Loch Leven 2003: physical, chemical and algal aspects of water quality

Report to Scottish Natural Heritage

Laurence Carvalho and Alex Kirika

Centre for Ecology and Hydrology
Edinburgh Laboratory, Bush Estate, Penicuik
Midlothian EH26 OQB, Scotland, UK
Telephone 031 445 4343; Fax 031 445 3943

Date: 19 October 2005

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Final Report to Scottish Natural Heritage

Laurence Carvalho and Alex Kirika, Centre for Ecology & Hydrology

SUMMARY

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 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 water quality parameters are presented and considered in relation to long-term trends and established restoration targets.

MAIN FINDINGS

The 2003 monitoring data reveals clear evidence of a deterioration in water quality in comparison with previous years. Overall, phytoplankton abundance showed only a slight increase in 2003 compared with the previous year, with an annual mean chlorophyll$_a$ concentration of around 40 µg l^{-1}. The annual mean total phosphorus (TP) concentration, however, showed an increase to 68 µg l^{-1} from 49-50 µg l^{-1} for the previous two years. Chlorophyll and TP concentrations both exceeded the respective statutory target concentrations of 15 µg l^{-1} and 40 µg l^{-1} set by the Loch Leven Area Management Advisory Group. Water clarity was also very poor in 2003 with an annual mean Secchi disc depth of 1.33 m compared with 1.71 m, 2.00 m and 1.47 m in 2000, 2001 and 2002 respectively and the 30-year average (1.58 m), providing further supporting evidence that recovery of Loch Leven is not being sustained, and in fact water quality appears to have deteriorated again. Analysis of phytoplankton samples revealed the dominance of diatoms throughout much of the year, although cyanobacteria (blue-green algae) dominated periods of spring and autumn and remained relatively abundant until December.

A combination of enhanced sediment re-suspension and increased nutrient loading are suggested as being responsible for the deterioration observed in 2003. This is worrying evidence against recent opinion that a sustained recovery associated with reduced internal nutrient loading was establishing at Loch Leven.

There is clearly a need for continued lake and catchment management at Loch Leven to further the ecological recovery and to reduce the large inter-annual variability in water quality observed at the site. Despite the large reductions in external phosphorus loadings that have been achieved so far, current loadings do not yet appear to be delivering nutrient concentrations sufficiently low enough to stabilise internal loading and enhance coverage of macrophyte beds. The monitoring also indicates that nitrogen is more likely to be limiting phytoplankton crops during summer as concentrations are consistently below detection limits from July to October, whilst reactive phosphorus concentrations remain relatively available. Catchment management should, therefore, aim to identify and reduce significant sources of nitrogen, as well as phosphorus.

For further information on this project contact:
Richard Cooper, SNH, Battleby, Redgorton, Perth, PH1 3EW. Tel.no: 01738 444177
For further information on the SNH Research & Technical Support Programme contact: The Co-ordination group; Advisory Services, 2 Anderson Place, Edinburgh. Tel: 0131 446 2400

1 INTRODUCTION

Loch Leven is the largest naturally 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 external loadings of phosphorus to the loch from its catchment (Bailey-Watts and Kirika 1999; Loch Leven Catchment Management Project 1999).

2 METHODS

During 2003, water samples were collected at least at monthly and generally at fortnightly intervals. This amounted to a total of 20 sampling visits. Four sampling sites on the loch were used. The most representative sampling location was a site to the south of Reed Bower (site 'RB').. Here, the water depth is similar to that often cited as the mean depth of the loch, i.e. 3.9m. On one occasion (19th August), when the weather was too rough for open-water sampling to take place, a site at the Public Pier (PP) in the Kirkgate Park was used instead of the RB site. 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.

A number of physical and chemical variables (surface water temperature, water level and clarity, dissolved oxygen content, conductivity, pH, silica, nitrogen and phosphorus) were measured on each sampling occasion. Field sampling and laboratory analyses followed the methods adopted over the past 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 0.25 m above the sediment surface. As a result of fluctuations in water level brought about by the control of the outflow, sample depths varied from 3.0 to 3.5 metres.

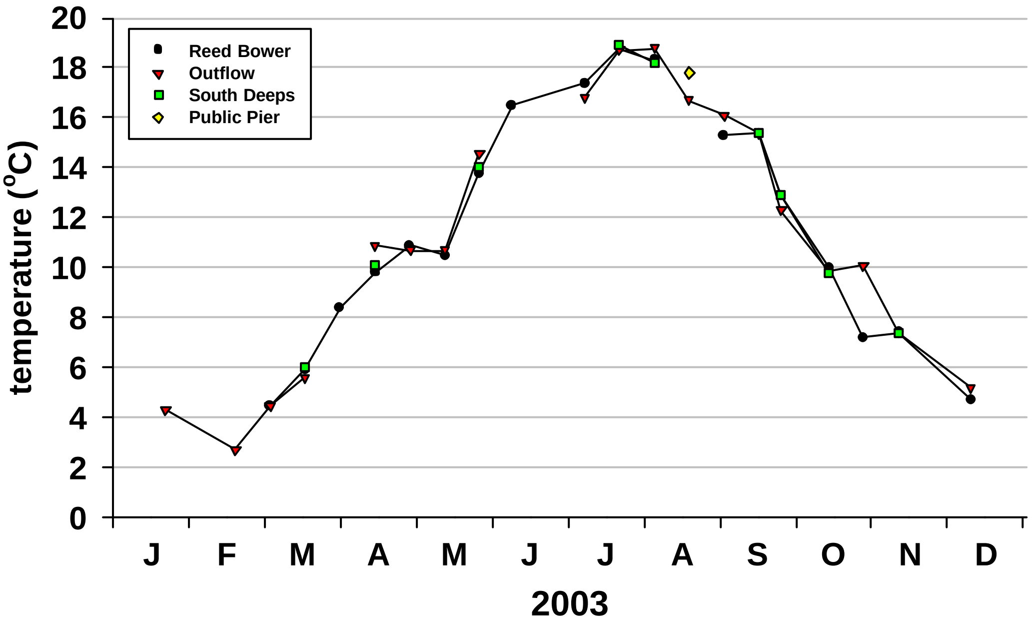
3 RESULTS

3.1 Physical factors

3.1.1 *Water temperature*

Variation in surface water temperature followed a generally simple pattern over the year, with a maximum of 18.9 ^{o}C being recorded at SD on the 5th of August (Figure 1). Once extensive ice-cover (encountered on the 18th of February) had cleared, there was a straightforward rise to 10 ^{o}C by mid April, this figure being reached almost one month earlier than in the previous year. The water then remained at 10-11 ^{o}C for about a month, before resuming a steady increase to the maximum temperature recorded. In general, the loch appeared to retain its heat for longer in 2003 than 2002, cooling to 6 °C only at the end of November 2003, compared to the end of October in 2002 and 2001.

