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Nutrients and phytoplankton in Loch Leven 1991 - a good year for *Anabaena* in spite of earlier reduction in the external phosphorus loading?

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INTRODUCTION

The nutrient status and plankton sequences of Loch Leven are well-documented (eg Holden and Caines 1974; Bailey-Watts 1976a, 1978, 1982, 1986, 1988), and the phosphorus loading has been reasonably well measured (Bailey-Watts, Sargent, Kirika and Smith 1987; Bailey-Watts and Kirika 1987). Moreover, since information on weather, especially rainfall because of its effect on flushing rate, has been added to the database, our conceptual models of the controls over a number of processes have been markedly improved (Bailey-Watts, Smith and Kirika 1989a, 1989b; Bailey-Watts, Kirika, May and Jones 1990; Bailey-Watts 1991); these include:

(i) changes in water temperature, and the occurrence of temperature extremes

(ii) the supplies and in-lake dynamics of phosphorus (especially inorganic phosphate), nitrogen (especially nitrate) and silica

(iii) fluctuations in the abundance of a number of phytoplankton types, even certain species

(iv) grazing interactions between certain rotifers, micro-Crustacea and planktonic algae.

The over-riding influence of the weather on this broad, shallow lake, has also been emphasised by the results of the surveillance of nutrients and plankton over the last 7 years. This extends from 1985, when the major P loading study was carried out (Bailey-Watts, Sargent, Kirika and Smith 1987), through the period 1988-1989 when the external P loading was reduced (Bailey-Watts, May and Kirika, 1991), to the present (end 1991).

The aim of this report is to firstly summarise the thinking on, and the content and results of, the work done following the loading study and up to the end of 1990, and secondly, report on the initial results obtained from the 1991 surveillance.

RESULTS AND DISCUSSION

1985 to 1990 inclusive

The rationale for controlling the supplies of P (as opposed to those of other nutrients) and more specifically, the scientific basis for targetting the inputs of industrial P-rich waste to Loch Leven, are discussed in the earlier reports and papers. Model-based predictions of the effects of the control are also summarised in relation to the 1985 results, when a total of 20.5 t P (including 8.1 t in runoff, 6.3 t in the industrial effluent and 5.3 t in treated sewage effluent) entered the loch, and mean in-loch concentrations of 62 μg TP l^{-1} and 21 μg chlorophyll *a* l^{-1} were recorded. The analysis suggested that by eradicating the industrial contribution, the annual P and chlorophyll levels would be reduced to *ca* 57 μg l^{-1} and 17 μg l^{-1} respectively, assuming a flushing of 1.88 loch volumes y^{-1} (the long-term average);

the calculations also predicted that P and algal levels would fall to the lower values within *ca* 0.5 to 1.6 years of the P loading being reduced to the extent envisaged.

The P reduction was amply achieved, such that by late 1989, no effluent was being discharged by the industry previously involved. Thus, during 1990, *ca* 2.0 t P was transported to the loch by the stream formerly receiving the mill waste. This figure is in keeping with conventional agricultural runoff P losses and, in being higher than the figure of 1.7 t measured for the agricultural part of the drainage area of this stream in 1985, reflects the fact that 1990 was a somewhat wetter year than 1985. To this extent, the reduction in P burden to the loch brought about by diversion of mill effluent, was partly offset by the heavier rainfall in 1990; indeed, as 6.3 t was 'diverted', and an extra 1.6 t in total runoff (ie all streams) and direct rain was introduced to the loch, the net reduction is only *ca* 4.6 t, ie. 22% of the 1985 total of 20.5 t. Nevertheless, a reduction was achieved and in addition to establishing this over the period 1988 to 1989, the 1991 report (Bailey-Watts, May and Kirika 1991) aimed to assess its early effects (if any) on P and phytoplankton content. Continuing 8-daily measurements in 1990 showed, however, considerably elevated levels of TP and pigment, ie 80 $\mu g\ l^{-1}$ and 50 $\mu g\ l^{-1}$ respectively. Initially, the findings were considered to be all the more puzzling, bearing in mind that 1990 was a very wet year - a factor likely to suppress planktonic algal growth, if not the inputs of P; as a consequence flushing was high, with a value of 2.94 loch volumes, compared to the 1985 figure of 2.57, which at the time was judged to be *fairly exceptional. Much of that report examined the apparent anomaly, and* concluded that mean annual figures for e.g. rainfall, flushing, and P and phytoplankton concentrations mislead; only when seasonal fluctuations in e.g. precipitation and algal abundance were considered, did the reasons for elevated P and phytoplankton become clearer. The striking contrasts between conditions prevailing in 1985, and those observed in 1990, were described to emphasise the importance of temporal variability.

