Chapter 8

Potential and Constraints of Macrophyte Manipulation for Shallow Lake Management

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Additional information is available at the end of the chapter

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Abstract

Palic and Ludas lakes are shallow Pannonian lakes, which have undergone rapid eutrophication. High concentrations of nutrients, along with significantly high values of fecal indicators in water samples, indicate that the Palic-Ludas canal, which connects them, contributes to the pollution of the recipient Lake Ludas, a central part of a special nature reserve. In order to improve water quality in the canal and decrease nutrient load of Lake Ludas, it is suggested to use environmentally friendly solutions, so-called bio-barriers (bio-bridges and biobanks), which will contribute to self-purification efficiency. The given model assumes 10 zones with bio-bridges and 0.4 ha covered by biobanks, using plants common in the area, e.g. *Typha* spp., *Phragmites* spp., *Juncus* spp., *Scirpus* spp. and *Carex* spp. The main disadvantage of this technology is occupation of large area; thus, the solution seems to be undersized. It removes 4% TN/year and 8% TP/year of the total amount necessary to achieve good ecological status. Nevertheless, the role of bio-bridges in permanent nutrient removal, through preventing the deposition of organic matter at the bottom sediment and later return of nutrients in water, together with indirect influence through enhancement of biodiversity should not be underestimated.

Keywords: bio-bridge, bio-barrier, ecoremediation, eutrophication, macrophyte species, lake degradation, Pannonian lakes

1. Introduction

Shallow lakes have an important role for the humanity and maintenance of environmental quality. They contribute to water supply and represent a resource for plant, fish and amphibian biodiversity, and also they are habitat for different bird species and have a recreational and socio-economic significance and esthetic values. However, shallow aquatic ecosystems are affected by numerous stressors as eutrophication, pollution, invasion of different species, drought, uncontrolled fishery and climate changes. Mentioned stressors often have a synergistic impact that enlarges the consequences and contributes to accelerated degradation of shallow lake ecosystem. Ecology of shallow lakes differs in comparison to deep stratified lakes according to many characteristics, so their shift from the clean state with dominated macrophytes to the status with dominated algae happens very fast during eutrophication process [1]. Eutrophication or nutrient enrichment affects the entire aquatic system by altering trophic structure, biodiversity and biogeochemical cycles, as well as seasonal dynamics. Many shallow lakes lost their ecological value in the past decades, through occurrence of eutrophication, acidification, invasion of new species and climate change [2–4]. Today, water pollution caused by excessive input of N and P from agriculture, urbanization and industrial discharge has a very negative effect and becomes a global issue [5]. Eutrophication is the critical problem impairing surface water quality (especially in lakes and reservoirs), and the effective control of lake eutrophication is needed. European member states have an obligation to develop ecological system based on estimation of biological communities defined by a certain number of elements of biological quality and to adjust water management with the aim to achieve at least "good" ecological status for all water bodies by 2015 and ultimately to 2027 [6]. Eutrophication has many undesirable side effects, major economic costs and transnational implications [7, 8]. Large efforts have been made to combat eutrophication by reducing the external loading of phosphorus in many countries of Europe and North America [9]. In the USA, annual costs are about $ 2.2 billion as a result of freshwater eutrophication [10].

Implementation of different measures that are mainly based on control of nutrient input and interventions on complex food web in lakes is necessary to re-establish their function [11]. Reduction of nutrient input as a single measure is not sufficient to reverse the effects of eutrophication in shallow lakes [9, 12]. Among other restoration methods, biomanipulation has been widely studied and applied to control eutrophication because of its high and more important long-term efficiency [13–15]. Several actions are usually necessary to achieve and maintain "clear" state in shallow lakes, as reduction of external loading, internal phosphorous loading and the presence of stable submerged macrophyte communities [16]. Aquatic macrophytes have an important role in cleaning eutrophic runoff water from agriculture and urban areas [17] by employing several mechanisms in aquatic ecosystems, such as competing with phytoplankton for nutrients, reducing the resuspension of the sediment and providing a refuge for zooplankton; therefore, their potential use has been extensively studied [13, 15, 17, 18]. In sync with ecological interactions, many physicochemical and biological processes such as sedimentation, filtration, precipitation, plant uptake and microbial decomposition are frequently involved in ecological engineering [19], such as creating wetlands [20] and wastewater treatment [21] improving ecosystem quality [22].

The scope of this chapter is to highlight the importance of the preservation of natural diversity of shallow lakes and how to maintain satisfactory environmental quality through macrophyte manipulation. Researchers suggest different restoration methods for shallow lakes with disturbed natural balance, using chemical or biological treatments, although there is no unique method for their restoration. Special cases are protected areas and special nature reserves, similarly, where limited actions can be performed.

2. Characteristics of shallow Pannonian lakes

Most of the lakes of the Pannonian Plain in Hungary, eastern Austria and northern Serbia are originally saline with water of carbonate type [23]. However, with urbanization and industrial development, their water chemistry has changed, and even some problems occurred, usually due to pollution. One of the examples is Lake Balaton in Hungary. Significant socio-economic development on the watershed since the 1960s resulted in increasing external loads and decline in water quality [24]. To retain the nutrients from the lake, the solution was to design and implement Kis-Balaton Water Protection System, i.e. to do wetland reconstruction at the lower part of the River Zala, which is the main tributary of the Lake Balaton [25]. As reported by Tatrai et al. [25], the efficiency of nutrient retention of the protection system was higher than expected. In part of Pannonian Plain that lies in Vojvodina (north Serbia), there are 75 shallow alkaline lakes and ponds [26]. They usually lie in depressions, often with depths less than 0.5 m. Two relatively large shallow lakes with exceptional natural value that are affected by human influence, lakes Palic and Ludas, are the subject of this study.

Pannonian lakes, Palic and Ludas, are very shallow lakes located at the periphery of the Suboticko-Horgoska Pescara (sand area), at the north of the Republic of Serbia. Both lakes are exceptional, since they are home to diverse habitats (aquatic, swamp, meadow and steppe) with a number of plant and animal species, some of which are strictly protected. They are a part of IBA (Important Bird and Biodiversity Area) site. Lake Palic is also a part of a natural park, which is a protected area of local significance. Lake Ludas belongs to the first category of protection, as a natural area of exceptional significance, and it is on the list of Ramsar sites.

The surrounding area is characterized by continental climate, with severe winters, hot summers and irregular distribution of precipitation. The average air temperature is 10.8°C, air humidity 69% and air pressure 1007 mbar. The annual number of rainy days is 105, and mean annual precipitation value amounts 561.1 mm, while the number of days with snow cover is 59 per year. This area is also characterized by strong winds (wind speed more than 6 Bf, i.e. 34 km/h), during 104 days per year. The highest precipitation output is during late spring and beginning of summer (June), and the lowest is in winter time—January, February and March (**Figure 1**). Dry season begins in July and lasts until October (**Figure 1**).

