ARCHIVES OF ENVIRONMENTAL PROTECTION
vol. 34 Special Issue pp. 79 - 89 2008

PL ISSN 0324-8461

THE USE OF PRE-DAMS WITH PLANT FILTERS TO IMPROVE WATER QUALITY IN STORAGE RESERVOIRS

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Keywords: Storage reservoirs, pre-dams, water quality, water protection.

Abstract: The paper presents the way of water quality improvement in storage reservoirs, using pre-dams with plant filters. Pre-dams, built above the main reservoirs, reduce the inflow of pollutants transported by the river and take over most of biochemical processes responsible for eutrophication of the stored water. As a result, water flowing to the main reservoir contains smaller loads of pollutants. The above-mentioned method is more economic, requires relatively short construction time and is less laborious than generally used methods of surface water protection. It is specially recommended to improve the quality of water in small reservoirs, where quick silting and eutrophication occur. Proper functioning of pre-dams depends on proper selection of their parameters, such as: water storage time, water flow velocity, filling depth and type of plant filters. The authors estimated the effectiveness of a pre-dam reservoir situated above the main reservoir in Mściwojów on the Wierzbiak River. The pre-dam reservoir consists of a three-chamber sediment tank and three chambers with plant barriers. The purpose of the chambers is to decrease the quantity of sediments, the biogenic substances and other pollutants carried with water flowing to the main reservoir. Research carried out during the period 2000–2001 showed that pre-dams significantly contributed to the improvement of the water quality in the main reservoir – nitrates were eliminated in ca 65% and phosphates in ca 52%.

INTRODUCTION

Dammed storage reservoirs – due to their location in the lowest parts of the catchment and river valleys – are the areas of accumulation of organic and mineral matter carried out by the supplying watercourses. This results in silting and water quality deterioration. In many cases water stored in the reservoirs undergoes degradation processes and loses its use values [4]. Increased eutrophication of water environments causes many changes in ecosystems, which are unfavorable from the point of view of an economic activity. Nutrient enrichment of surface waters results in abundant development of plant communities, mainly plankton, with all side effects diminishing the use value of water and aesthetic values of the reservoirs [8]. Under favorable meteorological conditions – usually in late summer – on the surface of the fertile reservoir waters Cyanobacteria blooms in the form of a blue-green scum can be observed. This is not only an esthetical problem but also – and first and foremost – a health problem due to the production of acute toxins [12].

The eutrophication process is a serious obstruction in the efficient water management, particularly in the case of retained water [14]. Therefore, the aim should be to improve the water quality and remove biogens from the water system with a simultaneous reduction of their inflow from outside.

The methods for prevention of water eutrophication have been studied out for many years. One of them is based on the use of the so called pre-dams [11].

Methods for reduction of pollutant inflow to the reservoirs

Protection of water reservoirs is usually based on the reduction of biogenic and organic substances flowing from the catchment. This is, however, very laborious, time-consuming and expensive. It includes reduction – and preferably – liquidation of point, diffuse and area sources of pollution in the catchment [5].

The reduction of biogenic compound inflow to the reservoir is an important and often sufficient measure to prevent degradation of the water stored in the reservoir. This aim can be achieved by:

(a) reorganizing of water supply and sewage disposal in the supplying watercourse catchment, which includes:
  - construction of a sewage system and sewage treatment plant,
  - using proper type of fertilizer, excluding winter and autumn ones,
  - taking erosion preventive measures, including afforestation of high slope areas, forecrop and aftercrop cultivation,

(b) application of a pre-dam, built above the main reservoir,

(c) building a barrier in the backwater zone of the storage reservoir.

The best results in the reduction of pollutant inflow to the reservoir can be achieved by using comprehensive measures referred to in Clause (a). These are, however, long-lasting and labor-consuming actions, requiring great financial outlays. Therefore, in the engineering practice, more and more often pre-dams with plant filters or barriers in the backwater zone of reservoirs are used [5, 6]. These enable:

- stopping of suspended loads, bed loads and fertilizing substances,
- biodegradation of organic pollutants supplied from the catchment,
- protection of the main reservoir from emergency discharge of pollutants, which is particularly important in the case of water supply reservoirs,
- protection from uncovering a part of the reservoir in backwater zones,
- creation of water reserves.

