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*Original Research*

# Surface Water Quality Assessment in the Troja River Catchment in the Context of Włodzienin Reservoir Construction

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### Abstract

In the context of construction of the Włodzienin Reservoir in Poland, the water quality of the main tributaries (Troja River – five sampling points, Braciszowski Brook and Levicki Brook – one sampling point each) was investigated from January to December 2006. The following physico-chemical parameters were measured: $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $BOD_5$, pH, conductivity, and water temperature. Statistical analysis of the data allowed the classification of the water pollution indicators according to ordinances of the Polish Ministry of the Environment. Strong pollution of the streams was revealed and consequences for water quality of the Włodzienin Reservoir were assessed. The reservoir will be stabilized and thermally stratified in summer. Because of the polytrophic conditions, it will be strongly affected by mass developments of phytoplankton in the epilimnion and anaerobic conditions in the hypolimnion. Some measures that can be taken to improve the trophic situation of the reservoir are discussed.

**Keywords:** catchment basin, reservoir tributaries, water quality, trophic state, water protection

## Introduction

The EU Water Framework Directive (EUWFD) [1] obliges each Member State to establish a surface water monitoring system to provide detailed and coherent information on the ecological and chemical status of the waters in each catchment. The implementation of the EUWFD generally requires water quality data that allows the classification of water bodies.

Small reservoirs such as the Włodzienin Reservoir are considered the main elements of the so-called "small retention" and intended for various further purposes [2]. However, dams strongly affect not only the hydrological water balance but also the ecological state of the upstream and downstream river system in a complex way.

The usability of such reservoirs depends on its water quality, which is primarily influenced by the tributaries loading with pollutants. Settlements without effective wastewater management systems (point sources) and pollutants exported from intensively used farmland (diffusive sources) contribute the most to surface water degradation in rural areas [3-5]. The soluble inorganic forms of phosphorus (in particular soluble reactive phosphorus SRP) and nitrogen (nitrate, nitrite, and ammonia) compounds have the strongest impact on the water quality of reservoirs. High concentrations of these nutrients in rivers flowing into stagnant waters cause intensive growth of vegetation, mainly of

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Table 1. Basic characteristics (and symbols) of the Włodzienin Reservoir and its catchment basin (according to [11] and own estimations).

| Catchment basin | | Reservoir | | |
|---|---|---|---|---|
| Total catchment area | 55.4 $km^2$ | Max. fill level: | | |
| Thereof: | | Surface elevation | $h_{max}$ | 265.2 m a.s.l. |
| Braciszowski Brook | ca. 12.0 $km^2$ | Surface | $A_{max}$ | 116 ha |
| Lewicki Brook | 14.3 $km^2$ | Volume | $V_{max}$ | 5.6 $10^6 m^3$ |
| Catchment use: | | Max. depth | $z_{max}$ | ca. 15 m |
| Arable land | ca. 50.0% | Operational fill level | | |
| Grassland | ca. 28.6% | Surface elevation | $h_0$ | 263.5 m a.s.l. |
| Forests | ca. 12.7% | Surface | $A_0$ | 86 ha |
| Population density | ca. 75 inh. $km^{-2}$ | Volume | $V_0$ | 4.0 $10^6 m^3$ |
| Average precipitation | 584 mm $a^{-1}$ | Mean depth | $\bar{z}$ | 4.7 m |
| Average discharge (TR5) | 0.18 $m^3 s^{-1}$ | Theor. retention time | $\bar{t}$ | 0.7 a |

phytoplankton. In extreme cases, massive algae blooms – particularly cyanobacteria forming a thick green scum at the water surface – can be observed in highly eutrophicated reservoirs and slowly flowing rivers in summer [6, 7].

The eutrophication process has been a key issue for specialists in water protection and management for a long time. It seriously obstructs efficient water management [8, 9]. Therefore, it is essential that the eutrophication process is considered in an early stage of case studies reservoir design. It has to be clarified whether unfavorable biological and chemical processes caused by eutrophication will be intensified in a given dam [10].

