ACTA HYDROBIOL.	29	2	149—191	KRAKÓW 1987

Ecological aspects of the mass appearance of planktonic algae in dam reservoirs of southern Poland

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Manuscript submitted September 9, 1986, accepted January 20, 1987

Abstract — A synthesis of studies on the mass appearances of planktonic algae was made, based on the author's own results and the publications of other authors. Single-species water blooms were distinctive in the first years following the flooding of reservoirs but usually mixed ones later. Their appearance depended chiefly on nutrient concentrations and also on the time of water retention and the age of the reservoir. *Microcystis aeruginosa* was the commonest species of blue-green alga forming water blooms. An increase in the numbers of chlorococcous algae was also found.

Key words: dam reservoirs, planktonic algae, "water blooms".

1. Introduction

The mass occurrence of some species of planktonic algae in different bodies of water has for a long time excited the interest of many authors. The complexity of the processes accompanying these appearances inclined investigators to make thorough laboratory and field observations in order to identify the factors governing these phenomena. Their investigations took into consideration various aspects, particularly strongly stressed in the recent years of increasing hazard to surface waters, frequently overexploited and uneconomically used.

In work of this kind carried out in Poland, among the problems addressed was the pollution of water resulting from the mass development of algae and their influence on its quality (Jankowski 1973), or the effect of a suitable or unfavourable structure of the biocenoses of phyto- and zooplankton developing in ponds used for fish production (Grygierek et al. 1976). In turn, in other studies (Sosnowska 1976a, 1976b, 1977) attention was drawn to the abundant occurrence of mainly planktonic blue-green algae, stressing their adverse effect on fish, and to the conditions giving rise to water blooms, and the methods of eliminating them and preventing their formation. The results of these studies indicated among other things that the activity of algicides (such as copper sulphate) destroying the water blooms, is usually greater at higher temperatures, declining with their frequent use, this being connected with the ability of the algae to become resistant to them (Spodniewska 1971). The method of removing a large algal mass by biological means, described in the paper by Sosnowska (1977), advocated the acclimatization in Poland of Asian planktivorous fish (mainly the grass carp), feeding on nannoplanktonic green algae. Much earlier, Kulmatycki (1934) had presented his comments on "water blooms" in carp ponds, in which the exchange and movement of water are a factor making their formation impossible. Hence the use of mechanical mixers, as recommended by him, was more advisable than that of harmful chemicals.

The problem of the formation of water blooms and their counteraction was investigated in detail by Czech researchers (Štěpánek, Zelinka 1961, Fuksa 1963, Štěpánek et al. 1963, Švec, Krčma 1963). Their publications made familiar the methods of applying algicides to destroy algae, mainly blue-green ones, in mains supply reservoirs and those used for recreational purposes, in Czechoslovakia.

In East Germany in the 1980's, biomanipulation was used (e.g. in the hypertrophic Bautzen Reservoir), giving in effect a considerable decrease in biomass of the phytoplankton (Benndorf et al. 1981). This method consisted in introducing into the reservoir various species of carnivorous fish (pike and pikeperch) in order to reduce the large numbers of small perch feeding on the zooplankton. A wide range of uses has also been found for the method of biological elimination of P in "pre-dam" reservoirs. This consists in the incorporation of phosphates into the biomass of phytoplankton and the sedimentation of algae in such reservoirs, resulting in a marked improvement in water quality. For example, in the previously eutrophic Wahnbach Reservoir, W. Germany, the blue-green algae previously forming dense water blooms receded or completely disappeared (Bernhardt, Clasen 1981).

To date, the greatest amount of information given in various review papers has concerned planktonic blue-green algae, causing frequent water blooms (Siemińska 1952, 1953, Horne, Fogg 1970, Spodniewska, 1971, Horne et al. 1972, Romstad, Skulberg 1972, Reynolds, Walsby 1975, Skulberg 1978, Østensvik et al. 1981), and to a smaller extent other algae of the remaining systematic groups (Spodniewska 1974, Lund et al. 1975).

The main purpose of the present work was to summarize the existing data on the mass occurrence of planktonic algae in dam reservoirs in southern Poland, primarily on the basis of results from the author's own publications (Bucka 1965, Bombówna, Bucka 1974, Bucka 1985, 1986) and earlier papers by other authors (Siemińska 1952, Szklarczyk 1956, Biernacka 1959, 1963). It should be stressed that the author's own papers, which formed part of collective studies carried out over many years by the Institute of Freshwater Biology of the Polish Academy of Sciences in Kraków were not directed specifically to the tracing of "water blooms". They were carried out as a sideline during studies on the dynamics of the development of the whole phytoplankton carried out over a period of one or more years, at great time intervals. The earlier investigations of other authors in the same reservoirs were of similar character, even in the case of the Goczałkowice Reservoir, where the continuity was maintained from 1955 to 1982 (Krzyżanek et al. 1986, Pająk 1986).

Though the above observations on mass appearances of planktonic algae were incidental, the compilation of all this varied information in one review seemed worth while since it will be more readily accessible to readers interested in the problem. Moreover, comparing the author's own results with those of other authors may help to elucidate the reasons for the excessive development of these algae, governed by the configuration of various environmental factors. Also of importance are the various comments of other authors, concerning the ecology of several blue-green planktonic algae, and especially those forming frequent water blooms. These data, which are often the result of many years of investigation, will broaden our knowledge of these specific species of algae.

A further purpose for which the preparation of this review was undertaken was to fill a certain gap encountered in interpreting the phenomenon of water blooms. Moreover, the present review may be of some assistance to other algologists, especially applied algologists, in their attempts to solve the difficult problem of water blooms in dam reservoirs which have been functioning for many years, or in newly established ones. The excessive development of algae, often leading to "water blooms", is an unwanted phenomenon especially in reservoirs of drinking water. Yet without the participation of algae, no processes of water self-purification could take place (Štěpánek et al. 1963).

2. Study area

The shortage of water resources in Poland necessitates the construction of dam reservoirs of large capacity (Tuszko 1982). These increase the discharge in rivers fed with their water, which is of considerable importance when they are in flood. Tuszko (1982) stresses that in these brief periods great amounts of river water escape to the sea and are not utilized. Hence dam reservoirs fulfil a variety of roles, for example, some acts at the same time for flood control and retention, storing water and preventing natural disasters. This water is also used by the energy industries, it is a valuable resource for industry and agriculture, and above all it feeds waterworks, meeting the population's need for water, hence requiring a high degree of purity to be maintained. Dam reservoirs are also utilized for sailing, for other recreational purposes, and in commercial fishing. They constitute a specific aquatic environment, creating conditions suitable for the development of various aquatic organisms, including planktonic algae. They differ from lakes in the asymetry of their basins which in longitudinal section are more or less triangular in shape and hence are deepest at the dam, and shallow at the inflow (Starmach 1958, 1969). According to that author, they may have a riverine or lacustrine character, depending on the size of the reservoir and the inflow, this being connected with the rate of water exchange. Starmach (1958) therefore distinguished two types of re-

Table I. Some features of the dam reservoirs of southern Poland according to Wróbel (1969) and Tuszko (1982) with division into 2 types (l - limnic; r - rheolimnic) according to Starmach (1958) and characteristics of the investigation of phytoplankton. Methods of investigation: a - assessment; b-f - quantitative; b - one - to four-week; c - twice yearly; d - seasonal yearly; e - seasonal for several years; f - continuous for many years

Dam reservoir: years of investigation / Author, year of publication	Methods of investigation	River	Altitude m	Year of filling	Area of: catchment basin km^2	Area of: inundation km^2	Capacity $10^6 m^3$	Depth: maximum m	Depth: mean m	Retention time in days	Type of dam reservoir
Goczałkowice: 1955-1982		Wisła	256	1955	532	32.0	163	10-13	5.2	190	l
Rumek 1957, Starmach 1957,1961 after Krzyżanek et al., 1986	f										
Bombówna, Bucka, 1974	c										
Pająk, 1986	e										
Tresna: 1967, 1968-1969		Soła	346	1966	1030	10.0	107	20-24	9.0	60	l
Bombówna, Bucka, 1974	c										
Kyselowa, Krzeczkowska-Wołoszyn, 1974	d										
Porąbka: 1967, 1968-1969		Soła	322	1936	1089	3.67	28	12-18	7.4	30	r
Bombówna, Bucka, 1974	c										
Kyselowa, Krzeczkowska-Wołoszyn, 1974	d										
Czaniec: 1968-1969											
Kyselowa, Krzeczkowska-Wołoszyn, 1974	d	Soła	320	1966	1130	0.45	1.3	5-6	3.1	2	r
Rożnów: 1943, 1946-1949, 1957, 1958, 1963-1964, 1982-1983		Dunajec	350	1941	4883	16.0	184	25-28	11.5	32	r
Olszewski, 1946	a										
Siemińska, 1952	a e										
Biernacka, 1959	a b										
Biernacka, 1963	b										
Bucka, 1965	a d										
Bucka, 1986	d										
Czchów: 1963-1964											
Bucka, 1965	a d	Dunajec	320	1949	5335	3.46	12	7-8	3.5	2	r
Kozłowa Góra: 1951-1953, 1976-1979											
Szklarczyk, 1956	a	Brynica	180	1939	184	4.62	18	ca 5	ca 3	72	l
Bucka, 1985	e										

servoir: limnic — with a low throughflow, with an exchange of water roughly every 2—6 months, and rheolimnic — throughflow, with a frequent water exchange, more than 10 times a year. The former, with a developed littoral zone, has the character of a lake or pond, depending on its size and depth, while the latter also has the features of a lake, but lacks littoral vegetation. It has a deep zone which begins right at the banks.

The present paper has been based on investigations of phytoplankton carried out in various years in the seven dam reservoirs presented in Table I. It gives after Wróbel (1969) and Tuszko (1982) the characteristics of phytoplankton studies and some more important features of these reservoirs, with their division into two types.

The Goczałkowice Reservoir, impounded at the 67th kilometre of the River Vistula, lies at the entrance to the Oświęcim-Racibórz Valley. It has a concrete dam with a bottom outlet. It is also fed by a small, left-side tributary, the Bajerka. It is a storage reservoir for the Upper Vistula and was the first large shallow lowland one (length 12 km, width 5 km) supplying drinking water to the Upper Silesian Industrial Region. Water taken by the waterworks constitutes over 80% of that running into the reservoir. Water exchange takes places 2—4 times a year. In connection with the carrying out of repair work, the reservoir was drained and refilled in 1965, 1972, and 1978 (Krzyżanek et al. 1986). This caused the formation of shallows and the exposure of large areas of the reservoir bed, rapidly colonized by macrophytes — which also recurs in periods of drought and increased water consumption.

The "cascade" of reservoirs on the River Soła was formed by building three dams — in Porąbka (a concrete dam with 5 spillways), in Tresna (earthen and boulder dam, with a clay core) and in Czaniec (earthen dam) (Tuszko 1982). According to that author, of the Carpathian affluents of the Vistula, the Rives Soła is among those which are very dangerous during floods, owing to the large scale of fluctuation in its discharge. The construction of several dam reservoirs on one river was to make possible their cooperation in equalizing the discharges of the Upper Vistula. The purpose of building the cascade, besides flood protection was to supply water to the Silesian-Dąbrowa Industrial Region and to two hydroelectric power stations, in Tresna and Porąbka. The third reservoir in Czaniec has the role of an equalizing reservoir for the power station at Porąbka, and when necessary supplements any shortage in water supplies for the inhabitants of the Upper Silesian Industrial Region. According to the data of Tuszko (1982), the cascade construction on the Soła increased the minimum discharge of this river ninefold, i.e. to 9.1 m^3 sec^{-1} thus ensuring its uninterrupted and varied utilization.

In connection with the cascade on the River Soła, fed by an affluent of the River Koszarawa, a municipal waterworks was built in Żywiec, and a sewerage system with sewage treatment plants (including several treating industrial wastes for various factories), this greatly helping to protect and improve the quality of the water of the reservoir in Tresna, with its affluents, the Rivers Żylica and Łękawka.

The Rożnów Reservoir was built on the River Dunajec with large water resources, one of the most beautiful, but also one of the most dangerous of montane rivers when in flood. It has a concrete dam, equipped with spillways and bottom outlets. It was constructed on layers of sandstone with an admixture of shales (Tuszko 1982). This is a deep, submontane reservoir of the trough type, the longest of those studied (the shoreline is 56 km long). When filled to capacity it reaches 20 km in length, with a width varying from 300 to 1500 m (Siemińska 1965). At low water levels only the backwaters of the reservoir are periodically exposed. The banks of the middle part of the reservoir border on arable fields and patches of mixed woodland and those near the dam on a steep, forested slope and a road. The reservoir feeds a hydroelectric power station built into the body of the dam.

The Czchów Reservoir, situated on the Dunajec, with an earthen dam, was constructed on layers of clay shales below which lie sandstones (Tuszko 1982). This is a shallow submontane reservoir 9 km in length with an inflowing clean stream, the Łososina, fed by water of the Rożnów Reservoir, brought in with the River Dunajec. A hydroelectric power station is also part of this reservoir. Above both reservoirs the River Dunajec receives a large load of sewage from Nowy Sącz, which is directly released into it and its affluent, the Kamienica Nawojowska, whose mouth lies within this town. The task of both reservoirs is to reduce the flood surge on the Dunajec and the Upper Vistula, and to increase the low discharge downriver in order to meet the water requirements of the population and of industry.

The Kozłowa Góra Reservoir was built on the River Brynica (middle course), a right-bank tributary of the River Przemsza falling into the Vistula. It has an earthen dam and a side embankment from the western side. The bottom of he valley of the River Brynica is sandy, with a layer of peat and soils (podsols and rendzinas). In the whole catchment area forest areas prevail (coniferous forests with an admixture of broadleaved) and arable land. The flood plain is covered by meadows, peat bogs, and cleared forest. This is a shallow reservoir for mains water supply purposes, and also used for angling. Almost all the incoming water is transferred to the waterworks. A complete exchange of water takes place every 2—3 months, and in the spring and autumn it is thoroughly mixed by the wind. As a result, shallows 1—1.5 m deep are formed, covering about 30% of the area of the reservoir surface and overgrown by macrophytes. Large patches of the bottom (usually sandy-silt) are also uncovered then and exposed to the effects of the ambient atmosphere. This reservoir lies in the Upper Silesian Industrial Region, close to large urban agglomerations and foundries of heavy metals (zinc, lead, cadmium) emitting into the atmosphere large quantities of dusts, rich in these metals and sulphides, and acidifying local soils and water. Rain-water run-off and small amounts of farm and domestic sewage also have a polluting and eutrophicating effect on the catchment area (Zięba 1985).

