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External Loading of Phosphorus in Deep, Stratified Lake Affected with Drainage Water

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External Loading of Phosphorus in Deep, Stratified Lake Affected with Drainage Water

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Abstract. The Water Framework Directive (2000/60/EC) requires from European countries to achieve environmental objectives. In relation to lakes, it is a good qualitative and quantitative status of all water bodies. Deep and stratified lakes resist anthropopressure for a long time, so they do not seem to require active protection. However, these types of ecosystems are also undergo a degradation processes. This is particularly true for lakes with tributaries - potential outbreaks of nutrients. Even small streams with visually "clean water" can carry loads of pollution exceeding the self-cleaning capacity of water bodies. Our paper presents the impact of anthropogenic watershed (agricultural and urban management) on the environmental conditions in small (deep (15.3m) stratified lake (Lake Święte in Obra, Wielkopolskie Lakeland, Poland). In the research, loads of biogenic pollutants feeding the reservoir from the main external sources were compared: drainage water supply (Pintus watercourse), atmospheric deposition, surface load from direct catchment, angling, and watering place. It has been shown that about 80% of the annual phosphorus load reaches the lake along with an inconspicuous watercourse (average flow $0.04 \ m^3 \, s^{-1}$, phosphorus concentration 0.1 - 0.5 $mgP \, l^{-1}$), to which drainage water from the surrounding area is discharged. The second major source of pollution is surface runoff. The total load of phosphorus contaminants was compared with the load discharged outside the ecosystem and the so-called critical level, calculated in accordance with the Vollenweider model (1976).

The results of our research indicate that Święte Lake is a trap for pollution transferred through a drainage and watercourses network. At the same time, the volume of external loading of phosphorus several times exceeds the critical level and indicates the scenario of further eutrophication of the lake. Unexpectedly for the local community and lake users, this pollution is primarily due to the inconspicuous mid-field stream. On the basis of the results obtained, a plan of protective measures was developed, the main element of which is the elimination of this source of pollution. The work also discusses the possible techniques of revitalizing the lake ecosystem.

The research indicates the need to appreciate the role of small watercourses in the process of eutrophication of lakes and the role of early conservation measures taking place before the appearance of symptoms of ecosystem degradation, especially before the achievement by lakes of the turbid state - dominated by phytoplankton.

1. Introduction

Poland is European Egypt - this popular statement reflects well the water resources of our country. Easily available surface water resources, per capita, are relatively small in our country compared to

other European Union countries [1]. Polish water resources, calculated per capita amount to about 1600 m^3 per year, which places Poland on the fourth position in Europe (from the end of the list). At the same time, a significant percentage of fresh water resources are lakes and reservoirs. They play the role in landscape-forming, habitat-forming, economic and ensuring security of access to freshwater resources for people. Definitely negative for the welfare of these ecosystems is the fact that small and shallow lakes predominate in Poland [2]. Due to the relatively smaller possibilities of dilution of pollutant load they are subjected to rapid evolution in the conditions of agricultural catchments, often called anthropogenic eutrophication. Historical neglect in the water and sewage sector also for decades weakened these extremely valuable ecosystems, often leading to their degradation. Therefore deep lakes are particularly valuable, more resistant to degradation, but often more exposed to anthropopressure, because they are able to endure of pollution loading without any visible symptoms.

Usually, with a visual deterioration of water quality, we discover that their ecosystem is already very strongly degraded by long-term accumulation of pollution. An example of this type of scenario is the object of these studies - the Święte Lake in Obra (Wielkopolskie Lakeland). In this work analyzed in detail the conditions and implications of the catchment's external impact as a source of biogenic matter for this limnic ecosystem.

