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Commissioned Report No. 030

Loch Leven 2002: physical, chemical and algal aspects of water quality

(ROAME No. F01LH03B)

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COMMISSIONED REPORT Summary

Loch Leven 2002: physical, chemical and algal aspects of water quality

Commissioned Report No. 030 (ROAME No. F01LH03B)
Contractor: Laurence Carvalho and Alex Kirika (Centre for Ecology and Hydrology)

Background

Loch Leven is eutrophic and has suffered from periodic cyanobacterial blooms for many years. These blooms have a direct impact on the various users of the loch and on the local economy. In terms of conservation interest, algal blooms also reduce light penetration into the water, reducing macrophyte growth, with associated changes in macroinvertebrate, fish and bird communities.

This report is one of a series that describe and interpret physical, chemical and phytoplankton information from Loch Leven on an annual basis. Temporal and spatial variation in a number of key factors, and interactions among them, are discussed. The data are also evaluated in relation to changes in water quality following reductions in phosphorus loading to the loch. Evidence of ecological recovery is also discussed.

Main findings

Phytoplankton crops in Loch Leven showed an overall increase in 2002 compared with the previous year. This is illustrated by an annual mean chlorophyll$_a$ concentration of 40μg l^{-1} compared with a mean of 24.5μg l^{-1} for 2001. Despite this change, the annual mean total phosphorus (TP) concentration of 48μg l^{-1} was unchanged. These concentrations still exceed the statutory target concentrations of 15μg chlorophyll$_a$ l^{-1} and 40μg TP l^{-1} set by the Loch Leven Area Management Group (LLAMAG) in 1993 (LLAMAG 1993) and endorsed in the Loch Leven Management Plan (Loch Leven Catchment Management Project 1999).

The most marked difference from the previous two years has been the generally decreased water clarity, most notably over the period of May and June. On only one occasion, May 14th, did the Secchi disc reading exceed 2m, with a mean value of 1.47m for the year as a whole compared with 2.00m and 1.71m for the preceding two years.

Diatoms dominated the phytoplankton throughout most of the year, most notably *Aulacoseira* spp. In late May and June, cyanobacteria were the dominant algal group (*Anabaena flos-aquae*) reaching much higher densities than in 2001, sufficient to merit warning signs to the public.

In general, the data suggest that 2002 does not show further evidence for recovery. On the contrary, there is a deterioration in comparison to the previous two years. The data for 2002 was, however, fairly typical of mean conditions over the past five years and a considerable improvement compared with the first five years (1968–1972). The deterioration in water clarity in particular is still a significant threat to the site's conservation and socio-economic interests and highlights a need for continued vigilance and further catchment management at the site.

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1 INTRODUCTION

Loch Leven is the largest eutrophic freshwater body in Scotland. It has suffered from periodic cyanobacterial blooms for many years. These have occurred, largely, as a result of large amounts of phosphorus entering the loch, combined with a relatively low flushing rate and a favourable light-climate (Bailey-Watts and Kirika 1999). These blooms have a direct impact on the various users of the loch, on the local economy, and occasionally pose a potential risk to human health. In terms of conservation interest, algal blooms also reduce light penetration into the water, reducing macrophyte growth, with associated changes in macroinvertebrate, fish and bird communities.

Recent management of Loch Leven has aimed at reducing the risk of these blooms occurring by reducing the loadings of phosphorus into the loch (Bailey-Watts and Kirika 1999; Loch Leven Catchment Management Project 1999).

Annual monitoring and evaluation of the status of the phytoplankton populations in Loch Leven is regarded as an important part of the assessment of water quality and ecological recovery. Frequent reporting on the status of the loch's phytoplankton populations is also invaluable in providing an early warning of the occurrence of severe cyanobacterial blooms that may be toxic to both people and animals.

2 METHODS

During 2002, water samples were collected at generally fortnightly intervals. This amounted to a total of 26 sampling visits. Four sampling sites on the loch were used. The most representative sampling location was the 'Reed Bower' (RB) site which lies to the south of the island of that name, where the water depth is similar to that often cited as the mean depth of the loch ie 3.9m. However, at times of very rough weather, ice cover or other unfavourable conditions, a site at the Public Pier (PP) in the Kirkgate Park was used instead. On almost all sampling occasions the outflow site ('L') was sampled, this being accessible from the land or by boat. The South Deeps (SD) site, at approximately 25m depth, was visited occasionally.

For each sampling occasion, a number of physical and chemical variables (water temperature, level and clarity, dissolved oxygen, conductivity, pH, silica, nitrogen and phosphorus) were measured. Field sampling and laboratory analyses followed the methods adopted over the last 30 years (Bailey-Watts and Kirika 2000), with the exception of those for inorganic nitrogen (N). In this report, total oxidised nitrogen (TON) concentrations, determined by the Scottish Environment Protection Agency's Riccarton laboratory were used. It should also be noted that the 'whole water-column' samples, collected with an integrated tube sampler at the Reed Bower site, usually extended from the water surface to around 0.25m above the sediment surface. As a result of fluctuations in water level brought about by the control of the outflow, sample depths varied from 3–3.75m.

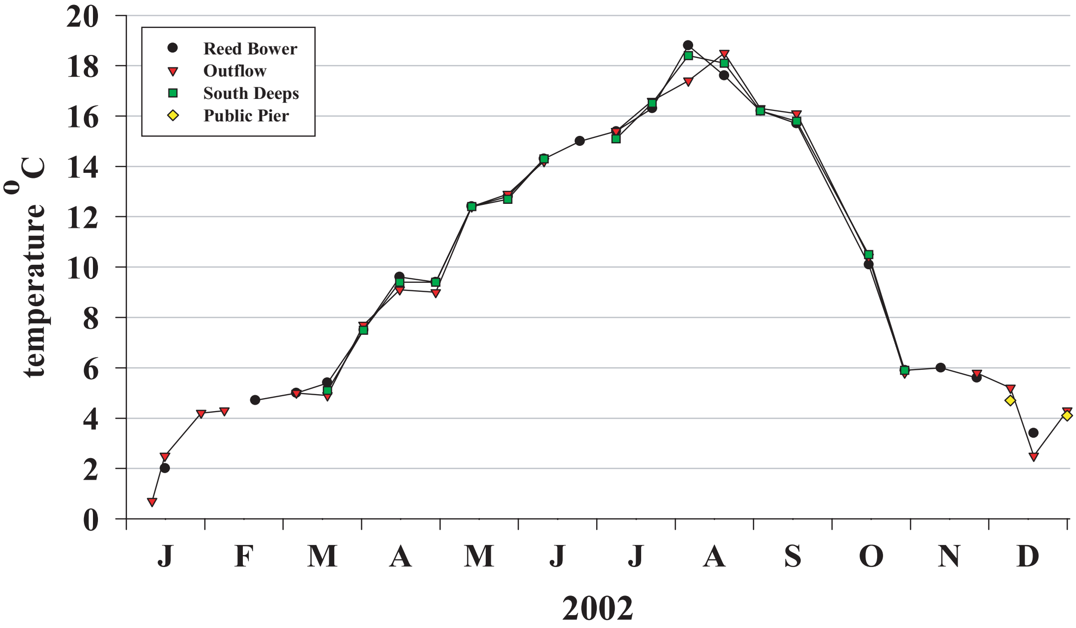
3 RESULTS

3.1 Physical factors

3.1.1 Water temperature

Variation in water temperature followed a generally simple pattern over the year with a maximum of 18.8°C being recorded at RB on the 6th of August (Figure 1). There would appear to have been no intermittent rises and falls in temperature up to this maximum, as exhibited in the previous two years. After an initial continuous rise through January, the next period of marked increase was late March to mid April, with a slight check into May followed by a steady increase to August. The warm period, however, was confined to August, for from mid September to the end of October there was a decrease of 10°C, although the infrequency of sampling at this time may well mask a more complex picture.

