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Institute of Freshwater Ecology
Edinburgh Laboratory, Bush Estate, Penicuik, Midlothian
EH6 OQB

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Scottish Natural Heritage,
Publications Section,
Battleby, Redgorton, Perth PH1 3EW,
UNITED KINGDOM.

Scottish Natural Heritage,
Research and Advisory Services Directorate,
2-5 Anderson Place, Edinburgh EH6 5NP,
UNITED KINGDOM.

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Summary

1. In spite of a cutback by the end of 1987, of phosphorus-rich mill effluent previously contributing approximately 6t P y^{-1}, and subsequent, but un-quantified reductions in the P loading due to sewage treatment works upgrades, total P levels in Loch Leven averaged *ca* 90μg l^{-1} and 60μg l^{-1} in 1992 and 1993 respectively. Releases of inorganic phosphate (SRP) from the sediments contributed to these figures, especially in 1992 which had the calmer and warmer summer; mean annual SRP concentrations of 20μg l^{-1} and 30μg l^{-1} depending on sampling station, are calculated for 1992, while figures of between 7μg l^{-1} and 8μg l^{-1} are obtained for 1993.

2. Although SRP levels were higher overall in 1992, the mean concentrations of chlorophyll$_a$ were very similar in the two years i.e. 39μg l^{-1} in 1992 and 36μg l^{-1} in 1993, and the maximum value achieved in both years was *ca* 100μg l^{-1}. However, the temporal patterns in pigment levels differed considerably between the two years with the main peaks occurring in June in 1992, and October 1993.

3. Unicellular centric diatoms produced sizeable crops in spring and September in both years, but the autumnal maximum in 1993 approximated to 50000 ml^{-1}, while that of 1992 was estimated at just under 30000 ml^{-1}. The population maxima of a number of other phytoplankton species differed by an order-of-magnitude between the years. For example, the diatom *Fragilaria crotonensis* produced a crop of 4000 cells ml^{-1} in 1993, having been hardly recorded at all in 1992. Of the blue-green algae, *Anabaena* formed the main blooms in summer 1992, while *Gomphosphaeria* dominated the less noticeable crops in summer 1993.

4. While calm conditions enhanced the ability of the larger blue-green algae to form surface blooms and edge scums in summer 1992, algal cell numbers had already exceeded 1000 ml^{-1} over the loch as a whole by the previous spring; these species thus have the ability to survive under conditions other than those traditionally associated with such scums. Moreover, the lake-wide population densities in the summer could have been achieved by as few as two doublings (cell divisions) of the spring crop. In terms of overall biomass (e.g.chlorophyll$_a$ concentration), some of the crops of diatoms which are normally associated with well-mixed conditions and are thus distributed evenly over the loch, constitute larger lake-wide populations than the blue-green algae. These considerations strengthen the view that the blue-green algal problem stems not from biomass *per se*, but the peculiar ability of these organisms to rise to the surface and perhaps accumulate further on a shore, when many other algae would sink onto the sediments.

5. Of the nutrients likely to be limiting the production of algal cells, P was the most important, although SiO_2 influenced the seasonal performance of diatoms. Light availability does not appear to have been a major limiting factor except perhaps in mid-winter. Rapid increases in the numbers of certain diatoms in February 1993 are attributed more to wind-induced, re-suspension of cells from the sediments, than to true growth. Secchi disc transparency readings ranged from *ca* 1m to 3m, indicating that for much of the year, the majority of the algal cells would have been in the productive, 'euphotic' zone.

6. Of the 'loss' factors determining what fraction of the algal cells produced are observed as biomass in the water column, flushing rate and zooplankton food preferences are considered, and the influence of the following are discussed: the passage of a volume of water equivalent to >70% of the loch in January 1993 on cell washout; the spells of very low flushing equivalent to <0.1 loch volumes mo^{-1} in summer 1992 on SRP releases from the sediments and accumulation of (blue-green) algal biomass; and the population dynamics of *Daphnia* in relation to the size structure of the phytoplankton.

7. The annual mean concentrations of chlorophyll$_a$ in the two years covered here contrast with values of 21μg l^{-1} in 1985, 50μg l^{-1} in 1990 and ≥60μg l^{-1} from 1968 to 1973 inclusive, but they do not differ significantly from the other 12 years for which suitably intensive data are available i.e. 1974 to 1983

inclusive, and 1988 and 1989. A major data analytical programme is planned, and this will explore other features of the dynamics of nutrients and phytoplankton that may indicate whether the P reduction strategies to date have been effective. It is also recommended that an attempt be made to quantify the (assumed) reductions in P loading due to STW upgrades.

8. An analysis of a pair of surface sediment cores taken from each of 40 sites distributed at random within the muddy zone of the loch (≥ 3m water depth; covering 7.6km^2), yielded a total range of P contents per unit sediment dry weight of 0.07% to 0.26%, with the majority lying within a 2-fold band - 0.12% to 0.23%. These values are well in keeping with the findings of previous studies on Loch Leven and those published on other eutrophic waters. P levels expressed per unit wet weight of sediment ranged between 0.010% and 0.036%, while the figures found per unit volume of the deposits varied mainly between 11g m^{-2} and 16g m^{-2} over the uppermost 5cm. A recent publication suggests that approximately one-third of the total P in the upper sediments is in loosely bound and/or reductant-soluble forms i.e. the fractions implicated in phosphate release events.

9. Although most of the values exceeding 0.2% of dry weight corresponded to a central area bounded by the north shore of St. Serf's Island to the east, Castle Island to the west, and a point offshore of the mouth of the Gairney Water to the south, there are no consistent relationships between P levels and depth of water, whether the nutrient content is expressed on a basis of sediment dry weight, wet weight or volume.

10. A similar lack of a consistent relationships with water depth, was found with the levels of soluble P in both the interstitial water of the top 5cm of sediment, and the water overlying this sediment.

11. Some explanations are outlined for the lack of any reasonably restricted areas loch bottom where sedimentation might be primarily focused and the concentrations of P might be correspondingly higher than elsewhere; this feature is also discussed in relation to the feasibility of dredging of sediment to remove P.

12. It is calculated that the average total P content in the top 5cm of the mud zone is equivalent to between 7 and 11 years' input from external sources, corrected for a retention coefficient of 0.6.

Contents

1. GENERAL INTRODUCTION - SCOPE AND AIMS

This report covers first, the results from the latest phase of monitoring nutrient levels, phytoplankton status and associated physico-chemical conditions in Loch Leven. The work follows reductions in the external loading of phosphorus (P) of some 6t y^{-1} (equivalent to *ca* 30% of the total measured in 1985) by the end of 1987, and subsequent reductions after upgrading of various sewage treatment works in the catchment.

Table 1. Physico-chemical, nutrient and phytoplankton studies on Loch Leven 1992/93.

determinand	**numbers of samples and temporal coverage**
water temperature **pH** **conductivity** **dissolved oxygen** **nitrate-N** **phosphorus fractions** **silica fractions** **chlorophyll$_a$** **algal species and cell numbers** **size spectra**	*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. *July 1992 to September 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. *October and December 1993*: as above but fortnightly sampling and at 3 loch sites and the lower South Queich only. *Analyses*: all determinands listed except that no phytoplankton analyses are done on the Queich samples, and while rapid checks are sometimes made on cyanobacterial numbers in most samples when pigment analyses indicate a patchy distribution, only one sample is assessed fully for phytoplankton species and abundance data.

Table 1 summarises what has been measured and how often samples have been taken to chart the changes in nutrients and phytoplankton. The second part of the work concerns the distribution of P in the sediments with the main aim of establishing where, if at all, any major concentrations are situated. The need for preliminary information on this was identified in discussions with Scottish Natural Heritage and the Forth River Purification Board which suggested that, while the logistics and costs of removal of P-rich deposits over the whole loch bed by dredging was prohibitory, this might not be the case if a more restricted area of main 'hot spots' as regards P content was identified. **Table 2** indicates the extent of work on sediment P at Loch

Leven, and the present report presents the results of the 1992 and 1993 surveys, and discusses these in relation to the studies by Blake (1989) and Farmer *et al* (1994) referred to in the Table.

The plankton and nutrient studies, and the sediment investigations 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.

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

year and dates	studies carried out
1968-71: various dates (with the Freshwater Fisheries Laboratory, Pitlochry).	Total P content in the surface sediments (Holden and Caines 1974).
1975-1979: various dates (with the Department of Microbiology, Edinburgh University).	P solubilisation by bacteria (Wilson 1979).
1986: 24 and 30 April; 8, 14, 19 and 29 May; 2, 5, 10, 24 and 30 June (with Napier College).	Cores collected from sediments beneath water of 4m and 10m, 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 (with Napier College).	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) - Blake (1989).
1990: 28 January (with the Department of Environmental Chemistry, Edinburgh University).	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 (Farmer *et al*, in press).
1992: 28 October.	Spatial survey of 7 sites, for the analysis of the total P content in the uppermost 5cm of sediment.
1993: June to August (with the Department of Biological Sciences, Lancaster University).	Spatial survey of 40 sites in the mud zone (i.e. lying below water of ≥3m), for the analysis of the total P content, and interstitial P levels in the uppermost 5cm of sediment, and dissolved P concentrations in the overlying water; incubation-release experiments. See Miller (1993).

For convenience of assessing the changes in phytoplankton and the influence of selected physical and chemical factors on the abundance and species composition of these algae, the report covers the two calendar years 1992 and 1993 - although very few samples were collected before April 1992. Funding for Loch Leven work in 1992 only commenced on 1 June as a direct result of certain blue-green algae (cyanobacteria) becoming very abundant. Indeed, the main surveillance programme that incorporated the large numbers of sampling sites indicated in **Table 1**, was started in early July in order to assess as reasonably as possible the lake-wide abundances of particularly the large blue-green species such as *Anabaena* and *Microcystis* whose populations had by then reached bloom proportions. Under favourable conditions, these organisms can buoy up to the surface and exhibit a heterogeneous pattern of abundance in the vertical plane. At such times too, they are often distributed very patchily across the loch.

Field and laboratory methods are only described in any detail for the sediment work. Full accounts of the various procedures followed in the plankton studies are given in a number of reports produced by this laboratory for the Forth River Purification Board, Scottish Natural Heritage, The Nature Conservancy Council for Scotland, The Nature Conservancy Council and the original Nature Conservancy. Of major relevance, however, is that apart from the algal and chemical samples taken from near the outflow of the loch where a bucket was caste from the edge or dipped into the water from a boat, water was collected by bucket in the case of sites <2m deep, and with a 2-m long, 6-cm diameter Marley tube at stations deeper than 2m. Thus, the vast majority of the concentrations of nutrients and algae reported here are representative of at least the top 2m of the water column. Previous studies suggest that such samples are representative of the whole water column on most occasions.

2. PHYTOPLANKTON ECOLOGY - GENERAL CONSIDERATIONS

Literature on aspects of phytoplankton ecology of special relevance to the findings from the observations made in 1992 and 1993, has been recently collated elsewhere (Bailey-Watts *et al* 1994). A considerable number of physical, chemical and biotic factors control the observed sequences and population density changes of many dozens of phytoplankton species recorded. The algal growth patterns observed represent the net outcome of the relative abilities of the different types to capitalise on, or cope with the ever-changing scene as regards these factors. Over the two-year period covered here, however, shifts in nutrients, flushing rate, the underwater light climate and *Daphnia* abundance, explain many of the fluctuations in the cyanobacterial and diatom species which dominate the assemblages.

There are three nutrients of major importance: dissolved nitrate (NO_3-N), inorganic phosphate (PO_4-P, or soluble reactive P, SRP) and silica (SiO_2). Where algal production overall is limited by a nutrient, SRP is the most likely cause in this part of the world. It is the fraction of P that is most immediately available for plant growth, and it is required by all plants. Moreover, the general trophic status of the loch is determined by the total P content (TP) and the interactions between SRP and the particulate fraction of this total (PP). The other nutrients may fall to levels that limit algal production, but in contrast to SRP, the production of specific groups of algae only. SiO_2 shortages will ultimately affect only the diatoms, as these are the only algae having an absolute requirement for this nutrient; that is, even nuclear division cannot proceed in the absence of SiO_2 (Sullivan and Volcani 1981). NO_3-N can be used by all plants, and is required by most, but with the important exception of certain cyanobacteria which in the absence of nitrate can fix atmospheric N dissolved in the water (Carr and Whitton 1982).

Physical factors are also important, not least in determining to what extent nutrient supplies are utilised to support phytoplankton production and growth, and influencing species sequences. Water clarity and the degree to which the loch is mixed control production through their influence on the light perceived by the cells of these photosynthetic organisms. The light climate can also determine what types of algae are produced, there being 'light' and 'shade' species. The dynamics of the phytoplankton populations also mirror well the observed changes in flushing rate. By determining for how long a mass of water remains in the loch, the flushing regime certainly influences the amounts (biomass) of algae observed. This factor could also affect the types of algae produced. The more rapid the flushing, for example, the faster a species will have to grow in order to build up its population density.

The nature of the zooplankton can also explain certain aspects of phytoplankton 'succession'. Studies at Loch Leven have highlighted the influence of these animals on the success of relatively large algae - including the most troublesome bloom-forming blue-green species - in summer.

3. RESULTS ON PHYTOPLANKTON ECOLOGY

3.1 Temporal fluctuations in total and particulate phosphorus and phytoplankton chlorophyll$_a$

TP levels ranged overall (i.e. including the results for all sites sampled) from *ca* 20μg l^{-1} to nearly 400μg l^{-1} although few values exceeded 200μg l^{-1} (**Figure 1a**). The points plotted describe more-or-less simple wave-like curves with 4 peaks. Although there are minor peaks of 80μg l^{-1} in March 1992 and *ca* 95μg l^{-1} in March 1993, the clusters of values averaging *ca* 150μg P l^{-1} in late June-early July 1992 and *ca* 100μg l^{-1} in September-October 1993 are the main features of Figure 1. Annual mean values were approximately 90μg l^{-1} in 1992 and 60μg l^{-1} in 1993. Changes in the concentrations of the particulate P components describe a similar pattern to that of TP.

Inter-annual differences in the timing of, and to some extent the concentrations of P achieved at, the TP maxima, are very marked. This is in character with the year-to-year variation in the dynamics of the phytoplankton, of nutrients and of such a basic feature as water clarity (see below), in this waterbody.

Eight chlorophyll$_a$ maxima including 4 which correspond to the TP peaks identified above, are highlighted with the names of the main algae contributing to them, in **Figure 1b**. Temporal variation is considerable over scales of weeks, months and seasons, and between years. Interestingly, however, the annual mean pigment concentration of 39μg l^{-1} calculated for 1992 is not significantly different from the corresponding value of 36μg l^{-1} obtained for 1993. Wind-induced changes in the spatial distribution of chlorophyll$_a$ are discussed in Section 3.3.

3.2 Population dynamics of individual phytoplankton species

As already indicated by the variety of algal types associated with the different chlorophyll$_a$ maxima (**Figure 1b**), 1992 contrasts considerably with 1993 in the seasonal abundance patterns of even the dominant algae (**Figure 2a**). Within the cyanobacteria, 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 1992. It had approached 10^3 individuals ml^{-1} even in late March of that year (**Figure 2a**). A loch-wide concentration in June 1992 of *ca* 5000 individuals ml^{-1} (i.e. a density equivalent to little more than 2 doublings of the spring population), is some 100 times the figures recorded during the same month in 1993.

In 1992, *Microcystis aeruginosa* Kutz. *emend.* Elenkin, succeeded *A. flos-aquae* and so did not dominate the scene until late August with a peak biomass of *ca* 450 colonies ml^{-1} (**Figure 2b**). The period of its main increase in biomass in 1993 took place approximately one month later than that in 1992, and the maximum population density recorded was less than one-sixth of the 1992 value.

While the two genera already discussed were less abundant during 1993, another cyanobacterium - the colonial *Gomphosphaeria* (near *G. lacustris* Chodat) - was much more common, and dominated the plankton in July and August (**Figure 2c**).

