could deteriorate the quality of water in the reservoir. Some reparatory actions to improve water quality in the reservoir were presented. One of them is rearrangement of water and wastewater management in the reservoir catchment. This must precede the construction of the reservoir. Another solution is construction of a pre-dam which will contribute to the improvement of water quality in the reservoir and extend its lifetime.

## INTRODUCTION

Small water reservoirs, such as Kluczbork reservoir, constitute the basic elements of the so-called "small retention" and improve water balance. They are built mainly for storing water in the period of its overflow and for providing it in the low-flow periods. They have also some economic functions (agricultural irrigation, watering place, water supply for villages) and can be used for energy, natural and recreational purposes [20, 24, 26, 29, 31, 37]. They can also contribute to flood protection [27]. Moreover, quite significant is their impact on the adjacent areas [25]. Since in the upper and middle Odra River basin the possibilities for constructing big retention reservoirs are rather limited due to location and costs, the construction of small retention reservoirs seems to be justified.

When building a water reservoir one should take into consideration not only the quantitative aspect but also the quality of water to be stored in the reservoir. There are various opinions on water quality and the impact of water storage in the reservoir on water quality changes. According to the prevailing opinion this contributes to intensification of a self-purification process [21, 43, 48–50]. However, in small reservoirs the quality of heavily contaminated water deteriorates [49, 51, 53]. Changes caused by damming up water in dams in water environment are rather complicated and may vary in time, depending on the use and age of the reservoir. Very often contaminants flowing to the reservoir with water and bed load can jeopardize the use and existence of the reservoir [1, 19, 23, 28].

What is important here is providing monitoring in river basins, in which small water reservoirs are to be built. These basins are usually not controlled hydrological. No water quality analyses are carried out. Therefore, contamination of planned and constructed reservoirs is one of the key issues [6, 16, 33, 34, 48, 52–54].

As far as water quality in the reservoir is concerned a significant role is played by the quality of water feeding the reservoir, which usually results from water and wastewater management in the basin [9, 52]. Phosphorus and nitrogen compounds are the key factors having an impact on the quality of water in the reservoir. The effect of nutrition of surface water is excessive growth of plant communities, mainly plankton.

This can be easily noticed in summer in the form of "water blooms" covering small water reservoirs [11, 15, 51]. This eutrophication process should be taken into account already in studies and at the stage of designing of water reservoirs so that after their construction no unfavorable biochemical processes causing eutrophication would develop in the reservoir bowl.

This must be carried out in compliance with the Water Act [45], which says that "at designing, construction and maintenance of water devices one should follow the principle of sustainable development, preserving good ecological state of water". For many years people have been looking for methods to prevent eutrophication. One of them is based on the use of pre-dams [3–5, 30, 36, 49, 51].

The aim of this study is to analyze hydrochemical parameters of water in the Stobrawa River to evaluate the possibilities of storing it in the planned Kluczbork water reservoir. A preliminary assessment of the reservoir water quality and its usability was made, as well as some actions to improve the quality of water feeding the designed reservoir were presented. Construction of a pre-dam in the backwater of Kluczbork reservoir was proposed.

## CHARACTERISTICS OF KLUCZBORK RESERVOIR AND THE STOBRAWA RIVER CATCHMENT

Kluczbork reservoir will be located at the 61.5 km of the Stobrawa River (right tributary of the Odra River), about 1000 m eastwards, above the town of Kluczbork. From the administrative point of view it will be situated in Opolskie Voivodeship (Southern Poland), Figure 1.

Kluczbork reservoir will be used for the following purposes: irrigation, reduction of flood wave, electric energy generation, fire protection for rural areas and forests, sports and recreation [32, 44].

The area where the reservoir is to be constructed is flat, covered with meadows, scrubs and fallow lands. On the right and left sides of the bowl there are gravel pits (old and new gravel pit) filled with water [44] (Fig. 1).

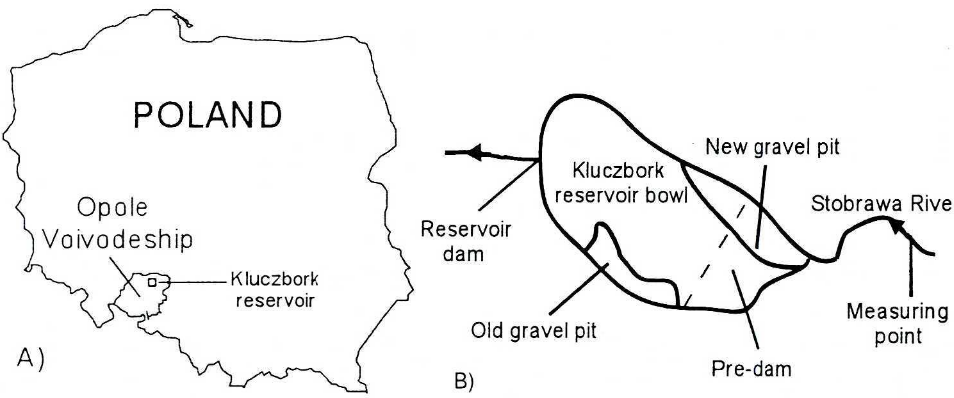


Fig. 1. Location of the planned Kluczbork storage reservoir on the Stobrawa River
A) reservoir catchment, B) reservoir bowl with hydrochemical measuring point

In the reservoir catchment there are Quaternary formations, mainly sand and gravel, accumulated on Tertiary silts. The area of the valley is covered with organic soil, alluvion and peat [44]. The depth of the permeable layer at the front dam varies from 3.7 to 10.5 m. Such geological structure imposes the necessity of constructing a tight, deep barrier reaching the impermeable layer [32]. In the vicinity of Kluczbork reservoir surface water a Main Groundwater Reservoir (GZWP) called Dolina Kopalna Stobrawy is located. These are four groundwater intakes providing water for the town. A part of the bowl of the future reservoir will be situated in the area of indirect protection of groundwater intakes, the northern border of which is formed by the Stobrawa River [38]. In this context the sealing must be made very carefully so that no exchange of surface- and groundwater would occur.