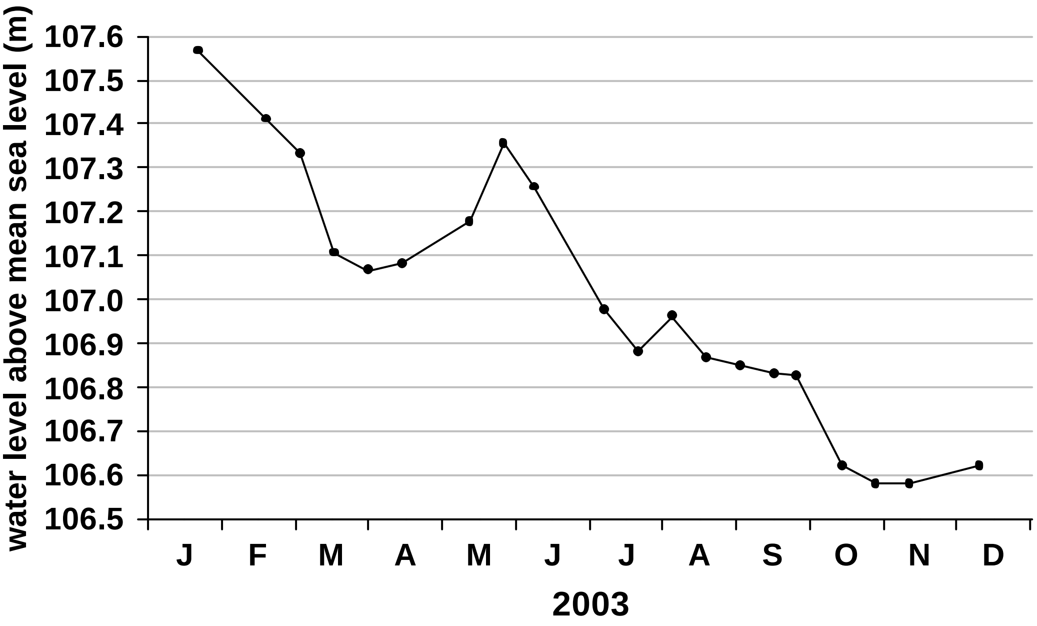
Figure 1 Spatial and temporal variation in surface water temperature



3.1.2 *Water level*

With the exception of a rise and fall of around 30cm between mid April and late June, the water level fell almost continually throughout 2003. By December, the water level was almost 1m lower than that recorded in January (i.e. approximately 25% of the mean depth of the loch, Figure 2). This is partly a result of the control exercised by the operation of the sluice-gates at the outflow.

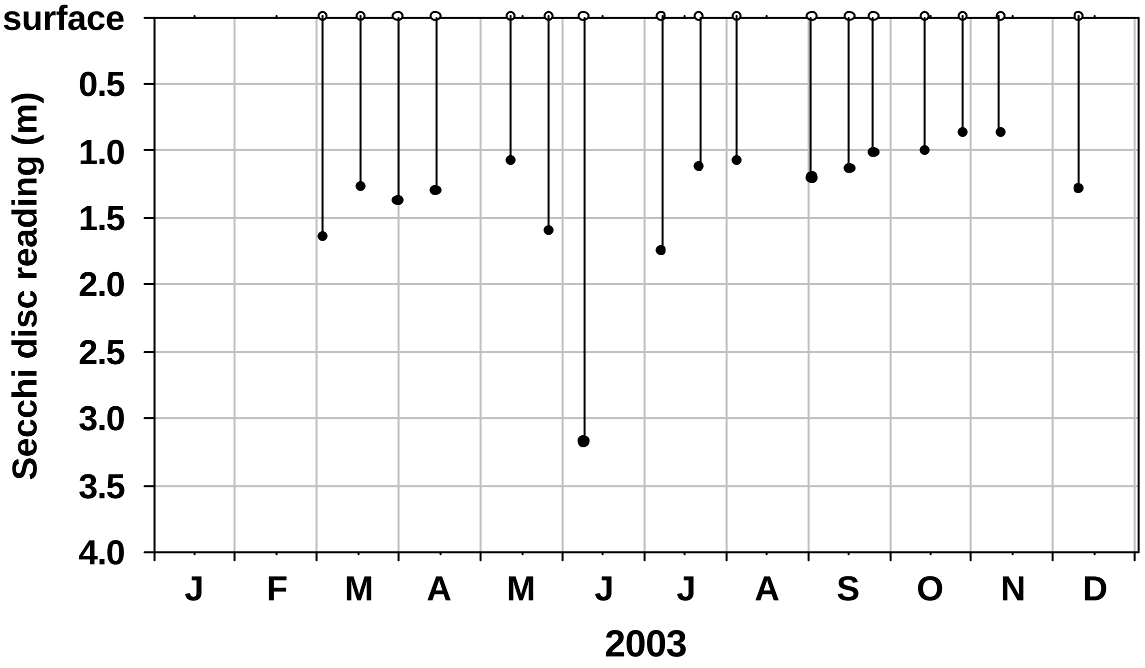
Figure 2 Water level fluctuation at the Harbour



3.1.3 *Water clarity*

With the exception of a single, brief “clearwater” phase in early June (i.e. Secchi disc reading of 3.17 m on the 9th of June 2003), the overall picture is one of reduced water clarity in 2003 in comparison with values recorded in 2002. The annual mean figure for 2003 was 1.33 m (*c.f.* 1.47 m in 2002). The period from late July through to December was characterised by consistently low values of around one metre, compared to around 1.5 m in 2002.

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

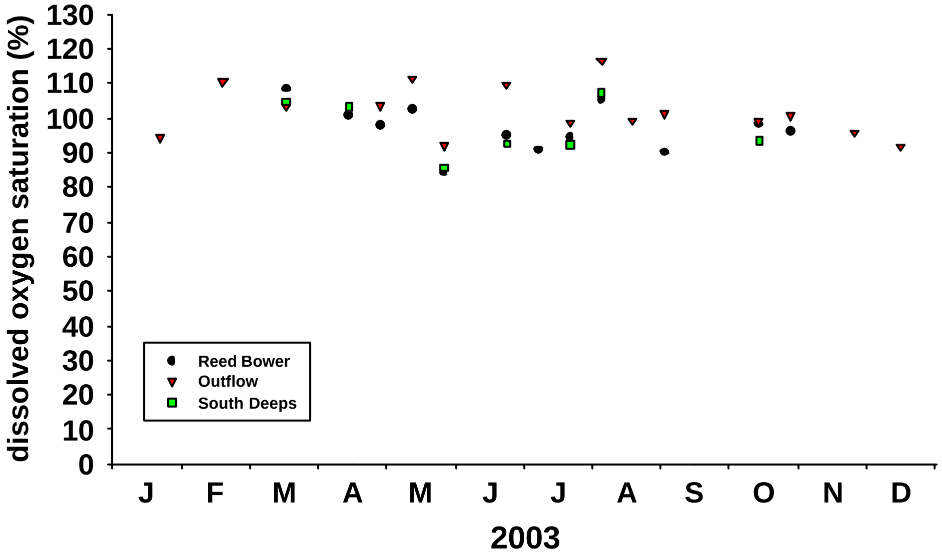


3.2 Chemical factors

3.2.1 *Dissolved oxygen*

Measurements of dissolved oxygen (D.O.) concentration and saturation were supplied by the Scottish Environment Protection Agency. The values suggest that, as in previous years, the surface waters of the loch are well-supplied with oxygen, with mean readings close to 100% saturation at all three sites. The lowest saturation reading was 85%, in late May.

