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Blooms of *Aphanizomenon flos-aquae* associated with historical trophic changes occurring in Lake Świętokrzyskie, Poland

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Abstract

Sediment records and more recent water quality and phytoplankton analyses have been used together to identify the changing trophic status of Lake Świetokrzyskie over the past 7,570 years. These changes have been more rapid in recent times due to expanding human influence and urban development surrounding this lake (e.g., since approximately 1300 A.D.). Changing algal populations have accompanied this transition in the lake and include the increasing dominance of *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah. 1888 as a summer bloom producer. Several water quality relationships to the algae have included greater biomass levels of *A. flos-*

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aquae and several morphological features in the development of this taxon. These include the increased number and greater size of its vacuoles with iron concentrations >0.18 mg l^{-1} in the lake during its early development stages that have enhanced *A. flos-aquae* buoyancy and surface abundance. Other relationships include the increased production of its heterocytes and spores when phosphate levels exceeded 0.3 mg l^{-1}.

INTRODUCTION

Lake Świętokrzyskie is a shallow, highly eutrophic lake located within the urban complex of Gniezno, Poland. The ontogenesis of Świętokrzyskie Lake since ca. 7570 +/- 150 years BP has shown trophic changes resulting from both "natural" eutrophication processes within the lake and periods of disturbance to biological communities due to "cultural" eutrophication from urban surroundings. These included deforestation of the surrounding area, the gradual increase of atmospheric contaminants, and increased surface run-off bringing additional substances and pollution into the lake. These additional external influences to the lake have resulted in changes in water quality which have accelerated its development toward hypertrophy.

MATERIALS AND METHODS

Phytoplankton collection and composition studies were conducted in recent years in Lake Świętokrzyskie by Burchardt (1987) and Burchardt and Pańczakowa (1987a, b). In the current study, lake sediments were analyzed historically, carbon dated, and the pigment was analyzed. Additionally, quantitative changes in major algal categories were determined or referenced as were major nutrients and heavy metals (see Battarbee 1986, Burchardt 1987).

Phytoplankton samples from the middle of Lake Świętokrzyskie were collected at the surface level (0-0.5 m) with a Limnos sampler (volume 5 l). Samples were collected bimonthly in 1977-1979, biweekly from June to September 1997 and 1998, and approximately monthly from May to October 1999. The samples were preserved with acidified Lugol`s solution and stored under dark, cool conditions until counting. Species composition and biomass were determined using an inverted microscope at ×400 magnification according to Utermöhl (1958). Prior to counting, water samples were allowed to settle for 48 h in 2 to 10 ml cylinders. The counting units were cells, colonies, or trichomes. The phytoplankton biomass was determined based on volumetric cell determinations using geometric approximations. Water chemistry samples were taken at the same time as the phytoplankton samples. Ammonium nitrate (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), total nitrogen (TN), orthophosphate phosphorus (PO_4), total phosphorus (TP), and chlorophyll *a* were analyzed according to international standards.

For historical analysis, a 17 m sediment core sample was collected from a central location in Lake Swietokrzyskie in February 1986. Sub-samples from the 0-1 m section of the core were collected in 5 cm intervals, from the 1-8 m section at 10 cm intervals, and from the 8-16.9 m section at 50 cm intervals. Chlorophyll *a*, carotenoids, and the percentage composition of diatoms and other algal categories from 1 cm^3 of the sediment samples were analyzed according to the *Handbook of Holocene Palaeoecology and Palaeohydrology* (Berglund 1986). Radiocarbon dating and chemical analysis, including that of the heavy metal concentrations were conducted on several sections of the sediment core in Poland by the Institute of Physics, Silesian University of Technology.

RESULTS

The results of algal composition and abundance analyses indicate there were major biological responses to the lake's increasing trophic status. The core sediment analysis contained a dominant centric diatom flora ca. 7570 years BP, followed later by chrysophytes ca. 2500 years BP (Fig. 1). Ca. 1830 years BP there was a jointly dominant pennate and centric diatom complex that became centric dominant ca. 600 years later (1210 years BP). This period continued to

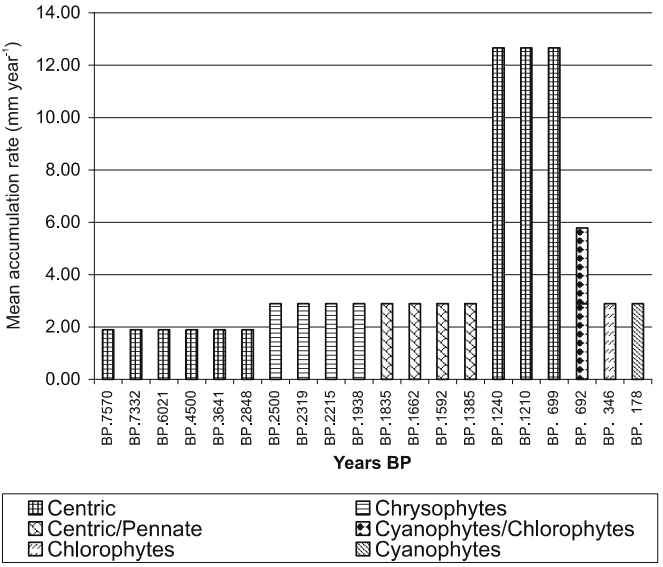

Fig. 1. Mean sediment accumulation rates of different algal categories in Lake Świętokrzyskie.