2. Material and methods

The research was carried out on Święte Lake (figure 1), including its water inputs, together with artificial drainage net water, water output and drainage basin. The field studies, cartographic studies and laboratory water analyses were made in one year period (from April 2017 to April 2018).
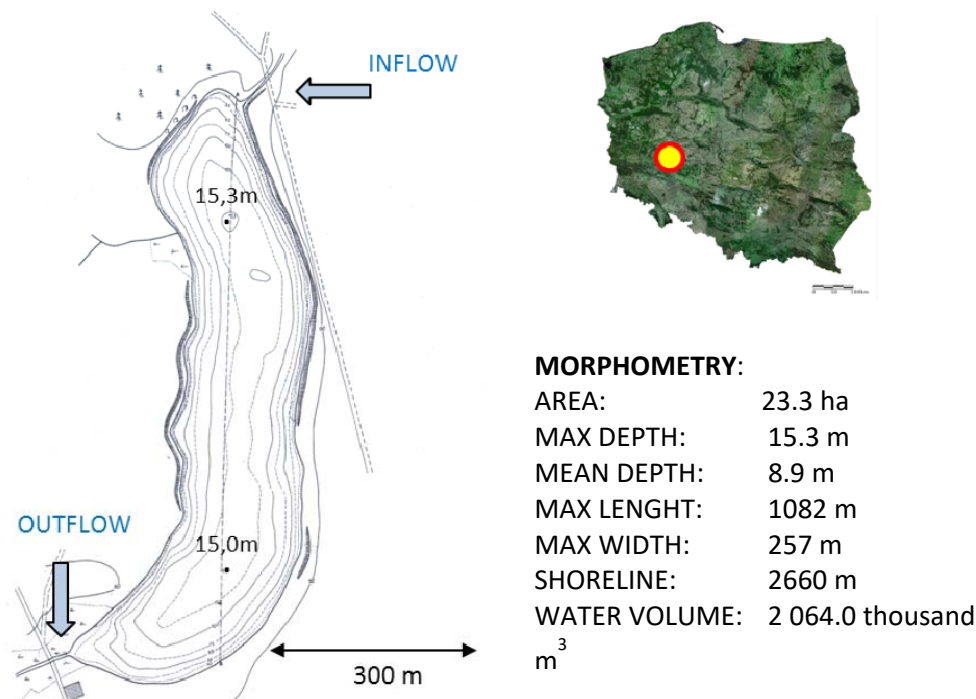

MORPHOMETRY:
AREA: 23.3 ha
MAX DEPTH: 15.3 m
MEAN DEPTH: 8.9 m
MAX LENGHT: 1082 m
MAX WIDTH: 257 m
SHORELINE: 2660 m
WATER VOLUME: 2 064.0 thousand m^3

Figure 1. Location and morphometry of Lake Święte in Obra, bathymetric plan basing on the date of Inland Fisheries Institute in Olsztyn [3].

2.1. The study object

Lake Święte in Obra is rather small, but deep reservoir. It represents dimictic water mixing type – with two circulations (spring and autumn) and two stagnation periods (summer and winter) Max. depth

exceeds 15 m and it is associated with small water table area (max length 1,082 m, max width 257 m) and western winds course domination in perpendicular direction to lake axis allows to create of lull thermal stratification. Epilimnion usually is 4 m deep, the thermocline is located below, with 4-5 m of thickness, and hypolimnetic cold water zone starts ca. on 9-10 m depth. The ice cover is usually formed during winter. Basic morphometric data of the lake are presented on figure 1.

2.2. Methods
The total load of phosphorus which enters to Lake Święte is a sum of a several pollution sources. Considering the hydrological and catchment conditions it was taken that the main directions of nutrient migration into the lake are:

- water input with Pintus watercourse together with artificial drainage water,
- surface runoff from direct catchment area
- angling (pollution loading from groundbaits)
- atmospheric deposition
- bathing place (beach)

