Seasonal dynamics of phytoplankton in the inner Neva Estuary in the 1980s and 1990s*

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Vera N. Nikulina
Zoological Institute,
Russian Academy of Sciences,
Universitetskay nab. 1, 199034 St. Petersburg, Russia;
e-mail: micropl@zin.ru

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Abstract

The phytoplankton in the inner Neva Estuary is described from data obtained from 1996 to 2000. The seasonal dynamics of the phytoplankton biomass are characterized by a bimodal curve with a summer maximum. The average seasonal biomass was approximately 3 mg l^{-1}, the maximum biomass was 8–11 mg l^{-1}.

The species composition and quantitative parameters were compared to those observed in the 1980s. A notable, nearly 1.5–2 fold, increase in the biomass in the summer–autumn period and the predominance of *Oscillatoria* species among the blue-green algae were observed. A decline in the nutrient load in the water body at the end of the 1990s appeared to be insufficient to bring about a decrease in the proportion of *Oscillatoria* algae in the total species composition or a decline in the biomass of the entire phytoplankton community.

In 2000 a certain change in the structural composition of the phytoplankton complex was noted. Species that had been predominant in the 1980s and had lost their advantage in the early 1990s, regained their earlier status.

1. Introduction

The River Neva estuary is divided by natural and artificial boundaries into an upper part (the Neva Bay) and a lower part – the inner and outer

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estuary (Panov et al. 2002). These regions differ essentially in the abiotic and structural-functional characteristics of the ecosystem. The lower part of the estuary is characterized by a zone of mixing of freshwaters and brackish waters – the salt barrier. A characteristic feature of this barrier is a higher concentration of living organisms, the so-called 'biological plugs' (Lisitzin 1999, Golubkov et al. 2001). The biological barrier coincides with the hydrodynamic barrier situated in the shallow water region. The hydrodynamic barrier is characterized by circulation currents covering the entire water layer (Gorbatsky et al. 1997).

The northern shallow-water part of the Gulf of Finland is a resort area of St. Petersburg subject to strong anthropogenic impact. The functioning of this ecosystem is affected not only by the use of the coast as a resort area, but also by the hydraulic structures. Construction of the flood protection barrier has somewhat altered the hydrodynamic conditions in the eastern part of the Gulf of Finland.

A quasi-stationary vortex structure brought about by the transit current of Neva water and the flow of brackish water from the Gulf of Finland along the northern coast was formed under natural conditions in the shallow water zone (Znamenskiy 2000).

The above-mentioned characteristics of this water area and the anthropogenic impact favour formation of a rich phytoplankton complex, which has a great impact on the functioning of the entire lower part of the estuary ecosystem.

The phytoplankton of the Neva Bay and the eastern part of the Gulf of Finland has been studied continuously by the author from 1982 up till the present. Current and previous studies (Nikulina 1987, 1991, 1996, Shishkin et al. 1989, Telesh & Nikulina 1997, Nikulina et al. 1999) conducted in the estuary of the Neva River permit us to make comparisons and assess the changes that occurred in phytoplankton community during two stages of the 'technogenic period' (Alimov et al. 1996).

In the 1980s the first stage was characterized by the construction of a number of hydraulic structures within the entire water system. It included the erection of dams for the flood protection barrier and the completion of the major structures in 1986, the implementation of the second stage of the Central Aeration Station and the construction of the Northern Aeration Station situated in the Neva Bay.

The second stage is the 1990s, when new hydrological conditions were established under which the composition of plankton communities was to become stabilized.

Detailed seasonal observations on the phytoplankton of the shallow water region of the eastern part of the Gulf of Finland were conducted from 1982 to 1989, during the period of the dam construction, and from 1996 to 2000.

The task of the study was to discover the patterns of the dynamics of the structural and quantitative parameters of planktonic algae in the northern resort region in the eastern part of the Gulf of Finland during the growing seasons from 1996 to 2000, and to compare the present state of the phytoplankton community with that observed in the 1980s.