The main issues are as follows:

- while rainfall (and thus flushing and runoff P loadings) were the higher in 1990, the difference from 1985 is not great. However, some 60% of the *annual throughput of water occurred in the first 3-3½ months of 1990*, while an additional proportion of only 5-10% was delivered between April and September and the remainder of the year was reasonably dry; contrastingly *ca* 30% of the 1985 rain fell in July and August and the autumn was also wet.

- the coincidence of warm weather and the summer period of low water renewal in 1990, enhanced denitrification which resulted in low nitrate concentrations, and in turn, led to a rapid and marked release of soluble reactive P from the sediments, to a peak concentration of 78 μg SRP l^{-1} in August; the increase over the very moderate background levels of 6 μg l^{-1} represents an internal loading of *ca* 3.7 t to the water column, an amount equivalent to *ca* 60% of that estimated to have entered the loch from the mill in 1985 and now diverted.

- on the return of somewhat cooler weather and reduced de-nitrification, much of the P released was readsorbed by the sediments, but a proportion was sequestered by phytoplankton which were able to accumulate biomass on account of the relatively low flushing rates prevailing over the remainder of the year.

Even in the absence of a weather regime as unusual as 1990 when conditions appeared to 'conspire' to negate effects of the present phase of P loading reduction, it was considered likely that more time would be needed to assess these effects. The good fortune of having attracted funding from the Nature Conservancy Council (Scotland), to maintain the limnological surveillance, was noted. It was recommended that this be continued until the end of 1993, by which time a more informed judgement could probably be passed on whether further P reduction measures such as tertiary treatment of effluent from the major sewage works, are necessary or appropriate.

1991

The only information available for reporting at this time, is that on (i) flows within main feeder streams, (ii) in-lake chlorophyll levels, and (iii) some observations on the species composition and densities of the phytoplankton. [Samples for nutrient and zooplankton determinations are still being analysed, and should be available during the next month.] These few data, however, are sufficient to make some pronouncements on the likely major features of nutrients and plankton in Loch

Leven during 1991; indeed, the present lack of actual figures on nutrients and full data on phytoplankton, provides an unexpected opportunity to test our ability to predict them, using just flow and chlorophyll data.

Previous work (Smith 1974; Bailey-Watts, Sargent, Kirika and Smith 1987) shows that some 25% of the total runoff of water to Loch Leven (ie excluding rain falling onto the lake surface), enters *via* the South Queich. The patterns of discharge from this stream parallel those of the other main feeder waters, and generally the run of water through the loch as a whole, ie the flushing rate. The most recent report is also based on South Queich data (Bailey-Watts, May and Kirika 1991), since this stream used to receive the mill effluent referred to above. **Figure 1** displays the cumulative discharge patterns for 1985 and 1988 to 1991.

On the basis of these years (ie those for which nutrient and plankton data are also available), the periods January to March have become progressively, relatively wetter, while the spring-to-summer periods, and especially the late summer-to-autumn months, have become drier. Annual mean discharges vary, but, apart from the very dry year 1989 (734 $l\ s^{-1}$), they lie between 913 $l\ s^{-1}$ (1985) and 1023 $l\ s^{-1}$ in 1990. The seasonal pattern for 1991 is similar to that of the previous two years, in that (i) some 60% of the annual input of water entered the loch by the end of April, and only a further 10% came in during the next 5 months. However, while in October of 1989 and of 1990, an input of 10-12% of the corresponding annual discharges were recorded, the October of 1991 saw an input of only 5% - thus extending the period of low flushing (long residence time) to some 6 months in this year.

