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LOCH LEVEN NNR: WATER QUALITY 1992-1994 WITH SPECIAL REFERENCE TO NUTRIENTS AND PHYTOPLANKTON, AND AN ASSESSMENT OF PHOSPHORUS LEVELS IN THE LOCH SEDIMENTS

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Introduction

This study covers two aspects: (i) the monitoring of nutrient and phytoplankton status and associated physico-chemical conditions, and (ii) the assessment of the distribution of phosphorus (P) in the sediments of the loch. The two areas are closely related. In 1992 (and in *ca* 50% of the previous 20 years for which there are data), major changes in P concentrations in the water column, are considered to be due largely to release of inorganic phosphate from the sediments - and not so much to immediate inputs of the nutrient to the loch from outside. This report deals almost exclusively with the work on phytoplankton ecology, and **Table 1** summarises what has been measured and how often. Comparatively little has been done on sediment P this year, apart from a spatial survey in October 1992, and the results from this are only just emerging. Considerably more sediment work is planned for 1993-94, however, and the new findings will eventually be presented along with a review of all sediment studies carried out at Loch Leven. For present purposes, **Table 2** simply lists these studies.

Table 1. Physico-chemical, nutrient and phytoplankton studies on Loch Leven 1992/93. * denotes areas discussed below.

determinand	numbers of samples and temporal coverage
water temperature *pH* *conductivity* *dissolved oxygen*	*April, May and June 1992*: two samples per month from the Sluices site (near the outflow) and from the edge of the Kirkgate Pier, and the lower South Queich. Additional, samples (e.g. edge scums) taken on an *ad hoc* basis. *Each month July 1992 to March 1993*: sampling once in every week (not necessarily at 7-day intervals), and alternating between a 4-site programme (middle of West Bay due south of Kirkgate Pier, mid-water south of Reed Bower, the Sluices and the lower South Queich), and coverage of these sites plus another 7 over the length and breadth of the loch. *Analyses*: all determinands listed except that no phytoplankton analyses are done on the Queich samples, and while rapid checks are made on cyanobacterial numbers in most samples when pigment analyses indicate a patchy distribution, only one or two samples are assessed fully for phytoplankton species and abundance data.
*nitrate-N**	
*phosphorus fractions**	
*silica fractions**	
*chlorophyll a**	
*algal species and cell numbers**	
size spectra	

The report covers the financial year 1 April 1992 to 31 March 1993, even though contract funding did not commence until 1 June 1992. By this time, the population densities of certain blue-green algae (cyanobacteria) such as *Anabaena*, were already considerable and, as subsequently well-appreciated even by the public, heralding aggregations of massive, 'bloom' proportions.

Indeed, the sampling programme that was started in early July, incorporated many more sampling sites, in order to assess more effectively the lake-wide population abundances of particularly the large blue-green algae (e.g. *Anabaena, Microcystis*) which under the 'right' conditions, can not only buoy up to the surface, but also exhibit a spatially very patchy distribution.

Table 2. Scope of work on phosphorus in Loch Leven sediments.

year and dates	studies carried out
1968-71: various dates (by the Freshwater Fisheries Laboratory, Pitlochry.	Total P content in the surface sediments.
1986: 24 and 30 April; 8, 14, 19 and 29 May; 2, 5, 10, 24 and 30 June.	Cores collected from sediments at 4m and 10m water depths, for the determination of soluble reactive P (SRP) and total soluble P (TSP) (and dissolved silica) in the pore waters; analyses carried out on 1-cm slices of mud down to 10 cm, and on the 15- to 16-cm slice.
1989: 22 June; 18 and 27 July; 2 and 16 August.	A pair of cores was taken at 3 sampling points along one transect passing from shallow to deep water, and at 5 sampling points along another transect, for the analysis of pore SRP and TSP (and silica), and for incubation to determine the rates of release of phosphate (and silicate).
1990: 28 January.	Sequential extraction of loosely bound, iron and calcium bound fractions of P, in 1-cm slices of the top 10cm of mud in a pair of cores taken in 15m water depth.
1992: 28 October.	Spatial survey of 10 sites, for the analysis of the total P content in the uppermost 5 cm of sediment.

