SCOTTISH NATURAL HERITAGE

COMMISSIONED REPORT

Commissioned Report No. 031

Long-term patterns of change in physical, chemical and biological aspects of water quality at Loch Leven

(ROAME No. F01LH03C)

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Summary

Long-term patterns of change in physical, chemical and biological aspects of water quality at Loch Leven

Commissioned Report No. 031 (ROAME No. F01LH03C)
Contractor: Laurence Carvalho, Alex Kirika and Iain Gunn (Centre for Ecology and Hydrology)

Background

Loch Leven has suffered from periodic cyanobacterial blooms for many years, largely, as a result of substantial amounts of phosphorus entering the loch, combined with a relatively low flushing rate and a favourable light-climate. The blooms have a direct impact on the various users of the loch, and in terms of conservation interest, reduce light penetration into the water, reducing macrophyte growth, with associated impacts on macro-invertebrate, fish and bird communities.

Since the 1970s there has been an action programme to improve the ecology and water quality of Loch Leven aimed, primarily, at reducing the intensity and frequency of phytoplankton blooms, and enhancing water clarity by reducing the loadings of phosphorus to the loch. This report provides a synthesis of all water quality monitoring undertaken at Loch Leven up to and including 2001, together with published ecological data from a variety of sources. The review aims to examine long-term patterns of change in key water quality parameters in response to the reduction in external phosphorus load, and evaluate any evidence of ecological recovery. In addition to this, the report explores the role of each parameter in the understanding of changes in water quality, and makes recommendations for future monitoring and management.

Main findings

The review illustrates:

- how long-term datasets offer unique insights into how pressures such as eutrophication and climate change impact on Scottish freshwater habitats;
- the difficulty in assessing recovery even with such datasets;
- the magnitude of recovery at Loch Leven appears to be a conflicting response to decreasing nutrient concentrations and increasing temperatures, with further strong interactive effects from internal processes (*Daphnia* grazing and sediment release of phosphorus);
- Loch Leven is just beginning to show real and sustainable signs of recovery in both water quality and ecology;
- nutrient concentrations have significantly declined and there are strong signs that phytoplankton biomass has declined in recent years in response to this;

- submerged macrophytes are showing an improving trend in terms of extending their coverage into deeper water; and
- macro-invertebrate species richness has greatly increased.

The evidence for recovery is particularly strong for the last few years.

The report recommends:

- the current management target of an annual mean of 40µg l^{-1} total phosphorus (TP) should be maintained;
- that *Daphnia* densities should be a key management target with an annual mean threshold density of around 3 individuals l^{-1};
- more explicit conservation targets related to known historical accounts of the biology, such as maximum growing depth of *Chara* or Gastropod richness, are considered;
- continuing monitoring key water quality parameters and phytoplankton populations, and to re-introduce monthly monitoring of zooplankton populations, particularly *Daphnia*;
- the colonisation depth of submerged macrophytes is assessed each summer and more detailed macrophyte and littoral invertebrate surveys continue every three years to assess whether ecological recovery is sustained.

This project was co-funded by Scottish Environment Protection Agency and Scottish Natural Heritage.

Acknowledgements

We would like to thank Sir David Montgomery for providing access to the Loch for the duration of the monitoring period. We are also grateful to Loch Leven Estates, SNH, SEPA and staff at CEH for their frequent help with fieldwork and supply of data. A number of staff in the Scottish Freshwater Ecosystems Section at CEH have, over the years, contributed data and ideas on Loch Leven that are used in this review, most notably Dr Tony Bailey-Watts.

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1 INTRODUCTION

1.1 Background

Loch Leven is the largest, nutrient-rich, lowland loch in Scotland and is designated as a Site of Special Scientific Interest (SSSI), National Nature Reserve (NNR), Special Protected Area (SPA) and Ramsar site. It is particularly renowned for its large numbers of migratory, breeding and over-wintering waterfowl. Although the overall quality of the site is good, the loch has suffered from periodic cyanobacterial blooms for many years. These have occurred, largely, as a result of substantial amounts of phosphorus entering the loch, combined with a relatively low flushing rate and a favourable light-climate (Bailey-Watts and Kirika, 1999). The 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 impacts on macro-invertebrate, fish and bird communities.

Since the 1970s, Scottish Natural Heritage (SNH), Scottish Environment Protection Agency (SEPA), their predecessor bodies (NCC, FRPB), and other agencies have been involved in an action programme to improve the ecology and water quality of Loch Leven. This has aimed, primarily, at reducing the intensity and frequency of phytoplankton blooms, and enhancing water clarity by reducing the loadings of phosphorus to the loch (Bailey-Watts and Kirika, 1999). The programme has been successful in reducing the phosphorus load from point sources and the 1999 Loch Leven Catchment Management Plan has begun to address the problem of diffuse sources of nutrients.

The Centre for Ecology and Hydrology (CEH) (formerly the Nature Conservancy 1968–1973, the Institute of Terrestrial Ecology 1973–1989, the Institute of Freshwater Ecology 1989–2000) has been intensively monitoring various aspects of water quality at Loch Leven since 1968. Additionally a number of surveys of aquatic macrophyte, benthic invertebrate and fish communities have taken place.

1.2 Aims of review

This report provides a synthesis of all water quality monitoring undertaken by NC/ITE/IFE/CEH at Loch Leven up to and including 2001, together with published ecological data from a variety of sources. The study has two principle aims:

- To examine long-term patterns of change in key water quality parameters in response to the reduction in external phosphorus load.
- To evaluate any evidence of ecological recovery.

In addition to this, the report explores:

- The role of each parameter in the understanding of changes in water quality.
- Recommendations for future monitoring and management.

1.3 Site details

Loch Leven is a large, lowland loch, situated near Kinross in Eastern Scotland. Details of the loch and its catchment are summarised in Table 1.

Table 1 Details of Loch Leven and its catchment

National Grid Reference	No 145 015
Altitude (m)	107
Maximum depth (m)	25.5
Mean depth (m)	3.9
Loch area (km^2)	13.3
Loch volume (m^3)	52.4×10^6
Mean Flushing rate (y^{-1})	2.3
Catchment area (km^2)	145
Catchment geology	sandstone/glacial drift
Catchment land-use	arable (55%), grassland (19%), forestry (7%), urban (2%)

The catchment is drained by four main rivers: North Queich, South Queich, Gairney Water and Pow Burn. The River Leven provides an outlet for the loch. Water draining into the loch originates from a variety of sources, which includes treated sewage effluent, industrial effluent and agricultural run-off.

The loch is a major asset for the region. The substantial income generated by tourism, industry and recreational activities, such as trout fishing and bird watching, is dependent on high water quality. In 1992, a severe algal bloom is estimated to have cost the local economy about £1 million (LLAMAG, 1993).

1.4 Recent history of catchment management

Algal blooms are caused by a complex interaction of physical, chemical and biological processes. A key factor in the enhanced production of algal blooms is, however, the presence of sufficient quantities of plant nutrients, particularly phosphorus, in the water. The reduction of point sources of phosphorus entering the loch has been the main focus of the catchment management programme. A history of the phosphorus load and reduction measures is provided below, with the load reduction occurring throughout the whole monitoring period:

- 1973 Most effluent from the bleaching process at the woollen mill no longer discharged into the loch; transported off-site for disposal
- 1985 External load measured as 20.11 t TP y^{-1} (Bailey-Watts and Kirika, 1987)
- 1989 Woollen mill discharge ends (~6.29 t TP y^{-1} reduction)
- 1993 Effluent from Kinross South STW re-directed to upgraded Kinross North STW (~1.70 t TP y^{-1} reduction)
- 1995 Phosphorus stripping procedures implemented at Milnathort STW (~0.59 t TP y^{-1} reduction)
- 1995 External load measured as 7.99 t TP y^{-1} (Bailey-Watts and Kirika, 1999)
- 1997 Sewage from Kinnesswood STW diverted out of the catchment (~0.55 t TP y^{-1} reduction).

Sufficient time has now passed to examine whether these load reductions have resulted in sustained improvements in water quality and signs of ecological recovery.

2 METHODS

2.1 Data sources

The review focuses on two sets of historical data:

1. lake physics, chemistry and plankton populations, based on regular monitoring over the period 1968–2001, and

2. macrophytes, invertebrate and fish records based on irregular surveys carried out largely for SNH (see results section for details of sources).

The regular monitoring data were collated largely from internal CEH records, supplemented with data from SEPA in the early 1990s. Many chemical and physical variables are measured as part of the CEH monitoring regime, although only a few key parameters, which have data spanning the whole monitoring period since 1968, are examined. These include water temperature, water clarity (Secchi depth), silica, nitrate, soluble reactive phosphorus, total phosphorus and chlorophyll$_a$ concentrations. Where possible, data is based on the Reed Bower sampling location, but this is augmented by samples from the outflow when it was not possible to sample at Reed Bower. Analysis of spatial variation within the loch shows that this is generally acceptable for most variables for much of the year, but spatial differences can occur, particularly in particulate parameters, such as total phosphorus, in very windy conditions (Carvalho and Kirika, 2002).

Additionally, CEH hold data on phytoplankton and zooplankton populations for a good proportion of the monitoring period. Much of this data has not yet been transcribed into electronic format. This review, therefore, focuses on cyanobacteria, key ecological indicators of water quality, and *Daphnia*, the most significant zooplankton grazer in terms of its impact on phytoplankton abundance.

As is common with much environmental data, the quality of the data presents some problems for statistical analysis. The main problems concern strong seasonality, irregular time intervals between samples, and long gaps in the data.

2.1.1 Seasonality

The problem of seasonality in statistical analysis is solved either by using annual mean values, or by considering each season separately. In terms of seasonal analysis, if the raw data has more than one observation in any season then the data must be "collapsed", as described below. Samples were generally taken on a weekly, fortnightly, or monthly basis at Loch Leven, so it is appropriate to use the longest time interval, one calendar month, as the season. Helsel and Hirsch (1992) suggest two options where more than one sample has been taken per season:

1. if the variations in sampling frequency are random, the data should be collapsed to a single value by taking the mean or median of the available data, or

2. if there is a systematic trend in sampling frequency, the mean or median will induce a trend in variance, so, the observation closest to the midpoint of the month should be used.

In the case of the Loch Leven data, both of these situations arise. Sampling frequencies at certain times have no obvious pattern, at other times the frequency is more systematic. Only results using monthly mean values are examined here.

2.1.2 Irregular sampling

No consistent pattern of sampling is present for the complete period of record for each of the key variables. For example, TP samples in 1985 were taken every 8 days in order to ensure they were unbiased by potential day-of-the-week differences from the woollen mill and STWs. Many years, however, had seasonally-adjusted sampling frequencies, with more dynamic summer months being sampled more frequently than the relatively stable winter months. For example, samples were often taken on a weekly or fortnightly basis in the summer, but on a fortnightly or monthly basis in the winter. The fact that sampling frequency is not systematic throughout, makes statistical analysis of trends more complicated. Table 2 illustrates how sampling frequencies changed for three consecutive years.

