International Council for
the Exploration of the Sea.

C.M.1969/L:15
Plankton Committee, Ref.
Fisheries Improvement Committee.

POLLUTION EFFECT UPON THE PHYTOPLANKTON OF THE OSLOFJORD

by

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In 1917 Professor H.H. Gran observed a somewhat greater abundance in the August phytoplankton near the city of Oslo than further out and attributed it to a supply of nutrients from the city. 15 years later, a general hydro-biological study of the fjord revealed a definite fertilization effect of pollution within the whole inner Oslofjord, inside the Drøbak sound (Fig. 1). Subsequent studies in the thirties gave a rather drastic picture of the eutrophication of the inner fjord in summer. Recently a five years' comprehensive study of the pollution effect upon the inner Oslofjrod has been organized by The Norwegian Water Research Institute and our institute has had the responsibility for the phytoplankton part of the survey (Braarud and Nygaard 1967).

The general picture of the pollution effect upon the phytoplankton which emerged from the surveys in the thirties, presented in a paper from 1945 (Braarud 1945),has not been appreciably altered by the results of the recent survey, except for a clearer demonstration of very pronounced variations from year to year. A main effect was found to be a great abundance in summer of all the main groups, diatoms, dinoflagellates, coccolithophorids and euglenophytes. This is a conspicuous feature on the background of the relative poverty in summer of non-polluted waters of South-Norway in general.

I propose first to comment on the composition of the fjord phytoplankton and shall subsequently deal with the quantitative seasonal variations and their background, supplemented by some remarks on the complications caused by wind transport.

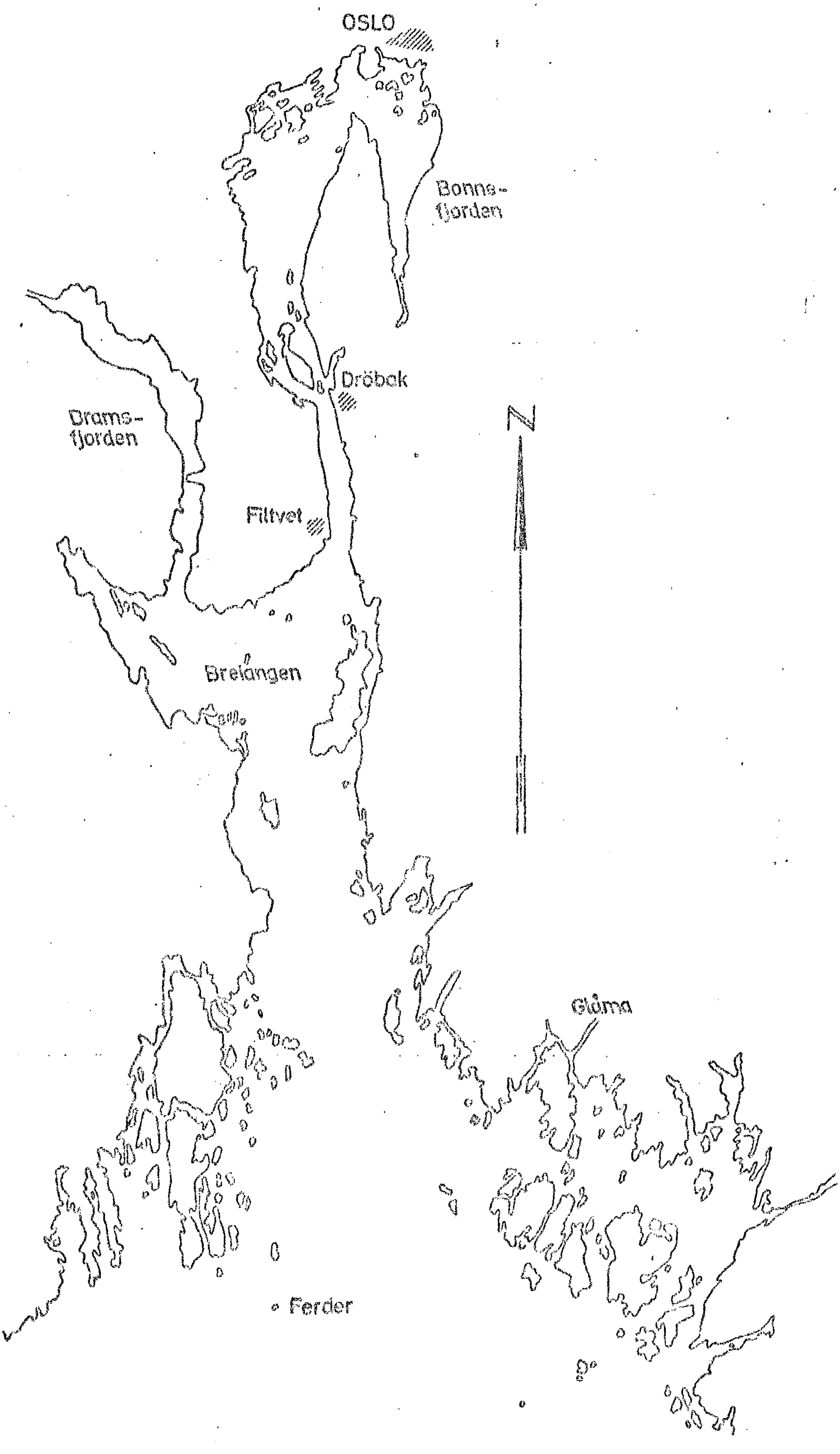


Fig.1 Oslofjorden

1. Composition. - Variations from year to year.

The societies encountered comprise a majority of coastal species, most of them meroplanktonic, with a component of oceanic species which at times may become predominant, such as *Coccolithus huxleyi*. A brackish component is also discernable, which may also reach predominance, as in the case of the diatom *Cyclotella caspia*.

Principally it can be stated that no single species can be regarded as an indicator of the polluted waters. The main pollution effect is found in the quantitative regional distribution pattern of the total population or its predominant species.

A conspicuous variation from year to year in the relative abundance of the various species is a characteristic part of the picture. Such a variation is not specific to polluted waters but it becomes accentuated there since populations become so much larger than in non-polluted waters. The variation occurs in the spring diatom societies as well as in the summer and autumn societies. In most cases it has not been possible to find explanations for the irregular and unpredictable changes in specific composition. As examples we shall consider species from spring, summer and autumn.

Diatom species.