2.2.1. Field examinations
The flowing water analyses were made 10 times - monthly (on average). The water samples were taken on the lake (surficial and bottom water layers) and on 4 stations located on the watercourses – 3 of them was located on the drainage ditch Pintus: 1- upper catchment, 2 – nearby drainage water pumping station, 3 – input to the lake and 4 – output from the lake (Fig. 2).
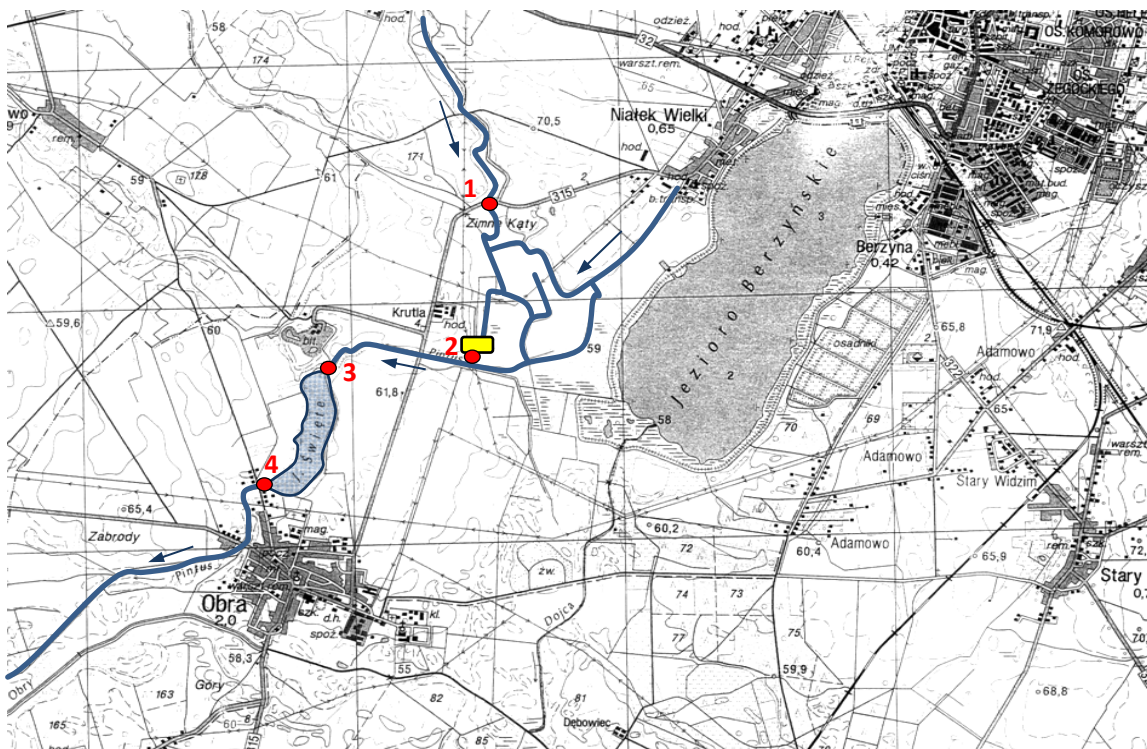

Figure 2. Location of sampling stations (red circles). Yellow rectangle – pump station, blue lines – local net of drainage ditches.

The flow values were measured basing on water speed in the measuring sections (electromagnetic gauge Valeport 811) and cross section of the riverbed.

The direct catchment using was defined basing on the field observations and comparing to the evidence maps, including the plots of land areas. For further calculations the five groups of land use were defined: arable lands, meadows and pastures, forests, urban areas and fallow lands.

2.2.2. Laboratory analyses

In the water samples the mineral phosphorus and total phosphorus (TP) (after mineralization) were measured by molybdenum blue method according to Standard Methods [4] using Nanocolor UV-VIS spectrophotometer. The organic phosphorus amount was calculated as difference between TP and mineral P.

2.2.3. Phosphorus external loading calculations

The calculation of phosphorus load of lake was made basing on products of flow value and current concentration of P in the water. Annual load was assessed taking into consideration the concentration and flow changes measured during field research.

The value of nutrients loading originated from direct catchment surface runoff was calculated using OECD method [5] – the loads were assessed using the runoff indexes, depended on the catchment area use type and area denivelation (slope) (Tab. 1), implemented for Polish conditions by Giercuszkiewicz-Bajtlik [6].

