



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Impact of the size of the inoculum on
summer levels of *Microcystis* in Lake
Volkerak-Zoom

Calculations with BLOOM II-DBS

October 1998

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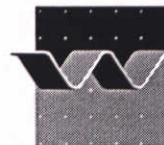
Calculations with BLOOM II-DBS

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: Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling/RIZA

TITEL: Impact of the size of the inoculum on summer levels of *Microcystis* in Lake Volkerak - Zoom
Calculations with BLOOM II - DBS

SAMENVATTING:

Het Volkerak - Zoommeer is een relatief jong systeem, dat aan het eind van de Delta werken is ontstaan. In de eerste jaren waren de biomassa's van fytoplankton lager dan verwacht. In de afgelopen jaren nemen echter de biomassa's van met name cyanobacteriën (blauwalgen) duidelijk toe. Mogelijk komt dit doordat met het groter worden van de populatie elk jaar meer cellen overwinteren op het sediment.

Het potentiële effect van de entgrootte (inoculum) is onderzocht met behulp van het model BLOOM II. Hierbij zijn groeisnelheden gebruikt, die in het laboratorium zijn gemeten. Op grond van de modelberekeningen is geconcludeerd, dat deze groeisnelheden voldoende groot zijn om een verkleining van het inoculum te compenseren. Er treedt slechts een geringe vertraging op.

Met behulp van DBS zijn berekeningen uitgevoerd inclusief competitie met andere soorten en graas door zooplankton. Ook uit deze berekeningen kan niet worden geconcludeerd dat de grootte van het inoculum een belangrijke factor is. Wel is het effect van een andere factor: graas van grote betekenis.

De modelresultaten worden besproken in het licht van de oorspronkelijke hypothese, de literatuur, de waarnemingen en het modelgedrag. Hierbij komen een aantal belangrijke onzekerheden en beperkingen van de studie aan de orde, op grond waarvan een aantal aanbevelingen voor verder onderzoek geformuleerd zijn.

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I Introduction

I.1 Lake Volkerak-Zoom

Lake Volkerak-Zoom was created only a decade ago, when the construction of a dam in 1987 isolated the lake from the North Sea. Although heavily loaded with nutrients right from the start, turbidity in lake Volkerak-Zoom was low during the first years of its existence. Grazing by zooplankton most probably limited phytoplankton density, allowing the rapid development of macrophytic vegetation. From 1990 onwards, however, population densities of planktivorous fish and of planktonic cyanobacteria began to increase, resulting in enhanced turbidity during summer. The Netherlands Institute for Inland Water Management and Waste Water Treatment (RIZA) has expressed the concern that, should the trend towards cyanobacterial dominance continue, the water quality in lake Volkerak-Zoom will deteriorate (Breukers *et al.*, 1996). Due to the present occurrence of populations of the colony-forming cyanobacteria *Microcystis* and *Aphanizomenon* in Lake Volkerak-Zoom and its potential to form severe nuisance blooms during summer (see chapter 1.2.3.), these species form a particular threat to the system.

Note: as *Microcystis* is the most important species of cyanobacteria in Lake Volkerak - Zoom, we will for simplicity often refer to this species only in this report when in fact we refer to all prokaryotic phytoplankton species in the lake.

I.2 Cyanobacterial dominance in eutrophicated freshwaters

Eutrophication of aquatic ecosystems can promote enhanced phytoplankton biomass production, in freshwater systems typically accompanied by a shift in species composition of the phytoplankton community from eukaryotic algae to cyanobacteria. Among these cyanobacteria, colony or aggregate forming, potentially buoyant cyanobacteria like *Microcystis*, *Anabaena*, and *Aphanizomenon* as well as some *Oscillatoria* species have been particularly successful. One explanation for their success is that eutrophicated aquatic ecosystems are often characterised by light limited growth of phototrophic organisms. Under these conditions, buoyant phytoplankters can gain a competitive advantage over both non-buoyant species of the phytoplankton as well as over benthic phototrophic organisms by concentrating their biomass in the upper, euphotic layers of the (stable) water column, thus increasing their daily photon dose (Ibelings *et al.*, 1991). The strategies include stratification at an optimal depth in the water column by *Oscillatoria* species and diel vertical migration pattern by *Microcystis* and sometimes *Anabaena* and *Aphanizomenon*. Other competitive advantages are, for example, resistance against grazing by zooplankton, formation of colonies or aggregates (e.g. Haney, 1987) and superior carbon dioxide concentrating mechanisms of cyanobacteria at high pH values (e.g. Raven, 1985).

Furthermore, *Anabaena* and *Aphanizomenon* are able to fix molecular nitrogen in the absence of sufficient concentrations of soluble inorganic nitrogen.

1.3 Harmful effects of cyanobacterial (*Microcystis*) dominance

Phototrophic organisms form the foundation of the food web of almost every known ecosystem. Eutrophication leads to enhanced primary production by phytoplankton and to changes in the food web of the aquatic ecosystems. Enhanced phytoplankton biomass density causes an increase in turbidity of the water column, generally resulting in a decrease of biomass density and spatial distribution of benthic plants and algae. A shift towards cyanobacterial dominance has harmful effects on the zooplankton community, since colony-forming cyanobacteria like *Microcystis* constitute a poor food source for zooplankton and may physically interfere with zooplankton grazing (e.g. Haney, 1987). These effects are reinforced by a positive feed-back loop due to selective zooplankton grazing of non-cyanobacterial phytoplankton species. Furthermore, many bloom-forming cyanobacteria produce toxins. Apart from harming zooplankton, some cyanobacterial toxins have direct adverse effects on higher organisms, depending on the specificity of the toxins. *Microcystis*, for example, is notorious for producing the potent toxin microcystin, which acts on the liver in mammals. Health problems of swimmers and death of cattle have been reported (e.g. Lawton and Codd, 1991). Some toxins may also accumulate in the food web which is harmful to consumers at higher trophic levels.

Another damaging effect of cyanobacterial dominance in general and surface scums of *Microcystis* in particular can be caused by the abundance of decaying organic matter settling onto the sediment during and after a dense phytoplankton bloom. The oxygen demand of the bacteria involved in mineralisation of the organic material can lead to a drastic reduction and even depletion of oxygen concentrations on the sediment and in bottom waters. This can be fatal for benthic organisms and fish. Furthermore, decaying organic matter can accumulate on the sediment, since anaerobic turn-over rates are lower than those achieved by aerobic metabolic routes. Bacterial production of the highly toxic compound hydrogen sulphide under these conditions can cause further damage.

Apart from the ecological damage, high biomass densities of cyanobacteria including surface scum formation usually diminishes the recreational value of a lake. High phytoplankton biomass concentrations cause high turbidity and thus poor visibility. *Microcystis* causes additional nuisance due to the formation of thick, foul-smelling surface scums in summer. When these surface scums reach shores or harbours, this will cause recreational problems. Furthermore, the potential toxicity of *Microcystis* poses a serious threat to public health. Hence, restoration plans for cyanobacteria-dominated lakes typically include a shift from cyanobacterial dominance to eukaryotic phytoplankton species and a return of macrophytes.

2 *Microcystis* in Lake Volkerak-Zoom

2.1 Species composition of the phytoplankton community

Dominated by eukaryotic algae until around 1990, Lake Volkerak-Zoom is apparently steadily changing into a system dominated by cyanobacteria during summer, mostly species of *Microcystis*, *Aphanizomenon* and *Anabaena*. No trend within the spring diatom bloom during the last years has been reported and the spring bloom is still followed by a clear water phase of several weeks. This is caused by grazing activity of large *Daphnia* species with highest population densities in May and June (Breukers *et al.*, 1996).