ca. 690 years BP, with their subsequent replacement by chlorophytes and cyanobacteria, which continues to the present day. The most abundant diatoms were species from the genera *Melosira* sp., *Tabellaria* sp., *Synedra* sp., and *Fragillaria* sp. These last 600-700 years were periods of increased human presence associated with deforestation, the development of agricultural practices, increased land runoff entering the lake, and the expansion of the city of Gniezno, which gradually surrounded the lake. A major product of this transition is the re-occurring summer blooms of various cyanobacteria (bluegreen algae) taxa (Kokociński et al. 2000). An analogous situation was observed in Lake Gosciaz (central Poland); fossil records from laminated sediments of the lake indicate that the human impact in the catchment area had an effect on trophic conditions (Van Geel et al. 1994). Recent studies and observations follow the progression of these blooms and identify the most abundant of species as *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah. 1888. These summer blooms generally occur at lake temperatures of 18-25°C, pH 8.5-9.0, and are preceded often by spring developments of chlorophytes and cryptophytes and followed by chlorophytes. During the entire study period, diatom abundance and dominance fluctuated, with a general decrease in dominance in more recent years.

Recurrent quantities of nitrogen and increased phosphorus in the summer, plus high phytoplankton biomass have suggested the additional influence in this lake of "cultural" eutrophication. There were significant correlations between diatom categories (e.g., pennate, centric) and total phosphorus, chlorophyll, and the carotinoids, with direct associations between chlorophyll and N:P ratio. Burchardt (1987) revealed that the specific composition of the elements constituting this phase manifested for the first time in 711 +/- 50 BP and progressed subsequently in 365 +/-50 BP and 197 +/- 50 BP. In recent examinations of *A. flos-aquae* during bloom development (summers of 1977-1979) the greater number and size of gas vesicles was associated with its high surface concentrations in the lake. This development and increased presence of gas vesicles was observed mainly during the initial phase of the bloom, and it is suggested that this was related to the iron concentration in excess of 0.18 mg l^{-1} that occurred at this time. The multiplication phase of vegetative cells of *A. flos-aquae* and the production of heterocytes occurred when phosphate levels exceeded 0.3 mg l^{-1} (Burchardt 1987). The situation when phosphorus concentration increases to a level that growth conditions become N-limited is characteristic for highly eutrophic lakes. Under such conditions, Cyanobacteria capable of nitrogen fixation (for example *Apahanizomenon flos-aquae*) are favored and can bloom (Van Geel et al. 1994, Van Geel et al. 1996). The historical records of Lake Świetokrzyskie bottom sediments and recent measurements of nutrients and other water quality variables also support these

relationships (Burchardt 1987). Additional associations between the nutrients in this lake and *A. flos-aquae* were present with the N:P coefficient and iron (Burchardt et al. 1988, Kokociński et al. 2000). The combined effect of mineral forms of iron to mineral forms of nitrogen and phosphate was found to be responsible for inhibiting *A. flos-aquae* development, and this was accompanied by the development of akinetes from the sediments. In addition, the availability of the mineral form of iron (III) was associated with increased abundance of *A. flos-aquae* in Lake Świętokrzyskie. High values of phytoplankton biomass in the lake (e.g., 82.0 - 611.7 mg l^{-1}) were associated with concentrations of 2.5 - 9.2 mg $N\text{-}NH_4$ l^{-1} and organic phosphorus of 0.97 to 3.07 mg l^{-1}; these conditions were associated with polytrophic status.

In addition to nutrient levels, there have also been relatively high levels of heavy metals (e.g., lead, iron, chromium) in lake sediments over the past 340 years. These high concentrations are attributed to pollution originating from Gniezno as well as the surrounding region that entered Lake Jelonek, which was temporarily connected to Lake Świetokrzyskie. This likely resulted in the passage of these metals into Lake Świetokrzyskie.

The lake's elevated trophic status is associated with the high concentrations of chlorophyll *a* that were recorded during the summers of 1977-1979 and 1997-1999. These chlorophyll values were considerably higher than those characteristic of less trophic waters and came primarily from significant blooms of *A. flos-aque,* especially during 1977-1979 (Table 1). In addition to this taxon, other cyanobacteria and representatives from other algal categories were also abundant and frequently produced blooms. For instance, chlorophytes were common as dominant taxa following the *A. flos-aquae* blooms. Note the dominant taxa present during these blooms in Table 1.

Table 1

Dominant taxa and chlorophyll *a* concentrations during summer periods of 1977-1979 and 1997-1999 in Lake Świętokrzyskie

Year of study	Dominant taxa	Chlorophyll *a* concentration (µg l^{-1})
1977-1979	*Aphanizomenon flos-aquae, Koliella longiseta, Pediastrum boryanum, Crucigenia quadrata, Ankistrodesmus falcatus* var. *acicularis, Selenestrum minutum, Scenedesmus* sp.	2.82-271.23
1997-1999	*Aphanizomenon flos-aquae, Anabaena affinis, Pseudanabaena limnetica, Pediastrum boryanum, Coelastrum microporum, Lagerheima genevensis, Ceratium hirundinella, Scenedesmus acuminatus* var. *minor*	2.67-141.13

SUMMARY

The increased eutrophication of Lake Świetokrzyskie supports, at this stage of its development, extensive blooms of cyanobacteria, most specifically *A. flos-aquae*. The specific relationships between the nutrient levels in this lake and its algal components influenced the onset and termination of these blooms, and presently are favorable to the development of *A. flos-aquae,* in addition to other cyanobacteria. This eutrophic status has accelerated over time due the added influence of the cultural and urban development of the surrounding region.

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