3. Material and methods

3.1. Determination of "water blooms"

In Poland Kulmatycki (1934), referring to an earlier paper of his from 1925, mentioned a "red bloom of the water" in lakes of Pomerania and East Prussia (Lake Ciche), caused by a mass appearance of *Oscillatoria rubescens* D.C. On the basis of a cited paper by Srokowski (1930), he also listed Masurian lakes (e.g. Lake Dolne and Lake Śniardwy) which in the late autumn and early spring at the turn of 1920 became covered with immense "brick-red and bright crimson" stains, caused by *Euglena sanguinea.*

An interesting description of the phenomenon of "water blooms" was given by Vallentyne (1974) in which he compared them to a dust bowl ("algal bowl — dust bowl"), explaining that this is connected with the Great Plains of the Mississipi, visited by dust storms several times in the 1930's. Both these bowls were formed through the inappropriate use of, in the first case water, and in the latter soil.

According to Reynolds and Walsby (1975), "water-blooms" are a widespread phenomenon, described in the literature by various synonyms. They quote such authors as Whipple (1899), who gave: "flowering of the waters" "Wasserblüthe" and „flos aquae", and Topachevskii (1968), "tsvyetyeniye vody". At the same time, those authors (Reynolds and Walsby) mentioned after Griffiths (1939) that the oldest record in Britain relating to water blooms comes from the 12th century (Lake Llangorse, north Breconshire). They also reminded the reader that the red-brown colouring of the surface of Lake Murtensee in Switzerland is now known to result from the mass occurrence of the blue-green alga *Oscillatoria rubescens* D.C. ex. Gom.

According to Reynolds and Walsby (1975), a water bloom caused by the appearance of a dense algal population is the outcome of fertilization of a given lake or other body of water owing to the input of various forms of pollution (sewage, agricultural run-off etc., as sources of phosphorus and nitrogen). The above definition applies particularly to planktonic blue-green algae, which gather in profusion on the water surface.

3.2. Criteria of assessing water blooms

3.2.1. In the studies of various authors

The initial criteria of quantitative assessments of phytoplankton were approximate. The abundance of species was described verbally (frequent, numerous, etc.) without giving their numerical value (Olszewski 1946). Hence, the present review, in some cases referring to earlier algological works, has been limited to specifying the names of various algal species considered by the given author to form water blooms. This was because it was impossible to compare the quantitative development of some species recorded in masses in the author's own studies with those reported by other authors who used different methods for assessing the quantity of phytoplankton (generally surface phytoplankton). This was usually an estimated scale adopted by the given author according to his own subjective appraisal, using the "+" sign (Biernacka 1959), and a six-grade scale of the frequency of the occurrence of algae, given by Starmach (1955) and used by Szklarczyk (1956). Moreover, some authors used two methods simultaneously, that of estimation and a quantitative one, and at times only one of them (Siemińska 1952). Additional difficulties were also connected with the fact that some people (Biernacka 1963) and later Krzyżanek et al. (1986) gave much smaller numbers for species causing water blooms than is the generally accepted criterion used for the mass appearance of algae.

In general, it can be said that with the development of studies on plankton there has been an improvement in the methods of study and the quantitative assessment of phytoplankton has been introduced.

Accordingly, Starmach (1955) and Starmach et al. (1976), in speaking of water blooms in eutrophic reservoirs, gave the number 10^4 algal cells per cm^3 of water, and in very fertile ponds 10^5—10^6 cells cm^{-3}. He used the term "bloom" for such a colouring of the water that results from a mass appearance of algae; this is visually discernible when the number of cells per cm^3 of water amounts to 10^3 and, as the bloom becomes stronger, it may even reach a quantity of 10^7. Towever, according to Turoboyski (1979), both the number $5 \cdot 10^2$ or 10^3 individuals of algae in one cm^3 of water is not always a sign of the onset of a water bloom. This is determined by the size of the given algal species which, at a greater size but smaller numbers than the values given above, may cause a bloom much more dangerous in result with respect to the usefulness of the water than in the case of more numerous but very small algal cells.

According to Sosnowska (1976a), the term "water bloom" has not to date been precisely defined. The author links it with the excessixe and rapid development of some planktonic algae, especially blue-green ones, in reservoirs of stagnant water, leading to changes in the water colouring. This is a qualitative assessment and only when the number $5 \cdot 10^2$ of individuals of algae per cm^3 of water is assumed can they be described quantitatively but, in her opinion, inadequately, owing to the wide size range of the cells of the planktonic algae. Thus, Sosnowska (1976a) drew attention to the current method of assessing them which is in increasingly common use, namely in terms of biomass calculated on the basis of numbers or the volume of the thallus of the given algal species.

According to the data of Pavoni (1963), Mikheeva (1969), and others (cit. Spodniewska 1974) the maximum value of wet weight, typical of a mass appearance of phytoplankton in a eutrophic lake, fluctuates from 7—10 mg dm^{-3}, while in very fertile lakes and dam reservoirs it may occasionally amount to $10^2 - 5 \cdot 10^2$ mg dm^{-3}. According to Pavoni, a biomass of 10 mg dm^{-3} is the lowest value assumed for water blooms.

Spodniewska (1974) also gave the mean values of wet weight (from 10 to 30 mg dm^{-3}, recorded in the epilimnion of Lake Mikołajskie in the summer (from 1963 to 1970) and dependent on water blooms caused by large dinoflagellates, *Ceratium hirundinella* (O.F.M.) Bergh., with a concurrent dominance of blue-green algae (with the participation of large colonies of *Gloeotrichia echinulata* (J. S. Smith) Richt., *Aphanizomenon flos aquae* (L.) Ralfs., and others.

Barica (1981) quotes after Hammer (1970), a precise description of water blooms, which corresponds to 0.5 mg of their mass per dm^3 of water. In addition he also gave other values typical of blooms, i.e. 50 μg dm^{-3} of chlorophyll "a" and a water transparency of 1m, measured with the Secchi disc.

Other authors (Kyselowa, Krzeczkowska-Wołoszyn 1974), besides algal numbers, gave also the area of their vertical projections, which to a certain extent were to replace calculations of biomass. The area of a vertical projection of an algal thallus is easy to measure, by referring it to a known area of the grid placed in the eyepiece of a microscope and multiplying it by an assumed factor of 2. The summed area of the vertical projection of the algal cells (given in μm^2 cm^{-3}, mm^2 cm^{-3}, or dm^{-3} of water) depends on the quantity and the relative proportion of dominating species of various size, which bear on the intensity of the water blooms in the reservoir. This method was elaborated by Starmach (Bombówna, Bucka 1974 after Starmach 1969). It has not, so far, been popular in studies of phytoplankton, though it is less time-consuming than calculations of biomass based on the numbers and volume of the thalli of given algal species, likened to various geometrical figures. Such an assessment of biomass is highly subjective, owing to the individual approach of authors to the choice of geometrical figures with respect to the shape of the algae encountered.

It is evident from this review that at present there are several ways of assessing both the numbers and biomass of planktonic algae. Hence the results of the studies of different authors are difficult to compare and often require additional calculation before they can be used, as was pointed out by Spodniewska (1974). According to her, this is not only a matter of using different methods but also of presenting the results in different units (per unit volume, unit of water surface, etc.).

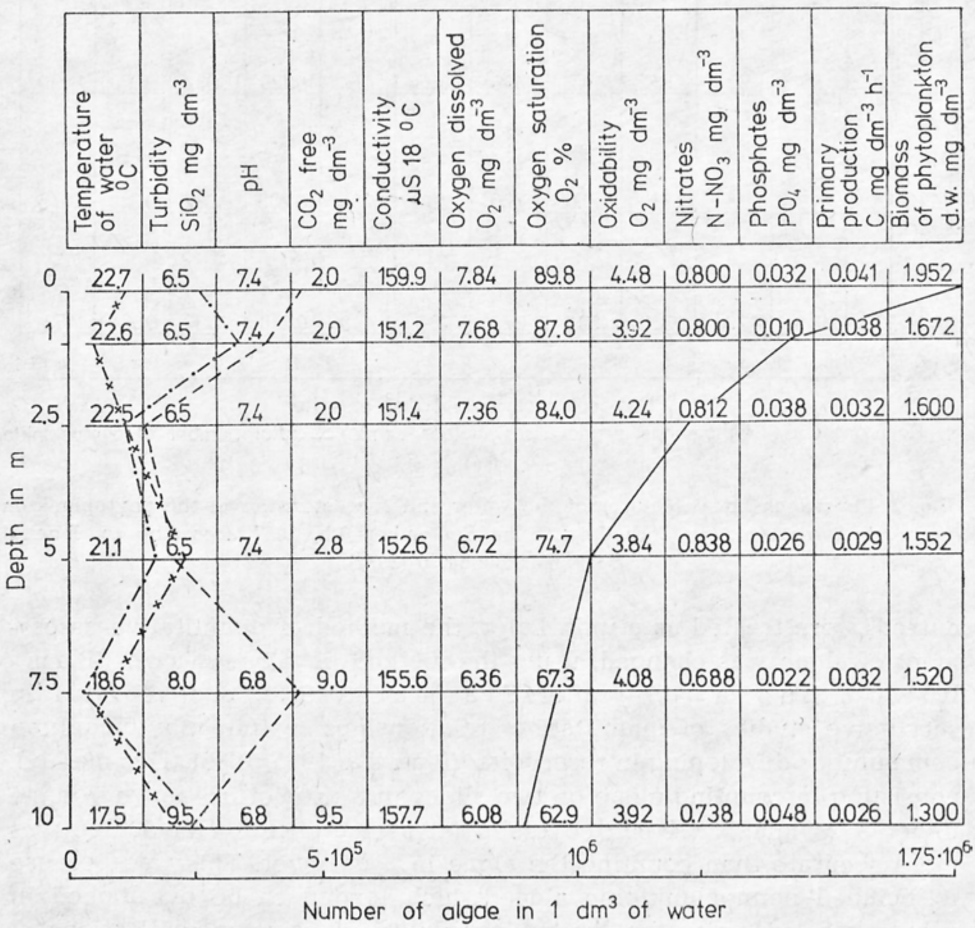
3.2.2. In the author's own studies

On the basis of the author's own work, she has adopted as the criterion of a "water bloom" numbers corresponding to $5 \cdot 10^2$, most frequently from 10^3 to several thousand algae per cm^3 of water, or in single cells (*Cyclotella*), coenobia (e.g. *Scenedesmus*), colonies of some other kind (*Microcystis, Asterionella, Melosira*), or trichomes (*Aphanizomenon*). Quantities of 10^2 to $5 \cdot 10^2$ cm^{-3} of water are considered to be an increased development of the algae, occasionally signalling the onset of a water bloom. However, such data for algae over 100 μm in size (e.g. *Ceratium hirundinella*) already signified a mass appearance.

As a basis for quantitative microscopic analysis of the algae, 0.5 dm^3 samples of unfiltered water were usually taken (in initial studies of the plankton of reservoirs), up to 1 dm^3 (in subsequent investigations), using a Patalas bathometer from previously selected depths and, likewise, also from every depth, samples of water filtered (through a no 25 plankton net), first 5 dm^3 in volume, then 50 dm^3. Initially, the samples of unfiltered water were fixed in situ using Lugol's solution according to Uthermöhl, and transported in 1 litre jars to the laboratory, where they were left in the dark to settle for 10 days. They were then siphoned off and a preserving solution was added (Starmach 1963). In later studies samples of unfiltered water were transported in vacuum flasks, without being fixed, to the laboratory, where they were used also for qualitative analysis *in vivo*. In turn, the samples of filtered water concentrated to 100 cm^3 were treated at the site of sampling with formalin, replaced in recent work by Lugol's solution, which better preserves the shapes of the cells, or perhaps their flagellae. Moreover, in the case of a shallow reservoir (Kozłowa Góra), net samples collected from various depths, were filtered together as an average sample from a whole column of water, and non-net samples were taken only from the surface (after small differences in the numbers and species composition of the algae had previously been found in microscopic analyses).

The samples were taken usually at monthly intervals, with the exception of a longer break following the freezing of the reservoir, i.e. eight times a year (Rożnów Reservoir), or five times a year for three consecutive years (Kozłowa Góra Reservoir). The Goczałkowice Reservoir and that on the cascade of the Soła alone were investigated only twice (but at very close dates), during one vegetation season (B o m b ó w n a, B u c k a 1974).