The dominance of cyanobacteria in summer, however, coincides with relatively high chlorophyll *a* concentrations and enhanced turbidity in that period. Still, average chlorophyll *a* concentrations and turbidity in summer are relatively low, keeping in mind the high nutrient levels in the system (Breukers *et al.*, 1996; Michielsen, 1996). One explanation for relatively low turbidity might be the fact that *Microcystis* cells forms colonies. Colony-formation results in a relatively low effect on turbidity as compared to a single-cell algal population of the same cell density. Even scum formation has little impact on the extinction coefficient of the entire water column, but it reduces the light penetration very considerably, so there is practically no light below a surface scum.

In summer, when the phytoplankton community is dominated by cyanobacteria, zooplankton population densities decline and chlorophyll *a* concentrations simultaneously increase (Breukers *et al.*, 1996). The following feed-back loop is at least in part responsible for this phenomenon: Cyanobacteria are a poor food source for the zooplankton, resulting in less predation on cyanobacteria than on eukaryotic algae. This leads to an even stronger increase of cyanobacterial growth, causing in turn further decrease in food-available for the zooplankton. The zooplankton community is even further diminished through predation by young fish in summer (Breukers *et al.*, 1996).

2.2 Annual cycle of *Microcystis*

The typical bloom period of *Microcystis* in temperate latitudes is late summer, more specifically August and September. In autumn, the remaining *Microcystis* population, settles on the sediment, along with other cyanobacterial species. Here, they overwinter as vegetative cells (e.g. Reynolds *et al.*, 1981; Takamuar *et al.*, 1984; Thomas and Walsby, 1986). Many possible explanations for the loss in buoyancy that causes settling on the sediment have been put forward (e.g. Reynolds and Rogers, 1976; Reynolds *et al.*, 1981; Thomas and Walsby, 1986; Visser *et al.*, 1995), but the exact physiological mechanisms have not been clarified yet.

After overwintering on the sediment, part of these colonies re-invade the water column in spring to initiate the next *Microcystis* population (e.g. Preston *et al.*, 1980) and the cycle is completed. The exact physiological mechanisms responsible for recruitment of *Microcystis* colonies from the sediment have not yet been clarified, either.

3 Remedies against *Microcystis* dominance - Aim of this study

Traditional remedies against dominance of *Microcystis* and surface scum formation in summer, include reduction of nutrient loadings and artificial mixing of the water column. Other measures, including filters and bubble screens, merely remedy the symptoms of a bloom, rather than trying to prevent its occurrence. In contrast with many other cyanobacteria, however, low concentrations of *Microcystis* are also present in many oligo- and mesotrophic lakes.

The best long term measure to reduce phytoplankton biomass in general and of cyanobacteria in particular should consequently be a reduction of the nitrogen and phosphate concentrations in the water. This has to be done mainly by reducing nutrient inputs through terrestrial run off, sewage inlets, and so forth. However, if lake sediments currently contain high nutrient concentrations, positive effects of nutrient reduction in surface water might not be found in the short term. As a short term measure against blooms of *Microcystis*, artificial mixing of the water column has among others been successfully tested in Ham's Lake, Oklahoma, USA (Toetz, 1981) and in the highly eutrophicated lake Nieuwe Meer, The Netherlands (Visser *et al.*, 1995). During artificial mixing in lake Nieuwe Meer, the phytoplankton community shifted from cyanobacterial dominance in summer to a mixed community of flagellates, green algae and diatoms, while nutrient concentrations in the water remained unchanged. However, the total chlorophyll *a* content of the water column increased (Visser *et al.*, 1995). Furthermore, artificial mixing of lake Volkerak-Zoom would be very costly and may not be very effective considering its average depth of about 5 meters.

Since *Microcystis* is thought to re-colonise the water column in spring after overwintering on the sediment (e.g. Reynolds *et al.*, 1981; Takamuar *et al.*, 1984; Thomas and Walsby, 1986; see also chapter 3.2.), decreasing the population size of overwintering colonies of *Microcystis* has been proposed as an alternative measure to prevent nuisance blooms of *Microcystis*. According to a theory by Reynolds (1997, pers.comm. B. Ibelings) the size of the inoculum is of utmost importance for slowly growing, K-selected species such as *Microcystis*. The gradual increase of *Microcystis* in Lake Volkerak - Zoom in recent years might be attributed to an increase in the size of the inoculum (Bijkerk, pers.comm. B. Ibelings). The chances for success of reducing cell densities of overwintering *Microcystis* colonies to hamper *Microcystis* population growth are not yet known.

This study aims at evaluating this option. This was done by making use of the phytoplankton model BLOOM II (Los, 1991), both as a stand-alone version (see chapter 4.2.) and as part of the water quality modelling package DELWAQ - BLOOM II - SWITCH, DBS (Los, 1993; see chapter 4.3.) that had been calibrated for lake Volkerak-Zoom by Michielsen (1996).

The following two questions were addressed in this study:

1. What is the effect of the initial biomass level (the inoculum) of *Microcystis* on its population size during summer?
2. To what level should the size of the inoculum be reduced in order to prevent a summer bloom?

As stated previously, grazing by zooplankton is a very important factor determining species composition and biomass densities of the phytoplankton community in lake Volkerak-Zoom. At the same time, grazing preferences are not exactly known and thus hard to quantify.

Therefore a third question was added:

What is the sensitivity of the outcome of competition among the species of the phytoplankton, computed for different initial values of biomass density, for grazing preference of the zooplankton?

4 Methods

The calculations were done with the phytoplankton model BLOOM II (Los, 1991), varying the base levels for initial biomass density of the species of the phytoplankton as described below. To this purpose, the stand-alone version of BLOOM II was used (chapter 4.2.) as well as the BLOOM II module in the environment of the modelling package DBS (Los, 1993; chapter 4.3.), which had been previously calibrated for lake Volkerak-Zoom (Michielsen, 1996). Additionally, the sensitivity of the outcome of the calculations to the grazing preference of zooplankton was tested with DBS.

4.1 Base levels of phytoplankton biomass density in BLOOM II

4.1.1 Introduction

Traditional phytoplankton models deal with a limited number of species. Unfortunately analysis of their equations show that competition is most sensitive to those coefficients, which are the least known i.e. the Monod coefficients of nutrient uptake. BLOOM II was constructed to overcome these uncertainties. Its original idea is quite simple: given the conditions as they are at a particular moment of time and at a particular place, what set of species is best adapted to meet these conditions? It computes this result by means of an optimisation technique ignoring the past: in essence it uses a steady state approach. This is valid if the characteristic time-scale of the dominant physiological processes is small relative to the time scale of the controlling environmental factors. In the natural environment these factors are not constant. For instance the time scale of the growth processes in a phytoplankter is in the order of one day under optimal conditions as it can double about once a day, but increases to several weeks when for instance the temperature is low. The time scale of the external forcing is also highly variable ranging from several weeks in a more or less isolated lake in summer to hours in flushing watersystems. To deal with these variations in time scales we have extended the original steady state BLOOM II model with additional constraints on the maximum amount of biomass growth and the maximum amount of biomass mortality that can occur within a period of time that we want to consider in the model. A thorough discussion on these matters is given by Los (1991).