2.1. Lakes Palic and Ludas

Lake Palic is a shallow Pannonian lake, created million years ago, during creation of pits and dunes by wind erosion. In the past, the lake was recharged mostly by atmospheric precipitation. It covers surface of 5.65 km^2. During the 1970's, it was split into four sectors to prolong retention time, as a part of former restoration project. The volume of the lake is approximately 11.5×10^6 m^3.

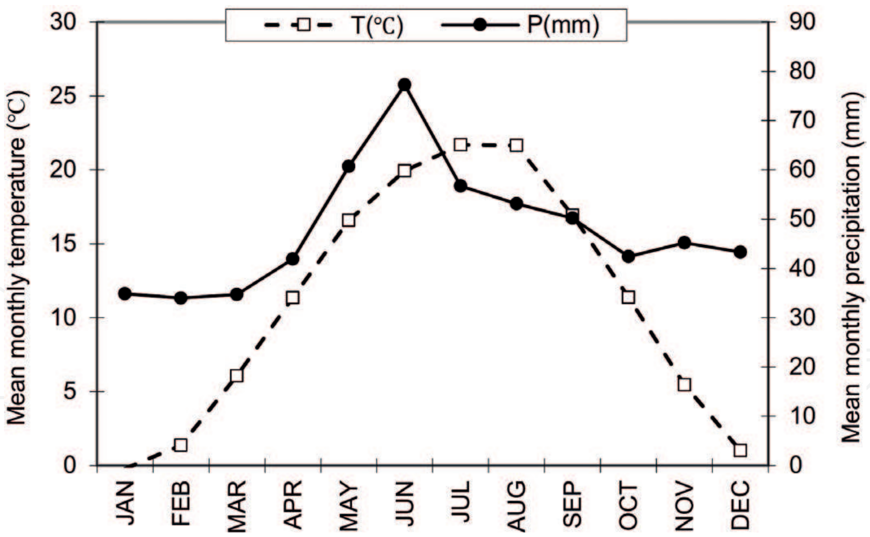


Figure 1. Climate diagram for meteorological station "Palic" (1978–2016).

Lake Ludas is oblong, with wide, low and marshy northern coast and narrow southern coast. It covers an area of 3.17 km^2, and its maximum (effective) length is approximately 4 km. In the past, Lake Ludas was a stagnant water body characterized by huge water-level fluctuations, which were the consequence of irregular periodic change of precipitation. The water regime of Ludas, as well as Palic, was entirely under the influence of meteorological factors, until the human factor became predominant.

There is a large amount of sediment deposited at the bottom of both lakes. The sediment thickness varies from 0.3 to 1.2 m, which additionally decreases the water column [27]. Consequently, the water depth of the (largest) sector 4 of Lake Palic is 1.9 m, while the mean depth of the whole lake is 2.3 m. The average depth of Lake Ludas is 0.9 m.

Urbanization for over 100 years led to changing their natural characteristics. Water regime regulation and introduction of complex drainage measures in wider area led to significant changes: natural wetlands were drained and ecosystems were changed. Nowadays, the main water source that recharges Lake Palic is wastewater treatment plant, which discharges around 13 million m^3 of water into the lake, whose quality satisfies the EU and Serbian standards [28]. The drawback of this system is that the volume of the lake is less than the discharged volume of treated wastewater during the year; therefore, there is no dilution in lake water, and nutrient load (mass) is huge. Lake Ludas also receives treated and untreated wastewater and runoff from agricultural plots that surround the lake. Cultivated areas with intensive farming surround the most part of the lakes' shores. There are also livestock farms without appropriate collection and treatment of wastewater in the surrounding area, as well as resident weekend facilities and rural settlements. All mentioned factors affect more or less the water quality in these lakes, but it is mostly influenced by water recharge [28–30]. Formerly, Lake Ludas received the biggest amount of water from the northern sandy terrain, by the Keres watercourse. Regulation of this watercourse changed water regime in the area. Today, Lake Ludas receives considerable amount of water from the Palic-Ludas canal, which connects these two lakes.

2.2. The Palic-Ludas canal

The Palic-Ludas canal was constructed with the purpose to carry treated wastewater from the wastewater treatment plant (WWTP), through parts of Palic and Ludas lakes to the Keres River. A part of this system, small bordering canal, was designed to carry untreated and treated wastewater from the WWTP to the Keres River, to avoid inflow of nutrient-rich water in lakes, but it has not been completed. The Palic-Ludas canal was sized to receive the flow of 3.0 m^3/s. The total length of the canal is 4.5 km. The width of the bottom of the canal is 1.5 m along the first 2.83 km and 2.5 m along the rest 1.67 km of the canal. The designed side slope is 1:2 and the bed slope is 0.3%. As stated by the regulation on the protection of the Special Nature Reserve "Lake Ludas", the Palic-Ludas canal is a part of the special nature reserve, designated as the area of the third degree of protection.