2. Material and methods

The station (F 21) chosen for the permanent observations was situated at a distance of approximately 6 km from Zelenogorsk (60°06′N, 29°42′E). The depth was 15 m, the salinity in the surface layer varied from 0.3 to 1.7 PSU, the Secchi depth was 1.7–2.0 m, the temperature stratification was established at the beginning of July with a thermocline at a depth of 8–10 m. According to previous studies carried out on all water areas of the eastern part of the Gulf of Finland this station is typical of the state of the planktonic ecosystem of the inner Neva estuary (Fig. 1).

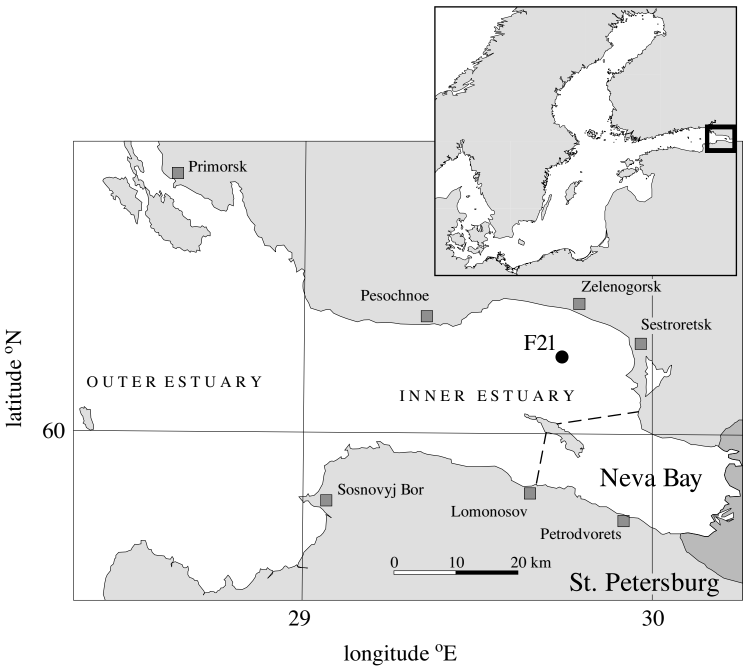

Fig. 1. Study area, F 21 – permanent sampling station

Phytoplankton samples were collected using a bathometer from the uppermost (0–3 m) water layer from the middle of May until October every two weeks. Phytoplankton was counted in sedimentation chambers using an inverted Hydro-Bios microscope according to the method of Utermöhl (1958). Those species numbers and/or biomasses, which at a certain period exceeded 10% of the total number or biomass, were regarded as predominant.

3. Results

The phytoplankton of this region is varied in composition and is represented by more than 200 species and varieties of algae. 31 species are considered as predominant for the period from 1997 to 2000 (Table 1).

The data on the spring complex of phytoplankton in the shallow region of the eastern part of the Gulf of Finland are represented in our research by the samples selected in May. Normally at this time, the spring

Table 1. Maximum number (10^3 cells l^{-1}) of dominant phytoplankton species, 1997–2000

Species	Spring	Summer	Autumn
Cyanophyta			
Anabaena circinalis Rabenh.	–	13482	3090
Anabaena flos-aquae (Lyngb.) Breb.	–	26760	623
Aphanizomenon gracile Lemm.	–	16080	2295
Aphanizomenon flos-aquae (L.) Ralfs	300	10314	3132
Aphanothece clathrata W. et G. S. West	–	2400	70
Limnothrix planctonica (Wolosz.) Meff.	3200	21400	8292
Merismopedia punctata Meyen	–	540	120
Microcystis aeruginosa Kutzing	900	27000	9760
Nodularia spumigena Mertens	79	813	317
Planktolyngbya limnetica (W. West) Anagn. a. Komarek	5000	75400	29700
Planktothrix agardhii (Gom.) Anagn. a. Komarek	310	23580	24345
Snowella lacustris (Chod.) Komarek et Hindak	6	5280	765
Chrysophyta			
Dinobryon divergens Imh.	21	528	28
Uroglena americana Calkins	180	228	30