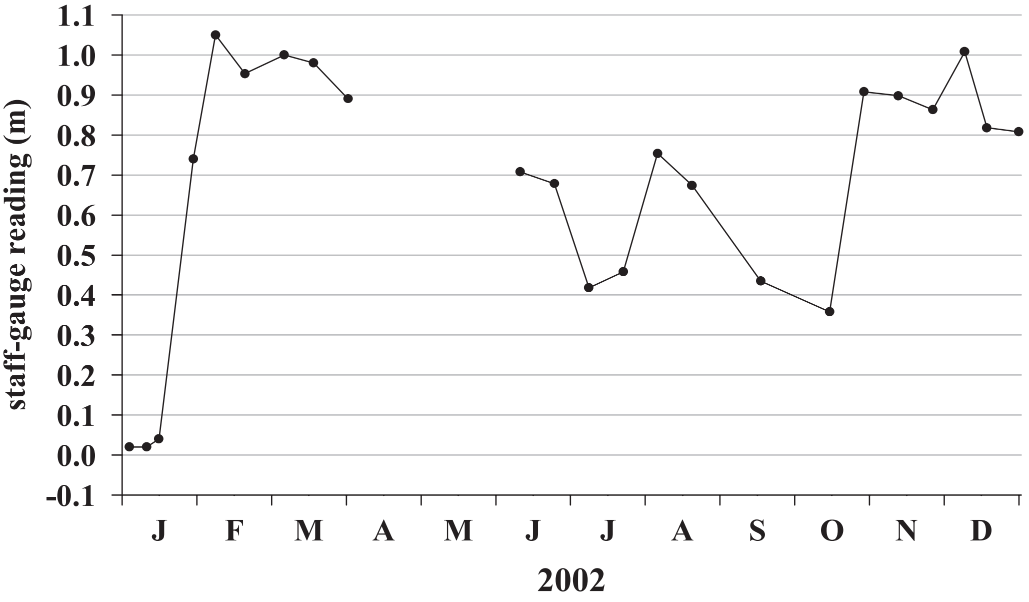
Figure 1 Spatial and temporal variation in surface water temperature



3.1.2 Water level

As in 2001, the water-level fluctuated by over 1m (ie approximately 25% of the mean depth of the loch) during 2002 (Figure 2). The outstanding feature of 2002 compared to the previous two years was the very low water level at the start of the year followed by a rise of just over 1m in a little over three weeks to the year's highest level in early February. This was followed by a more-or-less steady fall to mid October with the exception of an almost 0.30m rise in late July/early August. The measurement of the level, at the harbour, was disrupted for a time from April to early June, owing to construction work to enlarge the harbour basin, so any changes during this period went unrecorded, but visual appraisal at sampling visits suggested no major fluctuations. From mid to late October the level rose by over half a metre to a point that was maintained (with some minor variations) to the end of the year, so that the Loch finished the year some 80cm higher than it had started. The observed variations cannot be attributed solely to patterns of rainfall. The control on the water level exercised by the independently-controlled sluice gates at the outflow almost certainly had a major influence.

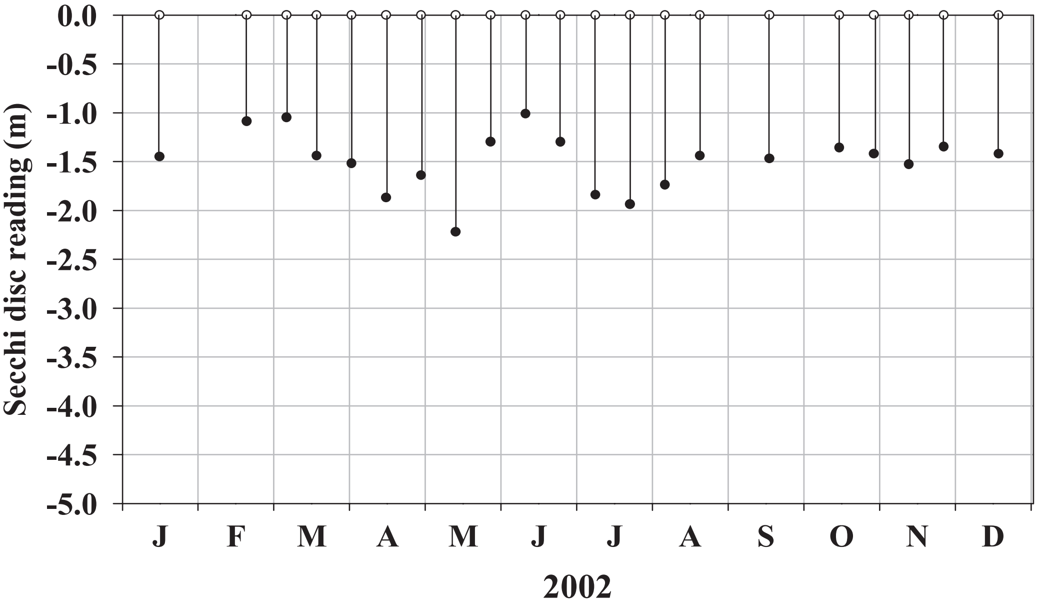
Figure 2 Water level fluctuation at the Harbour



3.1.3 Water clarity

The year was characterised by an overall deterioration in water clarity, and, in particular, the absence of a strong "clearwater" phase in May/June, which was observed in 2000 and 2001. Although the highest Secchi disc reading of 2002 was recorded on 14th May (2.35m at SD, 2.22m at RB), this was well short of the 4.55m at SD on 22nd May 2001, and was the only reading over 2m observed during 2002. The mean value for the year of 1.47m (based on monthly means rather than individual readings) was over half a metre less than the corresponding figure of 2.00m for the previous year.