Table 2 Number of samples collected for TP analysis during each month in the years 1990–1992

Year	J	F	M	A	M	J	J	A	S	O	N	D
1990	4	4	4	3	4	4	4	4	3	4	4	4
1991	0	0	3	2	2	2	3	3	1	2	1	0
1992	0	2	2	2	2	1	5	4	5	4	1	4

2.1.3 Gaps in the data

Gaps in the data are more common in the winter months, often because bad weather or ice cover makes it more difficult to take a boat out onto the loch or to obtain a representative sample at the outflow. This can sometimes mean that no samples have been taken in some months, as can be seen in Table 2. There are also longer gaps of several months or years, when staff time and financial constraints meant that no sampling was carried out at all. This was especially true of the 1980s, when no data were collected for several years (for example, 1984, 1986 and 1987). Again, this presents some problems for statistical analysis.

2.2 Statistical analysis

2.2.1 Trend analysis

Although there is an adequate amount of data available for the period of record, the seasonality, irregular sampling and gaps in the data restrict the methods of analysis available. Approaches for analysing the Loch Leven dataset were investigated by Snowling (2001). He recommended the use of non-parametric methods of analysis, especially the seasonal Mann-Kendall test for trend (Hirsch *et al.*, 1982) as this test can accommodate missing values and seasonality. A modified version of this test (Hirsch and Slack, 1984) deals with the additional problem of serial dependence (auto-correlation). The test makes no assumption about the form of the distribution of the data, so it is not necessary for the data to be normally distributed. The analysis presented in this report was carried out by Snowling (2001) in collaboration with CEH and SEPA.

The seasonal Mann-Kendall test is based on the ranking of the observations for each season over the whole time series. The observation with the lowest value is ranked 1, the next lowest value is ranked 2, and so on. Using ranks, rather than actual values, means that results are less likely to be skewed by extreme values, and the problem of dealing with outliers is removed from the data analysis. The null hypothesis of the test is that the observed values are randomly distributed over time. The alternative hypothesis is that the observations have a monotonic trend.

2.2.2 Comparison of means

The major drawback of the seasonal Mann-Kendall test is that it tests for monotonic trends, ie it can detect trends in one direction only; if there is an initial increase followed by a similar decrease, the test will not detect any significant pattern. As many of the data series do not, however, conform to a simple monotonic trend, another approach to assessing recovery has also been examined. This compares the mean values of a pre-reduction period with those of a post-reduction period. These tests are, however, affected by serial dependence and are, therefore, only applied where this is considered to be not significant, eg comparison of annual means of first five years (1968–1972) with those of the last five years (1997–2001), or January data from one year with January data from another. Difference of means tests (t-test) were carried out using Microsoft Excel.

2.2.3 Correlation analysis

Correlation analysis was carried out in Microsoft Excel to explore which factors were most closely related to two key water quality indicators, water clarity (Secchi disc depth) and phytoplankton biomass (chlorophyll$_a$). The identification of strong relationships can help identify causal relationships, although it should be noted that a strong relationship could also mean that both are related to some other underlying factor.

3 RESULTS

3.1 Physics, chemistry and plankton

3.1.1 Physical factors

3.1.1.1 Surface water temperature

Figure 1 shows the surface water temperatures over the 34-year monitoring period. No clear trend is obvious from the raw data series, however, if annual mean temperatures (calculated from monthly mean values) are plotted overlain with a linear regression line, an upward trend becomes clearly visible with annual mean water temperatures increasing by about 0.3°C per decade (Figure 2).

1996 was the warmest year on record, with an annual mean surface water temperature of 10.4°C, whereas 1985 was the coldest year at 8.0°C and also had the lowest summer peak temperature of 15.9°C.

Figure 1 Surface water temperature 1968–2001

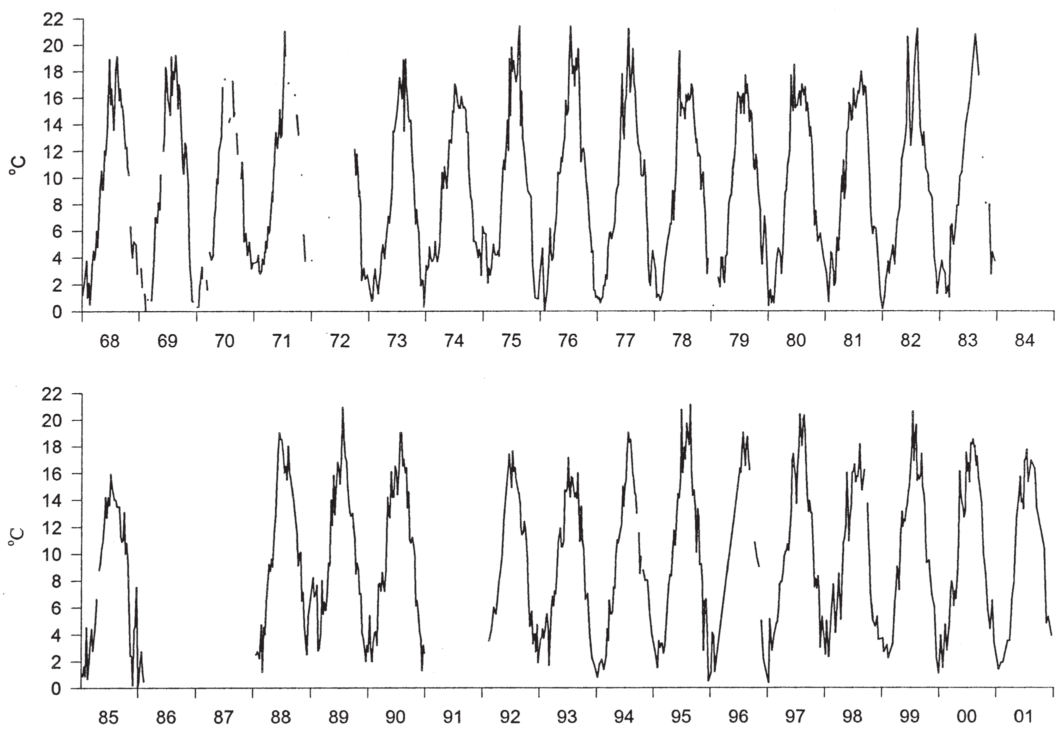
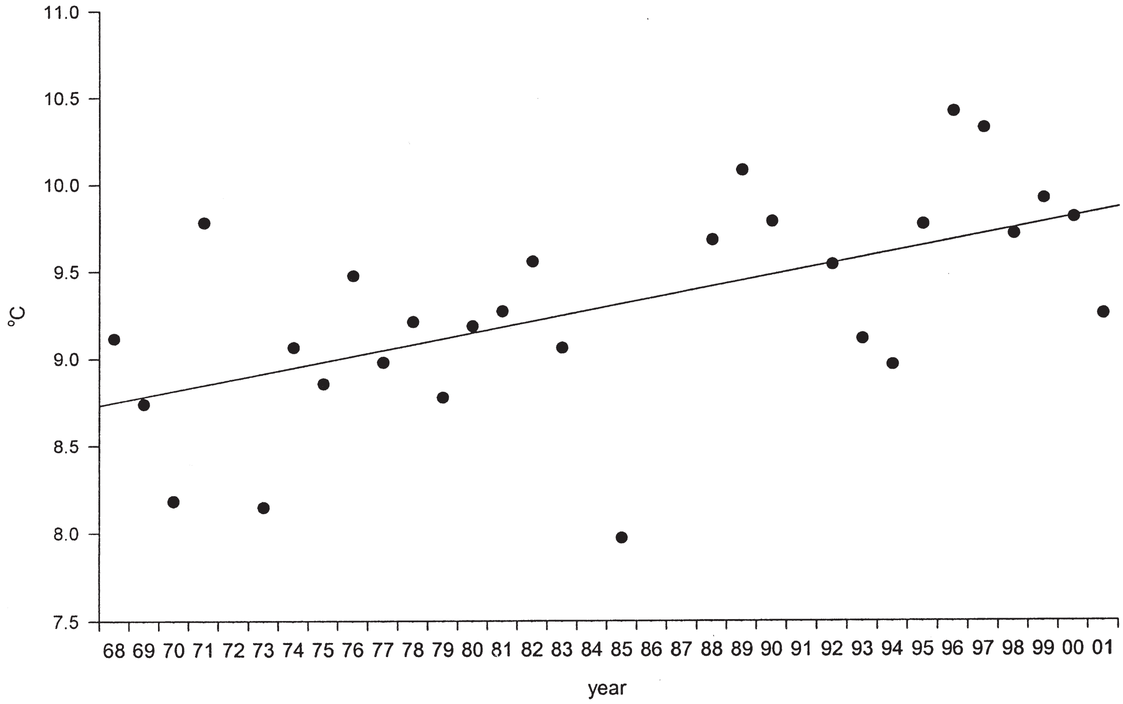


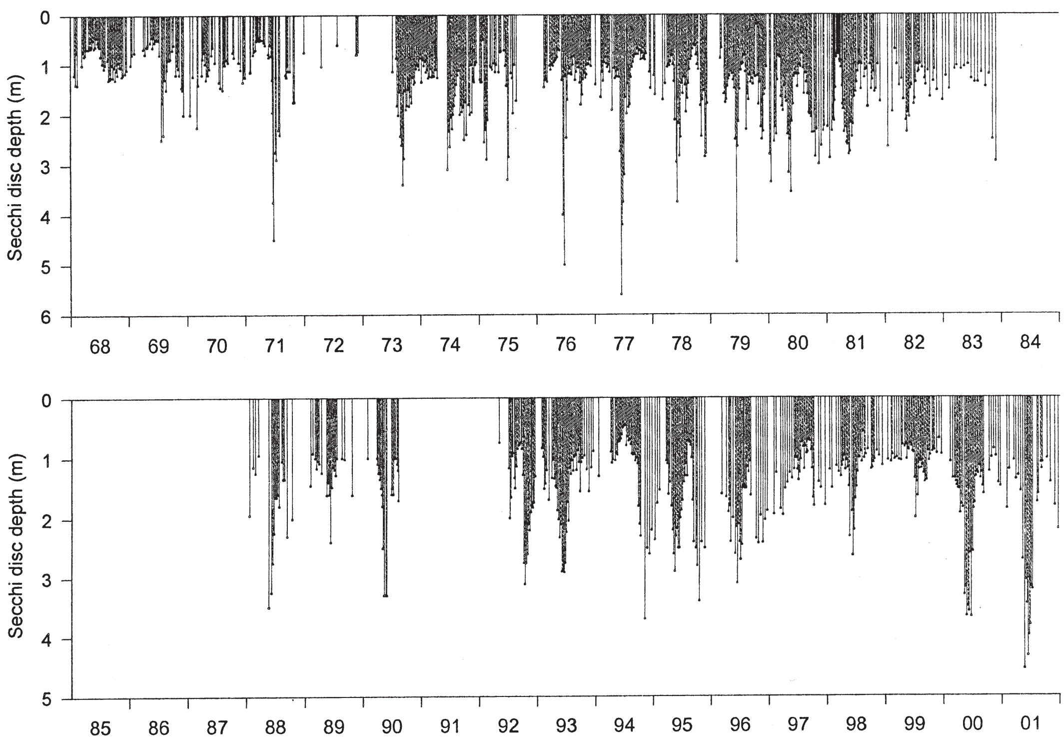
Figure 2 Annual mean surface water temperature 1968–2001



3.1.1.2 Water clarity

Figure 3 shows water clarity measured as Secchi disc transparency in Loch Leven over the 34-year monitoring period. The seasonal Mann-Kendal test for trend gives a Z-statistic of 0.31, which equates to a p-value of 0.76 (Snowling, 2001). There is, therefore, no evidence of a monotonic trend in the time series.