In 2007 a sewerage system was provided to the villages in the direct catchment of the constructed reservoir. Other villages and towns of the reservoir catchment are to be provided with sewerage system from the Cohesion Fund to the year 2013.

The main elements of Kluczbork reservoir are: front dam, spillway-discharge system and small water power plant. To improve the quality of water feeding Kluczbork reservoir the construction of a pre-sedimentation tank is planned. The area of the reservoir at a normal water lifting level will be 55.7 ha and at a maximum lifting level – 56.7 ha. The water lifting ordinate at the normal lifting level will be 186.00 m a.s.l., and at the maximum lifting level – 187.00 m a.s.l. The reservoir volume at the normal lifting level will be 1.1 mln $m^3$ and at the maximum level – 1.683 mln $m^3$. The average depth at the normal lifting level – 2 m and at the maximum level – 3 m. The length of the reservoir will be about 1400 m and its width – about 400 m [32].

The Stobrawa River in the planned reservoir cross-section is not controlled hydrological. The catchment area in the dam profile is 126 $km^2$. Characteristic flows in this section are the following: average discharge SSQ = 0.574 $m^3 \cdot s^{-1}$, average low discharge SNQ = 0.08 $m^3 \cdot s^{-1}$ and inviolable flow $Q_o$ = 0.04 $m^3 \cdot s^{-1}$. Average annual precipitation in Kluczbork in the period of 1971–2000 is 650 mm and the average air temperature – about 8°C [22]. There are many fish ponds and hydrotechnical structures in the catchment.

## METHODS

Water quality assessment in the Stobrawa River at the outlet to the planned reservoir was carried out based on the hydrochemical analyses performed at the measuring point located at the 63.5 km of the river course (Fig. 1).

The analyses were made from May 2005 to April 2008. Thirty four water samples were collected. Water was collected from the subsurface river current. The following indicators were taken into consideration in the water quality assessment: $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $BOD_5$, COD-Cr, water temperature, dissolved oxygen (DO), water pH, electrolytic conductivity and total suspended solids (TSS). Laboratory tests were performed in compliance with Polish standards [14]. Apart from water quality analyses also hydrometric measurements were made. Flow rate curve was determined. Based on the obtained water quality values and hydrometric measurements loads of contaminants carried out from the Stobrawa River catchment in the cross-section of the designed Kluczbork reservoir [kg] were calculated. Due to variable meteorological conditions two seasons were distinguished: the winter season (1 November – 30 April) and the summer season (1 May – 31 October). Physicochemical indicators were determined both for the whole year and for the above-mentioned seasons.

A statistical analysis of concentrations of particular physicochemical water quality indicators was performed. For the obtained results location measures (average measures) and dispersion (variability) values were calculated, which allowed to present differences in the values of the analyzed indicators.

As a location measure an arithmetic mean was assumed and as a dispersion measure – interval and standard deviation [18]. Moreover, average monthly loads and their ranges for nitrates, nitrites, ammonium and phosphates were compared. Correlations between flow rate and the Stobrawa water quality indicators were also analyzed. A statistical presentation of the correlations was made using a Pearson's linear correlation coefficient [47]. It was assumed that the correlation was statistically significant in the case of $p < 0.05$.

The quality of the Stobrawa water was assessed according to the Ordinance of the Minister of the Environment establishing way of classifying the state of uniform parts of surface waters [40] and water eutrophication process was assessed according to the Ordinance [41]. Water usability in the context of the possibility of its lifting in the designed reservoir was determined by comparison of the analyzed indicators with limit values for water suitable for fish [39] and bathing [42].

## RESULTS AND DISCUSSION

In the investigated period the discharge values in the analyzed cross-section varied from 0.150 to 1.880 $m^3 \cdot s^{-1}$. The average discharge value was 0.446 $m^3 \cdot s^{-1}$ and was lower than the one assumed in [32]. The highest discharge value was recorded in March 2006 and the lowest one in July 2006.

The analyses of the selected physicochemical indicators in the Stobrawa water were carried out in the cross-section of the designed reservoir from May 2005 to April 2008. The characteristic of these parameters is presented in Table 1.

Table 1. Water quality of the Stobrawa River in the cross-section of the designed reservoir (63.5 km of the river course)

