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PAST STUDIES AND POTENTIAL MEASURES FOR REHABILITATION OF THE SHALLOW LAKE (LAKE LUDAŠ)

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Abstract: Lake Ludaš has been under a strong anthropogenic influence for a very long time, so the history of fruitful scientific investigation was very often connected with the evaluation of a human impact and potential rehabilitation measures. Unfortunately, attempts to improve the lake's natural status remain more in the field of theoretical models than concrete practical solutions. Aiming to better understand the potential of different rehabilitation measures for Lake Ludaš, we combined our ecological analyses (unpublished results) and the literature survey. The continuous massive cyanobacterial bloom and the formation of a thick sediment layer rich in different organic and inorganic pollutants represent two major challenges in the lake's rehabilitation. The unknown ecological role of invasive species that have already colonised Lake Ludaš will make the attempts to improve conditions in the lake even more challenging. The reduction of nutrient load, changes in the intensity and directions of water circulation, as well as top sediment layer removal in the lake, are measures under consideration for several decades. But their combination, order of implementation and possibilities of successful execution are still under debate. However, there is no doubt that the restoration of a natural hydrological regime should be a key step in the rehabilitation of Lake Ludaš.

Keywords: shallow lake; Serbia; ecosystem assessment; lake degradation; revitalization

Introduction

There are many artificial stagnant water bodies in Serbia, mostly drinking water reservoirs, recreational and fish ponds, but only a few natural lakes. Lake Ludaš was shaped for hundreds of thousands of years by natural forces. Unfortunately, in less than two centuries, the damage caused by man to this fragile ecosystem was so devastating that the lake irreversibly lost its pristine

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character. Consequently, the only remaining attempt to re-establish an ecological balance of Lake Ludaš left the frame of term "restoration" which, *sensu stricto,* means "the bringing back to a former position or condition" (Merriam-Webster, n.d.), and entered the field of rehabilitation related to "a return of degraded systems to attainable approximations of pre-disturbance conditions, and the establishment of protection against future disturbances" (Cooke, 1999, p. 2). In the past, Lake Ludaš was an alkaline saline lake inhabited by organisms adapted to an extreme environment and even if we could re-establish saline conditions it would be impossible to re-colonise all the halophilic species.

The adverse human activities responsible for Lake Ludaš natural status degradation can be divided into several categories: (1) change of hydrological balance in the lake's catchment; (2) cultural eutrophication and pollution; and (3) introduction of invasive/alien species. In addition to the abovementioned anthropogenic factors, there are other threats, such as climate changes that include devastating floods and droughts which can influence ecological processes in the lake.

Two aeolian lakes in northern Serbia, Lake Palić and Lake Ludaš, are probably the most investigated shallow water bodies in the country. Studies dealing with Lake Ludaš include various topics: water and sediment quality, changes and modeling of its hydrological regime, microbiological community and phytoplankton dynamics, cyanobacterial bloom and their toxic effect on other aquatic organisms (Ćirić et al., 2019; Gavrilović et al., 2020; Grabić, Đurić, Ćirić, & Benka, 2018; Grba et al., 2017; M. Horvat & Horvat, 2018; Z. Horvat & Horvat, 2018; Pamer et al., 2011; Raicevic et al., 2013; Rudic et al., 2018; Rudić, Vujović, Božić, Arizanović, & Raičević, 2018; Rudić, Vujović, Božić, & Raičević, 2015; Seleši, 1981, 2006; Svirčev et al., 2013; Tokodi, 2016; Tokodi et al., 2018; Tokodi et al., 2020).

In this study we are focusing on the deterioration history of Lake Ludaš. We described changes done in the past, its present state and discussed its future perspectives. The specific objectives of this study were: (1) to define natural-state conditions of the lake; (2) to determine the main causes of the lake degradation; and (3) to discuss possible strategies for lake rehabilitation.