Figure 3 Water clarity (expressed as Secchi disc transparency) at the Reed Bower sampling site

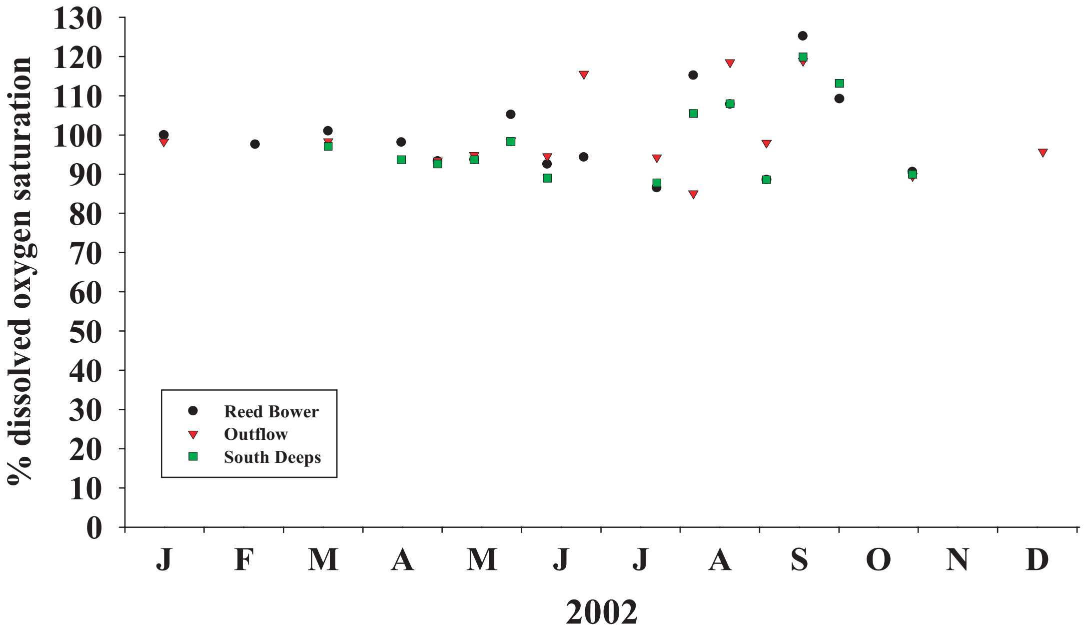


3.2 Chemical factors

3.2.1 Dissolved oxygen

Measurements of dissolved oxygen concentration and saturation were supplied by the Scottish Environment Protection Agency, the CEH D.O. probe having failed towards the end of 2001. The measurements suggest that the surface waters of the loch are well-supplied with oxygen, the mean readings being close to 100% saturation at ambient temperature at all three sites, with no reading less than 85% for the year.

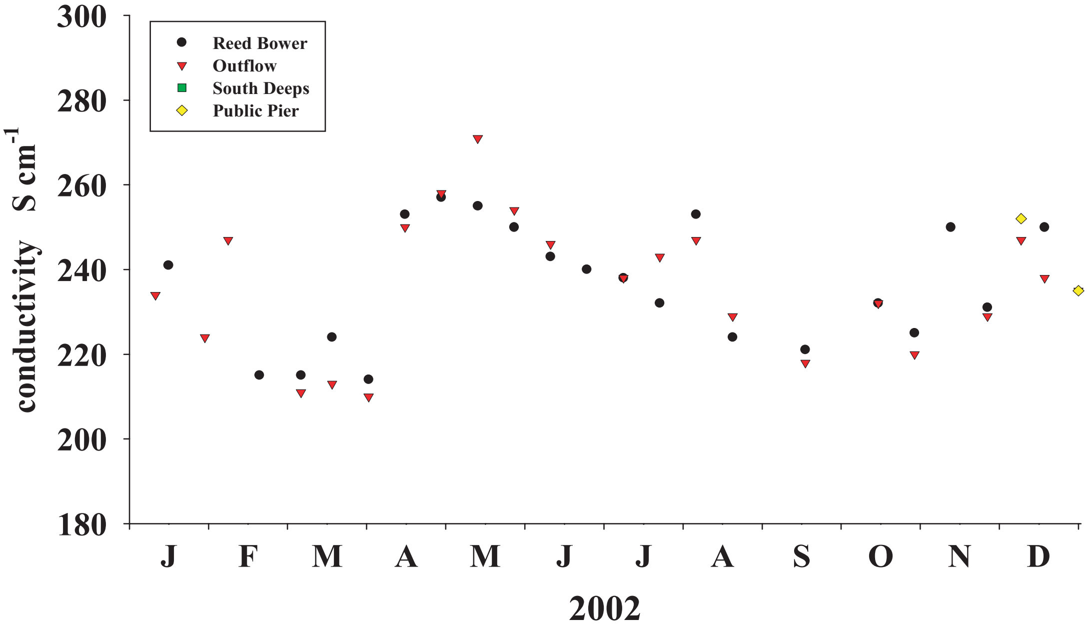
Figure 4 Dissolved oxygen saturation at ambient water temperatures (Source: SEPA)



3.2.2 Conductivity

The temperature-compensated conductivity values recorded at the four sampling sites are shown in Figure 5. The values ranged between 210μS cm^{-1}–271μS cm^{-1} and were typical for the loch.

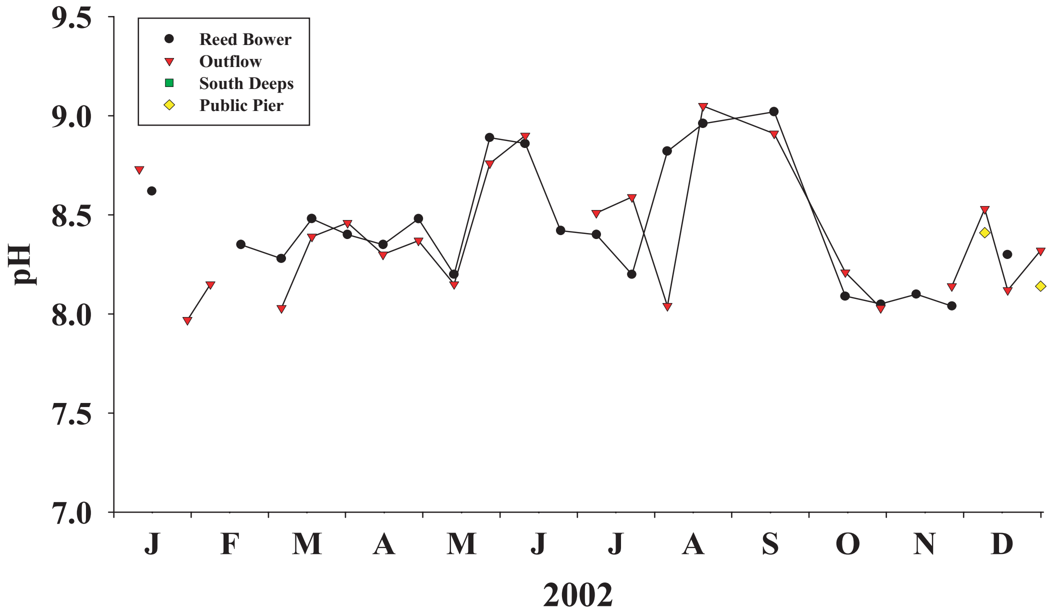
Figure 5 Electrical conductivity at ambient water temperature



3.2.3 pH

The range of pH values exhibited was fairly characteristic for the loch, ranging from just under pH 8 to just over pH 9, with the highest values being recorded during the short-lived and relatively insignificant surface aggregations of cyanobacteria observed in August and September.