BLOOM II can be used in two different ways depending on the questions that need to be answered. As a stand-alone model all environmental conditions are pre-specified in its input. This is true not only for meteorological conditions and bathymetry, but also for available nutrients. The model then computes the biomass compositions, the total amount, chlorophyll and the limiting factors. Usually the environmental conditions are derived from measurements, but they can also (partly) be set by the model user using a 'what if' type of analysis.

The stand-alone model version lacks feed-backs between the phytoplankton dynamics and nutrients and is therefore less suited for the prediction of future situations. To deal with these D(ELWAQ) - B(LOOM) - S(WITCH) was constructed. DBS is a water quality modelling package constructed by DELFT HYDRAULICS. Its initial development was cofinanced by RIZA. This model considers transports, complete nutrient cycles, several options for the bottom - water exchange of nutrients and several options to deal with grazing. Due to all these interactions, this integrated model is more difficult to operate than the stand-alone version of BLOOM. DELWAQ is the framework on which DBS is based. It contains physical schematisation, (pre-calculated) hydrodynamics and (surface) water chemistry. SWITCH simulates the chemical and physical processes that influence concentrations and fluxes of organic and inorganic matter in the sediment. DBS has been applied to a very wide range of water systems and is extensively validated (see Los et al. 1994 among others).

The number of phytoplankton groups (species) and types is variable. For practical reasons we often consider less groups and types within DBS compared to a stand-alone application of BLOOM II, but this is not strictly necessary.

4.1.2 Base level for initial biomass density

The concept of time-dependant growth and mortality constraints, as briefly introduced above, works for species that are present, but not for those that were absent from the system so far. Multiplying a biomass of zero with a (positive) growth rate, still results in a zero amount at the next time step. To deal with this problem we have introduced the idea of a 'base level' for the initial biomass density of all phytoplankton species into the model. In this case, the base level is used as an initial value for the population density to calculate potential growth rates. In general the model results are not very sensitive to the selection of the base level. The nominal value is a constant biomass in the order of 0.1 mg chlorophyll per m³. As an alternative the model can also use a variable base level which is a (constant) fraction of the steady state biomass. These base levels vary per species and as a function of time. In this study, the base levels for the initial biomass density of a phytoplankton species have been varied, both in the stand-alone version of BLOOM II and within DBS, to compute the effects of initial population density on the development of the *Microcystis* populations in Lake Volkerak-Zoom.

4.1.3 Lower threshold level for biomass density

It should be noted that BLOOM II contains another 'base level': To minimise calculation time, a second base level has been introduced. This base level has the function of a lower threshold level for biomass densities. By adjusting this threshold level, the user can decide at which point the biomass density of a species is so low that it can be neglected. Whenever the biomass density of a species drops below this level, the species is not included in the optimal solution any more; it is considered extinct. At the following time step, however, the species can reappear in the phytoplankton community due to the concept of the base level for initial biomass density described in the previous paragraph, or because it was imported due to transport. The base level that serves as a lower threshold level was not the subject of modelling within the context of this study.

However, since the values of this threshold level has to be chosen well below the value for the base level of initial biomass density for theoretical reasons, it had to be altered along with the base level for initial biomass density.

4.2 Potential population development (phase I)

To investigate the potential population development of cyanobacteria in lake Volkerak- Zoom, we have applied the phytoplankton model BLOOM II in its stand-alone version because this enabled us to manipulate several relevant factors independently without (complicated) interactions and feed-backs. So we were able to instigate during which part of the year *Microcystis* could appear in theory and what biomasses could be attained. For this analysis we have constructed input files for the years 1988 though 1995 using the following procedure:

1. We have used data on nutrients for segment "Volkerak-Oost-diep" from the previous application of DBS (Michielsen et al. 1996). This segment can be regarded as typical for the deeper parts of lake and was selected because the most extensive measurement dataset was available. We have furthermore performed a sensitivity analyse by step-wise decreasing the depth up to levels observed in other parts of the lake. These results are not shown, but the results are mentioned in chapter 7.
2. If necessary we have used linear interpolation to obtain weekly data as required by BLOOM II.
3. Temperature and solar radiation levels are copied from the input files used for DBS.
4. The depth was assumed to be 8 meters.
5. Total available phosphate was taken directly from the measurements.
6. Total available silicon was assumed to be equal to measured dissolved silicon because we had no time series of silicon in diatoms.
7. Total available nitrogen (N) was computed as

$$\text{measured nitrate} + \text{measured ammonia} + \text{Alga-N} + \text{Detritus-N}$$

- It was further assumed that

$$\text{Alga-N} = 0.075 * 100 * \text{measured chlorophyll } a$$

and

$$\text{detritus-N} = \text{Alga-N}.$$

These assumptions are fully explained in Los (1994).

- The background extinction was estimated as

$$\text{Maximum} [(\text{Measured total extinction} - 0.021 * \text{measured chlorophyll } a), 0.5]$$

The factor of 0.021 is the estimated specific extinction of phytoplankton plus detritus. The lowerbound of 0.5 per m is in accordance with the computed background extinction by "UITZICHT" which forms a part of DBS.

The model set up of BLOOM II for Lake Volkerak - Zoommeer includes 6 algal groups (species): diatoms, flagellates, green algae, *Aphanizomenon*, *Microcystis* and *Oscillatoria* and 15 algal types (phenotypes). The characteristics of the 15 algal types are identical to the description in Los (1991). However, as we wanted to demonstrate the potential of *Microcystis*, we removed all other species from the model input. Furthermore grazing was not taken into account in the computations with BLOOM II in its stand-alone version.

4.3 Actual population development (phase 2)

In addition to the calculations with the stand-alone version of BLOOM II (paragraph 4.2.), the water quality modelling package DBS (Los, 1993) was applied to compute the effects of the initial population density on the development of the *Microcystis* populations in Lake Volkerak-Zoom.

To assess the actual population development, BLOOM II was used in the DBS environment to be able to take the specific environmental factors in Lake Volkerak-Zoom into account as well. Important environmental factors include competition with other phytoplankton species and variations in grazing pressure by zooplankton. All model runs were done for the years 1988 through 1992. Michielsen (1996) has calibrated DBS for Lake Volkerak-Zoom according to Los *et al.* (1994). This version of DBS was used for the calculations in this study, with alterations in the following parameter settings of the BLOOM II module of DBS:

- phytoplankton groups and species;
- base levels - minimum initial phytoplankton biomass density (type of base level, constant or fraction of steady state biomass density; values of base level);
- grazing preference of zooplankton for the phytoplankton species.

4.3.1 Phytoplankton groups and species

In the version of DBS previously applied to Lake Volkerak-Zoom by Michielsen (1996), three phytoplankton groups were included: diatoms, green algae and cyanobacteria. For diatoms, a distinction between a phenotype adapted to light-limitation (energy limitation) and a phenotype adapted to phosphate-limitation was made. For green algae and cyanobacteria, phenotypes representing light- and phosphate-limitation as well as phenotypes for nitrogen-limitation were included. The total number of phenotypes in BLOOM II (types in BLOOM II) thus amounted to eight.

Since the objective of this study was more specific with respect to species composition and the presence of *Microcystis* was crucial, the group of cyanobacteria in BLOOM II was split into two species, *Aphanizomenon* and *Microcystis*. The settings for *Aphanizomenon* were taken from Los (1991) and the settings for *Microcystis* correspond to Los (1996). Essentially this means that we have used the nominal definition (parameters) of these species.