Table 1. Runoff indexes from the areas of different use and area slope [kg ha^{-1} per year]

inclination	arable lands	meadows and pastures	forests	urban areas	fallow lands
flat (<5%)	0.40	0.30	0.10	0.90	0.15
wavy (5-20%)	0.70	0.50	0.20	0.90	0.25
hilly (>20%)	0.80	0.60	0.30	0.90	0.30

The angling pressure was assessed basing on data provided by local fisheries user (Polish Anglers Association – unpublished data). It was taken for assumption that groundbaits are 85% as ready mixtures produced by companies; the rest was based on nutritional products such as bread, cereals, corn or bran. According to literature data [7, 8] it was assumed, that mean P contents in such fish food is 6.2 g P.

The calculation of atmospheric deposition was based on the pollution deposition indexes per lake surface area unit: 0.441 kg P ha^{-1}per year according to data provided for Wielkopolskievoivodeship by Regional Inspectorate for Environmental Protection [9].

The next element which can provide pollution to the lake is bathing people pressure. Basing on our observations, it was assumed that during bathing season (75 days) ca. 50 persons per day take a bath in lake. The unit loads according to Szyper [10] are 0.00005 kg per person per one bath.

3. Results and discussions

3.1. External nutrient loading.

Accurate, periodic studies of the Pintus watercourse made it possible to recognize the variability of its nutrient pollution level in different sections (Tab. 2). The fragments of the upper catchment were clearly the most abundant in phosphorus (st.1), which results not only from the agricultural use of land but also from the problems of water and sewage management in the neighbouring villages (Powodowo and NiałekWielki). At the same time, that station was characterized by the lowest flow, which promotes the concentration of substances dissolved in water. Significantly lower concentration ranges were recorded at station 2, below the drainage water pumping station, which drains the local basin.

The presence of a small field retention reservoir facilitating the operation of the pumping station is also favorable to self-purification processes. The positive role of this type of hydrographic objects is reported by many authors [11, 12]. Particularly during the summer period, a clear reduction in the concentration of phosphorus was observed that was probably the result of both, sedimentation of the suspension and the collection of plants growing overgrowth this pond. However, the disturbing fact is, that usually in the section between st. 2 and st. 3 a secondary increase in the concentration of biogenic pollutants was observed, which indicates a high impact of this agriculturally used part on the conditions of water chemistry of the watercourse.

Table 2. Phosphorus concentrations in investigated drainage ditches [mgP L^{-1}]

STATION	MINERAL			ORGANIC			TOTAL		
	mean	min	max	mean	min	max	mean	min	max
1	0.167	0.042	0.473	0.162	0.014	0.457	0.329	0.128	0.930
2	0.054	0.024	0.081	0.117	0.082	0.218	0.170	0.127	0.242
3	0.079	0.036	0.169	0.137	0.082	0.362	0.215	0.129	0.478
4	0.033	0.000	0.120	0.098	0.044	0.144	0.132	0.086	0.213

Taking into consideration the Pintus watercourse flow (41.7 L s^{-1}) on average, the final annual P load entering to LakeŚwięte, calculated for st. 3 (station before lake) amounts to 282.7 kg P per year.

The next nutrient source for LakeŚwięte is surficial runoff from direct catchment. The results of detailed analysis of this pollution load character are presented in Table 3.