Table 1. *(continued)*

Species	Spring	Summer	Autumn
Bacillariophyta			
Asterionella formosa Hass.	–	338	66
Aulacosira islandica O. Mull.	538	7	109
Diatoma elongatum (Lyngb.) Kutz.	2145	92	76
Fragilaria crotonensis Kitt.	210	35	93
Skeletonema subsalsum (Cl.) Bethge	–	23000	58
Tabellaria fenestrata (Lyngb.) Kutz.	11	116	28
Xanthophyta			
Tribonema affine West	2	594	54
Cryptophyta			
Chroomonas acuta Uterm.	260	1800	474
Cryptomonas erosa Ehr.	13	60	192
Cryptomonas marssonii Skuja	–	204	32
Cryptomonas ovata Ehr.	6	28	154
Dinophyta			
Peridiniella catenata (Lev.) Kof.	72	4	9
Euglenophyta			
Trachelomonas volvocina Ehr.	4	240	102
Chlorophyta			
Actinastrum hantzschii Lagerh.	–	336	288
Dictyosphaerium pulchellum Wood	–	768	82
Micractinium pusillum Fres.	–	1152	390
Monoraphidium contortum (Thur.) Kom.-Leg.	54	1584	350

water bloom is practically over. In May, freshwater species of the spring planktonic complex *Diatoma elongatum*, *Aulacosira islandica*, and normal representatives of the deep-water part of the Gulf of Finland, brackish water species *Peridiniella catenata* and sometimes the blue-green *Nodularia spumigena* retain their predominant role. The cryptophytes *Cryptomonas marssonii*, and *Chroomonas acuta* formed a large proportion of the total biomass in the late spring; in 1998, this proportion was particularly large, approximately 70% of the total biomass 1998. It should be noted that in the May samples the blue-green algae *Limnothrix planctonica* and *Planktolyngbya limnetica* attained from 3.6–5 $\times$ 10^6 cells l^{-1} to 5 $\times$ 10^6 cells l^{-1}, numbers of no mean significance.

In the summer the phytoplankton attained its greatest diversity. Nearly all the species given in Table 1 were predominant, except for the diatoms and dinophytes characteristic of the spring complex. The maximum diversity was represented by *Chlorophyta* (73 species), but they always played a only small role in the total biomass of phytoplankton. Apart from species that by their numbers were regarded as predominant, species of the genera *Coelastrum*, *Oocystis*, *Scenedesmus* and *Sphaerocystis*, and also filamentous forms of the green algae *Spirogyra* and *Mougeotia* were permanently present.

Of the diatoms, *Skeletonema subsalsum* was predominant in the summer complex. In the 1990s right through to 2000 the significance of this species in particular increased.

Maximum numbers of all predominant species of *Cryptophyta* in the inner Neva Estuary from 1997 to 2000 declined. Abundant growth of cryptophytes within the entire aquatic system from Lake Ladoga to the deep-water part of the Gulf of Finland was noted by the beginning of the 1990s and was interpreted as an indicator of the organic matter load on the system (Basova & Lange 1998, Trifonova et al. 1998).

The blue-green algae were predominant in the summer plankton complex throughout the research period. They constituted more than 90% of the abundance and sometimes of the total phytoplankton biomass (August 1999). A high abundance was noted for the filamentous forms *L. planctonica*, *P. limnetica*, but because of the small width of the trichomes (1.5–2.5 μm), their contribution to the biomass was insignificant. The species *Planktothrix agardhii* of the *Oscillatoria* complex has been predominant in the Gulf of Finland in summer since the late 1980s. The species *Aphanizomenon flos-aguae*, *Aphanizomenon gracile*, *Anabaena circinalis* and *Anabaena flos-aquae*, which can cause a surface water bloom, have been much less abundant.