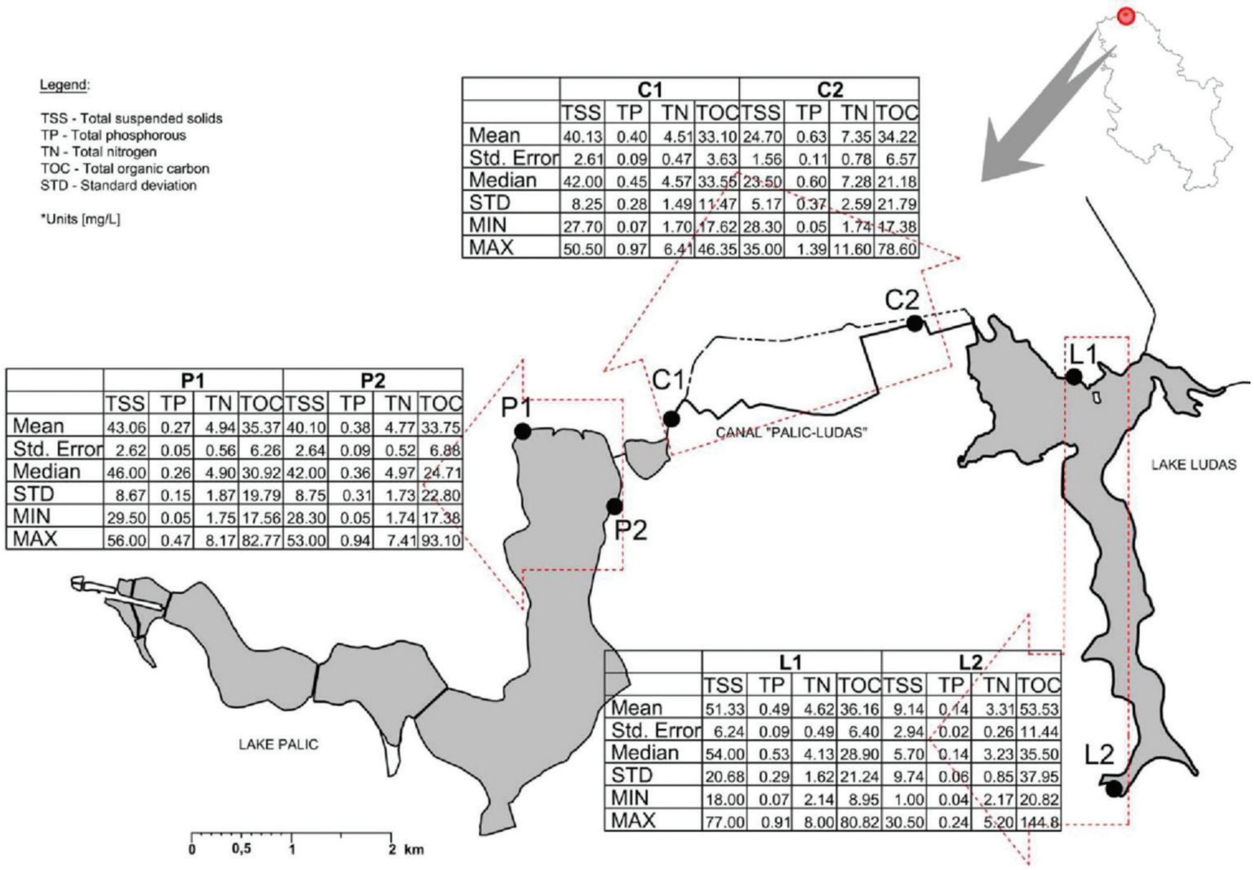
The Palic-Ludas canal carries a mixture of atmospheric water that is collected by open-canal network in the surroundings, treated and untreated wastewater and Palic's water. It would be expected that water that inflows Lake Ludas would be of better quality, due to self-purification abilities of water bodies. However, it is not the case, because the Palic-Ludas canal became an unofficial recipient for wastewater, which additionally increases mass nutrients and degree of eutrophication of Lake Ludas. A huge amount of unevenly distributed sediment at the bottom and wastewater discharge in the northern part of the lake are the most dominant eutrophication triggers [31].

3. Methods for water quality assessment

For the purpose of the study, water samples were collected during the period from November 2013 to March 2015, in total of 11 samples per location, on six locations (**Figure 2**). Water samples were collected at 20–50 cm beneath the water surface. Samples were transported in cool containers under 8°C and tested within 12–24 h. The analyses of collected samples have been done in laboratories of the Department of Ecological Microbiology, Faculty of Agriculture, University of Belgrade and Institute for the Development of Water Resources "Jaroslav Cerni". The analyses of easy variable parameters and microbial activity of samples were performed immediately after their receiving in laboratory.

Chemical analyses that include total suspended solids (TSS), total nitrogen (TN), phosphorous (TP) and total organic carbon (TOC) were determined according to the standard methods [32, 33].

Fecal contamination indicators (total coliforms, fecal coliforms and *Enterococcus*) were detected by the most probable number (MPN) method, using three tubes in each dilution. Presumptive test for total and fecal coliforms was done using the MacConkey (lactose) broth with inverted Durham tubes at 37°C for 48 h. Presumptive test of *Enterococcus* was done by using azide-dextrose broth (37°C/48 h) and the confirmation by inoculation on the bile esculin agar (37°C/24 h). Results are reported as MPN per 100 mL of water. The total number of aerobic heterotrophic bacteria was done using the meso-peptone agar (MPA), after incubation at



	C1				C2			
	TSS	TP	TN	TOC	TSS	TP	TN	TOC
Mean	40.13	0.40	4.51	33.10	24.70	0.63	7.35	34.22
Std. Error	2.61	0.09	0.47	3.63	1.56	0.11	0.78	6.57
Median	42.00	0.45	4.57	33.55	23.50	0.60	7.28	21.18
STD	8.25	0.28	1.49	11.47	5.17	0.37	2.59	21.79
MIN	27.70	0.07	1.70	17.62	28.30	0.05	1.74	17.38
MAX	50.50	0.97	6.41	46.35	35.00	1.39	11.60	78.60

	P1				P2			
	TSS	TP	TN	TOC	TSS	TP	TN	TOC
Mean	43.06	0.27	4.94	35.37	40.10	0.38	4.77	33.75
Std. Error	2.62	0.05	0.56	6.26	2.64	0.09	0.52	6.88
Median	46.00	0.26	4.90	30.92	42.00	0.36	4.97	24.71
STD	8.67	0.15	1.87	19.79	8.75	0.31	1.73	22.80
MIN	29.50	0.05	1.75	17.56	28.30	0.05	1.74	17.38
MAX	56.00	0.47	8.17	82.77	53.00	0.94	7.41	93.10

	L1				L2			
	TSS	TP	TN	TOC	TSS	TP	TN	TOC
Mean	51.33	0.49	4.62	36.16	9.14	0.14	3.31	53.53
Std. Error	6.24	0.09	0.49	6.40	2.94	0.02	0.26	11.44
Median	54.00	0.53	4.13	28.90	5.70	0.14	3.23	35.50
STD	20.68	0.29	1.62	21.24	9.74	0.06	0.85	37.95
MIN	18.00	0.07	2.14	8.95	1.00	0.04	2.17	20.82
MAX	77.00	0.91	8.00	80.82	30.50	0.24	5.20	144.8

Figure 2. Palic and Ludas lakes and their surroundings.

37°C during 48 h (mesophilic bacteria) and at 22°C during 3–5 days (psychrophilic bacteria). The amount of facultative oligotrophic bacteria was determined using 10 times of diluted MPA, after incubation at 22°C during 3–5 days. The results are expressed in CFU·mL^{-1}.

The determination of chlorophyll *a* concentration was done according to ISO 10260:1992. This method includes collection of algae by filtration, extraction of algal pigments and spectrometric determination of the chlorophyll *a* concentration in the extract.

The results were processed using MS Excel, R and RStudio [34].

4. Water quality: problem and targets

We used accustomed parameters to describe water quality of investigated water bodies. All samples showed rather high TOC values that indicate high organic matter loading; high values of chlorophyll *a* confirm the abundance of algae; and high contents of total nitrogen and phosphorous as well as TSS confirm previous statements.