Table 3. The values of surface runoff from the direct catchment of Lake Święte

land cover		Area [ha]	runoff coefficient [kg P ha^{-1} per year]	annual load [kg P]
West side area 73.1 ha drop 10.4 m mean slope 1.2 %	arable lands	57.1	0.4	22.83
	meadows	1.8	0.3	0.53
	fallow lands	5.0	0.15/0.25*	0.86
	forests	8.1	0.1 / 0.2*	1.41
	urban areas	1.2	0.9	1.12
East side area 79.6 ha drop 6.9 m mean slope 0.8 %	arable lands	57.9	0.4	23.15
	meadows	4.0	0.3	1.19
	fallow lands	6.4	0.15/0.25*	1.09
	urban areas	11.4	0.9	10.30
			AMOUNT	**62.5**

* - depending on the slope

It was assumed that angling groundbaits are the main sources of pollution resulting from the recreational use of the lake. On the basis of observation and analysis of formal and real conditions for angling and field intelligence, a load of 800-1000 man-days per year was assumed. The anglers use groundbaits during their stay on the water, usually 1.0 - 3.0 kg in this type of fishing grounds. With this assumption, the nutrient load will amount to 8.4 kg P per year.

It should be noted, that anglers also contribute to the removal of a certain pool of phosphorus and nitrogen from the lake together with caught fish - on average it is about 7 g P and 27 g N per 1 kg of fish [8]. Thus, in the case of trapping at the level of 1 kg, the amount of nutrients contained in the bait is theoretically balanced. However, this is only a statistical assumption. The environmental burden of introducing baits into the water is disproportionately larger than the "ecological profit" in the form of eliminating individuals, where nutrients are permanently embedded in tissues and inaccessible to

phytoplankton. In addition, the pressure of anglers is also directed at ecologically desirable species (pike, pikeperch).

The last two sources of nutrients for the ecosystem of the studied lake are atmospheric deposition and the influence of the bathing area. With a lake surface area of 23.1 ha and a deposition coefficient of 0.441 kg P per hectare per year, the load will be 10.2 kg P. The load resulting from the use of bathing will be much lower, which we estimate at 0.2 kg P per year.

Total load of nutrients from all of the sources mentioned above, reaching the Lake Święte during the year amounts to approximately 364 kg (Table 4).

Table 4. Sources and amounts of external phosphorus load entering Lake Święte

Source	phosphorus	
	kg per year	**percentage amount**
Pintus catchment	282.65	77.7%
direct watersched	62.48	17.2%
Angling (groundbaits)	8.37	2.3%
bathing place	0.1875	0.1%
Atmospheric deposition	10.2	2.8%
SUM	**363.88**	**100**

The above-mentioned statement clearly shows the greatest role of inflow of drainage waters in the eutrophication process of the lake. Despite the small size of the Pintus, its share in the external load of the lake reaches almost 80%. A similar power supply mechanism, this time as a spatial runoff from direct watershed, is also associated with the agricultural character of the catchment. Other sources of biogenic pollutants, including recreational activities, account for only around 5%.

3.2. Implications for ecosystem

Each lake is inseparably connected with the environment transforming energy and matter that flows through it. However, in a state appropriate for natural conditions, as a rule, the number of nutrient that reaches the lakes is very small, and in these water bodies eutrophication is extremely slow. As a result of human activity, this process has been multiplied, and annual charges of phosphorus and nitrogen enable a noticeable increase in the level of primary production, often manifesting by harmful blooms of algae and cyanobacteria.