Diatoms constitute the other main group of algae represented in the plankton of Loch Leven. Spring growths of small unicellular centric ('pill-box') types represented primarily by species of *Stephanodiscus* and *Cyclotella*, comprise one of the few fairly consistent features of the phytoplankton calendar in this loch. **Figure 2d** shows that they achieved population densities of at least 20000 cells ml^{-1} in March 1992 and April 1993. Their production of considerable autumnal crops which, as in the case of the two years covered here, are larger than the spring ones, is not such a common feature, however.

Two species of the filamentous centric diatom *Aulacoseira* i.e. *A. subarctica* (O. Mull.) Haworth (formerly *Melosira italica* subs. *subarctica* O. Mull) and *A. granulata*, and the colonial pennate diatoms *Asterionella formosa* Hassall and *Fragilaria crotonensis* Kitton also produced very noticeable populations. The marked contrasts in their respective dynamics, between 1992 and 1993, are shown in Figures **2e**, **2f** and **2g**.

Algal assemblages present when pigment levels were low, were generally more diverse than those associated with the more-or-less pure stands of blue-green algae and diatoms described above. For much the same effort that is required to estimate the algal densities in such relatively species-poor but dense growths, 20 or more different species could be recorded when $chlorophyll_a$ concentrations were around 5 or $10 \mu g\ l^{-1}$ - as in early October 1992 and much of June 1993, for example. The species list for the whole period reviewed here thus includes a variety of chrysomonads, cryptomonads, and colonial, coenobial and unicellular green algae, as well as diatoms and cyanobacteria. Within the group of relatively sparse organisms however, species of *Rhodomonas* and *Cryptomonas* (near *C. erosa*, *reflexa*, *ovata* and *marssonii*) were the most numerous.

3.3 Spatial patchiness of the phytoplankton

Even in the warmer year 1992, when spatial differences in organisms would be the more expected, diatom peaks correspond to relatively tight groupings of chlorophyll$_a$ values (see **Figure 1**). Lake-wide average pigment concentrations were then often considerably greater than when blue-green algae formed the major part of the phytoplankton crop. Indeed, autumnal diatoms constituted the peak annual biomass levels in both years. Yet, even discounting the extraordinarily intense public awareness of the blue-green algae in Loch Leven (in large part elicited by the SNH 'launch' in June 1992), the diatom populations passed unremarked. The 'algal problem' thus appears not to stem necessarily from massive biomass production. Rather, it is due to the peculiar ability of the large blue-green species such as *Anabaena* and *Microcystis* to rise rapidly to, and concentrate at, the water surface under calm conditions when many other algae would sink.

Although the number of sampling stations alternated each week between three and ten, sharp changes in the degree of patchiness in algal distribution over the loch are evident from the shifts in the range in chlorophyll$_a$ concentrations (**Figure 1b**). When the large cyanobacteria are dominant, pigment values often range widely, that is, in the horizontal plane as well as the vertical plane already noted. An extreme example of this concerns 9 July 1992 when values ranged from 10 to 200μg l^{-1}. In contrast, pigment concentrations differed very little one week earlier - in spite of the continued dominance of large blue-green algae. This mixing event co-incided with a decrease of more than 5 Celsius degrees in both the daily maximum and minimum air temperatures, following a protracted period of relatively stable weather (Bailey-Watts *et al* 1994).

Although at the height of the *Anabaena* bloom in mid-June 1992, surface and edge scums containing *ca* 10^6 individuals ml^{-1} could be found, it is unlikely that the mean, lake-wide, value ever exceeded about one two-hundredth of this concentration. However, concern was expressed even when mean levels of possibly only 3000 to 4000 ml^{-1} were present in summer. This is due to the peculiarly visible nature of these algae, and the fact that more people tend to be on or near the loch in summer than in winter, early spring, or autumn when diatoms are usually most abundant. It is during the months in 1992 when. In contrast to the situation described for 1992, pigment levels in 1993 remained much more uniform even when the blue-green alga *Gomphosphaeria* was prominent. However, as this is considerably smaller than the majority of *Microcystis aeruginosa* colonies and *Anabaena* aggregations, it does not (indeed, on physical grounds, cannot - Reynolds and Walsby 1975) rise very rapidly to the surface even under warm, calm conditions when the water column may well stabilise and even stratify.

3.4 Factors controlling phytoplankton abundance and species composition

This section deals with the interactions between the phytoplankton and nutrients, underwater light, flushing rate and certain aspects of the zooplankton. As weather conditions impinge on all of these factors, references to wind and temperature appear throughout.

3.4.1 Dissolved nutrients

As the SRP concentrations measured (**Figure 3a**) represent what has not been sequestered by the phytoplankton at the instant of sampling, and assuming that algal biomass was consistently limited by SRP availability, these concentrations would be expected to fall or remain low as algal numbers increased. This would appear to be the case during much of the first 6 months of 1992 and for somewhat longer in 1993. Indeed, the actual concentrations of SRP (and chlorophyll$_a$) over these periods are very moderate for an 'infamous' waterbody - and perhaps reflect the effects of a cutback of P inputs to the loch.

There are, however, two other periods in particular - early July 1992 and September 1993 - during which both algae and SRP levels increased. A closer examination of the data suggests that the sharp rise in SRP over the period mid-June to early July 1992, coincides with a decrease in algal biomass; chlorophyll$_a$ levels on 2 July which (as noted above) 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. The autumnal maxima of the diatoms *Stephanodiscus* and *Aulacoseira* (producing what was the loch-wide peak phytoplankton biomass for 1992), eventually reduced the SRP levels even further - to <5μg l^{-1} by mid-September.

The mean annual SRP levels were considerably lower in 1993 (7.3-8.3μg l^{-1} depending on sampling station) than in 1992 (20-30μg l^{-1}), and while a pulse of high SRP was recorded in both years, that of 1992 was recorded in July, while that of 1993 was observed in September. In both years, however, phytoplankton densities were already high before the main peaks in SRP are observed, though not as high as the crops that follow the SRP maxima. This suggests that sediment-augmented P supply might have fuelled some additional growth of algae - summer cyanobacteria in 1992 and autumn diatoms in 1993.

Since *Microcystis* and diatoms succeeded *Anabaena* in 1992, the question remains as to why *Anabaena* faded. The few nitrate data presently available, 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, and their main resurgence in mid-September corresponded to conditions of much higher nitrate levels. Their growth, though very marked, was short-lived however, due in part at least to low P levels.

Changes in silica (**Figure 3b**) are very clear, with some long periods of sustained increase or decrease. The following phases can be identified:-

in 1992

- 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}

in 1993

- January to mid-February: a decrease of *ca* 2mg l^{-1}
- mid-February to mid-March: a further, very sharp decrease of *ca* 6 mg l^{-1} to <0.1mg l^{-1}
- a more or less consistent increase of 2mg l^{-1} (and thus, to *ca* 2mg $^{-1}$) by mid-May
- an decrease of *ca* 1.5mg l^{-1} to the beginning of July
- an increase of *ca* 1.5mg l^{-1} to 2mg l^{-1} again by mid-August

- a rapid drop to levels near the detection limit which prevailed for much of September
- a somewhat erratic rise in values to *ca* 2mg l^{-1} by the turn of the year.

Increases in SiO_2 usually corresponded to declines or nil growth in the diatom populations, while decreases in the nutrient level often accompanied vigorous increases in diatom biomass (**Figures 2d-2g** above). However, the extensive build-up of SiO_2 in summer 1992 may well have been accelerated by sediment release; some of the rise occurred over the calm, warm, period during which P was also released. The silica release suggests that high pH was a contributory factor - and pH values exceeding 9 units were recorded around this time. Sediment release undoubtedly contributed to the considerably higher mean concentration of SiO_2 calculated for 1992 i.e. 5.0mg l^{-1} *cf* 1.5mg l^{-1} in 1993. Even so, the contrast between the years is generally mirrored in the greater prominence of diatoms in the plankton in 1993 (see above).

While low P was probably the main cause of the halt in the spring diatom growth in both years, and of the autumnal diatom maximum in 1992, SiO_2 was also reduced to very low levels. Thus, even if P levels had been higher, the available SiO_2 could not have supported but a fraction of a doubling in diatom numbers. This is a situation found in a number of previous years. The view that P is the main nutrient controlling algal production, however, is borne out by the results of enrichment experiments (Bailey-Watts, Kirika and Hakansson 1994). The only other time during which SiO_2 was likely to be the major limiting factor was September 1993.

Nitrate analyses completed so far suggest that the 1991/1992 winter maximum was *ca* 2.5mg l^{-1}. By mid-April 1992, levels of *ca* 0.4mg l^{-1} were recorded, and the decline continued more or less as in many other years, to very low concentrations 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 1992 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).

3.4.2 The underwater light climate

The factors controlling the underwater light climate and the light field perceived by planktonic algae are complex. Daylength and irradiance determine the amounts of light energy hitting the water surface, while reflectance determines how much of this energy enters the water column. Thereafter, the total energy, its distribution with depth and its spectral composition are influenced by factors that attenuate the light. Included here are detrital and other particles re-suspended from the sediments, and planktonic organisms including the algae themselves.

For much of the year in Loch Leven, the phytoplankton constitutes the major light-attenuating factor, accounting for an average of *ca* 75% of light extinction at the highest phytoplankton densities (Bindloss 1974). Indeed, in contrast to the peaty, humic-stained lochs which characterise much of Scotland's freshwater resource, the water itself in Loch Leven is intrinsically very clear. On occasions, however, this broad, exposed and shallow loch can become turbid due to flash flooding bringing in soil particles, and to wind-induced turbulence lifting material from the bottom deposits. Rapid increases such as that observed in February 1993, in the numbers of the diatom *Aulacoseira*, are thought to be due as much to wind-induced re-suspension of the filaments from the sediments as actual growth. A similar situation has been documented for the warm winter 1988-89 (Bailey-Watts 1990).

Open water clarity as measured by Secchi Disc ranged from *ca* 0.8m to just over 3m (**Figure 4a**) and related to chlorophyll$_a$ levels according to **Figure 4b**. In 1992, Secchi disc values remained <1m until mid-June before increasing rapidly to a peak level of 2m with the mixing of the blue-green algae by the end of that month. The water clouded again and the values decreased to *ca* 1m by mid-July. The water became clearer for a brief period after this, but values of <1m were again recorded with the increase in diatom numbers upto mid-September. Only after the collapse of these populations over the next fortnight did the water clear again - and to the clearest for 1992 with a maximum value of 3.05m. While the first phase of the subsequent decrease in water clarity right up to the end of 1992 is in line with increases in a variety of algae and especially *Cryptomonas*, the later phase corresponded to an overall decrease in phytoplankton.

Generally windy weather and turbulent conditions, and the associated dominance by 'heavy' diatoms, resulted in low clarity persisting for much of the first quarter of 1993. Not surprisingly in view of the considerable contrasts identified between the years as regards phytoplankton abundance and species composition, even the main peaks and troughs in water transparency in 1993 differ from those in 1992. First, even though there are few data for June 1992, it appears that the water during that month was considerably cloudier than it was a year later. Conversely, at the same period in 1992 when the water was at its clearest i.e. October, Secchi disc readings in 1993 were near the annual minimum value.

Bindloss (1976) found that Secchi disc transparency values over the period 1968-1971 were equivalent to approximately one-third of the euphotic depth, that is, the depth at which there is no net production because photosynthetic gains by algal cells are more or less balanced by respiratory losses. Only when cells are circulated through, or are able to move into, the better-illuminated zone above this depth, is net production positive. If the Secchi disc transparency-euphotic depth relationship found by Bindloss holds for the two-year period covered here, the euphotic depth has varied from marginally less than 3m to approximately 9m, accounting for *ca* 35% and 93% of the loch volume respectively (Smith 1974). There are thus few occasions on which cells of planktonic algae are not within the euphotic zone. It has been known for a long time too, that large areas of the loch bottom support substantial crops of algae (Bailey-Watts 1974).

3.4.3 Flushing rate

Data on Loch Leven extending back some 25 years show that a number of factors in addition to plankton losses by washout from the loch, are controlled by, or associated with, different rates of water throughput (Bailey-Watts *et al* 1990). Temperature maxima of the water (and the surface sediment in this shallow loch) in summer tend to be higher during spells of low flushing than in wetter periods; and fluxes of nitrate to, and - apparently as a consequence of this - phosphate from, the sediments are also more evident in low-flushing summers than wet summers. The contrasting flushing regimes of the two years covered here, appear to have influenced considerably the timing of SRP releases from the sediments (**Figure 5a**), and the build-up of chlorophyll$_a$ levels (**Figure 5b**).

A major feature of 1992 is the period May to August during which monthly flushing rates did not exceed 0.12 loch volumes. It was also warm. The conditions plainly favoured bloom formation of the blue-green algae which had maintained a moderate biomass over the previous few months. It is worth surmising in this connection that the dense blooms might not have occurred had not the algal population been able to survive, if not actually grow, over the previous months under conditions that would not normally be associated with these species. Equally, while there is a strong link between blooms and calm, warm weather, the material constituting the surface scums is often stressed (e.g. by high light intensity). By definition too, the time at which the maximum numbers are recorded, heralds the decline in the population.

As May 1993 was wetter than May 1992, and an amount of water equivalent to *ca* 70% of the loch volume had passed through in January 1993, significant accumulation of phytoplankton biomass was somewhat curtailed in comparison with 1993. Indeed, algal levels did not start to increase to any significant extent until the beginning of July. However, with low flushing during the following 8 weeks, and possibly for longer than this considering rainfall figures (there being no flushing rate data available at the time of writing), chlorophyll$_a$ concentrations approached 80μg l^{-1} which proved to be the maximum for 1993.

While increases in flushing rate are commonly accompanied or closely followed by declines in chlorophyll$_a$ levels, this is not always the case. In this connection the effects of the extremely rapid throughput of water in January 1993 appears to be rather minor. However, low light (short days) at this time of the year would suppress algal production even though (as is normally the case) all major nutrients were at or near their annual maximum concentrations.

There are also a number of instances during which the flushing rate falls but chlorophyll$_a$ levels do not increase. This can be due to nutrient or light limitation, or to the fact that while the overall phytoplankton density (as measured by chlorophyll$_a$ levels) may not increase, a particular population can be growing. As to why bloom-forming cyanobacteria were so sparse during and following the low-flushing month of July 1993, is attributed to other weather conditions and the fact that *Gomphosphaeria* was already abundant. At this time in 1993, it was often very windy, and the later success of a number of diatoms which favour well-mixed conditions reflect this. It is possible too, that these species were able to capitalise more efficiently than the large blue-green algae on the initially relatively low SRP concentrations. The increase in SRP at the end of August 1993 and over a period during which pigment levels were on the increase, is interesting. As water temperatures had dropped to *ca* 15°C, release from the sediments might not have been expected to be so marked. However, as it seems unlikely that a rise of some 60μg P l^{-1} (which is equivalent to 3000kg over the loch as a whole), stemmed immediately and so quickly from the catchment, recycling from the loch deposits must be implicated. Some of the initial fall in SRP levels may thus be due to re-sorption of phosphate as the water cooled further and windy conditions prevailed. The remaining and subsequent falls in

SRP are in line with the increases in chlorophyll$_a$ that were sustained through September during which time the annual phytoplankton maximum was recorded. By the end of the year phytoplankton levels were still at around 50μg l^{-1} while, perhaps not surprisingly, SRP concentrations were very low.

The massive increase in SiO_2 in early summer 1992 must be attributed to sediment release, and the low flushing conditions allowing this nutrient (as with SRP) to accumulate in the water column. However, while on resumption of slightly higher flushing rates SRP levels decline at a rate indicating re-sorption by the sediments, decreases in both of these nutrients correspond to increases in a number of diatom populations.