| Pollution indicator | Period | Value | | | Range | Standard deviation |
|---|---|---|---|---|---|---|
| | | Min. | Max. | Average | | |
| Nitrates [mg $NO_3^-\cdot dm^{-3}$] | year | 0.30 | 44.00 | 13.95 | 43.70 | 10.14 |
| | summer | 0.30 | 27.00 | 10.58 | 26.70 | 7.90 |
| | winter | 0.68 | 44.00 | 17.12 | 43.32 | 11.18 |
| Nitrites [mg $NO_2^-\cdot dm^{-3}$] | year | 0.07 | 3.40 | 0.24 | 3.39 | 0.61 |
| | summer | 0.02 | 0.36 | 0.09 | 0.34 | 0.09 |
| | winter | 0.16 | 3.40 | 0.34 | 3.38 | 0.77 |
| Ammonia [mg $NH_4^+\cdot dm^{-3}$] | year | 0.002 | 2.70 | 0.57 | 2.69 | 0.58 |
| | summer | 0.002 | 1.76 | 0.38 | 1.75 | 0.43 |
| | winter | 0.05 | 2.70 | 0.75 | 2.65 | 0.66 |
| Phosphates [mg $PO_4^{3-}\cdot dm^{-3}$] | year | 0.10 | 0.82 | 0.46 | 0.72 | 0.17 |
| | summer | 0.10 | 0.70 | 0.48 | 0.60 | 0.18 |
| | winter | 0.22 | 0.82 | 0.44 | 0.59 | 0.18 |
| BOD [mg $O_2\cdot dm^{-3}$] | year | 0.55 | 10.00 | 3.07 | 9.45 | 2.99 |
| | summer | 0.55 | 8.14 | 2.46 | 7.59 | 2.70 |
| | winter | 1.00 | 10.00 | 3.46 | 9.00 | 3.23 |
| COD [mg $O_2\cdot dm^{-3}$] | year | 3.70 | 66.00 | 23.89 | 62.30 | 17.91 |
| | summer | 3.70 | 63.00 | 18.45 | 59.30 | 16.68 |
| | winter | 7.20 | 66.00 | 28.49 | 58.80 | 18.24 |
| Water temperature [°C] | year | 0.50 | 20.30 | 9.56 | 19.80 | 5.73 |
| | summer | 6.00 | 20.30 | 14.33 | 14.30 | 4.10 |
| | winter | 0.50 | 14.50 | 5.90 | 14.00 | 3.75 |
| Dissolved oxygen [mg $O_2\cdot dm^{-3}$] | year | 7.00 | 10.90 | 8.49 | 3.90 | 1.24 |
| | summer | 7.00 | 9.60 | 8.04 | 2.60 | 0.98 |
| | winter | 7.20 | 10.90 | 8.94 | 3.70 | 1.39 |
| Reaction pH | year | 6.13 | 8.20 | 7.22 | 2.07 | 0.62 |
| | summer | 6.13 | 7.70 | 6.81 | 1.57 | 0.51 |
| | winter | 6.42 | 8.20 | 7.53 | 1.78 | 0.56 |
| Electrolytic conductivity [$\mu S\cdot cm^{-1}$] | year | 155 | 803 | 394.57 | 648 | 114.25 |
| | summer | 268 | 422 | 374.16 | 154 | 44.30 |
| | winter | 155 | 803 | 409.87 | 648 | 16.53 |
| Total suspended solids [$mg\cdot dm^{-3}$] | year | 1.00 | 316 | 46.74 | 315.00 | 68.66 |
| | summer | 1.00 | 120 | 35.33 | 119.00 | 36.99 |
| | winter | 3.00 | 316 | 55.86 | 313.00 | 86.49 |

Table 1 shows that average concentrations of the analyzed physicochemical indicator s were the highest in the winter season. The only exceptions were: concentration of phosphates and water temperature. Higher average values corresponded with higher intervals and deviations, which indicates higher variability of results. Concentrations of the main biogenes in the water of the Stobrawa River are presented in Figures 2 and 3.

Nitrate concentrations in the investigated period varied significantly (Fig. 2). The highest values were observed in the winter season (14 January 2008) – 44 mg $NO_3^-\cdot dm^{-3}$. It can be assumed that the high concentrations of this indicator came from area flows. The lowest concentrations of nitrates were recorded in s ummer, when the concentrations of this indicator were regulated by vege.

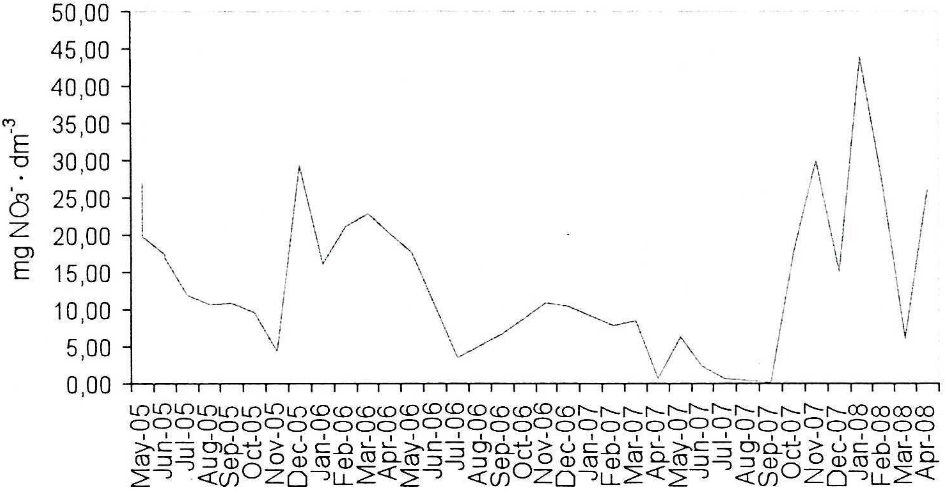


Fig. 2. Changes of nitrate concentrations in the Stobrawa River in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