As the most prominent diatom in spring as well as in summer, *Skeletonema costatum* reaches high concentrations every year. Its relative predominance varies, however, greatly.

In Table 1 is given the percentage of *Skeletonema* of the total diatom population during spring in the years 1962-65. If we consider the situation in March, at the peak of the spring bloom, it is seen that the *Skeletonema* percentage varies from only 50% in 1964 to 99% in 1965.

Even more spectacular variations in the diatom population were recorded during the summer. Although *Skeletonema* also at this season is a predominant species, other diatoms may in certain years attain large populations, while in other years the same species may be quite subordinate. Examples are given in Table 2.

Table 1

Variation in the relative abundance of Skeletonema costatum during spring in inner Oslofjord, based upon maximal concentrations at all stations, 1962-65.

Month	All diatoms, cells/l	Skeletonema, % of total
	1962	
January	174 000	90%
March	15 608 500	98%
	1963	
January	2 000	100%
February	3 436 300	85%
March	2 664 500	90%
	1964	
January	13 740	10%
February	189 280	80%
March	7 939 840	50%
	1965	
January	1 364 000	99%
February	7 614 000	99%
March	27 252 000	99%

Table 2

Highest and lowest maximal concentrations of some diatom species recorded during May-September 1962-64 at stations in inner Oslofjord. - Cells/l.

Species	Highest	(year)	Lowest	(year)
Cerataulina bergonii	1 220 000	(1963)	131 000	(1964)
Chaetoceros subsecundus	277 280	(1963)	-	(1962,1964)
Cyclotella caspia	7 570 000	(1964)	356 000	(1963)
Leptocylindrus danicus	4 576 000	(1962)	19 000	(1964)
Nitzschia"delicatissima"	2 377 000	(1964)	30 000	(1962)
Rhizosolenia fragilissima	890 000	(1962)	6 000	(1964)
Thalsssiosira sp.	429 920	(1964)	21 000	(1963)

Ceratia.

The Ceratium populations are known to vary in composition from one year to another in all parts of the Norwegian coastal waters. This is also demonstrated by the data from the Oslofjord in 1962-64, given in Table 3. The variation is especially marked in the two species which attain very large populations.

Table 3

Maximal concentrations of Ceratium species recorded at the stations in inner Oslofjord in the years 1962-64. - Cells/l.

Year	C.furca	C.fusus	C.tripos
1962	134 880	96 320	8 320
1963	320	126 880	2 400
1964	280	1 380	280

Other brown dinoflagellates.

Similar fluctuations occur in the common species Peridinium triquetrum, P.trochoideum and Prorocentrum micans, as shown in Table 4. As we shall see later, some of these fluctuations appear to be related to special conditions each year which influence the general abundance of the whole group, while others apparently act on the species level.

Table 4

Highest and lowest maximal concentrations for Peridinium triquetrum, P.trochoideum and Prorocentrum micans in inner Oslofjord in the years 1962-64. - Cells/l.

Species	Highest (year)	Lowest (year)
Peridinium triquetrum	4 360 000 (1963)	527 000 (1962)
- trochoideum	1 381 000 (1964)	2 000 (1962)
Prorocentrum micans	8 303 000 (1963)	112 000 (1962)

Coccolithus huxleyi

This species is the only coccolithophorid attaining really large populations in the inner Oslofjord. It is a regular member of the summer vegetation but, only in certain years and at irregular intervals, does it occur in such high concentrations that the fjord waters become discoloured. In these cases the water takes on a greenish and later white-greyish colour and becomes very turbid so it is unattractive for bathing. The phenomenon causes great public attention, since the inner Oslofjord is an important recreation area.

In Table 5, quantitative data for C.huxleyi are presented for a section from the inner Oslofjord to the outermost part, Ferder, worked in May, July and August, 1939, which was a typical C.huxleyi year. At all stations the population increased from moderate populations in May to very high ones in early August. At all three cruises the populations were largest inside the Drøbak sound, in the polluted part of the fjord. The maximal concentration recorded i 1939 was nearly 14 mill./l.

Table 5

Coccolithus huxleyi. Distribution in the Oslofjord, May, July and August 1939. - Cells/l. (From Birkenes and Braarud 1952)

Inner Oslofjord			Drøbak Sound	Outer Oslofjord	
Bonnefjord	Nesodden	Steilene		Tofteholmen	Ferder
		20-25 May			
	198 000	104 000		41 000	34 000
		5-12 July			
435 000	358 000	162 000	264 000	264 000	310 000
		2-5 August			
12.8 mill.	13.8 mill.	10.6 mill.	5 mill.	0.4 mill.	3.4 mill.

Table 6 gives the highest and lowest maximal concentrations for six stations in the inner fjord, recorded at seven cruises in the C.huxleyi summer of 1935. It shows a similar seasonal trend as in 1939, with a maximum in early August when the maximum of 33.5 mill./l was recorded. There was a characteristic local variation in the concentrations near the city, as indicated by the difference between maximum and minimum values for each cruise. The latter feature was found in all the more abundant phytoplankton species and is not clearly related to the distance from the main points of sewage discharge.

Unfortunately we do not have regular observations on the occurrence of such C.huxleyi summers. During the 1962-65 survey the concentrations of C.huxleyi were low, the maximum for the period being only 3 mill./l.

The obvious background for the occurrence of large populations of this species in the inner fjord during summer is the nutrient supply through pollution. Variations in the degree of pollution are not, however, responsible for the irregularity in the occurrence of the very large populations. We shall return to this problem later (p. 19), as it is of considerable interest in connection with the practical aspects of the eutrophication caused by sewage.