Since nitrogen-limitation did not occur in any of the calculations, only light- or phosphate-limited phenotypes were used for all phytoplankton species. Hence, the sum of all phenotypes was eight as well. By keeping the old amount of types we did not have to change the entire model input which would have been the case otherwise.

4.3.2 Minimum initial phytoplankton biomass density (base level)

In the version of DBS calibrated for Lake Volkerak-Zoom by Michielsen (1996), a constant base level, representing the minimum initial phytoplankton biomass density (see chapter 4.1.2.), was used with a value of 10 mg dry weight/m³ corresponding to approximately 0.1 mg chlorophyll per m³. The lower threshold level for biomass density (see chapter 4.1.3.) was 0.1 mg dry weight/m³.

In this study, calculations with constant base levels were done, with values decreasing stepwise from 40 mg dry weight/m³ to 10⁻⁶ mg dry weight/m³. Dividing these numbers by 100 gives the approximate chlorophyll levels. Base levels as fractions of the steady state biomass density were tested with values ranging from one (one hundred percent) to 10⁻⁵ (10⁻⁷ percent). In both cases, the lower threshold level for biomass density was varied along with the base level for initial phytoplankton biomass density, ensuring that the latter was at least 2 orders of magnitude larger than the first.

4.3.3 Grazing preference of zooplankton

In the version of DBS calibrated for Lake Volkerak-Zoom by Michielsen (1996), grazing preferences of the zooplankton for certain species of the phytoplankton were not included. The importance of grazing to the total biomass was very obvious in this study, however.

In this study, grazing preference of the zooplankton was varied to test the effects of selective grazing of the zooplankton on species composition of the phytoplankton community. While grazing preference for eukaryotic algae, diatoms and green algae, was always kept at one (hundred percent), grazing preference of cyanobacteria was stepwise decreased to zero. Two scenarios were tested: First, the effects of a higher preference of zooplankton for eukaryotic algae, diatoms and green algae, for cyanobacteria was tested, without making any further distinction between *Aphanizomenon* and *Microcystis*. Secondly, the preference for eukaryotic algae was combined with negative selectivity for *Microcystis* amongst the cyanobacteria. For both settings, grazing preferences were tested in combination with variations in the base level for initial phytoplankton biomass density.

5 Results

5.1 Potential population development (phase I)

The simulations with BLOOM II in its stand-alone version with only *Microcystis* (Fig. 5.1.) show that non-zero biomass levels of *Microcystis* are theoretically possible during about 200 days of the year under conditions typical for Lake Volkerak - Zoom. Its potential biomass is an order of magnitude higher than the observed total biomass in Lake Volkerak - Zoom, indicating that there is a severe limitation not considered in these worst-case computations. Remember that we have excluded all other phytoplankton species and grazing from these computations; i.e. there is no competition and no grazing, which in reality are important in the lake.

A stepwise decrease in base level for the initial biomass causes a delay in the onset of the *Microcystis* development, but even with a very small value of 0.00001 mg dry weight per m^3 , the delay is not more than about 20 days. During summer biomass levels are independent of the initial conditions hence all simulations are identical.

These computations were repeated for all years (1988 - 1995) for which we had data and also for a depth of 1.5 m, which is typical for the shallowest part of Lake Volkerak-Zoom. The results of all these simulations are essentially the same: with the smallest initial concentrations that we have considered *Microcystis* occurs about 20 days later in the year.

Notice that the initial biomass increase in these simulations appears to be rather fast. We will discuss this result in more detail in Chapter 6.

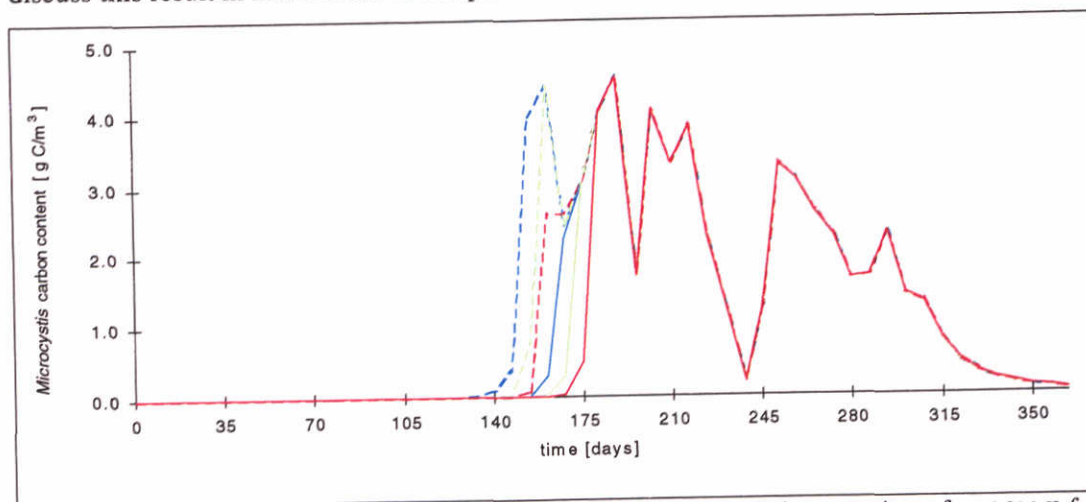


Fig. 5.1. Biomass density of *Microcystis* computed by the stand-alone version of BLOOM II for different constant base levels of initial biomass density without zooplankton grazing. Base levels for initial biomass density were 10 mg dry weight/ m^3 (blue dotted), 1 mg dry weight/ m^3 (green dotted), 0.1 mg dry weight/ m^3 (red dotted), 0.01 mg weight/ m^3 (blue straight), 0.001 mg dry weight/ m^3 (green straight), and 0.0001 mg dry weight/ m^3 (red straight).

5.2 Actual population development (phase 2)

5.2.1 Comparison with Michielsen (1996) and field measurements

The results of the simulations with DBS with the model adjusted as described in chapter 4.3., were compared with the results of the version of DBS calibrated for lake Volkerak-Zoom by Michielsen (1996) to check the impacts of replacing the generic group of BLUEGREENS used during the previous study by two individual species: *Microcystis* and *Aphanizomenon* used during this study. To enable this comparison, we used the original settings of DBS for lake Volkerak-Zoom: a value of the base level for initial biomass density of 10 mg dry weight/m³ and without grazing preference. A comparison of the chlorophyll *a* concentrations computed with the old and with the new settings of DBS is shown in Fig.5.2. There are almost no differences in chlorophyll *a* concentrations. Both computations show a reasonable agreement with the field measurements of chlorophyll *a* concentrations performed by the Institute for Inland Water Management and Waste Water Treatment (RIZA) in Lake Volkerak-Zoom that had been previously used to validate the original settings of DBS by Michielsen (1996).