The main goal of the pre-dams with plant filters is to stop pollutants transported in the river and take over most of biochemical processes responsible for eutrophication. As a result, water flowing to the main reservoir contains smaller loads of fertilizing substances as well as smaller suspended sediment loads and bed loads [2, 3].

In Poland there are still no sufficient experimental data on the effectiveness of pre-dams [15]. However, examples of the effectiveness of solutions aimed at the reduction of biogen inflow to the main reservoir using the above-mentioned pre-dams can be found in foreign literature [1]. All these studies show that the effectiveness of many pre-dams is high enough to protect the main reservoirs, situated below, from eutrophication.

Authors of this study carried out a long-term research on a technical scale in a storage reservoir in Mściwojów, equipped with a pre-dam and designed by specialists from the University of Environmental and Life Sciences in Wrocław, who determined the effectiveness of the pre-dam and assessed the selection of its technical parameters.

The main objective of this study is presentation of research results on water quality changes in the pre-dam and the main reservoir.

RESEARCH OBJECT CHARACTERISTICS

Location of the storage reservoir

Mściwojów storage reservoir is located on the Wierzbiak River (the Odra Basin), having its spring near the town of Strzegom (217.5 m a.s.l.). The total area of the Wierzbiak catchment is 280 km^2, whereas the area of the catchment up to the cross-section of the Mściwojów reservoir is 47 km^2, in which the partial area of the Zimnik (14.3 km^2) constitutes about 30% of the total catchment [13]. The Mściwojów reservoir catchment covers the area of municipalities of Mściwojów and Strzegom (Fig. 1).