Table 6

Coccolithus huxleyi. Distribution in Inner Oslofjord, July, August, September, October/November 1935.
Highest and lowest maximal concentrations at six localities.
(From Braarud 1945)

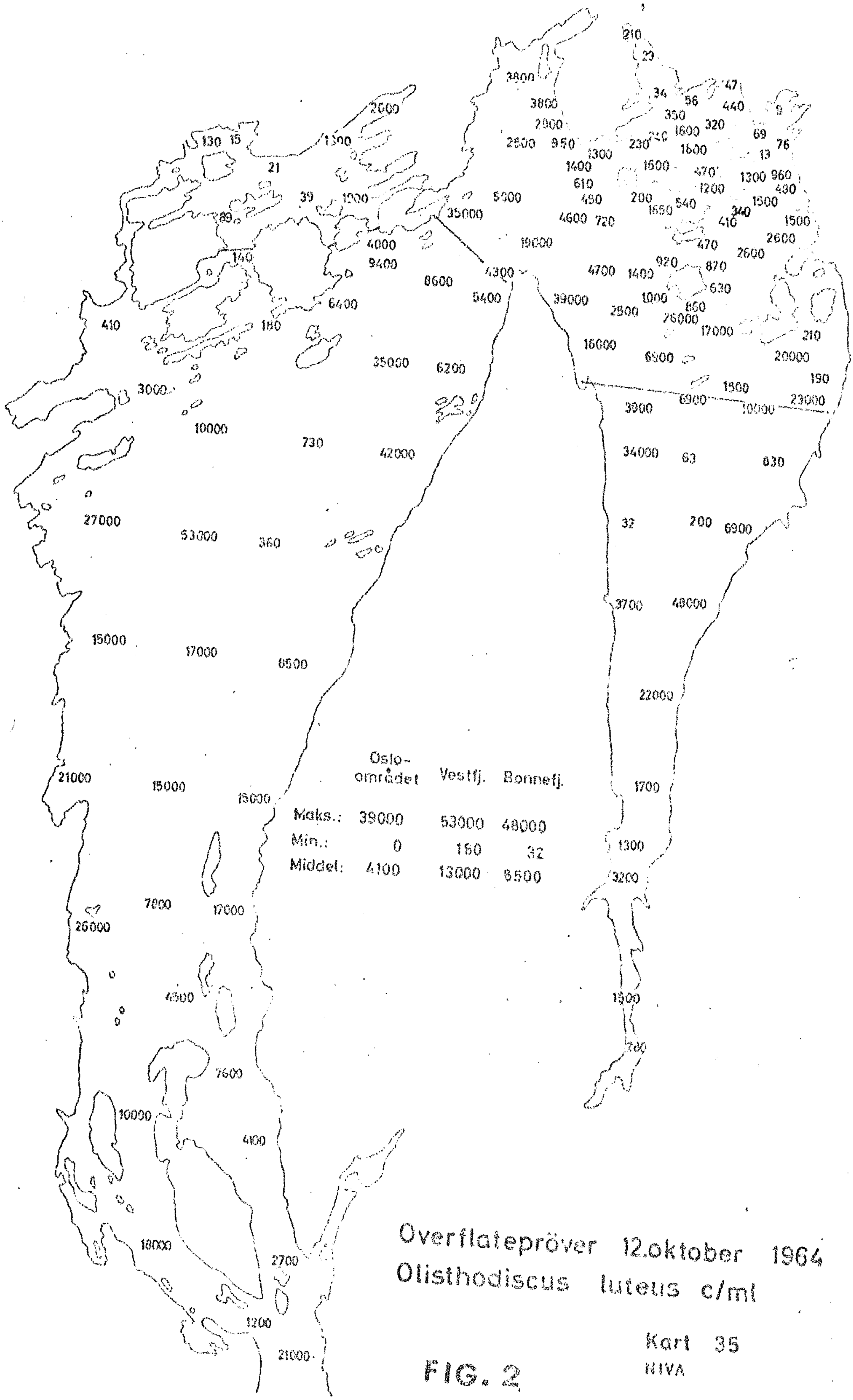
Cruise	Highest	Lowest
13-15 July	6.9 mill./l	0.6 mill./l
7-8 August	33.5 mill./l	7.8 mill./l
20-21 August	10.3 mill./l	1.4 mill./l
5-6 September	4.3 mill./l	0.3 mill./l
26-27 September	0.8 mill./l	0.001 mill./l
31 October/2 November	0.007 mill./l	-

At last an extreme case of variation from year to year may be mentioned, in this case from autumn.

Olisthodiscus luteus.

In October-November the phytoplankton populations are in most years declining. Reduced stability due to cooling and a decline in light supply lead to unfavourable conditions for the photosynthetic forms. However, when clear and quiet weather prevails for some time, growth conditions may allow growth of certain forms, especially motile ones. Large populations of ceratia have occasionally been observed at this time, but the most spectacular case was recorded in 1964, when the water of the inner fjord turned dark brown of huge populations of the small flagellate Olisthodiscus luteus. Maximal concentration was 53 mill./l. This species had not been recorded within the area before but, as it is not easily identified in preserved state, one cannot preclude that it may have occurred in low concentrations also in other years.

In Fig. 2 its distribution is shown for the whole inner fjord. The extreme irregularity in quantitative distribution may be due to the fact that large concentrations were restricted to a thin



	Oslo-området	Vestfj.	Bonnefj.
Maks.:	39000	53000	48000
Min.:	0	160	32
Middel:	4100	13000	8500

Overflateprøver 12.oktober 1964
Olisthodiscus luteus c/ml

Kart 35
NIVA

FIG. 2

surface layer, so traffic by ships and boats may easily have produced "holes" in the rich top layer.

Mass occurrence or blooms of single species is an enigma to phytoplankton ecologists and the general problem shall not be discussed here. An important ecological feature in the present species is doubtless its active phototactive response which makes it possible for it to take full advantage of the light supply to the very surface stratum.

Considering the recorded variations from year to year in the composition of the phytoplankton society of the polluted waters, it is apparent that they are due to a number of factors of different nature. We are inclined to stress the following ones: 1) Competion between autochthonous species, influenced by the initial populations occurring after the winter minimum, and by the growth rate of the various species at prevailing environmental conditions which doubtless vary considerably from year to year. 2) Irregularities in the introduction of allochthonous species from the Skagerak, caused by varying hydrographic conditions, not only in the Oslofjord at large but also in the North Sea-Skagerak system.

From a practical point of view, most of the variations from year to year may be of little consequence but, in a couple of cases they evoke great attention and are responsible for the alert attitude of the public towards the pollution problems in the fjord.

I have already pointed out the conspicuous, deleterious effect which the mass occurrence of Coccolithus huxleyi in certain summers have on the quality of the fjord waters from a recreational point of view. In such cases the papers are full of complaints about the general effect of pollution and highly voiced claims for measures to reduce this effect.

