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# Primary production of phytoplankton and nutrient metabolism during and after thermal pollution in a deep, oligotrophic lowland lake (Lake Stechlin, Germany)

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## Introduction

From 1966 to 1989 a nuclear power plant (NPP) was operated in the Lake Stechlin area. It had an external circulation system for its cooling water, which was taken from the mesotrophic Lake Nehmitz. The heated cooling water was pumped into the oligotrophic Lake Stechlin. Canal connections between both lakes completed the system and from Lake Stechlin the water was led back to Lake Nehmitz (see Table 2). From an ecological point of view, this manipulation of Lake Stechlin can be considered as a long-term experiment. Comparisons of biological, chemical and physical conditions before, during and after the cooling water circulation gave insights into material and energy balances as well as the dynamic biological interactions in the lake. Thus, there would be a solid basis for research programs on basic limnological problems. Lake Stechlin proved to be a sensitive laboratory in which to test the biotic and abiotic behavior of an aquatic ecosystem under various external influences, for example, changes of water circulation patterns, nutrient input and waste heat. The Lake Stechlin limnological studies, which now span more than 40 years, have covered a large range of subjects in understanding of the structure and function of an oligotrophic lowland lake in the temperate climate zone, while maintaining a general focus on influences of thermal and nutrient loadings on biocoenoses and bacterial, primary and secondary production as well as on heat and water balances. The operation of the NPP and its cooling water release into Lake Stechlin was terminated in 1989 and the relationships between those new conditions and subsequent changes of limnological effects and reactions in the lake have been studied as a quasi-experiment.

The present paper is based on studies that were intended to define the conditions of Lake Stechlin as it adjusted to a major alteration in hydrological stability, nutrient metabolism, primary production and succession of phytoplankton over a period of 10–30 years. The objective of the study was to summarize several long-term reactions and changes in the chemical composition and the phytoplankton productivity of a dimictic, oligotrophic lowland lake during and after the operation of cooling water circuits, and the subsequent consequences in trophic conditions.

## Description of the lake and methods

Lake Stechlin lies on the southern border of the Mecklenburg Lake District at 53° 10' N and 13° 02' E, roughly 100 km north of Berlin. The lake is a typically oligotrophic and dimictic (in some years warm monomictic) lowland lake of the Northern (Baltic) Land Ridge. Lake Stechlin has been described by CASPER (1985a), CASPER (1995), RICHTER (1997) and HOLZBECHER et al. (1999). Some morphological and hydrological characteristics are provided in Tables 1 and 2.

Some chemical and physical parameters were measured in the field, including temperature, pH, and oxygen content. Nutrient concentrations (e.g. phosphorus as SRP, TP, nitrate and ammonia nitrogen)

Table 1. Morphological and hydrological characteristics of Lake Stechlin (CASPER 1985a, KOSCHEL 1995, HOLZBECHER et al. 1999).

| | |
|---|---|
| Surface area, km$^2$ | 4.3 |
| Volume, $10^6$ m$^3$ | 96.9 |
| Maximum depth, m | 68 |
| Mean depth, m | 22.8 |
| Shoreline length, km | 16.1 |
| Catchment area, km$^2$ | 12.6 |
| share of forest, % | 95 |
| Phosphorus load (SRP) | |
| with cooling water influence, g P m$^{-2}$ year$^{-1}$ | 0.06 |
| without cooling water influence, g P m$^{-2}$ year$^{-1}$ | 0.04 |
| Retention time, year | >40 |

0368-0770/02/0028-0569 $ 1.75

were measured in the laboratory and the hypolimnetic accumulation rate of phosphorus was calculated from the SRP concentrations at 60-m depth at the beginning and the end of the summer stagnation period according to KLEEBERG et al. (2000). The phytoplankton were counted in Lugol fixed samples and phytoplankton biomass was estimated by geometrical approximation. Primary production of phytoplankton was analyzed with the $^{14}C$-in situ technique (e.g. KOSCHEL & SCHEFFLER 1985, CASPER 1985b, KOSCHEL 1997, PADISÁK et al. 1997, 1998, KÖHLER et al. 1999).