The results show that the water quality of all water bodies significantly varies during the year (**Figure 2**) and that the values exceed limits for good ecological status, proposed by the Serbian regulation [35]. If we examine first the consequence of the lake state expressed by chlorophyll

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a, we notice that the content is high at every of four sampling lake locations (**Figure 3**). High content of chlorophyll *a* at the north of Lake Ludas (L1) is several times higher than other sampling locations of the same lake (L2). This fact indicates high intensity of biomass production in Lake Ludas. Even in late autumn, the content of chlorophyll *a* was extraordinarily high due to the clear weather and relatively high temperatures. Low chlorophyll *a* content at L2 doesn't mean that there is no nutrient loading, but that the submerged macrophytes retained its domination (**Figure 4**). Luxuriant submerged vegetation in the southern part of Lake Ludas fits very shallow water and soft lake bottom. Samples taken from Lake Palic at P1 and P2 do not show such differences (**Figures 2** and **3**).

Organic matter loading, expressed by TOC values, indicates intensive organic output (**Figure 2**). TOC values exceed four to five times of the proposed values (6 and 7 mg/L) for good ecological status of shallow lakes and artificial watercourses, respectively. The same is with TP and TN concentrations. In shallow temperate lakes, TP concentrations show more pronounced summer peaks with increase in trophic class, which is often attributed to increased concentrations of recharge water or increased internal loading [36]. The median values are mostly doubled, with the exception of samples taken at the south of Lake Ludas (L2). TSS and TP concentrations are satisfactory with respect to the Serbian regulation. The difference between north and south of Lake Ludas is obvious on many levels.

Water quality at the beginning (C1) and the end (C2) of the canal also differs significantly, with respect to most of parameters (**Figure 2**). Water at the beginning of the canal has properties similar to the water of Lake Palic, since the discharge of the lake in the canal is very close to sampling location. The content of different parameters at C1 is not permanently lesser than values obtained at the end of the canal. Average content of suspended matter is generally higher at C1. Also, higher TOC values are probably the consequence of high content of algae

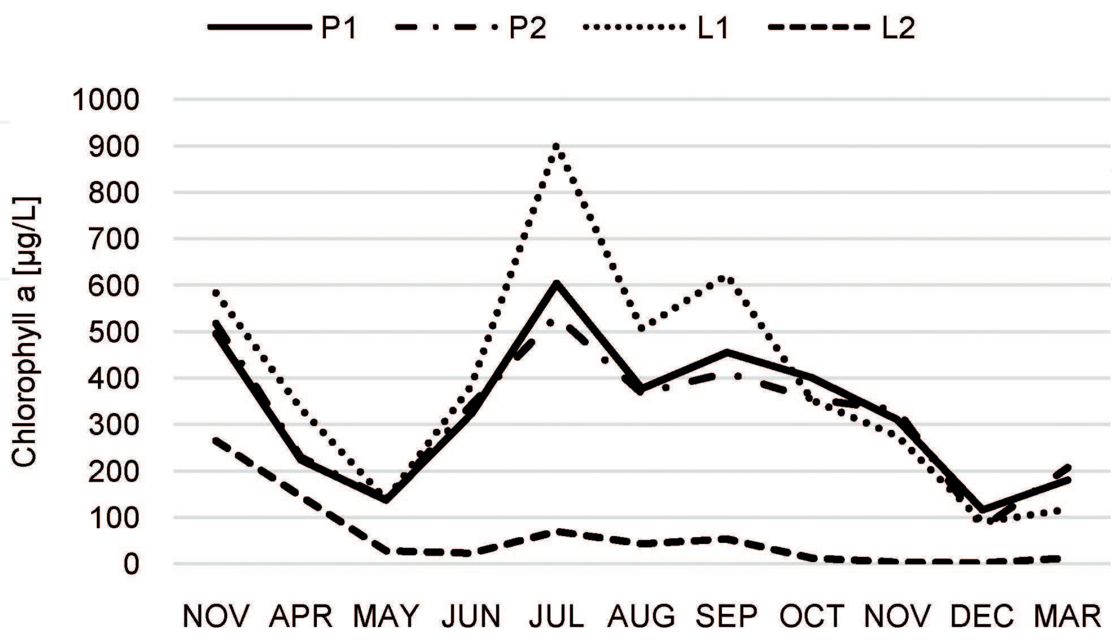

Figure 3. Lake states expressed by chlorophyll *a* during the year.

Figure 4. Lake Ludas (L1, left; L2, right).

in the water of Lake Palic that flows in the canal. Total phosphorus concentrations are in average of almost 10 times higher in the canal than the lake. The similar relation is with nitrogen concentrations (**Figure 2**).

These differences in chemical quality of water are confirmed by high fluctuation of bacterial counts during investigated period. After we analyzed separately each water body, we noticed some differences. Box plot diagrams (**Figure 5**) show the range of the obtained values, median and outliers. The range of registered values is wide, and the highest levels of fecal pollution indicators were registered in C2 samples.

We will use median for further commenting of obtained results rather than mean, since it gives a better idea of a "typical" value of each parameter. In Lake Palic, the registered number of bacteria was usually smaller at the site P2; particularly, median is notably lower for all indicator bacteria. At Lake Palic, total coliforms and enterococci exceed the limits of good ecological status in 18% of samples and fecal coliforms in 36% of samples. When considering just lake water, the worst sanitary quality is registered at L1 (Lake Ludas north). Fecal indicators are significantly higher in most samples taken from the L1. The range of observed values is wider, and median is higher for all examined parameters (**Figure 5**). Water at L2 was less bacteriologically polluted, regarding median values of indicator bacteria. This reveals that water from the Palic-Ludas canal has a considerable impact on the sanitary quality of water in the north of Lake Ludas, since the confluence of the canal is approximately 800 m away from the sampling point L1.

Majority of observed enterococci counts satisfied at least moderate ecological status (category III, in [35]) at all locations but C2. In 40% samples at C2, the ecological status with respect to this parameter was poor or unacceptable. The presence of coliform bacteria suggests that the canal receives fecal wastewater along the flow, which contributes to the reduction of effectiveness of self-purification process. Content of enterococci, as well as of total and fecal coliform bacteria, increases along the canal (**Figure 5**). The concentration range for enterococci at C2 is more expected for the raw sewage than surface water [37]. The origins of fecal matter in surface water could be organisms defecating in water, runoff from the surface and also discharge of poorly treated or untreated wastewater. Disposal of biological waste, as well as fertilization with manure, can in the same time increase the loading of nutrients (phosphorous, nitrogen) and coliforms in surface water [38].