Much of the work in this first year has thus focused on the ecology of the phytoplankton - weekly fluctuations in the biomass, and the seasonal alternation between the cyanobacteria and the other algae, particularly diatoms, which may form just as dense populations as e.g. *Anabaena* or *Microcystis* on a lake-wide basis, but which would only form surface blooms under very exceptional circumstances. Physical factors such as the state of the wind and water temperature, play an extremely large part in bloom formation, and flushing rate

determines what time an organism has to accumulate biomass. At this stage, however, the relevant data have not been analysed, so only very general remarks on these factors are made. Virtually all of the data on nutrients have been logged, however. Temporal shifts in the concentrations of P and silica (SiO_2) in particular, are presented here, since they explain major features of the observed sequences of phytoplankton species.

Field and laboratory methods are not described in any detail, as full accounts of the various procedures are given in a number of reports on studies done by this laboratory for SNH, NCCS, NCC and the original Nature Conservancy.

Results

Seasonal fluctuations in phytoplankton and nutrients

Particulate components

The general patterns of change in the levels of total P (TP - **Figure 1**), particulate P (PP - **Figure 2**) and chlorophyll *a* (**Figure 3**) are similar in that moderate values in late spring gave way to a period (mid-June to the end of September) in which higher concentrations were more common, and then a long spell (equivalent to half of the period covered here) of lower levels. Because the TP and chlorophyll results for each sampling station are plotted, another feature common to these graphs is the wide spread of concentrations obtained on certain days.

The largest spreads of values were recorded in June and July. This was when the large cyanobacteria were dominant, and the fluctuating ranges in chlorophyll particularly (even setting aside the fact that the number of stations sampled was not constant), reflect sharp changes in the degree of patchiness in their distribution. The *flos-aquae* form of *Anabaena flos-aquae* Breb. *ex* Born. *et* Flah. was present in almost pure stand in the blooms recorded in June, July and much of August, having been common (approaching 10^3 individuals ml^{-1}) even in late March. Contrastingly, *Microcystis aeruginosa* Kutz. *emend.* Elenkin, which succeeded *A. flos-aquae*, did not start to dominate the scene until late August; indeed, though generally larger than *A. flos-aquae*, it was still present at only *ca* 10 ml^{-1} (on a lake-wide basis - see below) in early July.

The *Microcystis* population waned during September as a crop of diatoms increased in abundance. This crop consisted mainly of small unicellular centric ('pill-box') forms represented by species of *Stephanodiscus* and *Cyclotella*, although the filamentous centric diatom *Aulacoseira subarctica* (formerly *Melosira italica* subs. *subarctica*) also increased over this period. The numbers of the unicellular forms increased very rapidly e.g. from ca 300 ml^{-1} on 28 August to a maximum of nearly 100 times this figure by 23 September.

This diatom peak and the still fairly dense population recorded on 30 September correspond to 2 relatively tight groupings of chlorophyll values (**Figure 3**). The data would suggest that these populations - not those of *Anabaena* or *Microcystis* - comprised the densest crops of the year. Yet, even discounting the extraordinarily intense public awareness of the blue-green algae in Loch Leven (in large part elicited by the SNH

'launch'), these diatom populations passed virtually unnoticed. The present data support the view (documented previously by these authors), that the 'blue-green algal problem' need not stem necessarily from massive biomass production, but from the peculiar ability of the large species to rise rapidly to the water surface under calm conditions when many, though not all, other algae are reduced to sinking. Although at the height of the *Anabaena* bloom in mid-June, edge scums containing *ca* 10^5 individuals ml^{-1} could be found, it is unlikely that the mean, lake-wide, value is ever more than about one hundredth of this. Yet, with mean levels of possibly only 3-4 x 10^3 ml^{-1}, concern was still expressed throughout much of July and August. Note that these densities are equivalent to no more than 2 doublings of the density of the population present in March and referred to above.