Figure 3 Water clarity measured as Secchi disc transparency 1968–2001



The large gaps in the Secchi depth data set are clearly seen in a plot of annual mean, minimum and maximum values (Figure 4); values being excluded if 3 or more months of data were missing. The plot illustrates the variability in the data series and the lack of any monotonic trend. Mean values increased from a low of 0.97m in 1968 to a peak of 2.05m in 1980, then a subsequent decline to 1.03m in 1999 followed by a rise to 2.0m in 2001. Despite this variability, there are indications of an overall improving trend in water clarity in all 3 parameters, particularly in terms of maximum values, with the last two years having Secchi depths greater than 3.5m during June.

The seasonal differences in water clarity have also changed considerably over the time series. Mean monthly values for 1968–1972 show particularly poor clarity in spring/early summer, with values below 1.0m, whereas for the last 5 years (1997–2001) these months have had the greatest water clarity, with mean values over 2.0m in May and June (Figure 5). All months, except August, show greater water clarity throughout the year.

Figure 4 Annual mean, minimum and maximum water clarity measured as Secchi disc transparency 1968–2001

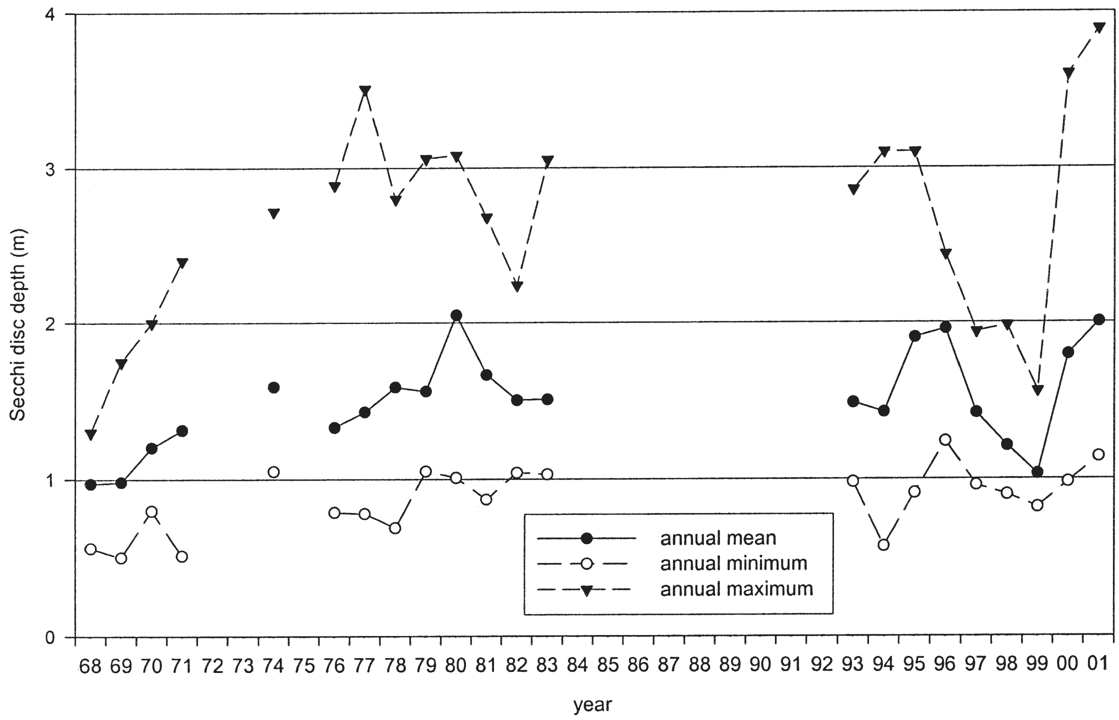
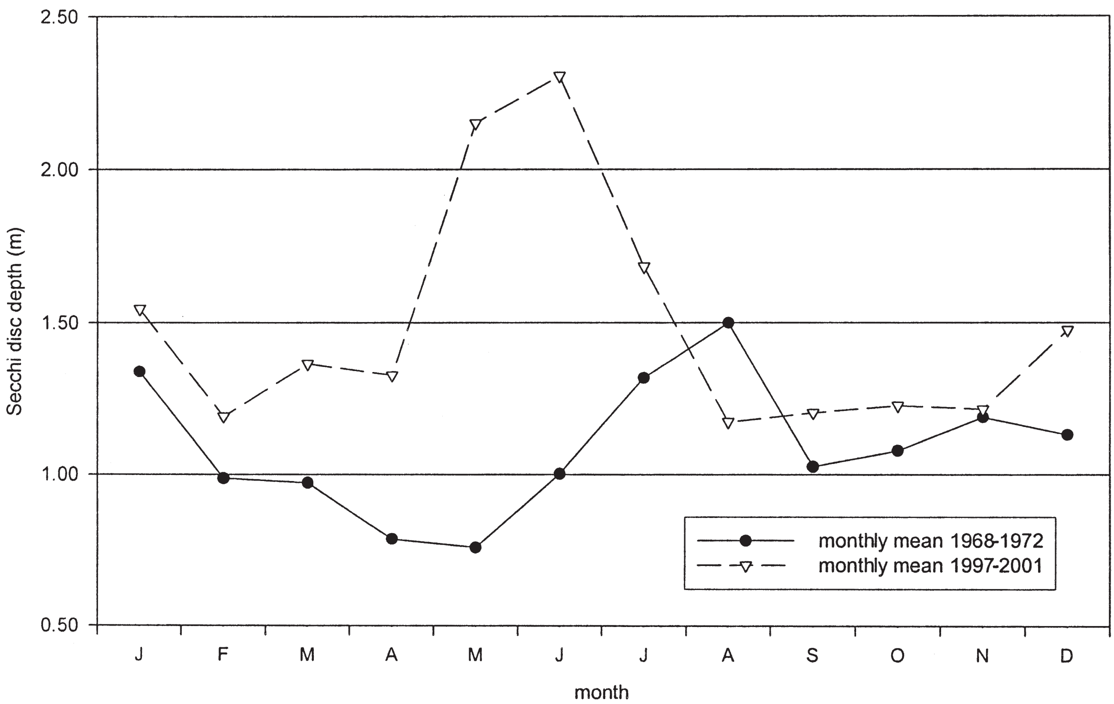


Figure 5 Monthly mean water clarity for two contrasting 5-year periods before and after the reduction in P loading



3.1.2 Chemical factors

3.1.2.1 Silica (SiO_2)

Figure 6 shows temporal changes in silica concentrations over the 34-year monitoring period. A declining trend in both annual mean and minimum values (derived from monthly means) is visible in the smoothed time series (Figure 7). The variability in concentrations is almost certainly a response to variability in diatom abundance over the time series (see section 3.1.3.2), although there may also have been variability in catchment loads associated with rainfall variability.

Figure 6 Silica concentrations 1968–2001

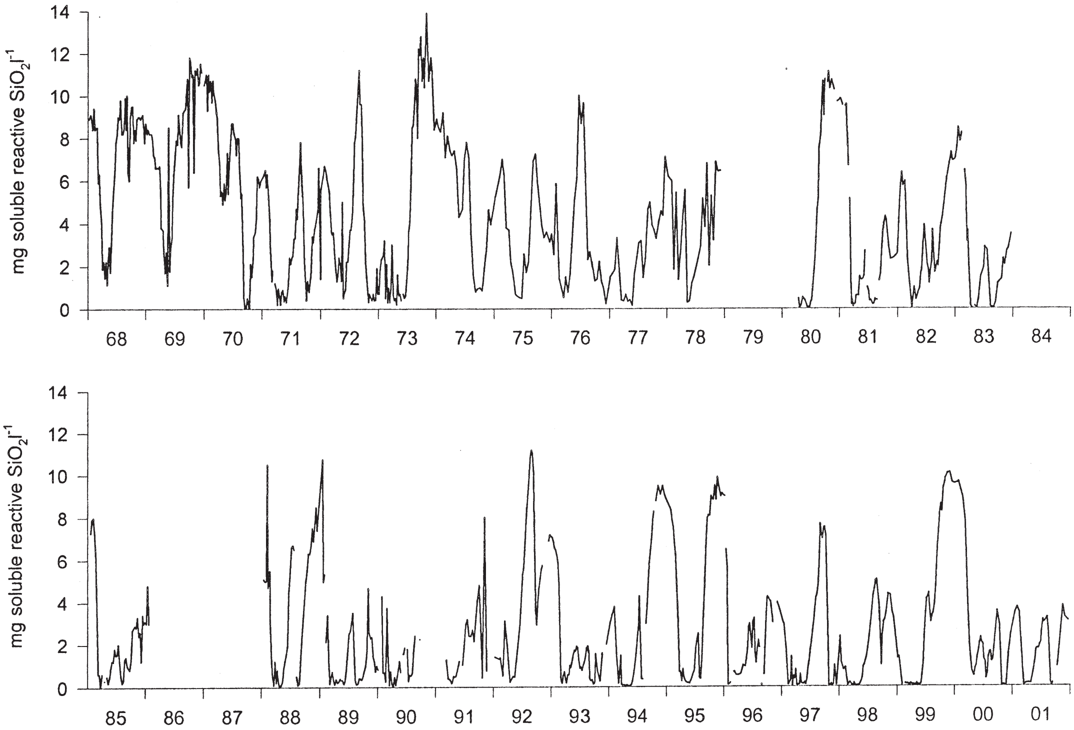
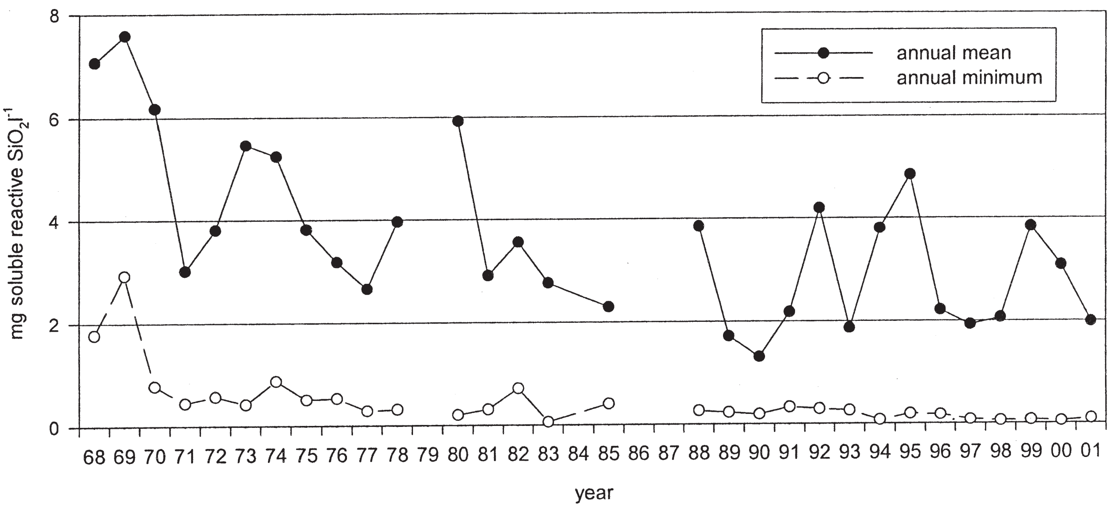


Figure 7 Annual mean and minimum silica concentrations 1968–2001



3.1.2.2 Nitrate-nitrogen

There is strong seasonality in nitrate concentrations with peak values in winter/early spring declining to minimum values that are close to the limits of detection, in summer (usually July/August) (Figure 8). No strong trend is apparent in annual mean concentrations (Figure 9), values having increased from a low of 0.52mgl^{-1} recorded in 1968 to a peak of 1.80mgl^{-1} in 1985, followed by a decline to 0.59mgl^{-1} recorded in 1999. Annual mean concentrations generally fluctuate about 1mgl^{-1}.