Description of Lake Ludaš

Lake Ludaš is the second largest aeolian lake in Serbia. It is located in the northern part of Serbia between the Danube and Tisa rivers, and close to the Hungarian border. It was formed approximately one million years ago on the sandy terrain of the Bačka loess plateau. The lake covers an area of 3.28 km^2 with a length of 4.5 km from north to south (Stanković, 2005). It was stated that the maximum depth is 2.25 m (Kovačev, 2002), but, in its recent state, it is probably no more than 1.7 m deep. Nowadays, this aeolian lake is fed mainly by surface water flowing through the Palić-Ludaš channel and the Kereš River (Figure 1). Other sources, such as groundwater and direct precipitation, can also be important in some years. Lake Ludaš is positioned in the area characterised by temperate climate with pronounced continental characteristics (Institute for Nature Conservation of Serbia, 2004). The first conservation measures aiming to protect Lake Ludaš were conducted in 1955. Since 1977 Lake Ludaš is on the list of Ramsar sites. Finally, in 2011 it was put under protection as a Special Nature Reserve (Institute for Nature Conservation of Serbia, 2004). It is also designated as Important Bird and Biodiversity Area (IBA) site.

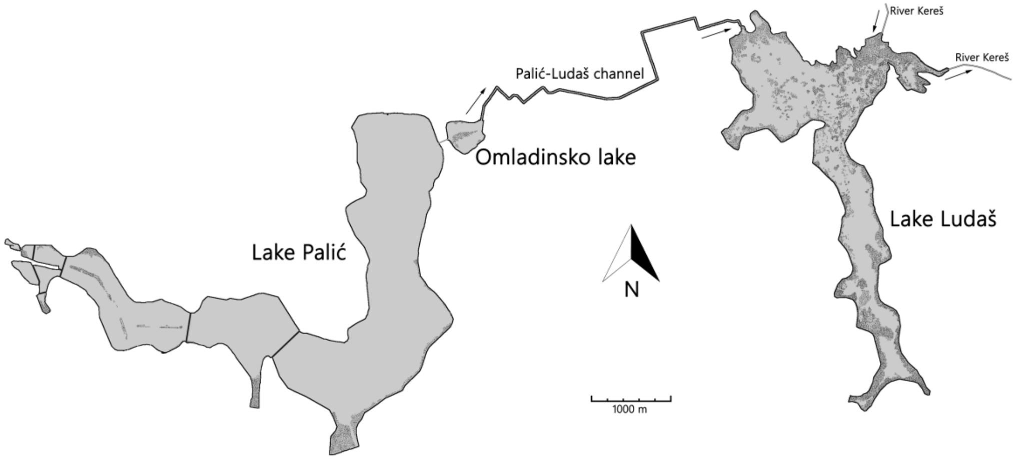

Figure 1. Lake Ludaš and its connection with other water bodies. Arrows indicate the direction of water flow. Gray texture on the water surface represent the distribution of reed within the lakes.

Changes of hydrological balance in the lake's catchment

Natural hydrological regime of Lake Ludaš

According to one theory, Lake Ludaš originated from a larger lake formed in the Early Pleistocene in the vicinity of the area which nowadays corresponds to the City of Subotica (Bukurov, 1954; Dugonjić, 1956). This lake fragmented into several smaller lakes, most likely as a result of climate changes (Dugonjić, 1956). These water bodies remained connected through a shallow depression (later used as a direction for digging Bege channel) that enabled surface water flow between them. In years with high water levels, the depression also allowed a connection with the river Tisa (Dugonjić, 1956).

In terms of ionic composition, Lake Ludaš was classified as Na-Mg-HCO_3 lake by Petrović (1981), but Seleši (1981) reported that other ions, such as SO_4^{2-}, can be dominant in some years. It was less saline than Lake Palić due to the surface flow system created by the inflow and outflow branches of the Kereš River. Before the dramatic human-induced hydrological change, Lake Ludaš actually consisted of a wetland (northern part) and a permanent lake (southern part). In extremely warm and dry years, the wetland dried out completely while the lake part became shallower and smaller in size (Dugonjić, 1956). In its natural state, the lake was characterized by the extreme fluctuation in a hydrological regime that was mainly dependent on groundwater level.