The algae were first counted in an 0.5 cm³ K o l k w i t z chamber, and additionally estimated on the basis of their numbers in assumed ranges of a six-grade scale, introduced in order to facilitate comparison of the author's results (B u c k a 1965) with the earlier publications of other authors (S i e m i ń s k a 1952). During counting of the algae all the individuals encountered, irrespective of the form in which they oc-



Depth in m	Temperature of water °C	Turbidity SiO_2 mg dm^{-3}	pH	CO_2 free mg dm^{-3}	Conductivity µS 18 °C	Oxygen dissolved O_2 mg dm^{-3}	Oxygen saturation O_2 %	Oxidability O_2 mg dm^{-3}	Nitrates N-NO_3 mg dm^{-3}	Phosphates PO_4 mg dm^{-3}	Primary production C mg dm^{-3} h^{-1}	Biomass of phytoplankton d.w. mg dm^{-3}
0	22.7	6.5	7.4	2.0	159.9	7.84	89.8	4.48	0.800	0.032	0.041	1.952
1	22.6	6.5	7.4	2.0	151.2	7.68	87.8	3.92	0.800	0.010	0.038	1.672
2.5	22.5	6.5	7.4	2.0	151.4	7.36	84.0	4.24	0.812	0.038	0.032	1.600
5	21.1	6.5	7.4	2.8	152.6	6.72	74.7	3.84	0.838	0.026	0.029	1.552
7.5	18.6	8.0	6.8	9.0	155.6	6.36	67.3	4.08	0.688	0.022	0.032	1.520
10	17.5	9.5	6.8	9.5	157.7	6.08	62.9	3.92	0.738	0.048	0.026	1.300

Dominants: ____ *Cyclotella comta*; _._._ *Chrysococcus minutus*; _x_x_ *Asterionella formosa*; _____ Total number of phytoplankton; d.w. dry weight

Fig. 1. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Goczałkowice on July 6th, 1967 according to B o m b ó w n a, B u c k a (1974)

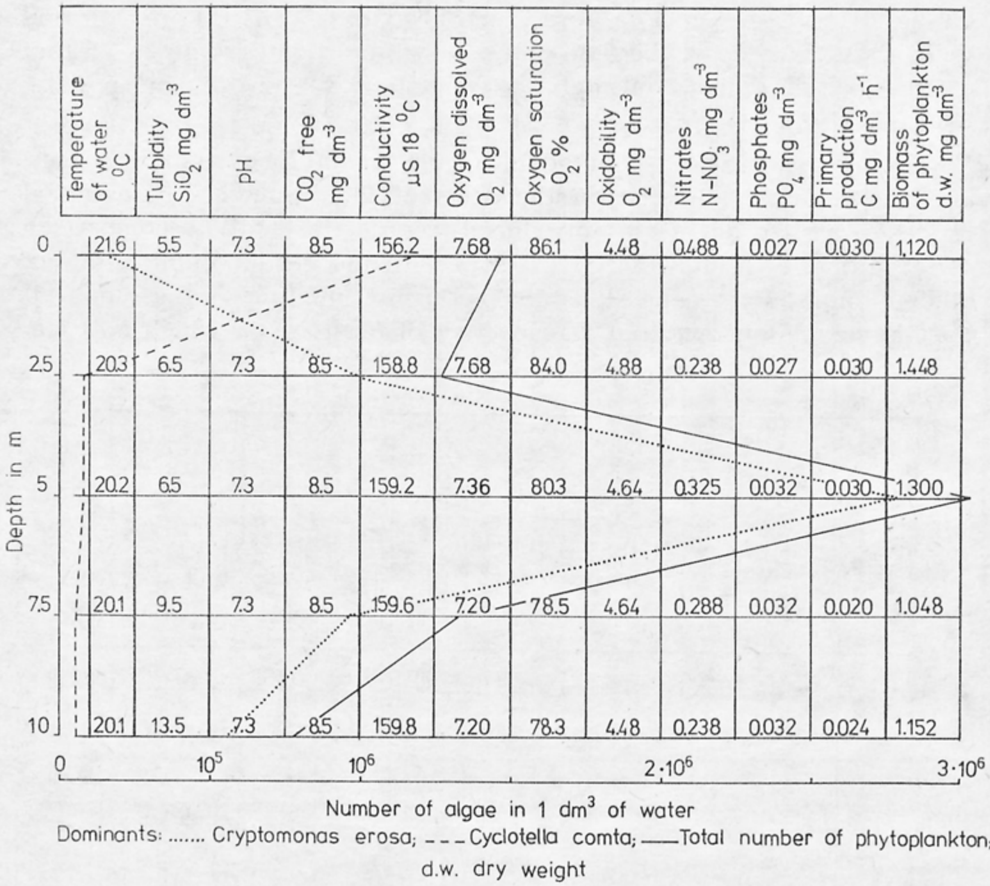
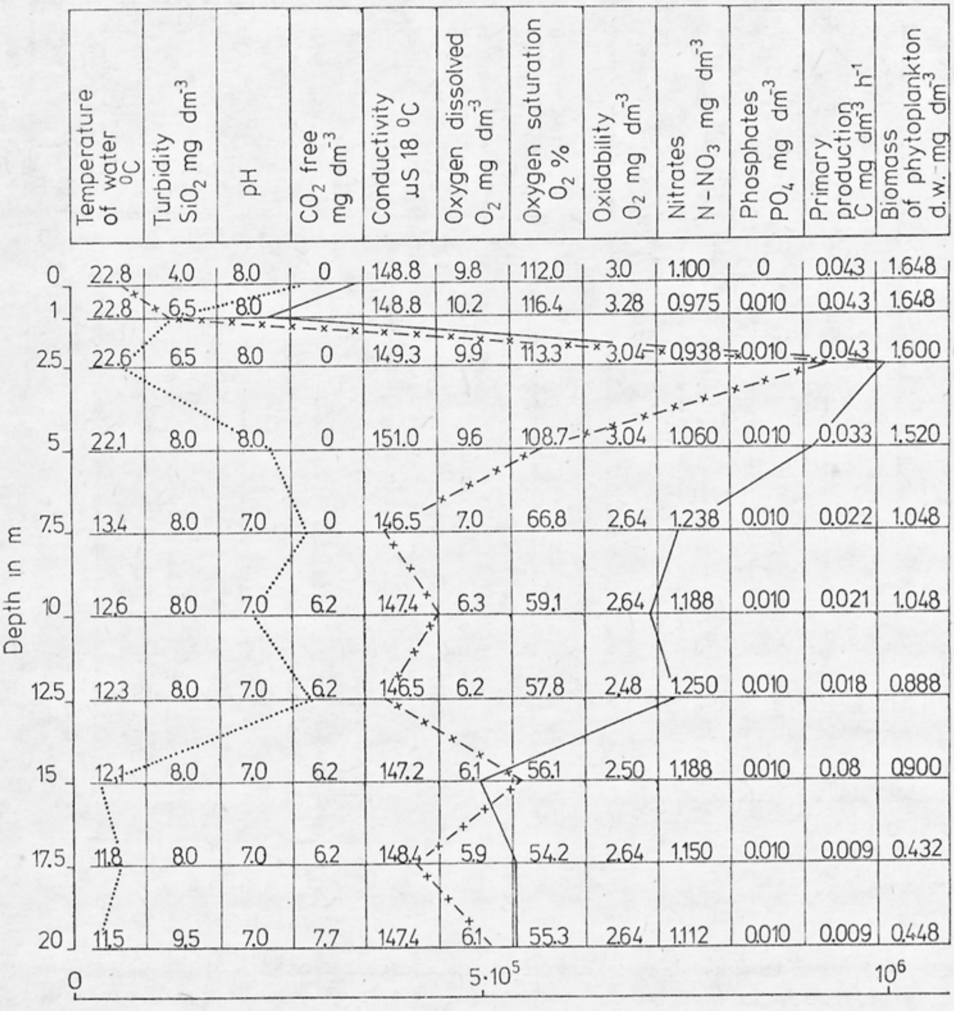


Fig. 2. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Goczałkowice on September 6th, 1967 according to Bombówna, Bucka (1974)

curred, were treated as a unit. Later, the method of quantitative assessment of algae was changed, using the method of Starmach (Bombówna, Bucka (1974) after Starmach 1969), and repeated in successive studies of quantitative relationships within phytoplankton communities developing in reservoirs (Bucka 1985, 1986). This method, consisting in counting algae on two slides in a droplet of known volume under a 24 mm × 24 mm coverslip (at a magnification of 500×), was more accurate than counting the algae in a chamber. This was because it included nannoplanktonic algae which tended to be overlooked in a chamber, owing to the limited possibility of using magnifications of over 150×.

Figures from 1—7 present the quantity of the whole phytoplankton and of several species of planktonic algae, forming water blooms in four dam reservoirs (Goczałkowice, Tresna, Porąbka, Rożnów), on the back-

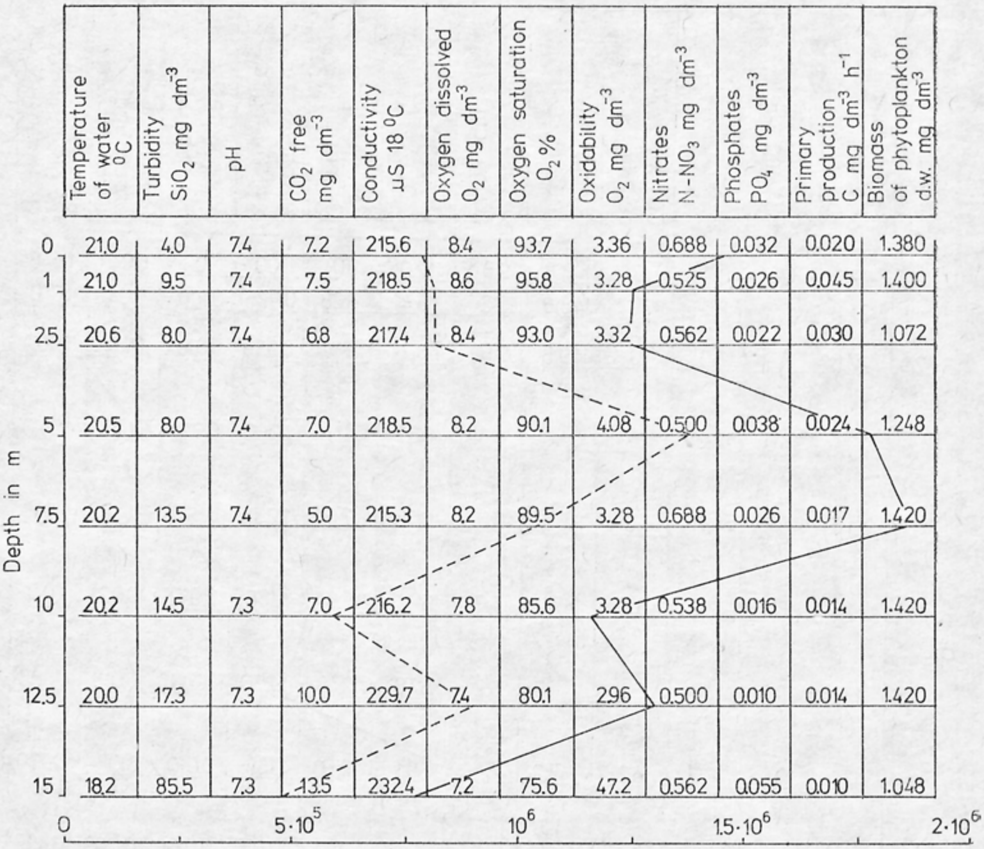


Depth in m	Temperature of water °C	Turbidity SiO_2 mg dm^{-3}	pH	CO_2 free mg dm^{-3}	Conductivity µS 18 °C	Oxygen dissolved O_2 mg dm^{-3}	Oxygen saturation O_2 %	Oxidability O_2 mg dm^{-3}	Nitrates $N-NO_3$ mg dm^{-3}	Phosphates PO_4 mg dm^{-3}	Primary production C mg dm^3 h^{-1}	Biomass of phytoplankton d.w. mg dm^{-3}
0	22.8	4.0	8.0	0	148.8	9.8	112.0	3.0	1.100	0	0.043	1.648
1	22.8	6.5	8.0		148.8	10.2	116.4	3.28	0.975	0.010	0.043	1.648
2.5	22.6	6.5	8.0	0	149.3	9.9	113.3	3.04	0.938	0.010	0.043	1.600
5	22.1	8.0	8.0	0	151.0	9.6	108.7	3.04	1.060	0.010	0.033	1.520
7.5	13.4	8.0	7.0	0	146.5	7.0	66.8	2.64	1.238	0.010	0.022	1.048
10	12.6	8.0	7.0	6.2	147.4	6.3	59.1	2.64	1.188	0.010	0.021	1.048
12.5	12.3	8.0	7.0	6.2	146.5	6.2	57.8	2.48	1.250	0.010	0.018	0.888
15	12.1	8.0	7.0	6.2	147.2	6.1	56.1	2.50	1.188	0.010	0.08	0.900
17.5	11.8	8.0	7.0	6.2	148.4	5.9	54.2	2.64	1.150	0.010	0.009	0.432
20	11.5	9.5	7.0	7.7	147.4	6.1	55.3	2.64	1.112	0.010	0.009	0.448

Dominants: —×—× Asterionella formosa; .... Cryptomonas erosa; —— Total number of phytoplankton; d.w. dry weight

Fig. 3. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Tresna on June 29th, 1967 according to B o m b ó w n a, B u c k a (1974)

ground of physico-chemical data for the water. Chemical analyses were carried out in parallel with studies of the phytoplankton (B o m b ó w n a, B u c k a 1974) (figs. 1—6) and B o m b ó w n a (unpubl. data) (fig. 7). Figures 1—6 also contain other data on primary production, expressed in mg C dm^{-3} h^{-1} and the biomass of the whole phytoplankton. The biomass was assayed by B o m b ó w n a from the content of chlorophyll, and given in mg dry weight per dm^3 of water.



Depth in m	Temperature of water °C	Turbidity SiO_2 mg dm^{-3}	pH	CO_2 free mg dm^{-3}	Conductivity µS 18 °C	Oxygen dissolved O_2 mg dm^{-3}	Oxygen saturation O_2 %	Oxidability O_2 mg dm^{-3}	Nitrates N-NO_3 mg dm^{-3}	Phosphates PO_4 mg dm^{-3}	Primary production C mg dm^{-3} h^{-1}	Biomass of phytoplankton d.w. mg dm^{-3}
0	21.0	4.0	7.4	7.2	215.6	8.4	93.7	3.36	0.688	0.032	0.020	1.380
1	21.0	9.5	7.4	7.5	218.5	8.6	95.8	3.28	0.525	0.026	0.045	1.400
2.5	20.6	8.0	7.4	6.8	217.4	8.4	93.0	3.32	0.562	0.022	0.030	1.072
5	20.5	8.0	7.4	7.0	218.5	8.2	90.1	4.08	0.500	0.038	0.024	1.248
7.5	20.2	13.5	7.4	5.0	215.3	8.2	89.5	3.28	0.688	0.026	0.017	1.420
10	20.2	14.5	7.3	7.0	216.2	7.8	85.6	3.28	0.538	0.016	0.014	1.420
12.5	20.0	17.3	7.3	10.0	229.7	7.4	80.1	2.96	0.500	0.010	0.014	1.420
15	18.2	85.5	7.3	13.5	232.4	7.2	75.6	47.2	0.562	0.055	0.010	1.048

Dominant: _ _ _ Cyclotella comta; ____ Total number of phytoplankton; d.w. dry weight

Fig. 4. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Tresna on September 4th, 1967 according to Bombówna, Bucka (1974)

In this period, also introduced into the above studies were additional calulations of the area of the vertical projections of the algal cells, in order to diagnose their mass appearance. These were also related to other measurements such as, for instance, primary production or chlorophyll content, this also proving very helpful in assessing the nutrient resources in the reservoir. These data were not taken into account in figs 1—6, as irrelevant to the present review.