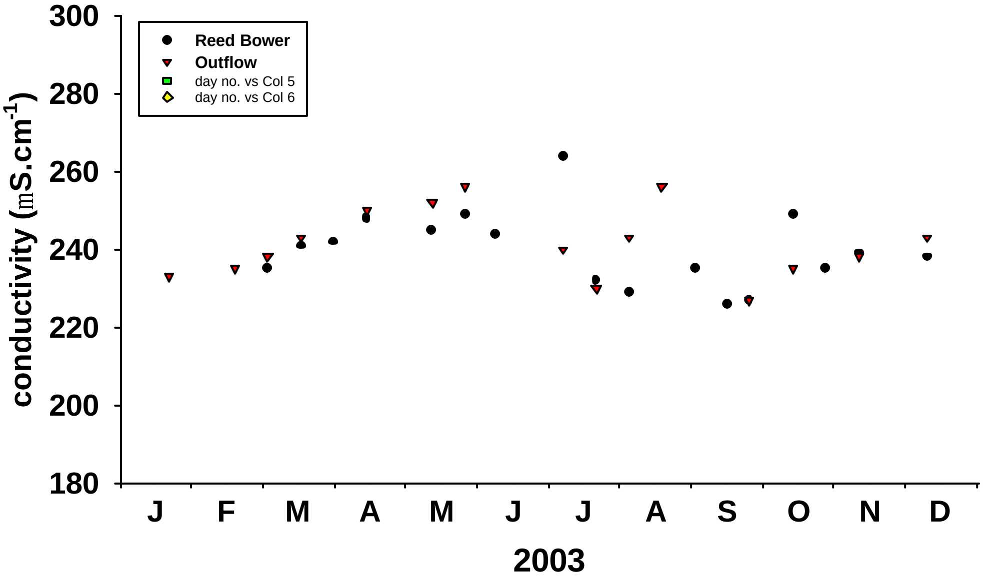
Figure 4 Dissolved oxygen saturation at ambient water temperatures (Source: SEPA)



3.2.2 *Conductivity*

The conductivity values recorded at two sampling sites are shown in Figure 5. The values ranged between 226 µS cm^{-1} to 264µS cm^{-1} and were typical for the loch.

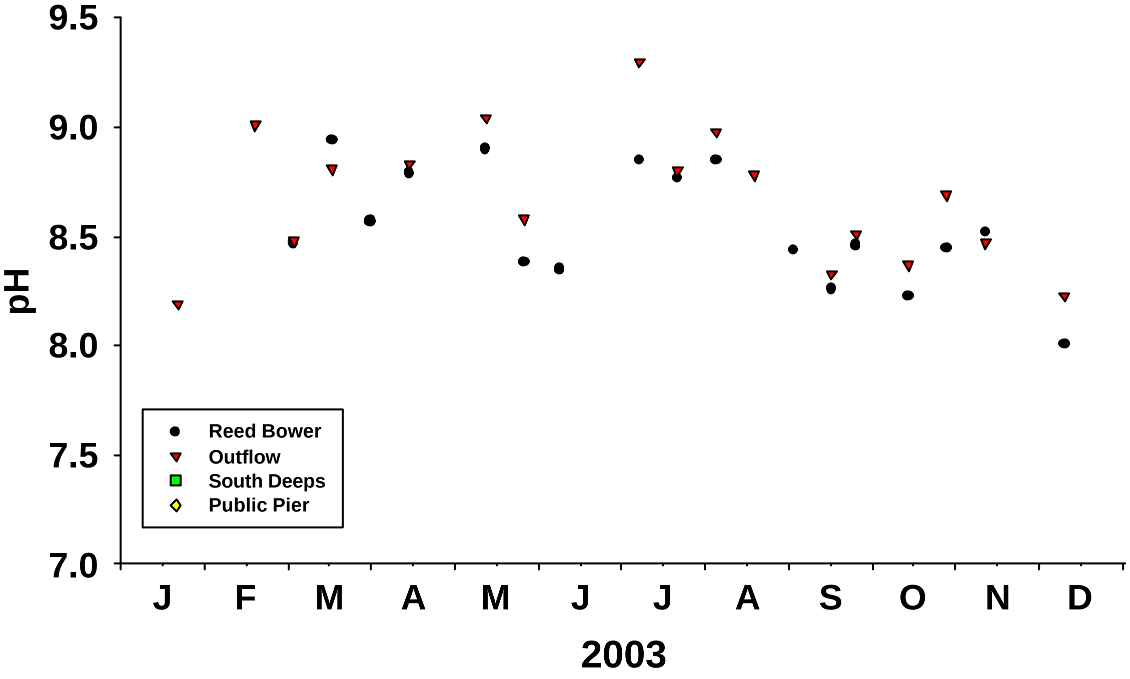
Figure 5 Electrical conductivity at ambient water temperature



3.2.3 *pH*

The range of pH values exhibited was fairly characteristic for the loch, ranging from just over pH 8 to pH 9.3.