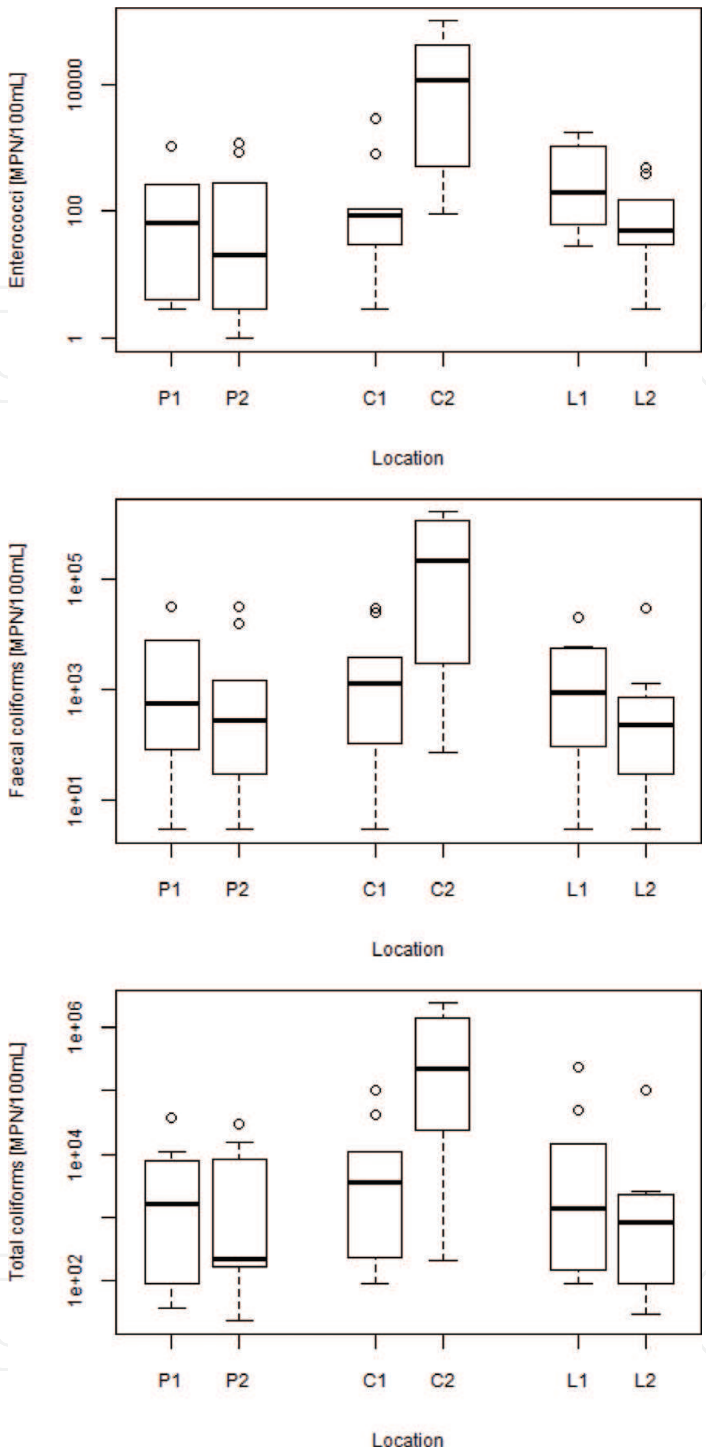

Figure 5. Microbial water quality.

For assessing self-purification ability, we used FO/H index [39]. Although this parameter is still not standard, Petrovic et al. [39] suggest using this parameter to obtain more in-depth ecological information about water quality. It represents the ratio between counts of facultative oligotrophic bacteria (FO) and heterotrophic bacteria (H). Accordingly, classification of water by self-purification ability is assessed as follows: FO/H < 1 pour, ≥1 satisfactory and >10

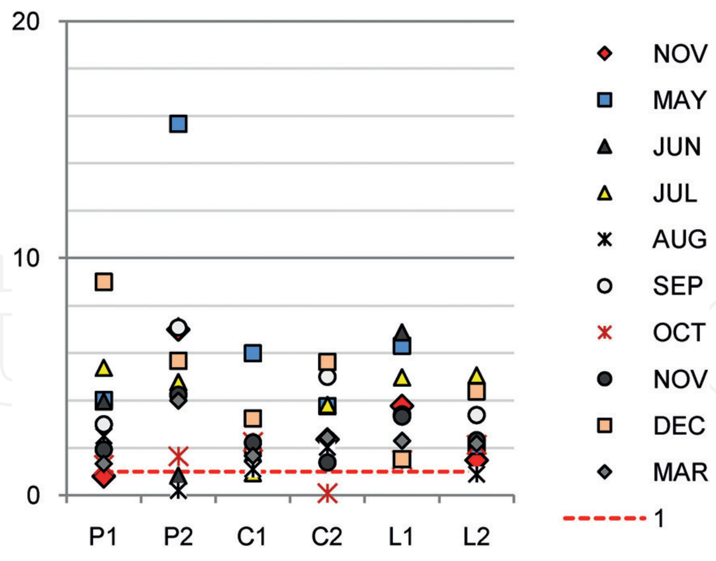

Figure 6. Self-purification ability expressed by FO/H index.

good. The self-purification process along the water flow, from Lake Palic through the canal to Lake Ludas, is satisfactory (**Figure 6**). However, the content of nutrients is still high, which indicates the existence of external sources.

Furthermore, finding widely distributed significant opportunistic pathogen of humans, animals and plants, *Pseudomonas aeruginosa* in Lake Palic and Palic-Ludas canal, but not in Lake Ludas itself [40], is in line with obtained self-purification capacity of water.

Differences in composition of saprophytic and potentially pathogenic microorganisms in different parts of the Lake Ludas can be explained not only by geographic features but also by quality of water that is transported by the canal into the northern part of the lake. Large organic load reflects also in a high (occasionally higher) number of saprophytic heterotrophic bacteria in comparison to indigenous oligotrophic bacteria, which reduces the self-purification ability and implies accelerated eutrophication of Lake Ludas and environmental threat.

Hence, Lake Ludas, a center of biological diversity, where numerously rare, endemic and relict species exist, deteriorates due to the processes of sedimentation and plant overgrowing. As a result of intensive sedimentation, reed migrates in other parts of the lake, while old reed beds deteriorate. Improvement of the state of this area is relevant for the local community as well as for improvement of the environment and tourism development [41]. Our target is to achieve good ecological status of water bodies (**Table 1**), using bioremediation technologies. The focus is on the canal, since the water quality decreases along its path.

Parameter	Shallow lake	Artificial water body
TN (mg/L)	2	2
TP (mg/L)	0.2	0.3

Table 1. Good ecological status (excerpt from [35]).

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5. Alternatives for water quality improvement

Aquatic macrophytes have multiple effects on nutrient cycling in lakes. Interactions among macrophytes, sediment and water may result in increase or decrease in the nutrient concentrations of the water, depending on the growth phase. Changes in biogeochemical cycles and food chains lead to the loss of biodiversity and the survival of a species that have adapted to the changes. These tolerant species in the new, changed, environmental conditions become dominant and their activities continue to alter the conditions of the environment, leading to a reduction in the ecological integrity and biological diversity necessary for the normal functioning of the ecosystem [42].