3.4.4 Crustacean zooplankton with special reference to Daphnia

Loch Leven zooplankton studies carried out since the turn of the century, and upto and including the two years of main concern in the present report, have been recently reviewed by Gunn, May and Bailey-Watts (1994). *Daphnia hyalina* Leydig is regarded as the main grazer of phytoplankton in Loch Leven (Bailey-Watts 1982, 1986; Bailey-Watts and Kirika 1981). Changes in its abundance correspond to seasonal, inter-annual and long-term fluctuations in the size structure of the phytoplankton assemblages. As *Daphnia* increases towards its peak densities the relative abundance of large phytoplankton - including bloom-forming blue-green species - also increases. This is the situation prevailing in June 1992 when the annual maximum numbers *Daphnia* were recorded in the presence of an *Anabaena*-dominated phytoplankton crop. In this respect, it is possible that the animal contributes to the success of these troublesome algae. The prevalence of small cyanobacteria in the summers of 1968-1970 during which time *Daphnia* was never recorded in the loch, supports this view. However, the 1993 peak (in May) was not accompanied by an increase in the relative abundance of large algae, although it did follow the decline in the numbers of small diatoms. In contrast to many of the other water quality features (including algal composition) assessed so far, the annual maxima of *Daphnia* were somewhat similar as regards their size and timing in the two years covered here (**Figure 6**).

More in line with the overall contrast between 1992 and 1993, are the seasonal trends in the population of another micro-Crustacean - the cyclopoid copepod *Cyclops abyssorum* Sars. 1993 was unusual in that the population maximum occurred in the autumn rather than the spring. The reason for this is unclear but it might be linked to an increase around this time, of the calanoid copepod *Eudiaptomus gracilis* Sars on which it preys (Fryer 1957). *Eudiaptomus* in turn, was probably capitalising on the relatively high phytoplankton levels (50-100μg chlorophyll$_a$l^{-1}) which prevailed at the time. Moreover, the algal crop was dominated by 'nanoplankton' i.e. small centric diatoms, with a background of small flagellates (Bailey-Watts *et al* 1994), on which *Eudiaptomus* is also known to feed preferentially (Gliwicz,1969).

4. CONCLUDING REMARKS ON NUTRIENT AND ALGAL ASPECTS OF WATER QUALITY: ADVANCES IN KNOWLEDGE AND THOUGHTS ON FUTURE RESEARCH REQUIREMENTS

The findings discussed above emphasise just how much information on changes in nutrients and phytoplankton in a lake like Loch Leven, is gained from a weekly/fortnightly surveillance programme. It is vital that such a schedule is continued into the foreseeable future, if the following impacts on the NNR are to be satisfactorily documented and explained: (i) the reduction in P loading (ii) the ever-varying weather regime, and (iii) the recent introduction of Rainbow Trout *Oncorhynchus mykiss.*

The work has begun to advance knowledge about the factors controlling the particular sequences of phytoplankton species, as well as the changes in the abundance of the different types in this loch. Attention has also been drawn to the fact that some of the troublesome bloom-forming cyanobacteria are quite capable of surviving conditions quite different from the warm, calm situations traditionally associated with them. Indeed, while calm weather is a pre-requisite to surface scum formation, it need not be warm. *Anabaena* species have been recorded in Loch Leven even in mid-winter. The observations made in 1992 illustrate how critical the timing of a particular shift in the weather (such as the sudden mixing event on 2 July) can prove as far as the success or otherwise of an algal population. The authors contend that had the gentle breezes on 13 June 1992 (the day of the SNH 'launch') not prevailed to the west and the fishing pier end of the loch, the high profile subsequently attained by the 'blue-green algal problem' would probably not have materialised.

Further insight has been gained into the role of phosphate re-mobilised from the sediments. While low-flushing conditions associated with release events will allow algae more time than otherwise to accumulate biomass, it appears that some of the re-cycled P enhances algal production. Nevertheless, more detailed studies are needed on the P content of algal cells over a period covering the development and decline of sediment release pulses.

There is also an urgent requirement to assess more adequately than hitherto, whether key chemical and biological features of water quality have changed as predicted by Bailey-Watts *et al* (1987) and Bailey-Watts, Gunn and Kirika (1993). Certainly, overall phytoplankton abundance as measured by the annual mean concentrations of chlorophyll$_a$, have shown no consistent trend, and certainly not one of decreasing values. The figures of 39μg l^{-1} and 36μg

l^{-1} calculated for 1992 and 1993, respectively, are considerably less than the values which ranged from *ca* 60μg l^{-1} to 90μg l^{-1} over the period 1968 to 1973 inclusive. However, apart from the concentrations of 21μg l^{-1} calculated for 1985 which was characterised by an extremely wet summer (Bailey-Watts *et al* 1987), and 50μg l^{-1} for the dry year 1990 (Bailey-Watts, May and Kirika 1991), the values range between 30μg l^{-1} and 40μg l^{-1} for the years 1974-1976 (Bailey-Watts 1978), 1977-1979 (Bailey-Watts *et al* 1983), 1980-1982 (Bailey-Watts 1982), 1983, 1988 and 1989 (Bailey-Watts, May and Kirika 1991).

A major data analytical programme is thus envisaged, which would aim to establish whether there are any long-term trends superimposed on the very prominent inter-annual and shorter-term fluctuations. The features that would be examined include, as examples, winter P levels, the duration of dense algal blooms, and aspects of the composition of the phytoplankton assemblages, including species diversity and trophic scores.

An attempt still has to be made to quantify the (assumed) reductions in P loading post-1987 i.e. following the major cutback of mill effluent recommended by Bailey-Watts *et al* (1987), and covering the period during which sewage treatment works have been upgraded.

5. THE DISTRIBUTION OF PHOSPHORUS IN THE MUDDY SEDIMENT: GENERAL APPROACH AND METHODS USED

A prominent feature of the bottom deposits of Loch Leven is the contrast between the north-eastern shelf which is composed of sand and corresponds closely to water up to 3m depth, and the much more organic, 'gyttja' type mud lying beneath water >3m (**Figure 7a** from Kirby 1971; **Figure 7b** from Calvert 1974). Stony areas exist, but they represent <5% of the area of the loch floor.

The present study focuses on the muddy zone which is estimated to cover 57% of the loch bottom (Charles *et al* 1974). These sediments contain a high proportion of P associated with iron (Bailey-Watts, May and Kirika 1991; Farmer *et al*, in press) and they can be readily induced to release phosphate (Blake 1989; Bailey-Watts, May and Kirika 1991; Miller 1993).

Forty sampling stations distributed at random within the area bounded by the 3-metre contour at the modal water level (as in **Figure 7a**) were chosen prior to going into the field. These points were located in the loch to within a maximum of 100m in any direction, and commonly much less than this, using a Global Positioning System. However, as the water level was low over the 6-week sampling period - 3 June to 14 July 1993 - the depth at 3 of the sites was found (using an echo-sounder) to be less than 3m. For convenience, these sites were re-positioned to the nearest point where the water was 3m.

At each site, two cores were collected with a Jenkin sampler. The cores are 7-cm in diameter and, depending on the weights attached to the corer, and the consistency of the deposits, they are usually between 8cm and 15cm long. Especially at the deeper sites (e.g. ≥10m), a check was taken on whether the near-sediment water temperature differed from the surface value. The largest differences were recorded on 13 July 1993 with 15.2^{0}C at the surface and 14.5^{0}C at 13.5m near the sluices corner of the loch, and 15.1^{0}C at the surface and 14.5^{0}C at 6.5m north of the west end of St. Serf's Island.

The water overlying the mud core was slowly siphoned off using a flexible, transparent plastic tube of 0.5-cm internal diameter. Care was taken not to disturb the surface sediment, and water from as near this surface as possible was retained for analysis. The sediment itself was extruded from the tube with a custom-built piston, and the uppermost 5cm of material was sliced off. The remainder of the core was discarded. A vertical sample of the 5-cm slice was then taken with a labelled, pre-weighed 50-ml (3-cm internal diameter) plastic centrifuge tube, the tapered bottom of which had been cut off and, after 'mini-coring', replaced with a small rubber bung.

The following procedures were used in the subsampling and the gravimetric and chemical analyses of the muddy material and the interstitial and overlying water. Each tube of mud sample brought in from the field was shaken to thoroughly mix the contents. A small subsample (approximating to 0.5g wet weight) was transferred by spatula into another pre-weighed plastic centrifuge tube. The wet weights of both the subsample and the main sample were measured. The efficiency of subsampling of the mud for the determination of the %P of sediment wet weight was high (**Appendix I**).

Distilled water was added to dilute the small, weighed subsample referred to above, to 50ml. A magnetic 'flea' and stirrer was used to mix the material while a 0.5ml subsample for TP analysis was withdrawn using a Finn pipette. The tube containing the main sample was centrifuged such that interstitial water could be drawn off for dissolved P analysis. The main analytical steps used to differentiate between the main dissolved and particulate fractions of P are as follows. Total P is determined on an unfiltered sample by the molybdenum blue method following acid-persulphate digestion. Total soluble P is determined as for TP but on a filtered sample. Soluble reactive P is also assessed on a filtered sample with the molybdenum blue technique, but without prior digestion with acid. The particulate component is calculated from the difference between TP and TSP, while the levels of dissolved organic P (soluble un-reactive P) are calculated from the difference between TSP and SRP.

In order to remove from the tube containing the main sample, as much of the remaining contents as possible for gravimetric and total organic carbon (TOC) analysis as an index of organic richness, the tube was deep-frozen. Following this, it was allowed to thaw until it was possible to tap out the contents in the form of an 'ice lolly' into a pre-weighed aluminium tray. This was then dried at 80^0C to constant weight, before grinding with a pestle and mortar, and removing a subsample which was weighed and submitted for analysis. The TOC results are not discussed in any detail here, but the method of determination was a modification of the Walkley-Black procedure.

6. RESULTS AND DISCUSSION ON SEDIMENT PHOSPHORUS

6.1 The total phosphorus content of the sediments, and the distribution with water depth

Small-scale patchiness in sediment composition, and errors inherent in the collection and handling, can lead to considerable differences between the analytical results even from cores from the same site. However, an analysis of variance (ANOVA) on the present data showed that variation in the TP content between sites was very significantly greater (99.9% probability) than the differences between pairs of cores at a single site.

Values expressed as %TP of sediment dry weight, with each being the mean of the two obtained from the pair of cores taken at each site, range overall nearly 4-fold - from less than 0.07% to just over 0.26%. However, 32 out of the 40 sites gave values within the 2-fold range 0.12% to 0.23%. The majority of the 12 sites where values of $\geq$0.2% were recorded, lie within a central zone of the loch where the depth exceeds 5m - roughly bounded by the north-eastern edge of St. Serf's Island, the western side of Castle Island, and the 3-metre contour off the southern shore of the loch opposite the mouth of the Gairney Water. Meanwhile, the lowest values for sediment dry weight i.e. of <0.1%P were generally confined to the shallow edges of the mud zone e.g. near Castle Island and in the region abutting the north-eastern sandy area. However, there is no consistent relationship. **Figure 8a** shows that some high values correspond to sites as shallow as 3m, and some of the deepest sites gave values as low as 0.08%.

The P contents are similar to those recorded by Bostrom, Jansson and Forsberg (1982), and they compare well with those detailed albeit for a single core by Farmer *et al* (1994). The range encompassing most of the values in the 1993 survey is also well in keeping with that found by Blake (1989) and reported by Bailey-Watts, Kirika and May (1991) from a study of 5 sites along a transect running from depths of 3.5m to 17m towards the North Deeps (**Figure 9**, from Blake 1989). Twenty-five P values i.e. one from each 2-cm slice from the surface of each core down to 10cm, ranged from 0.06% to 0.39% of sediment dry weight. Only one of these exceeded 0.22%, however - that corresponding to the uppermost section of the core taken at the deepest site, and perhaps representing recent, accelerated accumulation of material there. The highest value measured at the shallowest site was 0.15% and this was also in the top 2-cm slice and again suggested a slight enhancement of P levels; the rest of the core showed values ranging from

0.06% at the base, increasing linearly to 0.1% in the 2- to 4-cm slice. P levels decreased in much the same way down the other three cores. In contrast to the findings of the present study, there is some consistency in the relationship between overall P content of the sediment core, and the depth from which it was taken.

A consistent relationship is also lacking between water depth and P content expressed as a percentage of wet weight (**Figure 8b**). The overall range of values approach, like that found for the dry weight analyses, *ca* 4-fold, but 29 of the 40 sites yielded values within a band from 0.02% to 0.03%. Again, in common with the situation found with the percentages of P on a dry weight basis, values from sites of 3m depth spanned the complete range, and values of *ca* 0.03% were recorded at depths ranging from 3m to >20m. On the basis of the present survey too, the vast majority of the uppermost 5cm of the loch bed lying beneath water of at least 3m depth, contains between 12g P m^{-2} and 16g P m^{-2} (**Figure 10**). The 7-site sediment P survey in 1992 produced results which are generally in agreement with those presented here, with 13 of the 14 cores (7 pairs) giving values ranging from 10g P m^{-2} to 15g P m^{-2} over the top 5cm of sediment.

While P content seems not to relate in any consistent fashion to water depth, a statistically significant figure of *ca* 60% of the variation in %P of sediment dry weight is associated with variation in sediment water content (i.e. % water = 61 + 132% P). A similar statistically significant association (r^2 = 0.63) has been found between %P of sediment dry weight and the percentage of total organic carbon i.e. %P = 0.043 + 0.021%TOC.

6.2 The levels of soluble phosphorus in the interstitial water and the water immediately overlying the sediments, and their distribution with water depth

The lack of any clear relationship with water depth extends to the present data on soluble reactive P (SRP) in the sediment interstitial water and the water overlying the sediment. Moreover, since the dispersions of points in the two graphs plotted in **Figure 11** differ, there is no relationship between the two concentrations.

No patterns emerge either, from the data relating the interstitial and overlying water P levels to the total P or the total organic C contents of the sediment. Indeed, interstitial P levels, for example, seem to vary entirely independently of the %TP (r = -0.08) and the %TOC of sediment dry-weight (r = -0.38).

While there is little that can be determined as regards factors influencing the spatial variation in interstitial P levels, these are useful in reflecting the eutrophic state of the loch. Concentrations would need to be monitored throughout a year to calculate a true mean value, since Setting aside the fact that the concentrations may shift between summer and autumn as algal blooms settle and decay, for example, the range of TSP values recorded in Loch Leven - 0.25mg l^{-1} to 1.0mg l^{-1} - fit well with the series discussed by Martinova (1993) in which a few microgrammes per litre characterised oligotrophic waters, while upto 15 mg l^{-1} was measured in some hypereutrophic systems (see also Enell and Lofgren 1988). Golachowska (1979) also measured a maximum interstitial P level of 3.6 mg l^{-1} in Lake Plussee.

Overlying water P concentrations also appeared to follow no clear pattern with water depth, and most sites yielded TSP levels of between 10μg l^{-1} and 30μg l^{-1} although values of up to 90 μg l^{-1} were recorded. There was also little correspondence between P concentrations in the overlying waters and those measured in the sediment pore waters. This is in agreement with the findings of Bengtsson (1975) for Lake Sodra Bergundasjon in Sweden, which is like Loch Leven in being shallow and often well-mixed.

Bostrom *et al* (1982) found that interstitial P concentrations are normally 5 to 20 times those measured even in the water immediately overlying the sediment. The Loch Leven data are comparable with the upper value, with mean TSP values of 516μg l^{-1} in the interstitial water, and 22 μg l^{-1} in the overlying water. However, while the pore water values stem from measurements limited to the (richer) muddy zone of the loch, the overlying P levels probably reflect more the whole, loch-wide, situation including the influence of the shallow zones - even though wind-induced mixing can lead to releases of P from these shallow sediments. Indeed, although TSP levels in the water overlying the sediment were strongly skewed and their relationship with water depth could not be properly evaluated using a parametric ANOVA test, the albeit less powerful, non-parametric Kruskal-Wallis test showed no evidence of the P concentration in the overlying water varying any less between pairs of cores at one site, than over the loch as a whole.

7. CONCLUSIONS ON SEDIMENT PHOSPHORUS

Statistical analysis suggests to that P the content of the sediments in Loch Leven does vary spatially and is generally more concentrated in sediments with a high TOC and water content. A major finding, however, is that even though the majority of high P values were in the central area of the loch where the water is more than 5m deep, there are no consistent relationships between water depth and P content expressed as either dry or wet weight, or in terms of volume of sediment. This is in sharp contrast to what one might expect in a more linear or trench-like loch, in which sedimentary material will be more highly focused. The only example of this type of situation in Loch Leven, is that suggested by Blake's (1989) data i.e. a reasonable increase in P content with increasing water depth, due primarily to the fact that her samples were restricted to a transect running from relatively shallow water into the North Deeps 'kettle-hole'. Not only is Loch Leven more-or-less bereft of a significant single depositing area. Its main deeps - lying to the west and south of St. Serf's Island - is known to be relatively well-flushed with areas of hard, coarse deposits. Indeed, three attempts were made before successfully gaining a core from these deeps, due to areas of coarse or compacted sediments. Even then, 1 of the cores taken from this area, gave a value of only 0.09% P of dry weight, while the other core yielded a value of 0.24%.