Another species is the cause of similar public attention, namely Gonyaulax tamarensis, Through its production of an endotoxin, accumulated in mussels, it is the ultimate cause of the very dangerous paralytic mussel poisoning. Again it is the variability in the occurrence of the species which makes it difficult to tackle the problems which are involved. The species does not only exhibit pronounced variations in abundance from year to year but it has also a very irregular quantitative abundance within the polluted area. Determinations of the toxin content in mussels have been carried out for some years under the direction of Professor Steinar Hauge and it has been found that during the period April-June mussels in some years contain quantities far above the danger limit set by American institutions. Due to the irregular horizontal distribution of Gonyaulax tamarensis, a regular control would require very frequent and extensive sampling in order to obtain a satisfactory coverage. In addition, the general instability of the dinoflagellate society of the inner fjord makes it hazardous to guarantee that the dangerous period is restricted to April-June. As a matter of fact the species has been recorded in autumn as well and one cannot exclude the possibility that some year it may become abundant at that time.

At present, a general warning against consuming mussels from the inner Oslofjord is our main safeguard against serious disasters.

Before leaving the subject of variation from year to year in the composition of the phytoplankton, it may be stressed how important it is to have observations from many years in order to get a general view of the situation. A regular supervision would be the best but would be expensive.

2. Seasonal variation in phytoplankton abundance and its background.

For a discussion of the seasonal variation in phytoplankton quantities and more specifically in the main groups, we shall chiefly use the observations from the 1962-65 survey. They were made monthly at a few stations in a section from the innermost part to outside the Drøbak sound (Fig. 3).

Our observations are less representative than could be desired, partly because the time intervals between cruises were too long, partly because the stations should have been more numerous. Finances did, however, necessitate such a limitation. Supplementary observations which we shall not discuss here, indicate, however, that the main picture is not too distorted.

The three years for which we have observations from all seasons exhibit pronounced differences, especially as to the quantitative representation of the main groups in the summer. Time does not permit a detailed description of these. We shall confine the presentation to a coarse outline of the main trends in the seasonal changes in the population and try to indicate

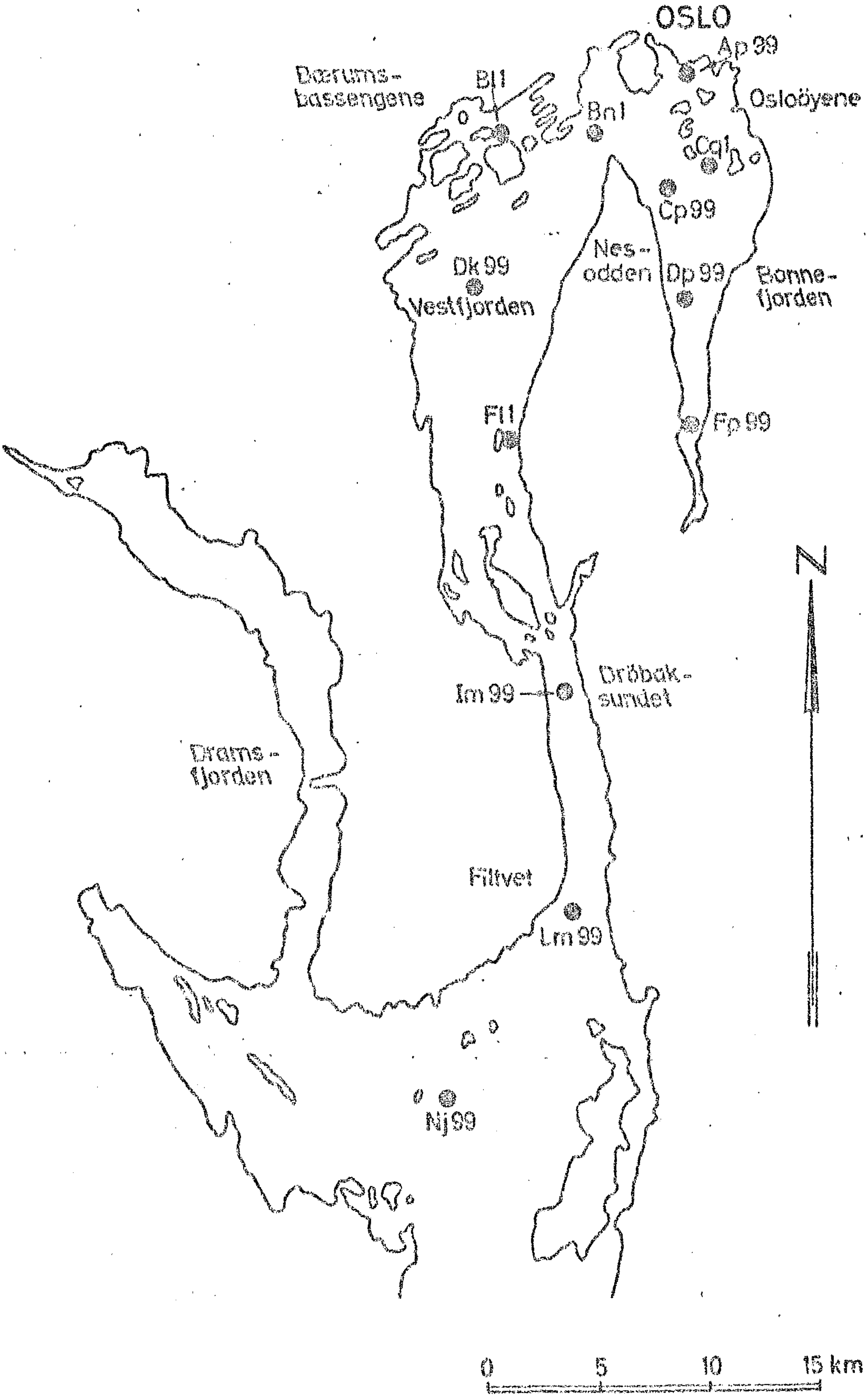


Fig. 3 Indre Oslofjord.

how these are related to environmental factors. A brief comment on each of these factors may facilitate our discussion on hand of a composite diagram.

Light. In Fig. 4 is shown the variation in incoming radiation through the year. The only available observations on the submarine light conditions within the polluted area in recent years are from 1967, when no phytoplankton observations were made. They may, however, indicate the general situation within the inner fjord.

In table 7 the depth of 1% of surface irradiance at four dates are presented, based upon observations which have been placed at our disposal by Mr. Eyvind Aas.