The typical autumn complex in the shallow water zone of the Gulf of Finland was most often not observed. In October a gradual decline in the numbers of all species and a very slight increase in diatoms *A. islandica* occurred.

The biomass of phytoplankton and the proportion of the different divisions of algae for the past four years are given in Table 2. As can be seen from the biomass values, the most productive months were July to September. In 2000 the phytoplankton biomass was twice as high as compared to the previous years: this was due not only to the abundant growth of blue-green algae, but also of diatoms *S. subsalsum*.

Table 2. Total phytoplankton biomass, biomass of different algal groups, and the percentage of the total

Year	Biomass	Cyano-phyta	Bacillario-phyta	Crypto-phyta	Chloro-phyta	Eugleno-phyta	Others
month	[mg l^{-1}]	[%]					
1997							
May	1.61	3.7	73.7	18.5	3.5	0.4	0.2
June	0.52	42.0	21.4	27.9	5.8	–	2.9
July	2.85	48.0	10.2	17.3	16.8	6.8	0.9
August	3.66	59.4	14.2	13.9	9.3	0.5	2.7
September	2.91	33.3	42.7	12.2	5.8	0.1	5.9
October	0.48	16.2	60.7	9.5	13.6	–	–
Mean	**2.11**	**37.5**	**31.8**	**16.4**	**10.2**	**1.3**	**2.1**
SD	0.35	6.2	8.6	3.6	2.4	1.2	1.0
1998							
May	1.78	0.8	27.7	69.8	1.7	–	–
June	1.08	38.5	21.9	18.0	10.0	0.3	1.3
July	3.34	76.8	4.1	11.1	7.1	0.1	0.8
August	1.82	84.9	12.6	1.9	0.5	–	0.1
September	4.85	94.4	2.8	2.5	0.3	–	–
October	1.48	84.8	1.9	12.3	1.0	–	–
Mean	**2.39**	**63.5**	**11.8**	**19.3**	**3.4**		
SD	0.67	16.2	4.6	12.0	1.2	–	–
1999							
May	0.66	0.7	66.4	20.4	11.9	–	0.6
June	1.37	51.3	1.9	27.2	8.9	0.5	0.2
July	1.79	59.2	0.5	26.5	13.4	–	0.4
August	5.18	94.4	1.6	1.5	1.0	0.2	1.3
September	2.29	87.2	3.4	3.2	2.4	3.8	–
October	1.46	80.4	5.9	6.7	7.0	–	–
Mean	**2.55**	**57.6**	**13.3**	**14.2**	**7.4**		**0.4**
SD	0.59	16.9	10.6	4.5	2.2	–	1.5
2000							
May	1.78	15.1	48.0	2.8	22.8	–	11.3
June	0.65	35.7	2.1	22.0	35.1	5.1	–
July	6.0	78.0	10.0	2.4	7.2	1.2	1.2
August	6.97	62.0	32.1	1.1	2.1	0.4	2.3
September	5.53	72.5	18.5	2.2	6.2	0.2	0.4
Mean	**4.44**	**57.8**	**18.1**	**7.0**	**14.2**	**0.8**	**3.0**
SD	0.8	7.2	4.9	3.5	4.2	0.5	2.4

In the 1980s the seasonal dynamics of the phytoplankton was represented by a bimodal curve: the period of depression following the spring bloom continued practically until the end of June, while the average summer –autumn biomass was approximately 2 mg l^{-1} (Fig. 2). At the end of August and throughout September a water 'bloom' caused by the blue-green algae *Aph. flos-aquae*, *Microcystis aeruginosa*, *A. flos-aquae* characteristic of mesotrophic water bodies took place. At first filamentous algae developed, then coccoid forms. The algae *L. planctonica*, *P. agardhii* of the *Oscillatoria* complex were ever-present, but did not form predominant assemblages.