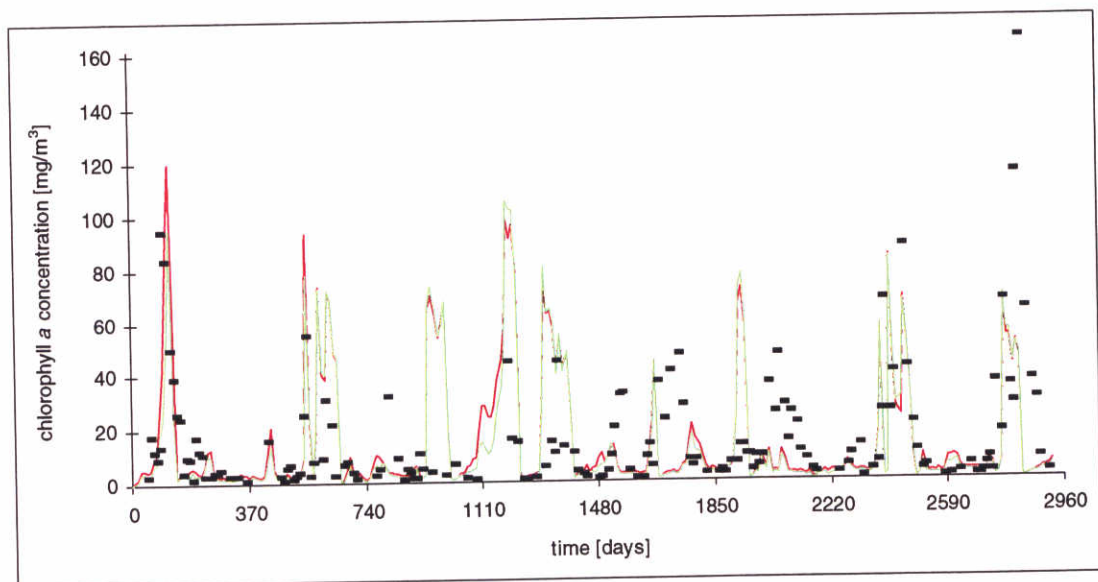


Fig. 5.2. Chlorophyll *a* concentrations in a deep segment in the eastern part of lake Volkerak-Zoom, as computed by DBS with the original settings of Michielsen (1996; red line) and the settings adjusted in this study (green line) for 1988 to 1995. Base level for initial biomass density = 10 mg dry weight/m³; no grazing preference. The black dots represent field measurements of chlorophyll *a* concentrations performed by the Institute for Inland Water Management and Waste Water Treatment (RIZA) in Lake Volkerak-Zoom, used to validate the original settings of DBS by Michielsen (1996).

In Fig 5.3, a comparison between cyanobacterial biomass densities computed by DBS with the version of Michielsen (1996) and with the settings adjusted in this study, is presented. In 1991 and 1993, the peaks in cyanobacterial biomass computed by the adjusted version are much lower than those computed by Michielsen (1996). During the rest of the period, there were hardly any differences between the two simulations.

It has to be noted, however, that both simulations did not succeed in reproducing the trend of increasing cyanobacterial dominance in lake Volkerak-Zoom described by Breukers *et al.* (1996).

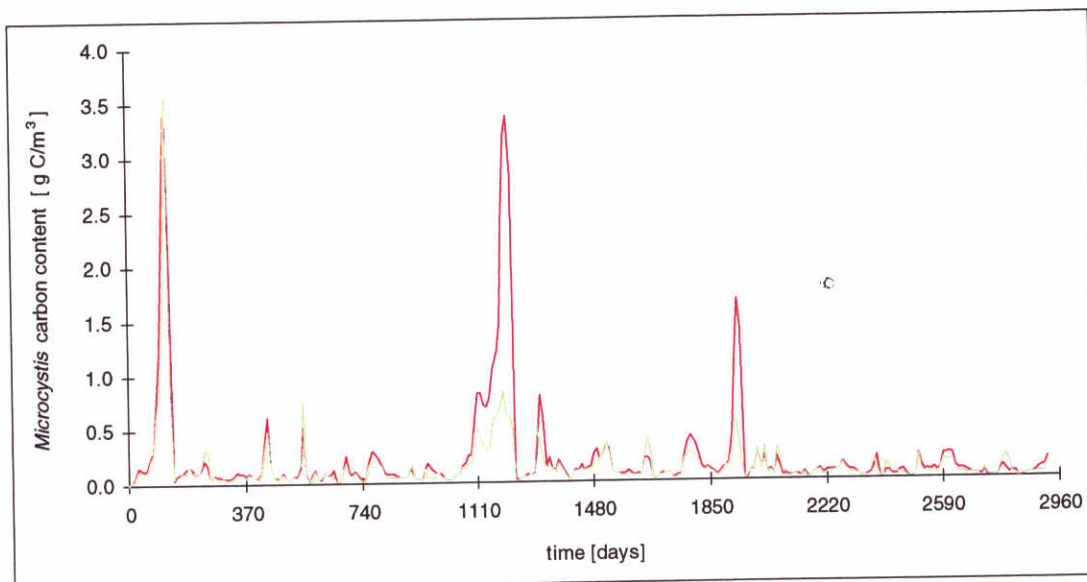


Fig. 5.3. Cyanobacterial biomass concentrations in the eastern part of Lake Volkerak, computed by DBS with the original settings of Michielsen (1996; red line) and the settings adjusted in this study (green line) for 1988 to 1995. Base level for initial biomass density = 10 mg dry weight/m³, no grazing preference

5.2.2 Effects of zooplankton grazing preference

The cyanobacteria *Microcystis* and *Aphanizomenon*, which were explicitly introduced into BLOOM II in the DBS environment calibrated for lake Volkerak-Zoom (chapter 4.3.1.), are most probably exposed to less grazing pressure by the zooplankton than the eukaryotic algae in this system (e.g. Breukers *et al.*, 1996). The grazing preferences of the zooplankton community in lake Volkerak-Zoom were therefore varied as described in chapter 4.3.3. Fig.5.4. shows the results of simulations of biomass density of *Microcystis* in lake Volkerak-Zoom as a result of different zooplankton grazing preferences. Here, zooplankton was assumed to prefer eukaryotic algae above cyanobacteria without further distinction between *Aphanizomenon* and *Microcystis*.

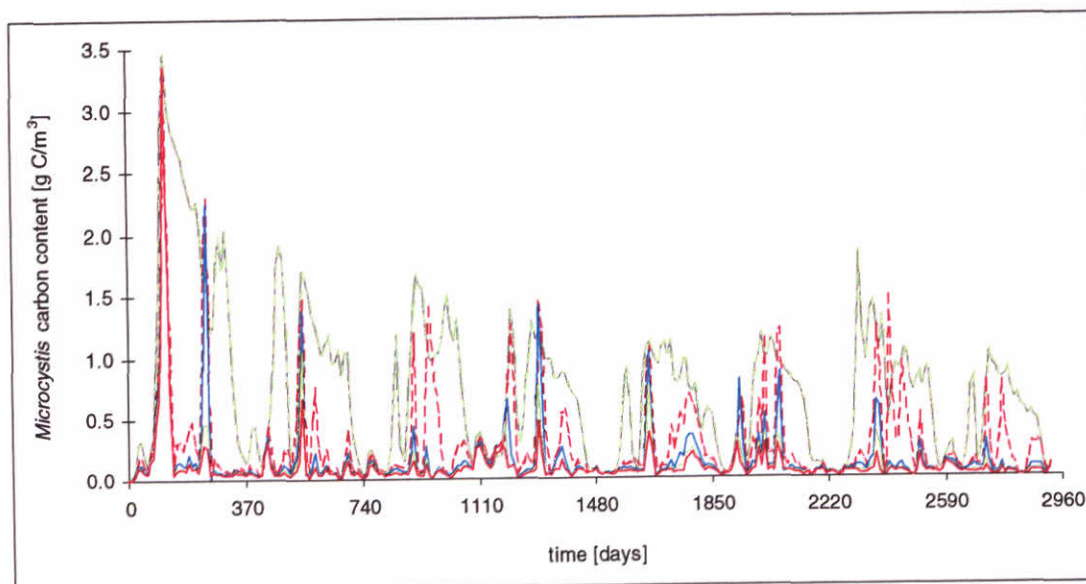


Fig. 5.4. Biomass density of *Microcystis* in the eastern part of Lake Volkerak, computed by DBS for different zooplankton grazing preferences for 1988 to 1995. Base level for initial biomass density = 10 mg dry weight/m³. In all runs, the grazing preference for eukaryotic algae was 1.0 (100%). The grazing preference for cyanobacteria was 1.0 (red straight), 0.9 (green straight), 0.75 (blue straight), 0.5 (red dotted) and 0.0 (green dotted).