Figure 6 Temporal and spatial variation in pH at ambient water temperature

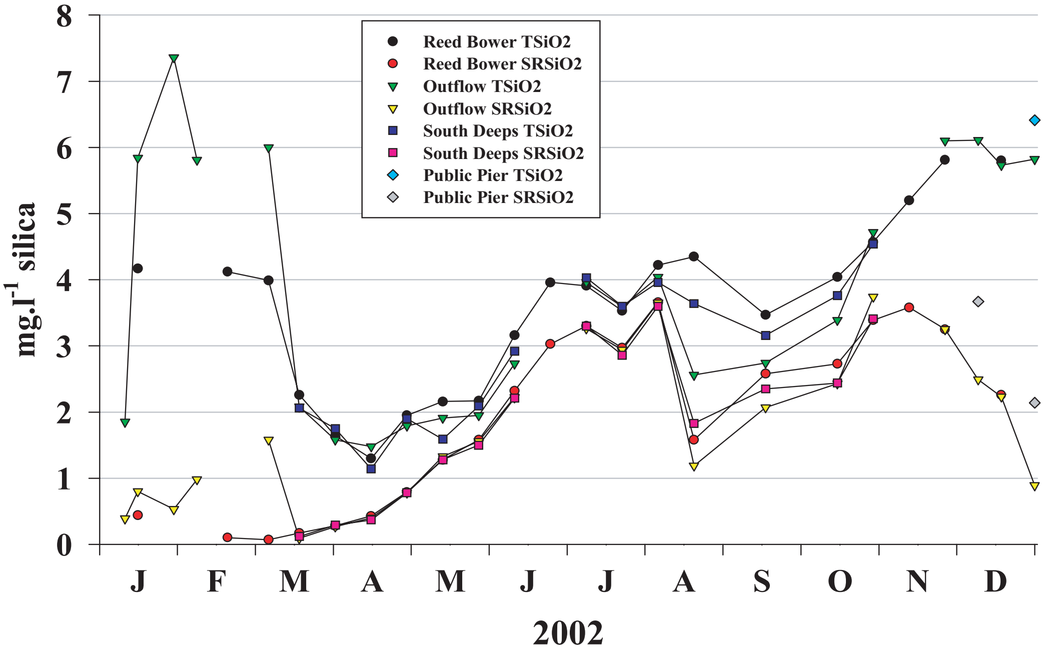


3.2.4 Total silica and soluble reactive silica

Silica, in the form of soluble reactive silica ($SRSiO_2$) is still generally the most abundant of the three main nutrients whose availability affects the abundance and species composition of the phytoplankton. This section examines temporal and spatial variations in both $SRSiO_2$ and total silica ($TSiO_2$), which, in this context, is taken as $SRSiO_2$ plus opaline (non-crystalline) silica. The latter is mainly incorporated in diatoms, but also occurs in scale-bearing chrysophytes, and is thus designated here as particulate silica ($PSiO_2$). As with concentrations of nitrate-N and phosphate-P, $SRSiO_2$ concentrations represent the instantaneously available nutrient resource that can, potentially, be taken up by the diatoms.

The last measured $SRSiO_2$ concentrations in 2001 of around $3mgl^{-1}$ (18th December) had shown a fairly dramatic decline to $0.4mgl^{-1}$ by the 10th January 2002 with concentrations in open water in particular staying well below $1mgl^{-1}$ until May, and indeed only starting to show an increase from mid-March. This period almost certainly coincided with a significant diatom population, as evidenced by open water $TSiO_2$ concentrations of around $4mgl^{-1}$, only declining to around $2mgl^{-1}$ in mid-March. The more erratic changes in concentrations observed at the outflow (L) are attributable to the relatively shallow water at that site, leading to wind-induced re-suspension of benthic material with the subsequent inclusion of episammic diatoms (non-planktonic, attached to sand grains) in the $TSiO_2$ analyses. The loch had frozen over in the first week of January 2002, and this would have lead to the sinking of diatoms out from the water column, owing to the relatively high density imparted by their silica frustule, coupled to the lack of wind-induced turbulence necessary to maintain them in suspension. This accounts for the decline in $TSiO_2$ concentration from over $5mgl^{-1}$ at the end of 2001 to under $2mgl^{-1}$ on 10th January 2002, at the outflow. The thawing of the loch by the sampling visit on 15th January would account for the dramatic rise in $TSiO_2$ concentration to just under $6mgl^{-1}$ at the outflow, at a time when the water level was still very low. Following the decline of the winter/early spring diatom population, the $SRSiO_2$ concentrations started to rise and, as in the previous year, reached a peak in early August. Microscopic analysis of the phytoplankton is required to account for the drop in $SRSiO_2$ coupled with the rise in $TSiO_2$ (and hence $PSiO_2$) witnessed in August – possibly indicating a short-lived increase in non-diatom silica-containing organisms. From early November, $SRSiO_2$ declined whilst $TSiO_2$ increased, indicating an increase in $PSiO_2$ and hence an increasing winter diatom population.

Figure 7 Spatial and temporal variation in concentrations of total silica ($TSiO_2$) and soluble reactive silica ($SRSiO_2$)



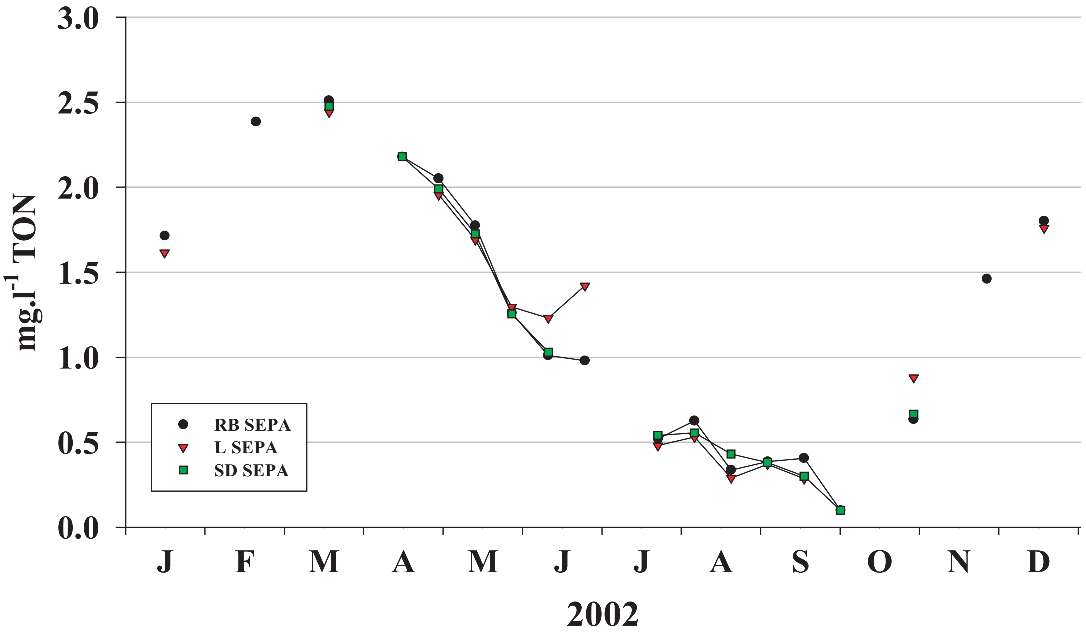
3.2.5 Total oxidised nitrogen

Patterns of change in the majority of physical and chemical factors can vary considerably from year to year. However, the seasonal pattern of change in NO_3-N/TON concentrations tends to be broadly similar each year – even if the concentration maxima and minima differ.