## Results and discussion

*Thermal pollution water circulation*

The effects of changed water circuit, waste heat and external nutrient loading on the ecology of Lake Stechlin during operation of the Rheinsberg NPP were mostly described in the 1980s and 1990s (e.g. CASPER 1985a, KOSCHEL & CASPER 1986, KOSCHEL 1995). These results proved that the effect of the cooling water circulation on the lake metabolism has been ambivalent. The considerable increase in water temperature and particularly in nutrient matter provides clear causes for tendencies towards eutrophication (Table 1, Table 2). On the other hand, the changes in the stability and position of the thermocline, and in the retention time of water bodies, are directed against eutrophication (KOSCHEL & CASPER 1986). Under thermal discharge, the thermocline decreases in thickness by 0.5 m and becomes compressed. Thus, its stability increases and the fast water exchange between Lake Stechlin and Lake Nehmitz works against eutrophication by reducing the nutrient and organic matter load of the hypolimnion (RICHTER & KOSCHEL 1985, KOSCHEL 1995, Table 2).

*Chemical composition*

The analysis of oxygen and nitrogen indicates that there were only minor changes during and after cooling water circulation in pelagic zones of Lake Stechlin. The mean of minimum oxygen concentration at the end of the summer stagnation period (November/December) at 60 m depth during the operation period (1972–1989) was 6.7 mg $L^{-1}$, and after operation (1990–2000) was 6.3 mg $L^{-1}$ (Fig. 1).

The annual mean (0–10 m) of dissolved

Table 2. Hydrophysical conditions in the Lake Stechlin System (Lake Stechlin, Lake Nehmitz North) before, during and after the operation period of the cooling water circuit of the Rheinsberg NPP (CASPER 1985a, KOSCHEL 1995).

| | Lake Stechlin (inflow of cooling water) | Lake Nehmitz-N (taking of cooling water) |
|---|---|---|
| Water exchange in the lake system during cooling water circulation[a] | | |
| total water volume, days | 335 | 21 |
| epilimnetic water volume, days | 124 | 17 |
| Water temperature difference under thermal load (yearly average)[b] | | |
| whole lake, K[c] | 1.0 | <0.5 |
| epilimnion (July/August), K | 2.0 | <0.5 |
| Thermocline temperature | | |
| under natural conditions[d] (mean), K $m^{-1}$ | 1.5–2.0 | |
| under thermal load (mean), K $m^{-1}$ | 2.0–2.5 | |
| Retention time | | |
| natural[d], year | >40 | 10 |
| with cooling water circuit[a] for whole lake system, year | >40 | >40 |

[a]Water exchange for the mean rate of flow of cooling water during operation period of the NPP (290.000 $m^3$ $day^{-1}$).

[b]Mean increase by thermal load during operation period of the NPP.

[c]K, Kelvin.

[d]Two single independent lakes before and after operation period of the NPP.

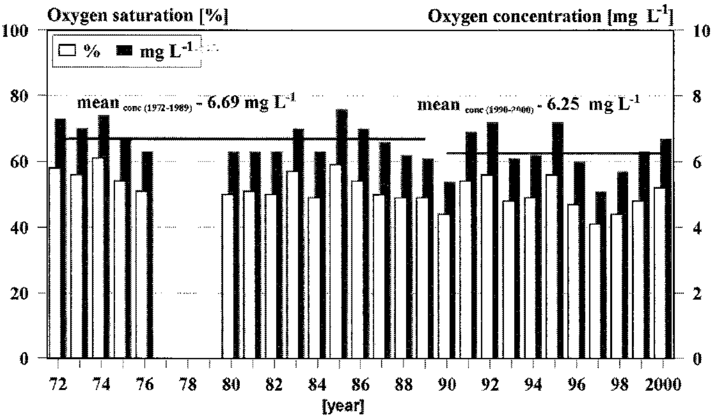



Fig. 1. Oxygen concentration and saturation at the end of the summer stagnation period (November/December) in deep hypolimnetic water (60 m) of Lake Stechlin from 1972 to 2000.

$NO_3$-N concentration in the euphotic zone varied between 24.3 (SD, 11.6; 1972–1977) and 21.3 µg $L^{-1}$ (SD, 9.7 µg $L^{-1}$; 1992–2000), the $NH_4$-N varied between 69 (SD, 29.7; 1973–1977) and 39.9 µg $L^{-1}$ (SD, 34.2 µg $L^{-1}$; 1992–2000).

Figure 2a shows how the average phosphorus concentration of the euphotic zone and of the deep aphotic zone (60 m) changed between 1970 and 2000. Averages of SRP and TP were not significantly different over the entire periods from 1970 to 1989 and from 1990 to 2000 ($SRP_{1970-1989}$: 2.3, $TP_{1970-1989}$: 12.3 and $SRP_{1990-2000}$: 2.5 and $TP_{1990-2000}$: 13.8 µg $L^{-1}$). However, during the operation of the NPP (1970–1989), phosphorus increased and after that (1990 and 2000) declined significantly.