The main objective of this study is to determine hydrochemical parameters in the catchment of the Włodzienin Reservoir that construction in the Troja River started at the end of 2006. A statistical analysis of the water quality results obtained for the Troja River and the two subsidiary streams, feeding the Włodzienin reservoir Braciszowski Brook and Lewicki Brook, was carried out. The consequences for water quality of the reservoir are estimated and discussed. Some proposals for the future protection of the reservoir are presented.

## Study Site and Experimental Procedure

The Troja River and Lewicki Brook are tributaries of the Włodzienin Reservoir, located in the southern part of Opole Voivodeship at the 25th km of the Troja. From the administrative point of view, the reservoir catchment is situated in the Branice and Głubczyce municipalities and covers the areas of the villages Zopowy, Zubrzyce, Jędrychowie, and Lewice, which are not provided with sewage systems. Sewage from households is mostly released directly into the receiving waters. It was even observed that septic tanks and cesspits were discharged into the brooks time after time. The area immediately surrounding the reservoir is not built up. Basic characteristics of the drainage basin and the reservoir are given in Table 1. The morphometric data of the Włodzienin Reservoir fulfill the ICOLD criteria for a large dam [12].

Water quality was assessed for the above-mentioned water bodies according to the ordinance of the Polish Ministry for the Environment dated 23 December 2002 [13]. The assessment is based on investigations carried out from January to December 2006. Water samples were collected once a month at the following stations (Fig. 1):

- TR1: Troja River near its spring, km 36.5 (50°09.23'N, 17°43.47'E),
- TR2: Troja River below Zopowy, km 32 (50°08.98'N, 17°45.68'E),
- BB: Braciszowski Brook 0.1 km upstream of its mouth into the Troja River (50°08.07'N, 17°47.14'E),
- TR3: Troja River below Zubrzyce, km 29 (50°08.05'N, 17°47.30'E),
- TR4: Troja River at Włodzienin-Lewice road, km 26 (50°07.22'N, 17°49.47'E),
- LB: Lewicki Brook 0.1 km upstream of its mouth into the Troja River (50°06.96'N, 17°49.55'E),
- TR5: Troja River at the position of the dam of the future reservoir, km 25 (50°07.00'N, 17°49.66'E).

The following physico-chemical parameters were determined according to Polish Standard Methods [14]: nitrate $NO_3^-$ (mg $L^{-1}$), nitrite $NO_2^-$ (mg $L^{-1}$), ammonia $NH_4^+$ (mg $L^{-1}$), soluble reactive phosphorus (SRP) $PO_4^{3-}$ (mg $L^{-1}$), $BOD_5$ (mg $L^{-1}$), pH-value, electrolytic conductivity (μS $cm^{-1}$), and water temperature (°C). Station water quality was characterized by statistical measurements of the parameters obtained (minimum, maximum, arithmetic mean ± standard deviation). Water quality classes (WQC) were determined based on comparison of the 90th percentiles P90 of the water quality indicators related to limits defined by the ordinance of the Minister for the Environment dated 11 February 2004 [15].

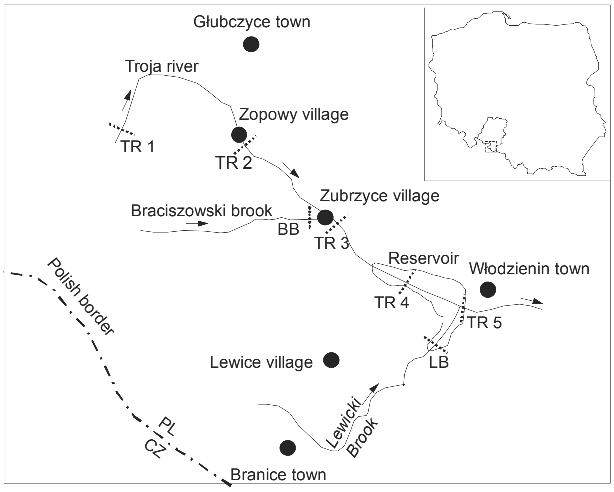


Fig. 1. Location of the sampling points in the catchment of the Włodzienin Reservoir.