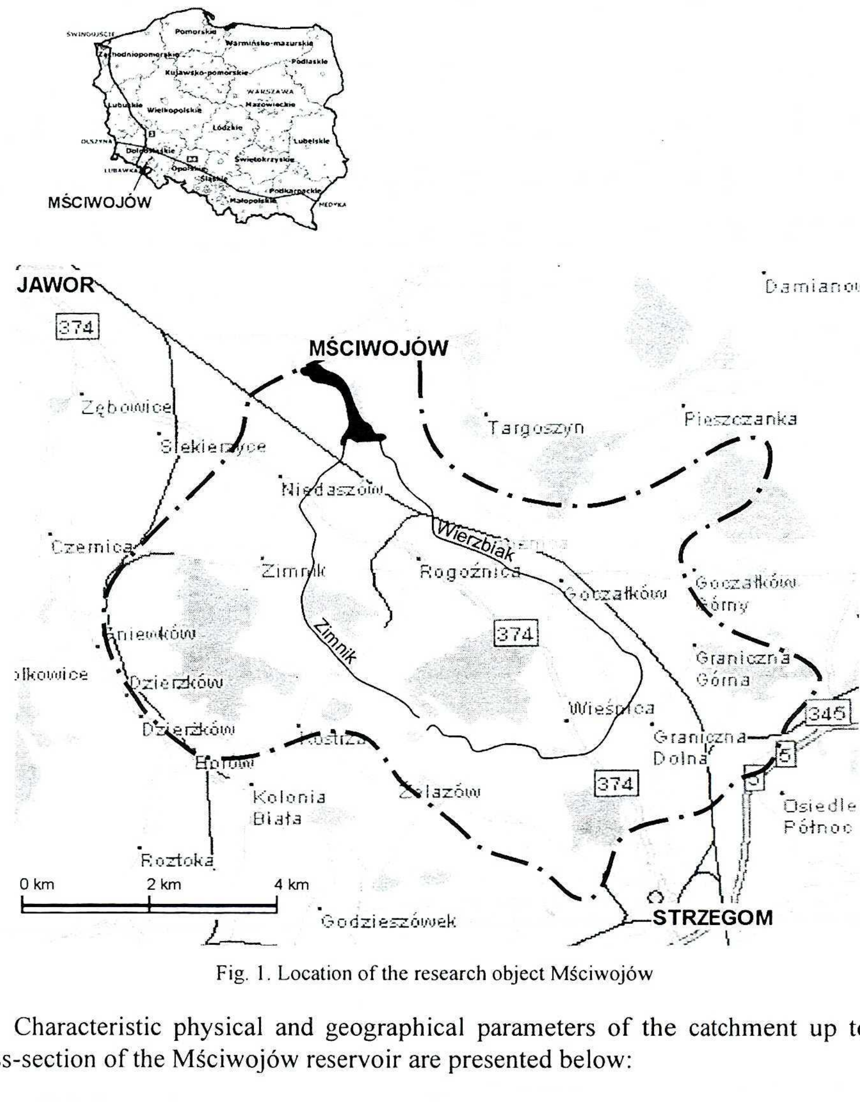

Fig. 1. Location of the research object Mściwojów

Characteristic physical and geographical parameters of the catchment up to the cross-section of the Mściwojów reservoir are presented below:

- catchment length (L) – 10.7 km;
- average width of the catchment – 4.4 km;
- catchment width coefficient $\delta = A/L^2$ – 0.41;
- watershed development index – 1.35;
- average height of the catchment – 265.07 m a.s.l.;
- average catchment slope – 2.26%;
- longitudinal river gradient – 0.3% (the Wierzbiak), 0.36% (the Zimnik);
- average flow in the research period – 0.124 m^3/s (the Wierzbiak), 0.050 m^3/s (the Zimnik).

The investigated region is located in the macroregion of Sudety Foreland and mesoregion of the Strzegomskie Hills [10]. The average annual precipitation in the period of 1961–1995 was 601 mm, in the hydrological year 2000/2001 – 732 mm. The average annual temperature in the above-mentioned period (1961–1995) was 8.5°C, whereas in the hydrological year 2000/2001 – 9.6°C.

The Wierzbiak catchment is an agricultural area. Poor afforestation of the catchment and majority of arable lands in agricultural areas pose hazard to the quality of surface waters and ground waters. The main water environmental hazard results from agricultural activity: use of mineral and organic fertilizers, pesticides, presence of animal farms and silage storage [7]. Moreover, quite significant is also the fact that such locality as: Niedaszów, Zimnik, Żółkiewka, Rogoźnica and Goczałków, situated in the Wierzbiak catchment, above the Mściwojów reservoir, do not have a sewage system.

There are no big industrial plants in the catchment, however, numerous quarries and stone works can be found. The inventory of sewage facilities carried out in July 2001 in localities situated in the Mściwojów catchment showed that the number of pollution sources was very high. Sewage generated in the Mściwojów catchment, mainly municipal and domestic sewage, is discharged directly to the Wierzbiak and the Zimnik, above the reservoir. In the Wierzbiak and the Zimnik catchment high contribution of point sources can be observed, which has a significant negative impact on the quality of water in this reservoir [13].

In Figure 2 the Mściwojów water reservoir is presented. Table 1 and 2 show parameters of the main reservoir and the Mściwojów pre-dam.

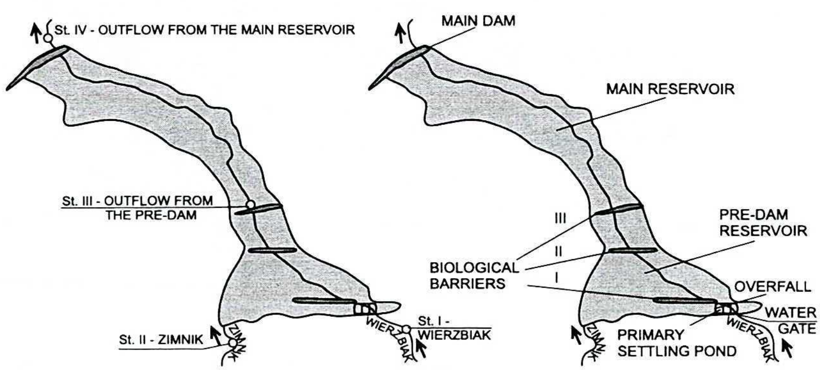

Fig. 2. Mściwojów water reservoir and location of the research stations: collecting samples for hydrochemical analyses St. I, St. II, St. III, St. IV; gauging sites St. I, St. II, St. IV; (inflow to the pre-dam: St. I – Wierzbiak stream and St. II – Zimnik stream; outflow from the pre-dam – St. III, outflow from the main reservoir – St. IV)

