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# The evolution of the trophic state of the Palić Lake (Serbia)

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*Abstract*: The Palić Lake is a shallow lake typical for the Pannonian Plain. Due inadequate water quality, it was dried out in 1971 and re-established in 1977 and since than its trophicity has been worsening. Investigation of the long-term changes in the trophic state of this lake were tracked over the total phosphorous (*TP*), total nitrogen (*TN*), chlorophyll-a and Secchi disk transparency (*SDT*), expressed as the Carlson trophic state index (*TSI*). Regarding the *TSI* values, the water of the Palić Lake has been constantly evolving from eutrophic to hypereutrophic. *TN*/*TP* values < 10 indicate that nitrogen is the limiting factor for algal growth.

*Keywords*: shallow lake; lake trophicity; eco-chemical status; trophic state index; eutrophication.

## INTRODUCTION

The Palić Lake is a natural lake located in the northern part of Serbia near Subotica, next to the Serbian–Hungarian border. It is a shallow lake typical for the Pannonian Plain, where the entire water column is frequently mixed. The Lake has recreational purposes but it is also a collector for treated municipal waste waters coming from the lagoons for active sludge water treatment. The Lake itself was in a very bad condition during late sixties of the last century, polluted and hypertrophic. Due to the inadequate quality of the water, a lot of mud in an anaerobic state, the mortification of aquatic plants and animals and, finally, the impossibility of using the Lake for recreational purposes, it was dried out in 1971 and re-established in 1977.

The sewage discharges from rapidly developing towns in the watershed and the growing use of fertilizers in agriculture have increased the nutrient loading to the Lake in the last decades. Again, a rapid eutrophication became apparent through the increased production of biomass and phytoplankton growth. In spite of clean-

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ing and remediation, which lasted for six years, today the Lake is again in a problematic condition; hence, it was necessary to define the current eco-chemical status and to investigate the evolving changes of the trophic state of the Lake from 1977 up till now. There is a range of factors that can influence the dynamics of eutrophication of a lake. They are useful only over a range of time scales, therefore, eutrophication dynamics may only be fully investigated when long-term, time-series data are available.[1] Eutrophication dynamics could serve to predict the Lake condition in the near future and to confirm whether immediate actions are needed or not. The most appropriate parameter for that purpose is the trophic state index or the Carlson *TSI*,[2] which has recently been adopted by the US EPA nutrient criteria recommendations for lakes and reservoirs.[3]

The aim of this work was to reconstruct the changes in the trophic state in the Palić Lake by application of the effects of the concentrations of nutrients on the changes in the trophic state and the increase of the eutrophication process in the Lake.

## EXPERIMENTAL

The main sampling material for the measurements was sampled lake water which was analyzed according to APHA (1976–1998)[4] and US EPA standard methods.[5] The measured parameters important for the determination of the eco-chemical status of the Palić Lake were temperature and pH of the water, oxygen saturation, the concentrations of $NH_4$, $NH_3$, $NO_2$, $NO_3$, *TN*, $PO_4$-P, *TP* and chlorophyll-a, and Secchi disk transparency (*SDT*) according to US EPA standards. Analysis of blanks and duplicates were the main instruments of quality control of the measurement throughout all the studied years.

Regular monthly measurements were performed every year, from March to October, typical vegetative months, for the period of the last 29 years (1977–2006). The remaining months were more or less winter months when samples were not taken due to low temperatures and ice.

Surface water samples were taken since they were assumed representative for the entire water column, as the water was always well mixed as a result of the shallow water depth. Sampling was performed 40 cm below the lake surface in the waterfront area, in order to prevent contamination of the sample by mud from the bottom or particles from the water surface. Samples were collected into 5-L plastic jerry cans.

The *SDT*, temperature and pH value of the water samples were determined on site. Samples for the determination of dissolved oxygen concentrations were collected and treated separately. All samples were stored at 4 °C and normally analyzed within a day. The maximum storage time was less than 3 days after sampling.

Unfiltered samples were used for dissolved oxygen determination, Kjeldahl nitrogen and total phosphorous. For chlorophyll-a analysis, homogeneous samples of water were filtered through Sartorius filter-paper.

The total phosphorous (*TP*) incorporated the total of all filterable and particulate phosphorus forms. It is probably the most often analyzed fraction of phosphorus because it is used in a wide variety of empirical models relating phosphorus to a wide variety of limnological variables.[6]

The total nitrogen (*TN*) is an operational value and represents the sum of nitrite, nitrate and Kjeldahl nitrogen, which were determined in unfiltered samples.

*Sampling locations*

The Palić Lake is divided into four sectors (Fig. 1). Sector I, adjacent to the main collector, serves as the collector for treated municipal waste waters from lagoons for active sludge water treatment. Sector IV, some 387 ha large, is mainly for recreation purposes. Between the first and the fourth sector, there are two additional sectors – the second of about 92 ha and the third of 80 ha. The sampling positions were selected to be at the end of the first accumulation (named sector II), at the end of the second accumulation (named sector III) and at the end of the recreation accumulation (named sector IV) right beside the outflow channel that connects the lake to the Tisa River.[7] Throughout this paper, only sector IV was considered since it is the largest segment of the Lake and because of its recreational purposes.