## Results and Discussion

The year 2006 was characterized by an unusually long and snow-rich winter. Intensive snowmelt was observed at the end of March. Except for August, the summer was rather warm and dry. Flow rates at TR5, higher than the long-term average of 0.18 $m^3$ $s^{-1}$, were only measured in April (Fig. 2).

The results of the statistical evaluation of the data measured along the upper 12 km of the Troja River from station TR1 below the spring down to station TR5 at the position of the Włodzienin Reservoir dam are shown in Fig. 3. The limits of the water quality classes I-IV of the water quality indicators are marked in Fig. 3 as well, and allow the classification of the stations based on the 90th percentile P90.

Water temperature *T* (°C) was uncritical at all stations (Fig. 3A) and varied seasonally in the normal range (Fig. 4). P90(*T*) never exceeded the limit of WQC I, not even in the warmest phase of the year in June and July. As a rule, pH-values between about 7 and 8 were measured (Fig. 3B). However, maximum pH-values higher than 8 were observed at all sampling points and P90(pH) of stations TR4 and TR5 is almost identical with the limit of WQC I.

Increased average ammonia concentrations (Fig. 3C) were found at TR2 (WQC III) and TR3 (WQC IV), both situated just below villages (Fig. 1). Maximum values higher than 2 mg $L^{-1}$ $NH_4^+$ were measured there and even at station TR1. Ammonia is an indicator for elevated pollution with organic substances (e.g. liquid manure, wastewater), which is typical for streams flowing through agricultural settlements without functioning sewage systems and fertilized farmland [16]. It is particularly produced at the degradation of animal and herbal proteins. High ammonia concentrations may indicate direct entries of organic and mineral fertilizers. Unpolluted forest streams typically show concentrations lower than 0.1 µg $L^{-1}$. The ionized fraction of ammonia (i.e. ammonium $NH_4^+$) forms dissociation equilibrium with the highly fish-toxic unionized fraction (i.e. ammoniac $NH_3$), depending on pH value and water temperature. At pH 7, the ammoniac concentration is low. However, an ammonia concentration of only 0.5 mg $L^{-1}$ is associated with an $NH_3$ concentration of about 0.02 mg $L^{-1}$ at pH 8 and 20°C, which is already critical for fish [17-19]. Furthermore, the average and maximum nitrite concentrations (Fig. 3D) were rather high and, thus, WQC III and IV were determined. Nitrite is an intermediate product of the ammonia oxidation and highly fish-toxic as well [18, 19]. Severe symptoms of fish poisoning have already been observed at $NO_2^-$ concentrations lower than 0.5 mg $L^{-1}$. It has to be concluded that fish cannot survive in the Troja River and even invertebrates are endangered.

The average and maximum nitrate concentrations increased from TR1 to TR3 (Fig. 3E). WQC better than III were found for TR1 and TR2 only. High $NO_3^-$ concentrations are typical for agriculturally used drainage basins [16, 20, 21]. The highest $NO_3^-$ concentrations were observed between July and November (Fig. 5), when the lowest discharges were measured. This is different from findings at German reservoirs with a high share of arable land in the watershed, where nitrate usually is maximal between November and April due to reduced $NO_3^-$ uptake by agricultural crops [21]. It seems that the nitrate concentration in the Troja River was strongly influenced by point sources (run-off from manure piles and cesspools in the settlements).

With respect to the eutrophication potential of the Troja River, the high SRP concentrations have to be considered most critical (Fig. 3F). Only stations TR1 and BB could be classified better than WQC III. Station LB showed even WQC V. $PO_4^{3-}$ varied relatively little around high average concentrations at all stations. In contrast to $NO_3^-$, $PO_4^{3-}$ is a relatively immobile ion that usually is strongly retained by soil particles. The run-off from residential areas without wastewater treatment was found contributing the most to the dissolved phosphorus loading of reservoir tributaries [16, 20]. The results observed at the Troja River seem to confirm these facts: stations TR1 and BB with the lowest influence of settlements showed the lowest $PO_4^{3-}$ concentrations and LB, most strongly affected by effluents, showed the highest $PO_4^{3-}$ concentrations, particularly in dry periods.