Table 1. The main reservoir Mściwojów parameters

Parameter	Unit	Values
Morphometric parameters:		
Maximum area of the reservoir	[m^2]	570 700
Area of the reservoir at normal water level	[m^2]	345 900
Average width at normal water level	[m]	150
Maximum width at normal water level	[m]	220
Average depth at normal water level	[m]	2.0
Maximum depth at normal water level	[m]	4.85
Length at normal water level	[m]	1 800
Length at maximum water level	[m]	2 200
Hydrological parameters:		
Maximum water level ordinate	[m a.s.l.]	194.50
Normal water level ordinate	[m a.s.l.]	193.35
Ordinate of the dam crest	[m a.s.l.]	195.60
Maximum capacity of the reservoir	[mln m^3]	1.35
Reservoir capacity at normal water level	[mln m^3]	0.735
Average inflow	[m^3/s]	0.171
Average time of water storage in reservoir	[days]	65

Table 2. The pre-dam reservoir parameters

Parameter	Unit	Values
The ordinate of water table at the normal water level	[m a.s.l.]	193.35
Capacity at the normal water level	[m^3]	~ 175 000
Area at the normal water level	[m^2]	~ 140 000
Length	[m]	~ 700
Average width	[m]	~ 295

Pre-dam operating principle

The pre-dam is situated above the main reservoir. It is responsible for improving the quality of water supplying the main reservoir. It consists of a sedimentation tank (settling pond) and a reservoir with three biological barriers (Fig. 2). The sedimentation tank and the biological barriers were designed to intercept the suspended sediment loads, bed loads, biogenic substances and other pollutants transported by water flowing to the reservoir. The sedimentation tank is divided into three chambers. In the first chamber big particles of suspended solids transported by the river are intercepted. The second chamber, covered with rooted vegetation, functions as a preliminary plant filter. The filter is composed of vegetation having a well developed root system, such as: *Schoenoplectus lacustris, Typha latifolia and Phragmites australis*. These plants take nutrients both from bottom sediments and water. In the third chamber sedimentation of fine parts of the suspended solids takes place. The water from this chamber water flows through a tower spillway to the main pre-dam bowl (area of about 14.0 ha), in which three biological barriers are placed (Fig. 2). The barriers are responsible for regulation of the water flow direction.

At constant water damming the third barrier remains under water, whereas the second and the first ones are partially above the water table. This forms some sort of islands, which become a wildlife habitat for water birds and other animals. This type of water circulation in the pre-dam enforces relatively long flow path and water contact with aquatic vegetation, which takes up biogenic substances required for its growth, improving, at the same time, the quality of the water. The aquatic vegetation is periodically mowed and removed from the reservoir. The main reservoir gets the water through the third barrier and it runs off to the Wierzbiak river-bed it runs off by two bottom outlets and a surface spillway.

SCOPE OF THE RESEARCH WORK

The following activities were carried out on the research object:

- hydrological monitoring, including water stage and water flow rate measurements (Fig. 2);
- hydrochemical monitoring, including water sampling and analyses of selected water quality indicators on the reservoir inflows (the Wierzbiak and the Zimnik) and outflows from the pre-dam and the main reservoir (Fig. 2).

The following physical and chemical water indicators were determined: nitrates, nitrites, ammonia, phosphates, water temperature and pH.

Location of sampling points

During the experiment the water quality at the inflow and outflow of the pre-dam and the main reservoir was determined. Samples were collected at the following sampling points: above the Mściwojów reservoir, on the Wierzbiak River – km 37+540 of its course (sampling point I); on the Zimnik River – km 0+800 of its course (sampling point II); at the outflow from the pre-dam (sampling point III) and at the outflow from the main reservoir (sampling point IV).

Location of the above-mentioned research stations collecting samples for hydrochemical analyses (stations I – IV) and water stage measurements (stations I, II, IV) are presented in Figure 2.

WATER QUALITY MEASUREMENT RESULTS

In this study the results of the following analyses were presented: concentrations of nitrates, nitrites, ammonia, phosphates, as well as water temperature and pH. The obtained results concerning the investigated physical and chemical indicators were analyzed using Statistica software. Location measures characterizing the average values of the observed features were calculated. An arithmetic mean ($\bar{x}$) (classical), calculated taking all observations into consideration, was assumed as the above-mentioned location measure. Besides, dispersion measures were also calculated, which allowed to generalize differences in the observed values at particular sampling points. As dispersion measure a range (R) was assumed, determined by the lowest and the highest value of a given feature. Another assumed dispersion measure was a standard deviation (s) which is an average of deviations of particular indicators from their average values.