Figure 2b illustrates a delayed reaction of phosphorus accumulation at 60-m depth. The phosphorus concentration progressively increased in the deep hypolimnetic water from the 1970s to the 1990s. The highest phosphorus concentrations at the end of the summer stagnation period were measured in the late 1990s, about 10 years after the operation of the cooling water circuit of the NPP was stopped, and with concentrations approximately four times higher than in the 1970s. The hypolimnetic phosphorus (SRP) accumulation rate drastically increased since the late 1980s. During 1997–1999 the mean SRP accumulation in water depths of more than 60 m was 1.02 ± 0.25 mg $m^{-2}$ $day^{-1}$, about 10 times higher than during 1979–1987 (0.11 ± 0.04 mg $m^{-2}$ $day^{-1}$). This indicates very strong changes in the diffusive release of SRP out of the sediments in the last 10 years, with a maximum in 1997–1998 (1.19 ± 0.07 mg $m^{-2}$ $day^{-1}$).

*Primary production of phytoplankton and phytoplankton community*

During and after the operation of the period of cooling water circuit, the quantity and seasonal periodicity of primary production were strongly influenced by the discontinued operation of the cooling water circulation of the NPP (Fig. 3; see also Koschel & Casper 1986). Altogether, the annual primary production averaged 97 g C $m^{-2}$ $year^{-1}$ during the operation (1970–1982) and 121 g C $m^{-2}$ $year^{-1}$ after the operation (1992–2000). The summer primary production (May–September) averaged 62 g C $m^{-2}$ $year^{-1}$ for the years during the operation and 73 g C $m^{-2}$ $year^{-1}$ for the years after the operation. The highest annual primary production was measured in 1995 (144 g C $m^{-2}$ $year^{-1}$). These elevations in primary production of phytoplankton occurred in accordance with the increased phosphorus concentration in the pelagic zone of the lake (Koschel & Scheffler 1985).

The seasonal periodicity and the abundance

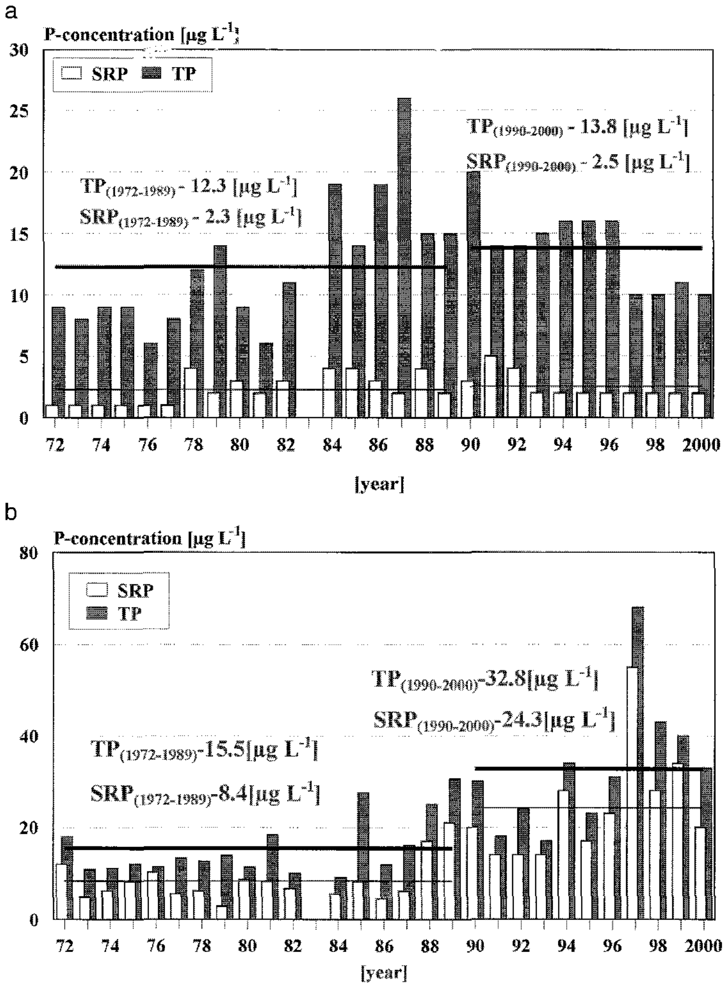



Fig. 2. (a) Annual means of phosphorus concentration (SRP, TP) in the euphotic zone (0–10 m depth) and (b) maximum phosphorus concentration at the end of the summer stagnation period (November/December) in deep water (60 m) of Lake Stechlin from 1972 to 2000.

of the phytoplankton community differ markedly between the operation and post-operation periods. In the 1970s and 1980s, phytoplankton was characterized by a *Fragilaria–Tabellaria–Mallomonas–Dinobryon* community with a subdominance of small phytoflagellates and diatoms (Casper 1985b). The yearly average phytoplankton biomass values oscillated considerably from 1970 to 1978 (1.4–12.9 g fw $m^{-2}$, for the euphotic zone to 17.5 m depth, Casper 1985b).