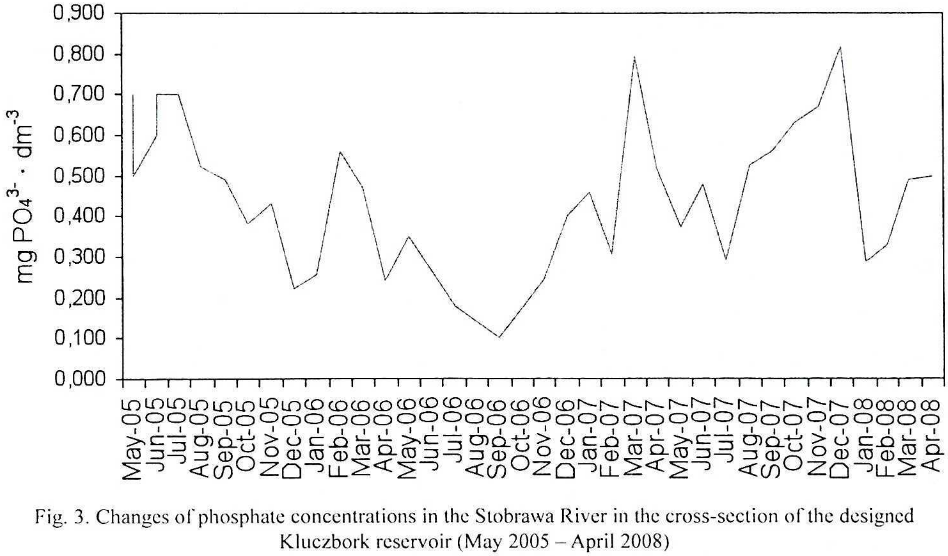


Fig. 3. Changes of phosphate concentrations in the Stobrawa River in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

The highest concentrations of nitrites were observed in spring and winter (Tab. 1). The highest content of nitrite nitrogen was recorded in December 2006 (3.4 mg $NO_2^- \cdot dm^{-3}$). The occurrence of this form of nitrogen in water testifies to penetration of household contaminants from villages located in the Stobrawa River catchment.

Ammonia concentrations in the Stobrawa River varied from 0.002 do 2.70 mg $NH_4^+ \cdot dm^{-3}$, and the average value of this indicator in the entire research period was 0.57 mg $NH_4^+ \cdot dm^{-3}$ (Tab. 1). Just like in the case of nitrite concentrations, the concentration of ammonia in winter season was higher than in summer. The ammonia content in water is an important indicator of contamination with albuminous substances which usually occur in great amounts in wastes.

As far as phosphates are concerned (Fig. 3), the lowest concentrations were observed in September 2006 (0.1 mg $PO_4^{3-}\cdot dm^{-3}$). The highest concentrations were recorded in March 2007 (0.796 mg $PO_4^{3-}\cdot dm^{-3}$) and December 2007 (0.82 mg $PO_4^{3-}\cdot dm^{-3}$). This may have resulted from the release of this chemical to water through the frozen land cover and from household wastes. Another reason for the increase of these compounds is aging and dying of macrophytes, which only in spring and summer take up nitrogen and phosphate compounds. Biogenes are nutrients for them [17]. In winter and spring the increase of phosphate, nitrate nitrogen and ammonium nitrogen loads can be observed, which in turn begin to decrease in summer due to macrophytes.

$BOD_5$ concentration in the Stobrawa River varied from 0.55 to 10.00 mg $O_2\cdot dm^{-3}$ (Tab. 1). Higher $BOD_5$ values were observed in the winter season (the highest recorded value was on 16 March 2008). Higher water contamination with easily degradable organic matter and higher $BOD_5$ values could be observed. COD-Cr concentration in the Stobrawa water during the investigated period varied from 3.70 to 66.0 mg $O_2\cdot dm^{-3}$ (Tab. 1).

The carried out research showed that the Stobrawa water temperature in the period 2005–2008 varied from 0.5°C to 20.3°C (Tab. 1).

Oxygen concentration in the Stobrawa River ranged from 7.00 to 10.90 mg $O_2\cdot dm^{-3}$. The average content of DO at the measuring point in the investigated period of 2005–2008 was 8.49 mg $O_2\cdot dm^{-3}$ (Tab. 1). Higher DO values were observed in months of lower temperatures (February, March, April) than in summer and autumn.

Water pH in the Stobrawa River varied from 6.13 to 8.20. The lowest pH was observed in September 2007 and the highest pH values – in March 2008 (Tab. 1).

Electrolytic conductivity of water depends on the content of dissolved ions and water temperature [10]. Electrolytic conductivity of the Stobrawa River ranged from 155 to 803 $\mu S\cdot cm^{-1}$ (Tab. 1).

The highest concentration of the total suspension (316 $mg\cdot dm^{-3}$) was recorded at a high water stage in the Stobrawa River catchment in March 2006 (Fig. 2). Therefore, it can be concluded that in the Stobrawa River catchment higher values of suspension were caused by spring thaw rather than by rainfalls. Higher concentrations were observed in the winter season (Tab. 1).

Graphic comparison of average values and load ranges of the selected indicators for the Stobrawa River is presented in Figures 4–7.

From the graphic analysis it can be concluded that the highest values of average monthly loads of nitrates, nitrites, ammonia and phosphates were observed in the winter period. In each analyzed case higher values of the interval and deviation corresponded with the higher average.

In Table 2 statistical significance of the correlation between water flow rate and water quality indicators in the Stobrawa River in the cross-section of the planned reservoir is presented.

The analysis of the linear correlation between the above-mentioned water quality indicators showed that some of them were significantly correlated. A statistically significant negative correlation was found between nitrates $NO_3^-$ and $BOD_5$. A positive significant correlation was observed between ammonia and COD. In the case of COD a positive significant correlation was also found in the case of TSS. Water flow was positively correlated with COD, water temperature and TSS.