Table 7

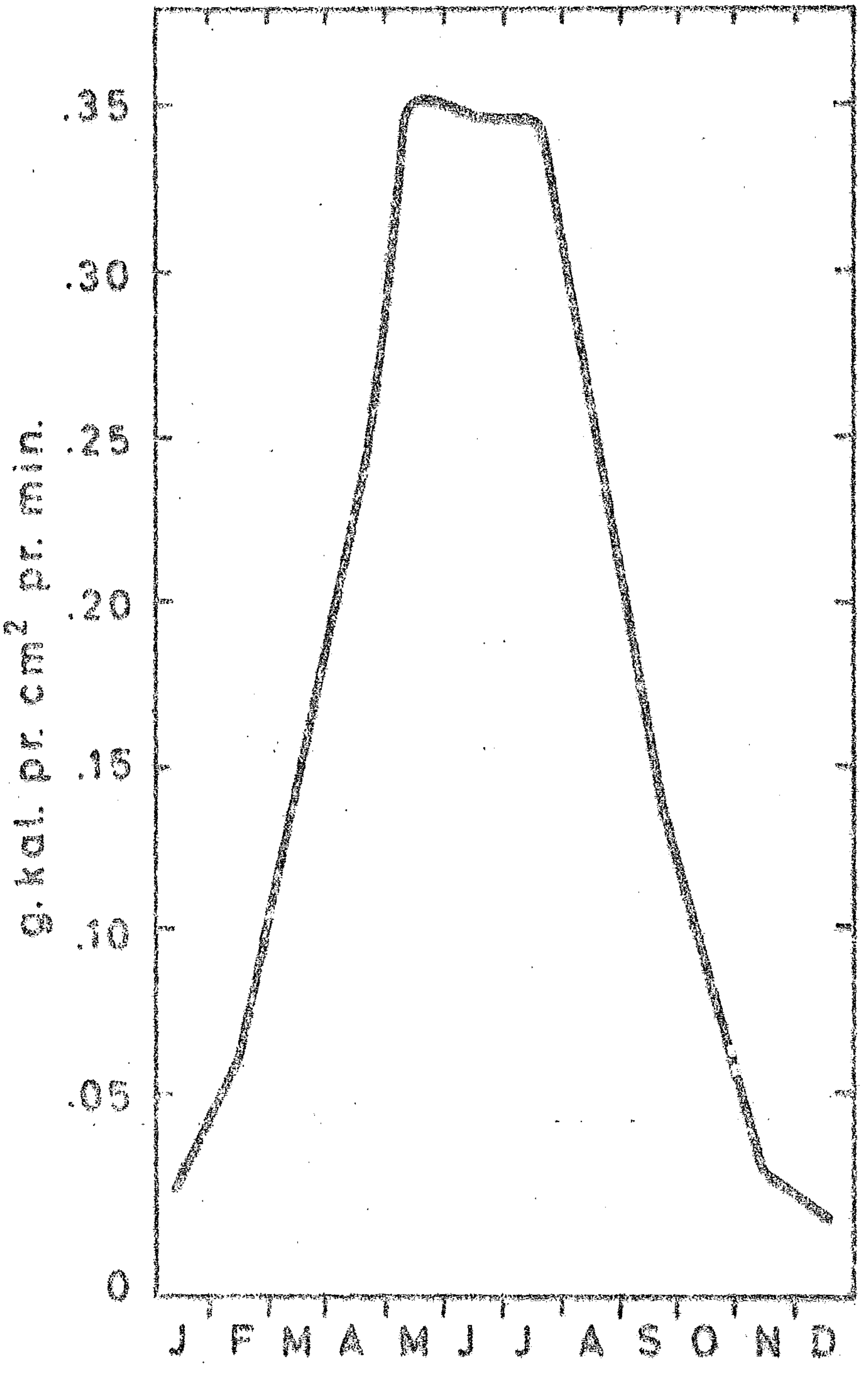
Depths of 1% of surface irradiance in the inner Oslofjord. St.01 is in the harbour. St.04 farthest out.

Stations	04	03	02	01
1. March	9 m			3 m
19. April	8 m	8 m	6 m	6 m
28. September	10 m	10 m	8 m	6 m
23. November	10 m	10 m	8.5 m	7.5 m

These observations indicate that the euphotic zone, even in late autumn, is very shallow and it may safely be assumed that in the summer it is even thinner than indicated by the present observations. In *Coccolithus huxleyi* summers the mass occurrence of this species leads to extremely high turbidity and 1% of surface irradiance may be found at 3.5 m, as observed by Buvig in 1939 (personal communication).

Stability. In the Oslofjord the waters are stratified all the year round but stability varies with the season, with a minimum in winter and a gradual increase during early spring towards maximum values in the summer. In the autumn a gradual decline in stability takes place, as in northern water in general.

Fig. 4 Seasonal changes in incoming radiation at Ferder. (after Smayda, 1959)



Apart from the coldest season, vertical transport of the population is doubtless of little significance in these sheltered waters. The pronounced stabilization during late spring and summer counteracts the supply of nutrients to the upper layer through hydrographical processes at these seasons.

Temperature per se may not in general be assumed to be of great importance for plant production but it affects the growth rate of the various components differently and accordingly influences composition. The seasonal changes in temperature seem, however, to be important for understanding the nutrient supply to the euphotic layer in polluted waters like the inner Oslofjord.

Inorganic nutrients. The plankton algae of the euphotic layer derive their inorganic nutrients from three sources. Through turbulent admixture - or what the hydrographers term diffusion- water from below the euphotic zone, with a considerable content of inorganic nutrients, is continuously supplied to the euphotic zone. The effectivity of this process depends upon the turbulent activity in the transitional layer and varies with the season according to the stability conditions of the water masses.

The other source is the regeneration within the euphotic layer of inorganic nutrients from particulate and dissolved organic matter. In polluted waters this source is of special importance, since sewage contributes large amounts of organic matter which partially is being decomposed within the upper layers.

Finally, sewage of any kind, no matter what kind of treatment it has been subjected to, contains quantities of inorganic nutrients. The amount contributed to the euphotic layer depends upon the method of sewage treatment and the depth at which sewage is discharged into the sea.

Seasonal changes of the environment influence the supply from these sources. Due to changes in the hydrographic situation, especially stability, a far more effective diffusion of deep water to the surface layers takes place in the cold season than in summer.

No observational data can be presented on the regeneration within the euphotic layer but it must be expected to be more intensive at the high temperature in summer than during the cold season.

On the whole, we have to confine our consideration of the seasonal variations in the total supply of nutrients to the plankton algae to theoretical speculations.

