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Loch Leven 1999: physical, chemical and algal aspects of water quality

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Summary

In spite of step-wise reductions in point-source phosphorus loadings since 1972, Loch Leven, phytoplankton crops in 1999 ranked amongst the highest ever recorded. Examples include chlorophyll$_a$ peaks of 70-90µg/l up to the end of July.

The annual mean chlorophyll$_a$ value of 48µg/l is more than three times the target of 15µg/l set by SEPA, while a mean total phosphorus level of 73µg/l exceeds the target value by 40µg/l.
The most prominent algal populations contributing to the 1999 'succession' were as follows: the diatom *Aulacoseira italica* which attained 3,800 filaments/ml; an assemblage of *Stephanodiscus* and *Cyclotella* unicellular centric species (6,300/ml); *Diatoma elongatum* (13,500 cells/ml); the lunate desmid, *Closterium acutum* (700/ml); a mixed assemblage of *Anabaena* species (1,200 filaments/ml); 600 *Gomphosphaeria lacustris* colonies/ml; and finally, an astonishing population of the large blue-green alga *Oscillatoria agardhii* var *isothrix*: its greatest numbers, of 4,600/ml) was equivalent to 700 **metres/l** on 21st September - whilst the maximum biomass estimated was **1,100m/l** - comprising 2,000 filaments/ml.

Shallow eutrophic systems are traditionally assumed to be poor in species. This does not seem to be the case at Loch Leven; a study of the phytoplankton covering the first 6 months yielded 92 species. A similar set of unpublished data for 1997 showed that many peaks and troughs in the numbers of species were preceded closely by, or coincided with, shifts in many environmental factors covered here. Similar relationships have been identified from the 1999 data, with water level, water temperature and flushing rate appearing to link especially often with algal fluctuations.

Low chlorophyll$_a$ values coincide with the maximum population density of *Daphnia hyalin* Says in late June. As crustacean numbers never exceeded 26 individuals per litre, and then for only a week or two, it is unlikely to have depleted algal crops. This view is supported by the fact that a background mixture of thousands of small colonial algae was present at the time. The mixture was dominated, however, by the cyanobacterium *Aphanothece*, which may not have been a preferred food item of *Daphnia.* Previous reports by the authors have suggested that the prevalence of small algae is partly due to predation by fish on daphnids consequent upon increased trout stocking. However, large algae dominated the algal biomass for virtually all of 1999.

Many aspects of the algal population dynamics fit with our growing understanding of changes in physical and chemical factors through the year, although the acutely capricious nature of the loch renders few aspects predictable. Equally however, and following three decades of intensive study, Loch Leven is still a very rich lake. Plainly, we remain ignorant of the causes as to why the lake should manifest such major reversions in water quality following substantial reductions in the loadings of bio-available P. At the very least, the authorities that have brought about the reductions in P loading, had reason to expect a stabilisation of enrichment trends at least.

We recommend the following, be initiated in addition to our on-going analysis and interpretation of the data already accrued:

- of the strategies aimed at improving the trout fishery, and the effects of the strategies on water quality
- an in-depth analysis of flushing rate and thus, water level, regimes; to date, these have been operated not for water quality *per se*, but understandable calls on water as dictated by downstream paper mill owners
- an improved quantitative understanding of the population dynamics, food preferences and feeding rates of *Daphnia.*

Contents

INTRODUCTION

This report describes and interprets physical, chemical and phytoplankton information gathered on Loch Leven during 1999. Data were generated, and observations were made, at primarily, the 'South of Reed Bower' site at weekly intervals from March to October inclusive, and fortnightly in other months. Temporal variation in a number of key factors and factor interactions are discussed.

A recently published paper on phosphorus loadings to the loch forms the background to this report (Bailey-Watts and Kirika, 1999). It estimated that eight tonnes of phosphorus in all forms (total phosphorus, TP) entered Loch Leven from its catchment in 1995, compared to 20t in 1985. Diffuse run-off from the land, and waste from over-wintering geese contributed 59% of the total loading in 1995 *cf* 42% in 1985. Point-sources of sewage, and waste-water from fish-rearing ponds, produced the rest. Inputs of phosphorus in soluble reactive form (SRP) totaled 5t, i.e. 63% of the TP loading in 1995, as compared with 1985 values of 11.8 t and 59%. Point-sources of SRP contributed 54% of the total SRP input in 1995 *cf* 69% in 1985.

Loadings from three sewage treatment works (STW) totaled 3.1t TP in 1995 as compared with 5.3t in 1985; this included 2.6t SRP (*cf* 3.6t). Daily *per capita* outputs of the upgraded Kinross North and Milnathort STWs were 0.68g and 0.81g TP respectively, compared with pre-upgrade values of 1.77g and 2.03g.

Nett reductions in TP and SRP loadings between 1985 and 1995, were 55% and 59% respectively. However, the reductions were attributable not just to the 'managed' elimination of P usage at a major industrial source, and upgrades of STWs: inter-annual differences in the weather were also very significant. 1,250mm of rain fell in 1985, whereas only 890mm fell in 1995. Thus, in spite of the expensive cutbacks in P supply, the combination of the lower rainfall, and an extraordinarily hot summer in 1995, negated the expected reduction in lake phosphorus and chlorophyll a levels.

The reduced specific areal loading of *ca* 0.7g P m^{-2} estimated for 1995 still exceeds the ideal maximum for the 3.9-metre deep loch considerably. These statistics nevertheless ignore (i) the significance of a reduction of *ca* 7t in P entering the system in bio-available form, (ii) a further planned upgrade of major STWs and (iii) channeling of effluent from a small works out of the catchment.

METHODS

The methods followed are those that have been adopted over the last 30 years. References to the reports produced for the present contractors and their forerunners are listed at the end of this report.

Water depth at the 'South of Reed Bower' is similar to that often cited as the usual mean depth of the loch i.e. 3.9m. However, we wish to point out that 'whole-water column' tube samples that we collect there, usually extend from the water surface to no nearer than 0.25m of the sediment surface. Consequent upon a considerable draw-down of the lake level, especially over the period mid-June to mid-October in 1999, many samples extend from the lake surface to as little as 3m.

RESULTS

Physical factors

Water temperature

Water temperature (**Fig. 1**) followed a generally simple pattern. Values rose from 4°C ≤over the first two months to a peak just in excess of 20°C in mid-July. Temperature fluctuated between that value and 16°C over the next 8 weeks, and then decreased in a more or less linear fashion to a value of 1.2°C on 29 December. From these observations, it is likely that releases of soluble reactive phosphorus, and possibly those of silica, would be observed during the month of July, and possibly a week either side of that period. Information presented later show that these predictions were generally upheld.

Water level

In contrast to the relatively simple pattern of described by water temperature, the water level regime consisted of two main changes (**Fig. 2**). The first of these comprised a more or less continual succession of moderate fluctuations in level. These extended from the beginning of the year to mid-June. Virtually all of the rest of the year however, was characterised by two very dramatic changes in water level. These were (i) a drop of approximately 0.6m over the period from a third of the way through June to mid-October, and (ii) a rise of very nearly 0.9m over the last six weeks of the year. The latter brought the water surface up to much the same level as that recorded at the beginning of the year. Very few factors showed such similarity between the start and end sampling of the year. The last change (increase) in water level mentioned above, approximates to 20% of the mean lake volume. There is some evidence that this diluted the planktonic organisms (see below).

Weekly excursions in water level of 10-20cm may not represent a major environmental change, but the much greater shifts (up and down) such as those outlined above, are likely to trigger other physical, chemical and algal changes.

Water clarity

Apart from a few weeks around the end of July and early August, when Secchi disc readings reached between 1.5m and 2.0m, water clarity fluctuated little from 1m (**Fig. 3**). The short period of relatively clearer water often appears to favour the large (and potentially toxic) blue-green algae (cyanobacteria).

Chemical factors

Dissolved oxygen

Out of approximately 60 dissolved oxygen level records, only one tenth registered < 80%. Concentrations of 100-110% were common.

pH

pH values (**Fig. 4**) fluctuated little outside a 1-pH band of 7.75 and 8.75 units. The lower values were generally confined to the cooler months, but a drop of nearly 1 pH unit lasted throughout much of June. This coincided with a release of soluble reactive phosphorus and silica, as well as a fall in overall phytoplankton biomass as reflected in the chlorophyll$_a$ concentrations. None of these values is particularly remarkable for Loch Leven, and they indicate the considerable phytoplankton productivity potential that prevails.

Conductivity

Fig. 5 features the conductivity values recorded at four sampling sites. Data from the South of Reed Bower station described a wave-like pattern within a small range of 240 to 260 µS/cm. Outlying values which exceeding the upper figure, were associated mainly with the outflow (sluices) site. These conductivity values also appear unremarkable.

Nitrate-nitrogen

In contrast to the fluctuations in the other factors considered in this report, nitrate-nitrogen concentrations conform to what is a more or less consistent annual pattern, even if maxima and minima vary in magnitude and timing between years. The first value for 1999 - 1.15 mg N/l on 5th January (**Fig. 6**) - is low compared to figures obtained at the start of many other years. Similar concentrations prevailed over the first 4 months of the year. These were followed by a considerable and erratic decrease to <0.1 mg/l by the beginning of August. Apart from an isolated peak of 0.3 mg/l, values of less than 0.1 mg/l were recorded up to and including the penultimate sampling date. During the last two weeks of the year however, the concentrations increased again to *ca.* 1.7 mg/l. This is considerably higher than that recorded at the beginning of 1999.

The timing and magnitude of the annual, summertime draw-down in nitrate depends on the water temperature as well as the temperature at the sediment surface - the two being much the same at the main sampling site. Classically, with rising temperatures, nitrate draw-down accelerates. This due primarily to enhanced bacterial de-nitrification and consequent reduced conditions at the sediment surface. **Figures 1 and 6** arguably demonstrate these interactions for Loch Leven in 1999. A combination of a lack of nitrate and reasonable dissolved inorganic phosphorus would be expected to enhance the production of N–fixing cyanobacteria such as species of *Anabaena*.

Soluble reactive phosphorus and total soluble phosphorus

The pattern of change in the total soluble phosphorus component (TSP, not plotted) is similar to that of the soluble reactive fraction (SRP, shown in **Fig. 7**). The two sets of data thus feature (i) relatively small changes from just after the start of the year to late-June (12-18µg TSP/l and 2.0-4.5µg SRP µg/l), (ii) increases to peak values of 48µg TSP/l and 18µg SRP/l in late June, and (iii) the rapid return to the previous low values within the same month. The relatively short-lived increases in P concentrations coincided with the highest of the year's water temperatures and even occurred as late as early August, with water temperatures as high as 18°C on occasions.

Note that at the beginning of August 1999, SRP concentrations did increase markedly as predicted above. This coincided with an increase in temperature, and a marked decrease in nitrate. However, nitrate was always detectable. Otherwise, the dynamic processes linking water temperature, nitrate, SRP and SiO_2 (see below) conform to the situation at Loch Leven in many other years.

Total phosphorus

Apart from a spurious high value obtained at the start of the year, total phosphorus concentrations remained largely within a band of approximately 45μg P/l (in mid-May) and 85μg/l (20th April) for the first seven months of the year **(Fig. 8)**. Thereafter, TP levels increased erratically to an annual maximum of 127μg/l on the penultimate sampling date of 15th December. Between then and our last sampling of the year (29th December) the concentration fell significantly by *ca* 40μg/l.

Soluble reactive silica

Silica in the form of dissolved SiO_2 is the third nutrient affecting temporal changes in the abundance and species composition of the phytoplankton. Like the concentrations of nitrate-N and phosphate-P, SiO_2 values represent the instantaneous nutrient resource that remains to be potentially by (in this case) silica-containing algae, mainly diatoms, but also scale-bearing chryso-flagellates for example. The dynamics of dissolved silica during 1999 **(Fig. 9)** illustrate two main features. These are (i) the very low concentrations prevailing virtually throughout the first five months of the year, and (ii) a more or less sustained re-charging of silica levels to just over 10mg/l by the end of the year.