In the most recent studies (Bucka 1986) biomass was calculated separately only for the blue-green alga *Aphanizomenon flos-aquae* (fig. 7), using a different method. This consists in multiplying the numbers of the given species of alga by the weight of its thalli, whether in the form of single cells, colonies, or trichomes. The quantity of the algae

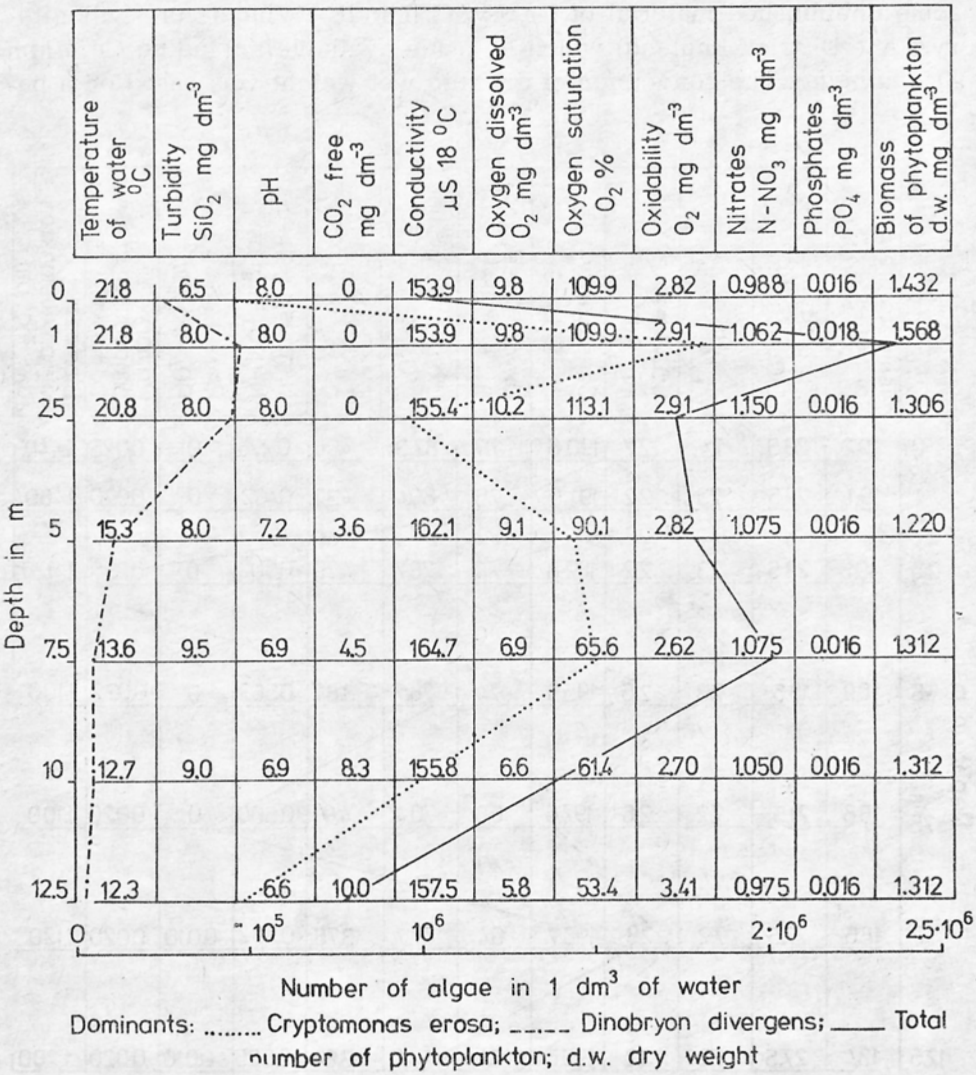
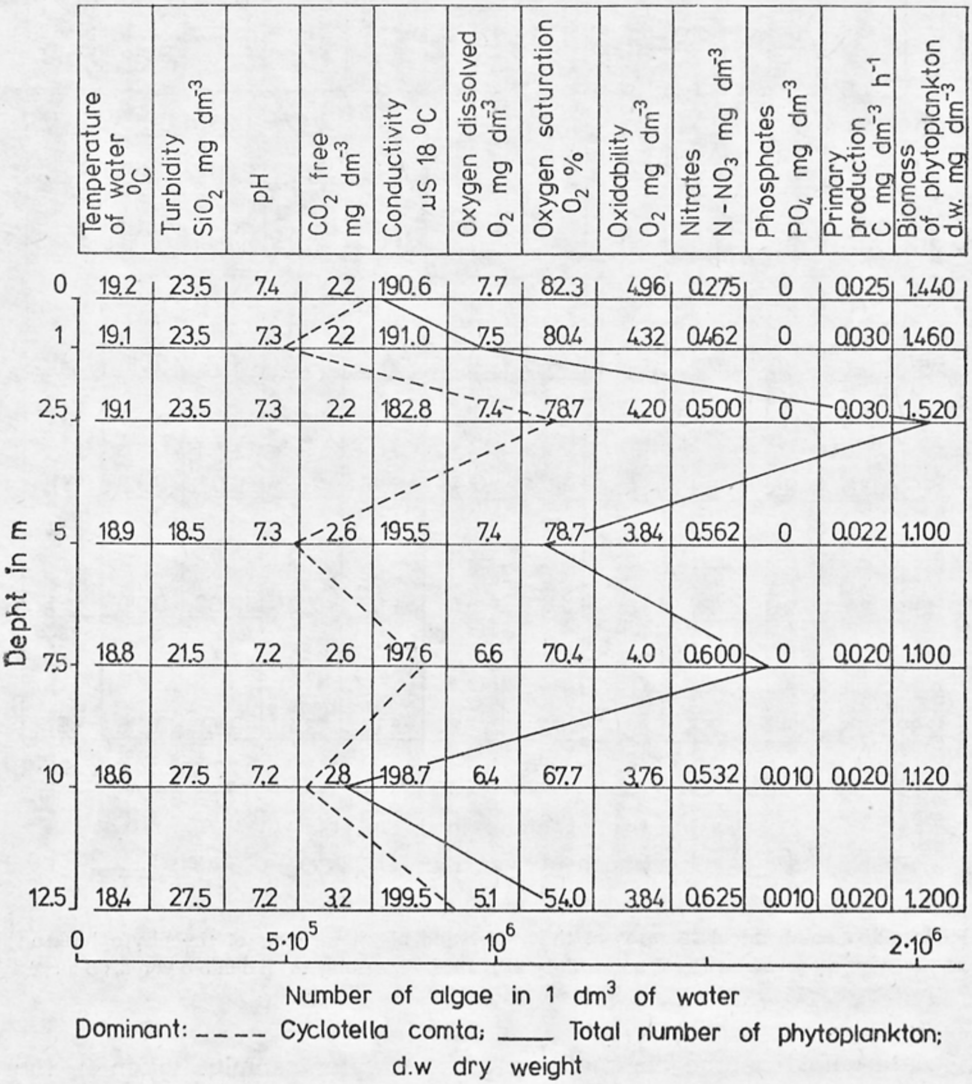


Fig. 5. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Porąbka on July 4th, 1967 according to B o m b ó w n a, B u c k a (1974)

is determined on the basis of analyses of water samples taken in the field, while the "weight ot thalli" of given algal species is obtained from their laboratory cultures, according to the method of L u n d et al. (1971).

In the above case, in calculations of biomass (given as dry or wet weight in µg and mg cm^{-3} or dm^{-3} of water), the author also used her own results obtained previously from cultures of certain algae, among them *Aphanizomenon flos-aquae* (B o m b ó w n a et al. 1975), and from some unpublished material of Dr J.W.G. Lund's (Windermere Laboratory, Lake District, England) which he made available (including *Ceratium hirundinella*). The conversion of dry into wet weight was based on a pa-



Depht in m	Temperature of water ^0C	Turbidity SiO_2 mg dm^{-3}	pH	CO_2 free mg dm^{-3}	Conductivity µS 18 ^0C	Oxygen dissolved O_2 mg dm^{-3}	Oxygen saturation O_2 %	Oxidability O_2 mg dm^{-3}	Nitrates N-NO_3 mg dm^{-3}	Phosphates PO_4 mg dm^{-3}	Primary production C mg dm^{-3} h^{-1}	Biomass of phytoplankton d.w. mg dm^{-3}
0	19.2	23.5	7.4	2.2	190.6	7.7	82.3	4.96	0.275	0	0.025	1.440
1	19.1	23.5	7.3	2.2	191.0	7.5	80.4	4.32	0.462	0	0.030	1.460
2.5	19.1	23.5	7.3	2.2	182.8	7.4	78.7	4.20	0.500	0	0.030	1.520
5	18.9	18.5	7.3	2.6	195.5	7.4	78.7	3.84	0.562	0	0.022	1.100
7.5	18.8	21.5	7.2	2.6	197.6	6.6	70.4	4.0	0.600	0	0.020	1.100
10	18.6	27.5	7.2	2.8	198.7	6.4	67.7	3.76	0.532	0.010	0.020	1.120
12.5	18.4	27.5	7.2	3.2	199.5	5.1	54.0	3.84	0.625	0.010	0.020	1.200

Fig. 6. Physico-chemical features of the water and characteristics of the phytoplankton of the dam reservoir at Porąbka on September 7th, 1967 according to Bombówna, Bucka (1974)

per by Naumann from 1955 (cit. Starmach 1955), according to whom the former amounts on average to 4% of the value of wet plankton.

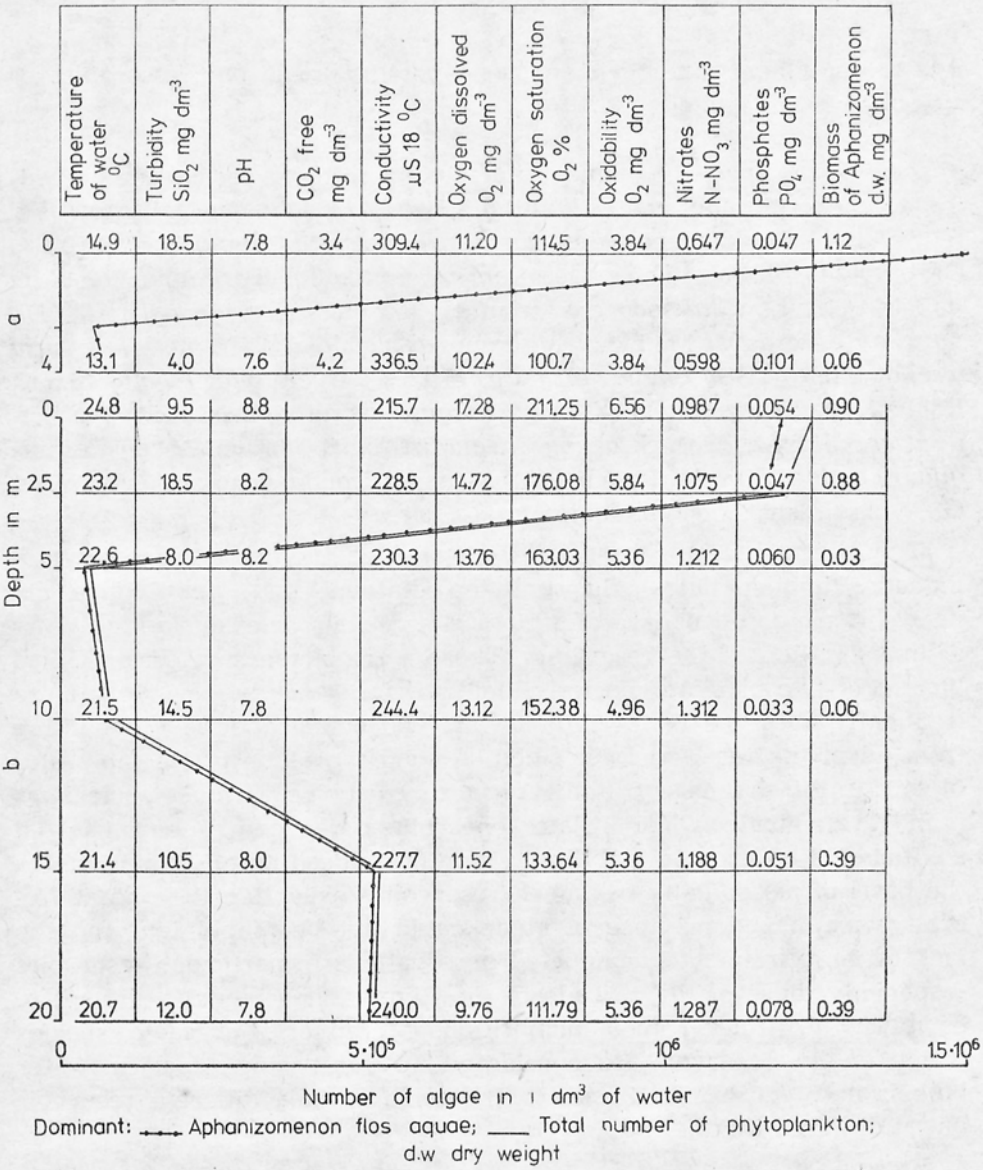


Fig. 7. Physico-chemical features of the water according to Bombówna (unpublished results) and characteristics of the phytoplankton of the dam reservoir at Rożnów according to Bucka (1986). a — in backwaters of the dam reservoir on October 12th, 1982; b — near the dam on July 12th, 1983

4. Results and discussion

4.1. Water blooms and their species diversity in the dam reservoirs of southern Poland

Among the species forming water blooms in those reservoirs, according to the criteria of various authors, were: *Anabaena scheremetievi* Elenk., *Aphanizomenon flos-aquae, Microcystis aeruginosa* Kütz., *Cryptomonas erosa* Ehr., *Ceratium hirundinella, Peridiniun cinctum* (O.F.M.) Ehr., *Chrysococcus minutus* (Fritzsch) Nygaard, *Dinobryon divergens* Imhof, *Mallomonas caudata* Iwanoff, *Synura uvella* Ehr., *Asterionella formosa* Hass., *Cyclotella comta* (Ehr.) Kütz., *C. meneghiniana* Kütz., *Fragilaria crotonensis* Kitt., *Synedra acus* Kütz. with *S. acus* var. *angustissima* Grun., *Scenedesmus quadricauda* (Turp.) Bréb. with *S. quadricauda* var. *maximus* W. et G. West., and *Phacotus lenticularis* Ehr.