Figure 8 Nitrate-nitrogen concentrations 1968–2001 (dotted lines are samples taken at the outflow)

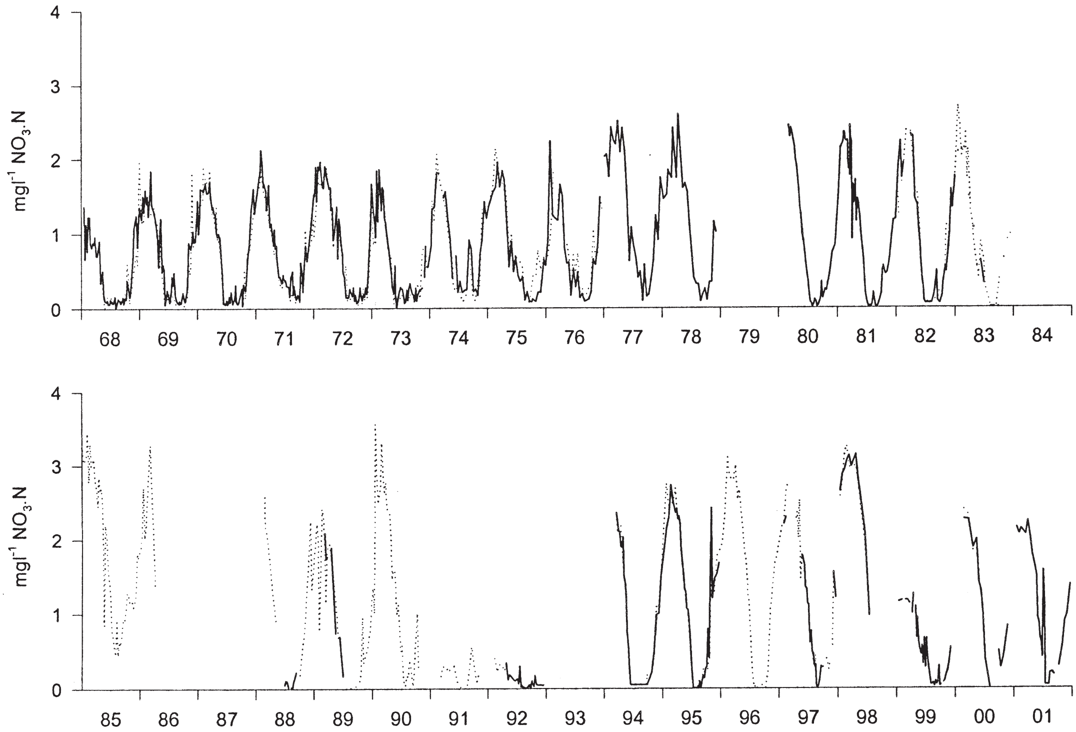
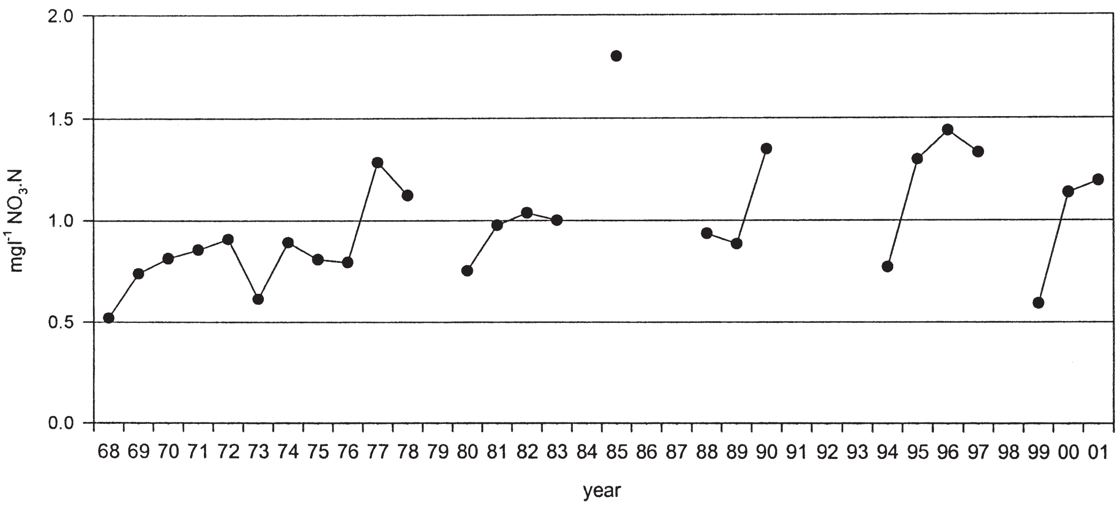


Figure 9 Annual mean nitrate-nitrogen concentrations 1968–2001



3.1.2.3 Soluble reactive phosphorus (SRP)

SRP concentrations are highly variable throughout the time series, with a changing magnitude of peak concentrations being clearly apparent (Figure 10). No strong trend is apparent in annual mean concentrations for most of the monitoring period, except for during the last five years when these concentrations appear to have declined sharply to the lowest values on record of 8µgl^{-1} or less (Figure 11) which reflects the much reduced peak concentrations shown in Figures 10 and 12.

Figure 10 Soluble reactive phosphorus concentrations 1968–2001

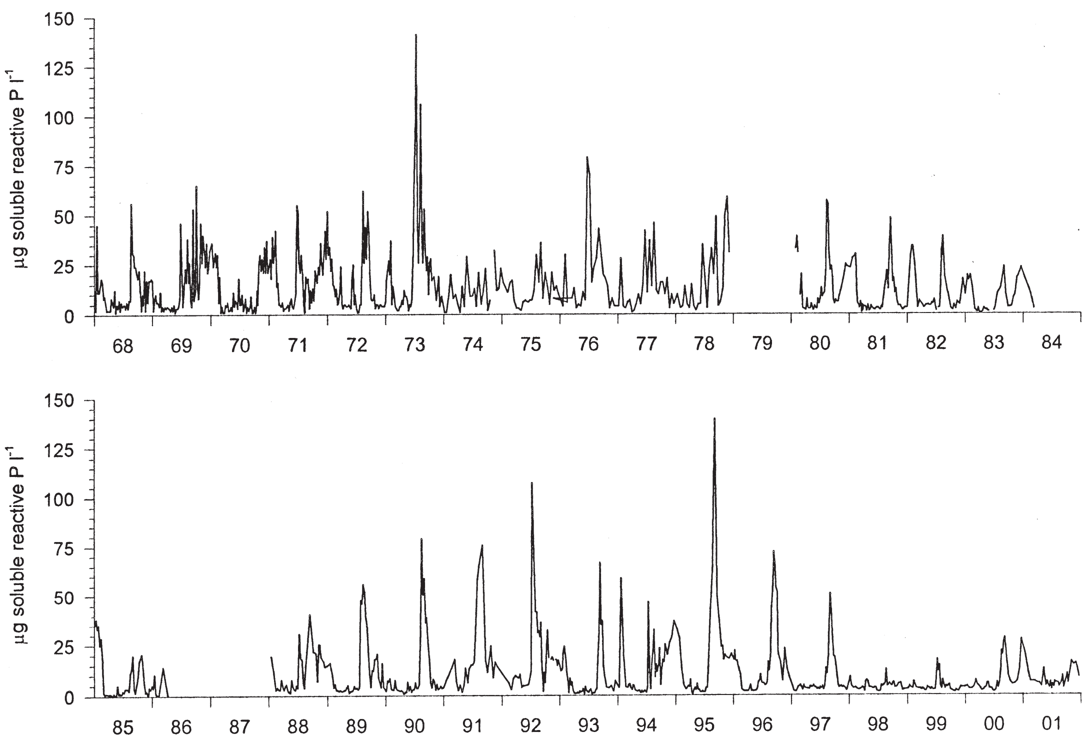
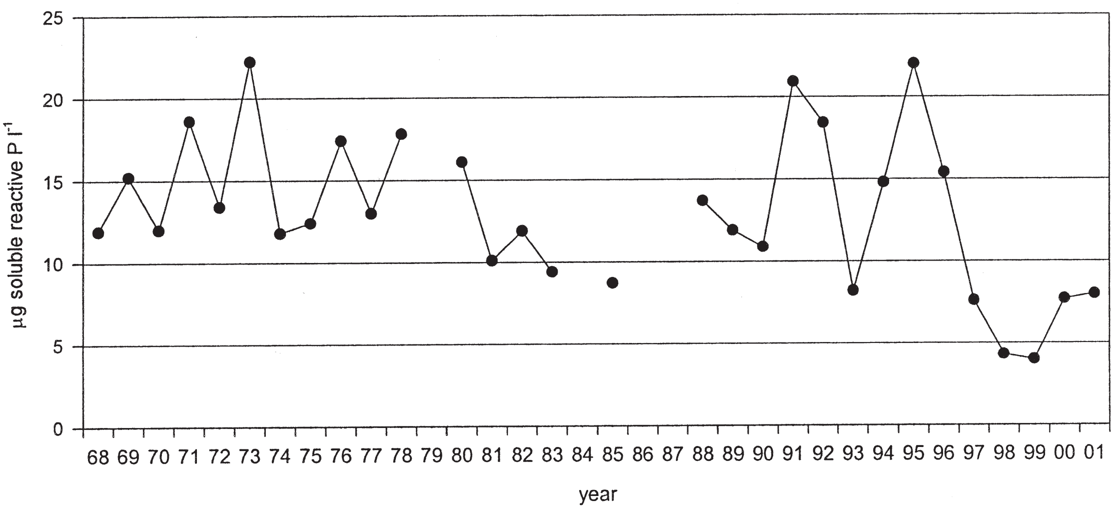
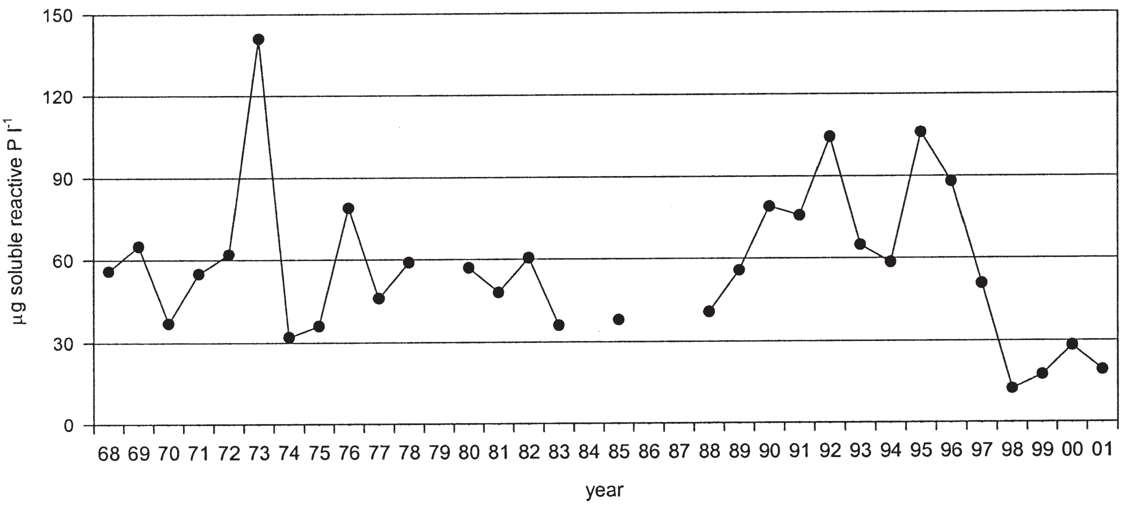