In the diagram (Fig.5) the changes in the diatoms, ceratia and other brown dinoflagellates have been indicated in a very coarse way, mainly aiming at demonstrating the general trends and disregarding the great variations from year to year in the relative quantities.

The three groups exhibit different patterns. Common to them all is a general poverty during the winter months, when light supply has a minimum and vertical transport due to turbulence may reduce the mean residence time of the algae within the euphotic layer to a minimum.

The diatoms show an increase in February towards a characteristic vernal maximum in late February or March. As regular as this spring bloom is a subsequent diatom minimum in April, in the same way as in non-polluted coastal waters. However, in the inner Oslofjord, the diatom population soon increases again and reaches a new maximum in May-June. This is again followed by a minimum during the subsequent period. A third, more irregular maximum, both as to time and size, occurs late in summer, in August-September.

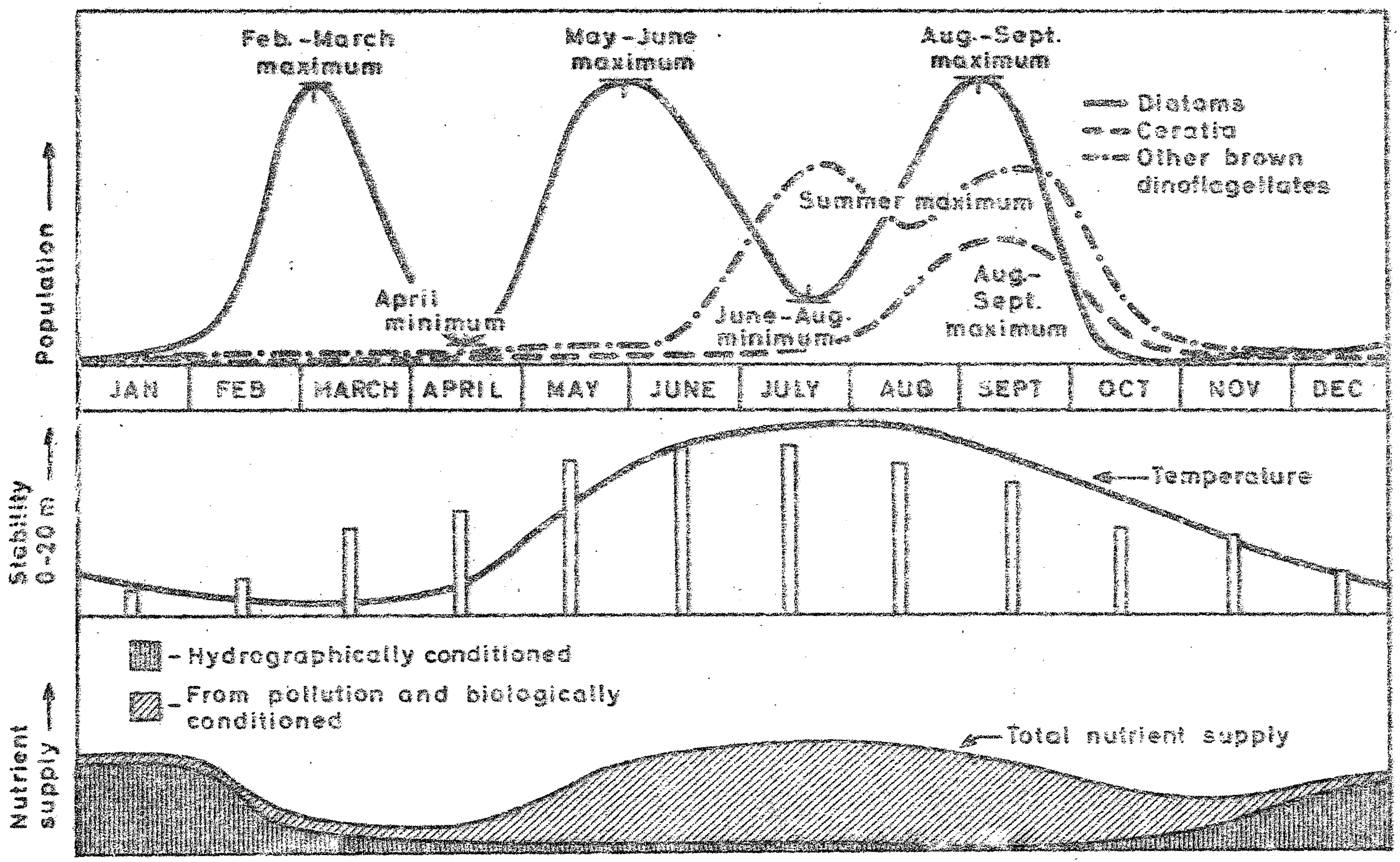
Grazing is doubtless a main cause of the reduction of the populations after the maxima but it is unaccountable to what degree variations in the grazing intensity is involved in summer.

Our hypothesis is that the main trend of the variations in the diatom population chiefly is governed by the supply of inorganic nutrients, while competition with other groups may modify the quantitative aspect differently in each year, particularly in summer.

In the lower part of the diagram, the variations in nutrient supply are indicated. A distinction has been made between the supply through hydrographic processes and the contribution from sewage and through decomposition of organic matter within the euphotic layer.

During winter, mixing and the lack of active consumption by phytoplankton secure the establishment of a stock of inorganic nutrients in the upper layers. At this time temperature is very low and regeneration from organic matter may be presumed to be

Fig. 5. Inner Oslofjord. - Diagram



very slow. During the spring bloom, the diatoms consume the winter stock of nutrients and, as a result, the growth rate goes down so finally grazing exceeds the production of new cells and we get the April minimum. During this period the stability increases and so does temperature. As a result the supply from deeper layers goes down and the contribution by regeneration gradually becomes the main source of supply and apparently suffices for another bloom of diatoms.

So far the diatoms have had no competitors, since at the prevailing temperature, none of the other groups of the phytoplankton society have a growth rate sufficient to allow the establishment of large populations. It is not till in June that dinoflagellates may reach large concentrations. It would seem as if the decrease after the May-June diatom maximum may to some extent be due to the competition by the group "Other brown dinoflagellates", which in certain years reaches extremely high concentrations as early as in June.

The ceratia do not become important competitors to the other groups till late in the summer, the reason apparently being that they require high temperature in order to reproduce effectively.