Diatom numbers decreased from their population maxima to <100 unicellular forms ml^{-1} and 10-20 *Aulacoseira* filaments ml^{-1} within 2-3 weeks. On 7 October, apart from a value of 9.1μg chlorophyll l^{-1} measured at a 2-m sampling station situated towards the north-east shore, pigment concentrations (over the other 9 sites) ranged from 4-7μg l^{-1}. Overall algal biomass increased once again before the turn of the year, but to no more than the equivalent of 25μg chlorophyll l^{-1} - over much of November. As might be expected, these comparatively sparse assemblages were generally more diverse than the summer blue-green and autumn diatom crops; for much the same effort put into counting these earlier species in their relatively pure stands, 15-20 different species were recorded in November, including chrysomonads, cryptomonads, and colonial, coenobial and unicellular green algae, as well as diatoms and occasional cyanobacteria. However, *Cryptomonas* (near *C. erosa, reflexa, ovata* and *marssonii*) was the most numerous alga over much of this time.

Chlorophyll levels remained below 25μg l^{-1} throughout December, January and the first half of February, and decreased to *ca* 15μg l^{-1} at the turn of the year. The upturn in pigment levels recorded in late February is one of the few regular features of the phytoplankton at Loch Leven. As is commonly the case at this time of the year too, diatoms were prominent. However, there the similarity to the situation in many past years, ends - and in two major respects. Firstly, in most years documented so far, unicellular Centrales have commonly gained dominance by the middle of March; on this occasion *Aulacoseira* as well as the unicellular species was prominent. Secondly, the unicellular diatoms have often attained quite extraordinarily dense populations (10^4 to 10^5 ml^{-1}) equivalent to 100-200μg chlorophyll l^{-1}; in March 1993, pigment levels rose to only 60μg l^{-1} before decreasing again.

Chlorophyll levels increased to *ca* 40μg l^{-1} by 1 April, but more as a result of wind-induced re-suspension of *Aulacoseira* filaments from the sediments than actual growth. In keeping with the characteristically vagarious sequences of phytoplankton in Loch Leven, *Anabaena* levels in late March 1993 were *ca* 10 ml^{-1}, i.e. one-hundredth the density at the same time in 1992. Overall, compared to the situations recorded during many other winters at Loch Leven, the latest turn of the year appears to have been marked by one of the sparsest phytoplankton crops. It is tempting to attribute this to the stepwise reduction in P loading, but information on other factors such as flushing, wind and temperature needs to be assimilated before a more definitive interpretation can be presented. Indeed, the phytoplankton sequences and biomass changes just reviewed, represent the outcome of the relative abilities of the different organisms to cope with or capitalise on changes in a

suite of physical conditions and a considerable array of chemical factors. A good deal of information on these remains to be collated and analysed, but enough data on nutrients is already to hand for a preliminary assessment of their influence on phytoplankton performance.

Nutrients and nutrient-algal interrelations

Of major relevance to phytoplankton, are the concentrations of soluble reactive P (SRP - **Figure 4**), dissolved SiO_2 (**Figure 5**) and nitrate-N (not illustrated, as relatively few data yet available). The general pattern exhibited by SRP with its summer maximum, is similar to that of the particulate components. It contrasts with these however, in being more evenly distributed over the loch i.e. better mixed. SRP is the fraction most immediately available for plant growth, but the concentrations recorded represent at the instant of sampling, what has not been sequestered by the phytoplankton, for example. It is interesting therefore, that in July when algae were generally prominent, the SRP levels were at their maximum. The high SRP values almost certainly result in part from the release of phosphate from the sediments (see below for comments on possible causal factors). A closer examination of **Figures 3** and **4**, however, suggests that the sharp rise in SRP over the period mid-June to early July, coincides with a decrease in algal biomass; chlorophyll levels on 2 July which was very windy, were around 28μg l^{-1} throughout the loch. SRP levels decreased thereafter, sharply at first as *Anabaena* became more prominent again, and less rapidly later on, and through to mid-September with the succession of *Microcystis* and unicellular diatom populations. This suggests that the sediment-augmented P supply did fuel further algal growth, and that the diatom maximum corresponding to what is likely to have been the annual phytoplankton peak, reduced the SRP levels to <5μg l^{-1} by mid-September. A comparison of particulate P and chlorophyll values also supports this view, in suggesting that the algal cells present in August contained more P than those recorded in June and July.