The phytoplankton succession patterns in the 1990s (after ending of the NPP circuit) were dominated by centric diatoms, cyanobacteria of picoplanktonic size and green algae (Padisák et al. 1998). Of the centric diatoms, species belonging to the genera *Cyclotella* and *Stephanodiscus* dominated, with high annual stochasticity at species level (Scheffler & Padisák 1997, 2000, Krienitz et al. 2000). *Stephanocostis chantaicus*, a species characteristic of oligo-mesotrophic waters with high transparency, developed a remarkable population density under ice cover during winter (Scheffler &

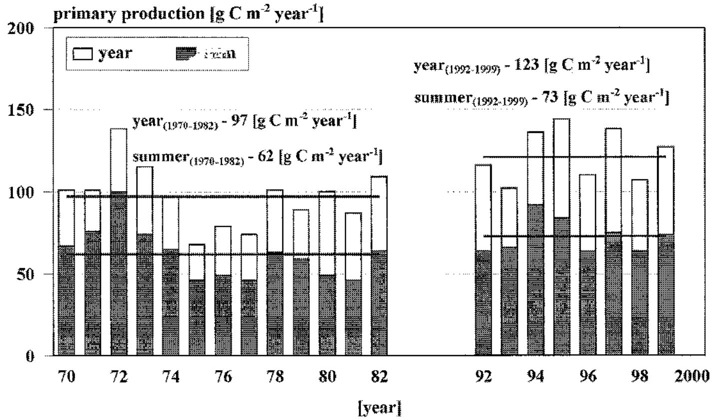



Fig. 3. Annual primary production of phytoplankton in Lake Stechlin from 1970 to 2000.

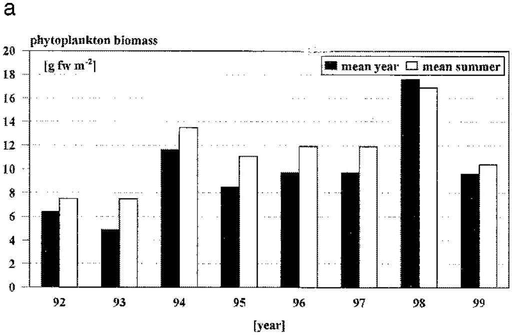
Padisák 2000).

The autotrophic picophytoplankton was mainly composed of two components: (a) solitary living '*Synechococcus*-like cyanobacteria' of the genus *Cyanobium* that established deep chlorophyll maxima during summer stratification periods, and (b) solitary living coccoid chlorophytes (*Choricystis*) and colonial chlorophytes (*Pseudodictyosphaerium*) that dominated in spring under isothermal conditions (Padisák et al. 1997, Gervais et al. 1997, Hepperle & Krienitz 2001). Furthermore, chrysoflagellates (*Mallomonas*, *Dinobryon*) and cryptophytes (*Cryptomonas*, *Rhodomonas*) were common in Lake Stechlin, especially during winter and within clear-water phases. A striking phenomenon was the dominance of *Planktothrix rubescens* in 1998. This filamentous cyanobacterium produced a biomass of more than 0.7 mg L$^{-1}$ during its maximal development in July 1998.

Analyses of the yearly average phytoplankton biomass and the yearly average specific activity of phytoplankton (P/B) in the euphotic zone after the operation period of cooling water circulation from 1992 to 1999 showed that the yearly average phytoplankton biomass values also changed considerably (6–18 g fw m$^{-2}$) (Fig. 4). In addition, when compared with the primary production, the biomass showed two general states: (a) phytoplankton communities with a high specific activity (dominant group: pico- and nanoplanktonic forms) and (b) phytoplankton assemblages with more reduced specific activity (dominant group: species with higher cell volumes). When *Planktothrix rubescens* became dominant in 1998, the biomass increased to a maximum yearly average of 18 g fw m$^{-2}$, which was paralleled by a decrease of annual mean P/B from 0.42 (without *Planktothrix rubescens*) to 0.17 (or a reduction in the mean summer P/B quotient from 0.45 to 0.25 g C m$^{-2}$ day$^{-1}$/ g C fw m$^{-2}$) (Fig. 4).