There is considerable consistency and agreement, however, between the levels of P determined by the studies carried out in 1992 and 1993, and those reported earlier for Loch Leven. In this regard, P levels in these sediments do not differ significantly from those found in eutrophic waters elsewhere.

The present findings on the area within the 3-m contour - which amounts to some 7.6km^2 - are none too encouraging, when considered in connection with thoughts on the feasibility of sediment dredging. This is one of a number of restorative measures collated briefly reviewed for the Loch Leven Area Management Group by Bailey-Watts, Gunn and Kirika (1993).

Firstly, as there appears to be no marked 'hot-spots' , that is, a reasonably restricted area or a small number of areas, with order-of-magnitude greater levels of P than found elsewhere, the target area may well have to include much of the whole zone bounded by the 3-metre contour. Secondly, even if much of uppermost 5cm of wet sediment had a density of no greater than that of water itself i.e 1g cm^3, a square metre of this thickness would occupy 50l and would weigh 50kg (and yet, rarely contain more than 16g of P). The finer organic sediments are likely to have a density of 1.01g cm^3, while for diatom-rich ooze with abundant opaline silica frustules with a density of 2.2 g cm^3, a much higher weight-to-volume ratio would be expected. Relatively more P would be removed per unit weight or volume of sediment if a shallower skim of surface material were removed - since there are signs of surface enhancement of P levels in the uppermost layers (Bailey-Watts, May and Kirika 1990; Farmer *et al* 1994). However, as P levels are still considerable over many centimetres into these deposits, it must be conjectured that the 'new' top layers so uncovered, would then be a problem in themselves having the potential to release phosphate. The present work has not considered P release potential *per se*, but the results of Farmer *et al* (1994) suggest that reductant soluble and loosely-bound fractions of P represent approximately one-third of the total P measured.

An average value of say, 12g P m^{-2} over the uppermost 5cm of the deposits over the muddy zone, can be compared to figures of 1.54g m^{-2} as the specific areal loading of P over the whole loch surface from all external sources in 1985 (Bailey-Watts *et al* (1987), and an annual figure of nearer 1.00g m^{-2} currently. If a P retention coefficient of 0.6 is applied to these values, the 12g P m^{-2} is equivalent to between 7 and 11 years' input of P to these sediments.

The current survey has identified a significant variation in interstitial P content from site to site, but there appear to be few links between the amounts of P in the interstitial water and either the total P in the surface sediment, or depth of water. Contrastingly, Eckerrot and Pettersson (1993) found that spatial variations in the concentration of interstitial SRP in a shallow eutrophic lake in Sweden were influenced mainly by water depth, although temperature was also important in this regard. However, Enell and Lofgren (1988), however, state that spatial variation in interstitial P concentrations is affected by many factors which include the percentage of organic matter present, groundwater seepage, redox conditions and pH. These authors also point out that temporal variations in P concentration can be large and may also be very rapid, occurring over the space of a few days in the upper sediment layers. It is because of this, that the present results on interstitial P must be interpreted with caution; the cores were collected over a period of 50 days due to the large number of samples involved.

More detailed information is still required on the distribution of P over the loch as a whole i.e. including the sandy area and zones near the mouths of the feeder streams. There is also a great need for knowledge about the P constituents with regard to potential re-cycling i.e. the proportions of reductant soluble and loosely bound phosphates; only one core has been analysed in this detail so far. Further P release determinations in the laboratory on e.g. sandy sediments are warranted. However, the main thrust of future work on the factors controlling, and the (potential) extent of, phosphate re-cycling in Loch Leven, should employ methods whereby temperature, redox conditions and sampling of the sediment are done in the field as soon as the cores are secured. More thought should also be given to the possibility of mounting a routine programme of sediment chemistry - however basic - that covers all seasons of the year, in addition to an intensive programme of sediment and water chemistry over a period leading up to, during, and immediately following a P release event.

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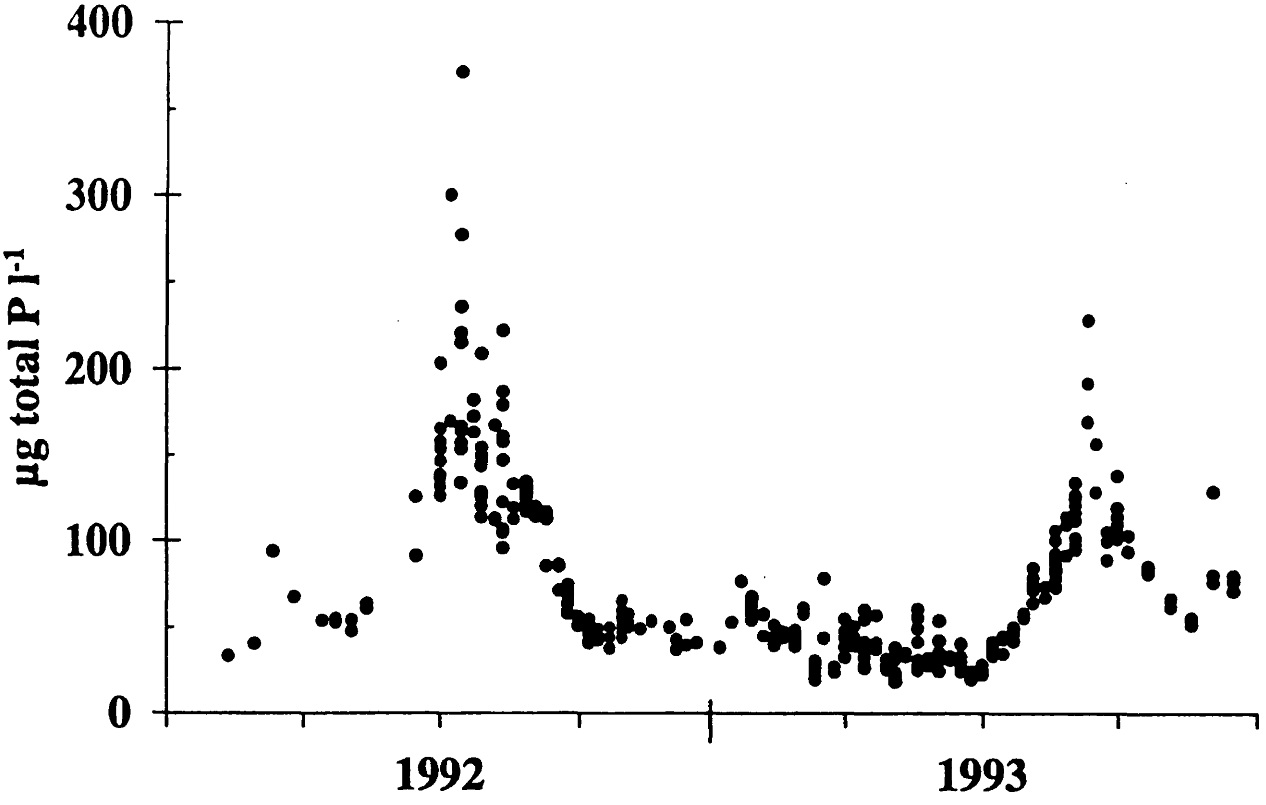
10. FIGURES

Figure 1. Changes at Loch Leven during 1992 and 1993 in the concentrations of total phosphorus (**a, upper panel**) and the overall abundance of phytoplankton measured as chlorophyll$_a$ (**b, lower panel**) with indications of the main species at various crop peaks (BG - Blue-green algae, D - Diatoms, C - Cryptomonads). Vertical lines connect the data points for all sites sampled on the same day.


total phosphorus

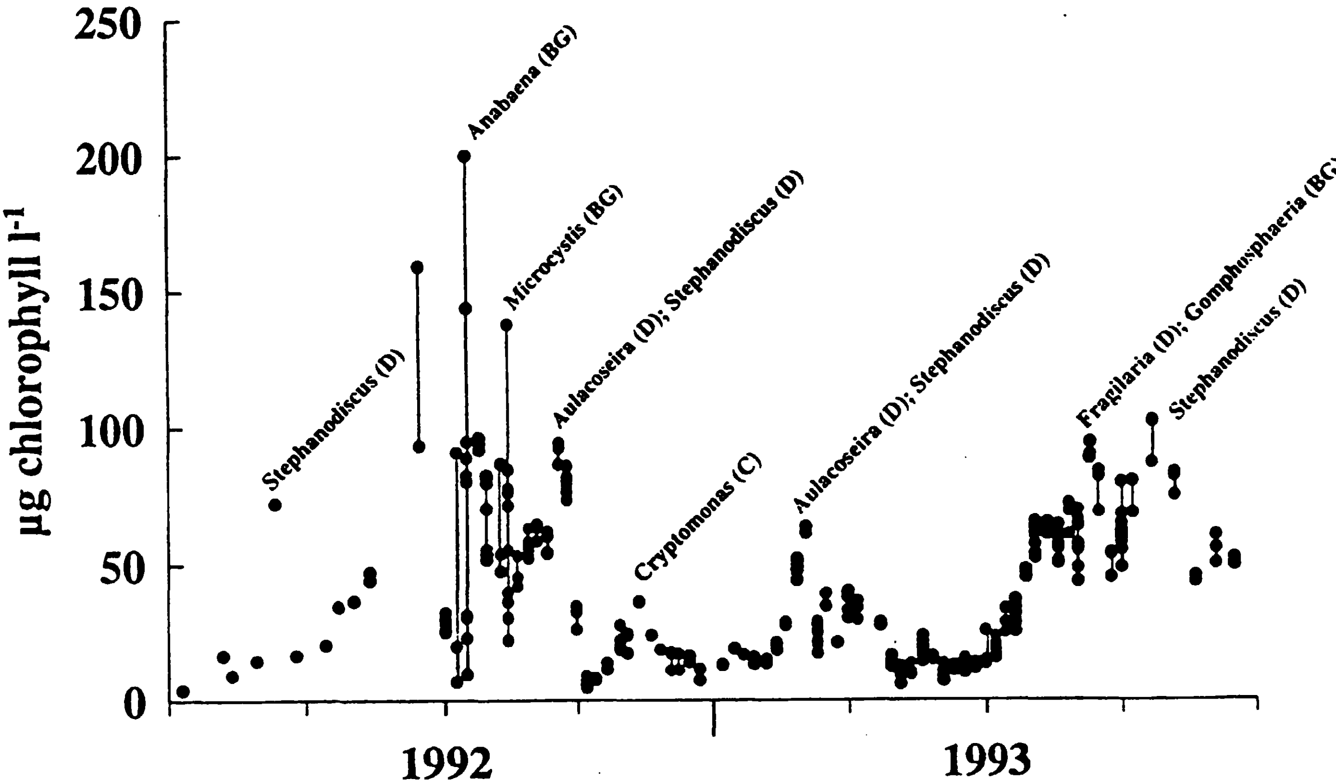
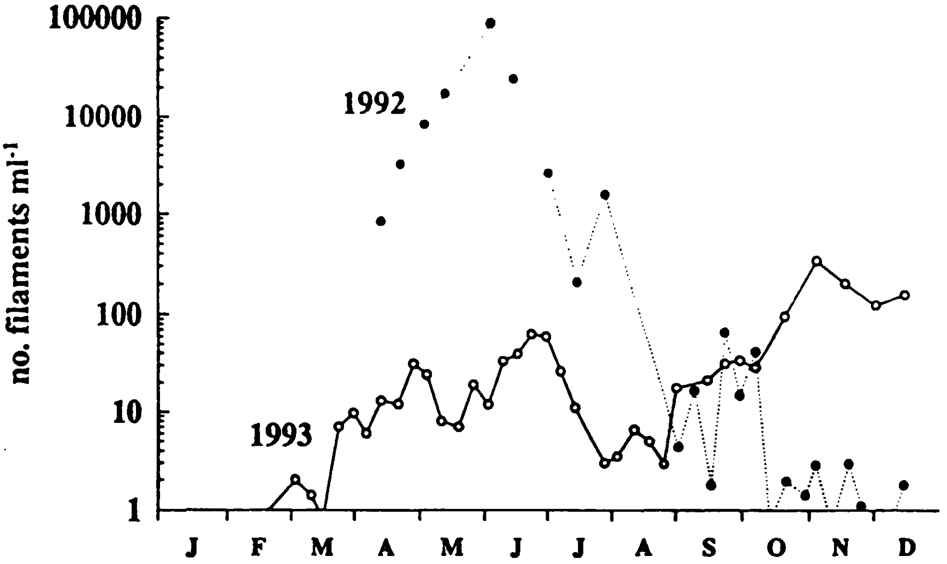
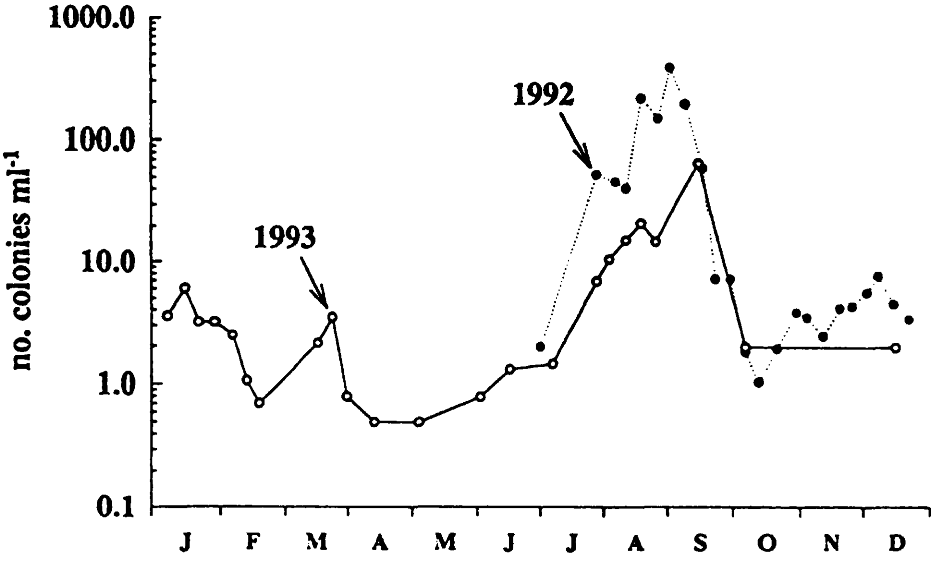

chlorophyll$_a$

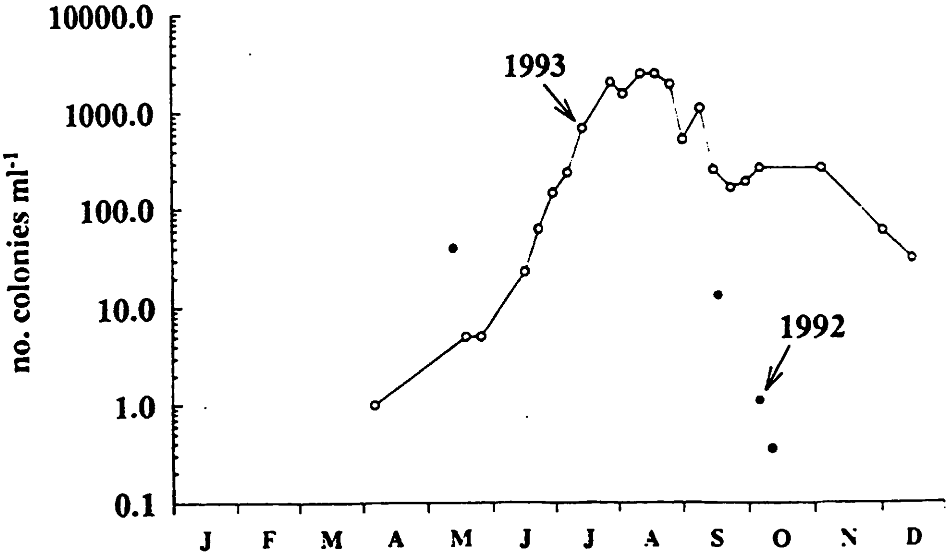
Figure 2. As Figure 1, for the populations of *Anabaena flos-aquae* (**a, upper panel**), *Microcystis aeruginosa* (**b, middle panel**) and *Gomphosphaeria* (**c, lower panel**). These estimates refer to the open water site south of Reed Bower, or in the case of very stormy weather, the sluices (outflow) station.