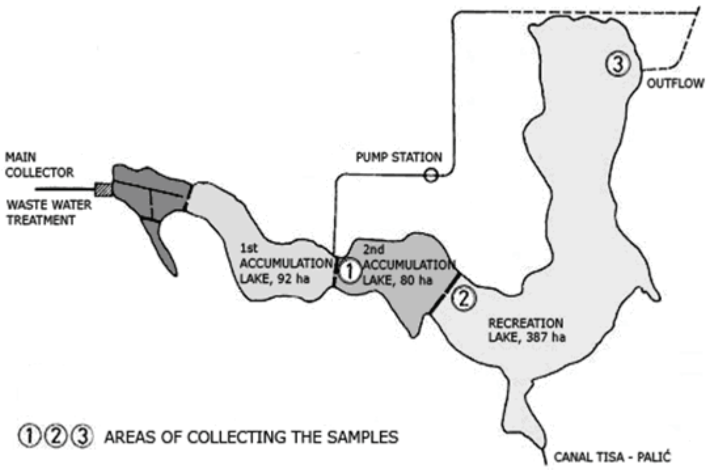


Fig. 1. The Palić Lake is divided into four sectors. Sampling locations are denoted as 1 (sector II), 2 (sector III) and 3 (sector IV). The weirs are presented with bold lines which trisect the lake.

*Characteristics of the Palić Lake*

The Palić Lake is a natural lake, located in the northern part of Serbia near Subotica, the second largest city of the Vojvodina Province, with a population of 150,000 inhabitants, next to the Serbian–Hungarian border on 46°16' north geographic latitude and 19°43' east geographic longitude (Fig. 2). It is a shallow lake typical for the Pannonian Plain, with an average depth of 2.4 m. As such, it is characterized by the variability of the water level, where the entire water column is frequently mixed – there is no stratification because the lake is shallow.

The Lake is 8 km long from the northern bank to the end of the western arm, and the width varies from 350 to 950 m. In the near vicinity of the Palić Lake lies the Ludaš Lake. The excess water in the Palić Lake is cadged from the east part of sector II, across a pump station, toward the lower Ludaš Lake.

Hydrographical characteristics of the Palić Lake are determined and depend on the geological, geomorphologic and climate characteristics. Urban development of the surrounding settlements (the city of Subotica and the settlement of Palić), development of close lake environment and activities in the surrounding areas have lead to an enhancement of the negative human influence on the water regime. Significant oscillations in the surface level cause constant problems in the water supply to the lake. According to the project of lake sanitation, the expected annual water wastage reached 411 mm of water column, that in relation to the surface of the lake in total means 2,500,000 $m^3$ water wastage by evaporation.[8] There are no significant confluents to the Palić Lake; therefore, the level of the surface is supported only by rainfall, refined waste water and underground water infiltration.


Fig. 2. Site maps showing the European and regional location of the Palić Lake.

The average inflow of water at sector I is about 11,440,000 $m^3$ (from $9.5\times10^6$ to $12.5\times10^6$ $m^3$) and the outflow at sector IV is almost the same. Under exceptional situations, when the inflow is too large, the water is led away through a channel by the end of sector II, or in cases when the water level is low, due to drought or extreme evaporation, water is brought into lake by a special cannel from the nearby Tisa River (some 20 km far-away from the Lake) at the very beginning of sector IV. The water volume in the Palić Lake is approximately 13,440,000 $m^3$ (total surface 560 ha and average depth 2.4 m). The average precipitation for the period 1977 to 2005 (Fig. 3) was 549 mm $year^{-1}$ (L $m^{-2}$), which means that the direct yearly rainfall into the lake was around 3,043,000 $m^3$ of water.

At a temperature of 15 °C, the level of the lake water decreases by 3 mm $day^{-1}$, due to evaporation; at 35 °C by 12mm $day^{-1}$.[9] As the average yearly temperature at Palić is some 14.7 °C, it is assumed that approximate yearly loss of water due to evaporation, is 3 mm $day^{-1}$ or 1068 mm $year^{-1}$, almost double the amount of water that the Lake receives per year by precipitation. The exact water balance of the lake has never been properly determined. Nevertheless, the Lake looses water through evaporation ($2.5\times10^6$ $m^3$) and outflow ($11\times10^6$ $m^3$) and gains water from inflow ($11\times10^6$ $m^3$), precipitation ($3\times10^6$ $m^3$) and from the Tisa River and groundwater ($3\times10^6$ $m^3$). A rough estimate says that the lake water exchange rate, the time required for a total exchange of water in the lake basin with fresh water is about one year.

In addition to wastewater and water from agricultural areas, wind deposit is a significant parameter for variations in the quality of the surface water in the Vojvodina Province. The prevailing winds from the north and north-west are characterized by erosive and accumulative effects that decrease the depth of the Lake Basin and also expedite negative transformations and cause extinction of the lake ecosystem.

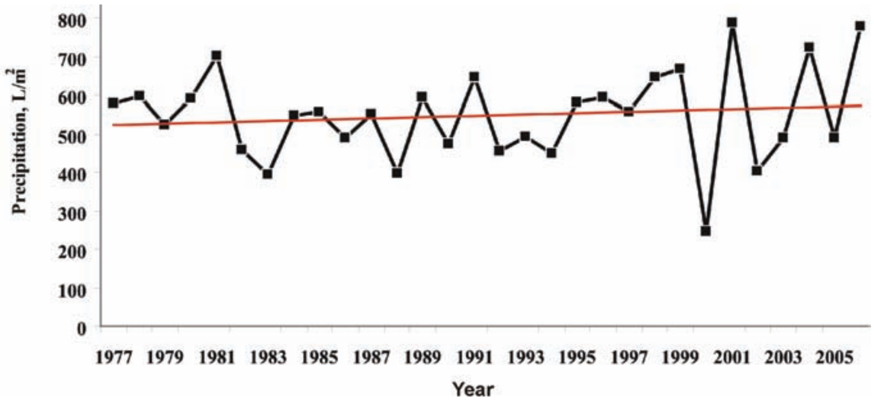


Fig. 3. Yearly precipitation in the region of the Palić Lake with trend line.