The dominant community in wetland ecosystems is reed beds. Reed covered vast shoals of Lake Ludas, mainly not only in the coastal region but also in the middle of lake, where it built a number of islands. This mosaic distribution turf like reed is a fundamental feature of Ludas, of particular importance as a nesting place of many rare species of birds. These islands have a significant phytosanitary and phytofiltration role. However, once lush and thick reeds are now at the stage of extinction. Reed tends to spread to the south, in the narrower part of Lake Ludas, with less deposited sediment. The reed belt, once found only along the southern coast of the lake, now spreads and slowly overgrows the open water zone. In the past, floating flowering was present between the reeds, but today only species is *Lemna minor* is present [43].

Finding solution for the improvement of lake water quality can be distinguished by implementing different chemical or biological treatment. Maintenance of clear water state in shallow lakes includes a reduction of external loading, internal phosphorous loading and presence of stable submerged macrophyte communities [16]. Every method has advantages and disadvantages, and every lake has certain specificities, so there is no recipe how to "cure" a shallow lake. But it is certain that the quality of water that recharges the lake is the key factor for maintaining satisfactory water quality of the lake. There are numerous factors that influence the best technique, starting with climate, location, elevation, surroundings, origin of pollution, intensity of agricultural practice, slopes, etc. [14]. Usually, complex measures are necessary to deal with human-induced problems. However, it is necessary to consider a cheap, environmentally friendly and durable approach to solve water pollution problems.

Macrophytes have a strong reductive effect on resuspension; they can substantially reduce internal phosphorus loading in lakes [44]. Macrophytes can also promote N retention in lakes by enhancing denitrification and by taking up nitrogen from the sediment [45]. In addition, macrophytes can successfully perform remediation of deposited sediment. Even some sensitive agricultural crops used for sediment phytoremediation, such as mustard or lettuce, showed satisfactory germination rates (60–80%) [46].

Inflow of a large amount of nutrients that influence the bloom of cyanobacteria is almost impossible to control in current conditions. As we mentioned before, nutrient concentrations in water of the Palic-Ludas canal are higher than in Palic, which proves the additional water pollution in the canal and represents additional burden for Lake Ludas. While the study area is a part of protected zone and these lakes are only possible recipients for treated and untreated wastewater, the only way to mitigate impact of discharged water is by careful management of macrophytes.

5.1. How to use macrophytes?

Macrophytes are extensive consumers of nutrients and have a great role in suspended solid removal, which means that rhizospheric oxidation has a major effect in wastewater purification. Previous research [47] showed that aquatic plants have a photosynthetic capacity to transform molecules and make them available for rhizospheric microorganisms which contribute to self-purification. Also, this process introduces the basis of phytoremediation. The application of appropriate macrophytes could be the right choice for in situ remediation technology which is very acceptable for developing countries [48]. Just 1 hectare of planted indigenous macrophytes can decrease nitrogen content in water for up to 8 t/year and phosphorous for up to 1 t/year (**Table 2**) [27]. Often, there is no enough space to plant such a large area, so floating mats with macrophytes can be a practical solution for enhancement of water quality [49, 50]. The mechanisms of nitrogen and phosphorus removal depend on the macrophyte ability of adsorption, but nitrogen removal also has a very close connection with microbial processes like nitrification and denitrification [51].

Constructed wetlands might be effective in treating nutrient pollution as well as in restoration of lake ecosystems, keeping in mind that constructed wetland systems should be carefully designed and managed [28, 52, 53]. The use of macrophytes in the ecological restoration and water remediation contributes to the establishment of ecological balance, due to their effectiveness in the assimilation of nutrients and its role in creating the conditions for microbial degradation of organic matter.

Plant species	pH optimum	Distance (m)	Rooting depth (m)	Nitrogen content (%)	Phosphorous content (%)	Dry matter yield (t/ha)
Emerged plants						
Typha spp.	4–10	0.60	0.3–0.5	14	2	30
Scirpus spp.	4–9	0.30	0.6	18	2	20
Phragmites spp.	2–8	0.60	0.4	20	2	40
Juncus spp.	5–7.5	0.15	0.3	15	2	50
Carex spp.	5–7.5	0.15	0.2	1	0.5	5
Submerged plants						
Potamogeton spp.	6–10	0.3		2–5	0.1–1	3
Myriophyllum spp.	6–10	0.3		2–5	0.1–1	9
Ceratophyllum spp.	6–10	0.3		2–5	0.1–1	10
Floating plants						
Lemna spp.				6	2	20 t/year

Table 2. Biomass and assimilated quantities of nutrients by common plants [27].

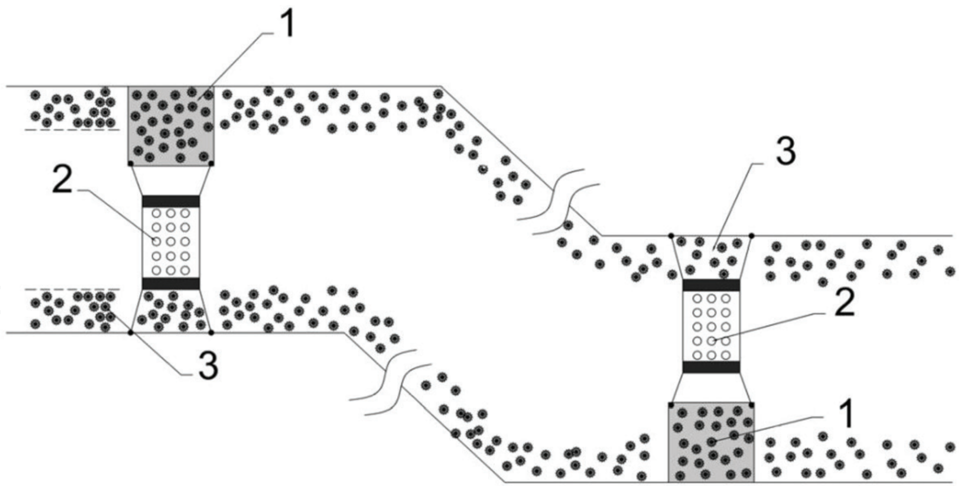

Figure 7. Bio-barriers placed alongside the canal: (1) reed on gravely substrate (biobank), (2) bio-bridge and (3) reed.

There are few solutions for improving the water self-purification ability in the canal. Usually, the good solution is to make more meanders, which increase the length of the water flow. It can be achieved by placing different types of barriers alternately alongside the canal (**Figure 7**). The study conducted by Lu et al. [54] showed that nutrient removal from aquatic ecosystem could become more effective by increasing hydraulic retention time. In this way microorganisms in water will have more time to decompose organic matter and release nutrients. Different plant species in canal will benefit from nutrients in readily available form. Joint activity between microorganisms and plants will contribute to the improvement of water quality. Open barriers in a form of small bridges along the canal will serve this purpose (**Figure 8**).