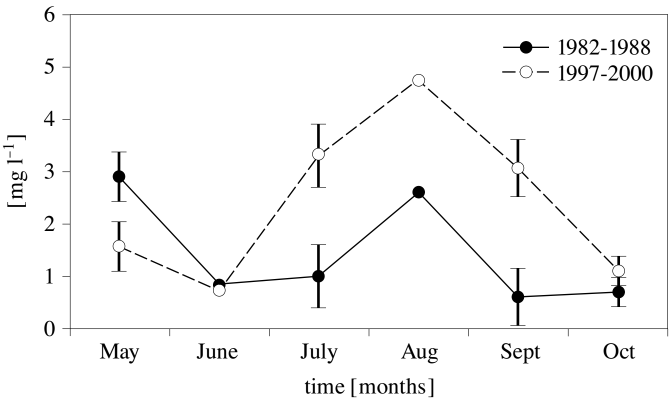

Fig. 2. Seasonal dynamics of the total biomass phytoplankton

Table 3. Total phytoplankton biomass and portion biomass different algal groups 1982–1988

Month	Biomass	Cyano-phyta	Bacillario-phyta	Crypto-phyta	Chloro-phyta	Eugleno-phyta	Others
	[mg l^{-1}]	[%]					
May	2.9	3	75	12	2	–	8
June	0.7	10	40	5	43	–	2
July	1.17	39	38	3	17	1.5	1.5
August	2.6	46	45	2	6	0.2	0.8
September	0.82	20	69	1	2	–	8
October	0.9	11	74	2	8	–	5
Mean	**1.52**	**21.50**	**56.83**	**4.17**	**13.00**	–	**4.22**
m	0.20	3.53	3.66	0.83	3.20		0.67

m – mean error

In the 1990s the *Oscillatoria* complex became predominant in the summer–autumn period. The species composition of the blue-green algae had undergone hardly any changes during the summer and autumn, and blue-green algae were predominant as early as the beginning of June.

In the seasonal development of phytoplankton there occurred a more protracted period of high summer biomasses (2–7 mg l^{-1}) characteristic of eutrophic water bodies. Tables 2 and 3 show the ratio of different groups of algae in the total biomass for both investigation periods. An abrupt increase of the proportion of blue-green algae and cryptophytes and a decrease in bacillariophytes in the 1990s is noted.

4. Discussion

It is known that the indicator of eutrophication of water bodies in mid-latitudes is the summer–autumn water 'bloom' of blue-green algae. Maximum development of phytoplankton occurred in the northern shallow water zone of the Gulf of Finland, where water 'blooms' caused by blue-green algae have often been observed (Nikulina 1989). When the predominant composition of blue-green algae in the 1980s is compared to that of the 1990s, we see that maximum values increased abruptly in 1987 and 1989 after the dams were completed. In the 1990s, when the seasonal dynamics of the phytoplankton was studied, high average and maximum biomasses of blue-green algae were always recorded. Changes have taken place in the structural composition of the predominant species of blue-green algae. Species of the genus *Anabaena* that had not been a part of the predominant complex became permanent components of it in 1998–2000. *M. aeruginosa* has not been recorded as being predominant since 1996. The part played by *P. agardhii*, an indicator alga of organic pollution, increased considerably in the 1990s. The nature of the seasonal dynamics of the various species of blue-green algae is presented in Fig. 3.

Thus, from July to October in the years 1996 to 2000 blue-green algae comprised more than 70% of the phytoplankton biomass in the shallow water region of the eastern Gulf of Finland. The species composition of the algae was such that in spite of the relatively high biomass, hardly any water 'bloom' was observed. A peculiarity of the phytoplankton in the eastern Gulf of Finland in the 1990s was the dominance of the blue-green alga *P. agardhii*. This species spread throughout the Gulf of Finland and occurred in both fresh and brackish waters (Kauppila et al. 1995, Nikulina 1996, Makarova 1997, Basova & Lange 1998).