Figure 11 Annual mean SRP concentrations 1968–2001



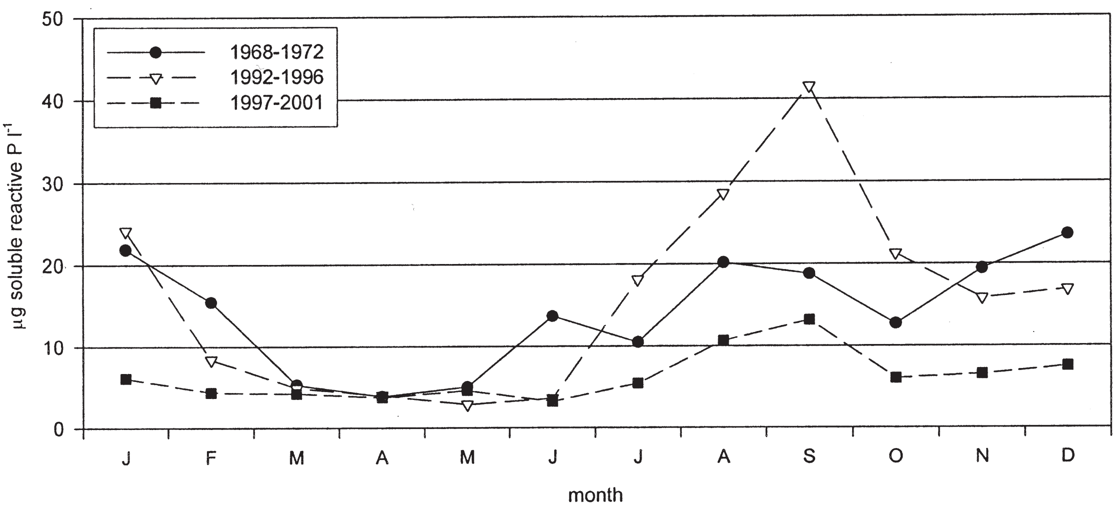
The dataset also reveals changing patterns in the magnitude (Figure 12) and seasonality (Figure 13) of SRP concentrations. In the first 5 years of monitoring, peak concentrations of around $60 \mu g l^{-1}$ occurred in winter (December) with a smaller peak in autumn (September). In the early 1990s, peak concentrations occurred in autumn (September) and these had increased to about $90 \mu g l^{-1}$. Finally, in the last 5 years, peak concentrations have also occurred in autumn (September) but have declined considerably to values below $30 \mu g l^{-1}$.

Figure 12 Annual maximum SRP concentrations 1968–2001



Minimum concentrations at, or close to, detection limits (below $3 \mu g l^{-1}$) occur in spring throughout the monitoring period. Figure 13 also shows, however, that the number of months in a year with very low SRP concentrations ($<10 \mu g l^{-1}$) has increased greatly in the last 5 years, from 4 or 5 in the periods 1968–1972 and 1992–1996, respectively, to 10 for 1997–2001.

Figure 13 Seasonal pattern in monthly mean SRP concentrations



3.1.2.4 Total phosphorus (TP)

Figure 14 illustrates the dynamic nature of total phosphorus concentrations in Loch Leven. No clear trend is immediately obvious from the time series. Recent years show a much greater frequency of values below 50µgl^{-1}, but they also show a greater frequency of very high values. The seasonal Mann-Kendal test for trend gives a Z-statistic of –2.75, which equates to a p-value of 0.006, below the 1% significance level (Snowling, 2001). As the test statistic is negative, it can be concluded that there is, therefore, a highly significant downward trend.

Figure 14 Total phosphorus concentrations 1968–2001

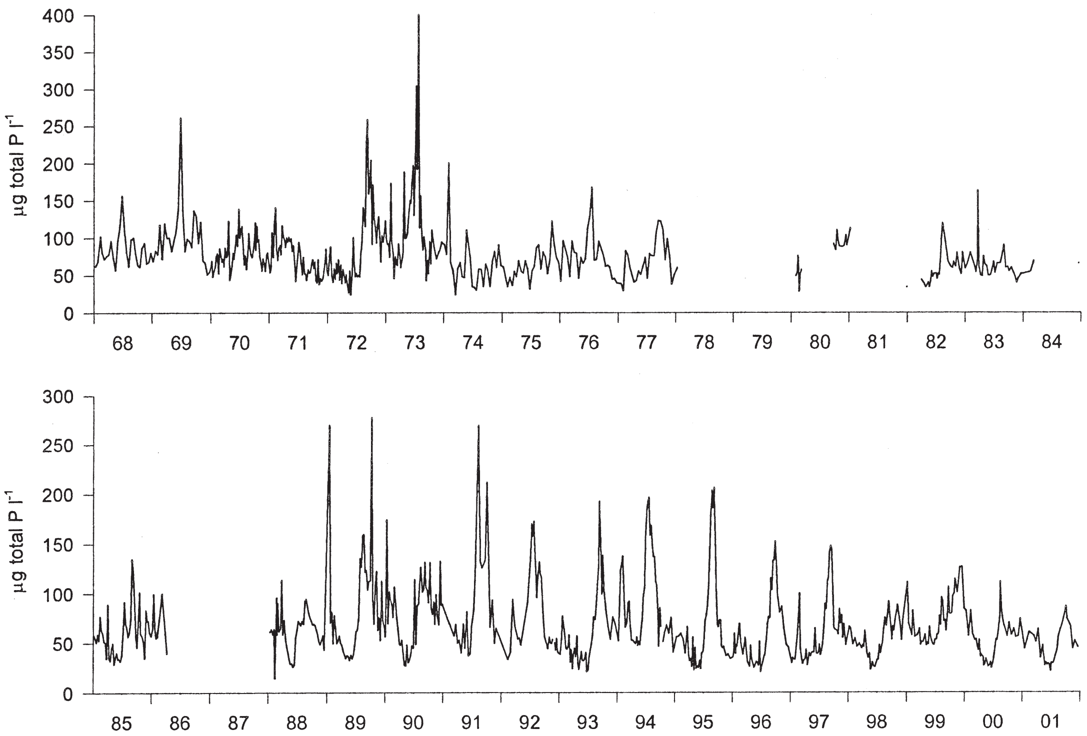
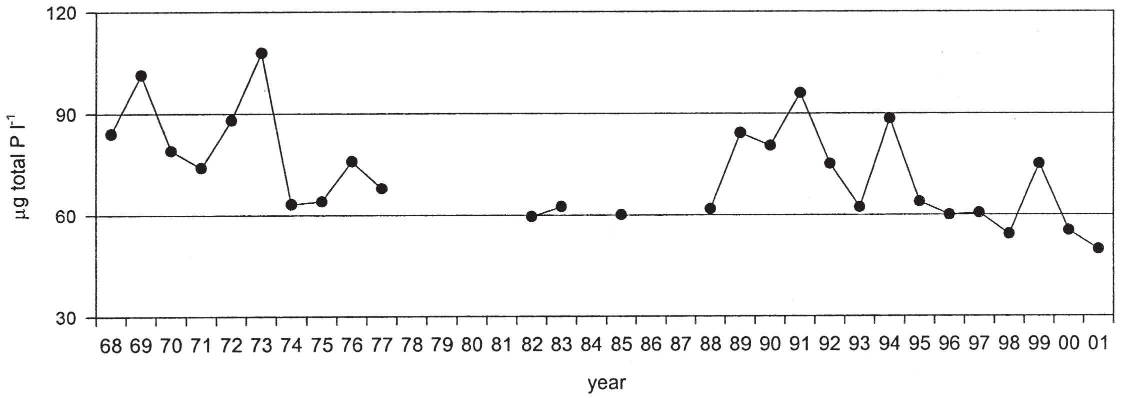


Figure 15 Annual mean TP concentrations 1968–2001



In terms of recovery, the greatest improvement is clearly visible from the mid-1990s onwards (Figure 15), following the reductions in external nutrient loading. Further positive indicators of recent recovery are the annual mean values for 1998, 2000 and 2001 (54, 55 and 50µgl^{-1} respectively), which are the three lowest values on record.

3.1.3 Plankton

3.1.3.1 Chlorophyll$_a$

Figure 16 illustrates the dynamic nature of chlorophyll$_a$ concentrations in Loch Leven over the past 34 years. There are usually one or two peaks each year, but with no consistent seasonal pattern. No clear recovery is evident from the time series. The seasonal Mann-Kendal test for trend gives a Z-statistic of −1.73, which equates to a p-value of 0.08, just above the 5% significance level (Snowling, 2001). There is, therefore, no significant evidence of a monotonic trend.