The relatively small but significant decrease in SiO_2 in late July is probably not due to any major diatom growth: very few algae of that type were present at the time. More likely, the decrease results from an *increase* just before that time, in silica released from the sediments. Note how closely the upturn in silica coincides with that of SRP released from the sediments **(Fig. 7)**.

Planktonic algae

Chlorophyll$_a$

Considerable changes in total phytoplankton biomass were recorded during 1999 **(Fig. 10)**. Chlorophyll$_a$ concentrations ranged from 12μg/l at beginning of July, to 90μg/l in mid-February). However, many of the decreases and increases persisted for a number of weeks. Overall biomass exhibited a substantial nett decrease over 1999: the '1st January 2000' figure is *ca* 30μg/l, whilst the '1st January 1999' value is 80μg/l. Such contrasts observed in other factors are presented later.

Low chlorophyll$_a$ values of *ca* 10μg/l coincide with the maximum population density of *Daphnia hyalin* Sars. At only some 20-25 individuals per litre, and then for no more than two weeks, the crustacean is unlikely to have depleted algal crops overall. This view is supported by the fact that a background mixture of thousands of small colonial cyanobacteria per milli-litre (including *Aphanothece*) was present, as well as a substantial crop of small green alga. The cyanobacterium could have flourished because it is not generally considered a preferred food item of *Daphnia*.

Algal species

Shallow eutrophic lakes like Loch Leven are often viewed as poor in species. However, Loch Leven manifests considerable diversity of planktonic algae at least. Surveys of 300 algal specimens at fortnightly intervals over the first 6 months of 1999 yielded 92 species. Small green algae of the Order Chlorococcales ('green algae') were the most prominent. Bwathondi *et al* (in press) recorded 35 species in a survey of net phytoplankton from Loch Leven in 1997, whilst material collected by exactly the same methods in the species-rich, oligotrophic Lake Tanganyika, East Africa, yielded only double this i.e. 74 species.

Included in these suites of species are seven species/species groups (**Figures 11-17**) which we view as representing the majority of the chlorophyll$_a$ and manifesting some of the highest population densities in Loch Leven in 1999. Their 'succession' is as follows:

Aulacoseira italica (Ehrenberg) Simonsen over the first three months (**Fig. 11**).

A major pulse of a mixed assemblage of *Stephanodiscus* and similarly structured unicellular centric diatoms from early March to the beginning of May (**Fig. 12**).

A population of the pennate diatom, *Diatoma elongatum* (Lyngb.) Ag.[1], from late February to the end of to June including and attaining its maximum population density of *ca* 13,500 cells/ml in mid-May (**Fig. 13**).

A short-lived but significant population of the lunate desmid, *Closterium aciculum* Breb. (**Fig. 14**) from mid-April to end June. The maximum population density, of 730 cells/ml was recorded in mid-June.

An assemblage of *Anabaena* species, dominated by *A. flos-aquae* fa. *flos-aquae* Breb ex Born. *et* Flab. which was evident from the end of 1998 through to early September 1999. An appreciable concentration of *ca* 200 filaments/ml was attained in mid-April, whilst the major, though short-lived, population that reached some 1,200 filaments was recorded in August (**Fig. 15**).

Another blue-green alga, *Gomphosphaeria* nr. *G. lacustris* Chod., recorded throughout the year, but most noticeable from mid-August to mid-October (**Fig. 16**).

A very durable an successful population of the large blue-green alga *Oscillatoria agardhii* var. *isothrix* Gomont[2] which achieved its largest concentrations of filaments - 4,600/ml in late September, **Fig. 17**).

[1] Some authorities use *D. tenuis* var *elongatum* Lyngeb.

[2] now *Planktothrix mougeotia*

Fig. 18 is worthy of further comment in view of the size of the *Oscillatoria* population. Filament numbers had remained at no more than double figures per milli-litre since 1998. The maximum concentration of filaments cited above was equivalent to a thread biomass of 700 **metres/l** on 21st September. The maximum biomass however, was1,100 **metres/l** of filament/l (=1.1 km/l) comprised of 2,000 filaments/ml. Much of the latter increase in biomass occurred during the continuous draw down in water level of 0.7m from early June to mid-October, and a rise of virtually 1 metre again by the end of the year.

DISCUSSION

Using physical and chemical factors as an example, **Figure 19** illustrates the very capricious nature that characterises the dynamics and functioning of Loch Leven. With the exception of conductivity, the factors exhibit wide ranges of values. Nevertheless, many aspects of the algal population dynamics described in this report, support and enhance our understanding of changes in physical and chemical factors through the year. The following examples illustrate this:

- the decline in diatom population densities as soon as silica concentrations are at the level of analytical detection
- warming of the water (and thus, the sediment surface) which enhances the draw-down of nitrate, triggers the release of phosphorus and silica from the sediments
- the scenario above, leading to increased prominence of N-fixing cyanobacteria such as *Anabaena* species
- very soon after nitrate levels began to rise (in tune with decreasing water temperatures), the year's most prominent species (*Oscillatoria agardhii* var *isothrix*)[3] had already embarked on its increase in biomass to a very high maximum
- apart from two short spells during the first five months, silica concentrations remained at, or very near the limit of analytical detection using the methods employed since 1967; however, almost on the same day that the silica concentrations increased (31 May), the last of a succession of four substantial diatom populations reached its maximum population density and thus, decreased in abundance, although by the end of the year, SiO_2 concentrations had been restored to more than 10mg/l.

Following the restoration of silica to the levels referred to above, we would have expected diatoms to dominate the scene in 2000. Indeed, the diatom *Aulacoseira*, is common. However, the ratios of silica, nitrate and phosphate, and particularly the N:P values lead us to suggest that these and any other algae may not attain large populations in the short-term at least. This is because the weight *ratios* of inorganic silica, nitrate and phosphorus may prevent this. The two ratios that we have calculated are as follows:

195 SiO_2:100 NO_3N:1 PO_4P at 5-1-99
and
2520 SiO_2:440 NO_3N:1 PO_4P at 29-12-99

These ratios suggest that the main limiting nutrient is, as usual, phosphorus. But the considerable degree to which SiO_2 and N concentrations exceed P, leads us to expect a relatively moderate

[3] We view this organism as not capable of fixing atmospheric nitrogen

algal biomass. The findings suggest very acute P limitation. The future situation is not easy to predict. However, high algal biomass could well prevail if the very dense *Oscillatoria* crop persists by drawing on its cellular resources. The same applies to other species present, but relatively sparse.

There remain many aspects of the ecology of the Loch Leven phytoplankton Some examples emerging from the data for1999 are worth mentioning. **Figure 9** suggests that non-siliceous planktonic (or benthic) algae, were out-competed by algae not requiring silica (e.g. green and blue-green forms); however, we do not know the true answer.

We are also plainly far from being able to predict any fluctuations (physical, chemical or algal) except in the very short-term, and then only if weather forecasts are successful. However, a brief review of our database which extends back to 1967, shows that if *Diatoma elongatum* is abundant and constitutes the major diatom species in the Spring, the following summer/autumn phytoplankton is often dominated by filamentous cyanobacteria such as the *Oscillatoria agardhii* - as in 1999.

The loch responds very quickly to weather-driven processes such as water mixing, flushing rate and level. **Table 1** illustrates the consequential inter-annual changes in the 'behavior' of the loch, by comparing the first and last sampling date values for a suite of physical and chemical factors.

Table 1. Values for a range of physical and chemical variables recorded in Loch Leven: first and last sampling dates in 1999 compared.

factor	value @ 5.1.99	value @ 29.12.99
water temperature (°C)	3.9	1.2
staff gauge reading (m)	0.95	1
water transparency (m)	1.04	0.95
pH	7.98	7.63
conductivity (µS/cm)	258	242
nitrate-N (mg/l)	1.15	1.67
dissolved reactive P (µg/l)	11.5	3.8
total soluble P (µg/l)	18.5	17.3
total P (µg/l)	126	85
dissolved reactive SiO_2 (mg/l)	2.24	9.58

Compared to the situation at the start of the year (1st sampling occasion, 5-1-99), lake conditions at the end of the year (last sampling occasion 29-12-99 - and thus, virtually the same as 5-1-00) are as follows:

- significantly cooler water
- a considerably greater nitrate concentration
- much less SRP, and
- very much more SiO_2.

Previous comments have highlighted the differences between the start and the end of the year, in the values of a range of physical and chemical factors. Such disparity is likely to effect equally erratic shifts in the algal 'succession'. Indeed, **Table 2** bears out this fact.

Table 2: Chlorophyll$_a$ concentrations (in µg/l) and the population densities (in numbers per milli-litre) of the 7 most prominent phytoplankton species recorded in Loch Leven: first and last sampling dates in 1999 compared.

chlorophyll$_a$ concentration	80	28
species	**population density @ 5.1.99**	**population density @ 29.12.99**
***Aulacoseira italica* (centric diatom)**	3700	100
other centric diatoms	960	'nil'
***Diatoma elongatum* (pennate diatom)**	'nil'	'nil'
***Closterium acutum* (lunate desmid)**	20	'nil'
Anabaena* spp. mainly *A. flos-aquae	26	'nil'
***Gomphosphaeria* nr. *lacustris* (colonial cyanobacterium)**	20	'nil'
***Oscillatoria agardhii* var. *isothrix* (filamentous cyanobacterium)[4]**	41	940

Albeit in the absence of hard data to the contrary, another factor may have enhanced the production and biomass accumulation of the phytoplankton. This is the continuous draw down of 0.7m in water level from early June to mid-October. Between mid-July and mid-September in particular, the drop was accompanied by a marked increase in a population of *Oscillatoria agardhii* i.e. from approximately 1 to 4,600. filaments/ml. The latter figure equates to 700m/l /l. The highest population density achieved was estimated at1,069m/l! This, and other filamentous

[4] Footnote: This cyanobacterium coincided with 1 dog death and an angler becoming sick after eating his catch.

cyanobacteria are commonly associated with shallow lakes in Europe. Examples include the Dutch polder systems. This species and other filamentous cyanobacteria are commonly associated with other shallow lakes in Europe.

Previous reports by the present authors have suggested that the prevalence of small algae is due in part at least, to enhanced predation of daphnids consequent upon increased trout stocking. However, large algae dominated the scene for virtually all of 1999.

We recommend the following, be initiated in addition our on-going analysis of the data already accrued:

- an in-depth analysis of the strategies aimed at improving the trout fishery, and the effects of the strategies on water quality
- an improved quantitative understanding of *Daphnia* population dynamics, food preferences and feeding rates
- more work on flushing rate (on which we have already published a significant amount (e.g. Bailey-Watts *et al* 1990) and thus, water level regimes (which we have neglected); traditionally the loch has been managed not for water quality *per se*, but for understandable, calls on water that are dictated by downstream paper mill owners.

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ACKOWEDGEMENTS

We are very grateful for discussions with Dr Ramesh Gulati and his Dutch colleagues who have also encountered difficulties in restoring shallow lakes.