Only in 2000, when species of the genera *Anabaena* and *Aphanizomenon* were predominant, were periods of insignificant water 'bloom' noted. The causes and factors responsible for the abundant growth of blue-green

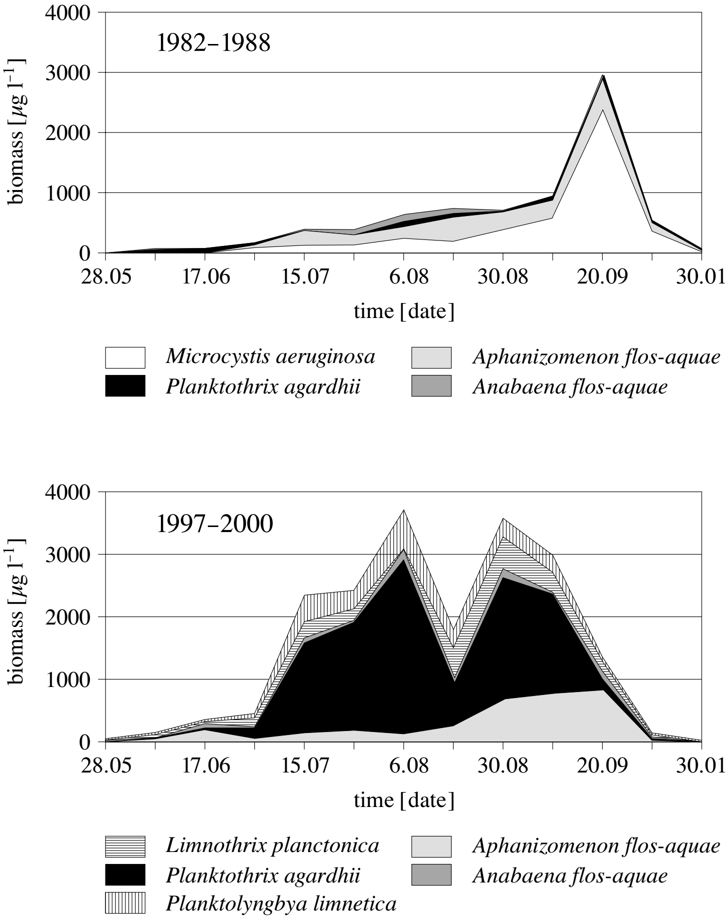

Fig. 3. Seasonal dynamics of dominant Cyanophyta species

algae have been considered in a large number of works. Reproduction of algae is most frequently associated with enrichment of waters by nitrogen and phosphorus. Moreover, of great importance are the temperature, the nitrogen : phosphorus ratio in water, the low light demand of blue-green algae, their inefficient consumption by zooplankton filterers, etc. When hypotheses explaining the water 'bloom' are generalized and checked, particular emphasis is placed on the nitrogen : phosphorus ratio in addition to the nutrient content (Varis 1993, Blomqvist et al. 1994). The water 'bloom' in the eastern Gulf of Finland consists mainly of nitrogen-fixing species such as *Anabaena* spp., *Aphanizomenon* spp. and *N. spumigena*. These algae have heterocysts, which can use N_2 from the air. As a rule, the water 'bloom' occurs when the ratio of dissolved mineral nitrogen and dissolved mineral phosphorus is low, i.e. < 20.

Of particular interest are studies of species shift in the overall blue-green algae complex. Thus, at a low nitrogen : phosphorus ratio in Lake Kasamigaura, *Microcystis* algae were predominant, but a constantly increasing inflow of nitrogen to the lake led to *Microcystis* being substituted by *P. agardhii*. At the same time it was shown that as soon as the flow of waste waters ceased, species of the genus *Oscillatoria* disappeared from the lake and the abundance of *Aphanizomenon* and *Microcystis* increased (Sakamoto & Okino 2000).

Moreover, for different species it is important which forms of nitrogen are predominant in the pool. The predominance of NH_4 and NO_2 led to the predominance of species of *Microcystis* and *Oscillatoria*, which do not fix nitrogen, while the lack of NO_3 was favourable for the development of *Anabaena* and *Aphanizomenon* species, which are able to fix molecular nitrogen (Blomqvist et al. 1994)

For the past few years, the nutrient load from agriculture and spot pollution sources on the Gulf of Finland has declined steadily. Discharges in 1998 in relation to maximum values were 30% for total phosphorus, 62% for total nitrogen, 53% for ammonium nitrogen, 76% for nitrites, and 89% for nitrates (Kondratyev et al. 1999).