To assess the significance of differences among arithmetic means of physical and chemical indicators a parametric t-Student test for independent samples was used. The test was performed at the assumed 95% confidence level.

In order to determine the impact of the pre-dam on the water quality in the main reservoir and below, it was necessary to determine average values of particular physical and chemical indicators of the Wierzbiak and the Zimnik water in the same time interval.

A formula of weighed arithmetic mean was applied, with the flow volume as the weight. Statistical characteristic of the water quality indicators is presented in Table 3.

Table 3. Statistical characteristics of water quality indicators

Pollution indicator	Sampling point	Min.	Max.	Average	Median	Range	Standard deviation
Nitrates [mg NO_3^-/dm^3]	I	2.40	52.00	18.79	21.50	49.60	14.57
	II	0.80	54.00	22.13	18.95	53.20	15.02
	III	0.50	26.00	6.41	3.30	25.50	6.63
	IV	0.50	12.90	4.02	2.80	12.40	3.33
Nitrites [mg NO_2^-/dm^3]	I	0.016	1.00	0.25	0.22	0.98	0.22
	II	0.016	1.00	0.44	0.29	0.98	0.38
	III	0.02	0.64	0.12	0.08	0.62	0.13
	IV	0.01	0.15	0.08	0.07	0.14	0.05
Ammonia [mg NH_4^+/dm^3]	I	0.09	1.40	0.32	0.25	1.31	0.26
	II	0.09	2.10	0.64	0.30	2.01	0.59
	III	0.09	0.30	0.18	0.20	0.21	0.08
	IV	0.09	0.36	0.18	0.15	0.27	0.09
Phosphates [mg PO_4^{3-}/dm^3]	I	0.20	2.00	0.56	0.40	1.80	0.41
	II	0.10	1.40	0.49	0.45	1.30	0.26
	III	0.10	2.00	0.26	0.10	1.90	0.43
	IV	0.10	1.80	0.28	0.10	1.70	0.39
Water temperature [°C]	I	2.60	24.50	15.29	15.65	21.90	6.36
	II	1.30	24.40	15.05	14.80	23.10	6.31
	III	0.90	26.70	16.64	18.20	25.80	7.43
	IV	2.90	26.40	15.91	17.10	23.50	6.64
pH	I	6.87	8.92	7.68	7.58	2.05	–
	II	7.27	8.40	7.79	7.82	1.13	–
	III	7.35	9.59	8.54	8.56	2.24	–
	IV	6.93	8.98	8.12	8.13	2.05	–

Data presented in Table 3 and referring to particular measurement cross-sections show great differences in the concentration of nitrates, nitrites and ammonia. The higher value of the average corresponded to the higher variability of results, higher values of the range and standard deviation. A lower dispersion of results was observed in the case of phosphates, which is reflected in the smaller scatter of results.

Moreover, the analyzed data show that the highest concentrations of nitrates, nitrites, ammonia and phosphates were observed at the inflows – at the sampling points II (the Zimnik) and I (the Wierzbiak). Their content in the analyzed water decreased remarkably after leaving the pre-dam, which testifies to its effectiveness. A graphical illustration and comparison of the average values and ranges of changes in nitrates, nitrites, ammonia and phosphates at particular sampling points (St. I – St. IV) are presented in Figures 3–5.

The analysis of pollution indicators at sampling points: I, II, III and IV was performed in order to determine the impact of the pre-dam on the improvement of the water quality in the main reservoir and at the reservoir outflow. Statistical significance of the selected water quality indicators using the t-Student test with the assumed significance level $p < 0.05$ is presented in Table 4.