Changes in silica (**Figure 5**) are very clear, with some long periods over which levels increased or decreased. The following 6 phases can be identified:-

- April-May: values <1mg l^{-1}
- June, July and August: an increase from *ca* 0.5mg l^{-1} to 10-11mg l^{-1}
- September: a sharp decrease to *ca* 3mg l^{-1}, mainly within 3 weeks
- October, November and December: an increase to *ca* 7mg l^{-1}
- January to mid-February: a decrease of *ca* 2mg l^{-1}
- mid-February to mid-March: a further decrease of *ca* 6mg l^{-1} to <1mg l^{-1}

These changes are generally in keeping with those of the diatom populations. Examples are (i) the low SiO_2 levels in April which is a legacy of the late winter-early spring growth (ii) the comparative sparseness of diatoms until early September accompanies the long rise in the dissolved nutrient (iii) the peak SiO_2 level coincides exactly with the upsurge of diatoms (iv) the (high) minimum SiO_2 concentration recorded in early October coincides with a diatom decline, and (v) the rise in SiO_2 is terminated in early January by a further diatom pulse.

These data suggest that the autumnal diatom maximum was controlled by P availability, although nitrate levels were also low; meanwhile, silica concentrations were comparatively high (*ca* 3mg l^{-1}). Contrastingly, while low P was probably the main cause of the halt in the spring diatom growth, silica too was very low. The extensive build-up of SiO_2 in the summer may well have been accelerated by release of the nutrient from the sediments; some of the rise occurred over the period during which P was also released. The silica changes suggest that high pH was a contributory factor - and indeed, pH values exceeding 9 units were recorded.

Nitrate analyses completed so far suggest that the 1991/1992 winter maximum was *ca* 2.5mg l^{-1}. By mid-April 1992, concentrations of *ca* 0.4mg l^{-1} were recorded, and the decline continued more or less as in many other years, to very low levels i.e. <100μg N l^{-1} by June. Even lower values (<20μg l^{-1}) were reached by August and these prevailed throughout that month and at least the first half of September. Only in October did the concentrations start to increase again - with some 200μg l^{-1} being attained by the end of that month (the last occasion for which data are presently available).

Since *Microcystis* and diatoms succeeded *Anabaena*, the question remains as to why *Anabaena* faded. The few data presently available on nitrate, suggest that the inorganic N to inorganic P (SRP) ratio was very low (0.5:1 to 3:1) at the beginning of July - as a result of enhanced inputs of phosphate from the sediments and the removal of nitrate (probably) by de-nitrifying bacteria. Yet, the ratio continued to decrease throughout July and August. Such conditions would have been expected to favour *Anabaena* which is capable of fixing the N_2 in the water, over *Microcystis* which is usually thought not to possess this ability. Diatoms almost certainly do not fix N in this way, but the main resurgence of these algae in mid-September corresponded to conditions of much higher nitrate levels. Their growth, though very marked, was short-lived, due in part at least to low P levels.

Concluding remarks

The work emphasises just how much information on changes in nutrients and phytoplankton in a lake like Loch Leven, would have been missed, had the weekly sampling schedule been shelved. It is absolutely vital that this programme is continued into the foreseeable future, if the impacts on the NNR, of (i) the reduction in P loading, as well as (ii) the ever-varying weather regime, and possibly (iii) the introduction of Rainbow Trout *Oncorhynchus mykiss*, are to be satisfactorily documented and explained.