The Palić Lake can be rated among lakes that were formed by wind erosion, which caused displacement of material that uncovered underground water and created dunes elsewhere by sedimentation process. This kind of erosion is characteristic for plain areas with a dry climate and a fine-structured, incoherent terrain, without protective vegetation. It is rated among "diffused" pollutants that depose alluvium permanently into natural and artificial water flows and lakes. Being part of the great Pannonian Plain, the territory of the Province of Vojvodina was not an exception in this process, especially in its northern and central Bačka subregion.

Until 1971, the Palić Lake was the recipient of unrefined wastewater from Subotica, which caused its degradation and massive loss of quality in the tourist area. The greatest contamination was produced by waste water from industry, especially from a meat processing factory and chemical industry. The revitalization of the lake that started during the same year lasted until 1977, when all sectors of the lake were refilled by underground water and refined wastewater from the central waste water cleaning unit.

## RESULTS AND DISCUSSION

The results obtained for the Palić Lake are discussed from three different aspects: trends of the measured parameters with time – investigation of long term changes, seasonal changes of the measured parameters for the period 1977–2006 and trophic state.

### *Trends of the measured parameters during years*

The source data sets contain hundreds of measurements with some of them having skewed distributions, therefore median, minimum and maximum values are the only remaining statistical parameters that give meaningful averaged data appropriate for discussion. The results obtained for the Palić Lake, sector IV, for the period 1977–2006 are given in Table I. Each presented number corresponds to a yearly median value which covers the measuring months, March to October.

TABLE I. Processed parameters for water qual ity (minimum – Min, maximum – Max, median value - Med); Palić Lake - Sector IV, obtained for the period 1977–2006 (for the years 1996, 1999 and 2000, there was no data for total *P*)

| Parameter | Level | Year | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 |
| Temperature, °C | Min | – | – | – | 5.0 | 11.5 | 4.0 | 10.5 | 5.0 | 10.0 | 9.0 | 0.3 | 6.0 | 9.0 |
| | Max | – | – | – | 25.0 | 26.0 | 27.0 | 22.0 | 20.5 | 23.0 | 24.0 | 22.0 | 24.0 | 23.0 |
| | Med | – | – | – | 18.0 | 19.1 | 20.5 | 17.5 | 17.8 | 18.8 | 16.3 | 14.0 | 19.5 | 19.5 |
| SD Transparency, cm | Min | 20.0 | 15.0 | 15 | 16.0 | 10.0 | 20.0 | 20.0 | 18.0 | 20.0 | 10.0 | 20.0 | 20.0 | 15.0 |
| | Max | 180.0 | 35.0 | 45 | 30.0 | 35.0 | 180.0 | 70.0 | 40.0 | 25.0 | 45.0 | 45.0 | 130.0 | 60.0 |
| | Med | 55 | 25 | 20.5 | 23.5 | 17.5 | 52.5 | 36.0 | 25.0 | 20.0 | 32.5 | 35.0 | 45.0 | 40.0 |
| pH | Min | 8.6 | 8.8 | 9.1 | 8.7 | 8.5 | 8.4 | 8.2 | 8.6 | 8.3 | 8.0 | 7.8 | 8.2 | 8.3 |
| | Max | 8.9 | 9.2 | 9.5 | 9.5 | 9.3 | 9.5 | 8.7 | 9.2 | 9.3 | 10.0 | 9.1 | 8.9 | 9.4 |
| | Med | 8.8 | 9.1 | 9.2 | 9.1 | 8.9 | 8.5 | 8.5 | 8.8 | 8.8 | 8.6 | 8.3 | 8.7 | 8.7 |
| Oxygen saturation, % | Min | 66 | 83 | 96 | 33 | 51 | 42 | 32 | 85 | 47 | 43 | 42 | 76 | 73 |
| | Max | 128 | 140 | 209 | 137 | 191 | 187 | 105 | 138 | 126 | 110 | 209 | 134 | 157 |
| | Med | 97 | 119 | 126 | 113 | 121 | 67 | 88 | 98 | 98 | 89 | 88 | 98 | 126 |
| Total N, mg/L | Min | 0.88 | 1.25 | 2.15 | 1.6 | 10.0 | 0.8 | 1.6 | 5.0 | 3.1 | 3.7 | 1.8 | 0.5 | 5.6 |
| | Max | 3.60 | 5.58 | 13.337 | 28.8 | 31.9 | 16.3 | 8.3 | 10.1 | 14.2 | 7.4 | 57.7 | 25.9 | 27.5 |
| | Med | 2.06 | 4.17 | 8.37 | 12.2 | 15.2 | 7.9 | 4.0 | 5.9 | 7.2 | 5.4 | 4.8 | 10.9 | 16.2 |
| Total *P*, mg/L | Min | 0.37 | 0.45 | 0.37 | 0.7 | 0.7 | 0.2 | 0.3 | 1.1 | 0.6 | 0.5 | 0.3 | 0.2 | 1.0 |
| | Max | 2.00 | 2.08 | 1.6 | 2.5 | 3.7 | 2.6 | 0.6 | 10.6 | 1.2 | 1.5 | 3.3 | 1.3 | 3.2 |
| | Med | 0.825 | 0.66 | 0.93 | 1.9 | 1.2 | 0.4 | 0.4 | 2.3 | 0.8 | 0.8 | 0.6 | 1.1 | 1.8 |
| Chlorophyll-a, mg/m$^3$ | Min | 3.0 | 26.6 | 46 | 88.0 | 1.8 | 1.7 | 2.2 | 27.5 | 10.6 | 25.1 | 8.5 | 5.9 | 7.4 |
| | Max | 54.0 | 189 | 215 | 423 | 425 | 112.4 | 29.6 | 607 | 115.4 | 167 | 3777 | 245.8 | 151.5 |
| | Med | 9 | 100 | 143 | 255 | 153.5 | 12.2 | 4.2 | 79.4 | 67.7 | 75.9 | 37.2 | 94.1 | 23.6 |