FIGURES 1-19

Figure 1. Fluctuations in water temperature during 1999.

water temperature

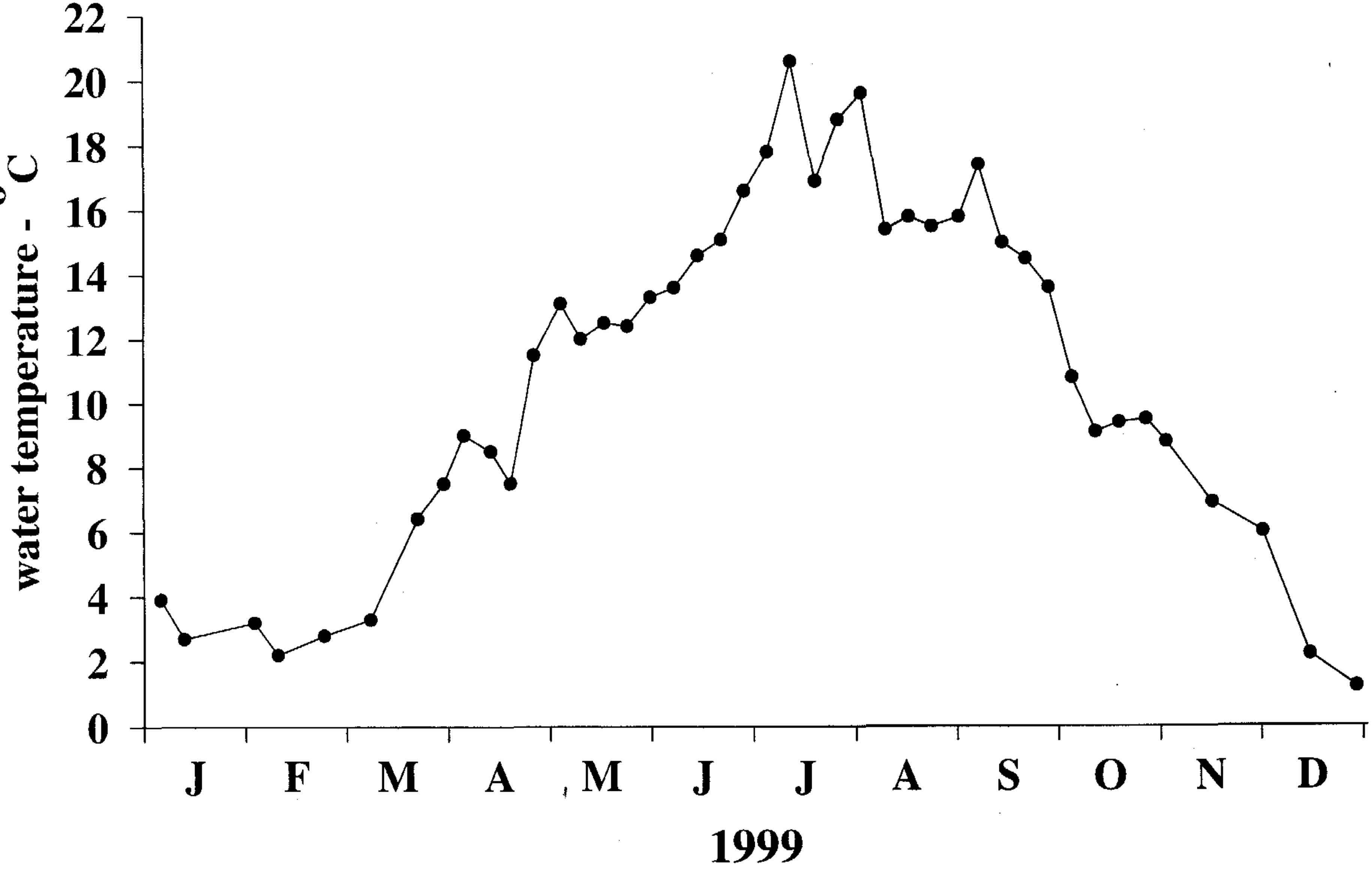

Figure 2. Water level fluctuation during 1999.

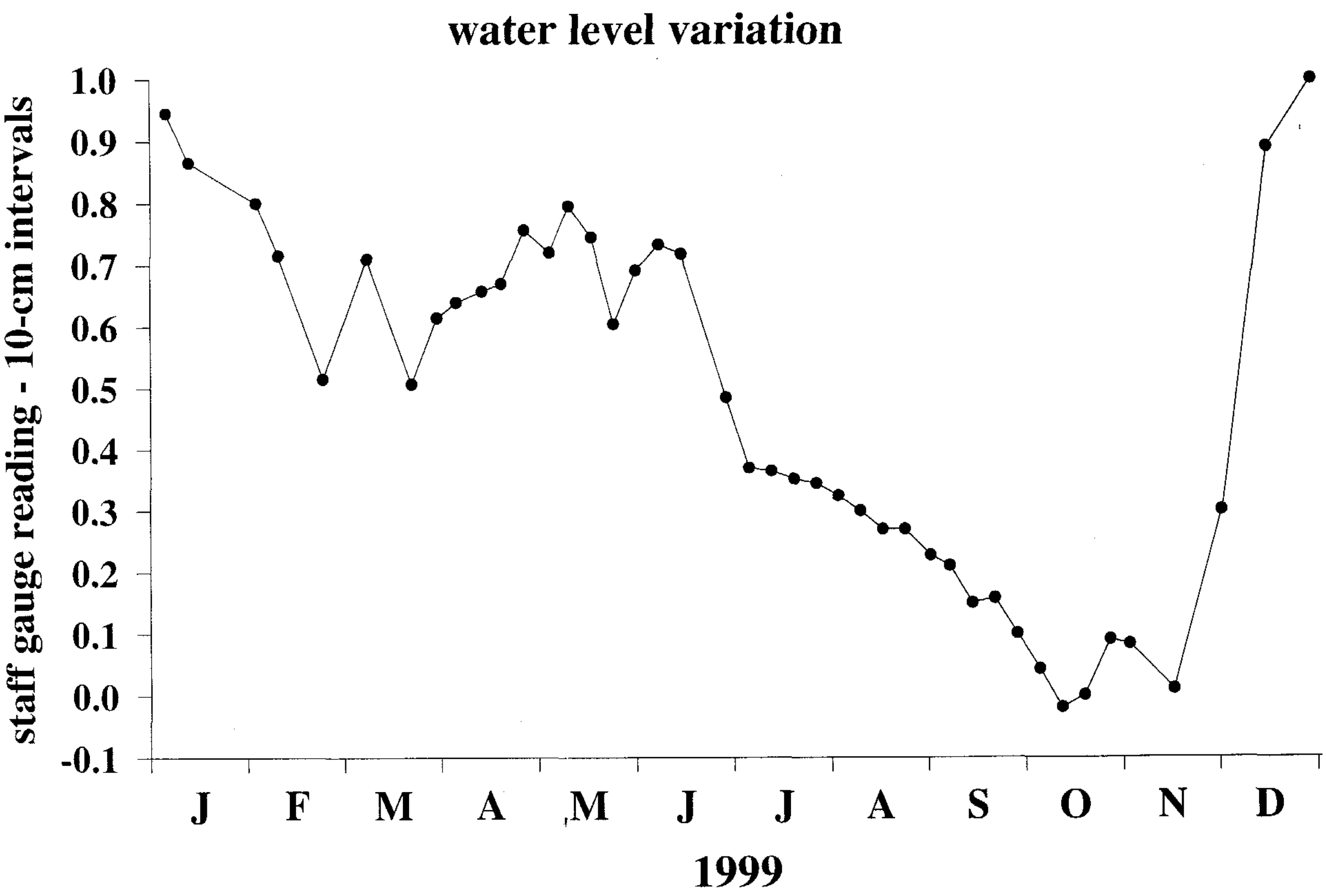
water level variation
staff gauge reading - 10-cm intervals
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
J F M A M J J A S O N D
1999

Figure 3. Fluctuations in water clarity during 1999.

water transparency

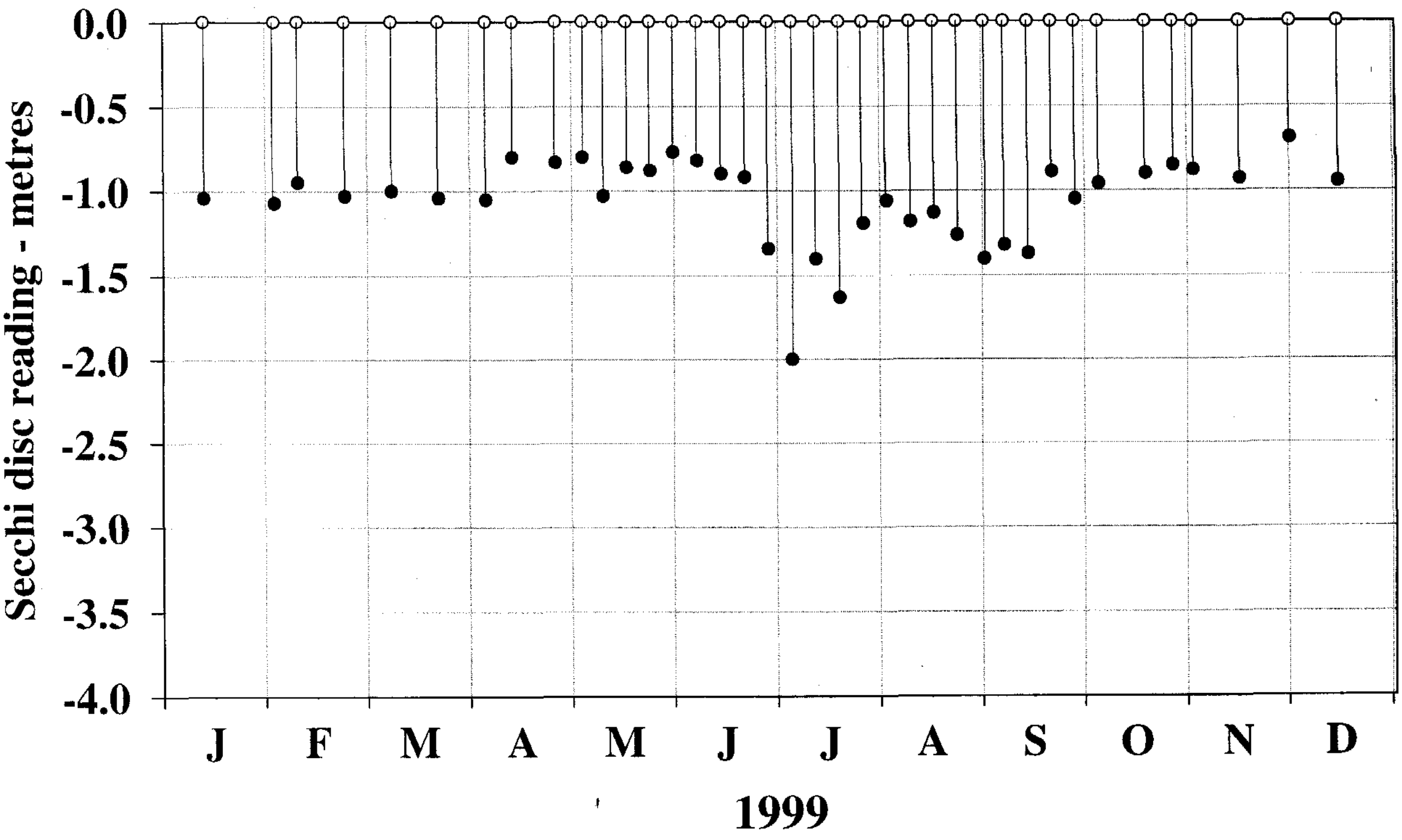

Figure 4. Fluctuations in pH during 1999.