According to our view, the whole summer period is characterized by a relatively ample supply of nutrients, derived from sewage, directly or after biological mineralization. Since the waters at this time are so highly stratified and a main part of the sewage discharge still takes place at the surface, the situation for a fertilizing effect should be particularly good, partly because the sewage component is not being diluted by mixing with lower strata, partly because the temperature is high. In addition comes a favourable wind effect, which will be discussed later (p. 20).

The coccolithophorid component has not been included in the diagram because it was insignificant these years.

It must be pointed out that the observations in 1962-64 give a variable picture of the late summer conditions. This is a detail I shall not be able to discuss here.

The transition to the autumn and winter situation is characterized by reduced light supply, reduced stability and sinking temperature, all leading to poorer conditions for growth of the phytoplankton, and we find declining populations. I have already mentioned that one year there was a striking deviation from this pattern when there was a bloom of Olistodiscus luteus in October.

Although many details in the picture which I have tried to present remain hypothetical, it seems to allow certain general conclusions of consequence for tackling the pollution problem of the fjord.

The abundance of phytoplankton in spring seems only to be slightly influenced by pollution. It is the regularly occurring rich phytoplankton in summer and early autumn which represents the most serious pollution effect. It is this period which is of special interest from a public point of view. The aim of technical measures towards a reduction of the adverse effects of pollution must be to reduce the supply of nutrients to the surface layers, 0-20 m, especially in the summer.

One may, however, foresee that even if the technical measures taken may lead to a fairly effective reduction of the sewage supply to the surface layers, it may not be feasible to reach a state comparable to that of unpolluted coastal waters. Particularly it may be expected that occasionally large populations of Coccolithus huxleyi may still occur in future and make the fjord waters turbid and unattractive. I may substantiate this conclusion by some comments on the "Coccolithus huxleyi summers".

In 1952 Birkenes and Braarud suggested that an introduction of populations from Skagerak early in the summer may be a prerequisite for a mass occurrence of the species. The general results from the 1962-64 survey seem to give some support for this view. If at the time of the diatom minimum in April, the coccolithophorid were introduced from the outside, it would have a fair chance to compete effectively with the diatoms during the following period and establish large populations. If the introduction took place later, when diatoms and subsequently other groups had established large populations, it might not be able to compete successfully. This hypothesis is based upon the view that C.huxleyi does not survive winter in northern waters but is being introduced via Atlantic water, a hydrographically rather complex process which I shall not comment on here. It is apparent that the process is effective, since the species is a regular member of the coastal waters in the summer, but the time schedule may vary from year to year and thus be the ultimate cause of the irregularity of the "*C.huxleyi* summers" in the Oslofjord.

3. Wind transport.

The brief review which has been given of the phytoplankton of the polluted inner Oslofjord is incomplete in many ways. One aspect which has been neglected so far, should, however, be mentioned, the effect of wind-driven transport of the surface layers.

With prevailing northerly wind the surface layers of the inner part are pressed outwards, even through the Drøbak sound, while southerly wind stows the top layers in the inner part. This wind transport has two obvious effects, upon the sewage material and upon the phytoplankton distribution.

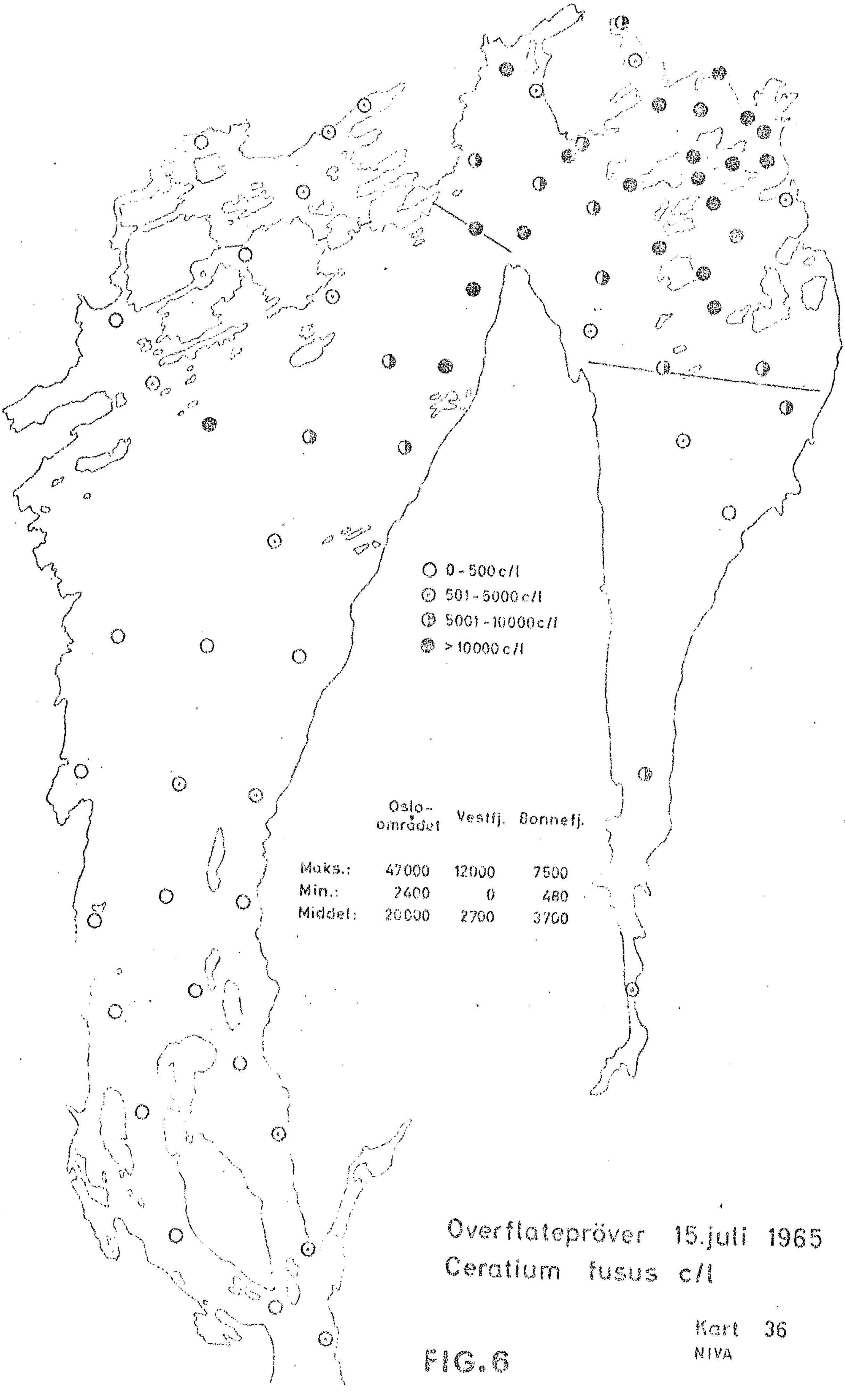
When wind transports surface waters of the inner part outwards, it means that sewage material discharged into the surface layers of the inner part will be dispersed and diluted. On the other hand, a stowing of the surface layers within the inner fjord will increase the retension time and lead to a stronger pollution effect than in the former case.