TABLE I. Continued

| Parameter | Level | Year | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1990 | 1992 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
| Temperature, °C | Min | 10.0 | 6.0 | 8.2 | 7.5 | 6.0 | 5.0 | 7.8 | 6.5 | 11.0 | 10.0 | 3.3 | 5.8 | 8.0 | 5.2 |
| | Max | 24.0 | 24.0 | 24.0 | 28.0 | 24.7 | 25.0 | 25.5 | 26.0 | 26.0 | 27.0 | 26.0 | 22.0 | 22.8 | 26.4 |
| | Med | 22.0 | 18.8 | 17.4 | 15.0 | 19.1 | 17.6 | 19.0 | 20.0 | 17.3 | 18.0 | 20.0 | 17.8 | 17.2 | 19.1 |
| SD Transparency, cm | Min | 20.0 | 20.0 | 20.0 | 15.0 | 10.0 | 10.0 | – | 15.0 | 5.0 | 5.0 | 10.0 | 10.0 | 10.0 | 5.0 |
| | Max | 30.0 | 60.0 | 100.0 | 70.0 | 80.0 | 80.0 | – | 80.0 | 30.0 | 15.0 | 50.0 | 50.0 | 30.0 | 10.0 |
| | Med | 25.0 | 30.0 | 60.0 | 20.0 | 35.0 | 65.0 | – | 30.0 | 30.0 | 15.0 | 17.5 | 10.0 | 15.0 | 10.0 |
| pH | Min | 8.1 | 8.1 | 7.6 | 8.2 | 8.1 | 7.6 | 9.0 | 9.1 | 9.3 | 8.4 | 8.9 | 9.0 | 9.2 | 9.17 |
| | Max | 9.5 | 9.0 | 9.3 | 9.2 | 9.1 | 8.7 | 10.5 | 10.0 | 10.1 | 9.8 | 10.3 | 10.4 | 10.13 | 10.30 |
| | Med | 9.4 | 8.9 | 8.9 | 8.9 | 8.7 | 8.2 | 9.6 | 9.5 | 9.6 | 9.4 | 9.8 | 9.8 | 9.91 | 9.71 |
| Oxygen saturation, % | Min | 81 | 77 | 66 | 62 | 37 | 53 | 95 | 82 | 77 | 87 | 71 | 39 | 81 | 71 |
| | Max | 117 | 165 | 108 | 147 | 107 | 222 | 244 | 226 | 194 | 129 | 236 | 151 | 191 | 240 |
| | Med | 98 | 116 | 95 | 106 | 83 | 78 | 126 | 121 | 122 | 106 | 94 | 91 | 138 | 122 |
| Total N, mg/L | Min | 3.0 | 1.8 | 9.1 | 2.3 | 0.5 | 4.1 | 3.7 | 3.6 | 1.9 | 3.4 | 1.3 | 13.6 | 10.97 | 9.83 |
| | Max | 20.7 | 53.5 | 20.1 | 37.3 | 13.6 | 35.7 | 12.5 | 16.9 | 14.0 | 20.3 | 33.0 | 33.1 | 29.19 | 22.84 |
| | Med | 17.1 | 7.6 | 15.7 | 6.7 | 3.4 | 12.8 | 6.4 | 7.9 | 9.7 | 7.9 | 12.1 | 19.8 | 20.55 | 12.81 |
| Total *P*, mg/L | Min | 1.1 | 1.1 | 1.3 | – | 1.5 | 2.5 | – | – | 0.3 | 0.4 | 0.3 | 0.7 | 0.52 | 0.53 |
| | Max | 7.5 | 1.9 | 1.8 | – | 2.6 | 4.9 | – | – | 0.6 | 1.4 | 1.1 | 4.7 | 1.84 | 2.44 |
| | Med | 2.6 | 1.6 | 1.7 | – | 1.7 | 3.5 | – | – | 0.4 | 0.9 | 0.5 | 0.9 | 0.86 | 1.22 |
| Chlorophyll-a, mg/m$^3$ | Min | 9.0 | 0.2 | 3.2 | 0.9 | 0.1 | 0.2 | 18.7 | 13.0 | 15.3 | 109.0 | 107.8 | 147.0 | 62.0 | 252 |
| | Max | 188.4 | 41.1 | 166 | 104 | 129.3 | 107.2 | 436 | 585 | 351 | 1289 | 1841 | 1188 | 918 | 1260 |
| | Med | 80.1 | 24.7 | 15.3 | 55.0 | 37.8 | 7.4 | 116 | 128.5 | 187.8 | 577.5 | 315 | 347.5 | 296 | 536.5 |

Medians were assumed sufficient and very useful for the purposes of the present work, but they are values that do not reflect individual outliers sometimes present in the large data sets.