The above-mentioned species from among blue-green algae, cryptomonads, dinoflagellates, chrysophytes, diatoms, and green algae appeared in masses, causing water blooms at various times during the years of investigation of the reservoirs. These were single species, or mixed blooms of two or more species. Single-species water blooms were more frequently observed in the initial years and mixed ones later, counting from when the reservoir was filled. Among the algae producing water blooms in the first year of the reservoir's existence various species was found to dominate, while in later ones blue-green and green algae did so. It should be stressed that the division introduced here is tentative. On the basis of periodically examined reservoirs (excepting the one at Goczałkowice) the dominance of algae could not be pinpointed, and the lack of more frequently conducted observations in particular reservoirs (especially those of the cascade of the River Soła) makes it difficult to establish fully their actual composition. Moreover, the same species which in one reservoir are considered to form single-species water blooms may cause mixed ones in the same or in a different reservoir but at different times.

4.2. Single-species water blooms

4.2.1. In the first years following flooding, with a dominance of blue-green algae, chrysophytes, diatoms, and dinoflagellates

In the Goczałkowice Reservoir single-species water blooms were formed by: *Aphanizomenon flos-aquae* in August and September 1955, followed by *Synura uvella* from the end of October 1955 till April 1956, *Asterionella formosa* in December 1956 up to the spring of 1957 and again in 1960, *Ceratium hirundinella* in 1958, then *Fragilaria crotonensis* and *Synedra acus* in 1959 (Krzyżanek et al. 1986, Pająk 1986). It is thus evident that some of them caused long-lasting water blooms, which according to Starmach et al. (1976) are typical of shallow dam reservoirs and ponds lacking thermal stratification.

In the Rożnów Reservoir, single-species water blooms were caused by *Ceratium hirundinella* in June, *Anabaena scheremetievi* in September 1946, and *Fragilaria crotonensis* in the late autumn of 1947 (Siemińska 1952).

A mass appearance with the exclusive participation of the large dinoflagellate *Ceratium hirundinella* took place once in August 1976, in the Chechło-Nakło worked out sandpit (area of the Upper Silesian Industrial Region, flooded in 1970, area 66 ha, maximum depth 4 m). Its numbers were $39 \cdot 10^4$ cells per dm^3 of water (Bucka 1985), this constituting 39 mg dm^{-3} of their wet weight. Hence, this was a higher value of biomass than that computed later for the blue-green alga *Aphanizomenon flos-aquae* (Bucka 1986) and lower than the maximum fresh weight found by Spodniewska (1974) in Lake Mikołajskie in the summer of 1970. It was 47 mg dm^{-3}, this corresponding to the maximum quantity of the species *Ceratium hirundinella,* namely $6 \cdot 10^5$ cells dm^{-3}.

Also connected with the Chechło-Nakło type of reservoir were much lower nutrient resources and a much lower electric conductivity with respect to the reservoir at Kozłowa Góra. In the Chechło-Nakło Reservoir, precipitation was the source of nutrients, as was run-off from the surrounding banks and a small affluent running into this reservoir. At the time of the water bloom the temperature of the water was 18.1°C here, the pH 6.9, total hardness 4.3°C. According to Starmach (1974) the reason for the frequent water blooms caused by this slow-moving dinoflagellate may be that, owing to its large size and peculiar shape, the zooplankton does not readily graze on it.

4.2.2. Further years after flooding with a dominance of blue-green algae, chrysophytes, diatoms, dinoflagellates, cryptomonads

In the Kozłowa Góra Reservoir, 12 years after flooding, single species water blooms were caused by the species: *Microcystis aeruginosa,* with the most intensive appearance in August and September 1951, *Asterionella formosa,* followed by *Dinobryon divergens* in June 1952, then *Mallomonas caudata* and *Fragilaria crotonensis* for two years in succession in 1951 and 1952 (Szklarczyk 1956). According to the latter, only two species of those mentioned formed long-lasting water blooms in this reservoir; i.e. the blue-green alga *Microcystis* from August to October 1951 and the diatom *Fragilaria* from June to August 1952. In later studies of the same reservoir (B u c k a 1985) the above chrysophytes were not found and the species *Fragilaria crotonensis* was encountered only in very small numbers.

S z k l a r c z y k (1956) observed, mainly toward the end of a water bloom formed by the blue-green alga Microcystis, the zoosporangia of a fungus (probably *Chytridium microcystidis* S k u j a?) with associated small flagellates. She associated the mass occurrence of this alga with the favourable weather conditions (a constant high water temperature, amounting to 21°C at its peak development, and a low water level from summer onward through a long, dry autumn), which were relevant with respect to a suitable concentration of nutrients. In this period, the chemical spectra indicated a moderate fertility of the above reservoir. Virtually all the nutrients except for nitrates occurred in small and moderate amounts.

It should be added that the blue-green algae forming water blooms usually occur in greater abundance in hard than in soft waters (R e y n o l d s, W a l s b y 1975). Surface water blooms caused by blue-green algae give an exaggerated impression of their abundance, as already pointed out in 1973 by F o g g, S t e w a r t, F a y and W a l s b y (cit. R e y n o l d s, W a l s b y as above). These authors' observations were confirmed by Reynolds (1973a) during his studies on blue-green algae, developing in masses in the lakes of northern England (north Shropshire meres). Their biomass was often small with respect to other groups of algae present in the plankton. According to R e y n o l d s and W a l s b y (1975), the surface water blooms caused by the species *Microcystis aeruginosa* result from the buoyant migration of the whole population toward the surface of the water (without any marked increase in numbers during this time). This takes place under conditions of reduced turbulence, especially with very low wind force on the lake surface (particularly at night, in anticyclonic weather, e.g. on Lake George, Uganda, with frequent water blooms to which the blue-green alga *Microcystis* contributed).

In the Kozłowa Góra Reservoir, the intensive development of the blue-green alga *Microcystis aeruginosa,* attaining $51 \cdot 10^4$ colonies per dm^3 of water, took place in a period following a flood in August 1977 (B u c k a 1985). In an affluent of the Brynica an increased content of nitrates was found, the phosphate content being fairly low. In the reservoir itself the amount of the former clearly declined from the surface to the bottom while in the latter it remained at a negligible level. At the time of the strongest growth of Microcystis the water temperature was 10°C, the pH 7.6, and total hardness 9.2°G (B o m b ó w n a 1985). From the data quoted here it can be seen that the blue-green alga *Microcystis aeruginosa* formed a single-species water bloom in the two investigations, distant in time (S z k l a r c z y k 1956, B u c k a 1985).

In the Goczałkowice Reservoir, several years after its filling (e.g. in 1967) mass appearances of such species as *Peridinium bipes* or *Cryptomonas marsonii* were recorded. Moreover, in this reservoir the species *Microcystis aeruginosa* also often appeared in various years (in 1975, 1976, 1978 — most abundantly; in 1979, 1981, and 1982, Krzyżanek et al. 1986), forming single-species water blooms, sometimes also mixed ones, usually with another blue-green alga, *Anabaena spiroides* Kleb., accompanying it. The mass development of algae, creating problems in treating the water for mains supply purposes, usually took place after a spate, during which considerable amounts of N and P compounds are brought in.

According to Krzyżanek et al. (1986) the period from the 1970's to the beginning of the 1980's constituted the fourth stage in the evolution of the Goczałkowice Reservoir, showing an increase in its fertility. According to the above authors, both the amount of nitrates (0.58—1.34 mg $N—NO_3$ dm^{-3}) and of phosphates (0.005—0.016 mg $P—PO_4$ dm^{-3}) are borderline values above which the mass development of algae can take place. The mean values of the nitrates and phosphates given here for the fourth period were 0.94 mg $N—NO_3$ dm^{-3} and 0.009 mg $P—PO_4$ dm^{-3}, respectively. The maximum numbers of these algae, noted during a bloom were proportional to the temperature of the water, and inversely proportional to its level in the reservoir (Pająk 1986).

In the Rożnów Reservoir in the 1980's the species *Aphanizomenon flos-aquae* caused two water blooms — in October 1982 (only the backwaters of the reservoir) and in July 1983 (the middle part and close to the dam). The maximum development of the alga in the autumn ($15 \cdot 10^5$ trichomes dm^{-3} of water, this constituting 28.1 mg wet weight) led to the formation of a virtual monoculture in the surface layers of the water (fig. 7). It was accompanied at that time by single individuals of chlorococcous green algae (*Coelastrum* sp. div., *Scenedesmus* sp. div., *Pediastrum* sp. div.). The surface temperature of the water was then 14.9°C, and the pH 7.8. According to Starmach et al. (1976) the blue-green alga *Aphanizomenon* (similarly as *Microcystis*) exhibits maximum development at a temperature of 25°C, though this was not confirmed in the present case.

During this bloom great turbidity of the water was observed, being connected with the self-shading caused by the density of the *Aphanizomenon* population in this shallow part of the reservoir. It occurred in conjunction with a decrease in phosphate concentration in the surface layer of the water. Healey and Hendzel 1976 (cit. after Barica 1978) noticed that the mass development of *Aphanizomenon* in more advanced stages was accompanied by a strong phosphorus deficiency. The water, yellowish in colour and with dense bundles of this alga, was also very turbid. In the Rożnów Reservoir (fig. 7) as compared with the summer water bloom with the participation of this blue green alga, the variations in oxygen concentration were slightly less pronounced, a saturation of about 100% being maintained down to the bottom.

The blue-green alga *Aphanizomenon flos-aquae* is a euplanktonic species, attached to stagnant water (Huber-Pestalozzi 1938). This was confirmed by its greater abundance in the backwaters of the reservoir, in the quiet zone occurring at a certain distance from the old riverbed. It is here in the reservoir that sewage flows in from Nowy Sącz, carried with the waters of the Dunajec. This affluent may be the reason for the formation of an intensive water bloom caused solely by the development of *Aphanizomenon* (Bucka 1986).

4.3. Mixed two- and multi-species water blooms with a dominance of cryptomonads, diatoms, chrysophytes, blue-green and green algae

As already mentioned, mixed water blooms were more frequently found in the later years of a reservoir's existence, though sometimes also in the first ones.

Cryptomonas erosa usually formed two-species water blooms. It was accompanied by the diatom Cyclotella comta in the Goczałkowice Reservoir in September 1967 (fig. 2) and by the chrysophyte *Dinobryon divergens* in that reservoir at Porąbka, in the summer of 1967 (fig. 5). The greatest numbers of *Cryptomonas* cells occurred in the Goczałkowice Reservoir at a depth of 2.5—5 m (ca 3 mln per dm^3 of water) and diatoms mainly at the surface (over a million cells per dm^3). In this period a considerable wet mass was also obtained for the whole phytoplankton, amounting at a maximum to 36.2 mg dm^{-3} of water. Primary production reached at that time a maximum of about 0.030 mg C dm^{-3} h^{-1} and chlorophyll content a maximum of 36 μg dm^{-3}.

It is worth adding that, according to Morgan and Kalff (1975) the species *Cryptomonas erosa* has a lower capacity than others to adapt to high intensities of light. Hence it can exist in the weak light of the aquatic environment, owing to its ability to migrate vertically. During its mass appearance in the Goczałkowice Reservoir in September 1967, both the temperature of the water (21.6°C at the surface, 20.1°C at the bottom) and the pH (7.3) were roughly equal throughout the water profile (Bombówna, Bucka 1974). Moreover, in the whole column of water there was found a smaller amount of nitrates, decreasing to the bottom, while the phosphate content was slightly lower than in the earlier water bloom in July in the reservoir at Goczałkowice. The oxygen saturation was very close to that recorded during the July bloom, showing a slight tendency to decrease towards the bottom.

The diatom *Asterionella formosa* had a considerable share in the mixed water blooms. In June 1967 in the reservoir at Tresna (fig. 3) a water bloom caused by the species *Asterionella formosa* and *Cryptomonas erosa* was observed. This diatom reached its highest quantity at a depth of 2.5 m (almost 1 mln individuals dm^{-3} of water), *Cryptomonas* occurring most numerously in the deeper layers of the water (ca $3 \cdot 10^5$ cells dm^{-3} of water). The maximum wet mass of the whole phytoplankton was 41.2 mg dm^{-3}, primary production being 0.043 mg C dm^{-3} h^{-1}, and chlorophyll content 41 μg dm^{-3}. Of the three reservoirs studied, these were the second highest values after those found in the Goczałkowice Reservoir in July. With a negligible participation of chlorococcous algae, the June water bloom in the reservoir at Tresna formed almost a bi-culture. During this water bloom a considerable amount of nitrates was found right down to the bottom, and a complete exhaustion of phosphates in the surface layer of the water (0—1 m), and barely 0.010 mg PO_4 dm^{-3} deeper down. A marked rise in temperature at a depth of 7.5 m corresponded with the biomass of these algae. Above this depth it was observed to increase, as did also the primary production and oxygen supersaturation, while below there was a distinct change in parameters down to the benthic zone. Free CO_2 remained at zero levels down to a depth of 7.5 m, rising with increasing depth and fall in temperature (B o m b ó w n a, B u c k a 1974).

The mixed water bloom with the participation of 3 species (*Cyclotella comta, Chrysococcus minutus,* and *Asterionella formosa*) recorded in the Goczałkowice Reservoir in July 1967 (fig. 1) attained a considerable abundance only in its joint composition, this amounting to a million individuals per dm^3 of water. Simultaneously in the surface layers of the water the greatest value of wet mass was recorded for the whole phytoplankton (48.8 mg dm^{-3} of water) as well as the highest chlorophyll content (49 μg dm^{-3}) and high primary production (0.041 mg C dm^{-3} h^{-1}). This was in conjunction with the participation of some chlorococcous green algae of the genera *Pediastrum* and *Scenedesmus,* accompanying the water bloom in small numbers but frequently larger in size than the dominating species (especially *Chrysococcus* and *Cyclotella*). Hence, the presence of green algae could have affected on the size of the biomass and chlorophyll content.