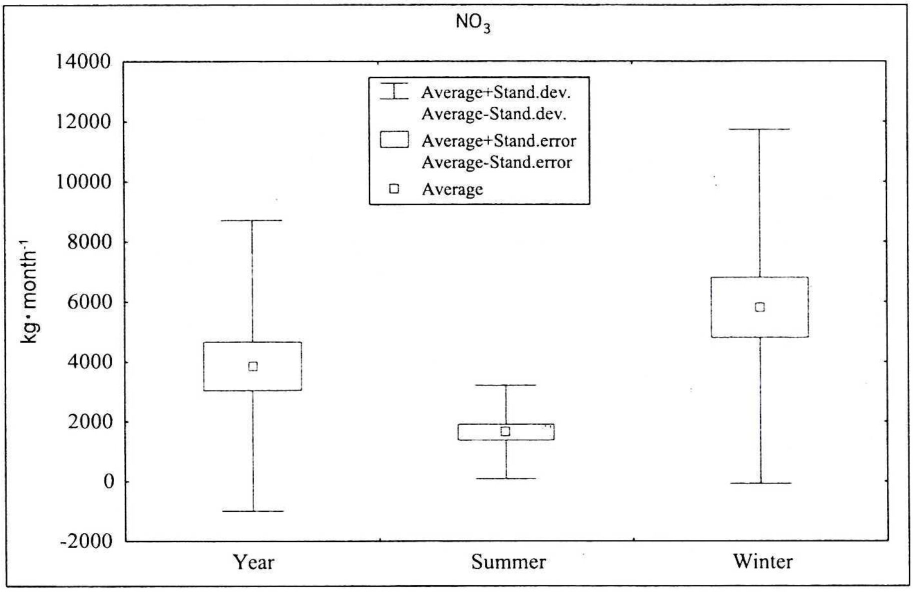


Fig. 4. Graphic comparison of average monthly loads of nitrates and their ranges in the Stobrawa River water in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

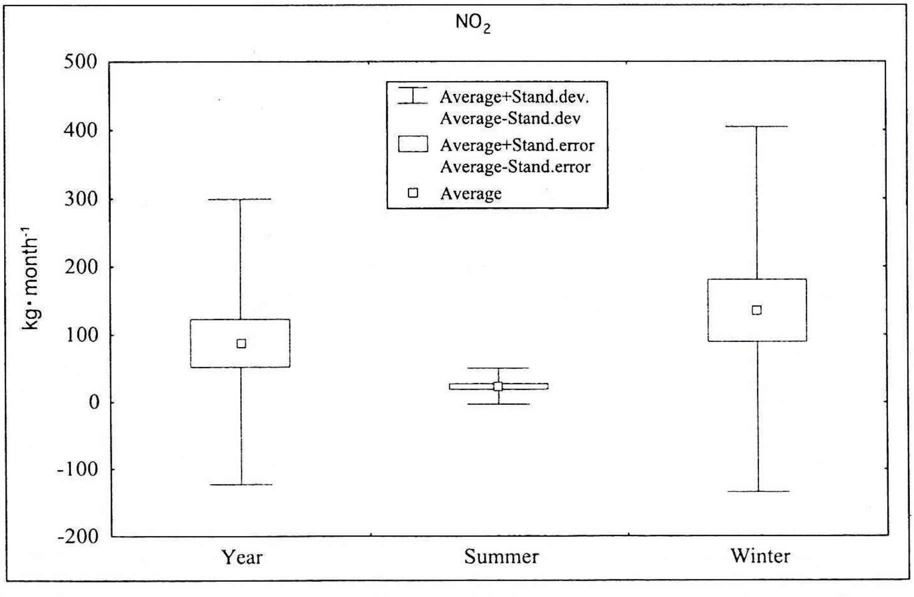


Fig. 5. Graphic comparison of average monthly loads of nitrites and their ranges in the Stobrawa River water in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

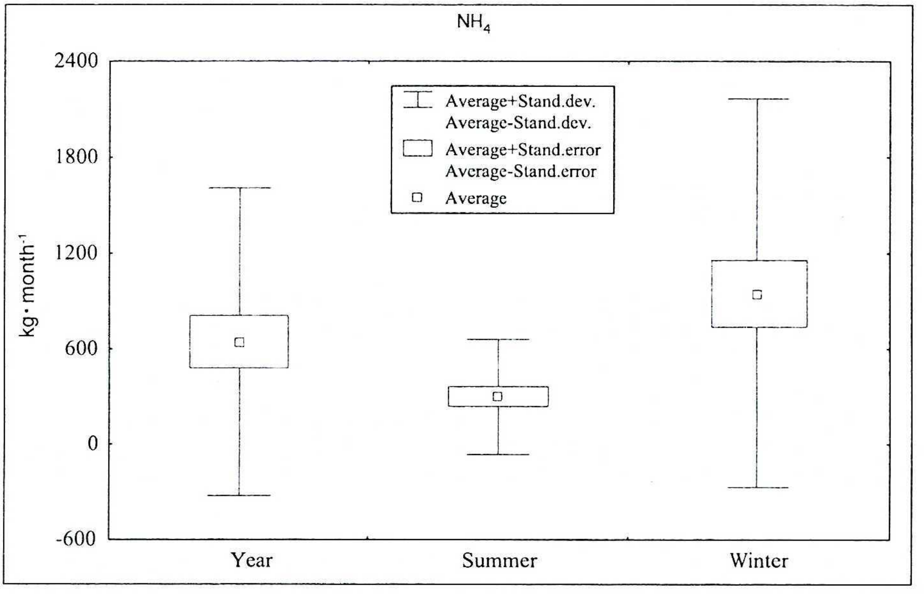


Fig. 6. Graphic comparison of average monthly loads of ammonia and their ranges in the Stobrawa River water in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