Anabaena flos-aquae

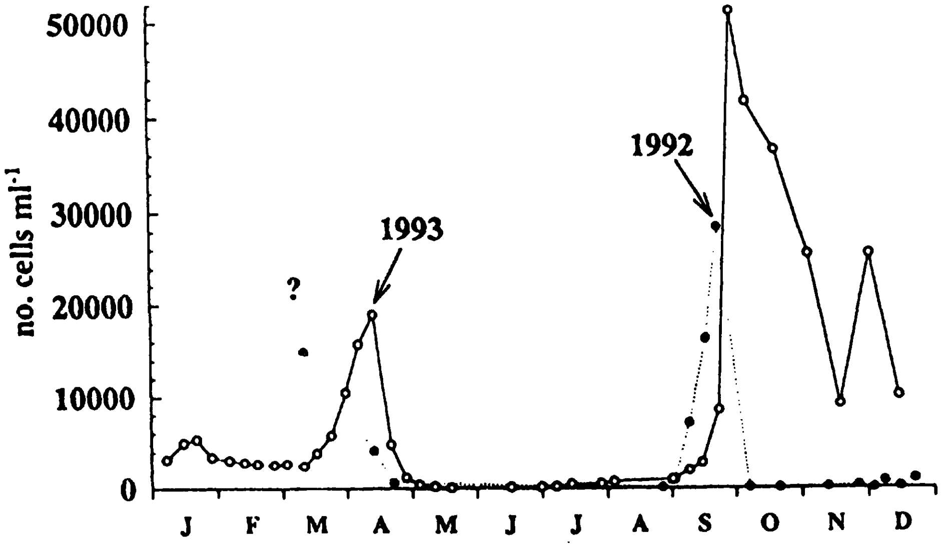


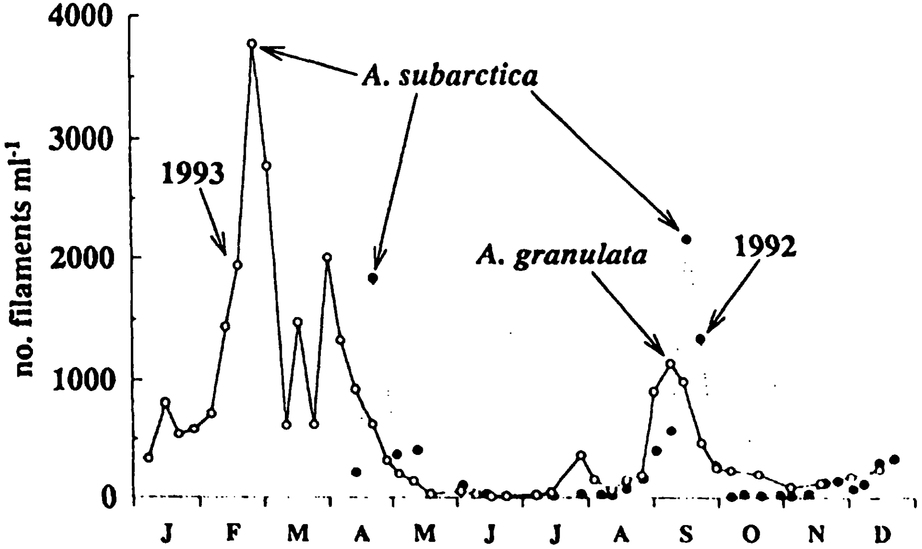
Microcystis aeruginosa

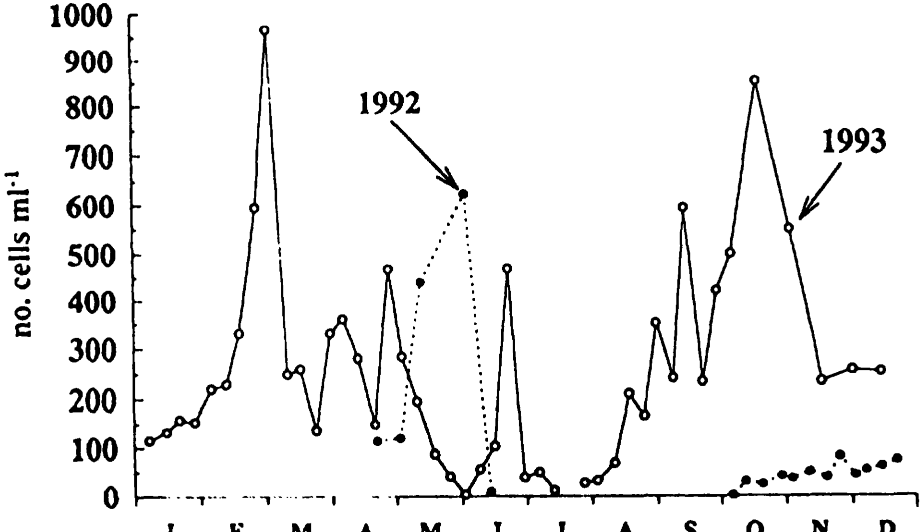


Gomphosphaeria lacustris

Figure 2, continued. Unicellular centric diatoms (**d, top left**), *Aulacoseira* species (**e, top right**), *Asterionella formosa* (**f, bottom left**) and *Fragilaria crotonensis* (**g, bottom right**).


unicellular centric diatoms (mainly *Stephanodiscus*)


Aulacoseira species


Asterionella formosa

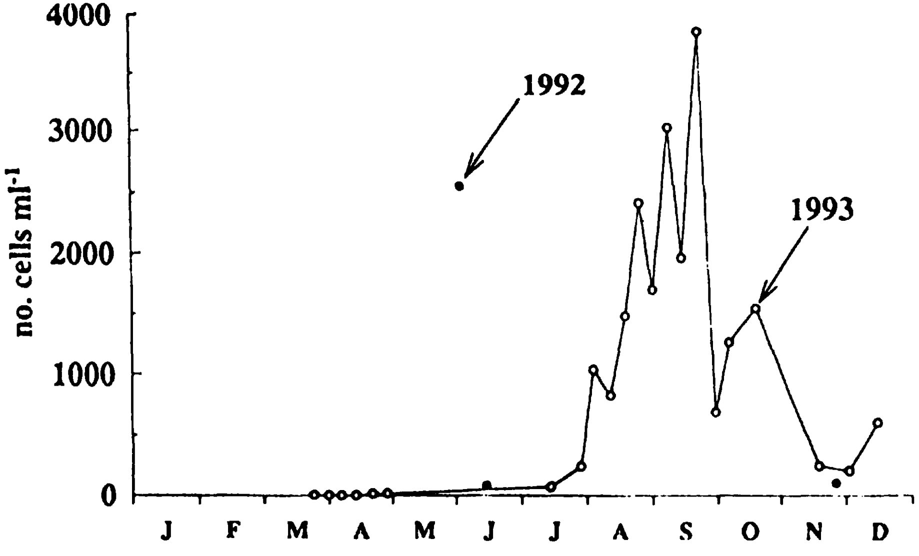
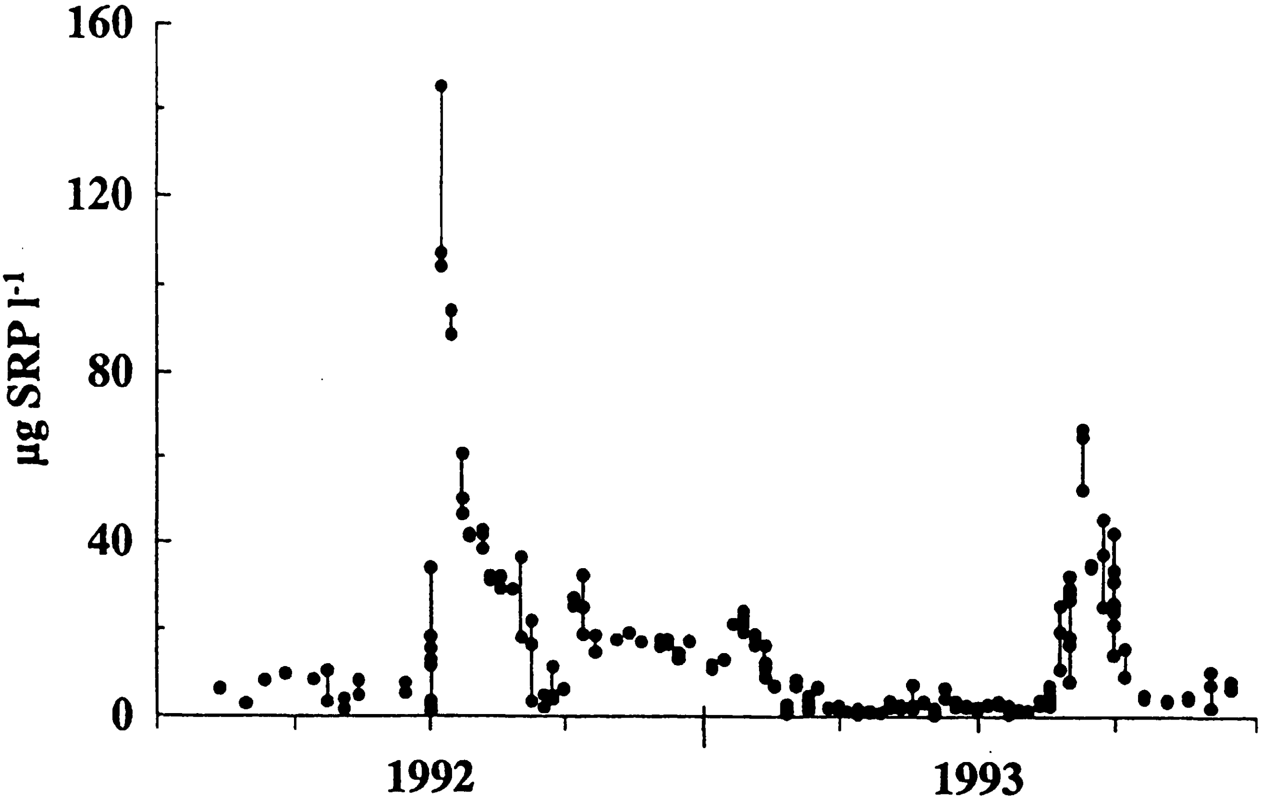

Fragilaria crotonensis

Figure 3. As Figure 1 for the concentrations of soluble reactive phosphorus (**a, upper panel**) and dissolved silica (**b, lower panel**).

soluble reactive phosphorus



dissolved silica

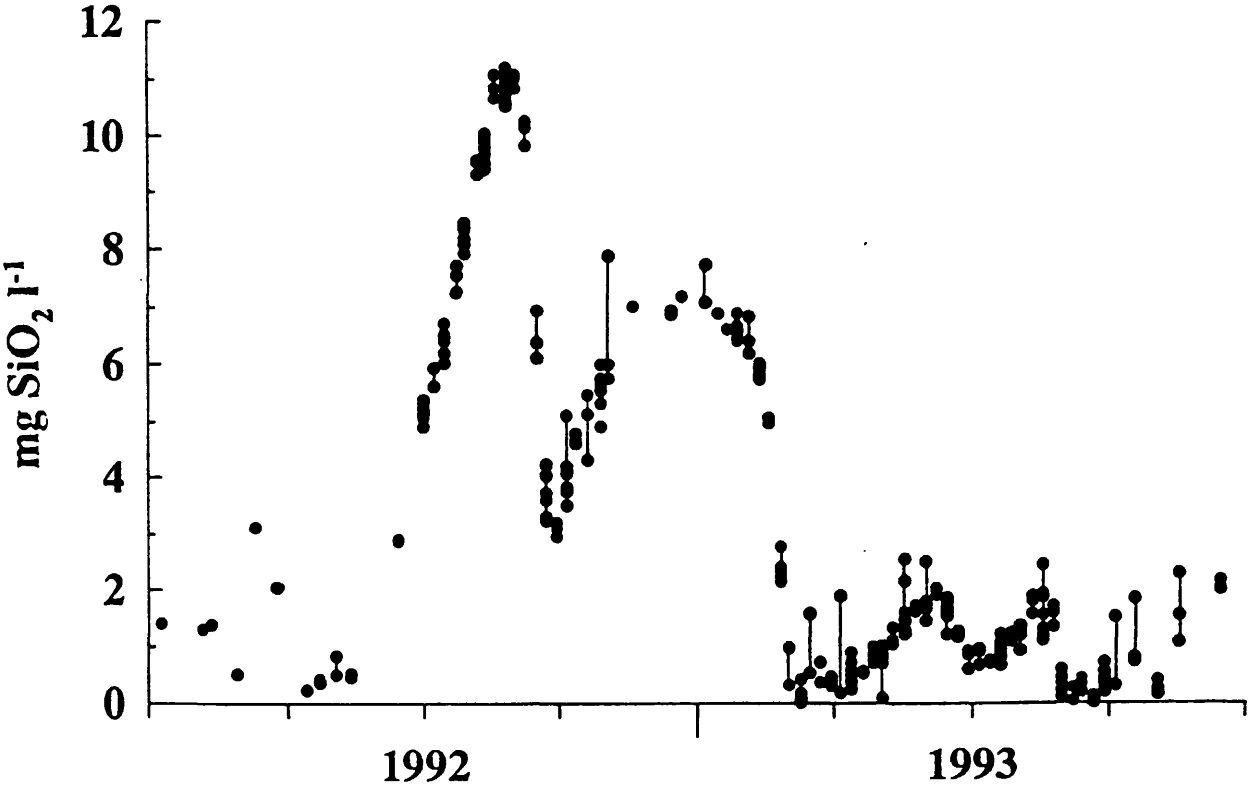
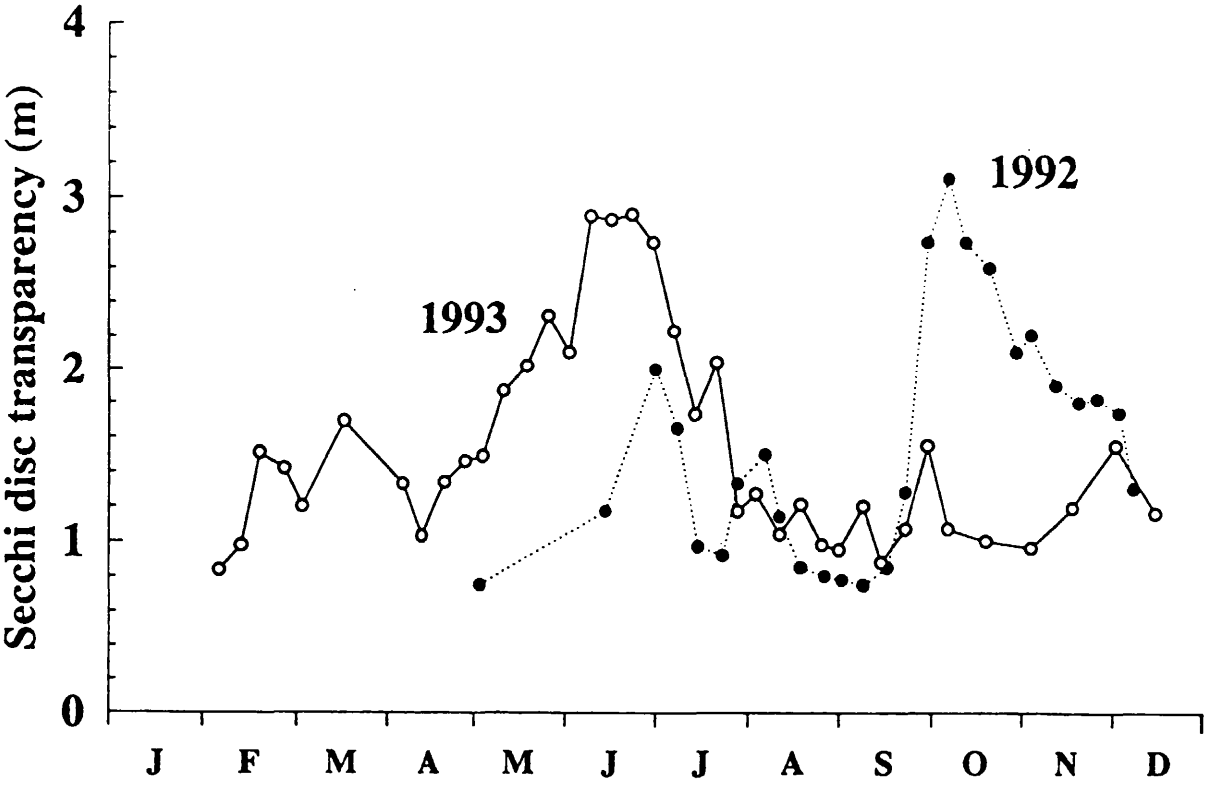