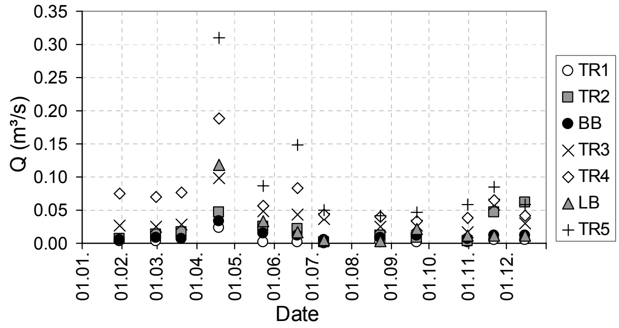


Fig. 2. Discharges measured at the sampling stations during 2006.

According to the saprobial pollution index of the EUWFD [1], streams with $BOD_5$ between 2 and 6 mg $L^{-1}$ are classified as moderately polluted. P90($BOD_5$) close to or higher than 6 mg $L^{-1}$ were determined for all stations except TR3 and TR4 (Fig. 3G), indicating critical loading with organic oxygen-consuming substances. The conductivity (Fig. 3H) was slightly increased and all stations were classified into WQC II.

Interrelationships between structure and utilization of drainage basins and stream water quality as well as their fundamental impact on the bio-chemical matter turnover and ecological structure of reservoirs have been frequently investigated in Poland [22-26]. Based on the results obtained in 2006, some rough estimates about the trophic state and water quality of the Włodzienin Reservoir are possible. Considering the mean $PO_4^{3-}$ concentration of 0.66 mg $L^{-1}$