Bio-bridges consist of holders with a lot of small holes drilled in light plastic platform, floating at the water surface. In the platform holes, there are pots with chosen plants. In fact, they represent a form of floating wetlands that are fixed between canal banks. The plant roots will absorb different nutrients and bind suspended matter and microorganisms. As live system, root has a very large surface with a large amount of inhabited microorganisms that use different organic matters for their metabolic activities. This additional root biomass with a large number of different microorganisms will increase water self-purification rate.

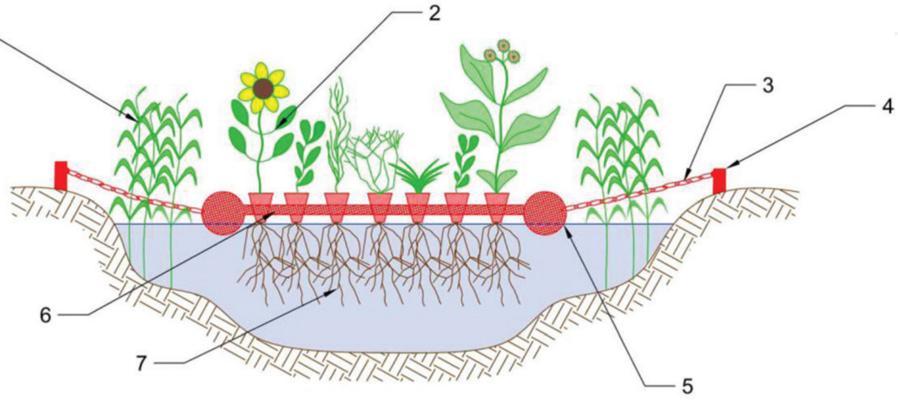

Figure 8. Bio-bridge: (1) reed, (2) different plants, (3) chain holder, (4) chain support, (5) floating carrier, (6) light platform with plants and (7) plant roots.

Generally, floating wetlands are more effective in comparison to other types. The large amount of nutrients is assimilated and eliminated from treated water, due to the removal of whole plant at the end of the growing season, not just above ground parts. Planted in this manner, macrophytes are forced to acquire their nutrition directly from the water column, which may enhance rates of nutrient and element uptake into biomass. This provides potential to enhance treatment performance by increasing the water depth retained during flow events to extend the detention time of storm waters in the wetland [50]. Plant species that can be used for floating wetlands, besides indigenous plants, are green salad, clover, alfalfa, mustards and sunflowers, although in that case, water below them should be aerated.

To improve self-purification, we suggest using a combination of bio-bridge and biobank, a kind of coarse sand/gravelly filter. This "filter" is in a steel net in a shape of parallelepiped that leans against the coast. Biobank performs coarse filtration of suspended matter. Moreover, it can be used as a substrate for planting autochthonous flora (**Figure 9**).

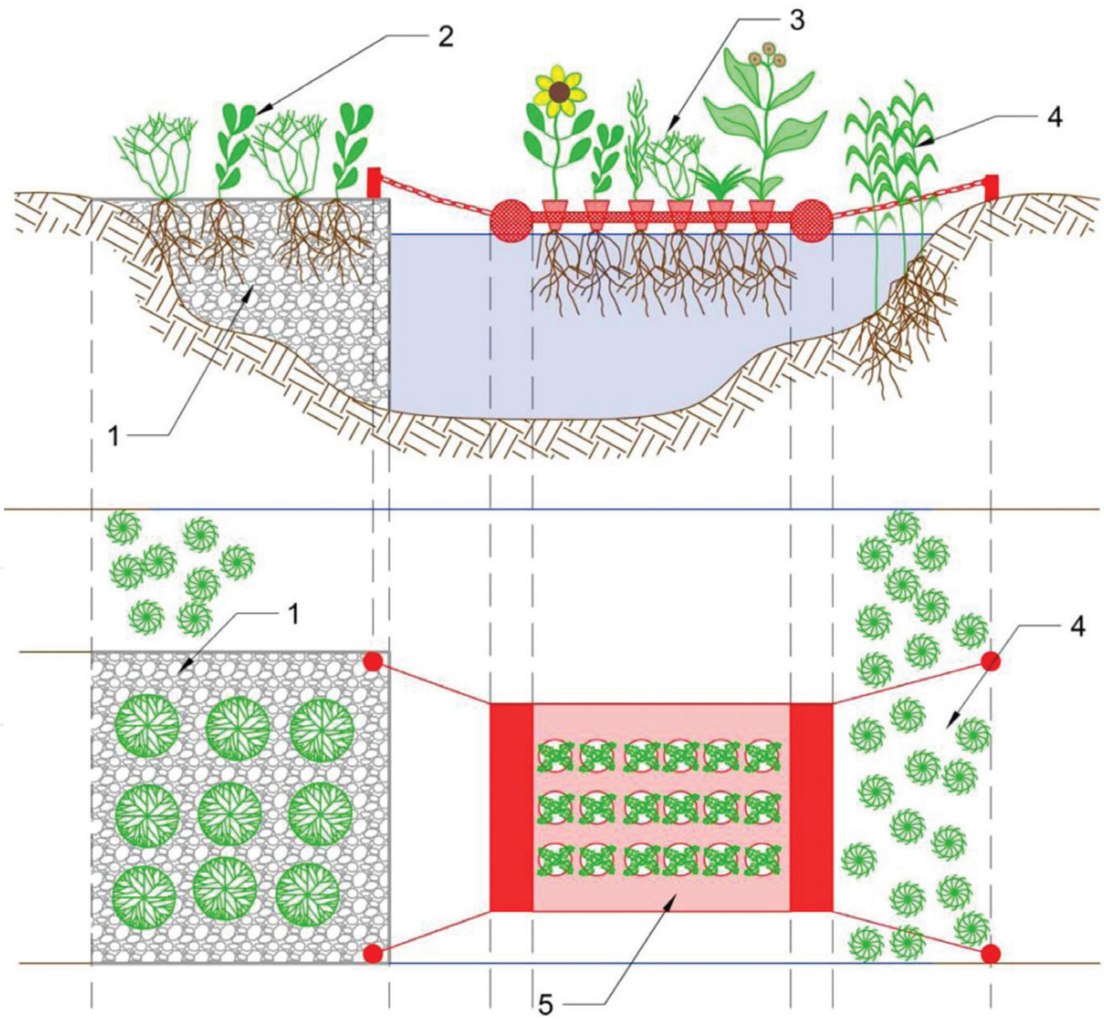

Figure 9. Biobank and bio-bridge: (1) gravelly substrate, (2, 3) different plants, (4) reed and (5) floating carrier of bio-bridge.