## Conclusions

In spite of the observed tendencies towards eutrophication caused by the cooling water circulation lasting for more than 20 years (1966–1989), Lake Stechlin has preserved its oligotrophic status at present (Klapper & Koschel 1985, Koschel 1995, Mietz & Vietinghoff 2000). The total phosphorus concentration and primary production of phytoplankton indicated a more oligotrophic to mesotrophic character from the late 1980s. The upper limit between oligo- and slightly eutrophic conditions must be set at the level of primary production of phytoplankton – about 120 g C m$^{-2}$ year$^{-1}$ in dimictic temperate lowland lakes (Koschel & Scheffler 1985, Köhler et al. 1999). This level was partly exceeded in the 1990s, 5–10 years after the NPP operation was terminated. The direct 'negative' effects on the water quality of Lake Stechlin are induced by increased nutrient load and 'thermal' pollution (Koschel et al. 1985, Koschel & Casper 1986). After that, time-delayed reactions (by many years) were observed in the ecosystem. The increased phosphorus loading and thermal pollution resulted more in moderately



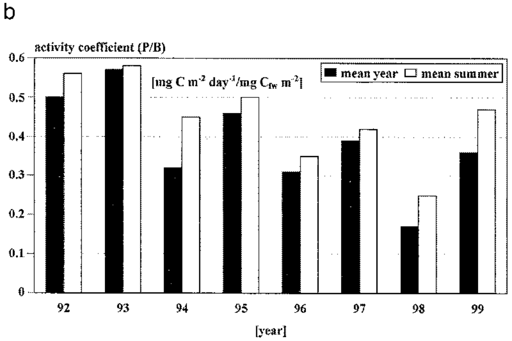




Fig. 4. (a) Annual average of phytoplankton biomass and (b) specific activity of phytoplankton (P/B)[1] in the euphotic zone (0–25-m depth)[2] in Lake Stechlin from 1992 to 1999.
[1]Conversion factor 1 mg fw = 0.1 mg C (WETZEL & LIKENS 1991).
[2]1992/1993 average biomass to 25 m by calculation of means from two to four depths (0–20 m, detailed SCHEFFLER unpublished); 1994 average biomass to 25 m by calculation of means from five to seven depths (0–15 m, PADISÁK et al. 1998); 1995–1999 average biomass to 25 m by calculation of means from 10 depths (0–25 m, PADISÁK et al. 1998).

higher primary production of phytoplankton than in important changes in the population structure of phytoplankton. Higher $CO_2$ net assimilation had a promotional effect on biogenic pelagic calcite precipitation in the calcium- and carbonate-rich Lake Stechlin. Calcite precipitation occurs in response to lowered solubility of $CaCO_3$ caused by the increased activity of $CO_3^{2-}$ resulting from net assimilation in the food web ($CO_2$-uptake by photoassimilation/$CO_2$-offtake by dissimilation) (KOSCHEL 1997). That process provided a high autochthonous self-protection potential by the co-precipitation of phosphorus, a rise in sedimentation velocity and a decreased release of phosphorus from the sediments, and it counters eutrophication (KOSCHEL et al. 1983, 1985, KOSCHEL 1990, 1997). The trophic state can be controlled in a positive manner by indirectly applying biotic feedback effects to the photosynthetically induced autochthonous calcite precipitation. In the late 1980s the phosphorus binding capacity of profundal sediments was limited and the phosphorus accumulation in the deep hypolimnetic water increased. The response of ecosystems to such 'autocatalytic' and 'autoinhibited' behavior is much more difficult to predict than the primary effects on chemical and physical structures by waste heat and/or nutrient load. Temporally delayed direct and indirect effects can have a negative influence or can be positively synergistic (BENNDORF 1994, 1995). As a consequence of such 'autocatalytic' or 'autoinhibited' regulation, in addition to the frequency of external forcing (thermal and phosphorus pollution and other stochastic influences), most pelagic systems are neither well organized nor successionally well advanced but are kept in a fairly primitive state of persistent re-establishment (REYNOLDS 1997). The pelagic system of Lake Stechlin is thus frequently open to development and growth and to invasion by phytoplankton species successfully utilizing the conditions offered. This explained the different patterns from a pico- and nanoplanktonic-dominated to a *Planktothrix rubescens*-dominated phytoplankton community, and its different primary production and specific activity (P/B) within the late 1990s in the dynamic, pulsing Lake Stechlin ecosystem.

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