The work has begun to offer some thoughts on not only the controls of the particular sequences of phytoplankton species occurring this year, but on whether phosphate re-mobilised from the sediments enhances algal production (as opposed to perhaps the low flushing conditions associated with release events, simply allowing algae more time to accumulate biomass in any event).
More work on sediment P is needed, and planned; however, there are 5 areas that should be considered for additional funding now, and beyond the end of the present programme (31.3.94):

(i) more detailed information on distribution - over the length and breadth of the loch as well as down to e.g. 20cm into the deposits

(ii) as (i) but with special reference areas near the mouths of feeder waters or other discharges

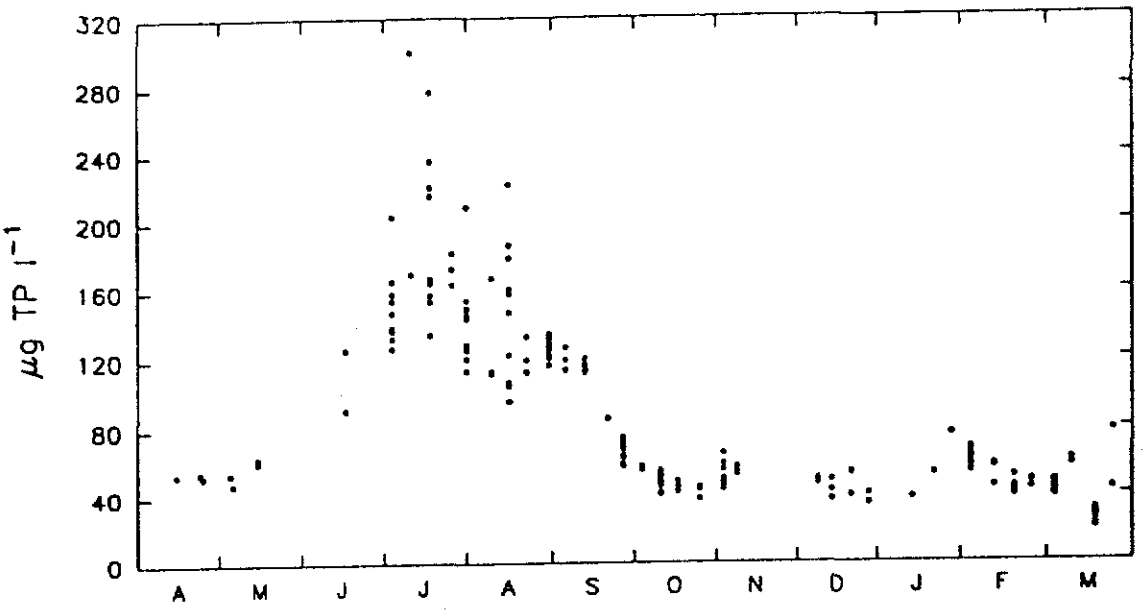
(iii) *in situ* P release assessments

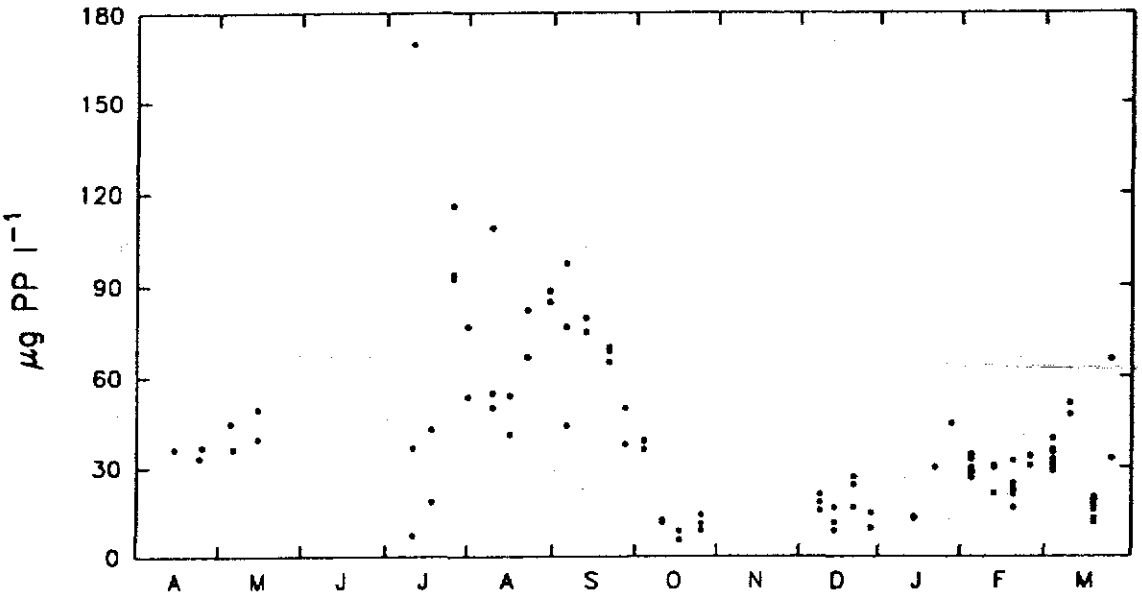
(iv) *in situ* measurements of redox conditions near the sediment-water interface