Figure 4. Changes in water clarity measured by Secchi disc at an open water site in Loch Leven during 1992 and 1993 (**a, upper panel**), and the relationship between Secchi disc transparency and chlorophyll$_a$ concentration (**b, lower panel**).

water clarity



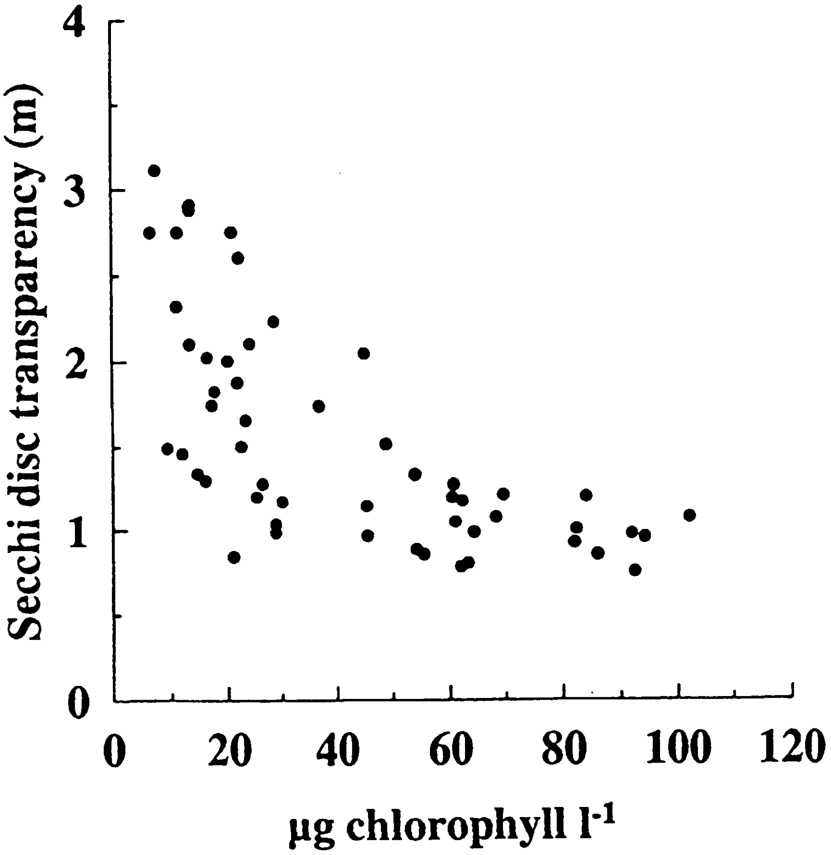
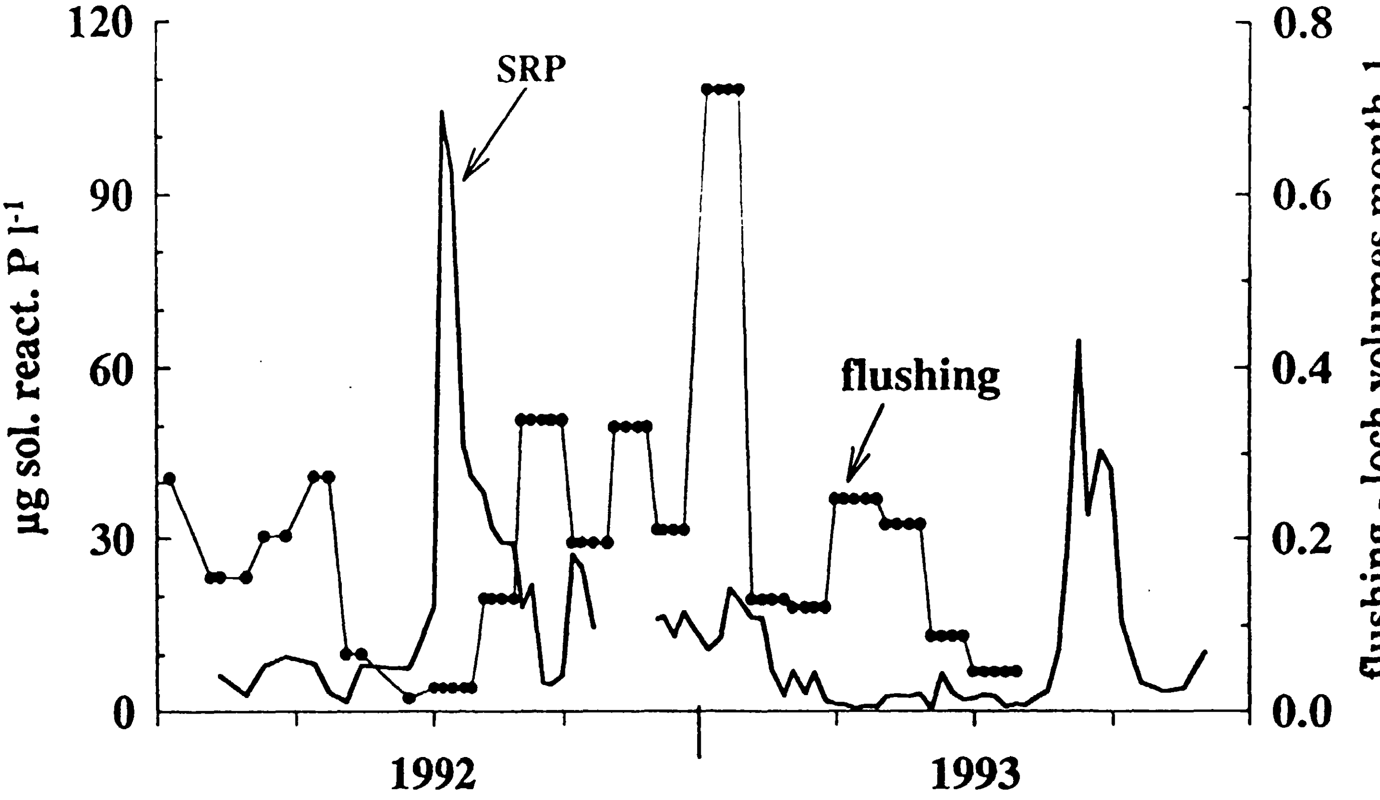


Figure 5. Changes in chlorophyll$_a$ (**a, upper panel**), and soluble reactive phosphorus (**b, lower panel**) measured at an open water site in Loch Leven 1992-1993, with the corresponding monthly flushing rate values.


SRP
flushing
μg sol. react. P l-1
flushing - loch volumes month-1
120
90
60
30
0
0.8
0.6
0.4
0.2
0.0
1992
1993

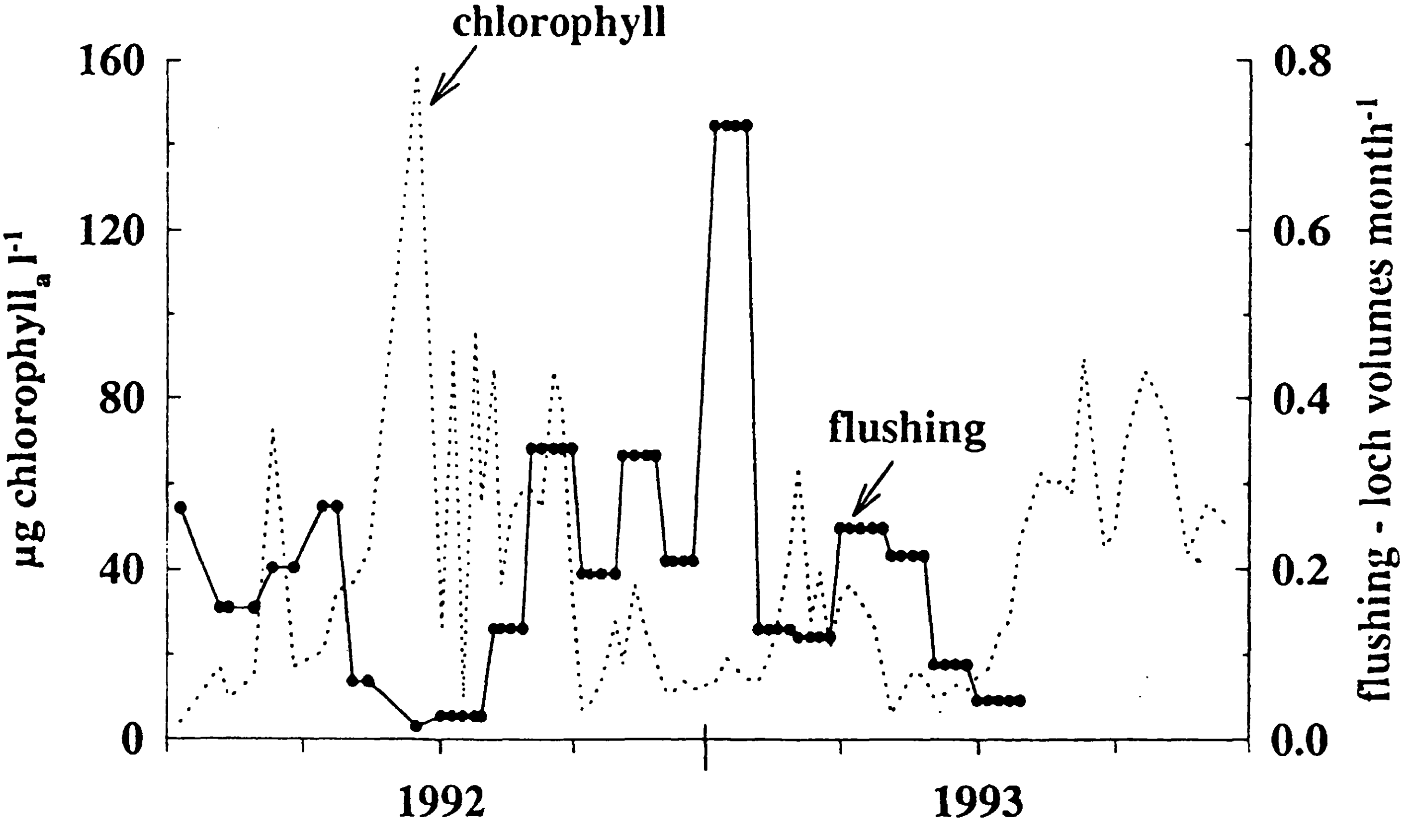

chlorophyll
flushing
μg chlorophyll_a l-1
flushing - loch volumes month-1
160
120
80
40
0
0.8
0.6
0.4
0.2
0.0
1992
1993

Figure 6. Changes in *Daphnia* abundance and chlorophyll$_a$ concentration in Loch Leven 1992-1993; data refer to the open water site south of Reed Bower. The sharp fluctuations in chlorophyll$_a$ concentration in summer 1992 are thought to be not due to zooplankton grazing, but to primarily, the week-by-week changes in the (patchy) distribution of the large blue-green algae that were abundant over this period.

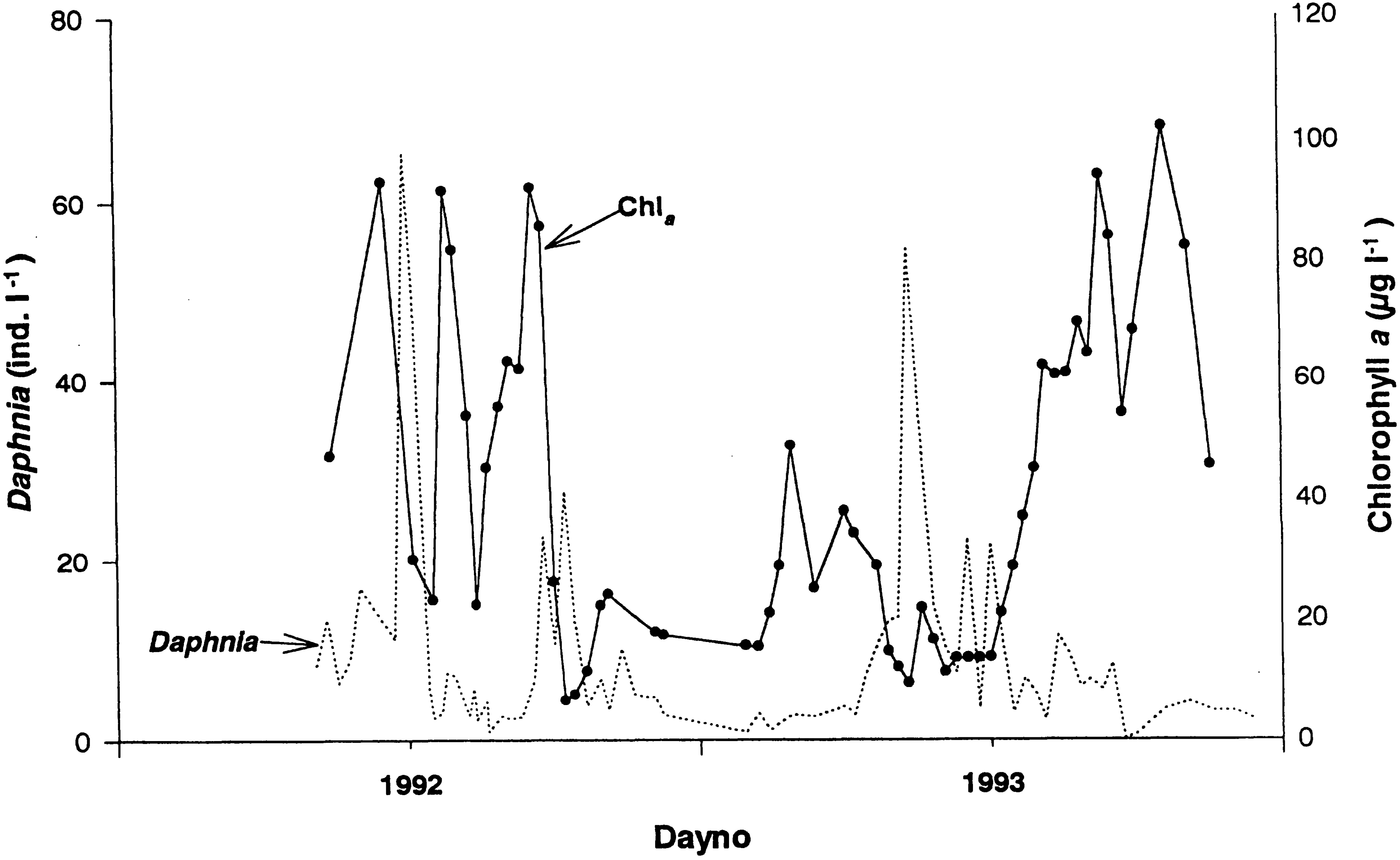
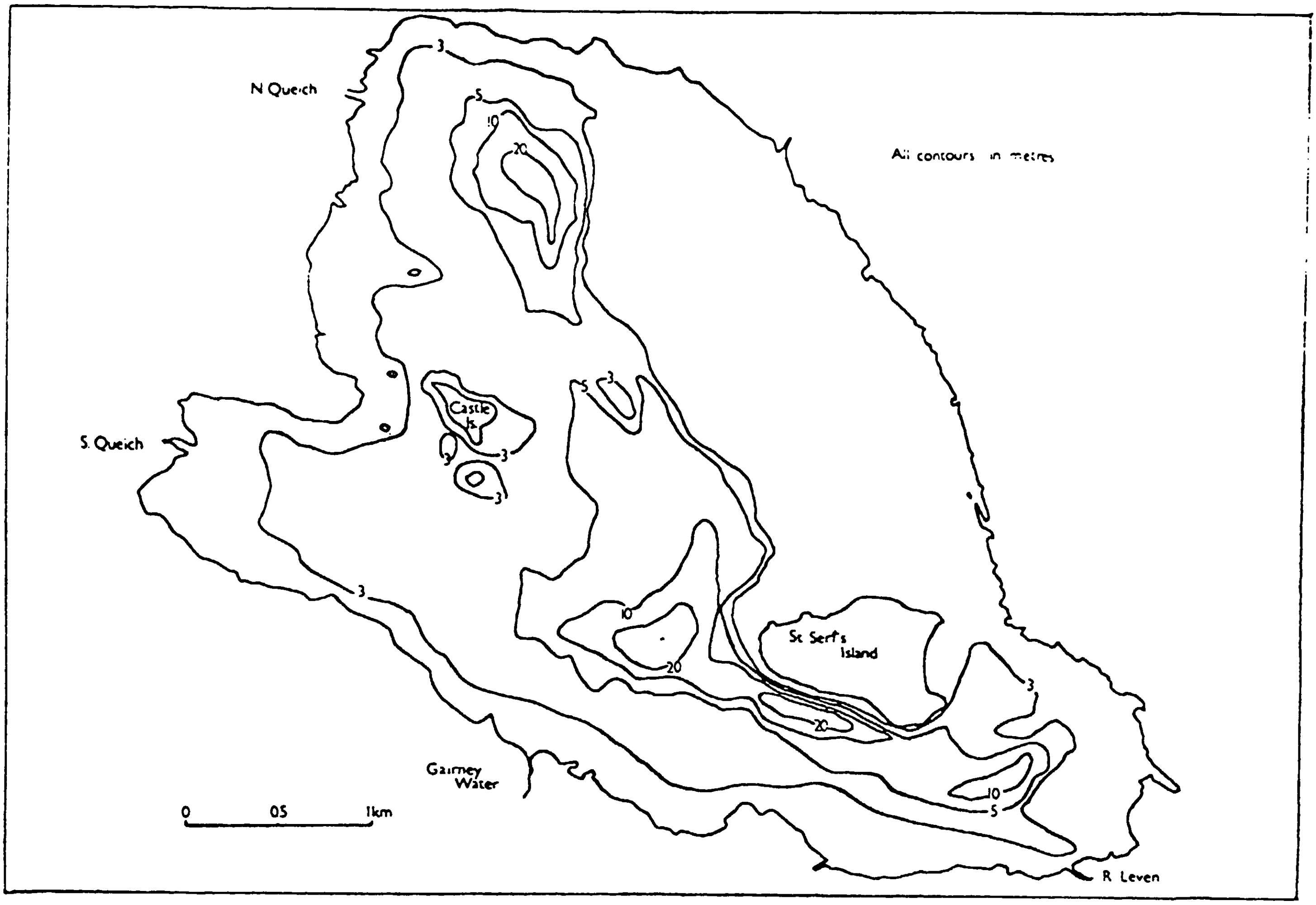