In Fig. 5.4., the dependence of the *Microcystis* population in Lake Volkerak-Zoom becomes evident. The less the grazing preference of the zooplankton for cyanobacteria, the higher is the biomass density of *Microcystis*. Comparable results were obtained for *Aphanizomenon* (not shown). The massive, direct effect of zooplankton grazing preference on species composition also became apparent when additional variations in grazing pressure among the two species of cyanobacteria included in the model simulations were applied (not shown): When higher grazing pressure on eukaryotic algae is combined with a relative preference for *Aphanizomenon* among the cyanobacteria, *Microcystis* becomes even more dominant. The same is true for *Aphanizomenon* if *Microcystis* is assumed to be the preferred type of prey among cyanobacteria.

The effect on chlorophyll of a decreasing preference of zooplankton for cyanobacteria is shown in Fig. 5.5. The peak levels are relatively unaffected as these occur when little zooplankton is present. In all other periods chlorophyll levels gradually increase as the preference for cyanobacteria gets smaller due to an increase in the biomass of cyanobacteria.

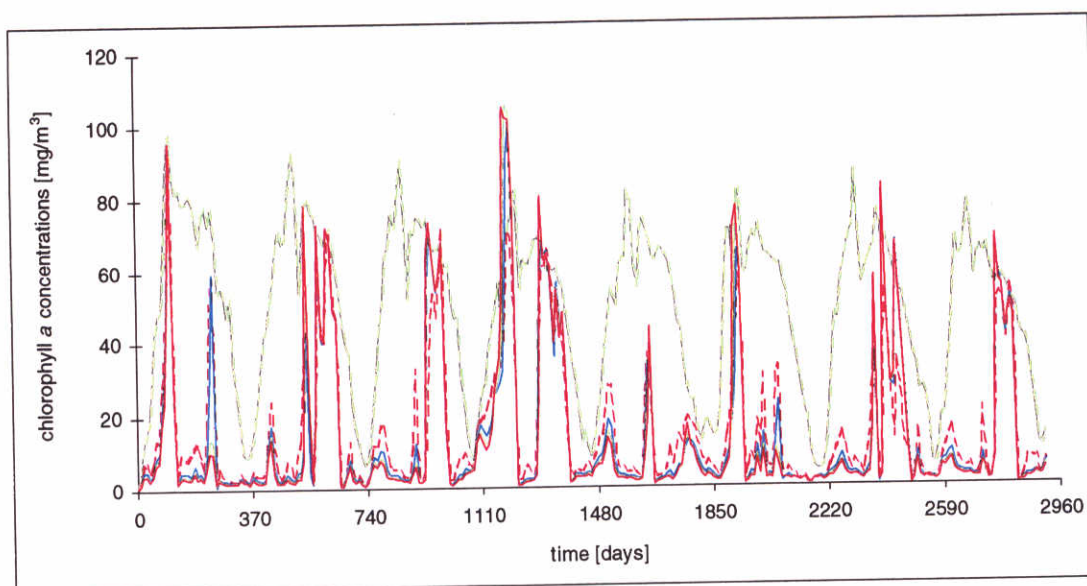


Fig. 5.5. Chlorophyll *a* concentrations in the eastern part of Lake Volkerak computed by DBS for different zooplankton grazing preferences. Base level for initial biomass density = 10 mg dry weight/m³. In all runs, the grazing preference for eukaryotic algae was 1.0 (100%). The grazing preference for cyanobacteria was 1.0 (red straight), 0.9 (green straight), 0.75 (blue straight), 0.5 (red dotted) and 0.0 (green dotted).

In Fig. 5.4. and Fig. 5.5., simulations performed with a base level for initial biomass density of 10 mg dry weight/m³, corresponding with the base level used in the original version of DBS, are presented. These calculations were done prior to adjusting the base level as well in order to test the sensitivity of the outcome of the simulations to variations in grazing preference, independently of changes in the base level. In the following chapters, the results of variations in the base level are presented.

5.2.3 Variations in initial biomass density

The effects of a wide range of base levels, both variable and constant, on the computations of DBS for species composition in general and the development of the *Microcystis* population in lake Volkerak-Zoom in particular, has been tested. In general, the computations of DBS for the biomass densities of the different phytoplankton species in Lake Volkerak-Zoom turned out to be rather independent of the base level for initial biomass density i.e. the size of the inoculum of DBS. For the non-diatom species including *Microcystis*, calculations with different constant base levels did result in some differences for certain years and species. However, the effects were minor. The phytoplankton group that showed the strongest dependence of annual population growth on the base level chosen in DBS were the diatoms (not shown).

Fig. 5.6. shows an example of the influence of the initial biomass density on the computations of the development of the *Microcystis* population in Lake Volkerak-Zoom. The simulations presented here were done with different constant base levels.

The grazing preference of the zooplankton in these examples was chosen to be 1.0 (100%) for eukaryotic algae and 0.75 for cyanobacteria. Comparable results were obtained for variations in the base level of initial biomass density as a fraction of the steady state biomass as well as for other scenarios of grazing preference of the zooplankton (both not shown). Since variations in the base levels of initial biomass density hardly had any effect on population growth of the individual species of the phytoplankton, the computations for chlorophyll *a* concentrations in lake Volkerak-Zoom were not affected by changes in the base level either (not shown).