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

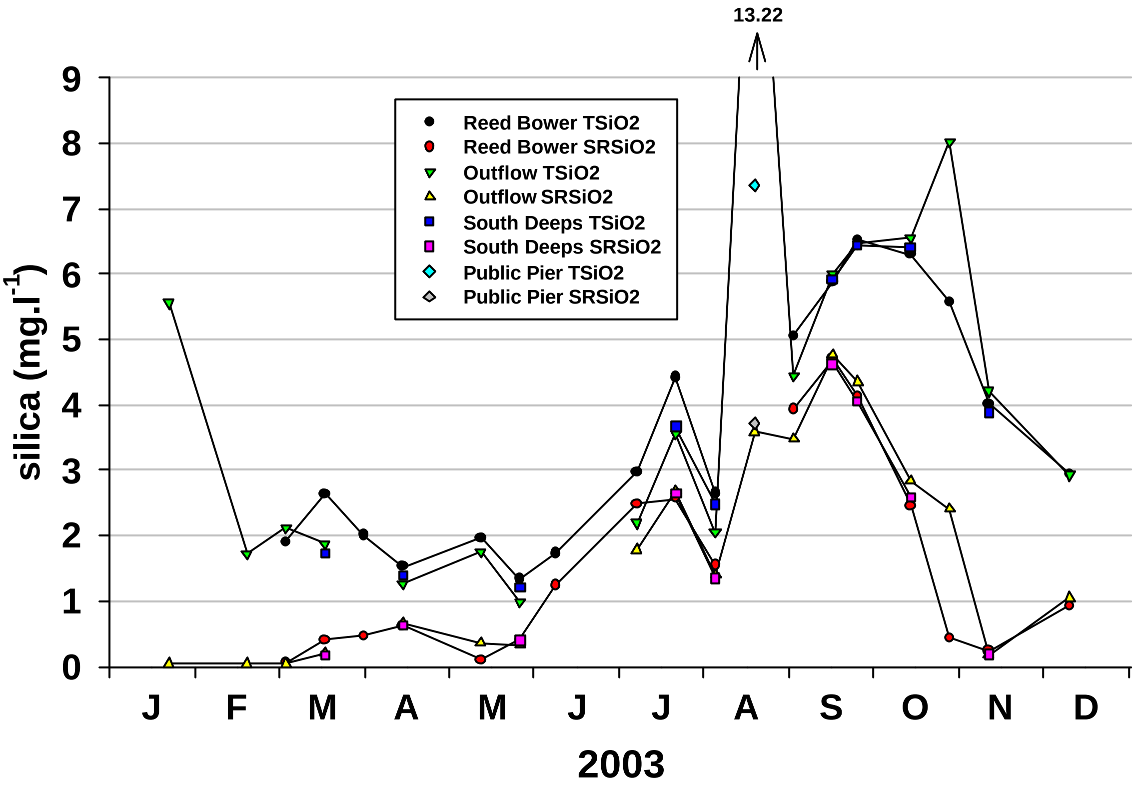


3.2.4 *Total silica and soluble reactive silica*

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. Figure 7 shows the 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. $SRSiO_2$ concentrations represent the instantaneously available nutrient resource that can, potentially, be taken up by the diatoms.

The decline in $SRSiO_2$ witnessed towards the end of 2002, from over 3 mg l^{-1} in early November to virtually nothing by mid January 2003, combined with a corresponding increase in $TSiO_2$, is evidence of uptake by the diatom population over this period. The subsequent sharp decline in $TSiO_2$ in early 2003, from over 5 mg l^{-1} in mid January to less than 2 mg l^{-1} by mid February, was probably due to the loch freezing over. This allowed the diatoms to settle out of the water column in the calm waters beneath the ice and limited the usual spring increase in diatom abundance. The usual annual increase in $SRSiO_2$ occurred from March onwards, reaching almost 5 mg l^{-1} by mid September. With the exception of a single, massive, turbulence-induced spike in $TSiO_2$ (caused by re-suspension of benthic material) on the 19th of August, the second main phase of (planktonic) diatom growth began in mid September, resulting in a more rapid subsequent decline in $SRSiO_2$ levels than was seen in 2002.

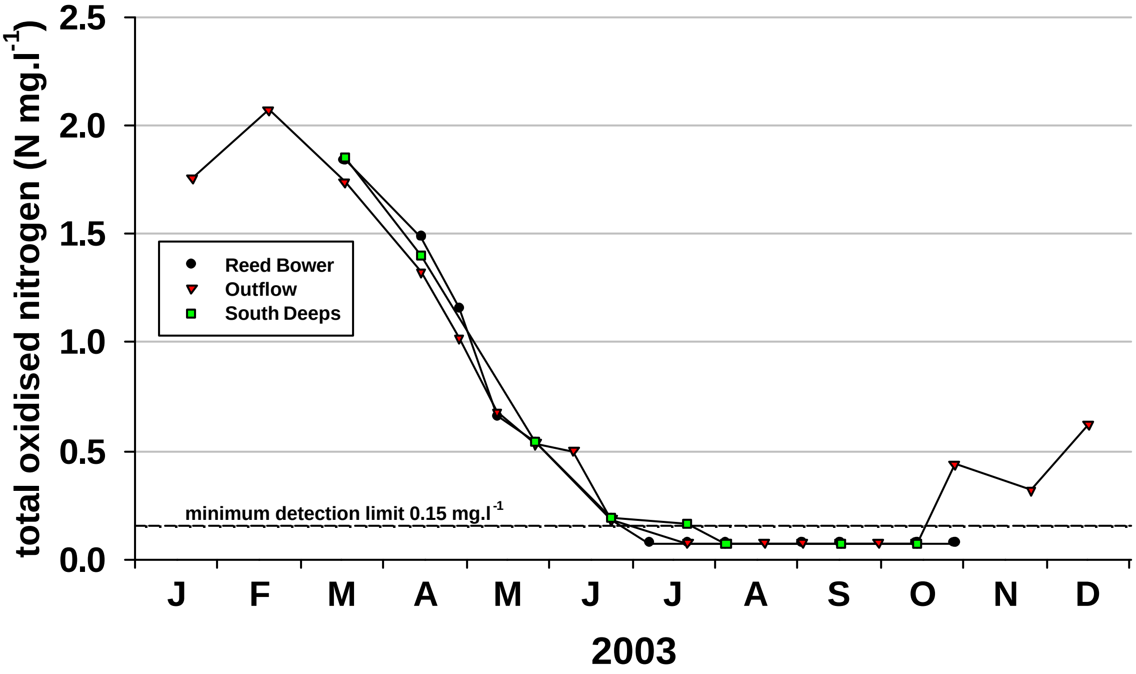
Figure 7 Spatial and temporal variation in concentrations of total silica ($TSiO_2$) and soluble reactive silica ($SRSiO_2$)



3.2.5 *Total oxidised nitrogen (TON)*

Patterns of change in the majority of physical and chemical parameters can vary considerably from year to year. However, the seasonal pattern of change in TON (nitrate and nitrite) concentrations tends to be broadly similar each year - even if the concentration maxima and minima differ – with the higher winter concentration declining to almost zero by midsummer before rising again during autumn and the onset of winter. There was a more rapid decrease in TON in 2003 compared with 2002, reaching the limit of detectability (0.15 mg l^{-1}) by late June, with a subsequent slower and less marked recovery from late October.

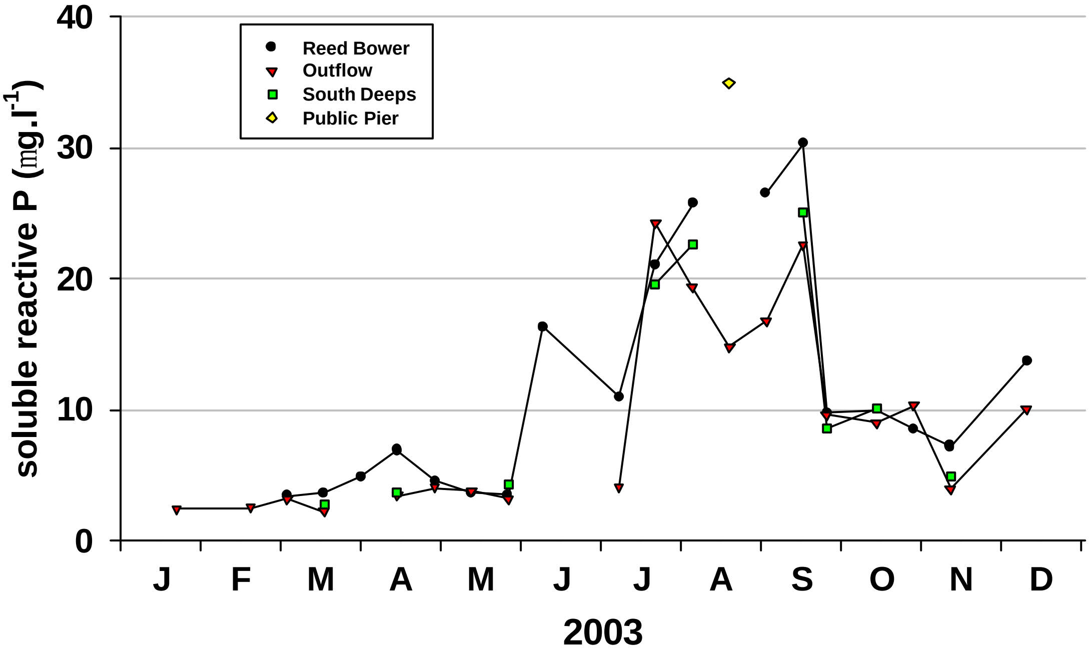
Figure 8 Temporal variation in concentrations of total oxidised nitrogen at the Reed Bower sampling site (Source: SEPA)