The occurrence of the water bloom was distinctive in its nutrient content, the greatest utilization of phosphates being at a depth of 1 m, with a concurrently small vertical variation in nitrate content, which decreased at a depth of 7.5 m. In oxygen saturation a downward trend from the surface to the bottom was observed (B o m b ó w n a, B u c k a 1974).

The small diatom *Cyclotella comta,* belonging to those species which frequently form mixed water blooms, also occasionally gave very high numbers (with a small proportion of some green algae — *Dictyosphaerium pulchellum* Wood and *Raphidonema longiseta* Vischer), e.g. in the reservoir at Tresna at the beginning of 1967 (fig. 4). At that time, these numbers varied from $75 \cdot 10^4$ to ca $14 \cdot 10^5$ dm^{-3} of water, while the maximum wet mass of the whole phytoplankton was 38 mg dm^{-3}, primary production 0.045 mg C dm^{-3} h^{-1}, and chlorophyll content 35 μg dm^{-3}. In this period the temperature of the water reached 21°C on the surface, 18.2°C at the bottom, and the pH correspondingly, 7.4 and 7.3. The increased development of this diatom in the above period took place with smaller amounts of nitrates and the constant presence of phosphates in the whole column of water in slightly greater amounts than in June, with a mixed water bloom caused by *Asterionella* and *Cryptomonas*. With the temperature falling slowly from the surface to the bottom, a slow decrease in oxygen was also recorded and little variation in pH. Both the biomass and the primary production of the phytoplankton were smaller than in June, when an almost two-species water bloom was formed.

The mass appearance of the diatom *Cyclotella comta* ($11 \cdot 10^5$ cells dm^{-3} of water) with the chlorococcous algae accompanying it (as above) was observed in the reservoir at Porąbka at the beginning of September 1967 (fig. 6). The maximum value of wet mass of the whole phytoplankton was at that time 38 mg dm^{-3}, primary production 0.030 mg C dm^{-3} h^{-1}, and the content of chlorophyll 38 μg dm^{-3} (almost identically as in this period in the reservoir at Tresna). These data would point to the influence of the first reservoir on the successive ones built on the River Soła in the cascade system, this being reflected in the same composition of dominants. The temperature of the water at the surface and at the bottom was 19.2°C and 18.4°C, and the pH 7.4 and 7.2, respectively. The mass appearance of this diatom occurred with smaller amounts of nitrates and a complete depletion of phosphates down to a depth of 7.5 m. The saturation with oxygen systematically decreased from the surface to the bottom, along with the temperature of the water (Bombówna, Bucka 1974).

An intensive mixed water bloom, caused by the presence of *Asterionella formosa* and other dominants almost equalling it in quantity, such as *Chrysococcus minutus*, *Synedra acus* with *S. acus* var. *angustissima*, and *Scenedesmus quadricauda* with *S. quadricauda* var. *maximus*, was noted at the beginning of May 1978, mainly at the dam in the Kozłowa Góra Reservoir. These algae were accompanied by the diatom *Cyclotella comta*, whose numbers exceeded 0.5 mln cells dm^{-3} of water, constituting a share twice as small as that of the remaining species of algae (Bucka 1985). The temperature of the water was then 11.2°C and 11.6°C (surface, bottom), and the pH 7.7 throughout the column of water. At the time of the water bloom the nitrate content in the reservoir and in the affluent were very similar, the content of phosphates in the affluent being slightly lower (0.054 mg PO_4 dm^{-3}) with a much greater degree of their depletion in the region near the dam (0.007 and 0.004 mg PO_4 dm^{-3} — surface and bottom). This mixed water bloom with a number of different algae caused a greater oxygen saturation of the water (almost equal vertically, with a very slight rise in oxidability — Bombówna 1985), than a later and less intensive mixed water bloom caused in June 1978 by *Cryptomonas* sp. together with the above-mentioned diatoms.

From the above-quoted summarized data concerning water blooms in the Kozłowa Góra Reservoir, both on the basis of investigations by Szklarczyk (1956) and by the present author (Bucka 1985), it would appear that of the diatoms *Asterionella formosa* was still preponderant, with a concurrent mass occurrence of other diatoms. Within chrysophytes, there occurred a change in dominant species over 25 years. Species previously noted in masses, such as *Mallomonas caudata* or *Dinobryon divergens,* were replaced by *Chrysococcus minutus.* According to Huber-Pestalozzi (1941), *Chrysococcus minutus* is a typically oligotrophic species, preferring the cooler months (March, April); this, however, was not confirmed in the studies of phytoplankton in the reservoirs considered here. The green alga *Scenedesmus quadricauda* var. *maximus*, rarely recorded by Szklarczyk (1956) in the first years, should not be omitted here, since these algae came to dominate the whole community of green algae in the late 1970's. According to Bombówna (1985), the mass development of chlorococcous green algae is probably connected with the abundant resources of nutrients, especially nitrates. In this reservoir, the green algae-diatom character of the phytoplankton has been maintained (with periodic, single-species water blooms caused by the blue-green alga *Microcystis aeruginosa*), for 25 years, counting from the first algological studies (Szklarczyk 1956).

In the Kozłowa Góra Reservoir, similarly as in Chechło-Nakło, during the water blooms in the years 1976, 1977, and 1978, large numbers of the sulphurous bacteriae *Beggiatoa alba* (Vaucher) Trevis and *B. minima* Winogr. (Bucka 1985) were found, their presence corresponding with the large concentration of sulphates. In the opinion of Bombówna (1985) this distinguishes the reservoirs of Kozłowa Góra and Chechło-Nakło from the Carpathian ones belonging to the right-side catchment area of the Upper Vistula (Bombówna, Bucka 1974).

The mixed water blooms found in various years in the Rożnów Reservoir were varied with respect to the taxonomic affiliation of species to systematic groups. They were caused by species of the genera *Dinobryon* (mainly *D. divergens* and *D. stipitatum* Stein) in the middle of May 1946, and *Cyclotella* (especially *C. comta* and *C. ocellata* Pant.)

at the turn of August 1948 (S i e m i ń s k a 1952). The latter author also observed at the beginning of August 1948 a mass appearance of a volvocalean green alga — *Phacotus lenticularis* ($1.3 \cdot 10^{-3}$ cells cm^{-3} of water), accompanied by diatoms (*Cyclotella* sp. div. and *Asterionella formosa*, ca. $24 \cdot 10^4$ cells and colonies per cm^3 of water). The water bloom covered almost the whole of the reservoir, with the greatest intensity at the dam. The temperature of the water at the surface amounted to 26.5°C in this period and transparency was 2 m. Towards the end of the 1950's, the increased occurrence of various algae (regarded as a water bloom) was noted by B i e r n a c k a (1959, 1963). During studies on plankton, carried out in two successive years she distinguished *Peridinium cinctum, Ceratium hirundinella, Asterionella formosa, Fragilaria crotonensis*, and *Synedra acus* in 1957, and in 1958, *Anabaena spiroides, Peridinium cinctum, Dinobryon divergens, Asterionella formosa, Attheya zachariasi* B r u n. and *Fragilaria crotonensis*. At the beginning of the 1960's mixed water blooms, with several species of the genera *Cyclotella* spp. (mainly *C. meneghiniana*) participating, were observed at the end of June and July 1963, and *Cryptomonas* spp. in October of the same year (B u c k a 1965). The greatest numbers of these algae, occurring in the periods of their most intensive development, were found at this time in the Rożnów Reservoir at depths of 2.5—7.5 m (at the dam) and 2.5—5.0 m in its middle part (similarly as in the Czchów Reservoir). During the time of mass development of *Cyclotella* populations, a decline in oxygen saturation throughout the water column was recorded, particularly near the bottom, with a considerable reduction in nitrate concentrations, the content of phosphates still being maintained in trace amounts. Constant silica resources and their periodic decline were also recorded during the abundant occurrence of diatoms, which caused their depletion. In the summer a markedly higher pH was noted in the surface layer of the water, diminishing towards the bottom to a mildly alkaline pH. Greater amounts of nitrates usually occurred in the spring and following summer floods. In the study years 1963/1964, in floodless periods, phosphates were exhausted already from early spring and during the summer through almost the entire column of water, except for some deeper regions close to the dam (B o m b ó w n a 1965).

The maximum development of the nannoplanktonic green alga *Phacotus lenticularis*, reaching about 1 mln cells dm^{-3} of water, took place in mid-August 1983 in the central part of the Rożnów Reservoir, with a large variability of the not numerous chlorococcous green algae, and fairly numerous desmids (B u c k a 1986).

In July 1983 in the same reservoir an even earlier water bloom caused by the blue-green alga *Aphanizomenon flos-aquae* was noted. This summer water bloom in the middle part of the reservoir was much less pronounced than in the same period near the dam. It was accompanied by the diatom *Melosira granulata* (Ehr.) Ralfs var. *angustissima* (O.F.M.) Hust., a green volvocalean alga, *Carteria klebsii* (Dang.) Dill, chlorococcous green algae, e.g. *Scenedesmus quadricauda* var. *maximus* and singly by other blue-green algae such as *Anabaena scheremetievi* and *Microcystis aeruginosa*. The temperature at the water surface amounted to 24.8°C, the pH being 8.6. At the dam (fig. 7) the same alga brought about a water bloom of double the density found in the middle of the reservoir ($12 \cdot 10^5$ trichomes dm^{-3}, maximum fresh weight 22.5 mg dm^{-3} of water). Hence it is likely that the movement of water masses had a considerable effect on its distribution down in the reservoir. From the investigations of Siemińska (1952) and Biernacka (1959) it may be concluded that the quantity of phytoplankton in the Rożnów Reservoir was inversely proportional to the depth, water level, and the degree of turbidity. The water bloom close to the dam was accompanied by almost the same algal species as in the middle part of the reservoir, excepting the green volvocalean alga, replaced here by chlorococcous green algae, mainly *Pediastrum* sp. div. The temperature of the water was 24.5°C at this time. More striking differences than in the autumn during the mass development of *Aphanizomenon* took place in the summer at the dam in connection with the greater proportion of other algae, amounting to 211% of oxygen saturation in the surface layers of the water, decreasing slowly towards the bottom (ca. 112% O_2 at a depth of 20 m). This demonstrates the considerable importance of the assimilative activity of the algae accompanying the dominant blue-green one, *Aphanizomenon*. At this time there was also a marked correlation with the pH, which fell from 8.8 at the surface to 7.8 at the bottom. In the summer of 1983, a mass appearance of the blue-green alga *Aphanizomenon* had a similar effect as in the autumn of 1982, depleting the nutrients, especially in the surface layer of the water (Bombówna unpublished data).

The greatest number of the species *Aphanizomenon flos-aquae* was noted then at the dam at a depth of 2.5 m with a distinct decrease in deeper regions and a subsequent increase from 10 m to the bottom (fig. 7). The vertical distribution of this alga might have been determined by the presence of gas vacuoles (typical also for other species of blue-green algae, particularly planktonic ones), allowing them to remain in the upper layers of the water. This species fixes atmospheric nitrogen, hence, according to Zevenboom and Mur (1980), it must absorb more light energy (72%) than other blue-green algae which do not fix nitrogen (e.g. *Oscillatoria*), in order to achieve the same growth rate. The mentioned authors are of the opinion that a greater utilization of solar energy is necessary, mainly for the production of heterocysts which in turn supply nitrogenase, an important enzyme in the process of nitrogen fixation.

The species *Aphanizomenon flos-aquae* occurs singly or accompanied by other species of blue-green algae, such as *Microcystis aeruginosa* and *Anabaena spiroides* (Prescott 1951). According to that author it is seldom found, except in eutrophic lakes or slow-running streams with hard, polluted water. It was also recorded in masses in the fish ponds fertilized with phosphates at Gołysz (Bucka 1966). According to Prescott (1951), the mass development of *Aphanizomenon takes* place in the presence of large amounts of nitrate compounds in the water, its consequence being a rise in pH, with a parallel increase in the concentration of calcium bicarbonates. High concentrations of the latter and also of nitrates were confirmed in studies on the chemical composition of the water in the Rożnów Reservoir (Bombówna unpublished data) carried out in 1982/1983 at the same time as those of phytoplankton. High values of the pH and temperature of the water were distinctly observed during the July bloom of the blue-green alga *Aphanizomenon,* in the middle and lower part of the reservoir, and somewhat less distinctly in the autumn in its upper part.

The periodic occurrence of water blooms with the participation of blue-green algae in the Rożnów Reservoir indicates its growing eutrophication in recent years in relation to the investigation period of 20 years ago (Bucka 1965, Bombówna 1965). In successive studies of phytoplankton, a change took place in the composition of its communities to the blue-green and green algal type found in the 1980's (Bucka 1986).

4.4. Remarks on the conditions of formation of water blooms with the participation of blue-green algae in limnic and rheolimnic reservoirs

Among the factors disturbing algal growth in dam reservoirs is the summer swelling of rivers, caused by heavy precipitation, which alters the thermal regimen of the water (Starmach et al. 1976). Hence, the formation of water blooms depends also on the frequency of water exchange. In lowland reservoirs with a fairly small flow (limnic ones), e.g. in the Goczałkowice Reservoir, the time of water retention is conducive to the development of algae. The conditions in limnic reservoirs with a more rapid water exchange are less favourable (Tresna, Kozłowa Góra), while those least favourable are found in rheolimnic ones (Porąbka, Czaniec, Rożnów) (Table I).