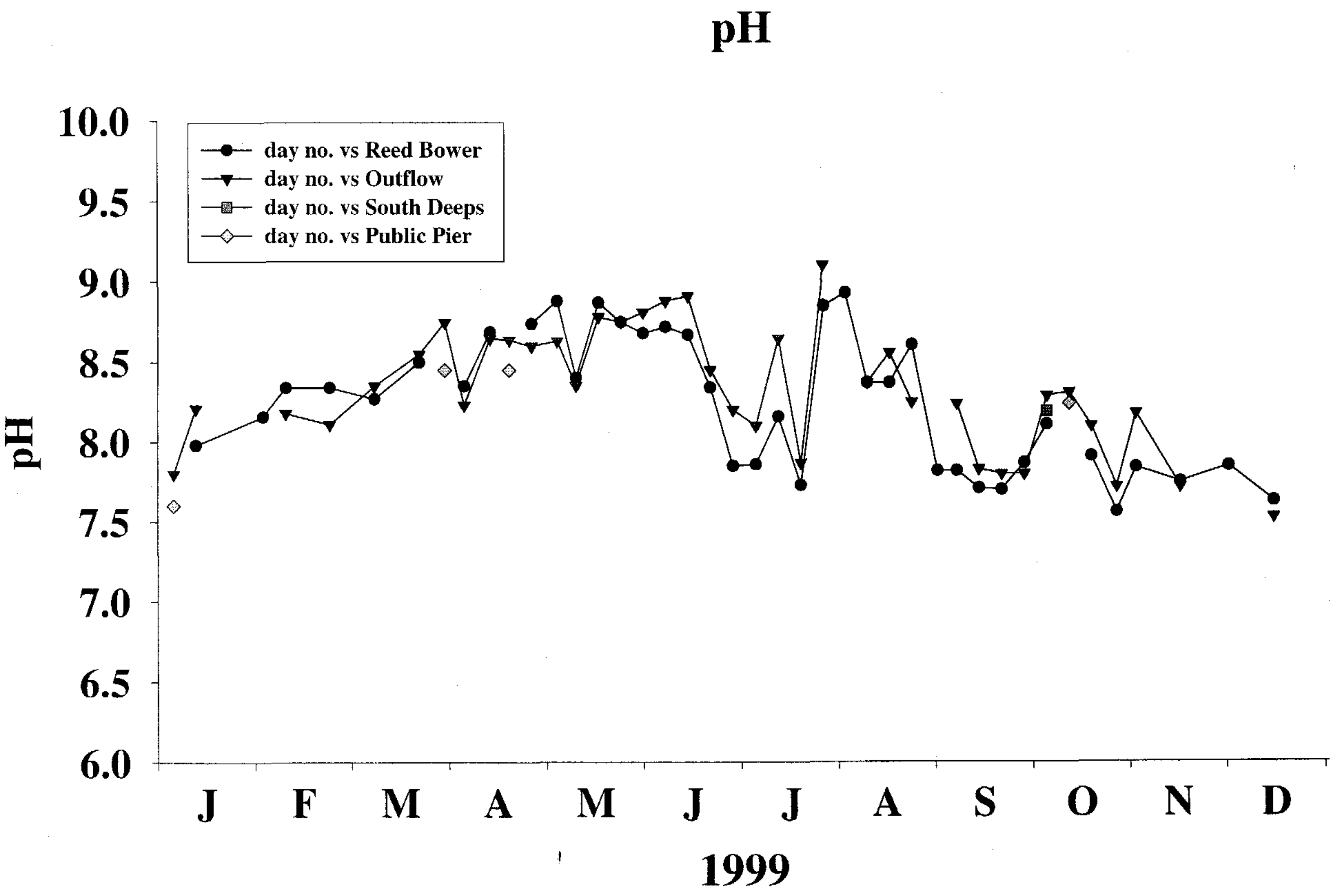
pH
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
pH
day no. vs Reed Bower
day no. vs Outflow
day no. vs South Deeps
day no. vs Public Pier
J F M A M J J A S O N D
1999

Figure 5. Fluctuations in electrical conductivity during 1999.

electrical conductivity - an overall index of ionic strength

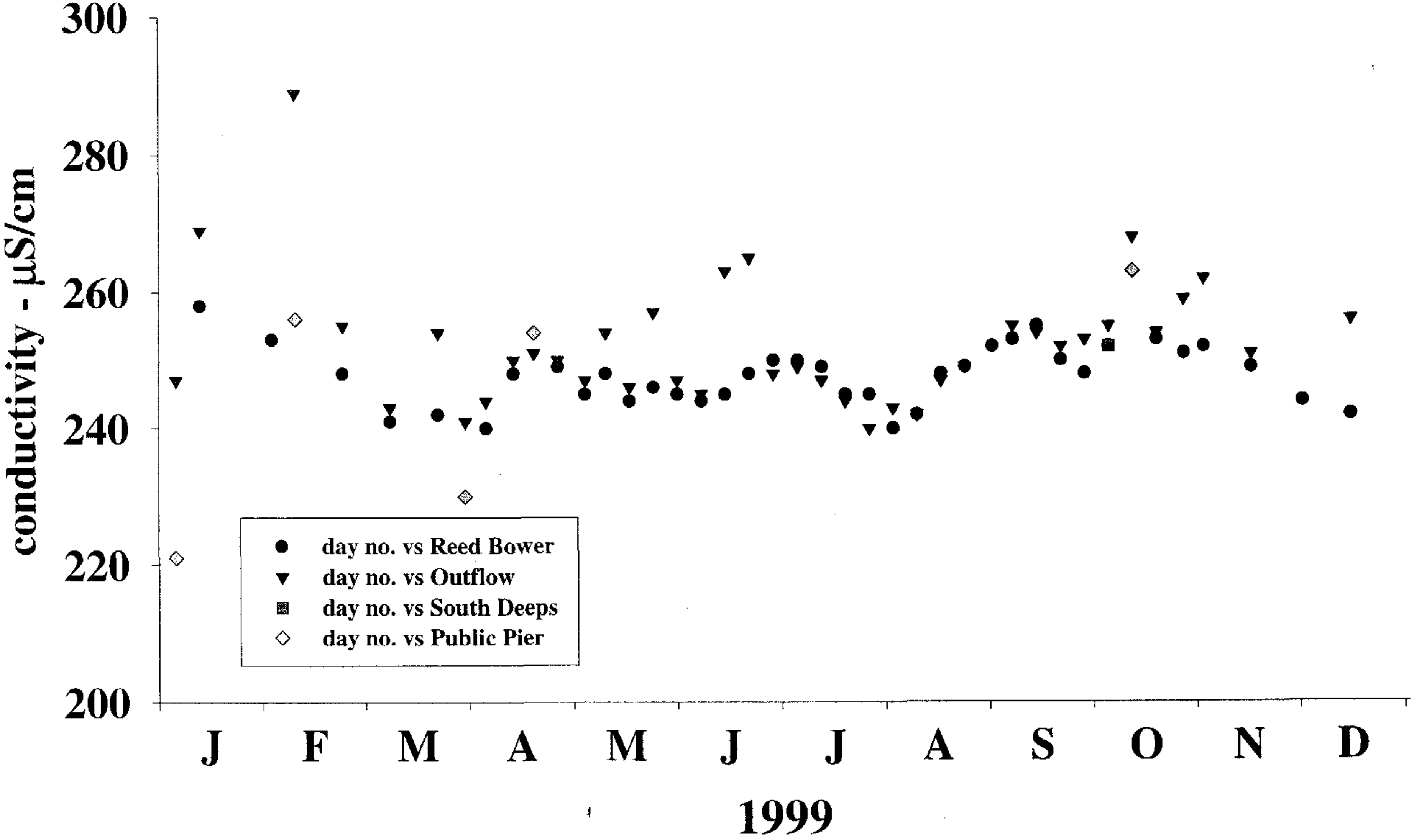

Figure 6. Fluctuations in nitrate-nitrogen during 1999.

nitrate-N concentrations

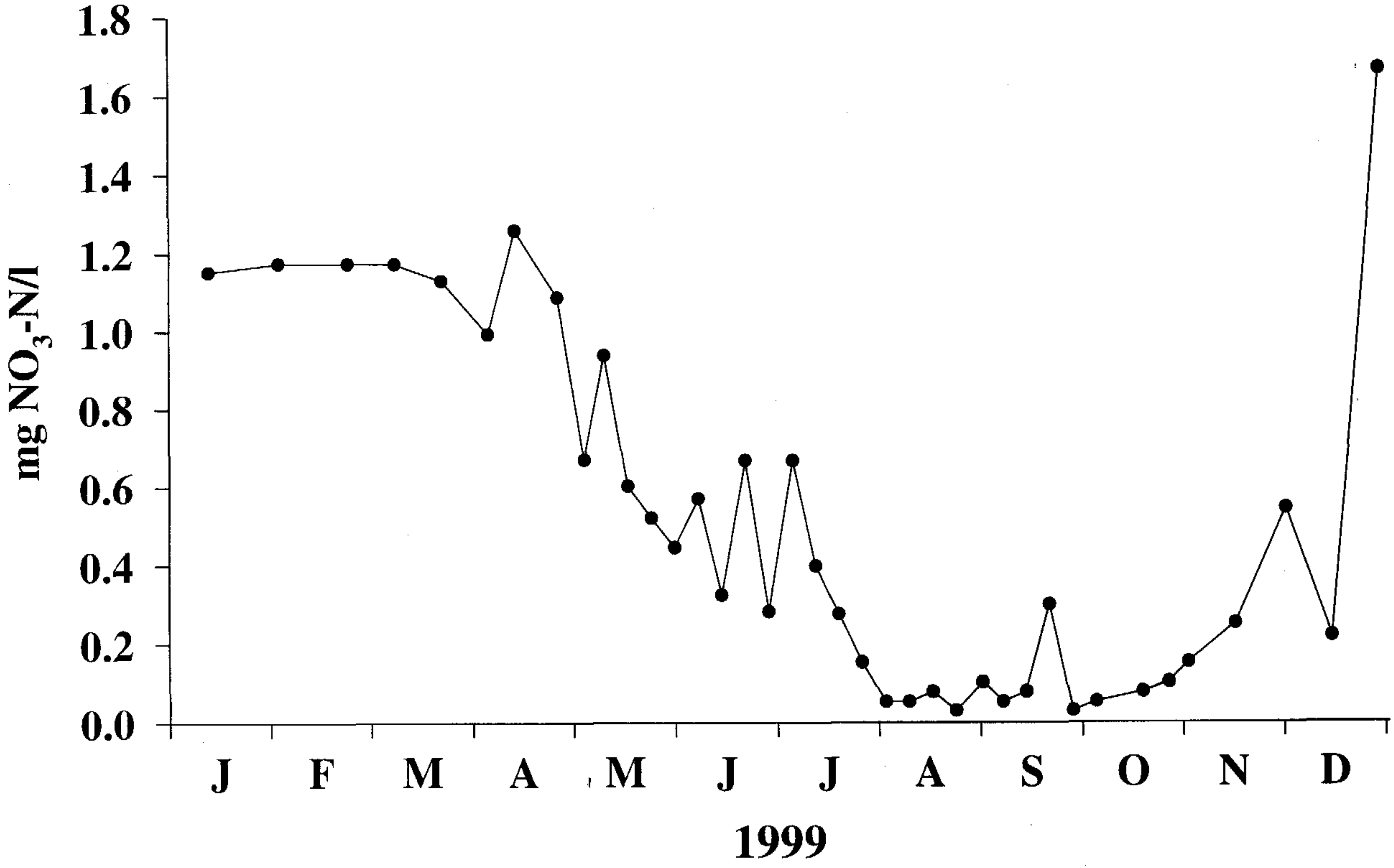

Figure 7. Fluctuations in soluble reactive phosphorus during 1999.