History of hydrological disturbances

After the construction of the first channel in 1817 (Bege channel) and the second in 1971 (the Palić-Ludaš channel), the problem of poor water quality in Lake Palić has spread to Lake Ludaš as well. The trouble with municipal wastewaters from the City of Subotica was solved with the construction of the wastewater treatment plant (WWTP). Processed water was fed into Lake Palić. At that time Lake Palić was split into four sectors in order to extend retention time (Rudic et al., 2018). The problem is that the nominal volume of Lake Palić is around 10 million m^3 per year, but the amount of processed water discharged from WWTP is 13 million m^3 per year. Through the Palić-Ludaš channel, almost undiluted processed water ends up in Lake Ludaš. Using a basic water budget model, Z. Horvat and Horvat (2018) concluded that WWTP has a significant impact on the water regime of the lake and without the inflow of water from WWTP the water level in Lake Ludaš would be reduced for 0.45 m. It is known that the extreme change in hydrological conditions (i.e., excessive amount of water fed into a shallow lake) can lead to a shift from a clear-water phase (dominated by macrophytes) to a turbid state (characterized by cyanobacteria dominance) (Dokulil & Mayer, 1996). It remains unclear whether this surplus of surface water was the main reason for abrupt changes in the biological community of Lake Ludaš or the catastrophe was primarily caused by a high nutrient load carried by two lake's inflows (the Palić-Ludaš channel and the Kereš River). In our opinion, the answer to this question is crucial for selecting an appropriate strategy for the lake's rehabilitation.

Cultural eutrophication

Nutrient overload

Similar to humans or any other organisms, lakes age, and during this process that lasts over centuries or millennia changes occur in sediment, water column and biological communities. Increased growth of aquatic plants and algae in response to the raised availability of one or more limiting growth factors needed for photosynthesis, such as carbon dioxide or nutrients, is known as eutrophication (Chislock, Doster, Zitomer, & Wilson, 2013). Man has accelerated the rate of eutrophication, especially in the last two centuries, with an invention and application of fertilizers and detergents that contain phosphates. Cyanobacterial blooming, as well as sediment degradation, are the most adverse consequences of an excessive external nutrient loading. Unfortunately, Lake Ludaš was not an exception since the amount of phosphorus (P) and nitrogen (N) entering the lake has not been reduced below the recommended limits. Even though the amount of nutrients discharged to Lake Palić, and consequently the Palić-Ludaš channel, has been reduced after the construction of WWTP, the concentrations of total P and N that flow into Lake Ludaš from the channel are still very high. In 2015 the Public Health Institute in Subotica increased the sampling frequency and incorporated sampling sites along the Palić-Ludaš channel into its regular monthly monitoring program (Zavod za javno zdravlje Subotica [ZJZS], 2013, 2014, 2015, 2016, 2017, 2018). The results of their measurements revealed that P and N increased along the pathway between Lake Palić and Lake Ludaš probably as a result of point-source discharges (illegal cesspits from households in the vicinity of the channel) and non-point loading (untreated wastewater from Palić and Hajdukovo village). Numerous households and business facilities are still not connected to the sewage network and WWTP (*Plan for the Improvement*, 2014). Agricultural activities around the lake also contribute to the nutrient loading. Our chemical analysis of water taken from the Palić-Ludaš channel in summer 2019 showed that maximum concentration of total P was > 1 mg/l and total N > 4 mg/l (Ćirić et al., 2019) which is in accordance with the reports of the Institute of Public Health in Subotica.

Sediment degradation

Aquatic ecologists have admitted that benthic habitats are a crucial component of lentic ecosystems (Schindler & Scheuerell, 2002). The relation between benthic and pelagic habitats, in other words between sediment and water above it, is much closer in small and shallow ponds and reservoirs than in large deep lakes. Consequently, the impairment of the structure and function of sediment usually has long-term adverse consequences for water quality and the whole lake ecosystem.

At a time when Lake Ludaš was not subjected to heavy wastewater pollution, there was a difference in sediment composition between its northern (wetland) and southern part (permanent lake) (Dugonjić, 1973). The wetland bottom was undulated and covered with mud deposited over a layer of clay, while the lake bed on the south was flat, solid and mostly consisted of clay. According to our results, the bottom of Lake Ludaš is nowadays structurally almost uniform along the axis north-south and covered with a thick layer of mud, except in a small bay at the most southern point where the lake's bed is covered with macrophyte vegetation. The sediment thickness varies from 0.3 to more than 1.2 m. Mud thickens is the greatest in the northern part of the lake, where eutrophication processes are most intensive.