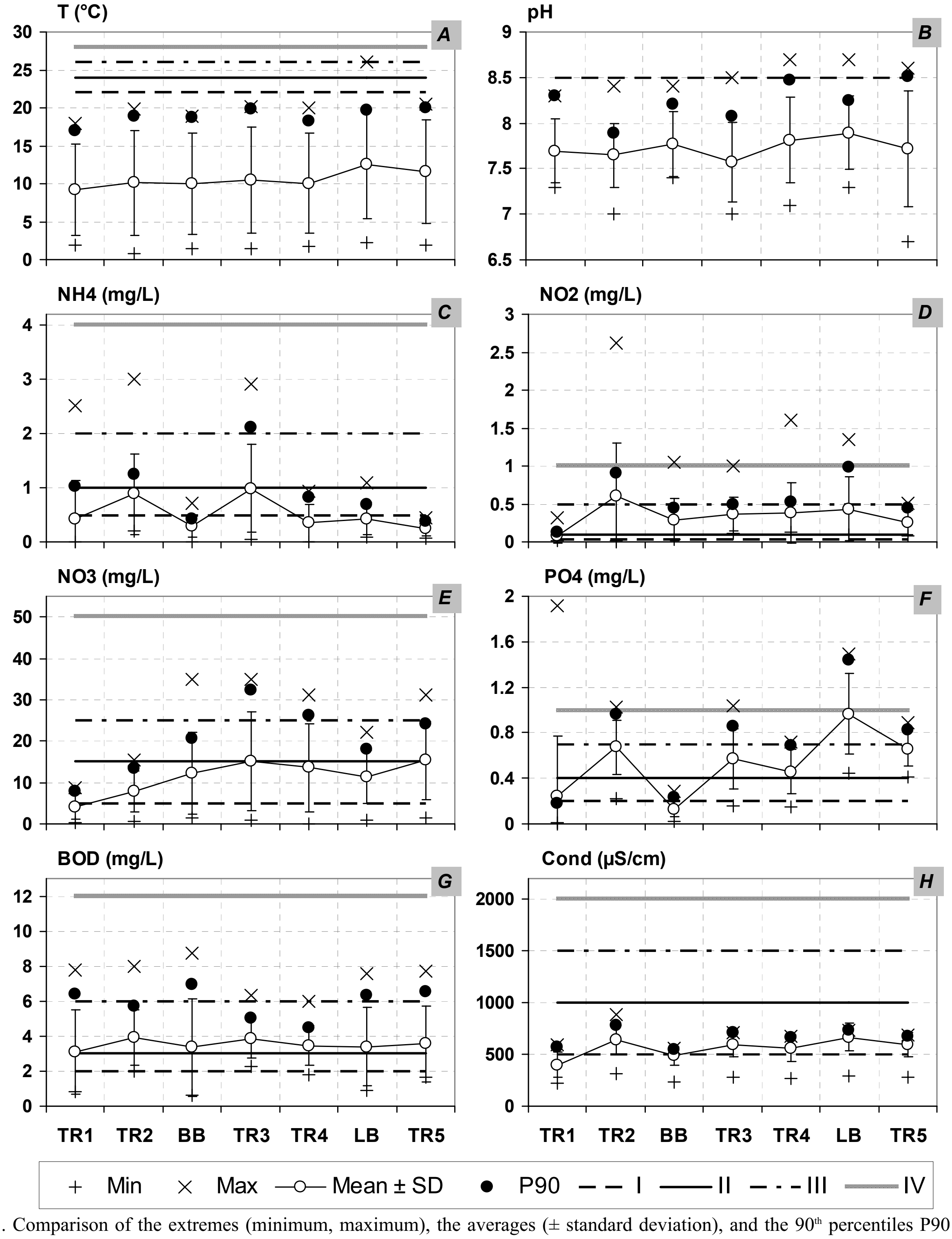


Fig. 3. Comparison of the extremes (minimum, maximum), the averages (± standard deviation), and the 90th percentiles P90 of the water quality parameters monthly measured at the different sampling stations in 2006. The limits of the water quality classes I-IV according to [15] are shown.

measured at TR5 and the average discharge of 0.18 $m^3 s^{-1}$ as representative for the total inflow into the reservoir, the annual SRP load $L_{SRP}$ is very high and amounts to approximately 1.26 t $a^{-1}$ $PO_4$-P. The areal SRP-load $L'_{SRP} = L_{SRP} / A_0 \approx 1.47$ g $m^{-2}$ $a^{-1}$ is related to $\bar{z}/\bar{t}$ = 6.7 m $a^{-1}$. Based on the trophic state classification concept developed by Vollenweider [27] and its modification by Benndorf [28] for SRP, the polytrophic status of the reservoir has to be expected (Fig. 5). Strong phytoplankton mass developments and low transparency of the water (frequently < 1 m) are most likely under such conditions during the entire ice-free time of the year [29].

The epilimnetic nutrient budget and the primary productivity of stagnant waters with high flushing rate primarily depend on the import of bioavailable nutrient fractions by the tributaries. The atomic N/P-ratio of the bioavailable dissolved inorganic N-fractions and SRP in the Troja River at TR5 varied around the Redfield ratio of 16:1 between about 7 and 37 during the summer months (average 22). Hence permanent N-limitation of the phytoplankton growth is probably not to be feared. However, a dominance of cyanobacteria has to be taken into account in polytrophic waters during longer phases in summer.