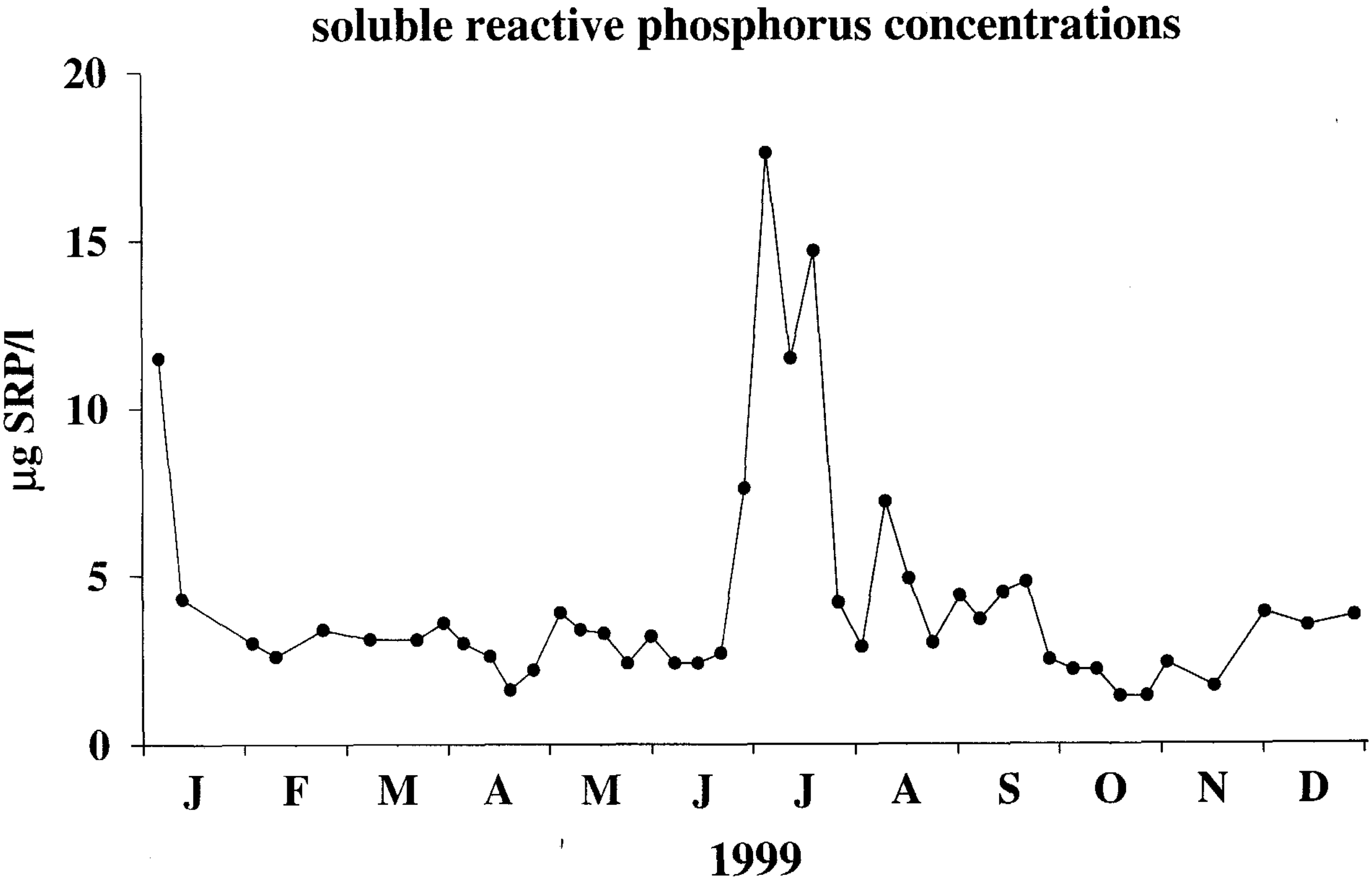
soluble reactive phosphorus concentrations
20
15
10
5
0
µg SRP/l
J F M A M J J A S O N D
1999

Figure 8. Fluctuations in total phosphorus concentrations during 1999.

total phosphorus concentrations

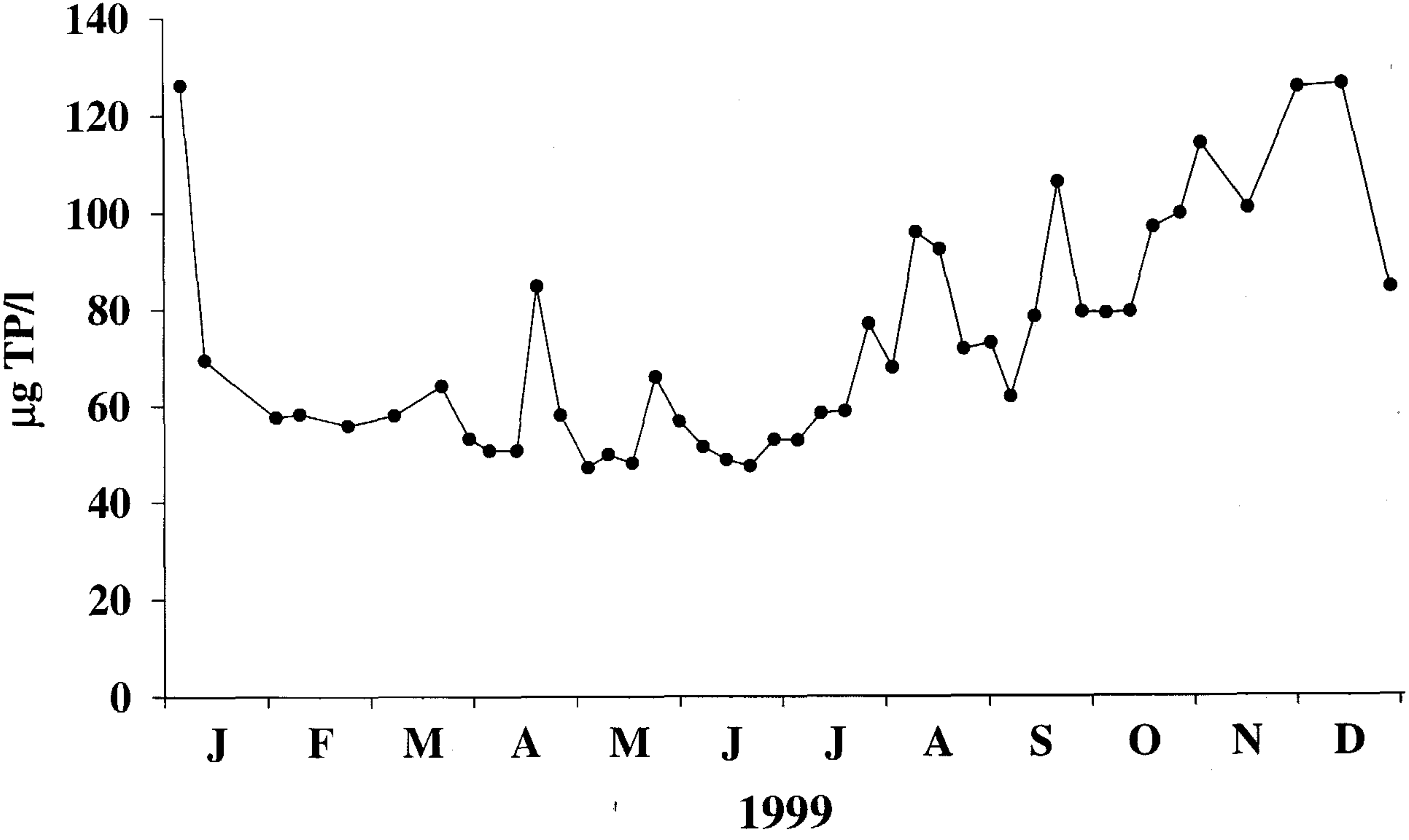

Figure 9. Fluctuations in dissolved silica concentrations during 1999.

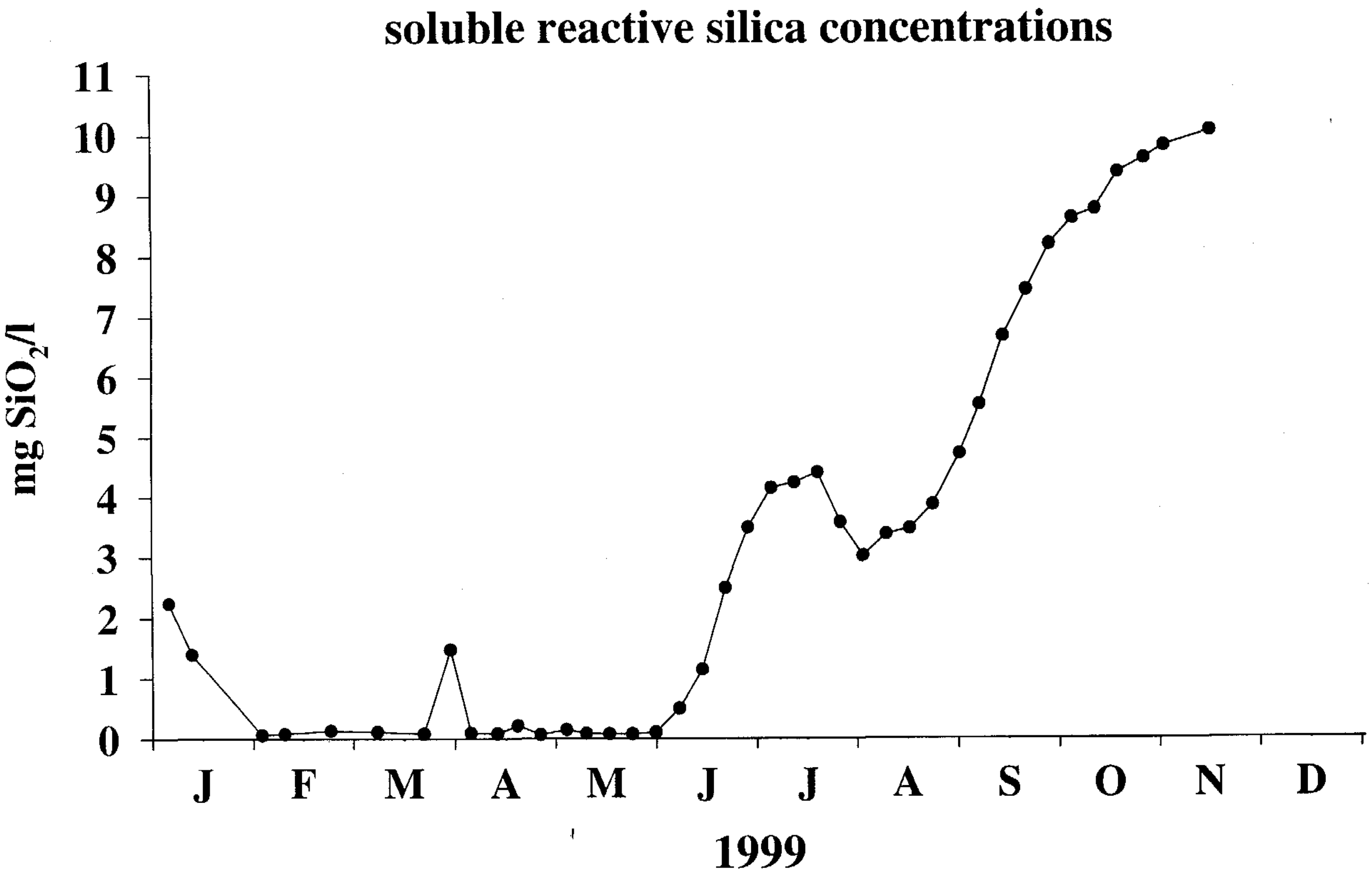
soluble reactive silica concentrations
mg SiO2/l
11
10
9
8
7
6
5
4
3
2
1
0
J
F
M
A
M
J
J
A
S
O
N
D
1999

Figure 10. Fluctuations in the chloropyhyll$_a$ concentration in 1999.