Considering the balance difference between the load of nutrient sentering and leaving the lakes, in the vast majority we observe the retention of this matter. In the case of the Lake Święte, this relationship can also be described as the "settling tank effect". Figure 3 presents the results of the phosphorus content before and below the lake. As you can see, the content of all forms of this element is reduced during the flow of water through the lake. The most spectacular change concerns mineral phosphorus, which is partially co-precipitated with natural minerals, especially calcite, as evidenced by its dominance in bottom sediments [13], and partially collected by indigenous primary producers, embedded in biomass and its remains are deposited in the bottom of the lake. However, the retention of organic forms is also effective, and its mechanism is primarily the deposition of the suspension in the northern lake basin [13].
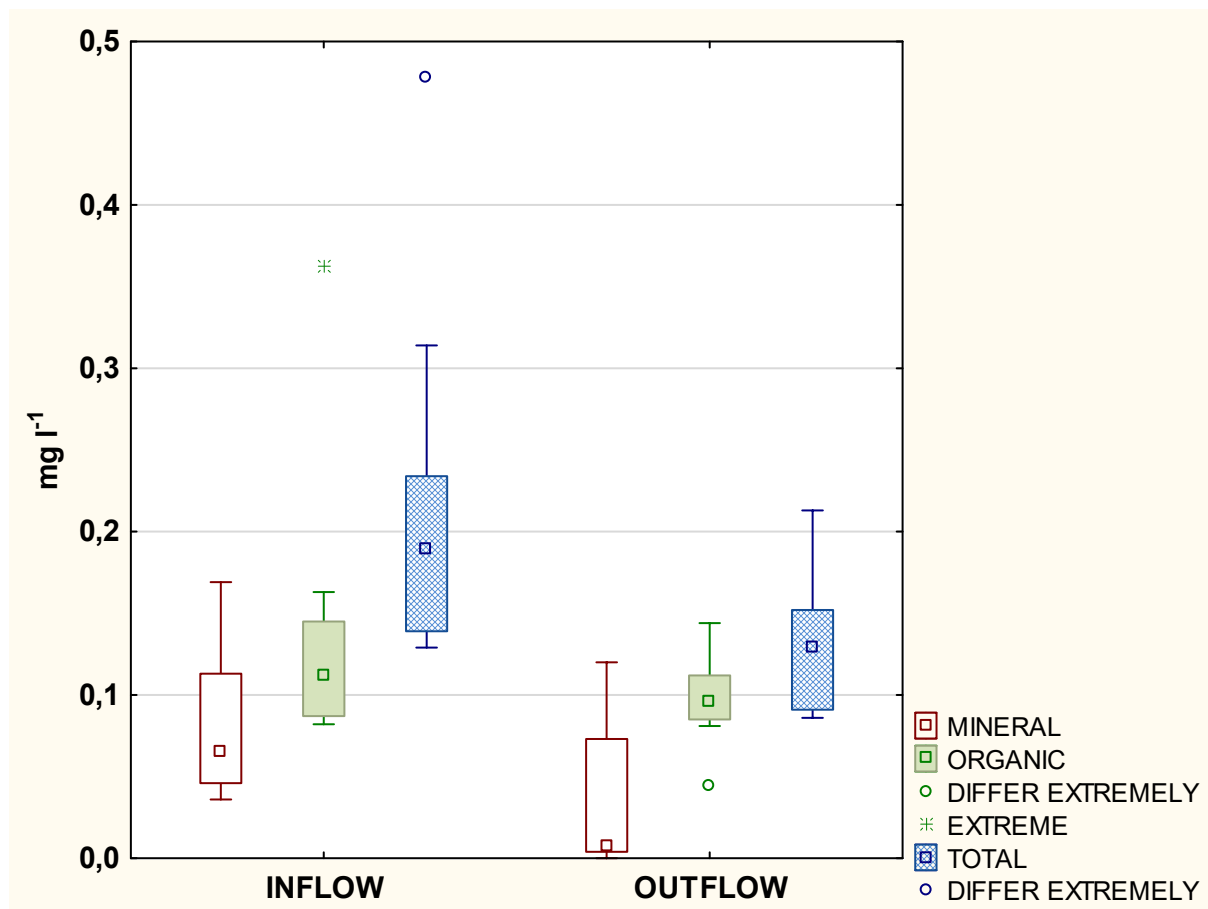
Figure 3. Phosphorus forms in the water of lake inflow and outflow. Central square: median, frame: 25-75% and tentacle: min-max of not-leaving records (n=10).