The Włodzienin Reservoir is a rather deep and stable thermal, and stratification from about May to September/October has to be expected. The effective wind fetch of the reservoir is about 1.5 km thus a characteristic thermocline depth $z_{mix}$ of ca. 5 m can be assumed [30, 31]. A model developed by Junge [32] was used to estimate the hypsographic curves of the Włodzienin Reservoir depending on $A_0$, $V_0$, and $z_{max}$ · With $z_{mix}$ = 5 m, a volume of the hypolimnion $V_{hypo} \approx 1.2$ $10^6$ $m^3$ comes out if the reservoir is filled up to the operational fill level ($h_0$ = 263.5 m a.s.l.). The ratio between the epilimnetic volume $V_{epi}$ and $V_{hypo}$ amounts to about 2.3. Serious oxygen depletion in the hypolimnion must be anticipated under such trophic and morphometric circumstances. Anaerobic conditions at the ground of the Włodzienin Reservoir have to be considered in June already. It would take only about 30 to 50 days until complete oxygen consumption in the hypolimnion if an average oxygen concentration of ca. 10 mg $L^{-1}$ at the beginning of the summer stratification (May) and a daily oxygen consumption rate of 0.2-0.3 mg $L^{-1}$ $d^{-1}$ in the hypolimnion are assumed, which was observed in the German Koberbach Reservoir with similar morphometry and P-loading [Paul, unpublished]. The development of hydrogen sulphide in the deep water layers before the onset of the autumn full circulation cannot be excluded. Furthermore, the P remobilization from sediments dramatically increases under anoxic conditions [33] and will most likely exacerbate the trophic state of the Włodzienin Reservoir.

Appropriate management of the reservoir can at least delay the incidence of anaerobic conditions in the hypolimnion. The water should be withdrawn from the reservoir's bottom outlets during the stratification periods as long as the outflowing water does not intolerably affect the population living downstream. As a result, the deepest water layers with the potentially highest oxygen depletion are continuously released and a certain water renewal in the hypolimnion will be achieved (vertically downward transport of oxygen). However, it would take more than 70 days to completely exchange the hypolimnion volume of about 1.2 · $10^6$ $m^3$ under average discharge conditions (0.18 $m^3 s^{-1}$); thus oxygen transport into the hypolimnion could not compensate for the depletion. Even more, the hypolimnetic temperature increase would be accelerated and oxygen consumption as well. Hence, the permanent deep water release identical to the inflow rate can only delay but not avoid the formation of anoxic conditions in the hypolimnion of the Włodzienin Reservoir during summer stratification. Additional measures eventually have to be taken into consideration (deep water aeration or artificial destratification).

The critical water quality to be expected in the Włodzienin Reservoir may seriously curtail its usability. The habitat of fishes in highly eutrophic stratified waters can be strongly restricted to a thin metalimnetic layer in the summer due to very high pH-values in the epilimnion, resulting from intensive phytoplankton photosynthesis and anoxic conditions just below the metalimnion. Lakes and

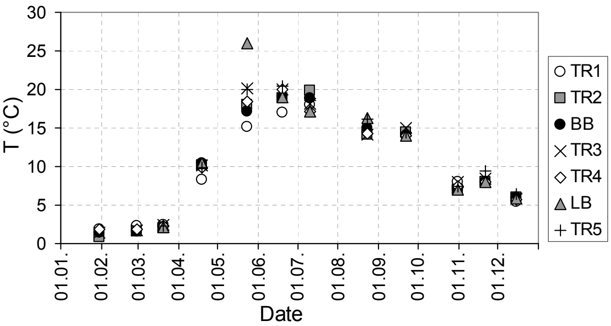


Fig. 4. Water temperature measured at the sampling stations during 2006.

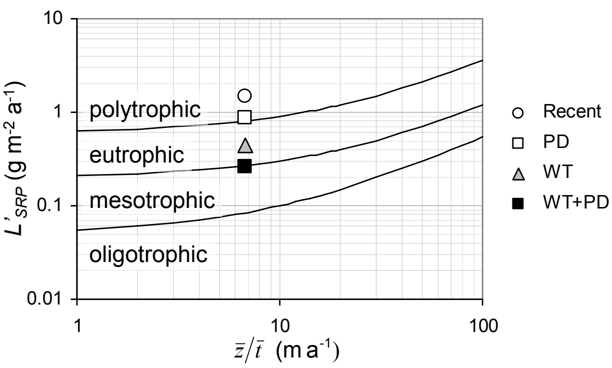


Fig. 5. Trophic state classification based on SRP according to [28] considering the following scenarios: Recent - recent loading, PD - average annual elimination of the inflowing SRP-load by 40% due to pre-dams of optimum size, WT - 70% reduction of the SRP-import by effective wastewater treatment in the settlements, WT+PD – 70% reduction of the SRP-import by wastewater treatment and 40% reduction of the remaining SRP-load by pre-dams (i.e. 82% total reduction).