The concentrations depicted in Figure 8 are from data supplied by the Scottish Environment Protection Agency. Whilst the general trend in TON through the year followed the usual pattern of lower concentrations during the summer with higher concentrations at either end of the year (ie over winter), it is uncertain how much can be read into the exact timings of the maximum and minimum concentrations given that the analyses had been carried out by a different laboratory than for the previous two years.

Declines in TON concentrations are often associated with development of phytoplankton biomass. In shallow lakes, however, as outlined by Bailey-Watts and Kirika (2000), the timing and magnitude of the annual summer draw-down in nitrate also, in part, depends upon the temperature at the sediment water interface. In Loch Leven, this is usually very similar to that of the surface water. One reason nitrate draw-down accelerates with rising temperatures is due to enhanced bacterial de-nitrification and consequent reducing (anoxic) conditions at the sediment surface. This results in a lack of nitrate in the water column, which, together with reducing conditions, often triggers a release of soluble inorganic phosphorus from the sediments.

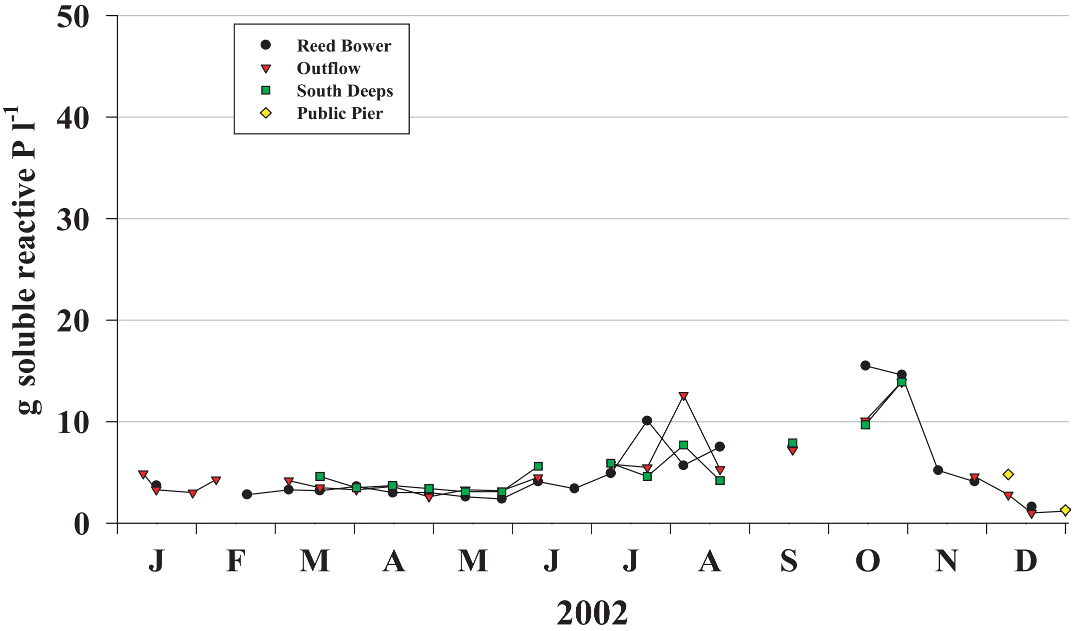
Figure 8 Temporal variation in concentrations of total oxidised nitrogen at the Reed Bower sampling site



3.2.6 Soluble reactive phosphorus

Soluble reactive phosphorus (SRP) concentrations remained fairly constant throughout the year, below 5μg P l^{-1} for most of the time, and only exceeding 10μg P l^{-1} on a few occasions in July/August and October (Figure 9). As in 2001, there appeared to be no major release from the sediments in late summer, or if there was, it was immediately sequestered by phytoplankton, benthic algae and macrophytes. Minimum concentration 1μg P l^{-1} maximum 16μg P l^{-1} mean 5μg P l^{-1}.

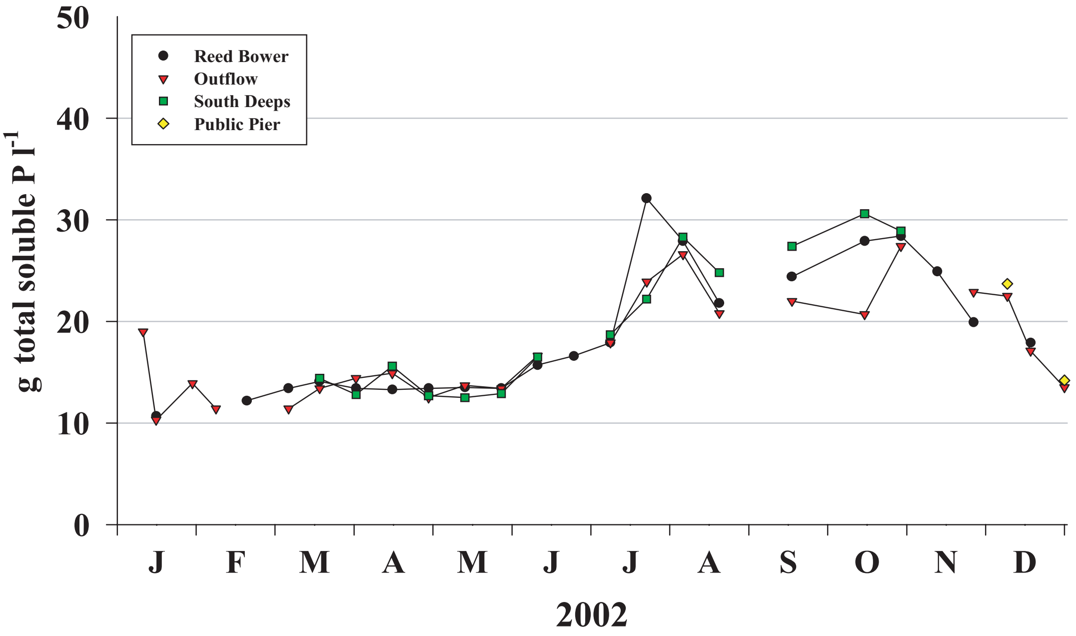
Figure 9 Spatial and temporal variations in concentrations of soluble reactive phosphorus



3.2.7 Total soluble phosphorus

The trends in total soluble phosphorus (TSP) concentration shown in Figure 10, largely parallel those of the soluble reactive component. However, whereas SRP levels fluctuated between 1μg P l^{-1} and 16μg P l^{-1} over the year, TSP levels varied between 11μg P l^{-1} and 32μg P l^{-1}, with a mean of 19μg P l^{-1}. There was, therefore, considerably more soluble organic P than inorganic P in the water column.