When it comes to the chemical composition of Lake Ludaš sediment, there were numerous measurements and studies that indicate the presence of different organic and inorganic pollutants. The most complete data set can be extracted from the reports of the Public Health Institute in Subotica, since this institution has conducted long-term sediment monitoring program (ZJZS, 2013, 2014, 2015, 2016, 2017, 2018). Since 2014, their sampling plan for the sediment analysis has included three sites in the lake (north, middle, and south—macrophyte zone) allowing a comparison of nutrient content along the longitudinal axis. The highest concentration of P and N, as well as organic matter, was most often recorded in the northern zone (ZJZS, 2013, 2014, 2015, 2016, 2017, 2018). Our analyses in 2018 and 2019 (unpublished data), were in accordance with the results of the Public Health Institute in Subotica indicating high P and N loading.

In addition to nutrients overloading, the problem with other pollutants in sediment has been extensively documented (Grba et al., 2017; Radic et al., 2013; Tričković, 2009). For example, Grba et al. (2017) revealed the relationship between the heavy metal content in the surface sediments of Lake Ludaš and traffic pollution from the city of Subotica. Moreover, the same authors found the elevated concentrations of Cd at all sampling sites as well as higher Cu and Hg values in the northern part of the lake. In spite of the fact that polycyclic aromatic hydrocarbons (PAH) concentrations were below a provisional guideline value for total concentration of carcinogens in sediments, the very high contribution of dibenzo[a,h]anthracene (DahA) was a warning signs for including these and similar priority substances into the future monitoring program (Grba et al., 2017).

The true extent of the problem with sediment degradation in Lake Palić and Lake Ludaš can be seen from the analysis given in the *Plan for the improvement of the ecological condition of Lake Palić and its surrounding* (2014). There were several studies, including one feasibility analysis of cleaning up sludge from the two lakes, but the high costs and dependence on external phosphorus reduction are the main obstacles for its implementation. If we accept the fact that sediment removal is "an expensive rehabilitation measure and its outcome is uncertain" than we have to be aware that even if we reduce the external phosphorus loading it is likely that Lake Ludaš will still release more phosphorus than it will receive in the next decade or longer, following the same rehabilitation pathway as Lake Søbygård in Denmark (Jeppesen, 1998).

Ecological role of alien and exotic species introduction

It is well known that invasive alien species represent a threat to biodiversity both in terrestrial and aquatic environments in almost every part of the world. However, it is less known that exotic species can also strongly affect ecosystem processes, e.g. amount and distribution of elements within an ecosystem (Ehrenfeld, 2010). For instance, an increase in biomass pool in some North American lakes was associated with the introduction of species *Dreissena polymorha*, an invasive mussel that forms dense colonies (Hecky et al., 2004).

According to studies of cyanobacteria and phytoplankton community in Lake Ludaš, at least two invasive species were recorded, *Raphidiopsis raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique, and Salerno (formerly known as *Cylindrospermopsis raciborskii*) and *Sphaerospermopsis aphanizomenoides* (Forti) Zapomelová, Jezberová, Hrouzek, Hisem, Reháková, and Komárková. Subtropical cyanobacterium *R. raciborskii* was discovered in Serbia for the first time in 2003 in the Ponjavica River (Karadžić et al., 2013). Shortly after, new published findings started to appear, mostly connected with carp ponds and reservoirs (Ćirić, Marković, Dulić, & Subakov-Simić, 2010; Simić, Mišćević, Đorđević, & Popović, 2011; Svirčev, Tokodi, & Drobac, 2017; Tokodi et al., 2020). This species has been regularly recorded in Lake Ludaš since 2013. According to the results of phytoplankton analyses, the species was dominant in the middle zone of Lake Ludaš in summer 2019 with maximum of 3×10^3 trichomes per ml. *R. raciborskii* is a very successful competitor thanks to its two abilities: high P uptake affinity and high P storage capacity (Padisák, 1997). For instance, *R. raciborskii* can accumulate between 24 and 45 times more biomass into its dormant cells (akinetes) than (native) *Aphanizomenon* species (Istvánovics, Shafik, Présing, & Juhos, 2000). When it comes to the effect of invasive species on a nutrient pool, this species may have a key role in the internal P load of shallow lakes (Padisák, 1997). Since *R. raciborskii* often blooms in Lake Ludaš it might have a strong impact on the internal P load in this lake.

Another invasive cyanobacterium *Sphaerospermopsis aphanizomenoides* (syn. *Aphanizomenon sphaericum*) was also recorded in Serbia for the first time in the Ponjavica River (Karadžić et al., 2013). In Lake Ludaš S. *aphanizomenoides* appeared in 2014 (Jovanović et al., 2015). It is still unknown whether this species has such a great influence on P flux in the lake like *R. raciborskii*. Moreover, this species is nitrogen-fixing cyanobacterium (diazotroph) and can affect N flux in the lake.