In limnology, various calculation models are used to determine the impact of the environment on the trophic processes of water reservoirs. One of the most commonly used is the method developed by Vollenweider [14, 15]. According to its assumptions, the rate of eutrophication is determined by the mutual dependence between the volume of supply of substances from the basin and the possibilities of withdrawal of this matter in the suspension sedimentation process or outside the lake ecosystem together with surface runoff waters. For lakes with no outflow, the model provides for calculations based on the possibility of withdrawing excess nutrients to bottom sediments. The result of the calculations is the value of the permissible and critical load of nutrients determined individually for a given reservoir. The first of these means the level of the catchment's influence, below which there is no acceleration of eutrophication, while the second one is manifested by the acceleration of the eutrophication and lake degradation rate. In practice, in the case of strongly changed anthropogenic catchments, the conclusion about the influence of the basin on lakes is related to critical loads. For the lake under consideration, the critical annual level of lake supply, calculated in accordance with this methodology, is 256 mg m^{-2} per year, which corresponds to 59.2 kg per year. In comparison to the actual catchment level, this means sixfold exceedance. This condition, lasting at least the last few decades, led to disturbance of ecological balance manifested by excessive increase of bottom sediments, deoxidation of hypolimnion and occurrence of harmful hydrogen sulfide in it, periodic and more frequent algal blooms [13] - all in conditions of phosphorus abundance at the level of advanced eutrophy (average for the testing period 0.135 mg P L^{-1}).

3.3 Necessary directions of remedial actions

The setting priority in the fight against the eutrophication of the Lake Święte should be limiting the nutrients loading. It is necessary to conduct more sustainable crop management in the catchment area. However, this is a solution that can occur in the distant future and therefore a good proposal will be a partial redirection of water from the drainage pumping station to other receivers (ditch and drainage canal systems), which is relatively easy technically.

However, the lake research has confirmed a significant accumulation of pollutants in the ecosystem itself, which means that even though the cutting off main source of phosphorus, the trophy will remain high. The phosphorus resources in the lake and bottom sediment still are very high. In connection with the weak sorption complex of bottom sediments and permanent hypolimnetic anoxia, this results in the occurrence of the internal P loading in the lake. This is described repeatedly in many sources that breakthrough moment of lake ripening, after which self-renewal occurs extremely rarely and coming back to the natural values and economic need a proper restoration technique.

Considering the essence of the problem of lake degradation, future reclamation activities should take into account the improvement of oxygen conditions in the lake and the removal or inactivation of excess phosphorus in the system circulation of matter between water and sediments. Recent experience of the authors' team indicates that a rational restoration action could consist in the use of Pintus water to oxygenate the lake [16] and inactivation of phosphorus in water and bottom sediments [17].

4. Conclusions

The results of the research presented in this work indicate the cumulative nature of the studied lake in relation to the matter that is directed to it from the basin. This scenario applies to the majority of water bodies located in agricultural catchments. The eutrophication process of this type of ecosystem is inevitable, but fortunately more and more resources are being spent on combating the degradation of lakes. However, to take the right steps, you need to diagnose the problem first. The example of the Święte Lake shows that only a thorough analysis of the external load allows to make correct selection of protective methods. Before undertaking these studies, lake users identified symptoms of eutrophication with too little inflow of "fresh" water from the catchment, which was considered clean. That's not all - the aim of proposed actions was to increase the flow of the lake by redirecting additional amount of water from a nearby, more degraded lake (Lake Berzyńskie – Fig 2.). Meanwhile, the results of our research clearly indicate the need to treat the drainage path as a point source of pollution, not a reservoir of waters that could rinse and clean up the reservoir

Our experience with the inhabitants of Obra, self-government authorities and anglers indicate the existence of high activity and willingness to counteract the effects of many years of neglect. The well-being of lake water is becoming a priority in social activity. Local associations and foundations in Poland have more and more opportunities to implement various environmental projects, but in the case of small, local grants very often strategies are prepared on the basis of superficial data and observations, not supported by professional research. Therefore, it is necessary to undertake educational campaigns, strengthen cooperation of research units with local communities and provide knowledge about the functioning of lakes as specific elements of the water and land system transforming and accumulating the external biogenic matter. A well-prepared project of protection and renovation of the lake will then allow for justified and balanced spending of social funds.

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