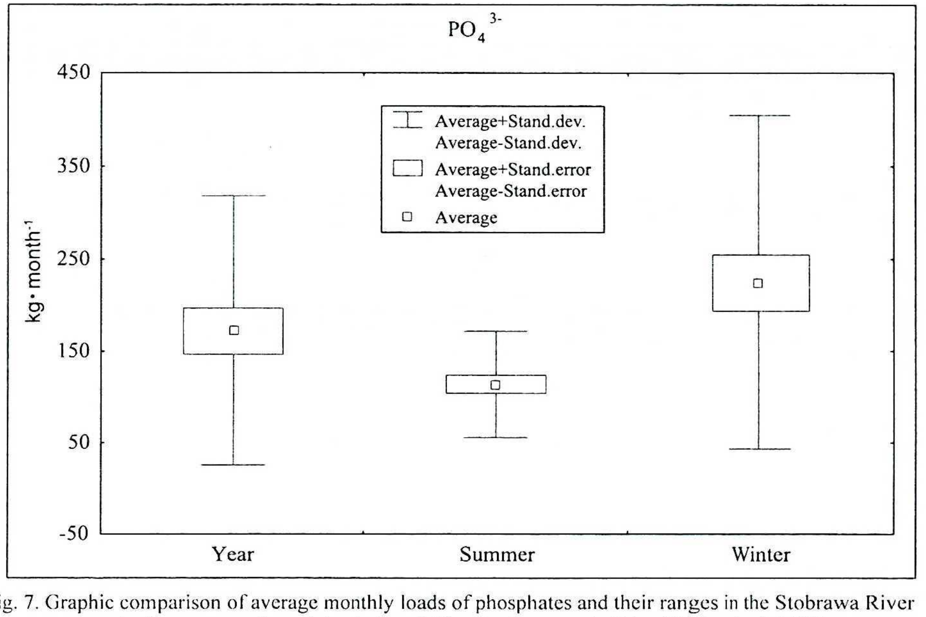


Fig. 7. Graphic comparison of average monthly loads of phosphates and their ranges in the Stobrawa River water in the cross-section of the designed Kluczbork reservoir (May 2005 – April 2008)

Table 2. Statistical significance of the correlation between water flow rate and water quality indicators in the Stobrawa River in the cross-section of the planned reservoir (63.5 km of the river course), correlation coefficient significant for $p < 0.05$ is bolded

| Indicator | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $NO_3^-$ | 1.00 | | | | | | | | | | | |
| | p = – | | | | | | | | | | | |
| $NO_2^-$ | 0.06 | 1.00 | | | | | | | | | | |
| | p = 0.749 | p = – | | | | | | | | | | |
| $NH_4^+$ | 0.10 | 0.12 | 1.00 | | | | | | | | | |
| | p = 0.575 | p = 0.529 | p = – | | | | | | | | | |
| $PO_4^{3-}$ | 0.04 | 0.00 | 0.11 | 1.00 | | | | | | | | |
| | p = 0.833 | p = 0.995 | p = 0.518 | p = – | | | | | | | | |
| BOD | **-0.47** | -0.17 | 0.03 | 0.18 | 1.00 | | | | | | | |
| | **p = 0.050** | p = 0.506 | p = 0.911 | p = 0.469 | p = – | | | | | | | |
| COD | 0.11 | -0.08 | **0.46** | 0.19 | -0.09 | 1.00 | | | | | | |
| | p = 0.593 | p = 0.713 | **p = 0.025** | p = 0.383 | p = 0.764 | p = – | | | | | | |
| Temp. | -0.08 | 0.03 | -0.30 | 0.39 | -0.11 | 0.13 | 1.00 | | | | | |
| | p = 0.717 | p = 0.903 | p = 0.162 | p = 0.068 | p = 0.714 | p = 0.652 | p = – | | | | | |
| DO | 0.23 | 0.24 | 0.42 | 0.54 | 0.09 | -0.22 | -0.32 | 1.00 | | | | |
| | p = 0.469 | p = 0.460 | p = 0.178 | p = 0.068 | p = 0.798 | p = 0.491 | p = 0.373 | p = – | | | | |
| pH | 0.27 | 0.14 | -0.18 | -0.31 | -0.19 | -0.01 | **-0.50** | -0.20 | 1.00 | | | |
| | p = 0.167 | p = 0.529 | p = 0.373 | p = 0.104 | p = 0.472 | p = 0.961 | **p = 0.015** | p = 0.557 | p = – | | | |
| Conductivity | -0.16 | 0.21 | -0.24 | 0.03 | -0.19 | -0.19 | 0.05 | 0.11 | 0.22 | 1.00 | | |
| | p = 0.416 | p = 0.336 | p = 0.219 | p = 0.880 | p = 0.480 | p = 0.472 | p = 0.808 | p = 0.753 | p = 0.266 | p = – | | |
| TSS | 0.36 | 0.06 | 0.14 | 0.17 | -0.18 | **0.57** | 0.22 | 0.15 | 0.32 | 0.08 | 1.00 | |
| | p = 0.064 | p = 0.772 | p = 0.495 | p = 0.398 | p = 0.482 | **p = 0.006** | p = 0.442 | p = 0.653 | p = 0.172 | p = 0.726 | p = – | |
| Discharge | 0.14 | -0.01 | 0.23 | 0.02 | -0.05 | **0.58** | **-0.55** | 0.12 | 0.29 | 0.32 | **0.64** | 1.00 |
| | p = 0.431 | p = 0.959 | p = 0.176 | p = 0.916 | p = 0.833 | **p = 0.003** | **p = 0.007** | p = 0.710 | p = 0.135 | p = 0.093 | **p = 0.000** | p = – |

## PRELIMINARY ASSESSMENT OF WATER QUALITY IN KLUCZBORK RESERVOIR

Out of 11 investigated indicators of the Stobrawa River quality 9 were considered in water quality classification [40]. The analysis of the water quality showed that water temperature, dissolved oxygen, pH and conductivity did not exceed the limit values for class I. However, concentrations of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$, $BOD_5$, COD and total suspended solids were higher than the limit values for water quality indicators for uniform parts of surface waters in natural watercourses such as rivers, typical of class II [40].