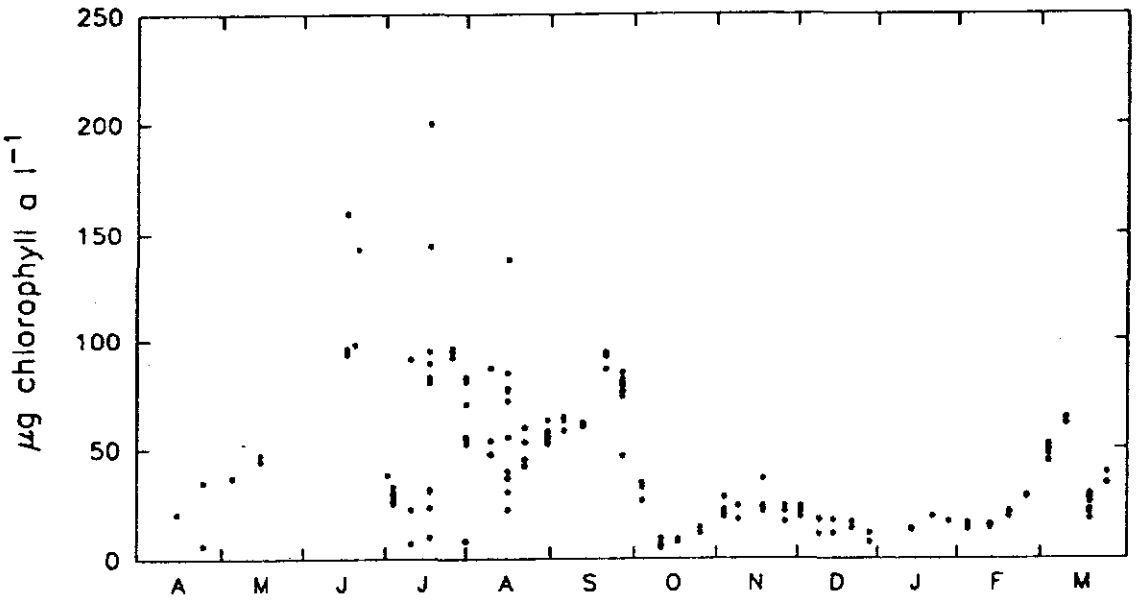
(v) close-time interval sampling for (iii) and (iv) to assess temporal trends.

FIGURES

Figure 1 (upper graph)
Figure 2 (middle graph)
Figure 3 (lower graph)