reservoirs are not attractive for tourists in phases of phytoplankton mass developments. Bathing in water containing high concentrations of cyanobacteria producing toxic microcystins entails fatal health risks [34]. Results of recent studies show that even irrigation with water containing microcystins has the potential to move these toxic substances into agricultural crops and vegetables and, hence, into farm animal and human food chains at concentrations that can exceed recommended tolerable limits [35].

The following measures could improve the trophic state of Włodzienin Reservoir:

1. Pre-dams of optimum size have proven their effectiveness to eliminate SRP from the inflows [36-41] and to protect reservoirs from fast siltation [42]. However, polytrophic conditions likely would still remain if an annual average SRP-elimination of 40% by pre-dams is supposed (Fig. 5).
2. The SRP-concentrations measured at TR1 and BB (Fig. 3F) can be considered as characteristic for parts of the drainage basin that are unaffected by direct entries of sewage from settlements. Hence, a reduction of the SRP-concentration at TR5 by 70% would be necessary to reach this level. This can only be achieved by the implementation of efficient wastewater treatment plants in the settlements of the catchment basin. A shift of the trophic state from polytrophic to eutrophic could be expected under these conditions.
3. A slightly eutrophic or even mesotrophic state would probably result if both measures – the implementation of wastewater treatment and pre-dams – could be realized (Fig. 5).
4. Last but not least, agricultural practices have to more seriously consider aspects of water protection (e.g. prevention of direct entries of fertilizers into the tributaries or reservoir, soil preserving tillage improving infiltration and reducing erosion, growing of intermediate crops; [21]).

Haste is required to prevent the development of a high internal P-pool by the accumulation of large quantities of P-enriched sediments, which would seriously aggravate the remediation of the reservoir.

## Conclusions

The most important purpose of the Włodzienin Reservoir – the improvement of flood protection – is highly appreciated by the authorities responsible for water management and the inhabitants of the Troja River catchment. Further motivation for planning and construction of the reservoir was its utilization for irrigation of farmland and tourism. However, at least the latter seems to be quite questionable due to the expected deficient water quality.

Investigations of the physico-chemical water quality of the Troja River and Lewicki Brook were carried out in 2006. The results show that both streams feeding the reservoir are highly polluted. Due to the very high SRP loading, originating primarily from the settlements in the drainage basin, polytrophic status of Włodzienin Reservoir has to be expected. Furthermore, stable thermal summer stratification with an inauspiciously high ratio between epi- and hypolimnion volume must be taken into account. Permanent high epilimnetic phytoplankton biomasses and anaerobic conditions in the hypolimnion already early in the summer are anticipated. It cannot be excluded that strongly elevated hydrogen sulphide concentrations may occur in the hypolimnion before the end of summer stratification. The habitat of fishes might be endangered and the attractiveness of Włodzienin Reservoir for tourists and anglers will most likely be strongly restricted.

Although the polytrophic symptoms can be slightly mitigated by an appropriate reservoir management (hypolimnetic water withdrawal as long as the outflowing water does not intolerably affect the population living downstream), there is no alternative for a reduction of the P-import into the reservoir by more than 80%. This can only be achieved by the installation of effective wastewater treatment plants in the settlements upstream from the reservoir. Furthermore, the functioning of the planned pre-dams with respect to their SRP elimination capacity has to be investigated and – if necessary – adapted.

The study shows that water quality monitoring in the tributaries (especially if those mostly small catchments are not subject to regular inspection programs by state environmental authorities) and an assessment of the bio-chemical matter turnover and ecological state in an early stage of planning and projection of a reservoir is essential to prevent unexpected restrictions of the desired uses and serious disturbances of the downstream river ecosystem.

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