80
60
40
20
0
Daphnia (ind. l-1)
120
100
80
60
40
20
0
Chlorophyll a (µg l-1)
Chla
Daphnia
1992
1993
Dayno

Figure 7. Bathymetric map of Loch Leven (from Kirby 1971, **a, upper panel**) and sediment grain size distribution (from Calvert 1974, **b, lower panel**).


N Queich
All contours in metres
3
5
10
20
Castle Is
S. Queich
St Serf's Island
Gairney Water
0
0.5
1km
R Leven

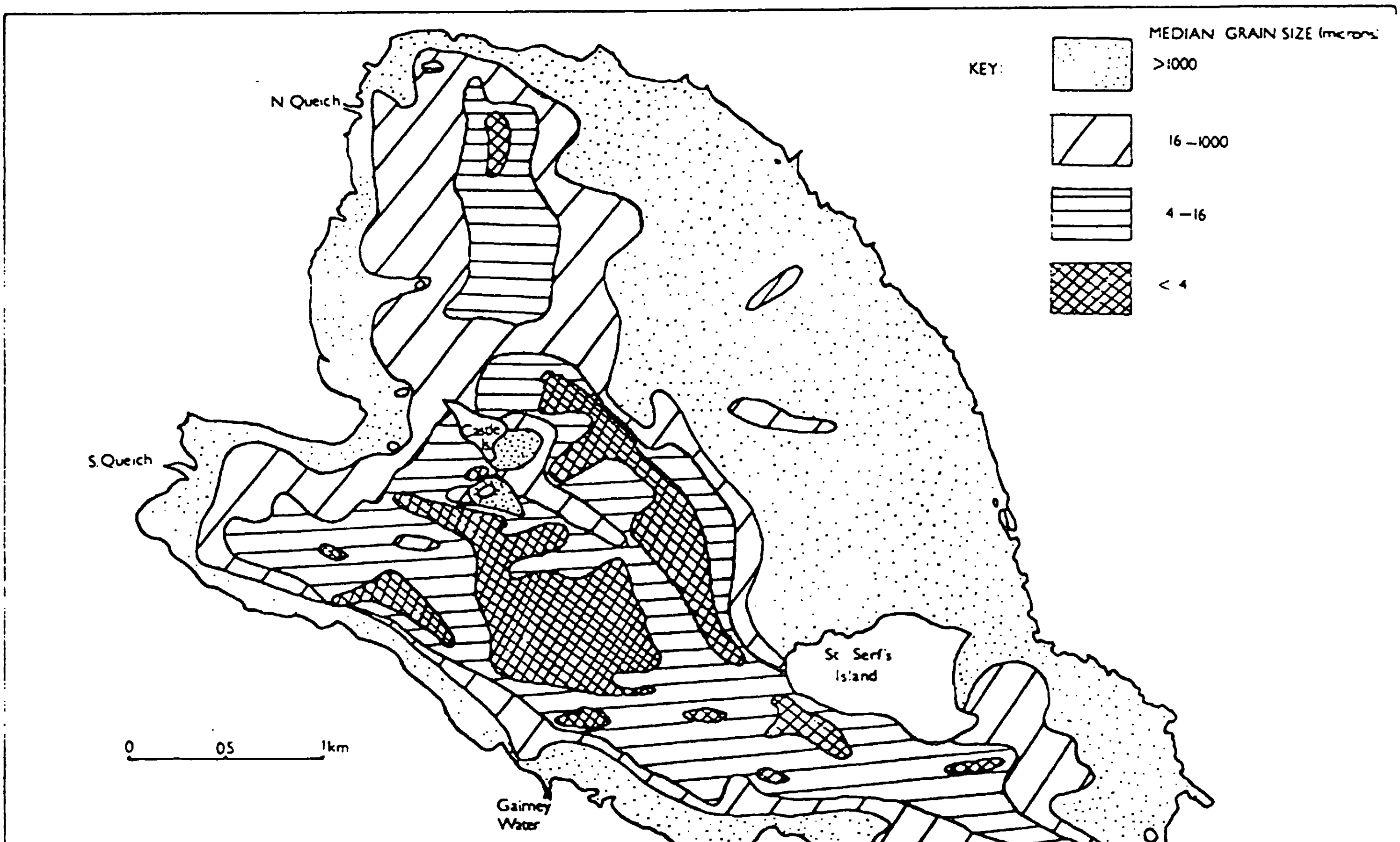
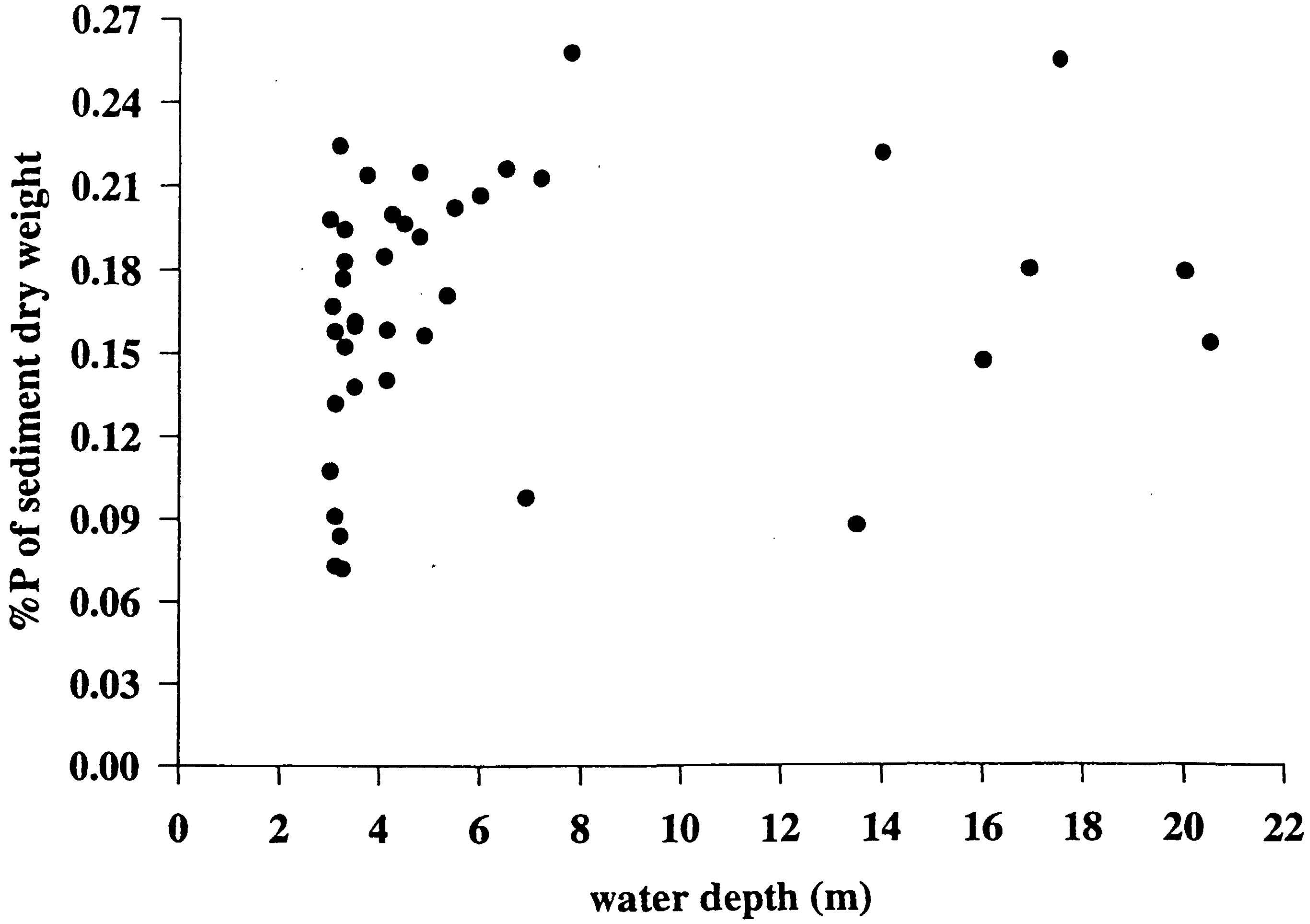

KEY:
MEDIAN GRAIN SIZE (microns)
>1000
16 – 1000
4 – 16
< 4
N Queich
Castle Is
S. Queich
St Serf's Island
Gairney Water
0
0.5
1km
R Leven

Figure 8. The relationship between water depth and the P content of the uppermost 5cm of mud sediment in Loch Leven, on the basis of dry-weight **(a, upper panel)** and wet weight **(b, lower panel)**.


%P of sediment dry weight
0.27
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
0.00
0
2
4
6
8
10
12
14
16
18
20
22
water depth (m)

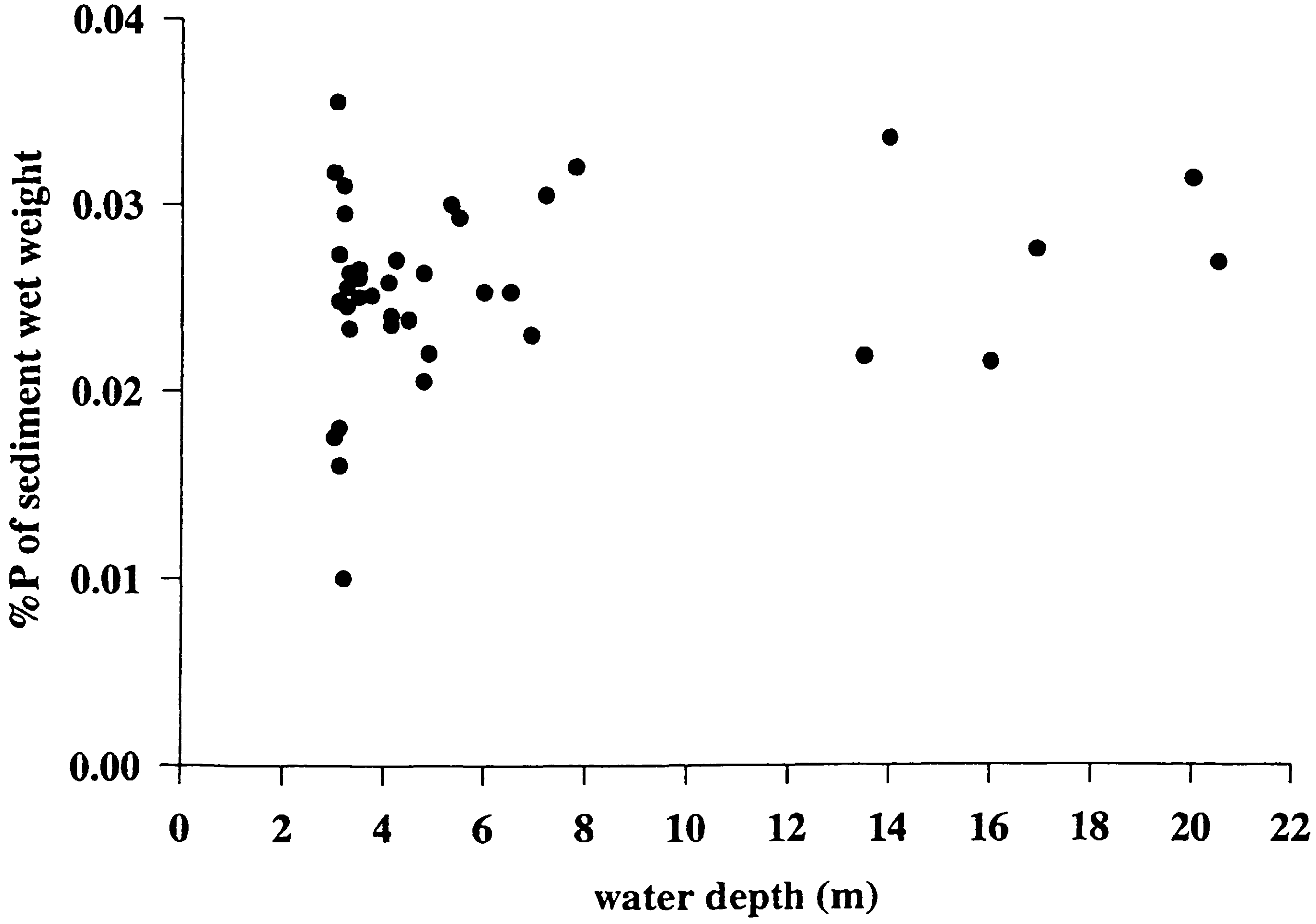

%P of sediment wet weight
0.04
0.03
0.02
0.01
0.00
0
2
4
6
8
10
12
14
16
18
20
22
water depth (m)

Figure 9. Depth profiles of the concentration of particulate phosphorus (>99% of the total amount of P) in 5 mud cores collected along a transect running from 3.5m water depth (site 1) into the North Deeps at 17m depth (site 5) *via* points at depths of 5.2m (site 2), 7.0m (site 3) and 10.0m (site 4). Taken from Blake 1989).

Particulate P at 5 sites – 2.8.89

sites 1,-○-;2,-○-;3,-●-;4,-●-;5,★.