Figure 16 Chlorophyll$_a$ concentrations 1968–2001

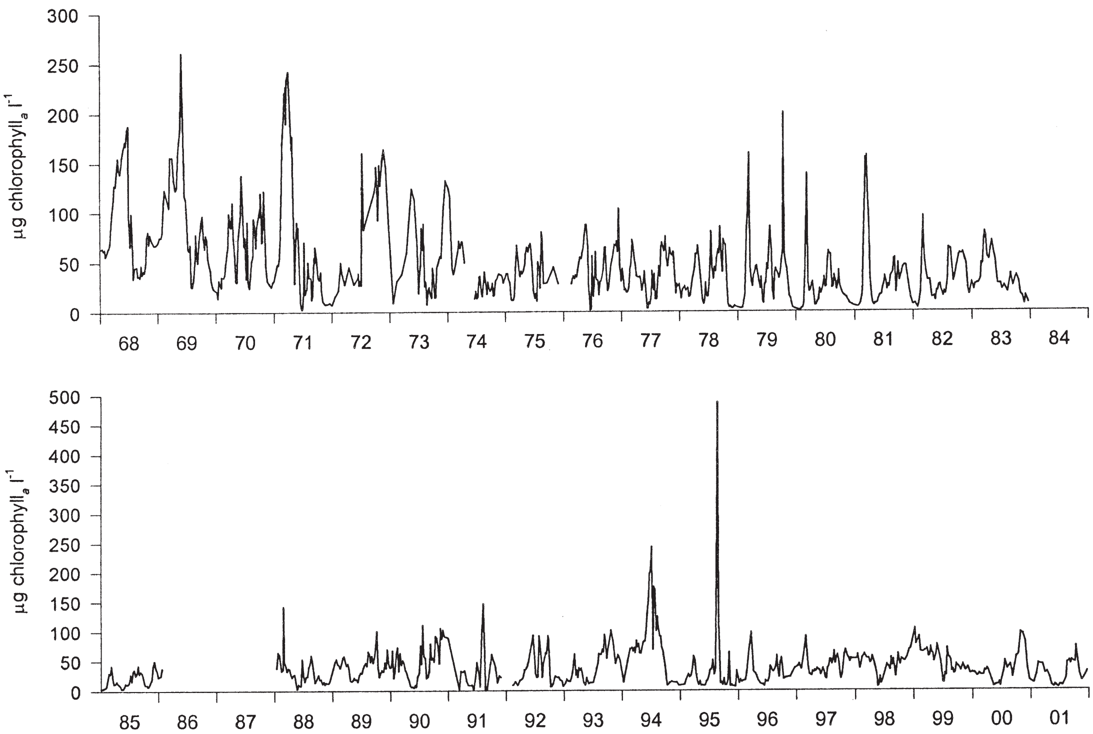
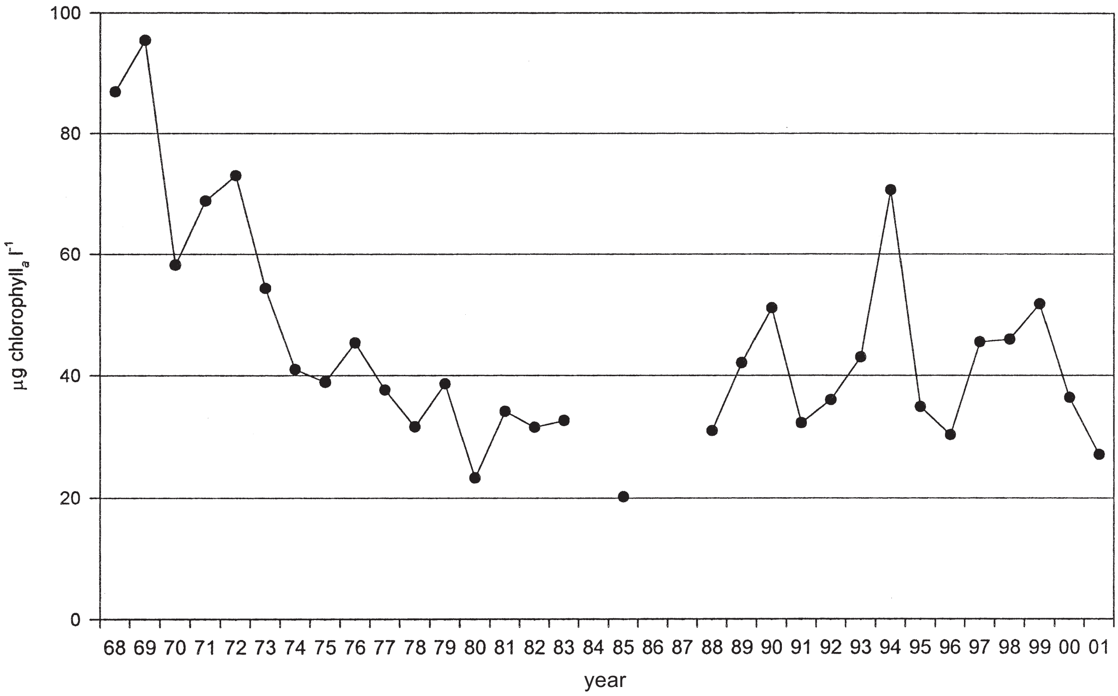


Figure 17 Annual mean chlorophyll$_a$ concentrations 1968–2001



In terms of recovery, the greatest improvement is clearly visible very early on in the time series in the early-1970s (Figure 17), before any major reduction in nutrient concentrations (Figures 9, 11 and 15). A t-test comparing the means of the first five years (76µgl^{-1}) with the last 5 years (41µgl^{-1}) reveals a highly significant difference (p <0.001), indicating a clear improvement between these two periods, although the annual mean concentration over the last 14 continuously sampled years has remained relatively constant at around 40µgl^{-1} (with the exception of 1994, where a summer cyanobacterial bloom pushed the annual mean to 71µgl^{-1}). One positive sign of recovery in more recent years is the annual mean value for 2001 (27µgl^{-1}), which is the third lowest value on record (only 20µgl^{-1} for 1985 and 23µgl^{-1} for 1980 being lower).

The dataset also reveals differences in the general seasonal pattern of phytoplankton development (Figure 18). In the last 5 years, on average, the spring phytoplankton peak has appeared earlier in the year and has strongly declined in abundance. A phytoplankton minimum now occurs through April to June, followed by a gradual rise to a second peak in October. Figure 18 also illustrates how the significant decline in chlorophyll$_a$ concentrations between the first five years and the last 5 years is particularly due to declines in spring. In fact, even though the formal seasonal Mann-Kendal test for trend showed no significant evidence of a monotonic trend, some of the individual months gave significant results. April, May and June all showed significant downward trends, whilst August actually showed the reverse, a significant upward trend, indicating worsening water quality (Snowling, 2001).

Figure 18 Seasonal pattern in monthly mean chlorophyll$_a$ concentrations

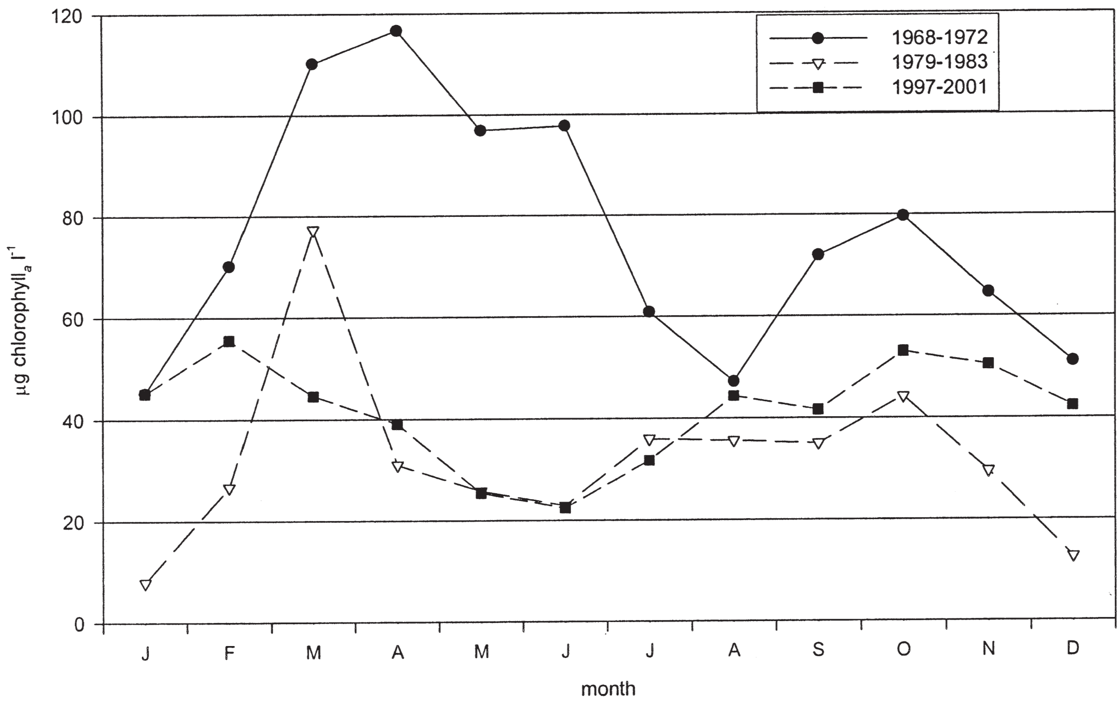
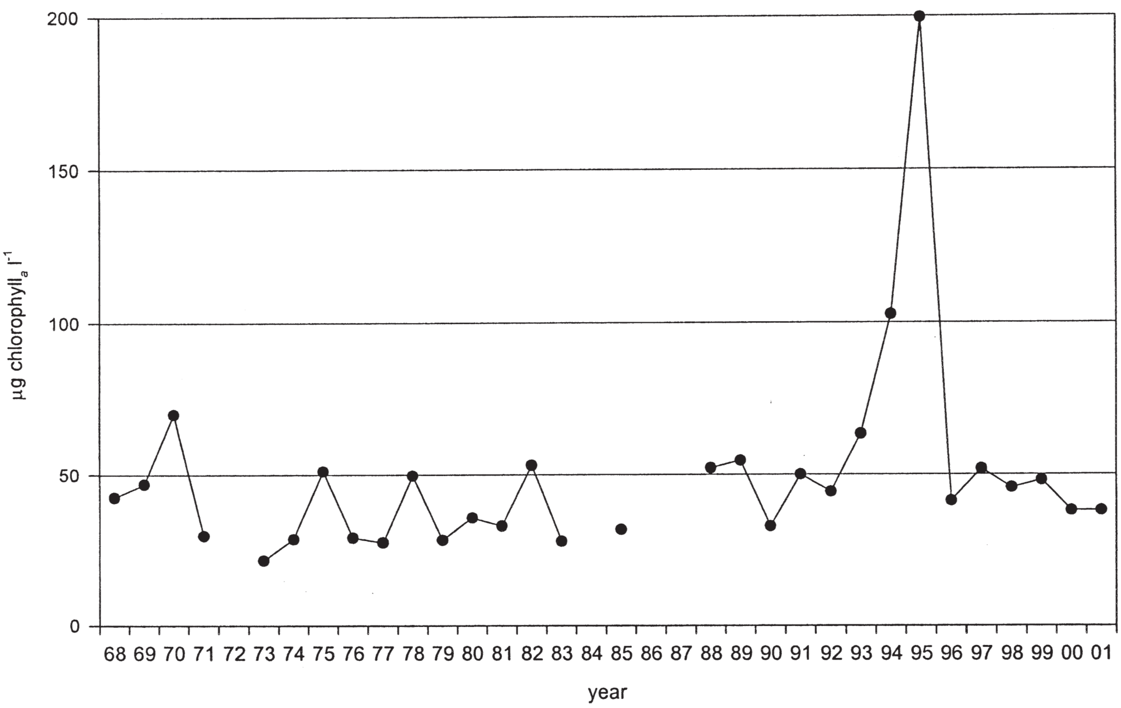


Figure 19 highlights how this declining trend in water quality for August was due to two particularly poor years, 1994 and 1995. Other than these years, concentrations have remained relatively constant for this month over the full 34-year period.