Bailey-Watts, Kirika, May and Jones (1990) discuss the effects of such a prolonged period of low flushing. Particularly over the summertime, the following are likely to occur in this large shallow waterbody:

(i) the temperature of the water will equate more closely to ambient air temperatures

(ii) the surface (at least) of the sediments will gain more heat than usual, and as a consequence, (a) nitrate will be more rapidly lost from the water column (by microbial de-nitrification) to become limiting, and - related to (a) - (b) the rate of releases of phosphorus and silica from the sediments will be greater, and they will probably take place over a longer period, than usual

(iii) if the weather is calm, heavy/non-motile algae are likely to be disadvantaged, while bouyant/motile forms would flourish and, with the reduced losses *via* washout, the successful species would produce more cells and, possibly (see (iv) below), accumulate more biomass

(iv) increases in temperature would lead to enhanced grazing rates of zooplankton on phytoplankton, with, in summer, large cladocerans which prefer the smaller algal species, predominating as a consequence, larger forms of phytoplankton would become more prominent.

That some dense crops of planktonic algae occurred in summer and early autumn is evident from **Figure 2**; the early August and late September chlorophyll maxima of *ca* 140 $\mu g\ l^{-1}$ and 60 $\mu g\ l^{-1}$ are considerable, and must have needed similar concentrations of P to support them.

Taking into account all of the information discussed so far, a nitrogen-fixing *Anabaena* species would be the most likely 'candidate' to dominate the scene in at least late summer 1991. Some morphological features, and aspects of its growth and reproductive strategies, that lead us to this conclusion are as follows:

(i) it is a relatively large and thus 'physically-unpalatable' to e.g. *Daphnia*

(ii) its large size and ability to produce gas-vacuoles, fit it well to an intermittently stratifying (calm) water column

(iii) its ability to fix atmospheric, elemental nitrogen, renders it immune from shortages of e.g. nitrate

(iv) it favours a high SRP-low nitrate environment

(v) even under less prolonged periods of low flushing, it would be capable of building up biomass by recruitment of cells from resting spores (akinetes) in lake sediments.

Of course, there are other algae that are e.g. large and gas vacuolate etc., but not with, as far as is known, the same combination or overall suite of features, as some of the *Anabaenas*.

Large gas-vacuolate *Oscillatoria* species (many of which have been re-named (on dubious grounds as far as the senior author is concerned) as *Tychonema* e.g. *T. bornetii*, or *Planktothrix* e.g. *P. agardhii* - see Anagnostidis and Komarek 1988, are not likely to survive prolonged periods of very low nitrate levels. What is more, many *Oscillatorias* require very long periods of low flushing to build up their populations, (Bailey-Watts 1974, 1978): the relatively wet early part of 1991 would have prevented them establishing themselves later in the year. Small *Oscillatorias* many of which have also been re-classified - as *Limnothrix*, e.g. *L. redekei*, by Meffert 1988, are similarly vulnerable; additionally, they have not been prominent in summer in Loch Leven since *Daphnia* 'returned' in 1971-1972 (Bailey-Watts 1982; Bailey-Watts, Kirika, May and Jones 1990). Small, but otherwise quite different, algae have been recorded in considerable abundance in Loch Leven e.g. *Rhodomonas* (a cryptomonad) under very warm, calm conditions in 1969 (Bailey-Watts 1973), but this too, was prior to the re-surgence of *Daphnia*. Nevertheless, large vacuolate cyanobacteria such as *Mycrocystis* species have been prominent in previous warm summers. Though not a nitrogen-fixer in the manner of *Anabaena*, this genus may owe its success to its ability, under stable, stratified conditions, to sink to nutrient-rich, near-sediment depths, and sequester nutrients from there, before readjusting its buoyancy and floating to the upper, lit layers, to fix carbon (Reynolds and Walsby 1985).

Finally, *Anabaena* - in common with an enormous number of algae - is susceptible to parasitism by Fungi, and/or 'grazing' by Protozoa. Whatever, the alga producing the maximum in August 1991, it collapsed suddenly and markedly afterwards. While even under the environmental conditions hypothesised above, nutrient limitation cannot be ruled out, the possibility of parasitism/grazing should also not be ignored.

Until our plankton counts and nutrient analyses are completed we shall not know what species prevailed, and under what conditions they fared, but the prospect of testing these 'predictions' is exciting!