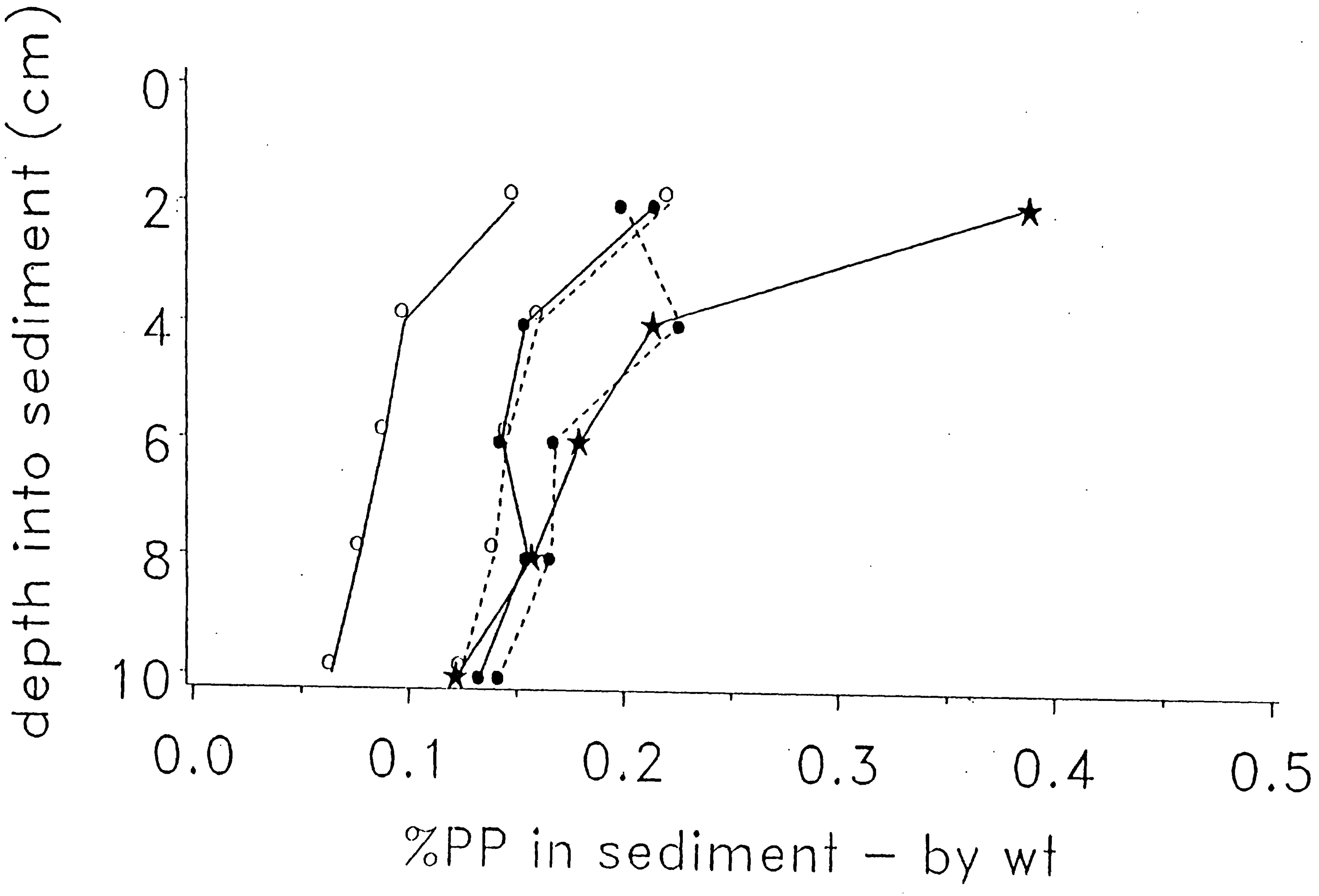


Figure 10. The relationship between water depth and the concentration of total P in the uppermost 5cm of mud sediment, expressed on an areal basis, in Loch Leven.

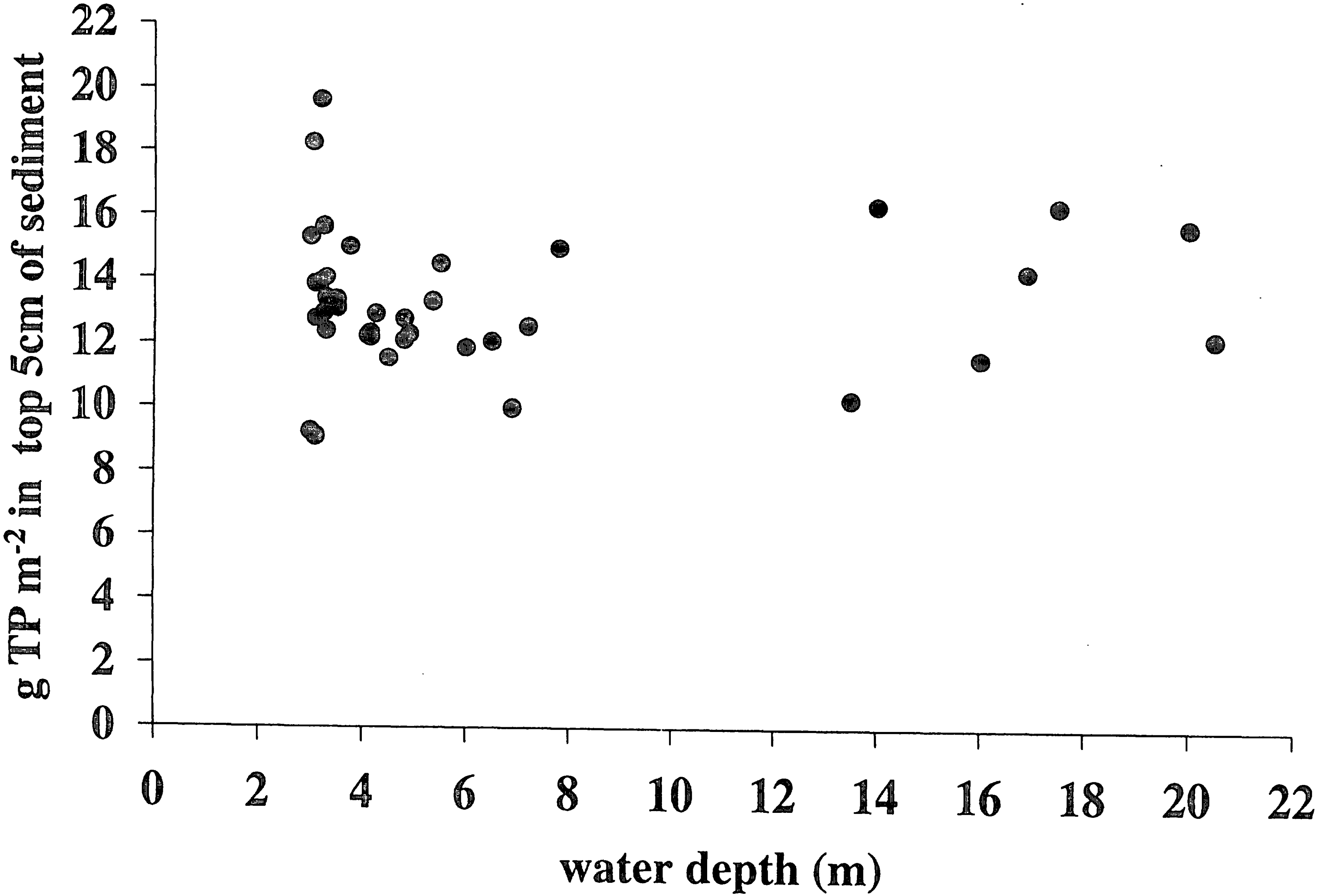
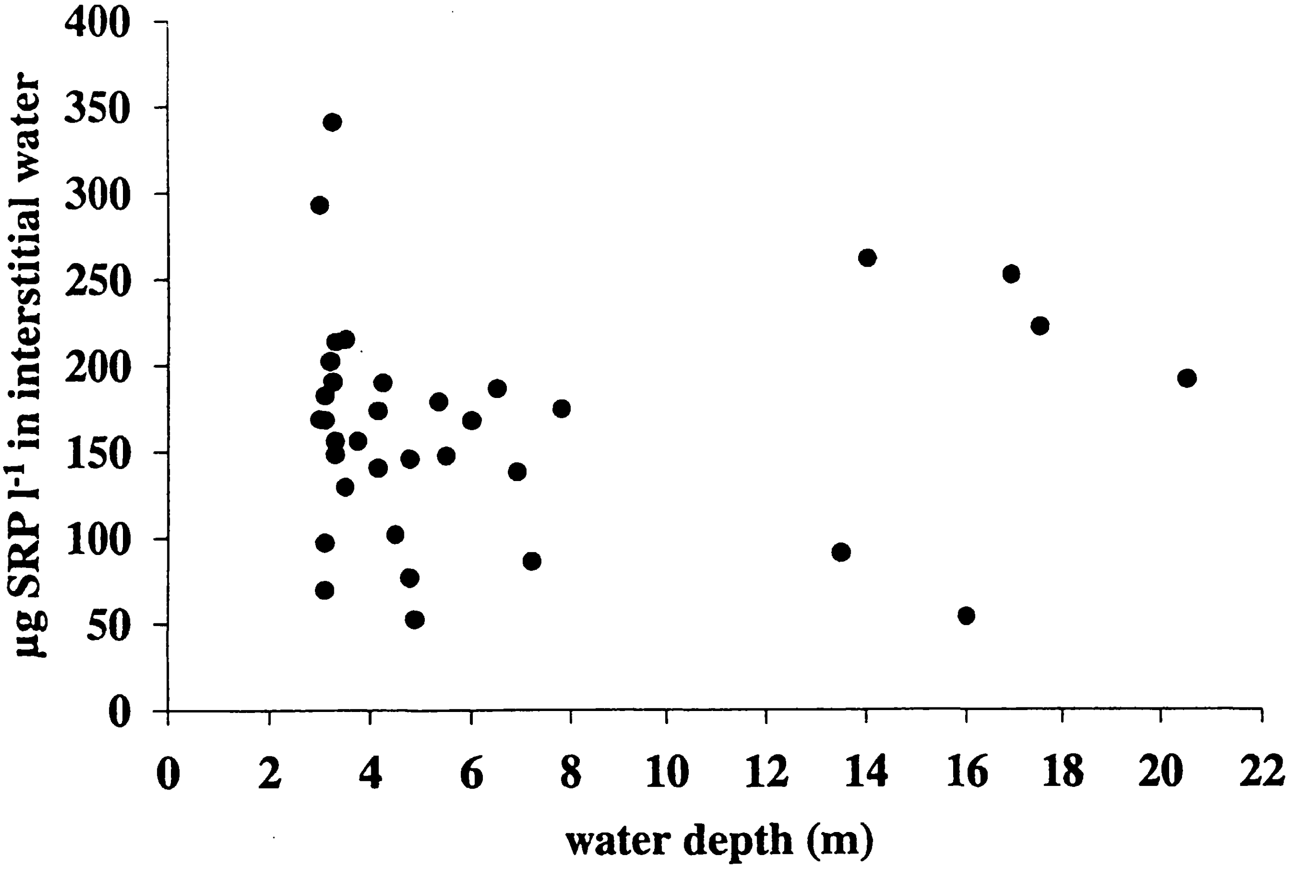
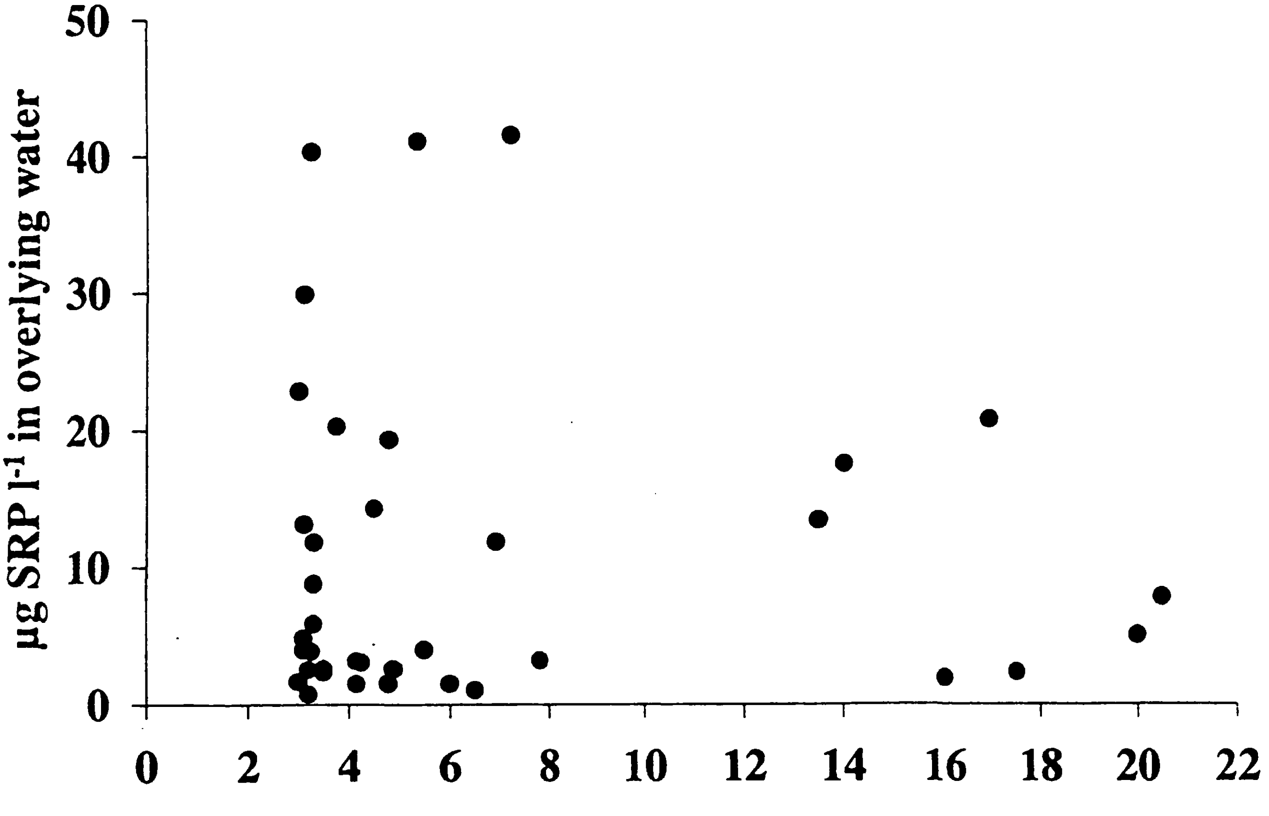

22
20
18
16
14
12
10
8
6
4
2
0
g TP m^{-2} in top 5cm of sediment
0
2
4
6
8
10
12
14
16
18
20
22
water depth (m)

Figure 11. The relationship between water depth at Loch Leven, and the concentration of soluble reactive P (SRP) in the pore water of the uppermost 5cm of (mud) sediment **(a, upper panel)** and the overlying water **(b, lower panel)**.


μg SRP l-1 in interstitial water
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
20
22
water depth (m)


μg SRP l-1 in overlying water
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
water depth (m)

Appendix I: Efficiency of subsampling for weighing and determining the total phosphorus content of mud sediment.

Sample	Sample Wt	Replicate	Mean Reading	TP Wt. (ug)	%TP
X1	0.3505	300.2 293.5 342.1	311.93	77.98	0.022
X2	0.5738	467.3 481.5 560.4	503.07	125.77	0.022
X3	0.4074	322 294.6 356.7	324.43	81.11	0.02
X4	0.3537	306.8 339.9 341.8	329.5	82.38	0.023
X5	0.4692	344.9 371.5 441	385.8	96.45	0.021
X6	0.334	293.7 315.5 320.3	309.83	77.46	0.023

Clearly, the six sub-samples produce %TP results which are not statistically different from each other so the sub-sampling process used in TP analysis is proven to be effective in obtaining representative samples of the top 5cm of sediment.

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Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland.

Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes - which has evolved through the long partnership between people and nature.

We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.