Figure 19 Monthly mean chlorophyll$_a$ concentrations for August 1968–2001



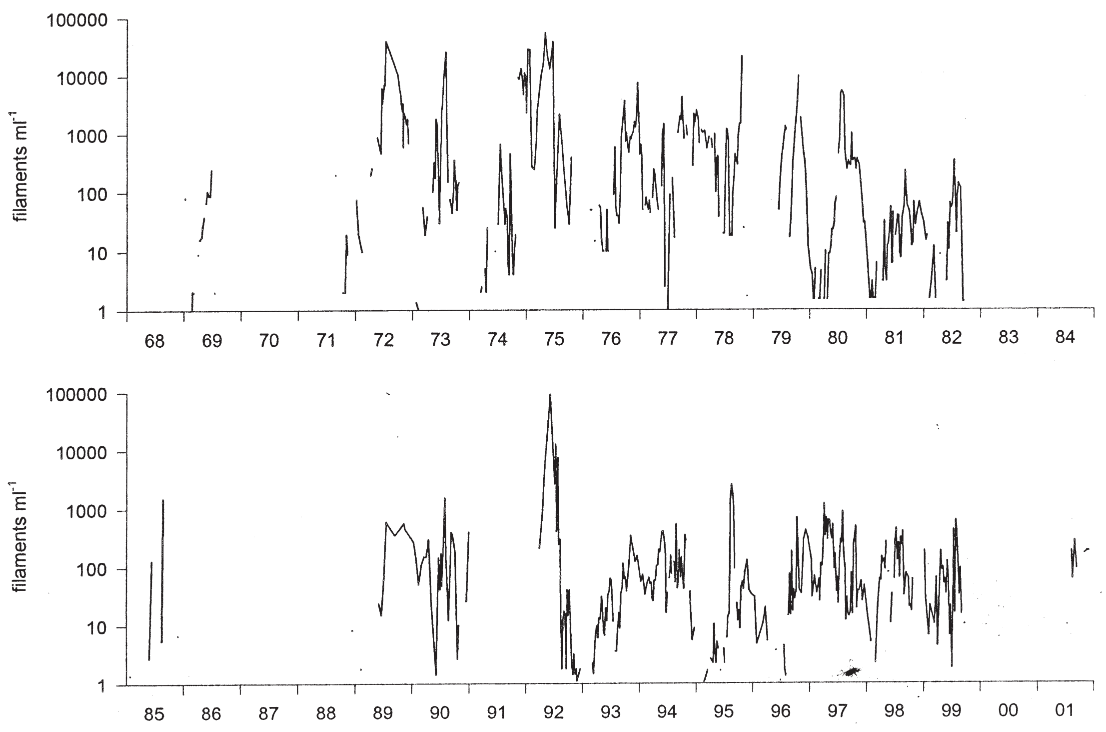
3.1.3.2 Algal species

Qualitatively, Loch Leven has been dominated throughout much of the 34-year period by diatoms (*Asterionella formosa*, *Aulacoseira* spp., *Cyclotella* spp., *Diatoma elongatum*, *Fragilaria crotonensis*, *Stephanodiscus* spp.), cyanobacteria (*Anabaena* spp., *Microcystis aeruginosa* and *Planktothrix agardhii*) and cryptophytes (*Cryptomonas* and *Rhodomonas* spp.). Quantitative data are not readily available in electronic format for detailing trends in most major algal groups or individual species.

However, the abundance of the three most significant cyanobacteria species in Loch Leven has been fully collated and can be used to illustrate changing patterns of abundance in this key algal group (Figures 20–22).

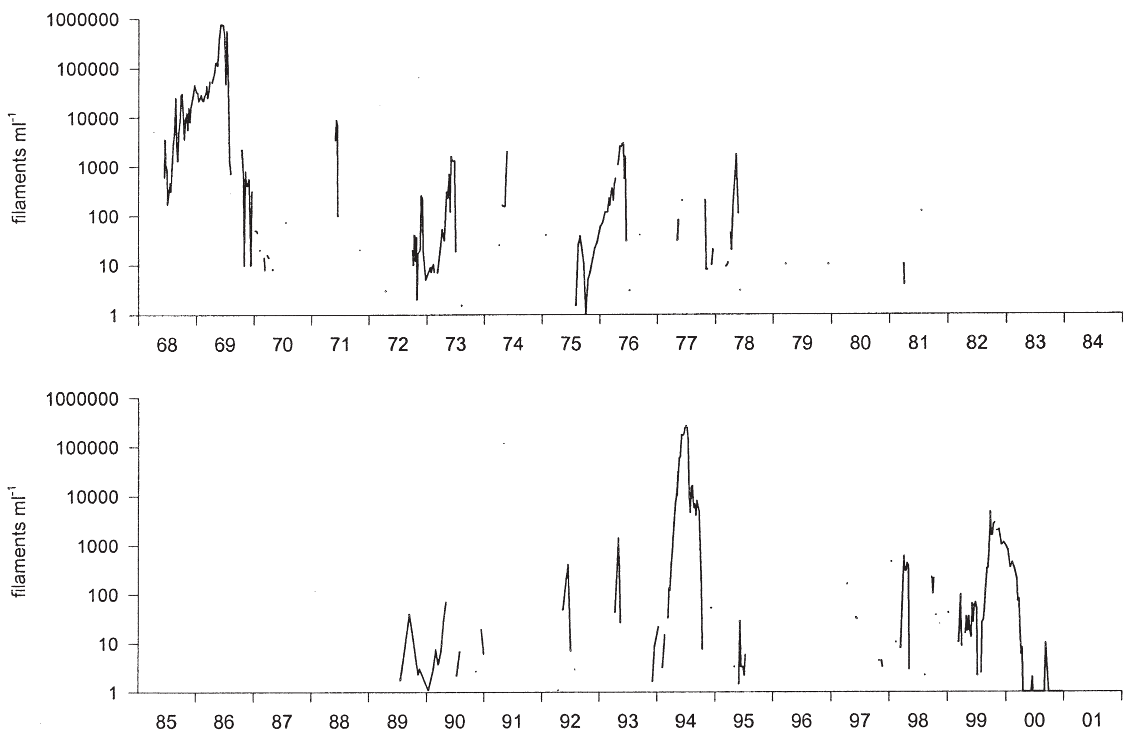
Anabaena flos-aquae, the most prominent of the *Anabaena* spp. occurring in Loch Leven, has been recorded in the phytoplankton in almost every year that sampling has taken place (Figure 20) and is probably one of the most dominant species throughout, in terms of algal biomass. Its abundance seems to have declined in the second half of the time series, with numbers rarely peaking above 1000 filaments ml^{-1} since 1989. Warning thresholds for *Anabaena* spp. are, however, generally about an order of magnitude less than this, ie 40–160 filaments ml^{-1} (Scottish Executive Health Department, 2002) and continue to be exceeded in most years. The data for 2000 and 2001 show a more promising trend, however, with *Anabaena* spp. recorded only for short periods in autumn and population densities remaining relatively low. Diatoms, particularly *Aulacoseira* spp., dominated the phytoplankton for much of 2000 and 2001.

Figure 20 *Anabaena flos-aquae* abundance (filaments ml^{-1}) 1968–2001



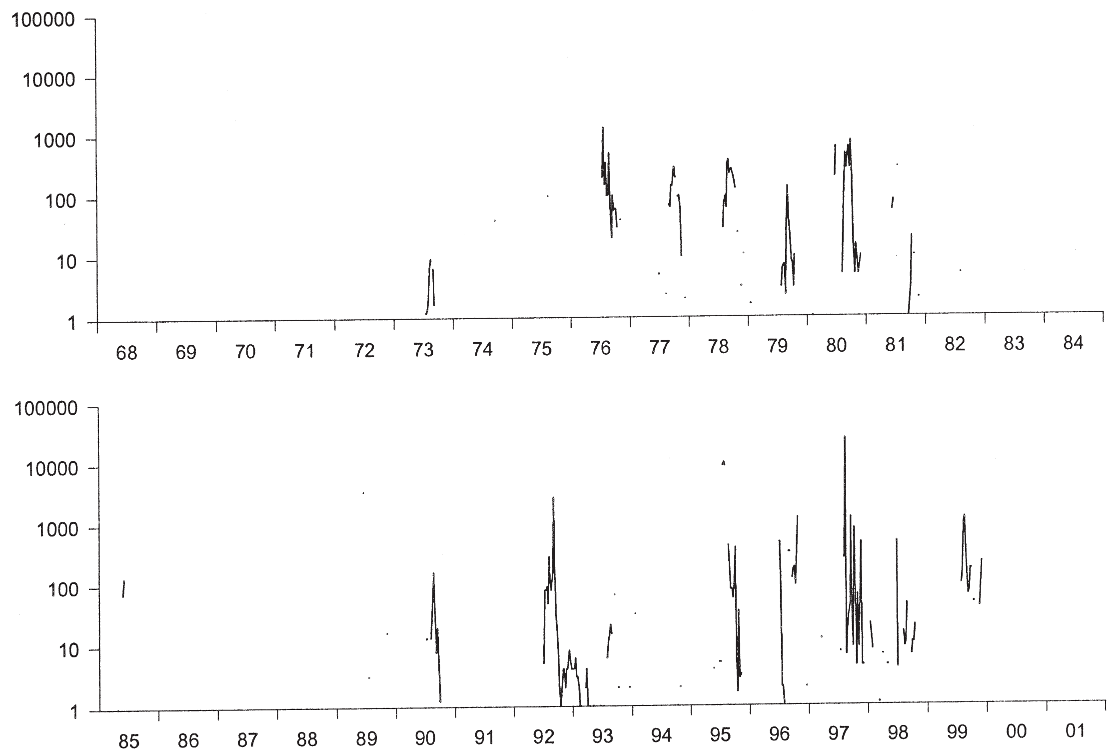
Planktothrix spp. (formerly *Oscillatoria*) are recorded less frequently than *A. flos-aquae*, nevertheless still achieving abundances greater than 100 filaments ml^{-1} in 14 of the 34 years (Figure 21). Three species have been prominent since 1968, with *P. agardhii* occurring the most frequently. 1968/9 saw a large, long-lasting population of *P. redekei* whilst the prominent peak of 1994 was due to *P. limnetica*. Warning thresholds for *P. agardhii* have been set at 250 filaments ml^{-1} (Scottish Executive Health Department, 2002) and have occasionally been exceeded.

Figure 21 *Planktothrix* spp. abundance (filaments ml^{-1}) 1968–2001



Microcystis aeruginosa, along with other species of *Microcystis*, was also recorded much less frequently than *A. flos-aquae*, but, nevertheless, still achieved abundances greater than 100 ml^{-1} in 12 of the 34 years (Figure 22). Warning thresholds for *M. aeruginosa* have been set at 40 colonies ml^{-1} for small colonies (90µm diameter) and only 3 colonies ml^{-1} for large colonies (200µm diameter) (Scottish Executive Health Department, 2002); when it is present, it often exceeds these.

Figure 22 ***Microcystis*** **spp. abundance (colonies ml^{-1}) 1968–2001**



3.1.3.3 Zooplankton

The zooplankton data presented here refers only to *Daphnia* populations, the most important phytoplankton grazer. There are large gaps in the *Daphnia* dataset, with no data for 1983–1988 and 1990. Pre-1975 data are also not currently available, although may be retrievable from PhD studies carried out at Stirling University at the time (Johnson and Walker, 1974). Data for 1999–2001 exist only for quarterly ECN monitoring, although fortnightly samples were taken alongside chemistry and phytoplankton samples for these years, and are currently being analysed for a MSc Research Project at Napier University. A number of publications provide information on other zooplankton groups at Loch Leven, particularly rotifers (Gunn and May, 1997, Gunn and May, 1999, May, 1980, May, 1983, May *et al.*, 1993).

Daphnia populations have been highly variable. Early species lists highlight the high abundance of *Daphnia* species (Scott, 1890; 1898 cited in Johnson and Walker, 1974) and they were also abundant in the early 1950s (Morgan, 1970). In terms of the 34-year monitoring period, they were, however, absent from regular loch samples from 1966 until July 1970 (Johnson and Walker, 1974). They re-appeared in the loch in August 1970 and reached very high densities in the summers of 1971 and 1972 (Johnson and Walker, 1974) (Figure 23). They have been the dominant zooplankton grazer since then although, unusually, they completely disappeared from the last four-months of regular samples analysed for 1998. There is no clear pattern in annual mean densities, with relatively large inter-annual variation (Figure 24).