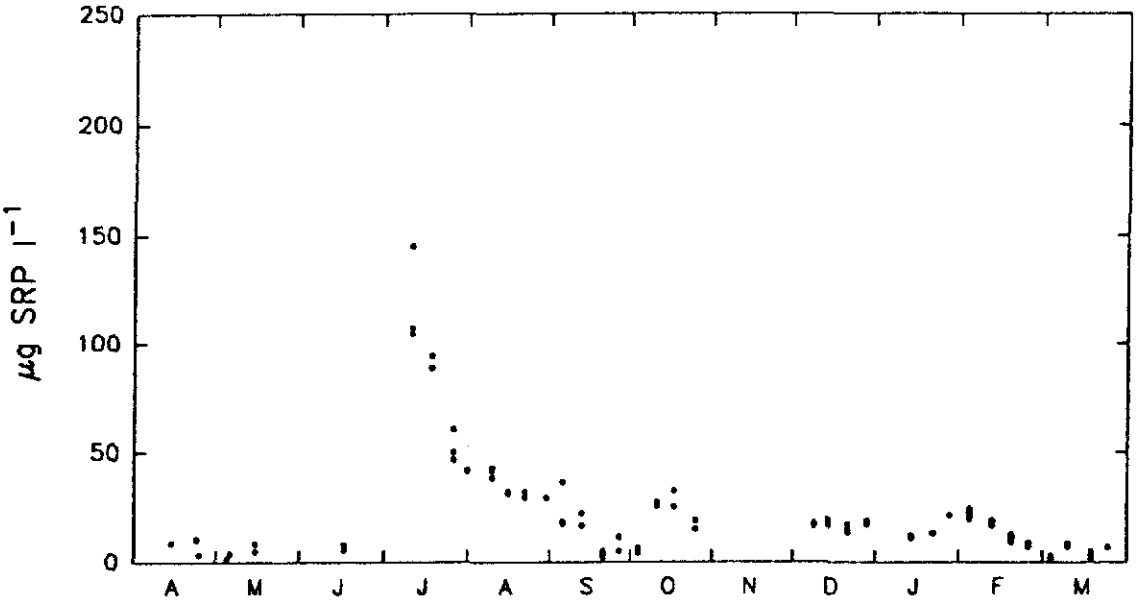






April 1992 – March 1993

Figure 4 (upper graph)
Figure 5 (lower graph)



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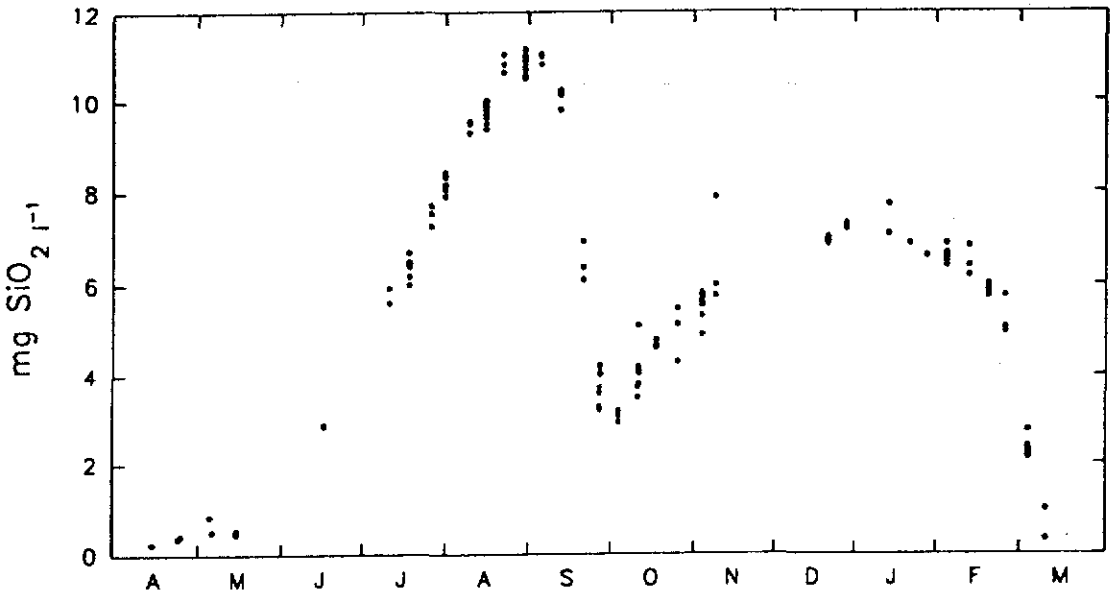

April 1992 – March 1993