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**Article** *in* Hydrobiologia · November 2003

DOI: 10.1023/B:HYDR.0000008585.37813.fa

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*Hydrobiologia* **506–509:** 759–765, 2003.

# Trophic state of a lowland reservoir during 10 years after restoration

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*Key words:* trophic state, reservoir ageing, chlorophyll-*a*, total phosphorus, Secchi depth

## Abstract

The restored Maltañski Reservoir was studied from its filling with water in 1990 till 2000. Total phosphorus, chlorophyll-*a*, and Secchi depth, as well as the Carlson's trophic state index (TSI) values based on those three parameters showed characteristic patterns of changes among seasons and years. Within each year, the lowest trophic state was usually observed in winter and the highest in summer. Because of the high loads of phosphorus received by the reservoir, this element did not limit primary production. TSI values calculated on the basis of total phosphorus were always markedly higher than calculated on chlorophyll-*a* and Secchi depth (similar to each other). The trophic upsurge phase lasted only a few months after the filling of the reservoir in 1990. Similar symptoms were observed after its refilling in the spring of 1993. The trophic depression phase lasted until the end of 1995. After that time a significant correlation between phosphorus concentration in the reservoir and in river waters flowing into the reservoir was observed. The successive phases of reservoir ageing, determined on the basis of phosphorus concentration, were not accompanied by changes in chlorophyll-*a* content. The influence of the top-down mechanism (biomanipulation effect) resulted in relatively low values of chlorophyll-*a* after the filling of the reservoir with water in 1990 and in 1993. As early as 1992 chlorophyll-*a* values reached a very high level and stayed at that level until the end of the study in 2000 (except for the short decline in 1993).

## Introduction

The process of ageing of dam reservoirs has been studied extensively, especially in the former Soviet Union, Czechoslovakia and the United States (for reviews, see Ostrofsky, 1978; Straškraba et al., 1993). Most of the studies concerned large reservoirs formed by flooding vast areas of meadows, fields, thickets, deforested land (sometimes even uncleared forest patches), or abandoned human settlements. As a result of leaching and decomposition of organic matter, large amounts of nutrients were usually released from the flooded areas into the water. This resulted in a strong increase in the trophic state of the reservoir after its flooding. The next phase concerns the gradual decrease of nutrient concentration and lasts usually several years. This decrease in trophic state is followed by slow eutrophication process, associated with the influence of the catchment (Straškraba et al., 1993).

In this study the process of ageing of the small and shallow Maltañski Reservoir, created on a polluted river was analysed. Before its filling with water, the bottom was reshaped artificially. The vegetation and the fertile layer of the soil were removed to minimize their influence on the quality of stored water. The objective of this paper was to analyse the ageing phases in this lowland reservoir influenced by the high external loads of nutrients and to determine if the special preparation of the basin before flooding had a long-term effect on the trophic state of such reservoirs.

## Study area and methods

The Maltañski Reservoir is located in the City of Poznañ, in the lowlands of mid-western Poland. It is relatively small and shallow (area 64 ha, volume $2 \times 10^6$ m$^3$, mean depth 3.1 m, max. depth 5 m). Its mean water residence time is 34 days, while the mean discharge of the Cybina River, which flows through the reservoir, is 0.67 m$^3$ s$^{-1}$.

The reservoir was built in 1952, and was intended for recreation and water sports. Because of the strong pollution of its waters and deposition of a thick layer of sediments, a decision was made to start its restoration. In the 1980s, the reservoir was emptied and the accumulated sediments were removed. Additionally, sewage flowing into the reservoir and into the Cybina River 6 km upstream was diverted. In that river section, 4 small preliminary reservoirs were created to improve the water quality above the Maltañski Reservoir (Gołdyn, 1994, 2000). In the spring of 1990, the reservoir was filled with water again, and since then it has been used for bathing and sports. From April till October many canoeing, rowing, and motor boat competitions are held every year.