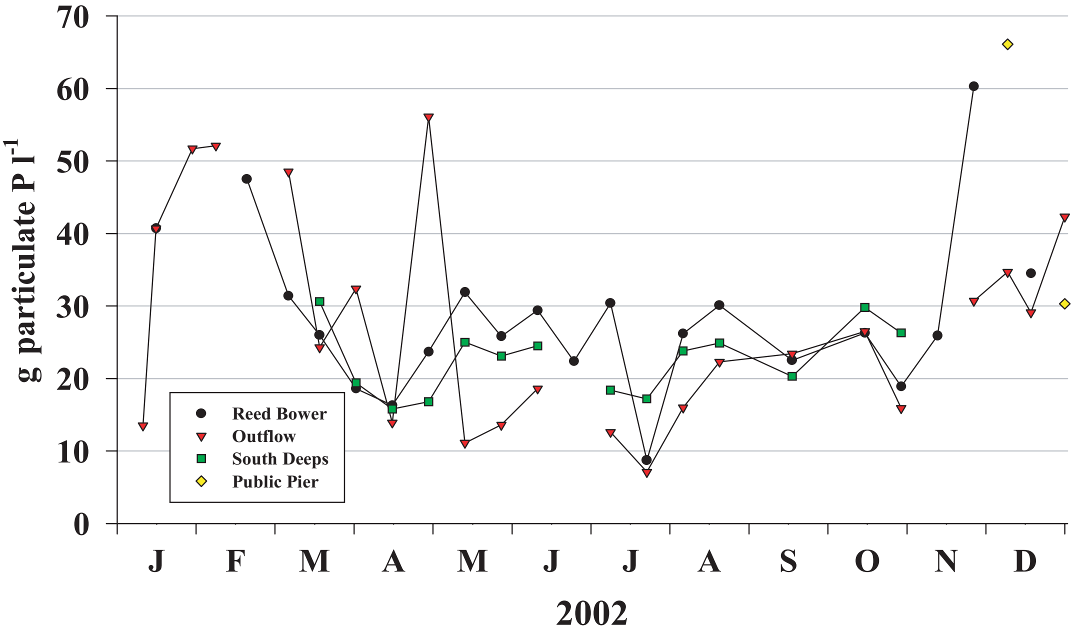
Figure 10 Temporal and spatial variation in concentrations of total soluble phosphorus



3.2.8 Particulate phosphorus

Variations in particulate phosphorus (PP) concentrations in 2002 are shown in Figure 11. The concentrations recorded reflect the phosphorus content of all phosphorus-containing particles in the water-column, including detritus, re-suspended sediments, algae and zooplankton. As a general rule, temporal patterns in PP concentrations follow those of chlorophyll$_a$ (compare Figures 11 and 13). The peaks in April (L) and November (RB) deserve comment owing to the nature of their origin. Such high concentrations of PP are usually caused by re-suspension of sediment, especially at the shallow outflow. In these two cases, however, the high PP concentrations are caused by a discrepancy between the subsamples, taken for analysis, from the field replicate samples. It appears that one of the replicate subsamples contained a large non-sediment-derived particle, possibly a zooplankter, thus increasing the PP concentration. This is borne out by comparing the replicate concentrations of the analyses for other sites sampled on the same day. If the enhanced PP concentrations were due to sediment re-suspension, then it would be expected that both of the field replicates and both of the analytical replicates would be more similar. This was indeed the case in early December when the samples collected at the Public Pier were considerably more turbid than those from the outflow, and there was little variation between the analytical replicates within each site.
Minimum concentration 9µg P l^{-1} maximum 52µg P l^{-1} mean 29µg P l^{-1}.

Figure 11 Temporal and spatial variation in levels of particulate phosphorus

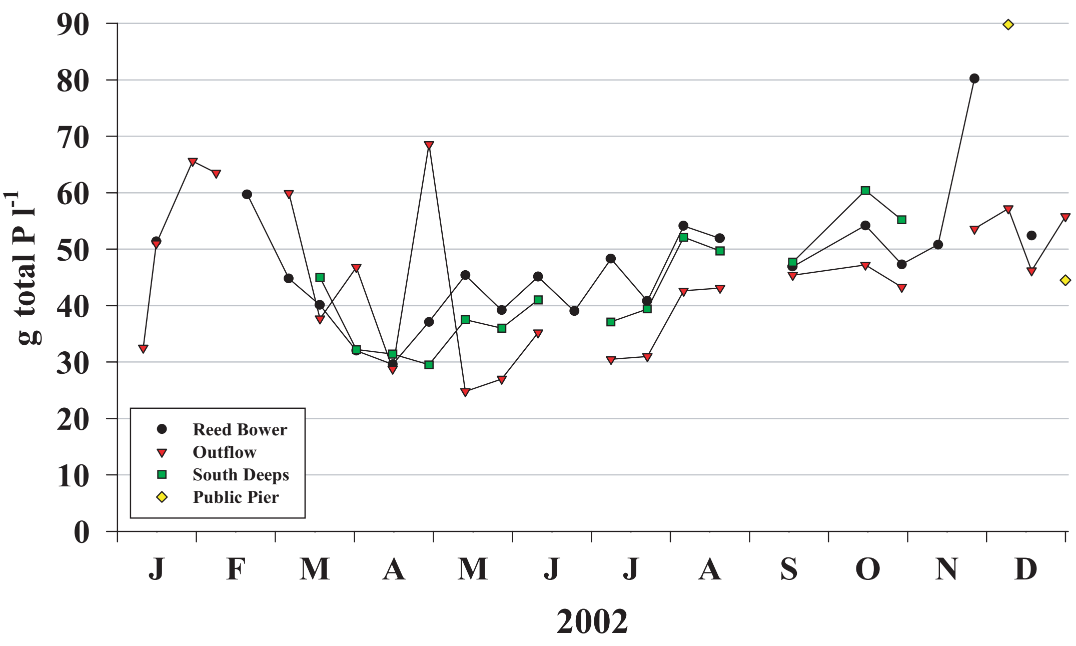


3.2.9 Total phosphorus

Total phosphorus (TP) concentrations provide a simple index of loch trophic status. The data for 2002 (Figure 12) yield minimum, mean and maximum concentrations of 30µg P l^{-1}, 48µg P l^{-1} and 66µg P l^{-1}, respectively (see previous section on particulate phosphorus for explanation of “spikes” on the graph).

The mean TP concentration recorded is higher than the target mean annual TP concentration of 40µg P l^{-1} set by the Loch Leven Area management Group (LLAMAG) in 1993 (LLAMAG 1993) and endorsed in the Loch Leven Management Plan (Loch Leven Catchment Management Project 1999). This suggests that the loch still has a little way to go in terms of recovery from eutrophication. The absence of any outflow (flushing) data, however, makes it impossible to say whether the observed TP levels were due to continuing inputs from the catchment or whether they occurred in response to increased P retention as a result of a particularly low flushing regime.

Figure 12 Temporal and spatial variation in concentrations of total phosphorus



3.3 Phytoplankton

3.3.1 Chlorophyll$_a$

The pattern of changes in phytoplankton biomass (estimated as chlorophyll$_a$ concentration) observed in 2002 was unusual in exhibiting four distinct peaks, in late January (83µgl^{-1} at L), early June (45µgl^{-1} at RB), late August (52µgl^{-1} at RB) and mid December (65µgl^{-1} at L). The peak concentration so early in the year was last manifest in 1999 (90µgl^{-1} at RB on 2nd February), a year that also saw poor water clarity throughout, with a maximum Secchi disc reading of 2.0m on the 6th of July, and an annual mean of 1.03m.