Linear regression analysis was used for determining the trends in the average values over time.

Selected parameters, oxygen saturation, chlorophyll-a, *TP*, *TN* and *SDT* were taken into account as the most indicative parameters that can directly show the evolution of the trophic state of the Palić Lake since 1977.

The oxygen in lake water is a very important parameter because it gives a general image of the quality of the lake environment. The regression slope for dissolved oxygen was positive (0.361) and the concentrations of oxygen were almost or above 100 %. Values greater than 100 % occur in eutrophic or hypertrophic environmental waters because of pure oxygen production by photosynthetically active organisms.[10]

Chlorophyll-a is the most appropriate parameter to follow the growth of both algae and C*yanobacteria* present in Palić Lake. Its load is a good indicator of the number of algae present in waters.[11] The most likely explanation for the increase in the chlorophyll abundance (fairly positive regression slope of 0.011) is an increase in nutrients, the food for algae, and the alkaline environment (pH around 8.9) is very favorable for algal growth.

Transparency was recorded using a Secchi disk. The readings can be affected by algae and by suspended solids in the water. Plankton scatters light, hence a lake which is less transparent tends to have more plankton and be more productive. The Palić Lake has a low transparency with a positive regression slope (0.361) and, therefore, is generally regarded as very productive. The higher the amounts of algae present in the waters, the lower is the water transparency.

The main nutrients for phytoplankton are phosphorus and nitrogen. The more nutrients there are in the water, the greater is the potential for growth. The nutrients have to be present in the right amounts and if one nutrient is lacking then growth can be retarded. Nutrients (nitrogen and phosphorous) are usually the limiting factors in algal growth. To compare the availability of these nutrients, the ratio *TN*/*TP* is used. Ratios smaller than 10 indicate that nitrogen is limiting.[12] Ratios greater than 30 indicate that phosphorus is limiting; whereas ratios greater than 10 and smaller than 30 indicate that there are enough of both nutrients for excessive algal growth.[12] Throughout all years, the *TN*/*TP* ratio was smaller than 10 (Table II), which indicates that nitrogen could be the limiting factor for algal growth in the Palić Lake.

If lake water oxygen saturation increases, the content of chlorophyll and nutrients (N and P) also gradually increase with time. An increase in the content chlorophyll-a is dependent on both water temperature and nutrient availability[13] and this was true for the present case as well. The oxygen saturation was positively correlated with the chlorophyll content ($r$ = 0.34) and *TN* ($r$ = 0.26), while it was negatively correlated with the *SDT* ($r$ = –0.51). The *TN* was positively correlated with chlorophyll ($r$ = 0.35) and with the *TP* ($r$ = 0.29), while it was negatively correlated with the *SDT* ($r$ = –0.21). This means with more nutrients, there are more algae and chlorophyll, which produce more oxygen and as a result the transparency of the lake decreases. This indicates very clearly that the trophic state of the Palić Lake has deteriorated with time.

TABLE II. Trends of the yearly medians with time (1977–2006); ⬀➚, increasing trend ⬂➘, decreasing trend and ⬄■, no trend – horizontal trend; median of yearly medians is given in paratheses

| Parameter | Palić Lake, Sector IV | Linear regression slope |
|---|---|---|
| Temperature of water, °C | ⬄■ (18.3) | 0.003 |
| *SDT*/ cm | ⬂➘ (27.5) | –0.551 |
| *P* | ⬀➚ (8.89) | 0.037 |
| Oxygen saturation, % | ⬀➚ (98.5) | 0.361 |
| *TN*/ mg L$^{-1}$ | ⬀➚ (7.95) | 0.285 |
| *TP*/ mg L$^{-1}$ | ⬄■ (0.91) | 0.006 |
| Chlorophyll-a, mg m$^{-3}$ | ⬀➚ (80.1) | 0.011 |
| *TN*/*TP* | 9.07 | – |

*Seasonal changes of the measured parameters for the period 1977–2006*

Trends of the measured parameters and seasonal changes are presented in Fig. 4. Each month corresponds to yearly medians of all measurements of a certain parameter obtained for the same month throughout the years from 1977 to 2006. The available results encompass data from March to October while the remaining months were more or less winter months when measurements were not performed due to low temperatures and ice.

In the vegetative period (from March to October), the dominant nutrient removal process was that of plankton uptake. The application of fertilizers in the spring time for the agricultural land nearby Palić Lake generated slightly higher concentrations of nitrogen and phosphorous in the Lake water, but these concentrations gradually decreased with time going to autumn. There are two explanations for this. First, during summer time, atmospheric precipitation is seldom, hence transfer of nitrogen and phosphorous compounds with rainwater from agricultural land into the lake is prevented, and second, due to algal activity, the consumption of the nutrients is much higher. In addition, the increase of temperature during the summer time favors algal growth resulting in increases in the chlorophyll-a concentration and decreases in transparency.