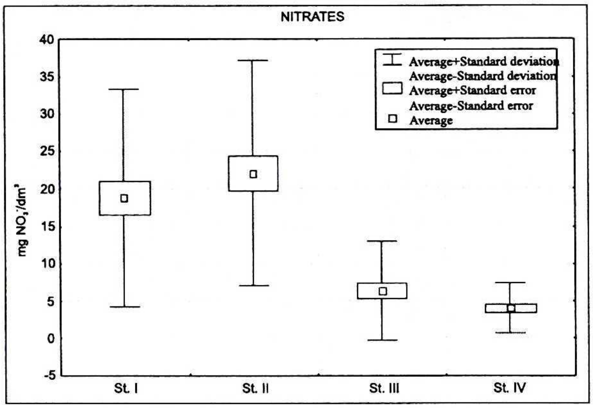

Fig. 3. Range of changes and average values of nitrate concentrations at particular sampling points St. I – St. IV

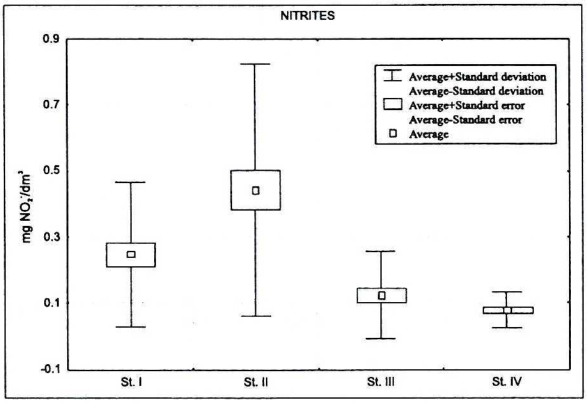

Fig. 4. Range of changes and average values of nitrite concentrations at particular sampling points St. I – St. IV

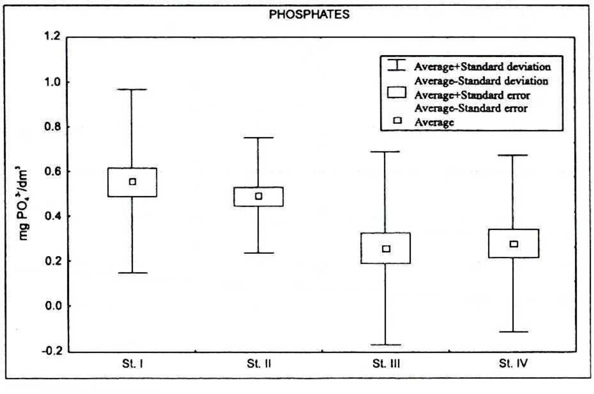

Fig. 5. Range of changes and average values of phosphate concentrations at particular sampling points St. I – St. IV

Table 4. Statistical significance of selected water quality indicators (t-Student test for independent samples)

Pollution indicator	Statistical significance of the difference		
	Inflow to the pre-dam	Inflow to the pre-dam	Outflow from the pre-dam
	Outflow from the pre-dam	Outflow from the main reservoir	Outflow from the main reservoir
Nitrates	$p < 0.005$	$p < 0.0005$	NS
Nitrites	$p < 0.05$	$p < 0.05$	NS
Ammonia	$p < 0.005$	$p < 0.0005$	NS
Phosphates	NS	$p < 0.05$	NS
Water temperature	$p < 0.05$	NS	NS
pH	$p < 0.00005$	$p < 0.005$	$p < 0.05$

NS – statistically insignificant difference

The analysis of pollution analysis of concentrations of the selected quality indicators for water flowing to the pre-dam (sampling point I and II) and outflowing (sampling point III) shows significant differences among the determined indicators ($p < 0.05$). The greatest difference in concentration levels was observed in the case of nitrates, ammonia and pH ($p < 0.005$, $p < 0.00005$).

Differences of the selected water quality indicators between the inflow to the pre-dam (sampling points I and II) and outflow from the main reservoir (sampling point IV) were also statistically significant ($p < 0.05$). The greatest difference ($p < 0.0005$) was observed in the case of nitrate and ammonia concentrations, the only exception was the water temperature. Statistically insignificant differences in the analyzed water quality indicators were noted in the case of water flowing out of the pre-dam – sampling point III and water flowing out of the main reservoir – sampling point IV ($p > 0.05$). The only exception was pH ($p < 0.05$). However, the difference in pH of the water flowing out of the pre-dam (sampling point III) and water flowing out of the main reservoir (sampling point IV) was not so statistically significant as in the case of water flowing to the pre-dam (sampling points I and II) and water flowing out of the pre-dam (sampling point III).