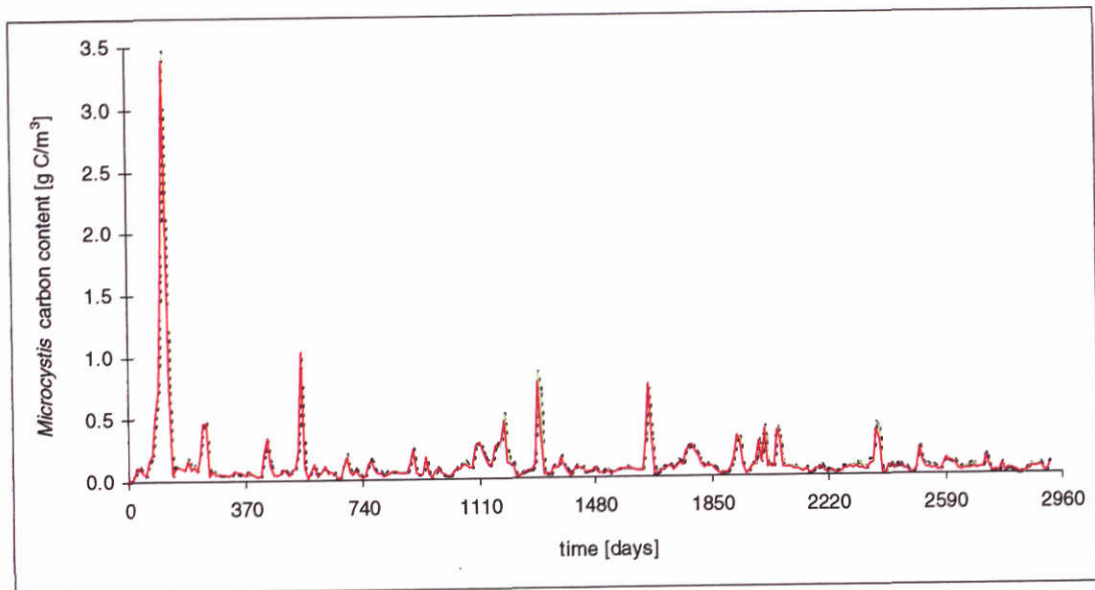


Fig. 5.6. Biomass density of *Microcystis* in the eastern part of Lake Volkerak computed by DBS for different constant base levels of initial biomass density for 1988 tot 1995. In all runs, the grazing preference was 1.0 (100%) for eukaryotic algae and 0.75 for cyanobacteria. Base level for initial biomass density were 10 mg dry weight/m³ (red straight), 0.1 mg dry weight/m³ (red dotted), 0.001 mg dry weight/m³ (blue straight), and 0.000001 mg dry weight/m³ (green straight).

6 Discussion

The study that we have performed is limited in scope. It is essentially a technical study to investigate whether a new management tactic to reduce the possible blooms of *Microcystis* seems promising using an existing mathematical model and an existing set-up for a specific lake. The time for literature research was very limited, but as some model results may seem counter intuitive at first sight, we will try to clarify these.

6.1 Potential versus actual growth rate

Microcystis has a reputation as a slow growing species because large changes in biomass are not frequently observed. The first question that we want to address is whether it deserves this reputation. Under laboratory conditions cyanobacteria, including single cells of *Microcystis*, achieve maximum growth rates in the order of 0.8 day^{-1} . Maximum growth rates of eukaryotic species are often in the range of 1.0 to 1.5 day^{-1} , which of course is a higher value, but the difference is not spectacular. In addition cyanobacteria have lower respiration rates and require less light. So the differences in net growth rates is even smaller.

We have used BLOOM II in its most simple form as a mono-specific model to investigate the potential growth rates of *Microcystis* under the prevailing abiotic conditions of Lake Volkerak - Zoom. We concluded that specific rates of increase in the order of 0.15 to 0.25 day^{-1} are possible. This implies that it can grow at about 25 to 30 percent of its maximum growth rate. This in our experience is quite a normal value under typical summer conditions. The main limiting factor is light, which is due to self-shading. So potentially *Microcystis* may not be among the fastest growing species of phytoplankton, but with a net rate of increase of about 0.2 day^{-1} , its biomass could still increase at a tremendous rate by a factor of 67 in 3 weeks, a factor of 400 in a month, a factor of 200.000 in two months etc.

There are a number of reasons why these rapid biomass explosions are infrequently observed:

- Trivial but true: it is difficult to monitor *Microcystis* accurately due to buoyancy regulation and colony formation.
- Regular sampling only takes place at two to four weekly intervals, which is too long to observe rapid changes in biomass should they occur.
- As *Microcystis* can only achieve high growth rates when the temperatures exceed 15 degrees centigrade, it is one of the last species that can start growing in a natural lake in the temperate regions. Hence it always has to compete with an existing community for possibly limiting resources and it has to wait for cells of those other species to die, for bacteria to mineralise the detritus etc.
- Its dependence on high temperatures delimits its growing season considerably, particularly in "bad" summers, which are moreover dominated by windy conditions hampering the benefits of its buoyancy regulation.

- Estimates of true in situ growth rates show larger differences between eukaryotic and prokaryotic species with the prokaryotic species falling behind. So perhaps the basic model input data for the growth rates of *Microcystis* are not representative for its in situ growth potential especially not when it is present in the form of colonies.

As an additional illustration we will now show some twenty years old results from the former drinking water storage reservoir Grote Rug near Dordrecht (Fig. 6.1). This reservoir was fed by Rhine water. The data were collected weekly and analysed thoroughly by the former National Drinking Water Institute under the responsibility of dr. J. v.d. Vlugt. The regular program included a conscientious estimation of phytoplankton species volumes using microscopic counting. Samples were collected at three depths and averaged later. The total number of cells that were counted was unusually high for this type of monitoring.

In both 1976 and 1977 a very large bloom of *Microcystis* was observed with maximum chlorophyll levels of over 200 mg/m³ in one of the basins (Fig. 6.1). From these data we draw the following conclusions:

- At the beginning of the growing season *Microcystis* grows rapidly. It achieves growth rates similar those computed by DBS.
- Considerable biomass fluctuations are observed. These correspond with growth rates of up to 0.25 day⁻¹ during periods of one or two weeks and of 0.15 day⁻¹ for over a month.
- *Microcystis* is not confined to the period of August and September; not only can it survive, but it can also increase in biomass even at the end of October.
- Zooplankton and algal biomass, including *Microcystis*, are negatively correlated in a very convincingly way.