As found by researchers from the petrochemical industry NIS[14], the sediment of the lake – its muddy bottom layer – contains relatively high concentrations of nitrogen and phosphorus. These can be released into the water, particularly under conditions of low oxygen concentrations. The nutrients in the sediment come from the past settling of algae and dead organic matter. The nutrients released from the sediments are referred to as the internal loading of a lake. Chemical and biological processes for N and P uptake are different. After sedimentation, most of the N load is removed by denitrification, whereas a major fraction of P is reversibly bound to sediments and may become available again after its concentration has decreased in water.[15] Therefore, N is accumulated in the sediments less than P and the time lag for N is expected to be shorter than for P.

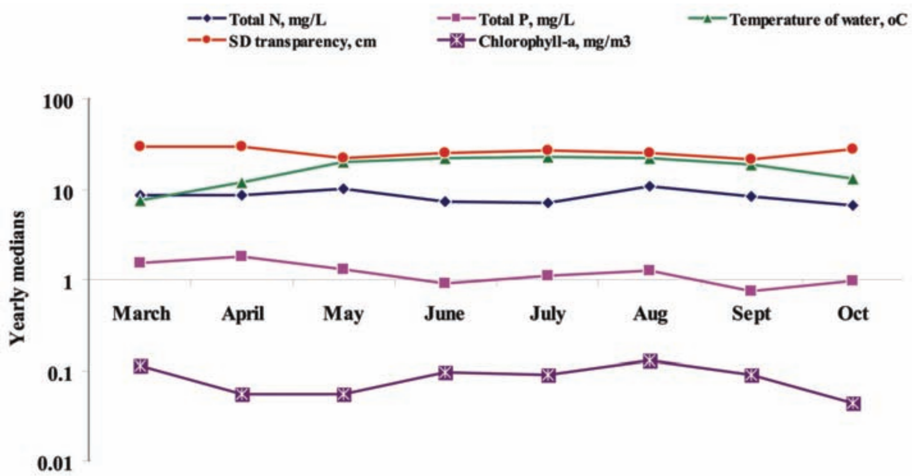


Fig. 4. Yearly medians of the *TN*, *TP*, chlorophyll-a, temperature of the water and *SDT* for Sector IV of the Palić Lake during the months March to October for the period 1977–2006.

The ratio *TN*/*TP* may be a useful method to establish the N and P reduction targets in the environment.[16] This ratio is one of the important components for the calculation of the trophic state index of lakes. Several studies showed that a *TN* to *TP* ratio ≤10:1 appears to favor algal blooms, especially of blue-green algae.[16]

The Palić Lake with a *TN*/*TP* ratio of 9/1 was classified as a N-limited lake and may have a higher probability for algal bloom because of its higher P levels. The *TN*/*TP* ratio increases from March to October for all three lake sectors (Fig. 5). Assuming that algal growth consumes nitrogen and in a constant ratio (the Redfield ratio) and that the concentrations of nitrogen and phosphorous decrease from spring to winter (Fig. 4), then the increasing trend of the *TN*/*TP* ratio indicates that during this time the input of nitrogen into Palić Lake increased slightly. This means that the retention of soluble nitrogen compounds in the lake water increases, or that phosphorus disappears from the water. There are many possible explanations for this; nitrogen compounds are soluble in water at any pH value, while phosphorus compounds tend to slowly precipitate under slightly alkaline conditions (pH > 8 ) and the pH of the Palić Lake water was around 8.9. The Lake water has such high pH values because photosynthetic organisms, such as algae, remove carbonic acid from the water causing the pH to rise. High pH values are not very favorable for lakes; at a pH of 9.3, the ratio between ammonia and ammonium ions is 1:1 and at these pH values, or even higher, the production of toxic free ammonia commences.[17]

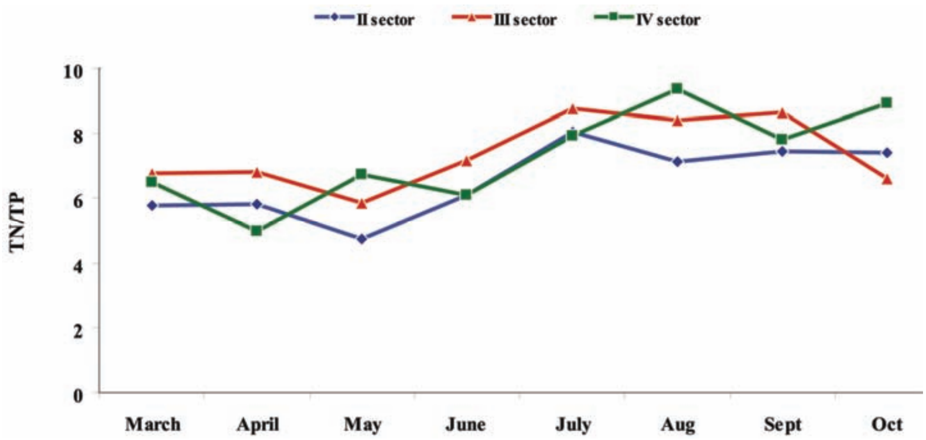


Fig. 5. Yearly medians of ratio *TN*/*TP* for Sectors II–IV of the Palić Lake during the months March to October for the period 1977–2006.

Schindler[18] indicated that a reduced N input into lakes increasingly favors the $N_2$-fixing activity of *Cyanobacteria* as a response by the phytoplankton community to seasonal N limitations. $N_2$ fixation is sufficient to allow continuation of biomass production in proportion to the P present in the water. This process contributes to lake eutrophication, despite extreme N seasonal limitations. These results indicate that for eutrophication reduction, lake management must focus on decreasing the P input.