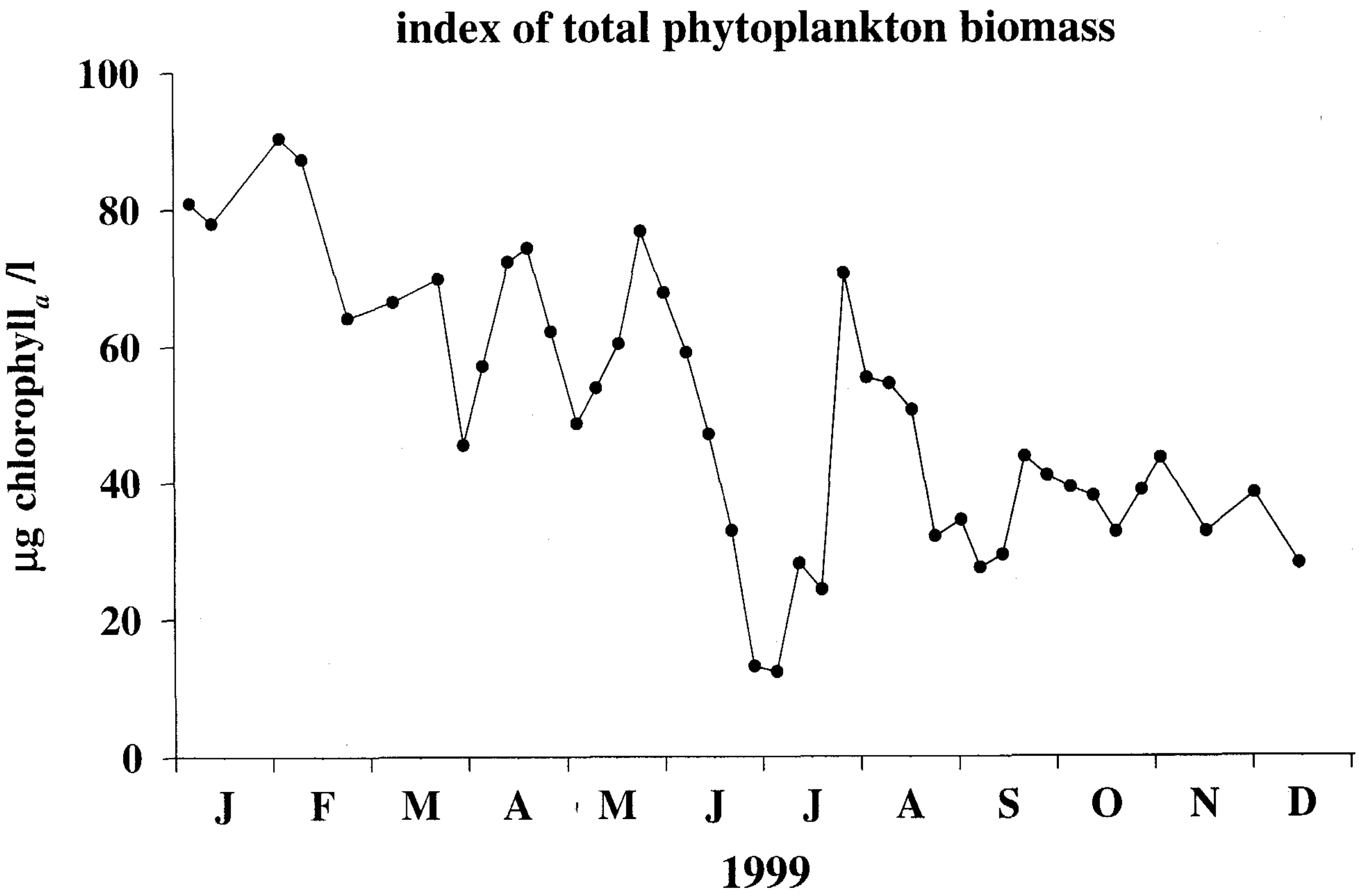
index of total phytoplankton biomass
µg chlorophyll a /l
100
80
60
40
20
0
J
F
M
A
M
J
J
A
S
O
N
D
1999

Figure 11. Fluctuations in the population densities of the filamentous diatom, *Aulacoseira italica* during 1999.

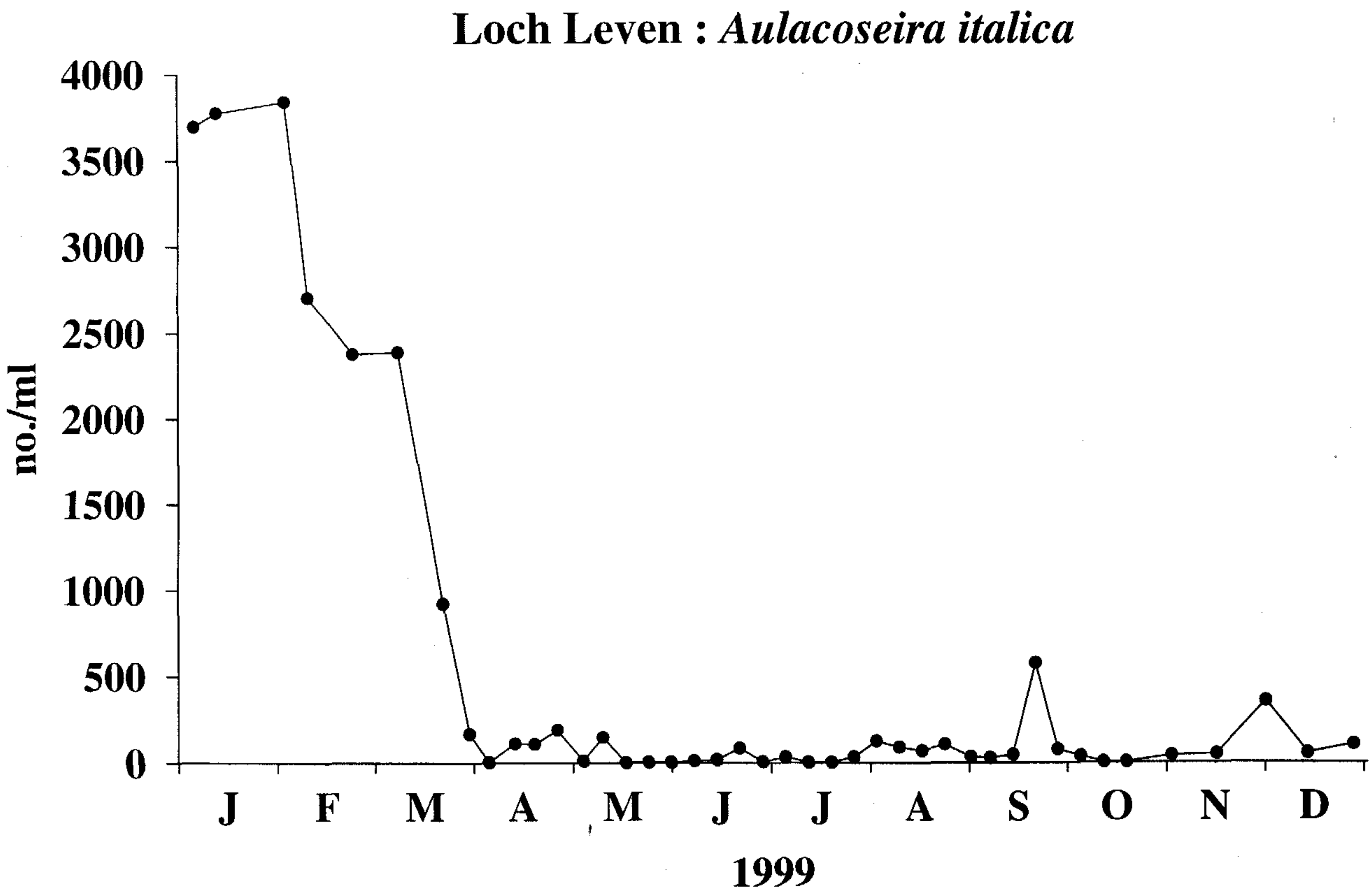
Loch Leven : *Aulacoseira italica*
no./ml
4000
3500
3000
2500
2000
1500
1000
500
0
J F M A M J J A S O N D
1999

Figure 12. Fluctuations in the combined population densities of unicellular centric diatoms in 1999.

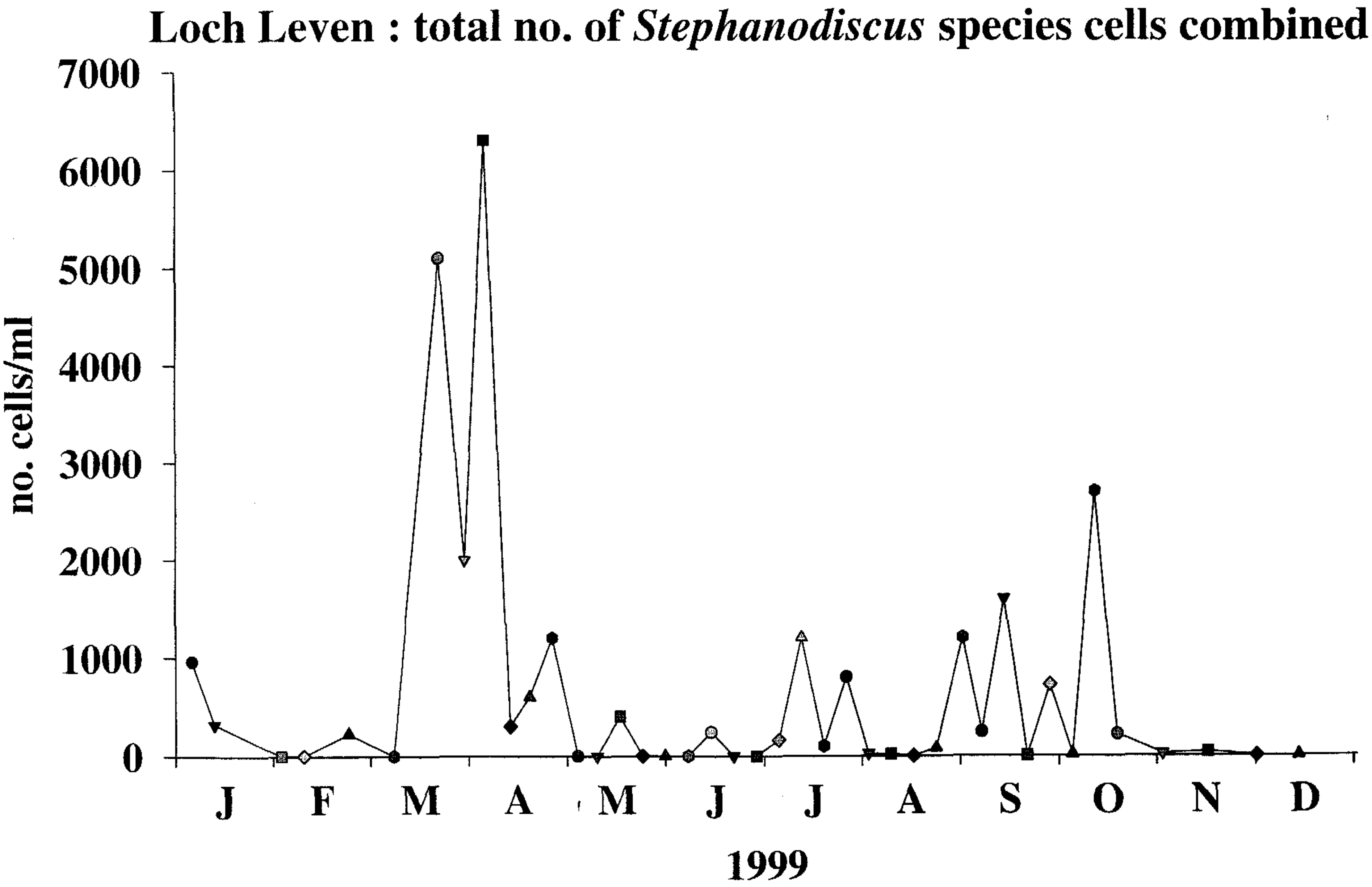
Loch Leven : total no. of *Stephanodiscus* species cells combined
7000
6000
5000
4000
3000
2000
1000
0
no. cells/ml
J
F
M
A
M
J
J
A
S
O
N
D
1999

Figure 13. Fluctuations in the population densities (as cells) of the colonial diatom, *Diatoma elongatum* during 1999.