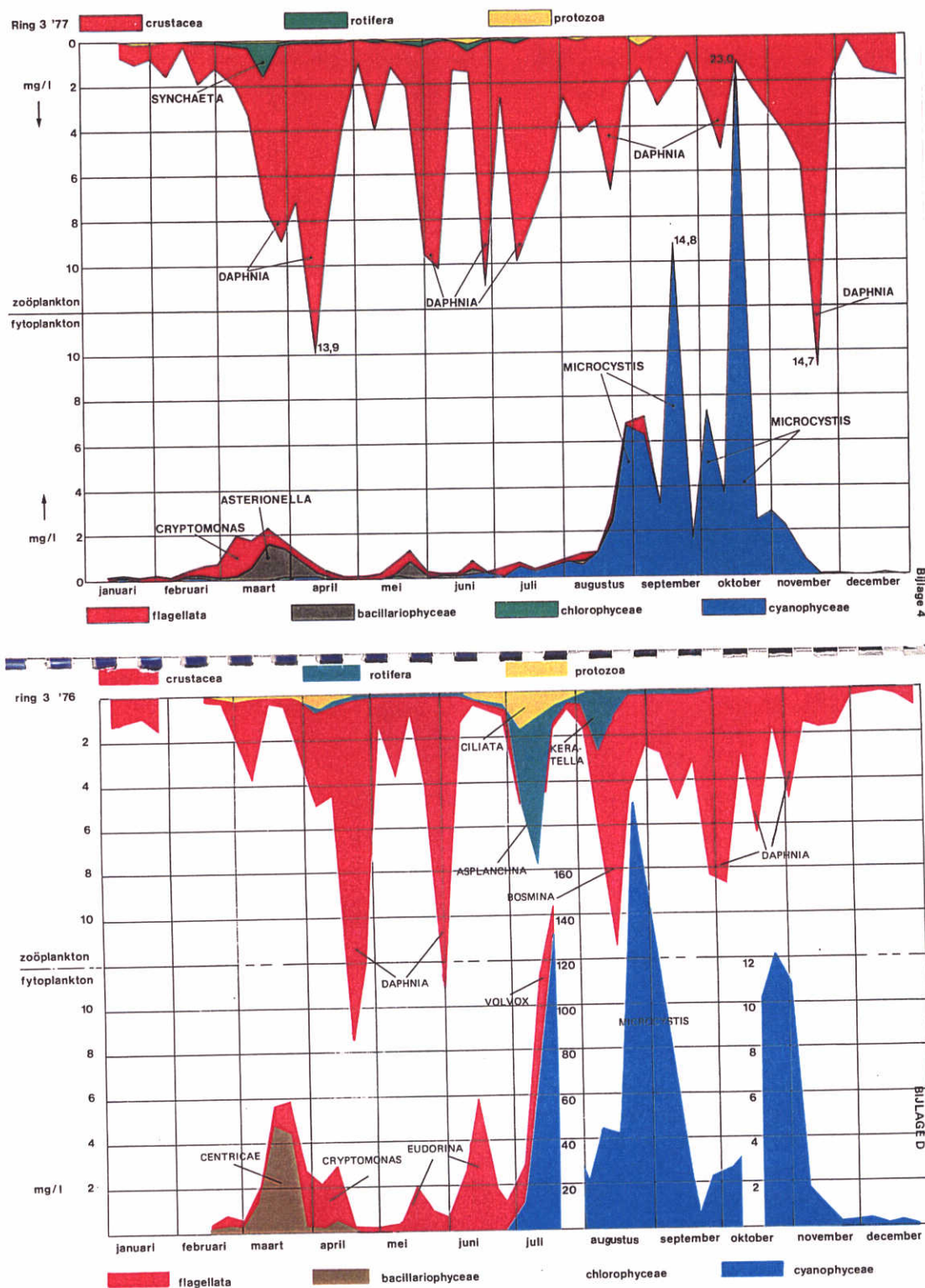


Fig. 6.1. Wet weight of phytoplankton (mg/m^3) in 1976 and 1977 in one of the basins of the former drinking water reservoir Grote Rug near Dordrecht. Data copied from annual reports of the former National Institute for Drinking Water. Samples collected at three depths are averaged.

6.2 The importance of zooplankton

Bases upon our modelling results there is evidence that grazing by zooplankton is the main biomass controlling factor in Lake Volkerak - Zoom (see also Michielsen et al., 1996). The results of DBS are sensitive to specific assumptions related to grazing such as the abundance of zooplankton, its filtration rate and its preference, if any, for particular sources of food. Grazing has the following direct and indirect impacts which are relevant here:

- The total phytoplankton biomass is reduced.
- As a side-effect the extinction of the water is increased. This means that the growth rate off *all* species is increased. Consequently it is easier for species just starting to grow to outcompete the existing dominant species than in the more turbid situation without grazing. However, due to differences in light response, an increase in the amount of available light is more favourable to eukaryotic species than to cyanobacteria.
- If there is any kind of preference, the competition between different species is directly affected.

Notice that zooplankton also changes the partitioning of nutrients among various available and unavailable forms, but this is not very important in Lake Volkerak - Zoom as nutrients are infrequently limiting for phytoplankton.

We have varied several model inputs to investigate its sensitivity to grazing.

7 Summary and Conclusions

From the simulations reported here we have reached the following conclusions:

- The *potential* biomass level of all species, including *Microcystis*, in Lake Volkerak - Zoom clearly exceed the measurements. According to the results of BLOOM II summer chlorophyll *a* levels of 50 to 100 mg/m³ could be supported under the prevailing abiotic conditions.
- A (strong) decrease in the base-level of *Microcystis* i.e. a decrease in the size of the inoculum, affects the onset, not the summer level or peak values of the BLOOM II results. With the lowest value considered (0.00001 mg dry weight per m³) the delay in the onset of the bloom is about three weeks. This result is basically the same in each year considered regardless of depth, which was varied during a sensitivity analysis (results not shown here).
- For the species definition of DBS the generic group "BLUE GREENS" was replaced by two individual cyanobacterial species: *Aphanizomenon* and *Microcystis*. With these new species, the results in terms of chlorophyll *a*, nutrients and extinction are comparable to those obtained previously for Lake Volkerak - Zoom (Michielsen, 1996).
- DBS considers grazing and competition as the most important factors ignored by the BLOOM II computations. In this model the effect of changes in initial values is even smaller than in the stand-alone version of BLOOM II, which is because in BLOOM II the initial biomass increase starts earlier under less favourable conditions.
- The results of DBS in terms of biomass and species composition are sensitive to the grazing pressure by zooplankton. The total biomass is reduced quite strongly with observed zooplankton levels, the species composition is sensitive to the preference assumptions for different species of algae. A (moderate) reduction in preference for cyanobacteria from 1.0 to 0.75 results in a clear shift in dominance from green algae to cyanobacteria.

With respect to the aim of this study we reach the following conclusion:

- From an aut-ecological perspective there is little doubt that *Microcystis* has the ability to overcome the impacts of harvesting. Regardless of the initial value (inoculum) it can maintain a sufficiently high growth rate for a sufficiently long period of time to achieve a steady state level limited by some nutrient or (more likely) light. This is because the power term of the exponential growth equation always gets "inifinite" in about 30 days after *Microcystis* starts growing.
- Hence it is not possible to define a lower limit for the *Microcystis* inoculum to prevent its possible blooming in the model representation of Lake Volkerak - Zoom assuming it cannot be eliminated completely by any management measure.

For *Microcystis* as part of the entire Lake Volkerak - Zoom ecosystem we cannot be as conclusive as several factors, that seem to be important, are not very well known in a quantitative, predictive way:

- The simulated variables of DBS as applied to Lake Volkerak - Zoom do not agree equally well with the actual observations as for other lakes to which the model was (recently) applied such as Lake IJssel, Lake Marken or the Loosdrecht lakes.
- These (and other) lakes are much more strongly controlled by abiotic factors. So far in Lake Volkerak - Zoom the top - down control due to grazing by zooplankton is the most important phytoplankton controlling factor .
- Other potentially important factors such as buoyancy regulation of cyanobacteria cannot be quantified adequately by the present generation of mathematical models including DBS. To this purpose it is necessary to adopt new modelling approaches in which physiological factors are integrated with state of the art turbulence models.

So we conclude that there are still a number of uncertainties that make it difficult to fully explain the competition between phytoplankton species in Lake Volkerak - Zoom. Changing the size of the inoculum is one way to manipulate the competition to a certain extent, but affecting grazing is perhaps even more important. It is, however, impossible to quantify all these effects more accurately within the limited scope of this project.

To enable a more solid, quantitative analysis we have the following recommendations:

- Investigate whether indeed the in-situ growth rates of *Microcystis* are significantly lower than the growth rates obtained from continuous cultures,
- To this purpose it is necessary to intensify the monitoring program of Lake Volkerak Zoom in order to collect enough samples during a relatively short period of time,
- Monitor the grazing pressure by zooplankton and mussels as a function of time for both eukaryotic species and for cyanobacteria,
- Perform an integrated research program of physical (i.e. turbulence) and biological factors affecting the growth of *Microcystis* with particular emphasis on its ability for buoyancy regulation and scum formation,
- Quantify the importance of the size of the inoculum relative to other sources of *Microcystis* such as import,
- As a result of the previous recommendations, change the model set-up of DBS for Lake Volkerak - Zoom in terms of formulations and/or coefficients in order to improve its ability to describe the observations.

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