Table 5. Comparison of particular physical and chemical indicators in water flowing to the pre-dam, flowing out from pre-dam and from main Mściwojów reservoir

Pollution indicator	Inflow to the pre-dam	Outflow from the pre-dam	Outflow from the main reservoir	Changes after flowing through [%]	
				the pre-dam	the pre-dam and main reservoir
Nitrates [mg NO_3^-/dm^3]	22.49	7.75	4.34	65.5	80.7
Nitrites [mg NO_2^-/dm^3]	0.26	0.13	0.09	50.0	65.4
Ammonia [mg NH_4^+/dm^3]	0.38	0.18	0.18	52.6	52.6
Phosphates [mg PO_4^{3-}/dm^3]	0.48	0.23	0.24	52.1	50.0
Water temperature [°C]	12.8	13.6	13.7	6.2	7.0
pH	7.70	8.51	8.13	10.5	5.6

The results of the water quality analysis, carried out in the Mściwojów reservoir, showed that the water quality improved after flowing through the pre-dam: a decrease in the concentration of nitrates, nitrites, ammonia and phosphates was observed. The water temperature and pH dropped slightly (Tab. 5).

In 2005/2006 a control test of the reservoir effectiveness was carried out [4]. The obtained results were similar to those obtained in 2000/2001.

CONCLUSIONS

- Long-term studies carried out in the Mściwojów storage reservoir showed that the pre-dam contributed to the elimination of the inflowing pollutants. Nitrates were eliminated in 65%, whereas nitrites, ammonia and phosphates in about 53%.
- Statistical comparison of concentrations of the selected water quality indicators for the water flowing to the pre-dam and water flowing out of the pre-dam and the main reservoir showed very significant differences ($p < 0.05$). Statistically insignificant differences were observed for the water flowing out of the pre-dam and water flowing out of the main reservoir ($p > 0.05$). The only exception was pH ($p < 0.05$).
- A proper functioning of pre-dams depends on proper selection of their parameters, such as: water storage time, waterflow velocity, filling depth and type of plant filters.
- Pre-dams have relatively short construction time, are less expensive than the commonly used pollutant reduction methods and can be recommended for the protection of surface waters.

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ZASTOSOWANIE ZBIORNIKÓW WSTĘPNYCH Z FILTREM ROŚLINNYM DO POPRAWY JAKOŚCI WODY W ZBIORNIKACH RETENCYJNYCH

W artykule przedstawiono metodę poprawy jakości wody w zbiornikach retencyjnych przy zastosowaniu zbiorników wstępnych z filtrem roślinnym. Zbiorniki wstępne lokalizowane powyżej zbiorników głównych zmniejszają dopływ zanieczyszczeń transportowanych rzeką i przejmują znaczną część procesów biochemicznych, które powodują eutrofizację retencjonowanej wody. W efekcie do zbiornika głównego dopływa woda ze zmniejszonym ładunkiem zanieczyszczeń. Metoda ta jest bardziej ekonomiczna, wymaga krótszego okresu realizacji i jest mniej pracochłonna niż ogólnie stosowane metody ochrony wód powierzchniowych. Jest ona szczególnie zalecana do poprawy jakości wody w małych zbiornikach podatnych na intensywne zamulanie i eutrofizację. Prawidłowa budowa i eksploatacja zbiorników wstępnych zależy od właściwego doboru ich parametrów, takich jak: czas magazynowania wody, prędkość przepływu wody, głębokość zalewu i doboru filtrów roślinnych. Autorzy ocenili skuteczność działania zbiornika wstępnego usytuowanego powyżej zbiornika głównego w Mściwojowie na rzece Wierzbiak. W zbiorniku wstępnym wydzielono (trzykomorowy) osadnik oraz trzy komory z przegrodami roślinnymi. Głównym celem tych urządzeń jest zmniejszenie ilości rumowiska, substancji biogennych oraz innych zanieczyszczeń niesionych wraz z dopływającą wodą do zbiornika głównego. Badania przeprowadzono w okresie 2000–2001. Otrzymane wyniki wykazały znaczącą rolę zbiornika wstępnego w poprawie jakości wody dopływającej do zbiornika głównego – nastąpiło zmniejszenie ilości azotanów o około 65%; fosforanów – o około 52%.