In the typically lowland, shallow Goczałkowice Reservoir built on the Vistula, with a low gradient of the river valley, impoundment caused extensive inundation over a wide area. Hence, variations in water level expose tracts of the reservoir which at low discharge during dry summers are rapidly overgrown by higher plants; in autumn during the rise in water level, the exposed bottom is again flooded. This causes decomposition of the mentioned vegetation and the release of stored nutrients. According to Krzyżanek et al. (1986), in the sediments of this reservoir an increase has recently been found in the content of total phosphorus to 0.157% P in the dry mass of the sediments, as compared with the situation more than 10 years ago when it amounted to 0.124% P. Meanwhile, in the water of the Vistula below the dam a reduction in major nutrients has been recorded — in phosphorus by at least 57.6%, nitrogen by at least 33.5%, and silica by at least 44.4% in relation to the inflowing waters. These data confirm that it is in the sediments that the accumulation of phosphorus takes place. A quite significant role is also played by undulation caused by the wind, and reaching the bottom in the shallow reservoir. This is also connected with the effect of the resuspension of sediments on biocenoses, both benthic (fauna and microphytobenthos), and planktonic. Hence, undulation does not create conditions conducive to the formation of a water bloom by the species *Microcystis aeruginosa.* According to Turoboyski (1979), the input of organic and mineral compounds washed down by rain from the adjacent land determines the increase in the reservoir's fertility, this being the reason why water blooms are produced in it. It is also favoured by the mechanism of bouyancy control, discussed by Reynolds (1971, 1973b), and also Reynolds and Walsby (1975), citing a paper by Gauf (1974). That author, writing of a water bloom formed by *Microcystis* in Lake George (Uganda), draws attention to the windless weather by night, making possible the formation of this surface water bloom. According to Reynolds and Walsby (1975), the capacity of *Microcystis* for buoyant migration depends on the abundance of buoyant algae, whose rate of development is not directly dependent on the concentration of nutrients. They believe that the strong water blooms caused by this alga result not from a rapid but from gradual fission below the water surface, followed by rapid movement to the surface. The interplay of these processes coupled with the dynamic instability of masses of water explains in their opinion the appearance of water blooms. The mechanism of buoyancy control may become unbalanced when photosynthesis is inhibited, e.g. by night or as a result of the ageing of populations of these algae (Reynolds 1978). The tendency towards a reduction in buoyancy in *Microcystis,* which are streamlined to a considerable degree, is smaller than in other blue-green algae, occurring in separate trichomes.

The mass appearance of the species *Microcystis aeruginosa* in the Kozłowa Góra Reservoir (lowland, of pond type, occupying an old cleared forest and peat-bog area) was first recorded by Szklarczyk (1956). She connected it with favourable temperatures and an appropriate (small and moderate) concentration of nutrients. A second instance of its excessive development in this reservoir (B u c k a 1985) occurred in a period following a flood, when in the affluent Brynica there was an increased amount of nitrates and a negligible one of phosphates, with a low content of these compounds in the reservoir itself. This would appear to support R e y n o l d s' views, contained in the above-cited papers, and particularly in that from 1971, in which he lists three conditions conducive to the formation of water blooms. They are: the presence of basic populations of blue-green algae in the reservoir (*Microcystis aeruginosa*), a sufficient quantity of gas vacuoles in the protoplasm of their cells, regulating the bouyancy of these algae, and low turbulence of the water.

In considering the situation in which water blooms are formed in a reservoir of through-flow-rheolimnic type, with an exchange of water more frequent that 10 times a year (e.g. the long and deep Rożnów Reservoir, lacking a littoral zone, in a steeply sloping valley), the different habitat conditions prevailing there should be borne in mind. In this type of reservoir the variations in water level expose only their upper regions and some of the organic matter produced is carried away with the outflow, the opposite taking place in limnic reservoirs in which it is utilized or deposited on the bottom (S t a r m a c h et al. 1976).

In the case of a mixed water bloom caused by the blue-green alga *Microcystis aeruginosa* (colonies lacking heterocysts) with *Aphanizomenon flos-aquae* or with *Anabaena spiroides* (trichomes with heterocysts), there exists an interrelationship between those species which fix atmospheric nitrogen and those which do not. It may be supposed that one species makes use of the nitrogen assimilated by the other, which in the summer, when this component is more depleted, is of great significance in the aquatic environment.

It should be remembered that in blue-green algae the dependence of the process of nitrogen assimilation on light intensity is twofold, since photosynthesis constitutes a source both of energy and of carbon, as pointed out in a review paper by K r u p k a (1984). She reported that of two thousand species of alga, about 40 are known to fix N_2. The process of nitrogen fixation takes place when the environment lacks any other forms of nitrogen which can be assimilated by the microorganisms. Nitrogen is fixed not only by blue-green algae which have heterocysts, but also those blue-green ones which do not, and by various free-living bacteria or those living in symbiosis. According to this relationship, recent study has shown that many species have the ability to fix atmospheric nitrogen under conditions of reduced oxygen content. The enzyme nitrogenase participates in the process; this has been isolated in blue-green algae, both from heterocysts and from vegetative cells. Ammonia nitrogen and urea are inhibitors of the enzyme, nitrate nitrogen and amino acids exerting a smaller influence on nitrogen fixation. The second condition which must be fulfilled in order that this process may proceed is the presence of macro- and microelements, particularly Mo and Fe. Under natural conditions, nitrogen fixation occurs in the presence of oxygen, though with a rise in its concentration, binding N_2 is markedly inhibited. In Lake Ergen — Sweden (moderately eutrophic), as reported by Krupka (1984), the fixation of N_2 corresponded with the presence of blue-green algae with heterocysts (mainly *Aphanizomenon flos--aquae*). The greatest values of fixed N_2 were achieved toward the end of August on the surface of Lake Erken, in a period preceding the mass appearance of this blue-green alga. It has been found that in deep lakes bacteria and blue-green algae fix similar quantities of nitrogen, while in shallow ones the amount of nitrogen fixed by the algae is three to four times greater than that by the bacteria. Krupka (1984) also pointed out how microorganisms safeguard nitrogenase from being inactivated by O_2. The thick walls of heterocysts or the symbiosis of blue-green algae with bacteria give such protection; the latter will be dealt with more fully later. It was observed that bacteria accumulate in the layer of mucilage (especially on heterocysts) secreted particularly intensively during water blooms.

Some difficulties are encountered in comparing "water blooms" in limnic and rheolimnic reservoirs, as the results obtained from algal studies carried out so far concern various stages of water blooms. According to Štěpánek (1959), most hydrobiologists agree that each species is capable of establishing its own rhythm, which determines its occurrence in certain periods of the year. It is also known that the rate of growth of various species of algae varies. According to Reynolds (1978), *Microcystis aeruginosa* doubles every 3—4 days, and *Ceratium hirundinella* every 5 days. Other authors have also drawn attention to the slow rate of doubling of this species, but giving different values as a result of using a slightly different method of calculating the divisions of its cells. Heller (1977) calculated 6.7 days, while Mueller and Smith (1985) gave 15.6 days for the populations studied in the beginning of July, and 7.2 days for populations studied in August.

Other difficulties concern explanations of the reasons for the occurrence of water blooms since quite frequently the results are taken to be the causes of the mass appearances of algae, as in the case of changes in the pH value, being a consequence of their rapid development. The rise in pH results from the strong photosynthesis and is not the cause of water bloom formation. Hence in new investigations the whole development cycle of the bloom should be followed. The Carpathian reservoirs following summer spates are suitable for this purpose. Of these the Goczałkowice Reservoir is a good testing area since studies have been carried out continuously from the time it was flooded; investigations of this type are about to be undertaken there.

4.5. The symbiosis of blue-green algae and bacteria in relation to "water blooms"

At this point the important role of CO_2 should be mentioned, since it is the main nutrient determining algal production but is underrated by various authors, who lay much more stress on the importance of nitrogen and phosphorus (Kuentzel 1969). The mentioned author, on the basis of a review of the literature, found that none of the papers took into consideration the highly important role of CO_2. Quoting a paper by Sigh (1953) he wrote that in lakes in India frequent water blooms are observed (caused by the species *Microcystis aeruginosa*), which are always connected with a strong pollution of the water by organic compounds. It is commonly assumed that the latter leads to the growth of algae, which, according to Kuentzel, is attributed more to the effects of inorganic components than of decomposing organic matter which constantly accompanies the development of algae. Kuentzel (1969), citing Taylor (1949), is of the opinion that bacterial activity depends on the amount of decomposing carbohydrates and can in a given lake be controlled on the basis of the amount of organic matter present in it. Here he mentions the paper of Silvey and Roach (1964), who held that at intensive development of bacteria precedes water blooms caused by algae. Their investigations showed that large quantities of mainly gram-negative bacteria (congregating in the gelatinous sheaths of filamentous algae) rose from April onwards, with their peak development in August lasting until the beginning of September, followed immediately by the development of blue-green algae. It is their opinion that bacteria create conditions under which the surface layers of the water are super-saturated by carbon dioxide. This state of affairs remains as long as the bacteria have an adequate supply of organic material, necessary to maintain CO_2 production. During the bacterial decomposition of organic matter CO_2 concentrations are often over 20 mg dm^{-3}, thus amounts similar to those required by algae for mass development. According to Hutchinson (1957, 1967 — cit. Kuentzel 1969), the amount of free CO_2 usually falls within the range 0.4 and 1.0 mg dm^{-3}. In natural water, the dissolved CO_2 is usually in equilibrium with that in the atmosphere. An adequate CO_2 supply is the key factor for algae to grow well. For optimum growth, blue-green algae require a slightly alkaline environment. Hence, under equilibrium there exist relatively small amounts of free CO_2 and its depletion owing to the development of algae leads in turn to alkalization of the environment, up to the slowing down and halting of algal growth. According to the above-cited author, the evening out of CO_2 concentrations in water is a very slow process, as is its replacement by carbonates in a mildly alkaline environment. Therefore, free CO_2 (from natural sources) probably never exceeds 1 mg dm^{-3} and is taken up very slowly. It can be seen that the availability of suitable amounts of CO_2, owing to the activity of bacteria in the decomposition of organic matter, determines the mass development of blue-green algae. It has been found that water containing over 0.01 mg dissolved P dm^{-3} but without organic pollution did not cause any tiresome problems with water blooms. Kuentzel stressed that efforts aimed at reducing the mass appearances of algae solely by limiting phosphorus concentrations will not be too successful because it is vital to inhibit concurrently the decomposition of organic matter. In his opinion, this almost perfect symbiosis of algae and bacteria which has lasted for millions of years consists in reciprocal "services" of these simplified organisms. Aerobic bacteria require oxygen for the decomposition of organic matter and production of CO_2, while algae require CO_2 to photosynthesize organic matter and to produce oxygen.

4.6. The composition of algae forming water blooms in the dam reservoirs of other European countries

In 1960/1961, Štěpánek et al. (1963) carried out investigations in 44 reservoirs in Czechoslovakia (Kružberk, Slapy, Orlik, Sedlice and others, being dam reservoirs, and ponds). They found that water blooms are most frequently caused by one genus of planktonic alga (*Aphanizomenon* or *Microcystis*, or *Anabaena*), two genera (*Microcystis* + *Anabaena, Aphanizomenon* + *Anabaena, Aphanizomenon* and *Microcystis*), or several genera (*Anabaena, Aphanizomenon, Microcystis,* or *Asterionella, Microcystis, Chlamydomonas*). Mixed water blooms composed of over four genera (blue-green algae as above, *Coelosphaerium* and *Pseudoanabaena,* green algae *Scenedesmus* and others, diatoms *Asterionella*) were considered by these authors to be the least frequent. They also drew attention to the fact that out of 65 species of algae causing water blooms or a vegetative colouring, only a few can evoke a critical state of the reservoir (*Aphanizomenon flos-aquae, Anabaena flos-aquae, Microcystis aeruginosa*). They also stressed that in the prevailing climatic conditions the phytoplankton has two main periods of development, i.e. in the spring (May, June), and in late summer (August, September).

Also Komárková (1974) gave certain data from the end of the 1960's, relating to primary production in two moderately fertile dam reservoirs on the Vltava in Czechoslovakia. These were the Kličava Reservoir, built for mains supply purposes, with a maximum depth of 31 m, the mean being 13.5 m, and a retention time of 534 days, and the Slapy Reservoir whose maximum depth was 53 m, its mean being 19.5 m, with an exchange of water every 38.5 days. The primary production measured here (in pipelike polythene containers set up in the investigated reservoirs according to a system elaborated by Dr Lund) varied from about 150—220 g C m^{-2} $year^{-1}$. In the Kličava Reservoir, the dominants were the diatoms *Cyclotella comta* and *Asterionella formosa,* the chrysophyte *Chrysococcus rufescens,* and Cryptomonas reflexa. In both reservoirs the factor limiting the development of the algae during the vegetation period was a deficiency of phosphates. In the Kličava Reservoir this was the only factor limiting the development of algae throughout the investigation period, while in the Slapy Reservoir it did not depend on the concentration of phosphorus in the water until the end of the growing season. The optimum concentration of P—PO_4 at which the algae attained their maximum numbers varied from 50 to 100 μg dm^{-3}. After limitation of P—PO_4 *Fragilaria* maintained its position among the dominants while *Chrysococcus* and *Cryptomonas* disappeared, but another diatom, *Stemphanodiscus hantzschii,* appeared.

The algae given both by Štěpánek et al. (1983) and Komárková (1974) which formed water blooms at this time or were present in considerable quantities in Czech dam reservoirs are numerously found in Polish reservoirs also. In Poland, however, the same genera (of chrysophytes or cryptomonads) were represented by other species (*Chrysococcus minutus*).

The intensive appearances of blue-green algae in meso- and eutrophic dam reservoirs lying in the European part of the USSR on mighty lowland rivers (the Volga, Dnieper, and Don), were the subject of Gusyeva's studies (1965). She drew attention to the specific environmental conditions which exist there and affect the occurrence of water blooms. Their intensity was not uniform in reservoirs situated on the same river but in a different geographical zone (e.g. the Rybinsky Reservoir lying farthest to the north, in the coniferous forest zone). The water blooms formed here were not as profuse as those in the Kuybyshevsky Reservoir or the Volgogratsky one occupying forest-steppe and steppe regions, with the surface waters richer in nutritive substances. In the Rybinsky Reservoir the maximum numbers of blue-green algal cells per cm^3 of water did not exceed $8 \cdot 10^4$ while in the Kuybyshevsky Reservoir they reached $3 \cdot 10^5$ (mainly in its bays).