Seasonal pH changes can give a good indication of how productive a lake is as increased algal activity raises the pH value. The increase of the pH of the Palić lake water was positively correlated with algal productivity ($r$ = 0.29), temperature ($r$ = 0.26) and *TN* ($r$ = 0.15), but it was negatively correlated with the *TP* ($r$ = –0.65). This negative correlation between pH and *TP* is explained with the fact that phosphorus becomes less available since fixation as calcium phosphate begins (Yamada *et al.*)[19] and the concentrations of phosphate in the water slightly decreased with increasing pH. This is a typical abiotic process of the settling of inorganic particulate P and the adsorption of dissolved inorganic P, which is responsible for P retention in the reservoir. In addition, the high pH values of the Lake water control the phosphorous concentration very well over time.

It seems that it is at about its maximum and it is rather equalized, fluctuating over a narrow interval around 0.9 mg $L^{-1}$.

*Trophic state*

An excellent indicator of the eco-chemical status of any lake would be its trophicity, described by the trophic state index (the Carlson *TSI*).[2] It is usually calculated based on data for the total phosphorus, chlorophyll-a and the Secchi disk transparency, according to the recommendations of the US EPA nutrient criteria for lakes and reservoirs.[3]

The graphs for the trophic state indexes, for phosphorous, *TSI* (P), chlorophyll-a, *TSI* (Ch), and *SDT*, *TSI* (*SDT*) were obtained applying the following formulas:[2]

$$TSI\ (\mathrm{P}) = 4.15 + 14.42\ln c_1 \quad (1)$$

$$TSI\ (\mathrm{Ch}) = 30.6 + 9.81\ln c_2 \quad (2)$$

$$TSI\ (SDT) = 60.0 - 14.41\ln SDT \quad (3)$$

where $c_1$ is concentration of *TP*, μg $L^{-1}$, $c_2$ is concentration of chlorophyll-a, μg $L^{-1}$, and *SDT* is the value of the *SDT*, m.

According to the US EPA standards, several categories of *TSI* values are possible (Table III). The obtained results for *TSI* (Fig. 6) show constant rising trends for all three parameters. The first parameter, *TSI* for *SDT* had a minimum of 66 and a maximum value of 93, indicating to constant change from a eutrophic to a hypereutrophic state, since the transparency of the Palić Lake was less than 1 m. For example, oligotrophic lakes tend to have water clarity greater than 3.9 m due to the low amounts of free-floating algae in the water column. The second parameter, *TSI* for *TP* had a minimum value of 90 and a maximum one of 122, indicating to a constant hypereutrophic status of the lake. The third parameter, the *TSI* for chlorophyll-a had a minimum value of 45 and a maximum of 93, indicating a rise from mesotrophic to hypereutrophic.

The method used for determining the trends in the average for *TSI* with time was linear regression analysis as well.

It is obvious from Fig. 6 and from the corresponding *TSI* trends and categories that the trophic state of the Palić Lake is worsening with time. The slopes of the regression (*SR*) for all three parameters are positive (*SR* (*SDT*) = 0.164; *SR* (*TP*) = 0.046 and *SR* (Ch) = 0.198). The great majority of all the trophic state indexes belong to eutrophic or even hypereutrophic lake conditions. Generally speaking the lake is showing constant tendency of a worsening of all parameters.

*Comparison with another shallow lake in the region*

The most significant shallow lake in Central and Western Europe is Lake Balaton, which is the greatest shallow lake in this region located in the western part of Hungary. Due to its low depth (3.3 m), the water temperature follows quickly the air temperature and reacts sensitively to hydro-meteorological changes. The average temperature of the water is 12.4 °C. The water is soft and rich in oxygen. The main use of the lake water is for recreational purposes and as a supply for the communal water demands. Selesi[20] compared water quality studies of the Palić Lake and the Balaton Lake. These systems show many similarities and differences:

– the Lakes are situated within the same climate zone but the Balaton Lake is about 100 times larger than the Palić Lake and is located some 160 km to the north-west in relation to the Palić Lake. The average water temperature of the Balaton is 12.4 °C and of Palić 14.7 °C;

TABLE III. Categories of *TSI* values (US EPA, 2000)[3]

| *TSI* | Chlorophyll-a, $\mu$g L$^{-1}$ | *SDT*/ cm | *TP*/ $\mu$g L$^{-1}$ | Attributes |
|---|---|---|---|---|
| <30 | <0.95 | >800 | <6 | Oligotrophic |
| 30–40 | 0.95–2.6 | 800–400 | 6–12 | Oligotrophic |
| 40–50 | 2.6–7.3 | 400–200 | 12–24 | Mesotrophic |
| 50–60 | 7.3–20 | 200–100 | 24–48 | Mildly eutrophic |
| 60–70 | 20–56 | 50–100 | 48–96 | Eutrophic |
| 70–80 | 56–155 | 25–50 | 96–192 | Hypereutrophic |
| >80 | >155 | <25 | 192–384 | Hypereutrophic |