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FIGURE 1

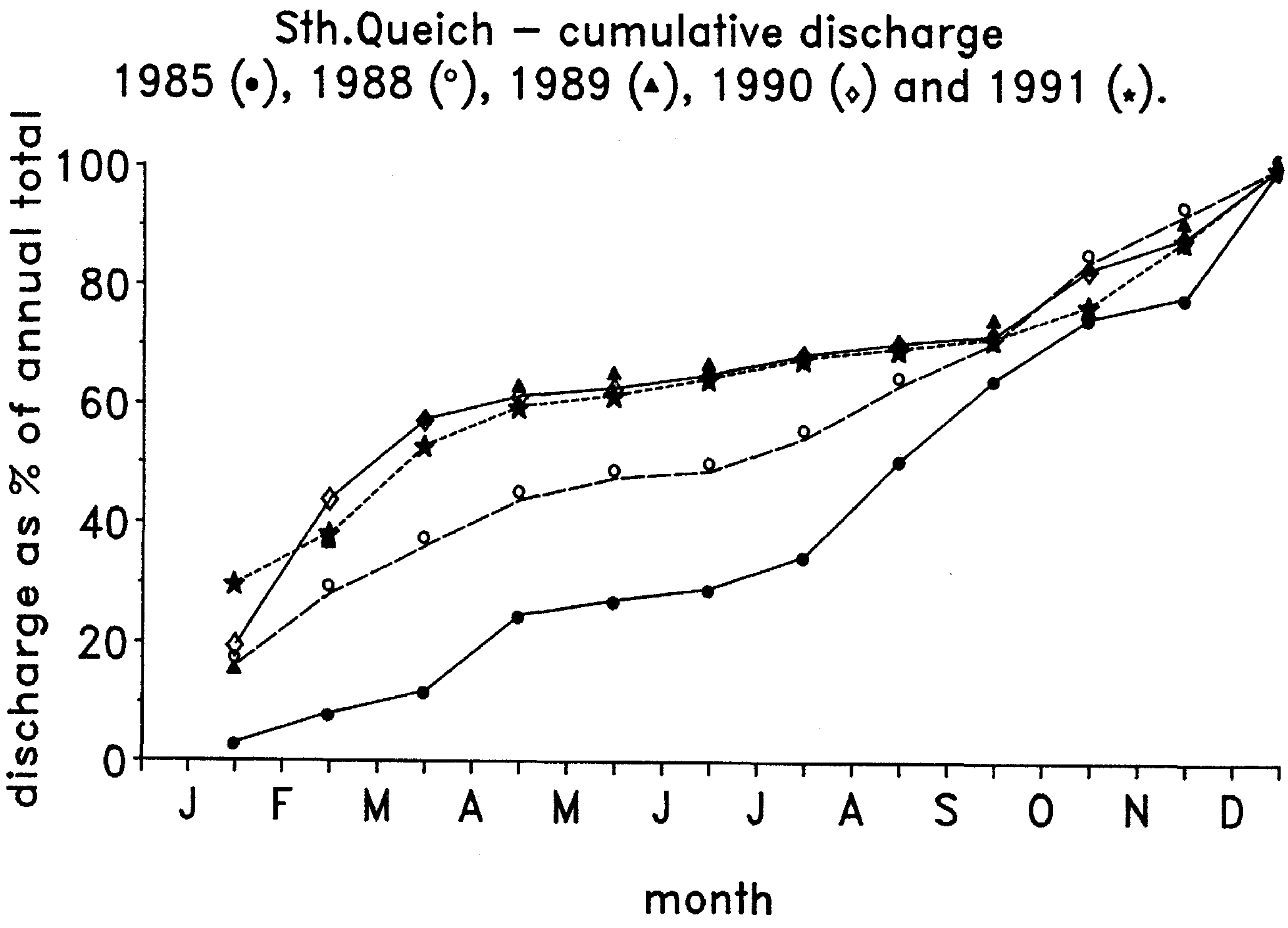
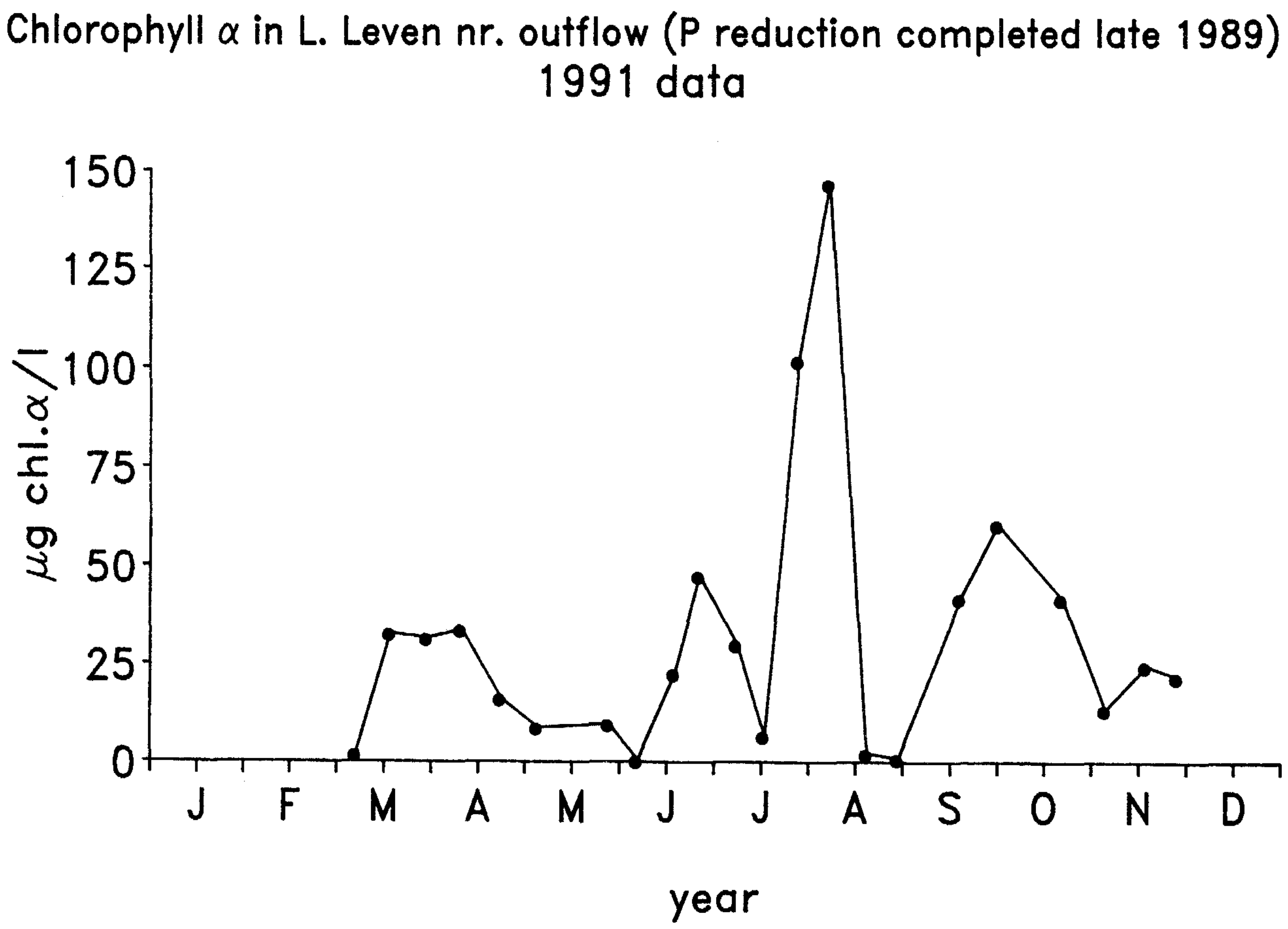

Sth.Queich – cumulative discharge
1985 (•), 1988 (°), 1989 (▴), 1990 (⋄) and 1991 (⋆).
discharge as % of annual total
100
80
60
40
20
0
J
F
M
A
M
J
J
A
S
O
N
D
month

FIGURE 2


Chlorophyll α in L. Leven nr. outflow (P reduction completed late 1989)
1991 data
150
125
100
75
50
25
0
μg chl.α/l
J
F
M
A
M
J
J
A
S
O
N
D
year