Gusyeva contrasted this to reservoirs of the oligotrophic type (dam reservoirs of the Caucasus, among others the Khramsky Reservoir), fed by mountain waters which were very turbid but had a low nutrient content, in which water blooms are not recorded or are rare. She stressed that in large dam reservoirs fluctuations in water level had no influence on the intensity of water blooms, the opposite being true in mid-current (the Rybinsky Reservoir). Their effect was marked in small reservoirs (the Uchinsky Reservoir), but in others only in their littoral regions. Gusyeva (1965) reported that with a decrease in the velocity of the current the numbers of blue-green algae increase (the shallower regions of the Rybinsky Reservoir). Generally speaking their maxima occur in August, but sometimes a little earlier (June and July) or later (September and October).

In dam reservoirs on lowland rivers, Gusyeva (1965) listed about 10 species of algae causing water blooms. Most frequent was *Aphanizomenon flos-aquae*, constituting the main mass of the phytoplankton in reservoirs on the Volga. Of other blue-green algae, the following should be listed: *Microcystis aeruginosa, Coelosphaerium dubium, Gomphosphaeria lacustris, Woronichinia naegeliana, Anabaena spiroides, A. scheremetievi, A. flos aquae* with the forms *A. lemmermannii* and *A. hassalii*, and *Oscillatoria aghardii*, noted only once in the small Uchinsky Reservoir.

From the above compilation it can be seen that some of the algae listed are also found in masses in Polish dam reservoirs.

Margalef et al. (1976) were interested in a similar phenomenon of the abundant development of algae but from different groups of phytoplankton in dam reservoirs in Spain. The authors carried out limnological studies in 105 dam reservoirs differing with respect to the geology of the regions of that country, classifying them into six groups according to increasing trophy. Dam reservoirs of high mountain regions were distinguished, built on crystalline rocks rich in silica, with a low mineralization and poor fertility (Groups I—III) and dam reservoirs lying in upland or lowland areas, built of sedimentary rocks (Groups IV—VI). The latter type of waters showed greater calcium concentrations with concurrently large amounts of magnesium and greater resources of nutrients than the waters of the mountain region.

In algal associations of reservoirs of Group I—III, with a decrease in alkalinity a decided dominance was found of the diatoms *Melosira granulata, Asterionella formosa, Fragilaria crotonensis*, and *Tabellaria flocculosa*, with a smaller quantity of *Eudorina elegans* of the volvocalean algae and *Gomphosphaeria lacustris* and *Microcystis aeruginosa* of the blue-green algae. In contrast, in the algal associations of the highly mineralized dam reservoirs of Groups IV—VI with increased eutrophy, the abundant occurrence of the dinoflagellate *Ceratium hirundinella* and the diatoms *Cyclotella ocellata, Melosira granulata, Asterionella formosa* and, in smaller numbers, the chlorococcous green algae *Pediastrum clathratum* and *P. boryanum* was observed, and of the blue-green algae, *Oscillatoria rubescens* and *Microcystis aeruginosa*. Altogether, in the phytoplankton of the dam reservoirs studied the mentioned authors distinguished over 700 species of algae, giving for comparative purposes the number of 467 algal species found in the Rybinsky Reservoir.

In should be stressed that in the dam reservoirs of southern Poland instances of more advanced eutrophication occurred chiefly in periods of the mass development of algae, especially *Microcystis aeruginosa* and, in recent studies, *Aphanizomenon flos-aquae*. The former did not occur in such abundance in the dam reservoirs of Spain, while the latter was not recorded at all. Moreover, in Polish dam reservoirs much greater numbers of chlorococcous green algae were found and smaller ones of volvocalean green algae which in Spanish reservoirs of increased trophy played no significant role. A greater quantity of chlorococcous algae in Polish dam reservoirs (especially the genera *Scenedesmus, Coelastrum, Pediastrum* which adapted readily to changing environmental conditions) is probably connected with the plentiful resources of nutrients, maily nitrates (B o m b ó w n a 1985).

The mass development of algae in dam reservoirs of Westphalia (B e r n h a r d t, C l a s e n 1981) aroused much interest, particularly towards the end of the 1960's and in the beginning of the 1970's, owing to the problem of water quality. In 1970, in the previously eutrophic Wahnbach Reservoir, near Bonn, a mass appearance was noted of the blue-green alga *Oscillatoria rubescens,* in numbers varying from $2 \cdot 10^7$ to $2 \cdot 10^8$ cells dm^{-3} of water, this leading to blockage of the filters and endangering human life. Troublesome water blooms were also caused by another alga, *Coelosphaerium naegelianum,* and the large diatoms such as *Melosira italica.* The excessive development of the latter was accompanied by a foul taste and smell of the water, which came from organic amine compounds released by it into the water. Earlier investigations by N u s c h (1975) in this dam reservoir disclosed the increased occurrence of other algae besides the above-mentioned one, such as diatoms of the genera: *Melosira, Fragilaria, Asterionella* and *Diatoma,* with the dinoflagellates *Gymnodinium helveticum* and *Ceratium hirundinella.* Their greatest development, taking place in the summer of 1970, was marked in their biomass, which amounted to 650 cm^3 m^{-2}, with a minimum of 20 cm^3 m^{-2}. The maximum chlorophyll content was from 30 μg dm^{-3} to 70 μg dm^{-3}. In turn, in July 1970, in the most eutrophic Möhne Reservoir, a water bloom caused by the blue-green alga *Microcystis aeruginosa* was observed. The maximum content of chlorophyll "a" being 59 μg dm^{-3} and the mean one 17 μg dm^{-3} in the vertical profile. Owing to the operation of the treatment plant built there (Phosphorus Elimination Plant), a reduction took place in the mean annual phosphate concentration, this being 16—26 μg P dm^{-3} to 6—10 μg P dm^{-3} in 1980, which in the case of the Wahnbach Reservoir led to recession of the mass appearance of blue-green algae.

From the above data it is clear that some of the algal species from among those dominating in the seventies in artificial reservoirs in W. Germany occurred also in Polish dam reservoirs. Above all, the blue--green alga *Microcystis aeruginosa* should be mentioned here (currently maintaining a temporary dominance in Polish reservoirs), the dinoflagellate *Ceratium hirundinella* and, of the diatoms, mainly the genus *Asterionella.* Meanwhile, the genus *Melosira* is in Poland still profusely represented only by the species *M. granulata* with the variety *M. granulata* var. *angustissima,* similarly as the genus *Fragilaria.* Moreover among the algae developing in masses in the German reservoirs, chlorococcous green algae were not reported (organisms indicatory of plentiful resources of nutrients rich in nitrates), contrary to the situation in Polish dam reservoirs.

5. Synthetic remarks

The periodic investigations carried out to date by various authors and relating to the structure and dynamics of phytoplankton development in the dam reservoirs of southern Poland yielded the following data on species of planktonic algae causing water blooms:
— in lowland dam reservoirs of the limnic type, the most frequently appearing species was the blue-green alga *Microcystis aeruginosa* (e.g. Goczałkowice Reservoir). The blue-green alga *Aphanizomenon flos-aquae* formed water blooms both in the lowland, limnic reservoirs and in a submontane one of the rheolimnic type (e.g. Rożnów Reservoir);
— in lowland, limnic reservoirs of the pond type the formation of surface water blooms with a decisive share of the blue-green alga *Microcystis* was dependent on the concentration of nutrients. Also favourable to them was a sufficient number of gas vacuoles in the cell protoplasm regulating the buoyancy of these algae, a streamlined shape of the colony, suitable climatic conditions, and a low turbulence of the water;
— similarly in a rheolimnic submontane reservoir, the formation of a water bloom by the blue-green alga *Aphanizomenon* was also connected with a high concentration of nutrients (nitrates, phosphates, and calcium bicarbonate). The greatest abundance of this species was recorded in the backwaters of the Rożnów Reservoir (quiet zone distant from the old riverbed), this evidencing its attachment to stagnant waters;
— out of 7 dam reservoirs studied in various years, neither in the Czaniec Reservoir nor in the Czchów one was a mass appearance of algae observed, only periodically their more numerous occurrence. This indicated a decrease in trophy in the cascade of the Soła and in the Czchów Reservoir, lying below the Rożnów one;
— the mass appearances of planktonic algae in dam reservoirs are also connected with the time of water retention and the age of the reservoir (single-species water blooms being more frequent in the first years following impoundment and, mixed ones usually later). Of the reservoirs investigated, the Goczałkowice Reservoir was the most favourable for algal development;
— the species composition of the algae forming water blooms, similar to that noted in Polish dam reservoirs, was found mainly in the dam

reservoirs of Czechoslovakia, a different one being observed particularly in Spanish reservoirs;
— of the algae developing in masses in the dam reservoirs of West Germany, first recorded were the blue-green alga *Microcystis aeruginosa* and the absence of chlorococcous green algae, which are indicators of high nitrate content. However, in recent years following the commissioning of a sewage treatment plant, the above blue-green alga has almost completely disappeared from the German reservoirs, while in Poland it continues to form periodic water blooms.

From the present review it can be seen that the knowledge concerning the causes of formation of water blooms, especially those with a predominant share of blue-green algae, in Polish dam reservoirs is still incomplete. It is not uncommon for the consequences to be taken as the causes of the mass appearance of algae (increase in pH). Moreover, the comparison of water blooms in limnic and rheolimnic reservoirs is impeded, because the existing results of algological research concern various stages of water blooms, found only incidentally during investigations on the dynamics of phytoplankton production. In new studies, therefore, particular attention should be paid to tracing the development of water blooms. Interdisciplinary investigations would be helpful here in obtaining more accurate data, taking into account also the role of pathogenic organisms (mainly parasitic fungi and protozoans) in the development of planktonic algae, especially during their mass occurrence and sudden dying off of the population.

Acknowledgements — The author would like to express her sincere gratitude to the Head of the Institute of Freshwater Biology of the Polish Academy of Sciences, Prof. Władysław Grodziński, for encouragement given during the preparation of this paper.

She is also greatly obliged to Dr Maria Bombówna for valuable comments to the analysis of her chemical data, and also to Dr Irena Spodniewska for helpful advice contained in her review.

Many thanks are also due to the Editorial Board of "Acta Hydrobiologica" — particularly to the Editors Prof. Ryszard Sowa, and Prof. Jan Włodek, for their useful comments and editing advice.

6. Polish summary

Ekologiczne aspekty masowego pojawu glonów planktonowych w zbiornikach zaporowych południowej Polski

Podsumowano dane o niektórych glonach planktonowych, tworzących zakwity wody (tabela I), na podstawie badań fitoplanktonu zarówno własnych, jak i innych autorów. Rozważono pojęcie „zakwitu wody", podając kryteria jego oceny oraz najczęściej spo-

tykany skład jakościowy, w oparciu o literaturę polską i obcą. Przeprowadzono dyskusję, analizując warunki powstawania zakwitów (głównie na przykładzie sinic) na tle poglądów różnych autorów.

Wyróżniono 17 gatunków glonów i 2 odmiany spośród sinic, kryptomonad, bruzdnic, złotowiciowców, okrzemek i zielenic, powodujących zakwity wody (ryc. 1—7). Niektóre glony tworzyły albo jednogatunkowe, albo mieszane dwu- i wielogatunkowe zakwity wody w dwóch typach zbiorników zaporowych — limnicznych i reolimnicznych. Jednogatunkowe zakwity z dominacją sinic (*Anabaena scheremetievi, Aphanizomenon flos-aquae*), złotowiciowców (*Mallomonas caudata*), okrzemek (*Asterionella formosa, Fragilaria crotonensis*) i bruzdnic (*Ceratium hirundinella*) notowano zazwyczaj w początkowych latach istnienia danego zbiornika, a mieszane częściej w dalszych latach po zalewie. Tworzyły je razem spośród kryptomonad — *Cryptomonas erosa*, okrzemek — *Cyclotella comta*, złotowiciowców — *Chrysococcus minutus*, sinic — *Microcystis aeruginosa, Aphanizomenon flos-aquae* i zielenic — *Scenedesmus quadricauda* var. *maximus*. Stwierdzono, że te same gatunki (*Microcystis aeruginosa*), wywołujące jednogatunkowe zakwity wody w danym zbiorniku zaporowym, wykształcały również i mieszane zakwity wody (*Microcystis aeruginosa* i *Anabaena spiroides*) w innym lub tym samym zbiorniku, ale w innym okresie, jak sinica *Aphanizomenon flos-aquae*.

Największą biomasę osiągnęła bruzdnica *Ceratium hirundinella* w wyrobisku piaskowym Chechło-Nakło i *Aphanizomenon flos-aquae* w zbiorniku Rożnowskim. Największą produkcję w całym słupie wody stwierdzono w zbiorniku w Tresnej podczas czerwcowego zakwitu z udziałem *Asterionella formosa* i *Cryptomonas erosa*, które decydowały o wielkości całkowitej biomasy fitoplanktonu. Największą wartość wilgotnej masy całego fitoplanktonu, jak też największą zawartość chlorofilu zanotowano w lipcu w zbiorniku Goczałkowickim w czasie mieszanego zakwitu złożonego z gatunków: *Cyclotella comta, Chrysococcus minutus, Asterionella formosa*. Udział większych zielenic chlorokokkowych z rodzajów *Scenedesmus* i *Pediastrum*, towarzyszących temu zakwitowi, wpływał wyraźnie na wielkość biomasy i zawartość chlorofilu w powyższym zbiorniku.

W zbiornikach zaporowych, nizinnych, limnicznych, typu stawowego, powstaniu zakwitów wody z decydującym udziałem sinic (*Microcystis*), oprócz koncentracji składników pokarmowych, sprzyjały: budowa komórek *Microcystis* (gazowe wakuole — mechanizm kontroli pławności, opływowy kształt kolonii, słaba turbulencja wody oraz odpowiednie warunki klimatyczne). Podobnie w zbiorniku podgórskim, reolimnicznym, utworzenie zakwitu wody przez sinicę *Aphanizomenon* łączyło się z dużą koncentracją składników pokarmowych (azotanów, fosforanów i kwaśnych węglanów wapnia). Ogólnie w obu typach zbiorników zaporowych, zakwity wody były uzależnione przede wszystkim od koncentracji składników pokarmowych, a ponadto od czasu retencji wody i wieku zbiornika.

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