Apart from its ability to influence nitrogen cycle in aquatic ecosystems, some *R. raciborskii* strains can produce different cyanotoxins. In Lake Ludaš, microcystins (MC) and saxitoxin (STX) were detected (Gavrilović et al., 2020; Simeunovic, Svircev, Karaman, Knezević, & Melar, 2010; Tokodi et al., 2020), but it is still unclear whether *R. raciborskii* is a potential STX producer in this lake.

In addition to the two invasive microorganisms, there is one important allochthonous vertebrate species, the Prussian carp (also silver Prussian carp or Gibel carp) *Carassius gibelio* Block, 1782 (before 2003 *Carassius auratus gibelio*, Cyprinidae). This fish is dominant in the lake and feeds on zooplankton and macro-vegetation thus disturbing the food chains and contributing to the excessive phytoplankton growth (*Plan for the Improvement*, 2014; Pujin & Budakov, 1979; Tokodi et al., 2020).

Recent studies and projects related to the lake's rehabilitation

The most comprehensive attempt to solve the problem of Lake Ludaš eutrophication and pollution is the recent project "Biodiversity and Water Protection Lake Palić and Lake Ludaš" financed by the Government of the Republic of Germany and KfW Bank (*Plan for the Improvement*, 2014). The main idea of the project is to improve the water quality of the two lakes as an essential prerequisite for biodiversity conservation and tourism development. The project is focused on the external nutrients reduction and involves the construction of a new sewage network and wider buffer zones around the two lakes. In addition, the project entails an improvement of fish community structure in Lake Palić.

During the last few years several research groups investigated different strategies for nutrient reduction and prevention of noxious cyanobacterial blooms. For instance, Tokodi et al. (2018) carried out *in vitro* assessment of a chemical method based on hydrogen peroxide treatment, but they concluded that the application of a dose required for successful cyanobacterial control would also be harmful to other aquatic organisms. On the other hand, Rudic et al. (2018) suggested the construction of wetlands, bio-bridges and biobanks, which can improve self-purification process. This method of so-called bio-barriers would be based on autochthonous plants, for example *Typha* spp, *Phragmites* spp., *Carex* spp., etc. However, the major obstacle seems to be a lack of space required for achieving proposed nutrient limits.

Even though it was almost forty years ago, it seems reasonable to mention here the work of Đula Seleši, a limnologist and one of the greatest authorities on Lake Ludaš, who proposed the following steps in the lake's rehabilitation: (1) to find an alternative to Palić-Ludaš channel with good water quality; (2) to halt the inflow of wastewater and processed wastewater into Lake Ludaš; (3) to prevent using of chemicals (pesticides etc.) in the vicinity of the lake; (4) to reduce or totally cease sport fishing in the lake, and (5) to remove the upper sediment layer in some parts of the lake (Seleši, 1981).

Conclusion

Originally, Lake Ludaš was an alkaline saline lake with an extreme water level fluctuations and it was more or less isolated from other water bodies. Today, this lake is closely connected with Palić Lake and since the second half of the 20th century it was included in the flood control of Kanjiža city. Its role in holding the surplus of water during heavy rains and its use for recreational purposes are in contrast with the lake's natural hydrological cycle.

Despite the fact that the total P concentration in the lake's inflow has been reduced in recent years, the overall nutrient loading is still above the recommended limits. The negative consequence of the increased P and N availability is a massive development of algae and cyanobacteria as well as the impairment of the sediment structure. The occurrence of invasive species, such as cyanobacterium *R. raciborskii*, that might influence internal P loading of Ludaš Lake represents an additional challenge for water managers.

The problem of eutrophication and pollution of Lake Palić and Lake Ludaš stem from the fact that the City of Subotica did not have options for wastewater recipients other than these two lakes. It seems that the current project "Biodiversity and Water Protection Lake Palić and Lake Ludaš" has so far the biggest potential for solving this problem. Even though the management plan includes both lakes, it is likely that the improvement of natural conditions in Lake Ludaš would be more successful if we could disconnect two lakes as it was before 1817 and start to think about alternative water sources for Lake Ludaš.

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