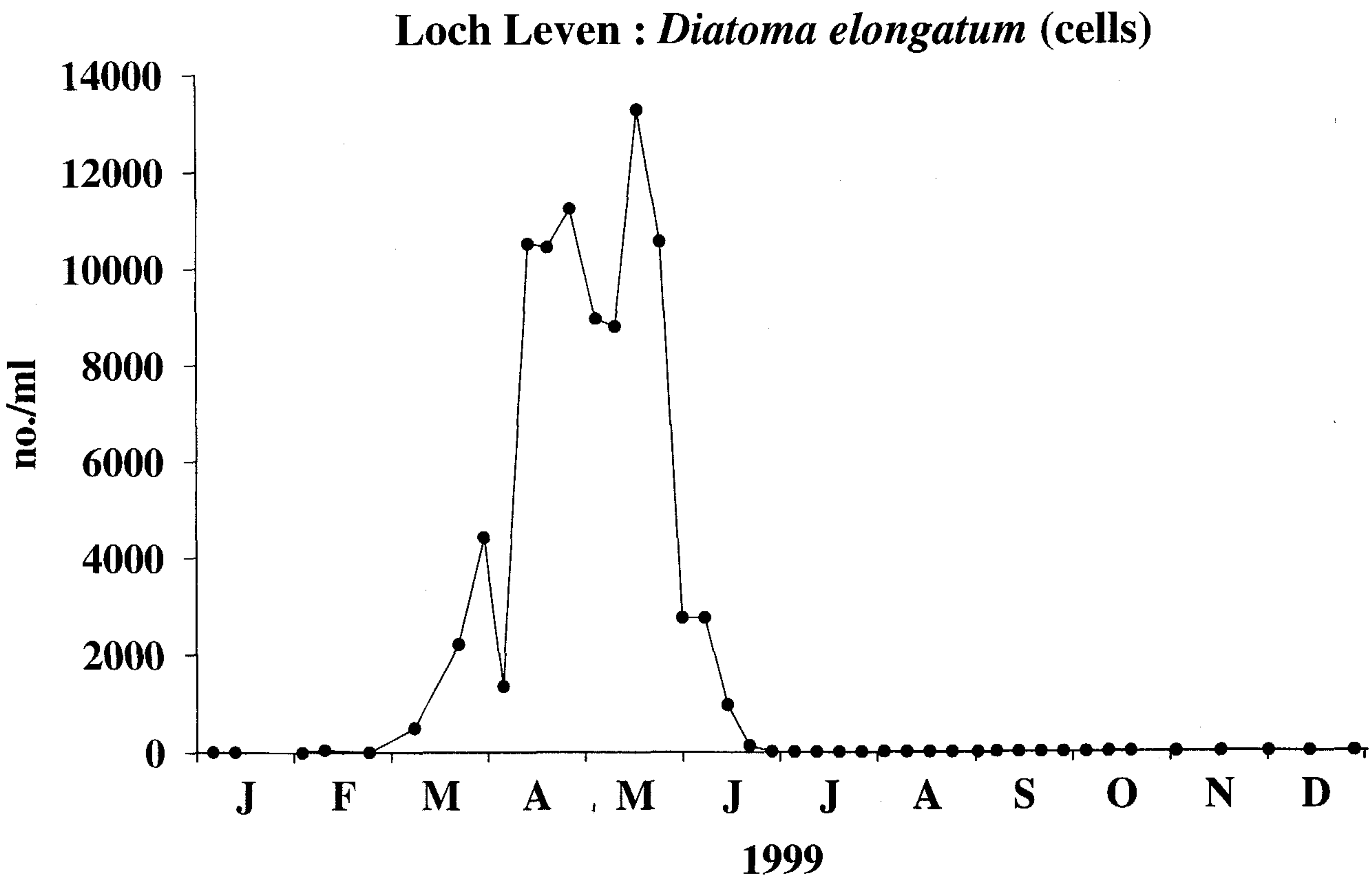
Loch Leven : Diatoma elongatum (cells)
no./ml
14000
12000
10000
8000
6000
4000
2000
0
J
F
M
A
M
J
J
A
S
O
N
D
1999

Figure 14. Fluctuations in the population densities of the lunate desmid, *Closterium acutum* during 1999.

Loch Leven : *Closterium acutum* cells

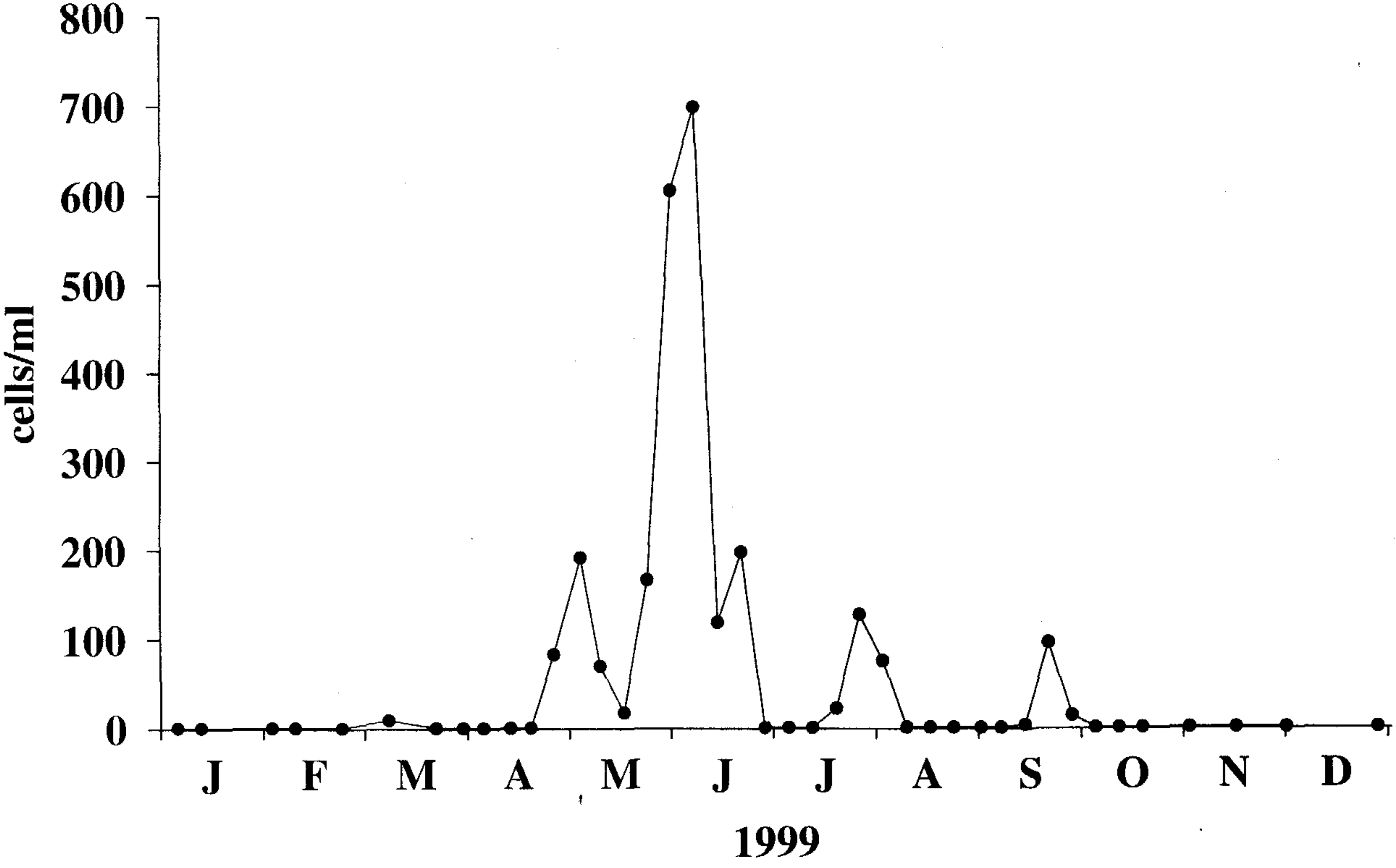

Figure 15. Fluctuations in the combined population densities of *Anabaena* spp. (mainly *A. flos-aquae*) , during 1999.

Anabaena spp. combined - mainly *A. flos-aquae* fo. *flos-aquae*

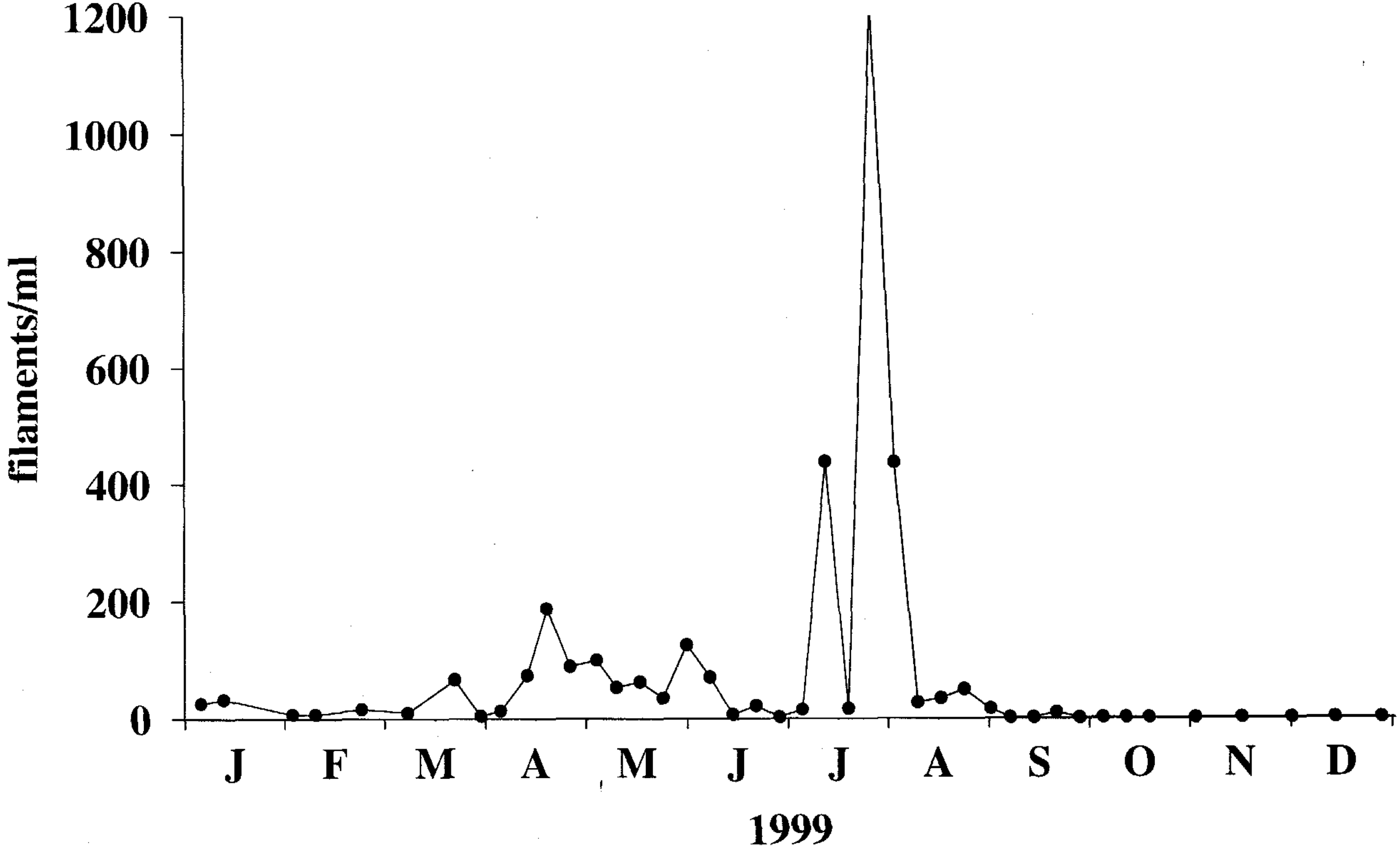

Figure 16. Fluctuations in the population densities (as colonies) of the cyanobacterium, *Gomphosphaeria* near *G. lacustris* during 1999.