3.2.6 *Soluble reactive phosphorus*

Soluble reactive phosphorus (SRP) concentrations (Figure 9) showed a major increase during the summer to a maximum of 30 µg P l^{-1} in mid September at Reed Bower.. This large increase was the primary reason for the much higher annual mean in 2003 compared with 2002. This increase was most likely caused by release from the sediments, and much of it appears to have been relatively rapidly sequestered by phytoplankton, benthic algae and macrophytes. The minimum measured concentration was 3 µg P l^{-1}, the maximum was 30 µg P l^{-1}, and the annual mean was 12 µg P l^{-1}.

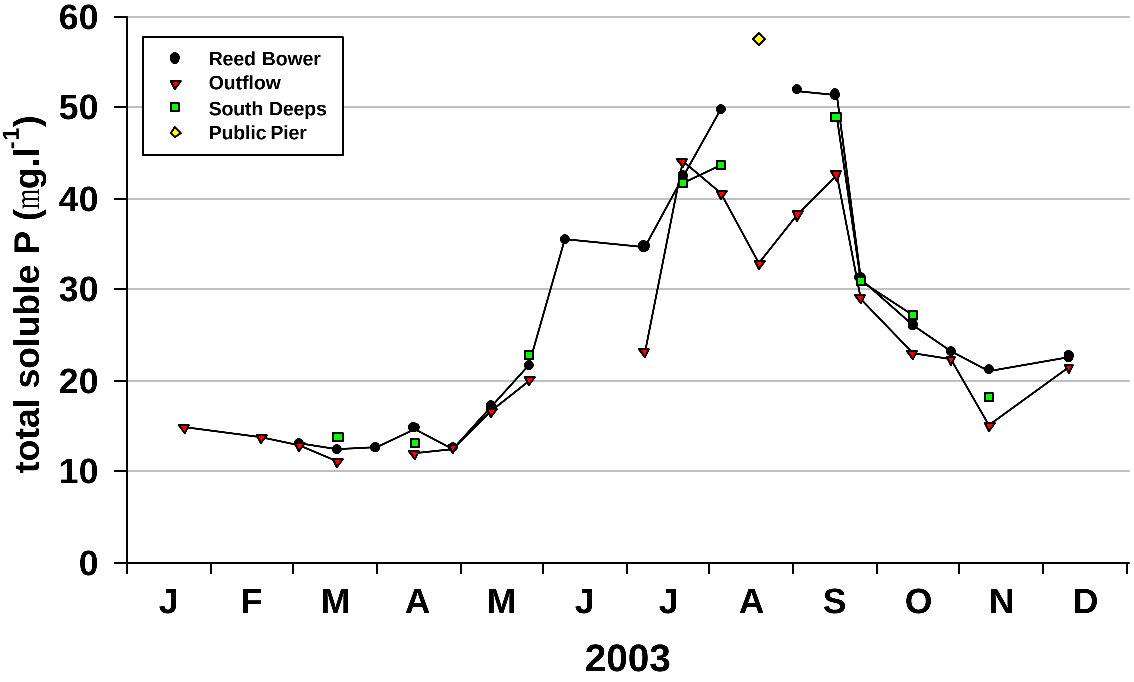
Figure 9 Spatial and temporal variations in concentrations of soluble reactive phosphorus



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 3 µg P l^{-1} and 30 µg P l^{-1} over the year with an annual mean of 12 µg P l^{-1}, TSP levels varied between 12 µg P l^{-1} and 58 µg P l^{-1}, with an annual mean of 27 µg P l^{-1}. There was, therefore, more soluble un-reactive (organic?) P than inorganic P in the water column.

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

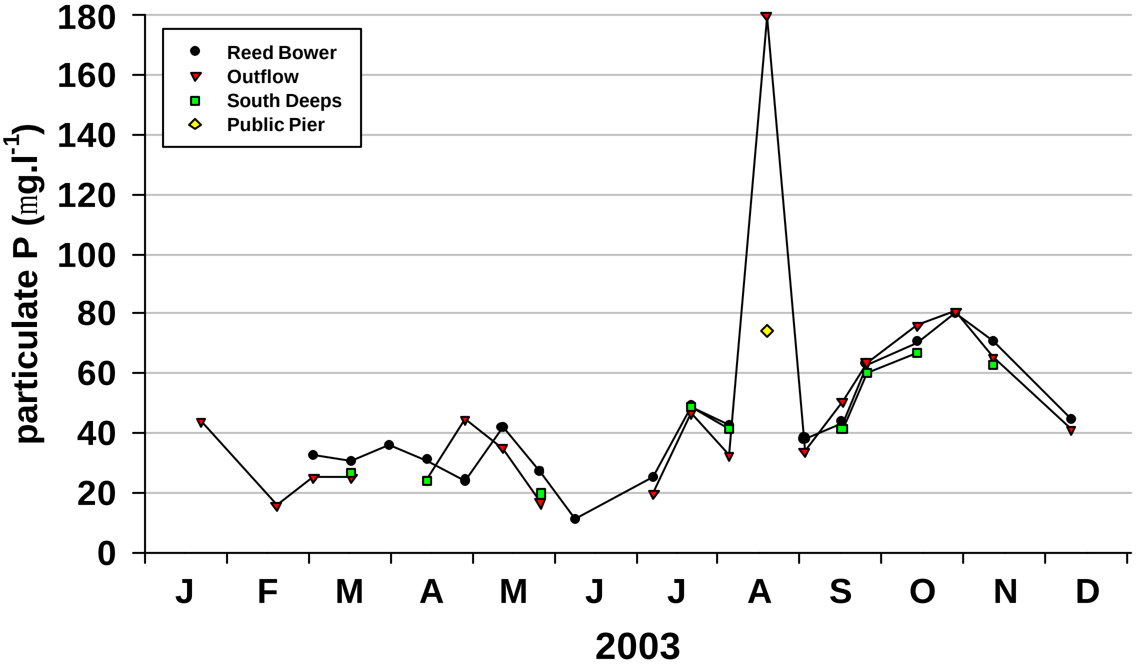


3.2.8 *Particulate phosphorus*

Variations in particulate phosphorus (PP) concentrations in 2003 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. Even allowing for the massive spike in August (caused by re-suspended benthic material), there appears to be a distinctly increasing trend from early June through to late October, which coincides with the trend in chlorophyll$_a$ shown in Figure 13, and hence with the growth of phytoplankton.