Waters in the Stobrawa River in the cross-section of the designed Kluczbork reservoir were classified as eutrophic waters. At this point the average annual concentration of nitrates exceeded the limit value (10 mg $NO_3 \cdot dm^{-3}$) for this indicator defined in the Ordinance [41]. It was found out that the Stobrawa River waters were not sensitive to contamination with nitrogen compounds from agricultural sources as the annual average concentration of nitrates was lower than the value recommended in the Ordinance (50 mg $NO_3^- \cdot dm^{-3}$) [41].

From the performed analysis it can be concluded that Kluczbork reservoir will be affected by large biogenic contaminants carried by the Stobrawa River. As presented in [53] the quality of contaminated water flowing through such a small reservoir may get worse.

The analyses of the Stobrawa River showed that such indicators as water temperature, dissolved oxygen and pH met the requirements for inland waters constituting natural habitat for salmon- and carp-like fishes. The most unfavorable conditions for fish are caused by: nitrites, which exceed the value of 0.01 mg $NO_2^- \cdot dm^{-3}$ for salmon-like species and 0.03 mg $NO_2^- \cdot dm^{-3}$ for carp-like species, as determined in [39], ammonium nitrogen $N\text{-}NH_4^+$, which exceeds the value of 0.78 mg $N\text{-}NH_4^+ \cdot dm^{-3}$ for salmon- and carp-like fishes, BOD which exceeds the value of 3 mg $O_2 \cdot dm^{-3}$ for salmon-like and 6 mg $O_2 \cdot dm^{-3}$ for carp-like fishes and total suspended solids exceeding the annual average value of 25 $mg \cdot dm^{-3}$ defined in [40].

Taking into account BOD, suspended solids and phosphate values the quality of the Stobrawa River does not meet the requirements for bathing in inland waters, either [42].

If compared with water quality results for the Stobrawa River in the cross-section of the planned reservoir which were presented in [48], some lower concentrations of nitrates, phosphates and slightly lower nitrite values can be observed. However, values of ammonia, BOD, water temperature and electrolytic conductivity increased.

Calculations were made to assess to what extent Kluczbork reservoir would be affected by eutrophication. Based on Vollenweider's criterion [46], in Benndorf's modification [2] and taking into account that the concentration of phosphates in the cross-section of the designed reservoir was 0.46 mg $PO_4^{3-} \cdot dm^{-3}$ (Tab. 1), it was found out that the phosphorus load was 2.06 Mg $P\text{-}PO_4 \cdot a^{-1}$. The amount of phosphorus per 1 $m^2$ of the reservoir was 3.7 g $P\text{-}PO_4 \cdot m^{-2} \cdot a^{-1}$, whereas the ratio of the reservoir average depth of 2 m (assumed according to [32]) to retention time was 0.078 $a^{-1}$ (calculated based on data provided in [32]). Inorganic nitrogen load flowing to the reservoir is 76.3 Mg $N \cdot a^{-1}$ Therefore, the designed Kluczbork reservoir was classified as an polytrophic reservoir. There is no doubt that at this biogene load and the reservoir parameters the polytrophic process will occur. Similar conclusions were presented in [38]: "significant deterioration of the water quality will occur in the reservoir". The content of dissolved oxygen in water will decrease and the increase of water temperature and pH will be observed".

## PROPOSAL FOR WATER PROTECTION OF KLUCZBORK RESERVOIR USING A PRE-DAM

Since the calculated biogene loads are too high and the reservoir will undergo eutrophication it would be advisable to increase its morphometric parameters, volume or depth. The only difficulty may be a too flat valley of the Stobrawa River at the place of the future reservoir. In this context all options for improvement of water quality of the Stobrawa River must be considered. The improvement can be achieved by reduction of point, diffuse and area pollution sources in the catchment. The main task here is rearrangement of water and wastewater management in the catchment. So far a sewerage system has been provided to villages adjacent to the future reservoir. Another option for water quality improvement is construction of a pre-dam with a macrophyte filter. There are several arguments for the construction of the pre-dam. First and foremost – low cost and short construction time. The pre-dam should be located at the inlet to the reservoir, in its backwater part. The quality of water in the reservoir should improve as all contaminants flowing with the river will accumulate in the pre-dam. According to the literature survey a properly built and used pre-dam can extend the lifetime of the reservoir and its proper operation [3, 4, 8, 49, 51].

Dimensions of the pre-dam suggested by the investor, area – ca. 2 ha and average depth – ca. 0.5 m, seem to be too low for the biogene loads flowing with the Stobrawa River [48]. Therefore, construction of a bigger pre-dam should be taken into consideration. Its dimensions should be selected very carefully so that it could function properly throughout the whole exploitation period. Based on the criteria described in [5, 7] draft working dimensions of the pre-dam were calculated. The average discharge (SQ) in the Stobrawa River is 0.446 $m^3 \cdot s^{-1}$ and assuming the water retention time in the pre-dam $\Delta t$ = 5 days, the required volume of Kluczbork pre-dam should be:

$$V_{pre\text{-}dam\text{-}5} = 86400 \cdot \Delta t \cdot SQ = 0.1927 \text{ mln m}^3 \quad (1)$$

Assuming the retention time in the pre-dam $\Delta t$ = 11 days:

$$V_{pre\text{-}dam\text{-}11} = 86400 \cdot \Delta t \cdot SQ = 0.4239 \text{ mln m}^3 \quad (2)$$

Another criterion determining the operating volume of the pre-dam refers to high flows. In order to store a 2 years' high flow $Q_{50\%}$ in the pre-dam (without the volume of the assumed sediments) for 12 hours, and assuming :

- volume of the main reservoir $V_{res}$ = 1.100 mln $m^3$,
- high flow $Q_{50\%}$ = 5.33 $m^3 \cdot s^{-1}$ [32],
- volume of accumulated sediments $V_s = 0.01 \cdot V_{res}$ = 0.011000 mln $m^3$

then the volume of the pre-dam should be:

$$V_{pre\text{-}dam} = Q_{50\%} \cdot 0.5 \cdot 86400 + V_s = 0.230256 \text{ mln m}^3 \quad (3)$$

The volume of the pre-dam, calculated according to equations 1–3, should be 0.2–0.4 mln $m^3$. It should be stressed here that constructing a too big pre-dam is not advisable as the planned rearrangement of the water and wastewater management in the catchment will reduce the amount of contaminants flowing to the reservoir. To ensure proper control of flood waters in the pre-dam (which are usually quite contaminated) a by-pass channel should be constructed.