The reservoir was emptied in the autumn (October) of 1992, 1996 and 2000, and refilled the following spring (March). All fish were then caught and weighed, so that their biomass could be calculated: 399, 391 and 618 kg ha$^{-1}$, respectively (Gołdyn & Mastyñski, 1998, and unpubl. data). In the first period (1990–1992) the reservoir was stocked with fish only once, in May 1992, with a small amount of pike (*Esox lucius*, 250 fingerlings ha$^{-1}$). In the second period (1993–1996), an extensive biomanipulation experiment was carried out – the reservoir was stocked with predatory fish, mainly pike, pikeperch (*Stizostedion lucioperca*) and wels (*Silurus glanis*), in successive years: 259, 600 and 1140 fingerlings ha$^{-1}$. Despite this, the fish species that had not been used for stocking accounted for as much as 82.6% of fish biomass in the autumn of 1996. Among them, roach (*Rutilus rutilus*), common bream (*Abramis brama*), crucian carp (*Carassius carassius*) and perch (*Perca fluviatilis*) were the most common (Gołdyn & Mastyñski, 1998). In the third period (1997–2000) the water body was stocked with a small amount of pike (470 fry ha$^{-1}$) in 1997 and pikeperch (490 fingerlings ha$^{-1}$) in 1998. Among the fish caught in 2000, the same species dominated as in 1996.

The water quality of the reservoir was monitored from July 1990 till September 2000. Water samples were collected at one station in the central part of the reservoir in the vertical profile: from the surface and from the depth of 1, 2 and 3 m. Samples were generally collected once a month, but from April till September in 1994–2000, they were taken every fortnight. However, no samples were collected when the reservoir was emptied and in the winter of 1997 and 1998. The following parameters were measured: Secchi depth, total phosphorus, chlorophyll-*a*, ammonium and nitrate nitrogen. For comparison, total phosphorus was assessed also in waters of the Cybina River flowing into the reservoir. Chlorophyll-*a* was assessed with Lorenzen method after extraction in acetone. Nutrients were analysed spectrophotometricly: total phosphorus with vanadomolybdophosphoric acid, ammonium nitrogen by the Nessler method, while nitrate nitrogen by the sodium salicylate method (Siepak, 1992). Volume-based data of chlorophyll-*a*, phosphorus and nitrogen from each depth of vertical section were averaged for every sampling session. Carlson's (1977) trophic state index (TSI) was calculated on the basis of Secchi depth (TSI$_{SD}$), chlorophyll-*a* content (TSI$_{Chl}$), and total phosphorus (TSI$_{TP}$).

## Results

Chlorophyll-*a*, Secchi depth and total phosphorus, as well as TSI calculated on the basis of these parameters showed a characteristic seasonal variation. In general, their values were lowest in winter and highest in summer of each year (Figs 1 and 2). Differences between those seasons (annual amplitudes) were high, reaching up to 52 units of TSI (Fig. 2). They attested to the mesotrophic state in winter and the eutrophic or hypertrophic state in summer. The annual amplitudes varied between years – the largest were usually at the beginning of each period (after filling of the reservoir), and smaller in successive years (Fig. 2).

In the first period (1990–1992), the minimum, maximum and mean TSI$_{Chl}$ values increased in successive years (Figs 2 and 3). The mean value was characteristic for the mesotrophic state in the first year, for the slightly eutrophic in the second, and for the strongly eutrophic in the third. In the second period (1993–1996) a similar trend was observed, but mean and minimum values were much higher than in respective years of the first period. In the third period (1997–2000), values of this parameter in successive years were within the range of 60–80 units, showing only small differences in mean values (Fig. 3). They were characteristic of the strongly eutrophic state. The comparison of annual mean values in the whole study period indicates that the reservoir reached the strongly eutrophic state as early as after the first three years, and stayed at that level until the end of the study in 2000. Only in 1993 a lower mean value was recorded.