The minimum measured concentration was 11 µg P l^{-1}, the maximum (open-water) concentration was 80 µg P l^{-1}, and the annual mean was 42 µg P l^{-1}.

Figure 11 Temporal and spatial variation in levels of particulate phosphorus

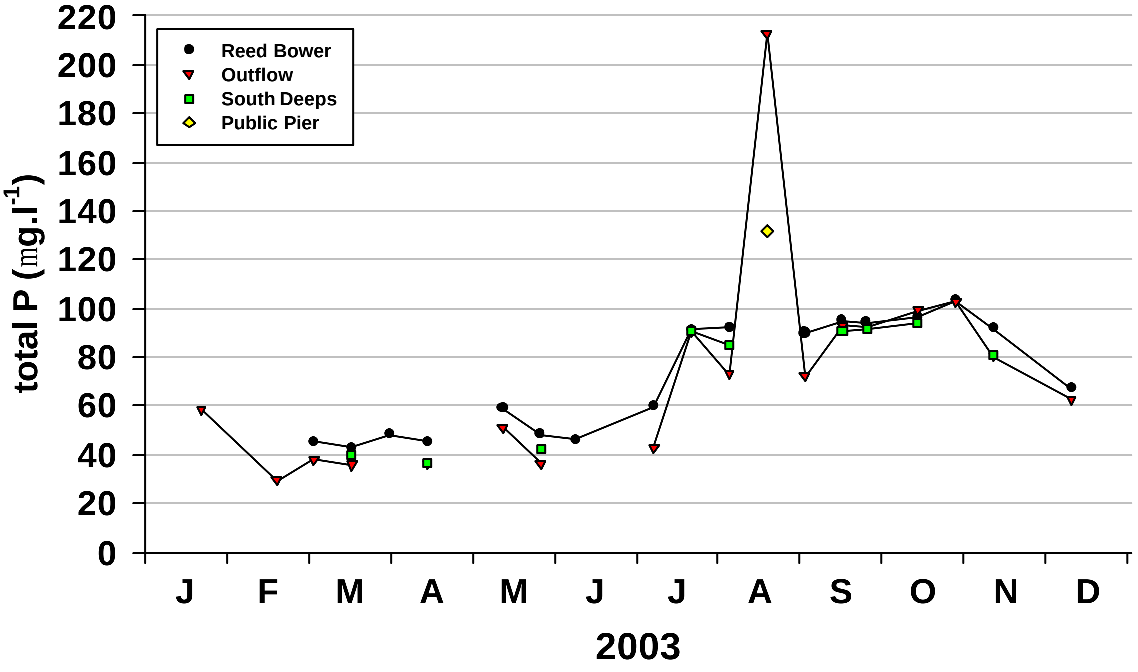


3.2.9 *Total phosphorus*

Total phosphorus (TP) concentrations provide a simple index of loch trophic status. The data for 2003 (Figure 12) yield minimum, maximum and mean concentrations of 30 µg P l^{-1}, 103 µg P l^{-1} and 68 µg P l^{-1}, respectively (excluding the August spike, which is of benthic origin in the shallow water near the outflow).

The mean TP concentration recorded is higher than the target mean annual TP concentration of 40 µg P l^{-1} set by the Loch Leven Area Management Advisory Group (LLAMAG 1993) and endorsed in the Loch Leven Catchment Management Plan (Loch Leven Catchment Management Project 1999). This suggests that the loch still has some way to go in terms of recovery from eutrophication (see discussion). 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

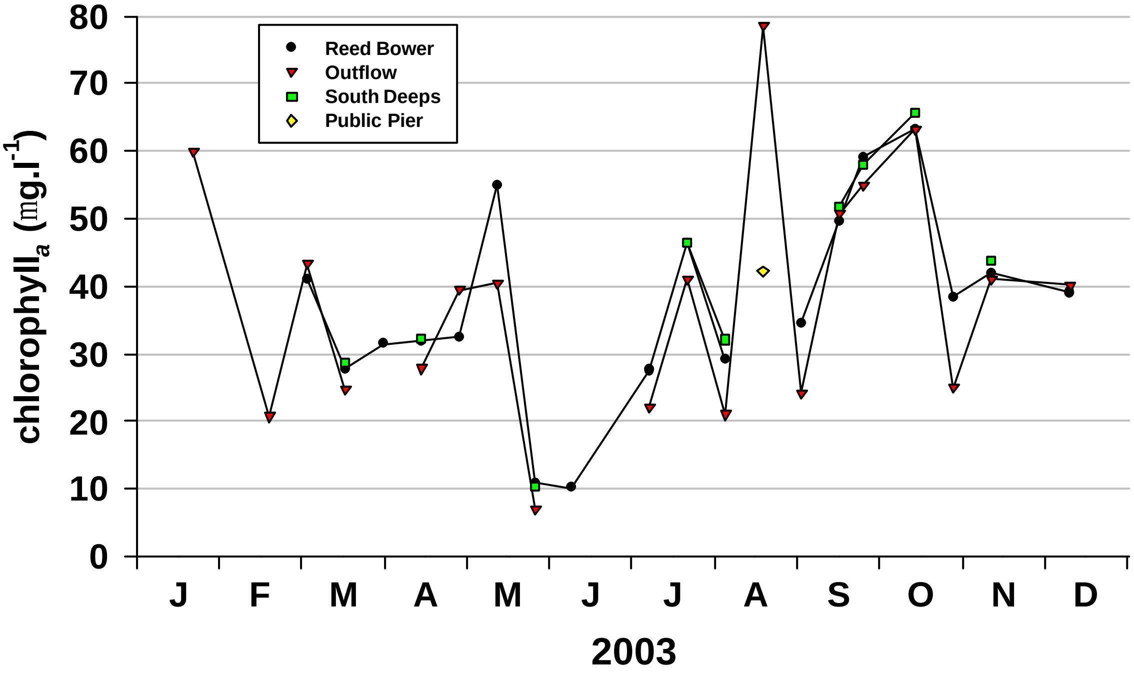


3.3 Phytoplankton

3.3.1 *Chlorophyll$_a$*

With the exception of late May and early June, all measured chlorophyll$_a$ concentrations exceeded 20 µg l^{-1}. However, the overall open-water values are little-changed from 2002, with maximum, minimum and annual mean concentrations of 66, 10 and 40 µg l^{-1}, respectively.