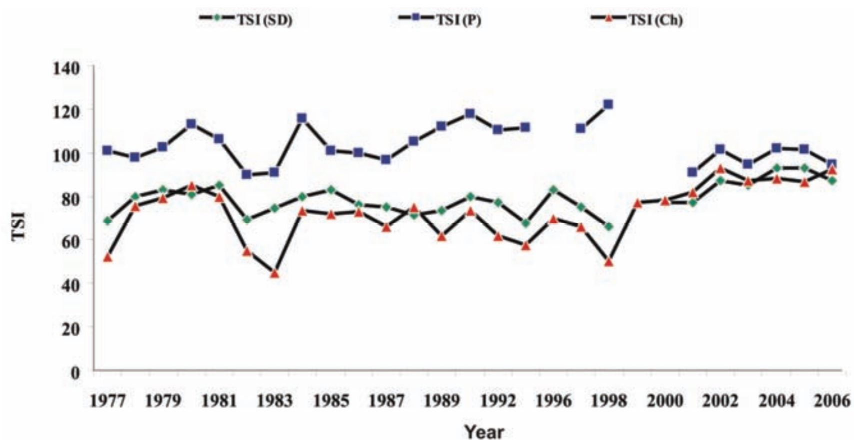


Fig. 6. Trophic state index (*TSI*) for *SDT*, *TP* and chlorophyll-a (Ch) for Sector IV of the Palić Lake for the period 1977–2006 (there was no data for *TP* for the years 1996, 1999 and 2000).

– regarding the water quality, the Balaton Lake was classified as mesotrophic to eutrophic,[21] while the Palić Lake is classified as eutrophic to hypereutrophic. The *SDT* for the Balaton ranges from 47 to 68 cm, while for the Palić, Sector IV, it is around 27.5 cm. The *TP* for the Balaton ranges from 0.1 to 0.03 mg L$^{-1}$, while for Palić, Sector IV, it is around 0.91 mg L$^{-1}$. Finally, the chlorophyll-a content for the Balaton ranges from 9.9 to 29.2 mg $m^{-3}$, while for the Palić, Sector IV, it is around 80.1 mg $m^{-3}$;

– both lakes receive water from sewage purification plants, but the Kis-Balaton reservoir system, located near the Zala River, established for the protection of the Balaton Lake against high nutrient loads is more efficient in comparison to the Palić system. The aim of Balaton system was that nutrients (primarily P) should be removed by macrophytes before entering the lake. In contrast to predictions, the system became an open lake dominated by algae. The retention efficiency has decreased considerably after reduction of the external load because of phosphorus removal at the wastewater treatment plant of the largest town, Zalaegerszeg, of the Zala catchment.[22] This observation can be explained by the increased contribution of the internal loading. Abiotic processes, such as settling of inorganic particulate P and the adsorption of dissolved inorganic P, responsible for the P retention in the reservoirs, are characteristic for both the Balaton and Palić Lakes;

– due to the vegetal nutritive materials available in the water, frequent over multiplication of algae, called "water flowering", during hot summer periods is characteristic for both lakes;

– nutrients discharged into Balaton Lake were utilized by the reeds and by various organisms living in the reeds, mainly fixed algae, and were nearly completely removed. In the autumn, the reeds die down and the materials they filtered out are mixed with lake water by wave action, with the exception of food materials.[23] In the case of the Palić Lake, the reed population declined, the reason for which has yet to be identified.

## CONCLUSIONS

Generally speaking, there are several negative factors that threaten the Palić Lake; short term factors, such as municipal waste waters inflow and high concentrations of nutrients which generate constant hypertrophic conditions in the lake and relatively low lake water exchange rate, and long term factor, such as global warming.

Taking into account the fact that 29 years of measurements demonstrate a constant trend of the worsening of the trophic state, it is not difficult to conclude that, with high confidence, the whole situation in the lake under current conditions will tend to worsen.

Positive factors that prevent complete and fast eutrophication of the lake are: there is an exchange of lake water with the nearby river, regardless of how slow it is, and there is still life in the lake, predominantly C*yprinidae*, which prefer weakly alkaline waters, pH 7.8–8.5.[24]

It is possible, but very expensive, to remove the upper nutrient-rich layer of sediment. Covering sediments with clay to seal them and thereby reduce internal loading has also been tried. Even when nutrients are removed in large amounts from wastewater, it often takes a long time before the nutrient concentrations fall in the upper sediment layer because they are still present in the water environment. Early reduction or elimination of nutrient sources is therefore very important.

Since the main reasons for reed decline are unknown, future research should also focus on involving reed-periphyton studies, which may provide a good basis to find the most appropriate ways to protect and restore the reed communities of shallow standing waters.

It is recommended that the following measures be taken to prevent further eutrophication:

– improvement of sewerage and sewage treatment plants, particularly for P removal;

– increase of the lake water exchange rate with water from the nearby Tisa River;

– enhanced treatment of the municipal waste waters that flow into the first sector of the lake;

– establishment of reservoirs on larger tributaries to retain plant nutrients.

Further and deeper examinations are necessary for a better understanding of the biochemical and biological processes.

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И З В О Д

ЕВОЛУЦИЈА ТРОФИЧКОГ СТАТУСА ЈЕЗЕРА ПАЛИЋ (СРБИЈА)

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Језеро Палић је плитко језеро типично за Панонску низију. Због неадекватног квалитета воде исушено је 1971. године и санирано до 1977. године и од тада се његов трофички статус погоршава. Дугорочна испитивања промене трофичког статуса, која обухватају анализе количине укупног фосфора, укупног азота, хлорофила-а и провидности воде преко Secchi-јевог диска, изражена су преко Карлсоновог индекса трофичког статуса. Вредност поменутог индекса указује да је вода језера Палић у еутрофичној и хипереутрофичној класи. Однос укупног азота и укупног фосфора, који је мањи од 10 указује на то да је азот лимитирајући фактор за раст алги.

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