Nevertheless, the changes in the phytoplankton community in the shallow water region of the Gulf of Finland reflects the changes in the nutrient regime in the ecosystem; the altered hydrological situation in the basin had little impact on the structure and quantitative development of phytoplankton. The wide distribution of *Oscillatoria* species suggests the predominance of nitrogen. The proportion of ammonium nitrogen is higher than the level required for the development of *M. aeruginosa*, which was a part of the complex of species predominant among the blue-green algae in the 1980s, while the present nitrogen content favours the development of *P. agardhii*.

Although the composition of the phytoplankton community has changed little in the past 5 years and the biomass in the summer–autumn period is nearly double that recorded in the 1980s, there has been a tendency to return to the earlier structural composition.

In the 2000 season the importance of the diatom *S. subsalsum* increased again. Nevertheless, during maximum development in August 2000 the biomass of this species made up only 27%, whereas from 1983 to 1988 it had been 46.2% of the total (Shishkin et al. 1989).

The proportion of cryptophytes has declined, while blue-green algae capable of fixing molecular nitrogen have increased.

Recent years have witnessed a marked deficiency of oxygen in deep water and anoxia at the bottom in the open, eastern Gulf of Finland.

Under such conditions there is active uptake of phosphorus by the water from the bottom. As a result the N/P-ratio in water is reduced, and this promotes the growth of nitrogen-fixing algae and the water 'bloom' (Pitkänen & Välipakka 1997, Pitkänen et al. 2002).

In the inner Neva Estuary a considerable 'bloom' of *A. flos-aquae* was observed during the particularly warm summer of 2002. The oxygen deficiency in the deep water was not marked, therefore the water 'bloom' was fed by nutrients draining mainly from the Neva Bay. All these algae are indicators of eutrophic conditions in the water body, but suggest that organic pollution has declined to some extent.

Moreover, in recent years there has been a decline in the variability of the phytoplankton biomass calculated as the ratio of minimum and maximum values during the season. In the 1980s from May to October the biomass varied 9 to 22 fold, and in 1997 to 2000 in the same period 9–12 fold. The variability in biomass dynamics increases with pollution and anthropogenic eutrophication (Alimov 2000).

The received data testify to some stabilization of phytoplankton community; however, the stabilization takes place at a higher level of summer –autumn biomass than in the first half of the 1980s.

5. Conclusions

In the plankton of the shallow-water region of the eastern Gulf of Finland 248 species of algae were recorded from May to October in 1996-2000. Of these, 31 species of algae made up more than 10% of the total abundance and/or phytoplankton biomass in different periods. The large-scale growth of blue-green algae throughout the growing season was noted. Species of the order *Oscillatoriales* played the most important role in the blue-green complex.

The seasonal dynamics of the phytoplankton biomass was characterized by a bimodal curve with a maximum in the summer period. The average seasonal biomass was approximately 3 mg l^{-1}, the maximum biomass was 8–11 mg l^{-1}.

As compared to the 1980s there occurred in the study period an increase in the importance of blue-green algae of the *Oscillatoria* complex, the species composition of which remained constant practically during the entire summer–autumn period, and the blue-green algae were predominant already in the first half of June. In the seasonal development of phytoplankton there occurred a longer period of high summer biomass 2–7 mg l^{-1} characteristic of eutrophic water bodies.

The decline in the nutrient load in the water as a result of water protection measures and the decrease in industry in the past decade is insufficient to explain the decline of the level of phytoplankton development.

In 2000 a certain change in the structural composition of the phytoplankton complex was noted. Species that were predominant in the 1980s and lost their advantage in the early 1990s, regained their dominant position.

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