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5.2. Sizing and application

The required area for future bio-bridges was calculated using average water quality at the end of the canal (**Figure 2**) and the required remedy level (**Table 1**) as input parameters. To achieve water quality that corresponds to good ecological status, it is necessary to remove about 64.470 kg TN/year and 3.980 kg TP/year. In addition, sizing was done according to efficiency of particular aquatic plants. Flora of lakes Palic and Ludas is characterized today by different aquatic marsh plants, such as *Phrarmites australis*, *Typha latifolia*, *Ceratophyllum demersum*, *Myriophyllum spicatum*, *Scirpus maritimus*, *Lemna minor*, etc. [43]. Plant composition for bio-bridges was selected accordingly (**Table 3**).

General drawback of constructed wetland application for restoration of surface water is their size. The canal has relatively small size, so the space for manipulation is limited. On the other hand, the flow should be slowed, not obstructed, so the obstacles have to leave enough space for water flow. Therefore, just 10 bio-bridges are anticipated for bioremediation. One hectare of planted macrophytes in this manner removes 6.075 kg TN/year and 730 kg TP/year or 9 and 18% of estimated total, respectively. Bio-bridges that cover much smaller area (120 m^2) assimilate only 9 kg TP/year and 73 kg TN/year, which is obviously insufficient for achieving planned targets. Biobank could stretch on maximum 0.8 ha, which would significantly improve efficiency of proposed system, but it might narrow down the cross-sectional area of the flow, i.e. the volume flow rate. Therefore, it is anticipated that biobanks cover an area of 0.4 ha. The places for installation of bio-bridges are proposed with respect to the change of water quality (deterioration along the water flow), nutrient content and allowed size (**Figure 10**).

Macrophytes assimilate considerable part of phosphorous from water, but some will precipitate, considering high water pH value. Together with the proven self-purification ability, it is possible to improve a certain extent of water quality that recharges Lake Ludas. Although it still seems to be insufficient for full treatment, it should be emphasized that bioavailable phosphorous which is incorporated in plant body will be permanently removed, and at least it will not make burden in the future by precipitating on the bottom sediment.

	Bio-bridges				**Biobanks**			
	Area	**DM***	**TN**	**TP**	**Area**	**DM***	**TN**	**TP**
	(m^2)	**(kg)**	**(kg)**	**(kg)**	**(m^2)**	**(kg)**	**(kg)**	**(kg)**
Typha spp. (30%)	36	108	15.1	2.2	1200	3600	504	72
Scirpus spp. (15%)	18	36	6.5	0.7	600	1200	216	24
Phragmites spp. (30%)	36	144	28.8	2.9	1200	4800	960	96
Juncus spp. (25%)	30	150	22.5	3.0	1000	5000	750	100
Total	120	438	72.9	8.8	4000	14,600	2430	292

*DM, dry matter.

Table 3. Nutrient removal by indigenous plants.

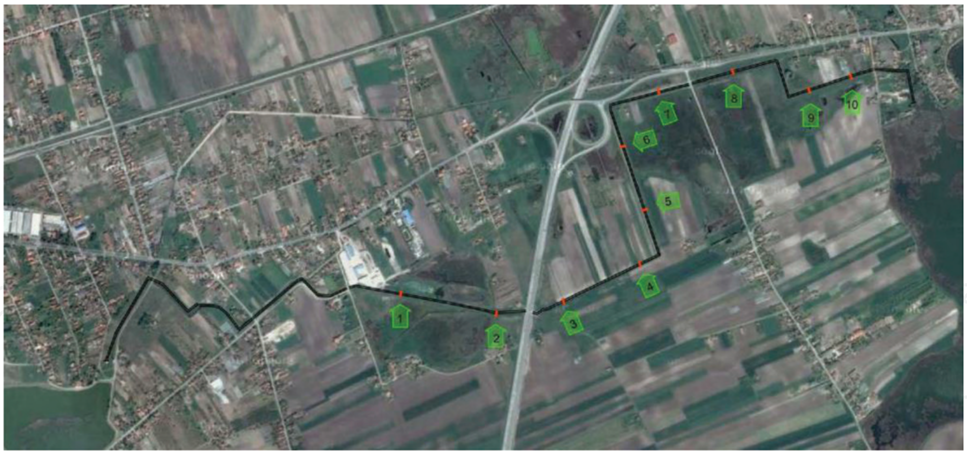

Figure 10. Locations for bio-bridges. They were set at 10 portions.

5.3. Advantages and disadvantages

The proposed system influences directly and indirectly the surroundings. Besides obvious advantage of proposed system of water treatment in environmentally friendly manner, it enhances biodiversity particularly when using autochthonous plants. Biobanks create heterogeneous habitats that are favorable for different macrophytes and for the growth and succession of other organisms, as well as for removing water pollutants. In sediment remediation study in [55], a general increase in microbial population was noticed in the lake sediment (2–5 times) after plant growth, which emphasizes the importance of phytoremediation. Inhabited bacteria play an important role in decomposition, and they are involved in various cyclic paths of different compounds in freshwater aquatic environments, which is particularly important for nutrient-rich aquatic environment. Semiaquatic coastal vegetation has also the anti-erosion role and affects sediment resuspension [56], which is of great importance since sediment resuspension has a strong effect on nutrient cycling of lakes [17].

The main disadvantage of this technology is occupation of large area, which is in this case a limiting factor. Consequently, bio-barriers for expected annual nutrient input seem to be undersized. In macrophyte management, one of the most important issues is the removal of plants (harvest). Plants absorb a significant amount of inorganic phosphorous, but after wilting nutrients are released in water again. Therefore, plant removal at the end of the growing season, before nutrient translocation, is significant for nutrient removal. In the absence of adequate machinery, the plant removal becomes labor-intensive.

Another advantage of bio-bridges is that they are completely removed at the end of the growing season, thus preventing the return of nutrients in the water. Produced biomass can further be used for different purposes like composting, energy production or building material.

6. Conclusions

Over decades the high concentration of nutrients, especially phosphorus, as well as change of hydrological balance in wider area, contributed to the disruption of ecological balance in the investigated shallow lakes, Lake Palic and Lake Ludas. Considering the input parameters of water quality and quantity, as well as target values, we proposed a model of constructed wetland, bio-barriers, within the artificial watercourse connecting two shallow lakes. It consists of several structures, so-called bio-bridges and biobanks, which maximize the potential of plants and microorganisms. Since limited action could be performed in protected areas, combination of different approaches for the improvement of their condition could be useful. In this way, macrophytes will contribute to restoration of biological structure and to the sustainable management of eutrophic water bodies. Despite spatial limitations, it is possible to remediate water to a certain extent, reduce the content of human pathogenic bacteria and remove nutrients with plant harvest.

Proposed concept is based on the plants that are tolerant to high levels of nutrients and predominantly indigenous species that grow in the surroundings of the canal and both lakes. This concept contributes, as the cost-effective and environmentally friendly technology, to the improvement of water quality, increase of biodiversity and maintenance of ecological balance in wider area.

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