A similar trend was observed in respect of changes in Secchi depth. In the first two periods the lowest annual mean, minimum and maximum values were re-

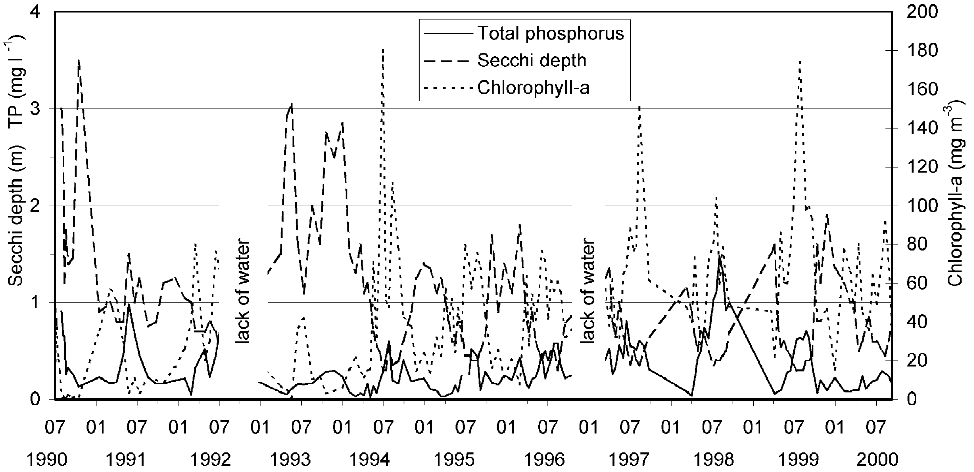

*Figure 1.* Secchi depth, concentrations of total phosphorus and chlorophyll-*a* in the Maltański Reservoir.

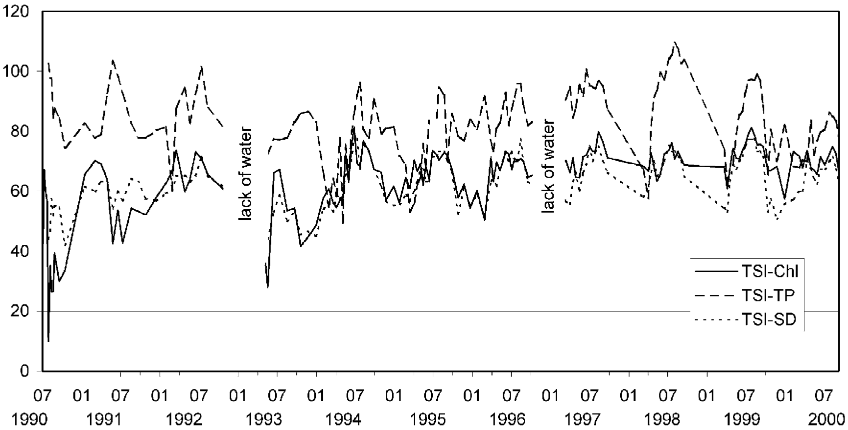

*Figure 2.* Variation in trophic state index calculated from Secchi depth, chlorophyll-*a* and total phosphorus for the Maltański Reservoir.

corded in the first year after the filling of the reservoir, and the highest values were recorded in the last year of both periods. In the third period (1997–2000) annual mean values were similar, and stayed at a high level characteristic of the eutrophic state (Fig. 3). As in the case of $\mathrm{TSI}_{Chl}$, mean values changed during the study period. Within the first three years they reached a high level (63.5), characteristic of the eutrophic state. They stayed at a similar level (up to 68.1) until 2000, except in 1993, when the mean value was markedly lower (Fig. 3).

A different long-term pattern of changes was observed in the case of $\mathrm{TSI}_{TP}$ (Figs 2 and 3). In the first period (1990–1992) the changes were irregular, but mean values generally showed a slight decreasing trend. In the second period (1993–1996) annual amplitudes of $\mathrm{TSI}_{TP}$ values declined in successive years, while minimum values showed an increasing trend. Initially the annual mean values slightly decreased, but in the last year a strong increase was noticed. In the third period (1997–2000) annual amplitudes also declined, and mean values decreased, especially in the last 3 years (Fig. 3). The long-term analysis of mean values suggests that their changes are not linked with the three phases of reservoir ageing. They declined in the first 6 years after restoration of the reservoir (1990–1995), then increased for 3 years (until 1998) and later declined again, until the end of the study period in 2000. In all years $\mathrm{TSI}_{TP}$ values were markedly higher (sometimes even twice as high) than $\mathrm{TSI}_{SD}$ and $\mathrm{TSI}_{Chl}$ (Fig. 3).