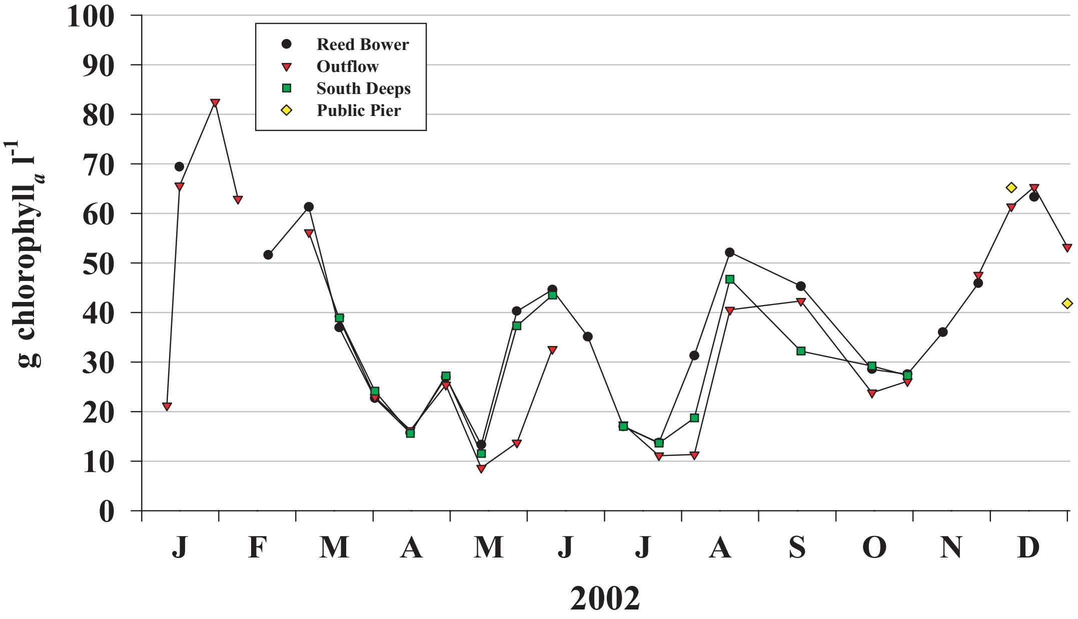
The chlorophyll$_a$ peaks at the beginning and end of 2002 can be attributed largely to populations of diatoms (Figure 15), the early "summer" peak to cyanobacteria (*Anabaena flos-aquae*) (Figures 15 and 16) and the late summer peak a mixture of diatoms and cyanobacteria contain more diverse phytoplankton assemblages.

Maximum, minimum and annual mean concentrations in open water (RB) were 69 (January 15th), 13 (May 14th) and 40µgl^{-1} respectively.

3.3.2 Phytoplankton composition

Some 53 taxa of phytoplankton were recorded in Loch Leven during the analysis of 23 samples collected from Loch Leven during 2002. In terms of cell/colony/filament densities, the phytoplankton was dominated by diatoms (Bacillariophyta), peaking in spring and late-autumn/winter and cyanobacteria dominant during summer (Figure 14). Small Cryptophyta and Chlorophyta were present in relatively smaller amounts throughout the year.

Figure 13 Temporal and spatial variation in chlorophyll$_a$ concentration



In terms of biovolume, which takes into account cell, filament or colony size, a similar pattern was evident, although more in agreement with chlorophyll$_a$ concentrations (Figure 15). The main difference between cell numbers (Figure 14) and biovolume (Figure 15) was during late summer when the abundance of cyanobacteria was largely due to small-celled Chroococcales, which in biovolume terms contributed relatively little. Apart from early summer, the phytoplankton biovolume was dominated by diatoms.

The majority of the algal numbers or biovolume throughout the year was accounted for by six phytoplankton taxa (Figure 16).

The diatom genus *Aulacoseira* was the most dominant taxon throughout most of the year, reaching peak biovolume in February and March (Figure 16). It declined in abundance through March associated with silica depletion and was absent through most of summer (small peak in August). An assemblage of centric diatoms, comprising mainly *Stephanodiscus* and *Cyclotella* species, was also abundant from autumn into winter. Unlike 2001, *Asterionella formosa* Hassall did not attain significant biomass in 2002.

Six species of blue-green algae (cyanobacteria) were recorded during the year, but only *Anabaena flos-aquae* was of any note, reaching a peak of approximately 5500 filaments ml^{-1} or 70,000 cells ml^{-1} in June. This was significantly greater growth than in 2001. Following revised Scottish Executive guidance on blue-green algae in inland waters (Scottish Executive Health Department, 2002), cyanobacteria densities warranting the display of notices warning of toxic algae were only necessary from late May to the end of June. Cyanobacteria, however, persisted sufficiently through to September that it would probably be advisable to maintain warning notices throughout summer.

The Cryptophytes *Rhodomonas minuta* and a group of *Cryptomonas* species were present throughout the year, but not significant amounts in terms of biovolume.

Figure 14 Temporal variation in phytoplankton groups (numbers per ml)

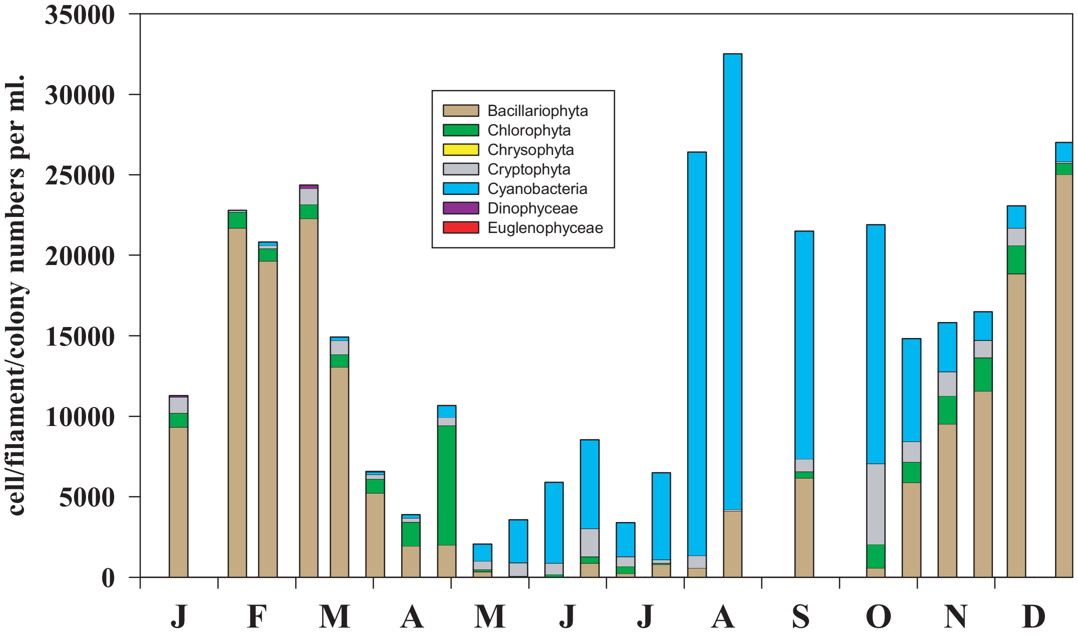


Figure 15 Temporal variation in phytoplankton biomass (biovolume and chlorophyll$_a$)