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



3.3.2 *Phytoplankton composition*

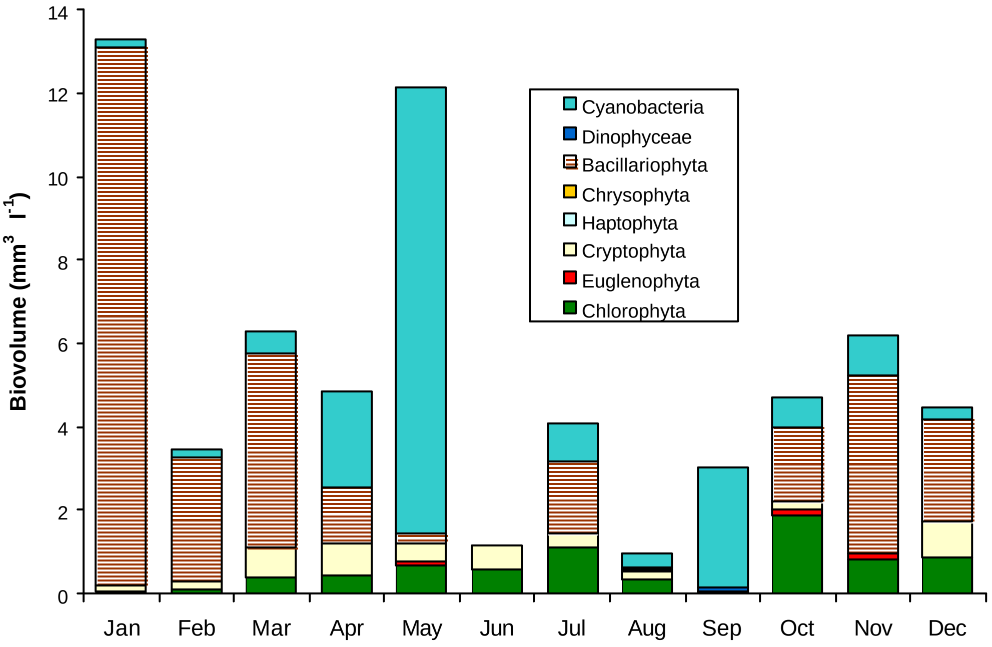
The year 2003 began with a large population of diatoms dominating the plankton. The January peak was the highest recorded that year and was dominated by the large, filamentous genus *Aulacoseira.* Small, single-celled centric diatoms became more prominent by March.

In late spring, the diatoms declined and, unusually, the phytoplankton biomass became dominated by several species of the filamentous cyanobacteria *Oscillatoria*, some of which are typically associated with sediments. Both the species concerned, and the high biovolume recorded, suggests that, at the time, the water column contained a relatively large amount of re-suspended sediment and associated algae.

Early summer was marked by a brief clear-water phase with a low biomass of phytoplankton. This was probably associated with peak densities of the main zooplankton grazers in this system, *Daphnia*. As summer progressed, populations of the filamentous cyanobacterium, *Anabaena*, and the colonial cyanobacterium, *Microcystis*, developed. This is a typical pattern of phytoplankton development at the site. The *Anabaena* populations persisted into autumn, although the autumn also saw the return of diatom dominance comprising both filamentous species, *Aulacoseira* spp., and colony-forming diatoms, *Diatoma* and *Asterionella*.

The majority of the algal biovolume recorded throughout the year was accounted for by the diatoms and cyanobacteria already mentioned. As in previous years, many other species and groups of algae developed relatively large populations in terms of numbers of cells, but not significant amounts in terms of total biovolume. These included the Cryptophyte *Rhodomonas minuta*, a group of *Cryptomonas* species, many species of green algae (Chlorophytes) and the Euglenophyte, *Trachelomonas*.

Figure 14. Temporal variation in phytoplankton biomass (monthly mean biovolume)



At least seven species of cyanobacteria were recorded during the year. The spring population of *Oscillatoria* species reached peaks greater than 5000 filaments ml^{-1} and the summer/autumn populations of *Microcystis* and *Anabaena* were also sufficiently abundant to warrant the display of notices warning of toxic algae throughout most of the year (Scottish Executive Health Department, 2002).

4 DISCUSSION

4.1 Recent Trends in Water Quality

The 2003 monitoring data show clear evidence of a deterioration from previous years in all three key water quality parameters. Chlorophyll$_a$ and TP concentrations both exceeded the respective statutory target concentrations of 15 µg l^{-1} and 40 µg 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 deteriorations were for TP and water clarity (Secchi depth), although there was still a brief clear-water phase in early June. The scale of deterioration can only be considered by putting data from 2003 into context with previous years monitoring results (Table 1 and Figs 15 and 16).

Table 1. Comparison of water quality data from 2003 with averages for three periods in the past (previous year, previous 5 years and previous 30 years)

Period		**TP (µg/l)**	**Chlorophyll$_a$ (µg/l)**	**Secchi Depth (m)**
Current Year	2003	68	40	1.33
Previous Year	2002	49	38	1.47
Previous 5 Years	1998-2002	57	39	1.51
30-Year Average	1972-2003	67	38	1.58

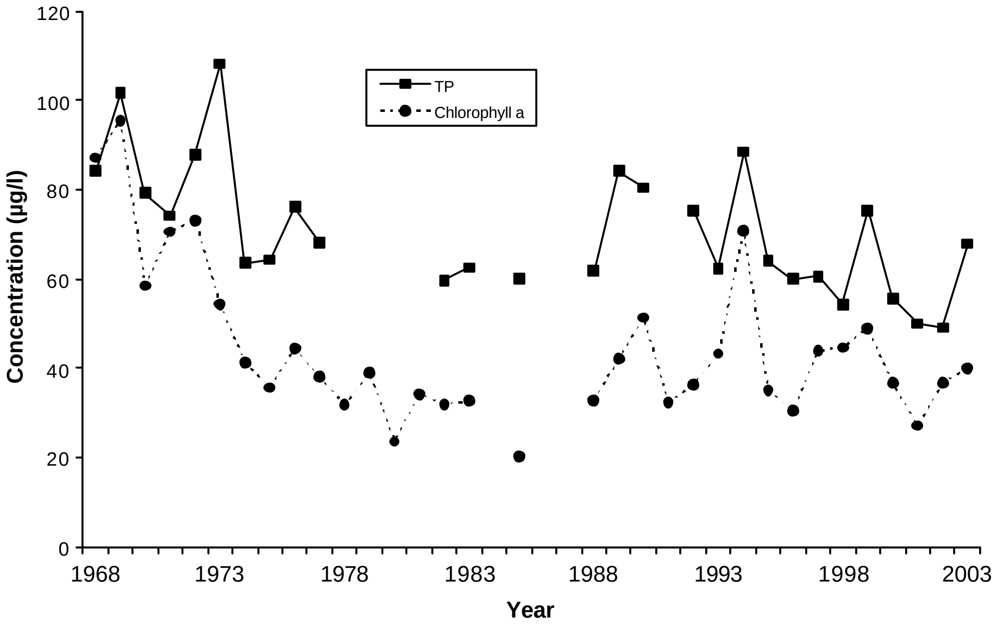
In terms of TP, the annual mean value for 2003 was significantly higher than the corresponding averages for the previous year and the previous 5-years. In fact, it was one of the highest values recorded over the last decade. The 2003 mean was even fractionally higher than the 30-year average, although it was still an improvement on that recorded during the first five years of regular monitoring at the site (85 µg l^{-1}, 1968-1972) (Table 1 and Figure 15).

The high TP concentrations in 2003 did not appear to be solely due to increased algal populations, as phytoplankton populations (measured as both chlorophyll$_a$ and biovolume) were only fractionally higher than the previous year and 5-year averages (Table 1). This suggests that the deterioration in TP in 2003 was due to either soluble phosphorus or non-algal particles (e.g. resuspended sediment). A comparison of the different P fractions in 2002 and 2003 (Table 2) indicates that both particulate phosphorus (PP) and soluble reactive phosphorus (SRP) concentrations were enhanced in 2003. This suggests that a combination of greater sediment re-suspension and increased nutrient loading was responsible for the deterioration observed in 2003.