Mineral forms of nitrogen also showed a high seasonal variation. Particularly high values of nitrate nitrogen were reached in winter and in early spring –

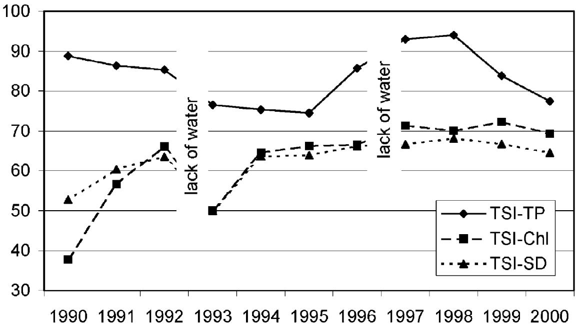

*Figure 3.* Mean annual values of trophic state index.

up to 18.6 mg N $l^{-1}$. Complete depletion of this form was observed in summer, but instead of this, increasing values of ammonium nitrogen were noted at that time (Fig. 4).

## Discussion

Carlson (1977) recommends basing the trophic state classification on data from spring and autumn mixing, when the phosphorus content is averaged in the vertical profile. However, in such shallow water bodies as the Maltański Reservoir, sampling in those seasons may confound, as the water is mixed frequently throughout the year. Increase in the temperature of water and bottom sediments in summer causes temporary oxygen deficits at the bottom and higher phosphorus concentrations in water (Gołdyn, 2000). Consequently, the highest values of the trophic state index based on phosphorus content are recorded in summer, not in spring as in the case of deep lakes (Dillon & Rigler, 1974; Reckhow & Chapra, 1983).

In the Maltański Reservoir, the classification of trophic state using$TSI_{Chl}$ and $TSI_{SD}$ is similar, but the classification using $TSI_{TP}$ is much higher (Fig. 3). It was confirmed by the good relationship between Secchi depth and chlorophyll-*a* concentration ($r = 0.764$, $p < 0.000$, $n = 146$). It means that transparency of water in the Maltański Reservoir depends mainly on the abundance of phytoplankton. The lack of correlation between $TSI_{Chl}$ and $TSI_{TP}$ ($r = 0.089$, $p = 0.289$, $n = 144$) indicates that in the Maltański Reservoir phosphorus is not a limiting factor. This is also confirmed by the weak correlation between gross primary production (PG), assessed in 1992–1997 (Joniak et al., 2003), and total phosphorus content ($r = 0.324$, $p = 0.006$, $n = 71$). Probably, light was the limiting factor in most parts of the study period because of self-shading, as PG in the surface layer was even 40-times higher than at 1 m depth (Joniak et al., 2003). Phosphorus concentration in the reservoir was usually too high to be depleted in the process of primary production. Only for short periods in the spring of 1994, 1995 and 1998, orthophosphates were not detected in the reservoir, so only then they could be a limiting factor. For this reason, Hern et al. (after Reckhow & Chapra, 1983) suggest that in such situations the trophic state should be assessed mainly on the basis of chlorophyll-*a* content.

Due to nitrate deficits associated with high levels of ammonium nitrogen in summer (Fig. 4), the phytoplankton was dominated by cyanobacteria (Blomqvist et al., 1994). This was confirmed by results of a study of the taxonomic composition and biomass of phytoplankton conducted till 1997 (Gołdyn et al., 1994, 1997a).

Straškraba et al. (1993) describe three phases of reservoir ageing. The first phase is characterized by an increase in trophic state, associated with flooding of new areas and release of nutrients from submerged soil (mainly from fertile arable fields), decomposition of the flooded terrestrial vegetation, etc. In large reservoirs this period lasts several years. According to those authors, the first phase is also distinguished by destruction of river phytoplankton flowing into the reservoir, and by the presence of abundant zooplankton. In the case of the Maltański Reservoir this period was relatively short and was limited to only several months after flooding. This phase was reflected in a higher concentration of total phosphorus in 1990 than in the following years. Unfortunately, no water samples were collected during the filling of the reservoir (from April till July 1990), when the release of nutrients from the bottom was probably the most intensive. The differences between mean concentrations of phosphorus in 1990 and 1991 are not large (Fig. 5), and maximum values are very similar. This was probably linked with the low level of phosphorus release from the bottom due to its special preparation before the filling of the reservoir (removal of the vegetation and the fertile layer of soil and levelling of the bottom).