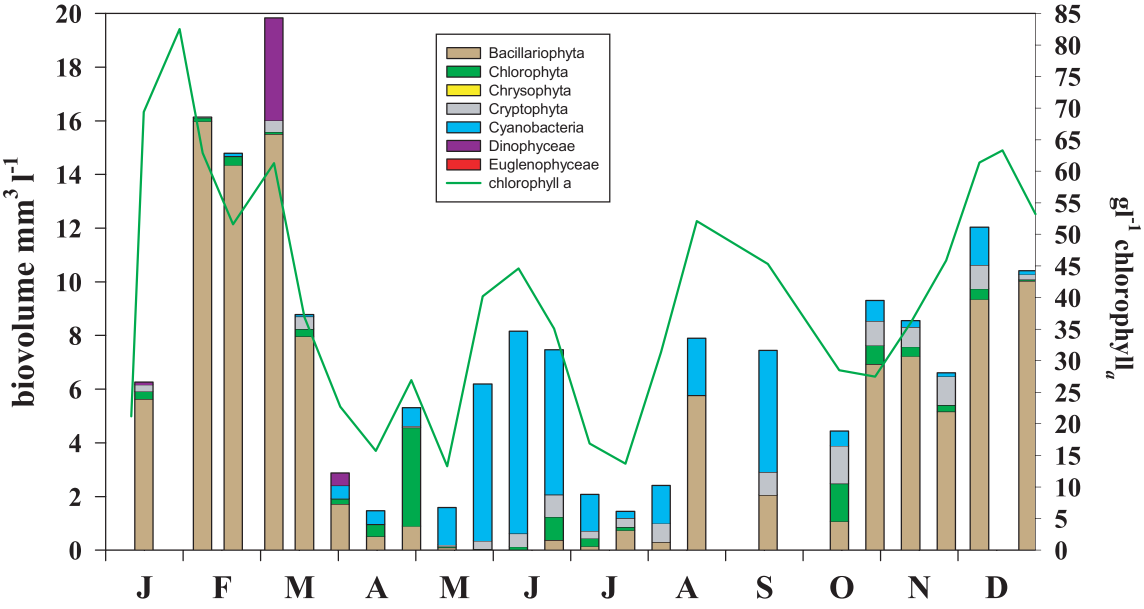
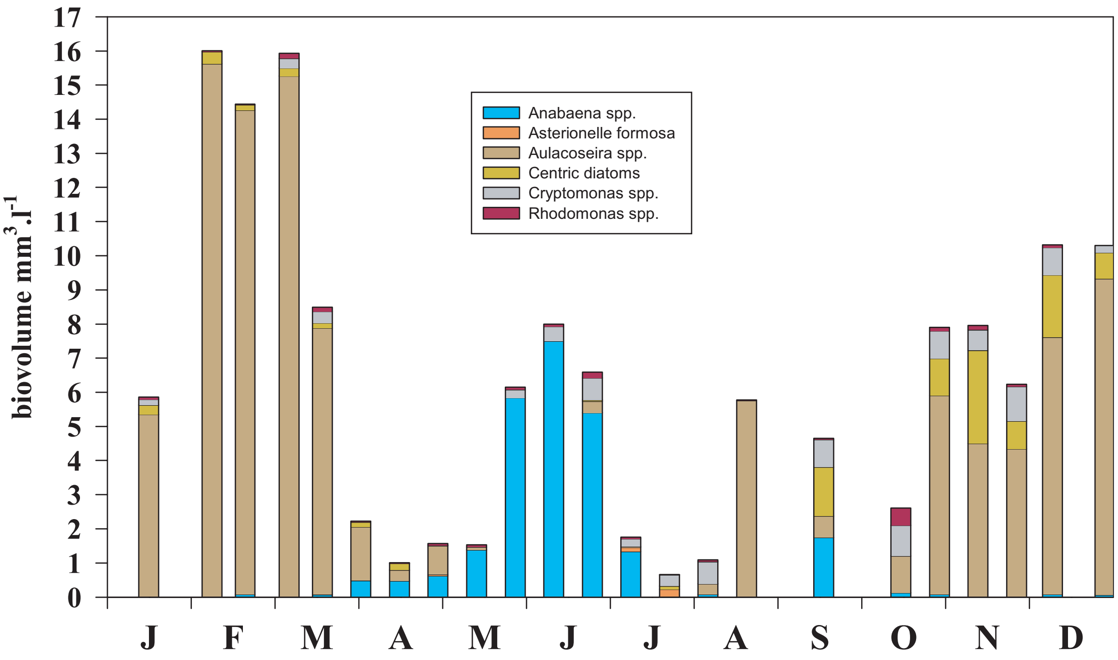


Figure 16 Temporal variation in dominant phytoplankton taxa (biovolume)



4 DISCUSSION

In general, the data suggests that 2002 does not show further evidence for recovery. On the contrary, there is a clear deterioration in two of the three key water quality indicators. The most marked difference from the previous two years was the generally poorer water clarity, most notably over the period of May and June. The mean Secchi disc reading of 2002 was 1.47m compared with 2.00m and 1.71m for the preceding two years.

Phytoplankton crops in Loch Leven also showed an overall increase in 2002 compared with the previous year (annual mean chlorophyll$_a$ concentration of 40μgl^{-1} compared with a mean of 24.5μgl^{-1} for 2001). Despite this, the annual mean total phosphorus (TP) concentration of 48μgl^{-1} was unchanged from the previous year. Cyanobacteria were also more abundant in 2002, although diatoms remained the dominant phytoplankton group throughout much of the year.

The scale of deterioration can only be considered by putting data from 2002 in context with previous years monitoring results (Table 1). Despite the apparent deterioration compared with the previous two years, the comparison shows that 2002 was fairly typical of mean conditions over the past five years and a considerable improvement compared with the first five years of regular monitoring at the site (1968–1972). The greatest threat to the loch's ecology and water quality in general appears to be the poor water clarity. Water clarity was poor throughout 2002, with no strong spring clear-water phase, despite the clear reductions in phytoplankton abundance during spring months. Reasons for this need to be investigated further. Wind re-suspension and the timing of water level changes could all be important.

Chlorophyll and TP concentrations exceeded the respective statutory target concentrations of 15μgl^{-1} and 40μgl^{-1} set by the Loch Leven Area Management Group (LLAMAG) in 1993 (LLAMAG 1993) and endorsed in the Loch Leven Management Plan (Loch Leven Catchment Management Project 1999), highlighting a need for continued vigilance and further lake and catchment management at the site.

Table 1 Water quality indicators: comparison of current year with previous periods

Period		**mean TP**	**mean chl.a**	**mean SDR**
Current year	(2002)	48	40	1.47
Previous 2 years	(2000–2001)	52	32	1.90
Previous 5 years	(1997–2001)	59	40	1.49
First 5 years	(1968–1972)	78	77	1.12
All years	(1968–2002)	68 (25 years)	46 (32 years)	1.50 (23 years)

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