Table 2. Comparison between concentrations (µg l^{-1}) of different phosphorus fractions for 2002 and 2003.

Phosphorus Fraction	**2002**	**2003**
Particulate Phosphorus	29	42
Soluble Unreactive Phosphorus	14	15
Soluble Reactive Phosphorus	5	12

Figure 15. Trends in total phosphorus and chlorophyll$_a$ concentrations in Loch Leven 1968-2003



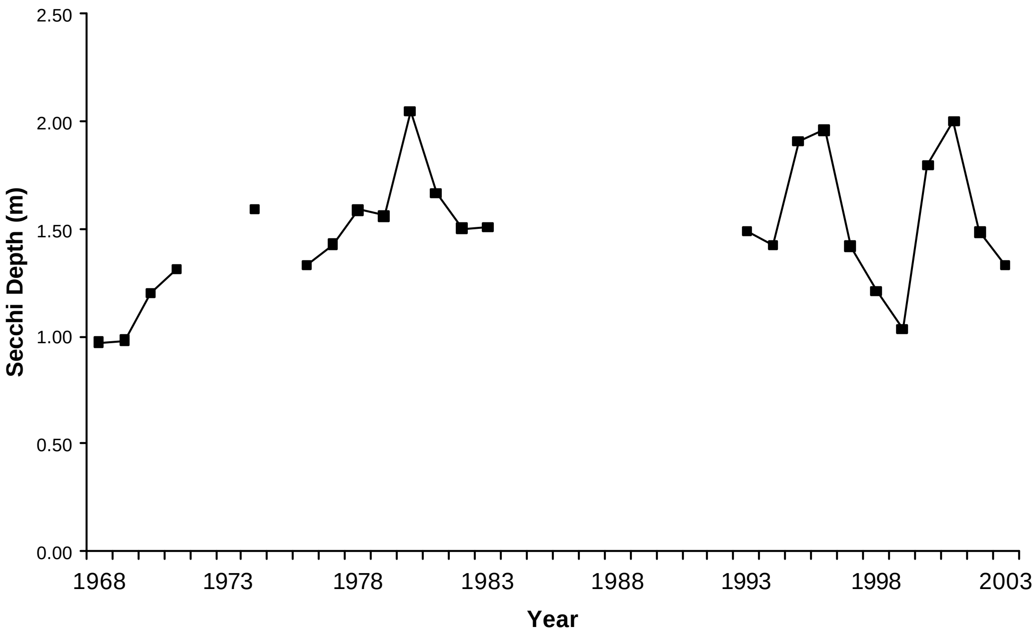
The increase in SRP can be explained by a number of possibilities:

1. Reduced flushing of the loch over the late summer/autumn months
2. Enhanced loading of available P from the catchment
3. Enhanced loading of P from the loch sediments

As no outflow data are currently available, it was not possible to examine the first possibility. The second possibility is being examined through a detailed catchment nutrient budget, currently being undertaken in 2005 by Lindsey Defew (CEH CASE studentship with SEPA). The third possibility is supported by the chemistry data from 2003: the late summer/autumn peak in SRP in 2003 (Figure 9) was much higher than that observed in any of the last four years, which suggests that internal loading from the P-rich sediments may have been a more significant problem in 2003. This continuing tendency for the Loch Leven sediments to release P has also been shown in recent experimental work at CEH (Spears et al., in press). This is worrying evidence that contradicts recent opinion that a sustained recovery was beginning to become established at Loch Leven (Carvalho, Kirika and Gunn, 2003).

In terms of water clarity, 2003 was a poor year compared to the previous three years and the 30-year average (Table 1 and Figure 16). 2002 was a similarly poor year for water clarity, providing further supporting evidence that recovery of Loch Leven is not being sustained, and in fact water quality appears to have deteriorated again. Water clarity has been particularly variable over the past ten years. This variability is correlated with chlorophyll concentrations, although other factors, such as wind re-suspension of bottom sediments, may also be important in contributing to, and possibly even driving, the magnitude of this variability (Bailey-Watts & Kirika, 1999).

Figure 16. Trends in Secchi Depth in Loch Leven 1968-2003



No analysis has yet been carried out to examine whether wind can explain much of the variability in water clarity. This will hopefully be considered in the analysis of climate change impacts at Loch Leven, being carried out as part of the Eurolimpacs project and a PhD being undertaken by Claire Ferguson (co-supervised by CEH and Glasgow University Statistics Dept). Additionally, CEH are planning on installing a new monitoring buoy at Loch Leven in early 2006 to record water quality and meteorological conditions at frequent intervals. The data produced should improve our understanding of the how weather and climate change may affect water quality at this site.

4.2 Lake and Catchment Management Implications

In summary, 2003 was a poor year in terms of water quality, representing a deterioration in status, rather than further ecological recovery. Delayed recovery following reduction in external nutrient loading is not unique to Loch Leven. A comparison of the recovery observed at Loch Leven with responses observed at other lakes reveals similar long delays in recovery, with factors such as enhanced internal loading typicallly responsible (Jeppesen et al., 2005)

There is clearly a need for continued lake and catchment management at Loch Leven to further ecological recovery and reduce the large inter-annual variability in water quality observed at the site. Increasing the coverage of macrophyte beds is widely recognised as the best way of delivering sustained water quality improvements in shallow lakes as they can compete with phytoplankton for nutrients and light and reduce sediment resuspension (and consequentlly internal loading) (Jeppesen et al, 1998; Scheffer, 1998). Enhanced macrophyte coverage at Loch Leven is also a long-term management goal (LLAMAG, 1993) as it provides increased habitat for invertebrate, fish and bird communities.

The key question is how can macrophyte coverage be enhanced at Loch Leven? In-lake manipulation of fisheries (biomanipulation) is not really a viable option for SNH to consider at the site and in fact the best long-term solution is to reduce external nutrient loading further. Despite the large reductions in external phosphorus loadings that have been achieved so far, current loadings do not yet appear to be at a level for delivering sustained in-lake TP concentrations <50 µg l^1, a value below which macrophyte stability is greatly enhanced

(Jeppesen et al, 1998; Scheffer, 1998). This may be in part, because internal P loadings still remain significant, but for whatever reason, external loadings remain the ultimate source.

It may also be highly relevant that nitrogen concentrations in Loch Leven have been slowly increasing over recent decades. The 2003 monitoring data does suggest that, rather than phosphorus, nitrogen is more likely to limit algal biomass from June to October. Catchment management should, therefore, aim to identify and reduce significant sources of nitrogen, as well as phosphorus.

It is also likely that other factors contribute to the variability in water quality of Loch Leven. Climate change, water level management, fisheries management and pesticide impacts on *Daphnia* grazers are all possible important pressures. It is difficult to specify which, if any, of these are more responsible in any one particular year. Current research at CEH aims to utilise the full long-term datasets to understand the impact of these other pressures either acting alone or in tandem with eutrophication pressures.

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