The second phase according to Straškraba et al. (1993) is the so-called trophic upsurge, when populations are at maximal densities. This phase lasts until the end of leaching of nutrients from submerged soil, and is characterized by domination of only several species in phytoplankton. In the Goczałkowice Reservoir on the Vistula River, this period lasted 3 years, until

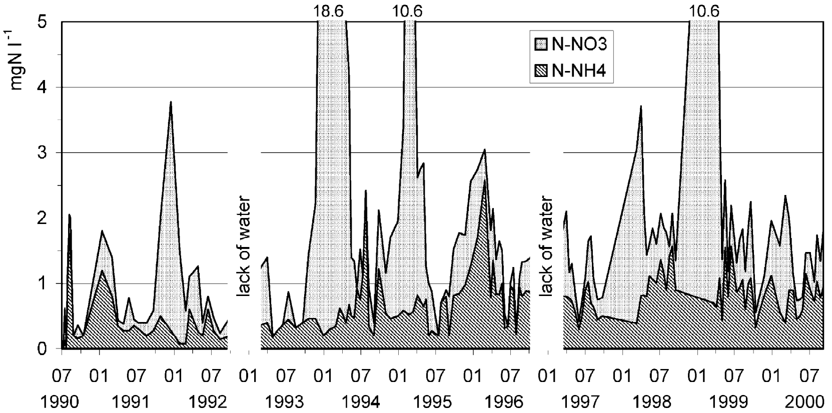

*Figure 4.* Concentration of mineral nitrogen (ammonium and nitrate form) in the Maltański Reservoir.

the suspended matter from the flood water formed a 1-cm layer of bottom sediments, which slowed down the release of nutrients from the primary bottom (Bombówna, 1962). In the Maltański Reservoir, this phase is difficult to distinguish, because the river waters do not contain large amounts of suspended solids that could form bottom sediments. In the phytoplankton a water bloom caused by *Aphanizomenon flos-aquae* was observed only in July and August 1990. It was also noticed after the refilling of the reservoir in 1993 (Gołdyn et al., 1994, 1997b). Thus we can assume that the second phase of ageing of the Maltański Reservoir lasted only 2 months in the first year after its filling with water. Ostrofsky (1978) defined the trophic upsurge phase as the period from flooding, till the end of the high levels of phosphorus in water. It is equivalent to the first two phases according to Straškraba et al. (1993). On the basis of equations proposed by Ostrofsky (1978), the duration of the trophic upsurge phase in the Maltański Reservoir was estimated at 0.53 year, i.e. from April till September 1990. This was the period of the above-mentioned development and decline of the water bloom caused by *Aphanizomenon flos-aquae*. Trophic upsurge phase that last a short period can be easily omitted. It was probably this reason that this phase was not stated in the newly flooded Sep Reservoir in France (Tadonlake et al., 2000).

The next phase is stabilization, when phosphorus concentration decreases, and the stable lacustrine phytoplankton assemblage has a smaller biomass than during the trophic upsurge. Ostrofsky (1978) named it the depression phase. A clear decrease in phosphorus concentration in the Maltański Reservoir was observed until 1995 (Fig. 5). Thus it can be concluded that this phase lasted there 6 years. However, a simultaneous decrease in phytoplankton biomass was observed only in 1993, and it was not a result of the lowering of phosphorus concentrations but the classic top-down mechanisms during the biomanipulation experiment conducted after second refilling of the reservoir. If the reservoir had not been drained-down, the phytoplankton community would probably remain stable until the end of the study period. Similar length of this period (ca. 6 years) was observed in the Siemianówka Reservoir (Górniak et al., 2003).

The next phase of reservoir evolution according to Straškraba et al. (1993) is a slow eutrophication associated with the influence of the catchment. It can be accelerated because of human activity in the catchment area, leading to a fast silting of the reservoir and deterioration of water quality. In the Maltański Reservoir this phase started in 1996 and lasted till the end of the study in 2000. In that period the annual mean concentration of phosphorus in water was closely related to its concentration in river waters flowing into the reservoir (Fig. 5). It was confirmed by statistical analysis ($r = 0.742$, $p < 0.000$, $n = 72$). The high concentrations of phosphorus in water flowing into the reservoir led to symptoms of the hypertrophic state even before the beginning of this phase, as early as in 1992 (very high concentrations of chlorophyll-*a* and a low transparency of water).