At the above-mentioned parameters of the pre-dam a preliminary reduction of inorganic nitrogen can be determined. It depends on ratio N:P (inorganic nitrogen to phosphates) at the inflow to the pre-dam and on the average water retention time. Functional dependencies describing this process were presented by Pütz and Benndorf [35, 36]. The relationship between reduction of inorganic nitrogen and the average retention time (N:P) can be widely applied in determining average reductions of nitrogen for future pre-dams. Based on the data obtained from Kluczbork reservoir, the ratio between inorganic nitrogen and phosphates N:P = 25:1 and retention time t = 7.8 days (at the volume 0.3 mln $m^3$), a significant reduction of inorganic nitrogen (by ca. 20–30%) can be expected in the pre-dam. According to the available literature, additional biological barriers and plant filters can contribute to the increased efficiency of the pre-dam. From [51] it can be concluded that in water flowing through the pre-dam that consists of a sedimentation tank and a plant filter, nitrate values decreased by 66.5% and phosphates by 52.8%. Similar results were presented in [8, 12, 13]. Authors of [43], however, found out that a pond located on a watercourse decreased concentrations and loads of phosphorus in the flowing water.

## CONCLUSIONS

Hydrochemical conditions occurring in the cross-section of the designed Kluczbork reservoir are unfavorable for it. From the point of view of eutrophication process water of the Stobrawa River flowing to the reservoir shows high content of biogenes: nitrates – 13.95 mg $NO_3^-\cdot dm^{-3}$, phosphates – 0.56 mg $PO_4^{3-}\cdot dm^{-3}$.

Among the investigated indicators the concentrations of nitrate nitrogen, ammonium nitrogen, $BOD_5$, COD and suspension exceeded the limit values defined for water quality indicators for uniform parts of surface waters in natural watercourses, typical of class II. A negative impact on the life of salmon- and carp-like fishes is exerted by nitrites, ammonia, $BOD_5$ and total suspended solids. The water quality of the Stobrawa River does not meet the criteria established for bathing due to the content of $BOD_5$, TSS and phosphates.

In order to avoid eutrophication it is necessary to reduce the content of biogenes in the water flowing to the reservoir. One of the basic solutions is rearrangement of water and wastewater management systems in the reservoir catchment, which must be completed before the construction of the reservoir. Another solution is construction of the pre-dam with a macrophyte filter, which will facilitate the improvement of water quality in the reservoir and extend its lifetime. These solutions should be considered both while designing new reservoirs and in the existing ones (if location permits).

Due to great importance of small water reservoirs in regional water management monitoring of water purity in the river feeding the reservoir, both at the stage of planning, construction and operation, seems to be essential.

More regular research, extended by analyses of other water quality indicators, should be continued in the catchment of the designed Kluczbork reservoir so that it could contribute to a more detailed water quality assessment.

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## UWARUNKOWANIA HYDROCHEMICZNE LOKALIZACJI MAŁYCH ZBIORNIKÓW WODNYCH NA PRZYKŁADZIE ZBIORNIKA KLUCZBORK

W pracy przedstawiono analizę warunków hydrochemicznych wody rzeki Stobrawy (prawostronny dopływ Odry) dla określenia możliwości jej retencjonowania w planowanym zbiorniku retencyjnym Kluczbork. Przedstawiono wstępną ocenę jakości wody zbiornika i oceniono jej walory użytkowe. Podstawowe funkcje zbiornika to ochrona przed powodzią, nawodnienia rolnicze i rekreacja, dlatego ważnym zagadnieniem jest jakość wody zbiornika. Scharakteryzowano jakość wody rzeki Stobrawy pod względem wskaźników fizyko-chemicznych: $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $BZT_5$, $ChZT_{Cr}$, tlenu rozpuszczonego, temperatury wody, pH, przewodności elektrolitycznej i zawiesiny ogólnej. Obliczono podstawowe statystyki opisowe dla badanych wskaźników jakości wody

i ładunków. Analizie statystycznej poddano związki korelacyjne pomiędzy wszystkimi badanymi wskaźnikami jakości wody i przepływem wody. Analiza ta wykazała, że niektóre wskaźniki są ze sobą wzajemnie i z przepływem skorelowane na poziomie istotności $p < 0,05$. Przeprowadzone badania wykazały, że zanieczyszczenie wody rzeki Stobrawy w przekroju planowanego zbiornika jest znaczne, w związku z czym woda ta może pogorszyć jakość wody zbiornika. W pracy przedstawiono propozycje zabiegów, które mogą się przyczynić do poprawy jakości wody w zbiorniku. Jednym z podstawowych rozwiązań jest uporządkowanie gospodarki wodno-ściekowej w zlewni zbiornika. Musi ono poprzedzać budowę zbiornika. Drugim rozwiązaniem jest budowa zbiornika wstępnego, który będzie wpływał na poprawę jakości wody w zbiorniku i wydłuży czas jego istnienia.