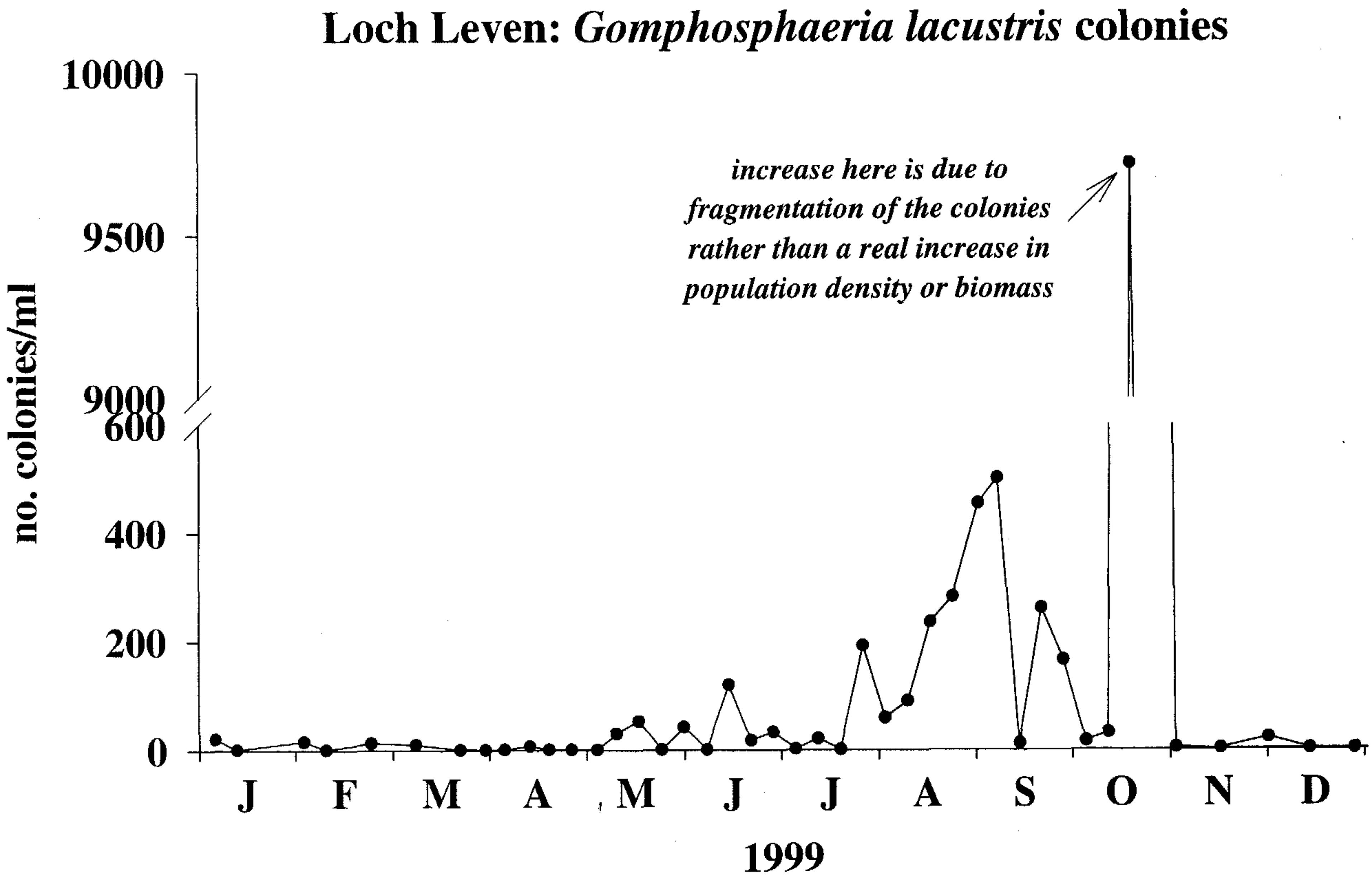
Loch Leven: *Gomphosphaeria lacustris* colonies
10000
9500
9000
600
400
200
0
no. colonies/ml
increase here is due to fragmentation of the colonies rather than a real increase in population density or biomass
J
F
M
A
M
J
J
A
S
O
N
D
1999

Figure 17. Fluctuations in the population densities (as filaments) of the cyanobacterium, *Oscillatoria agardhii* var *isothrix* during 1999. N.B. This organism has recently been renamed as *Planktothrix mougeotia*

Loch Leven : *Oscillatoria agardhii* var. *isothrix*

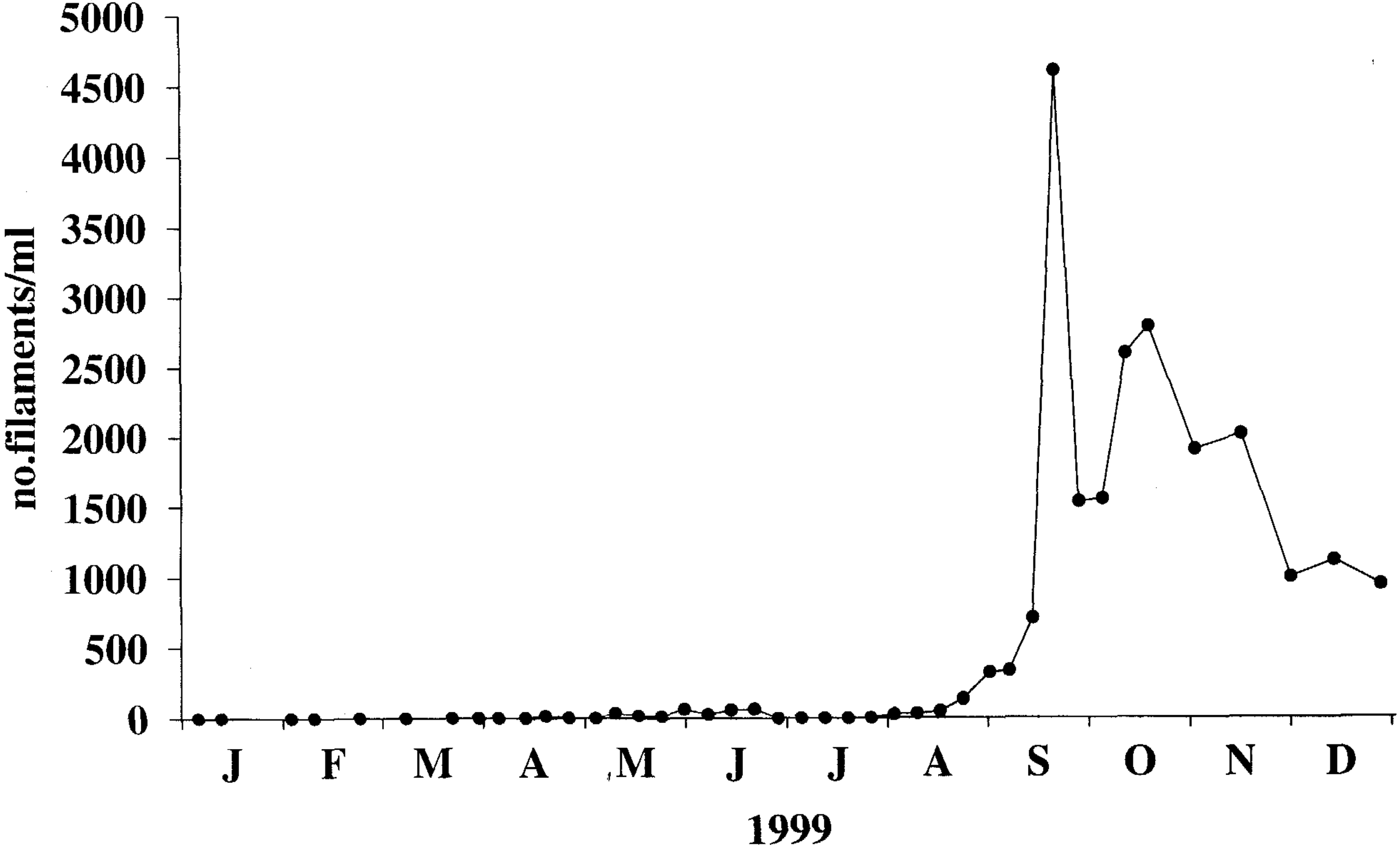

Figure 18. Fluctuations in the population densities of *Oscillatoria agardhii* var *isothrix* during 1999 expressed as filaments per milli-litre and metres per litre.

Loch Leven : *Oscillatoria agardhii* var. *isothrix* abundance expressed in numbers of filaments per millilitre and, from 1st August, the total filament length in metres per litre

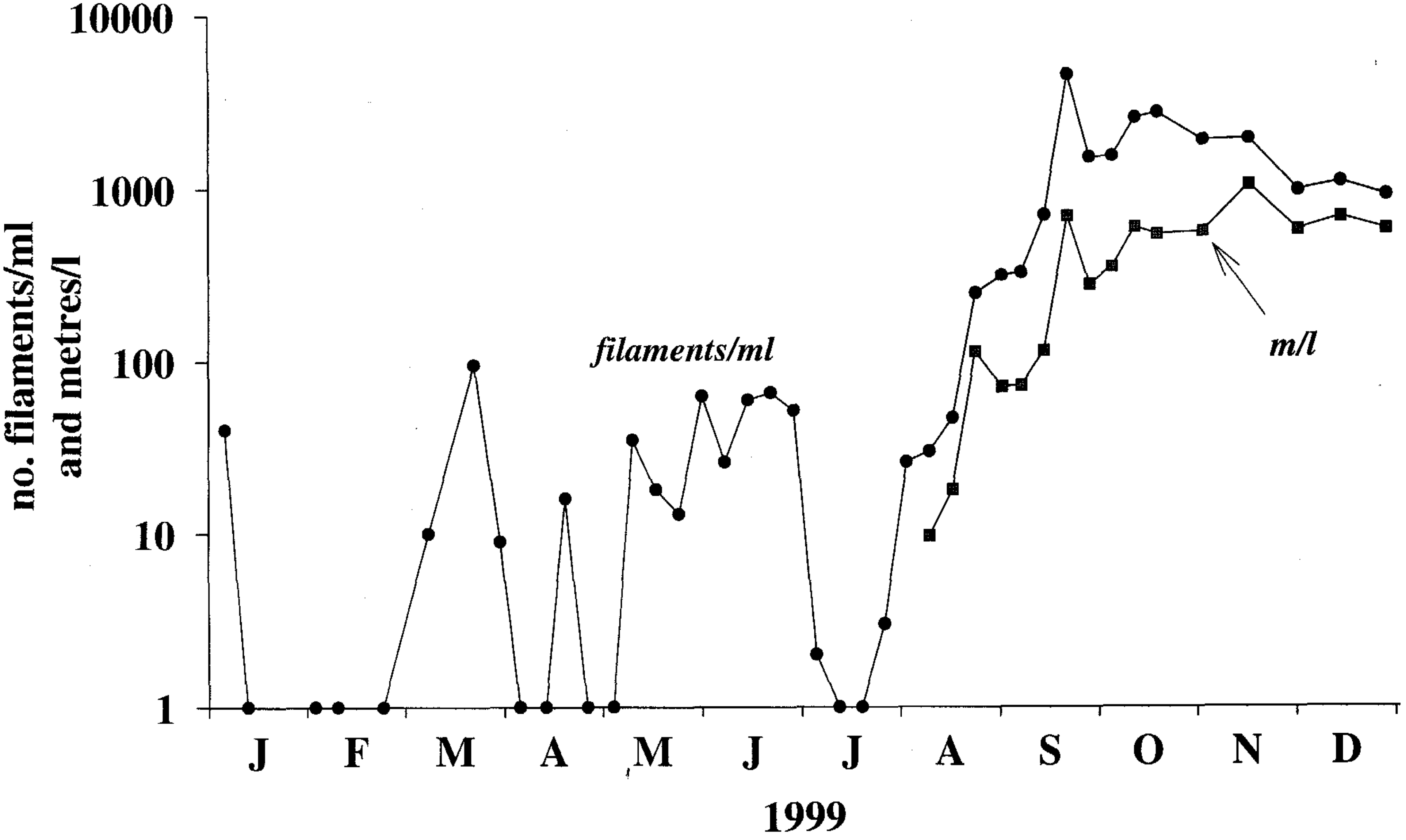

Figure 19. Ranges in the values for the major physical and chemical factors studied in 1999.

ranges in the values of some physical and chemical factors - Loch Leven 1999