Taking into account water quality parameters important for water users, such as presence/absence of water bloom, content of suspended solids and organic matter – in the Maltański Reservoir the phases of reservoir ageing were greatly shortened. The successive phases of reservoir ageing, determined using changes in phosphorus concentrations were preceded by results of next phases. Generally, no improvement in water quality typical for the trophic depression phase was observed. In the period when intensive processes of phosphorus deposition in bottom sediments should be accompanied by improved water quality, typical symptoms of eutrophication were observed in the reservoir (a strong increase in $\mathrm{TSI}_{Chl}$and $\mathrm{TSI}_{SD}$ values). The increasing trophic state index reflecting the growing chlorophyll content, observed in 1990–1992, would be observed no earlier than from 1996 under conditions of low external nutrient loading. In fact, the gradual increase in chlorophyll-*a* content in 1990–1992 was not associated with progressive eutrophication, but with a decreasing influence of top-down mechanisms (Gołdyn et al., 1997a). As the reservoir was not stocked with fish after filling, large cladocerans quickly became abundant and controlled phytoplankton growth despite the high concentrations of phosphorus released from the bottom and flowing into the reservoir with river water. The gradually increasing numbers of planktivorous fish reduced the efficiency of the top-down mechanisms and resulted in increasing chlorophyll-*a* content in successive years. The lack of full stabilization of the ecosystem of the reservoir after 1992, despite reaching maximum concentrations of chlorophyll-*a*, is reflected in the recurrence of the top-down mechanism in 1993 after its temporary drain-down and catching of all fish. Nevertheless, the mechanism was not observed in 1997, after the next drain-down of the reservoir and catching of fish. This suggests that bottom-up mechanisms prevail over top-down mechanisms in the period of full stabilization of processes responsible for the functioning of the ecosystem. Such a conclusion may be of great practical importance for biomanipulation experiments in dam reservoirs. It indicates that under conditions of heavy external loading with nutrients, biomanipulation can be successful only in the period of initial stabilization of the reservoir, when the process of phosphorus deposition in bottom sediments dominates over its release from the sediments. Since the moment of stabilization of this relationship, biomanipulation must be preceded by a reduction in external nutrient loading. Special preparation of the reservoir basin before its flooding was not consequence in the case of the Maltański Reservoir, because the concentrations of phosphorus in water throughout many years were far higher than possibilities of phytoplankton utilisation, first due to top-down mechanisms and later due to self-shading of plankton organisms.

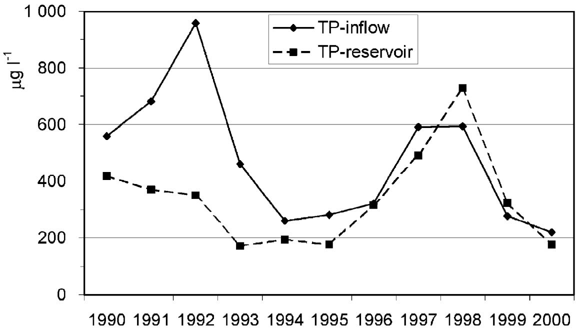

*Figure 5.* Mean annual concentrations of total phosphorus in the Maltański Reservoir and Cybina River flowing into the reservoir.

## Conclusions

The Maltański Reservoir is influenced by very complex environmental factors (among others: high external nutrient loading, periodical drain-down, biomanipulation measures), so typical ageing phases are not clearly visible.

In such lowland shallow reservoirs, successive ageing phases can be distinguished only on the basis of phosphorus concentrations in water.

Trophic state evaluated on the basis of Secchi depth and chlorophyll-*a* concentration is dependent not only on nutrient content but also on other parameters and processes and can be very advanced in a few years after flooding.

Non-intensive biomanipulation measures can effectively influence Secchi depth and chlorophyll content only in a depression phase. In the eutrophication phase of such reservoirs clear water state is critical. It requires external nutrient reduction and very intensive stock of predatory fish.

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