Our observations on the phytoplankton distribution at different wind situations have also demonstrated very clearly that when the wind shifts from southerly to northerly during summer, the large populations of the highly polluted inner area may soon be found farther out, even in the Drøbak sound.

These two effects of wind complicate the study of the pollution effect and during our analyses of the observations from the survey in 1962-65, we have had to make extensive use of wind data.

Generally speaking, one may expect that in summers with more wind from the north, the pollution effect upon the phytoplankton in the innermost part will be far less than in summers with more prevalent southerly wind situations, due to the more effective spreading and dilution of the sewage material.

In Figs. 6 and 7 are given two examples of distribution patterns, one from a period with prevailing southerly wind and one from a period with northerly winds.



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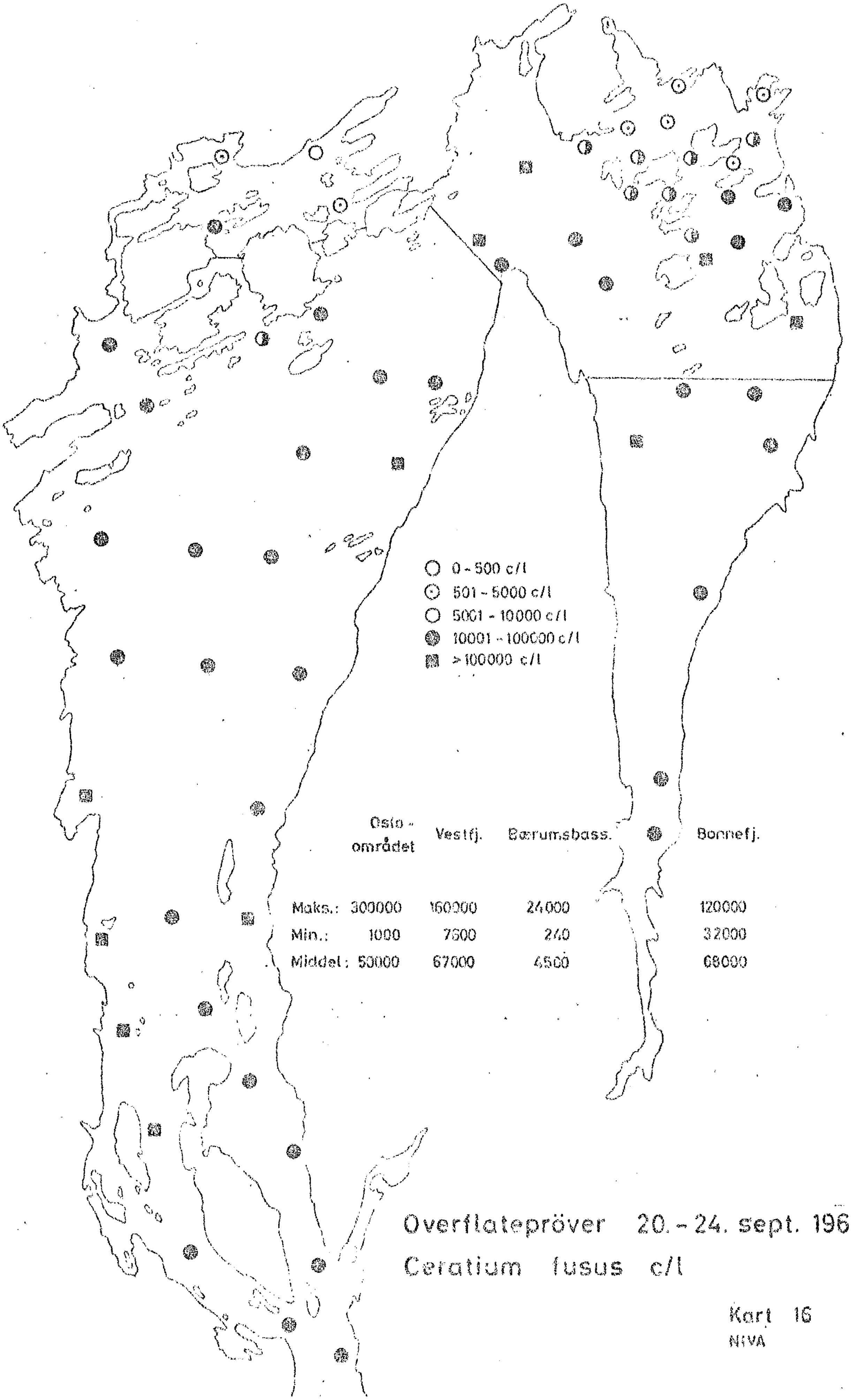
Maks.:	47000	12000	7500
Min.:	2400	0	480
Middel:	20000	2700	3700

Overflateprøver 15.juli 1965
Ceratium fusus c/l

Kart 36
NIVA

FIG.6



	Oslo-området	Vestfj.	Bærumsbass.	Bonnefj.
Maks.:	300000	160000	24000	120000
Min.:	1000	7600	240	32000
Middel:	50000	67000	4500	68000

Overflateprøver 20.-24. sept. 1963
Ceratium fusus c/l

Kart 16
NIVA

FIG. 7

A couple of practical aspects of the pollution effect upon the phytoplankton have already been mentioned. As a matter of fact, the reaction of the phytoplankton upon the pollution by sewage is a crucial subject when methods of attempting to alleviate the deleterious effects of pollution in general are considered. The reestablishment of organic matter on the basis of inorganic nutrients produced in sewage treatment plants, what often is termed "secondary pollution", has led to a demand for far more extensive treatment than previously was found necessary. Today, the removal of inorganic nutrients from the effluents is a main issue in sewage treatment, in order to hinder the eutrophication in the recipient and thus avoid the great effect of pollution upon phytoplankton abundance which has many other effects on the recipient than those considered here.

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