Figure 23 ***Daphnia*** **monthly mean densities 1968–2001**

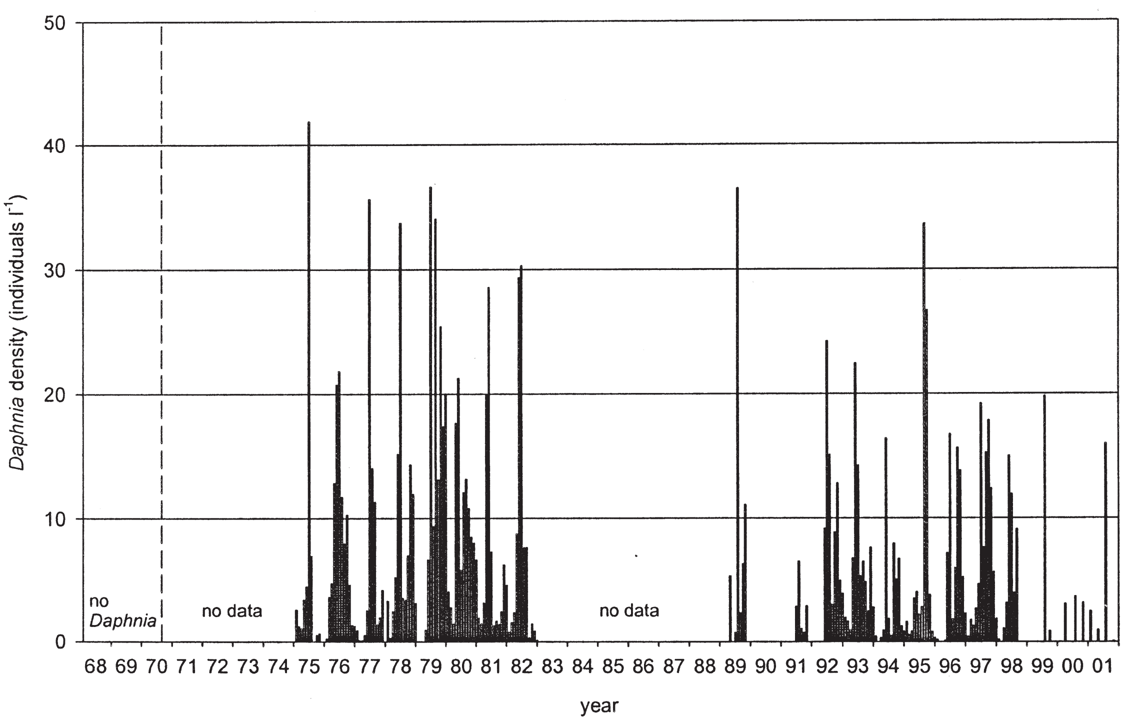
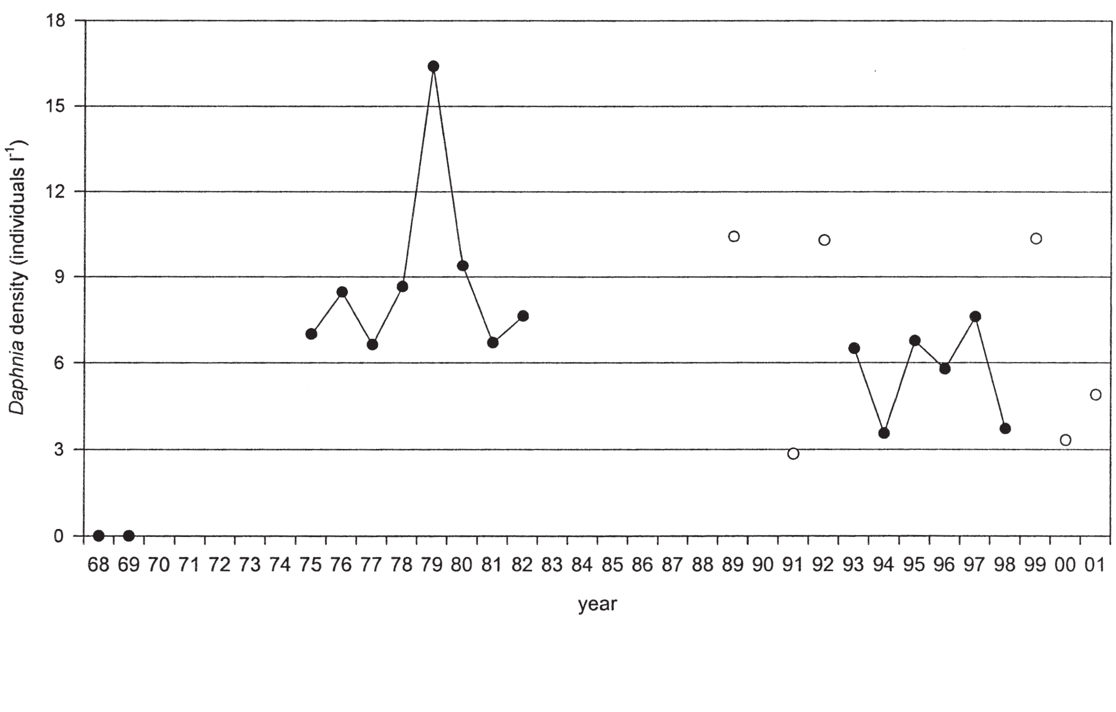
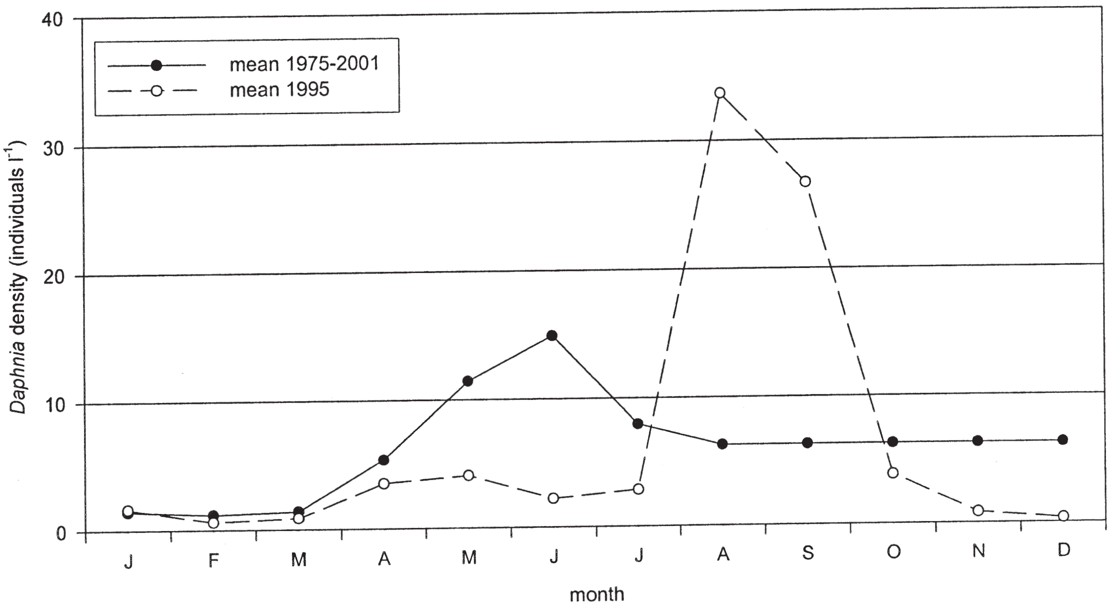


Figure 24 Annual mean *Daphnia* densities 1968–2001
(O indicates where the mean is based on few samples)



For most years for which data exist, there is a similar seasonal pattern in population development (Figure 25). Densities increase from April to June, decline in July and reach a second, smaller peak in August, before declining to a winter minimum. There were one or two exceptions to this pattern, such as their complete disappearance during the last four months of 1998, and in 1995, when populations remained very low throughout the year, except for the months of August and September (Figure 25).

Figure 25 Seasonal pattern in *Daphnia* densities



3.1.4 Correlation analysis

Correlation analysis was carried out to explore which factors were most closely related to, and possibly responsible for, two key water quality indicators, water clarity (Secchi depth) and phytoplankton biomass (chlorophyll$_a$).

In terms of Secchi depth, correlation analysis of annual mean values against a number of possible explanatory variables for the full 34-year period revealed the strongest relationship with chlorophyll$_a$ ($r = -0.75$), a strong negative correlation. This is even more apparent for the last five years (1997–2001), where >95% of the variability in annual mean Secchi depth can be explained by variability in annual mean chlorophyll$_a$ concentrations (Figure 26).

In terms of phytoplankton biomass, correlation analysis of annual mean chlorophyll$_a$ concentrations against a number of the possible explanatory variables for the full 34-year period reveals a strong negative correlation with *Daphnia* density ($r = -0.77$) (Figure 27), a modest positive correlation with TP ($r = 0.56$), and a very weak negative relationship with water temperature ($r = -0.04$).

Figure 26 Scatter plot of chlorophyll$_a$ against Secchi disc depth 1997–2001

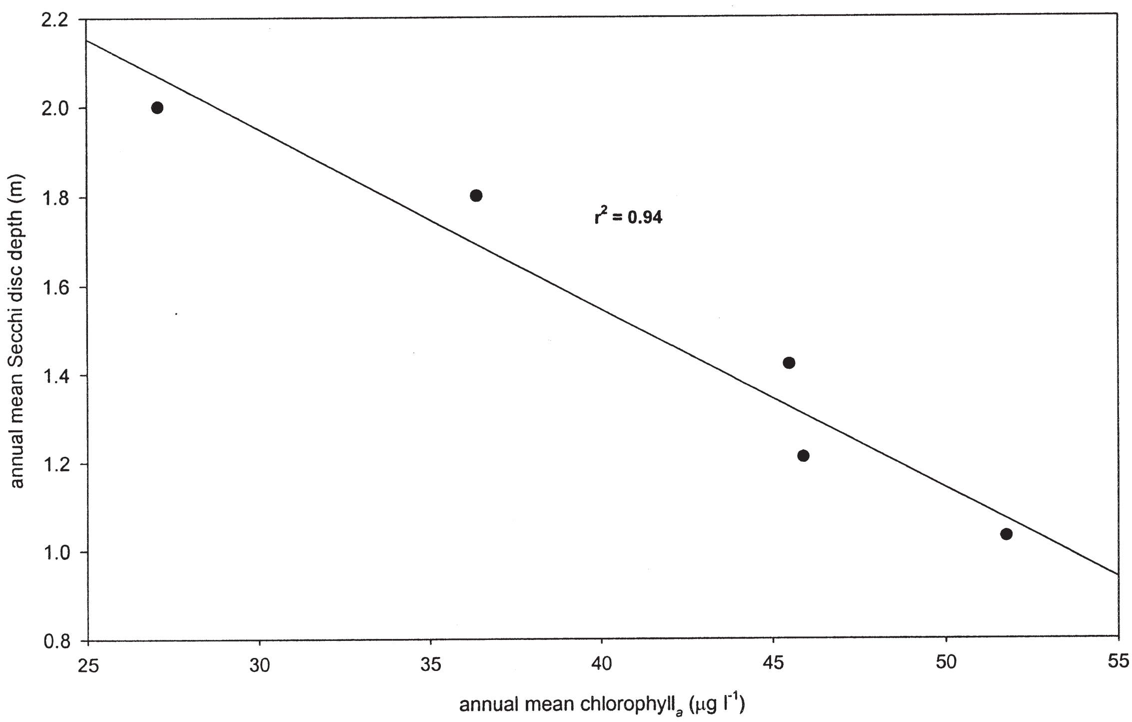
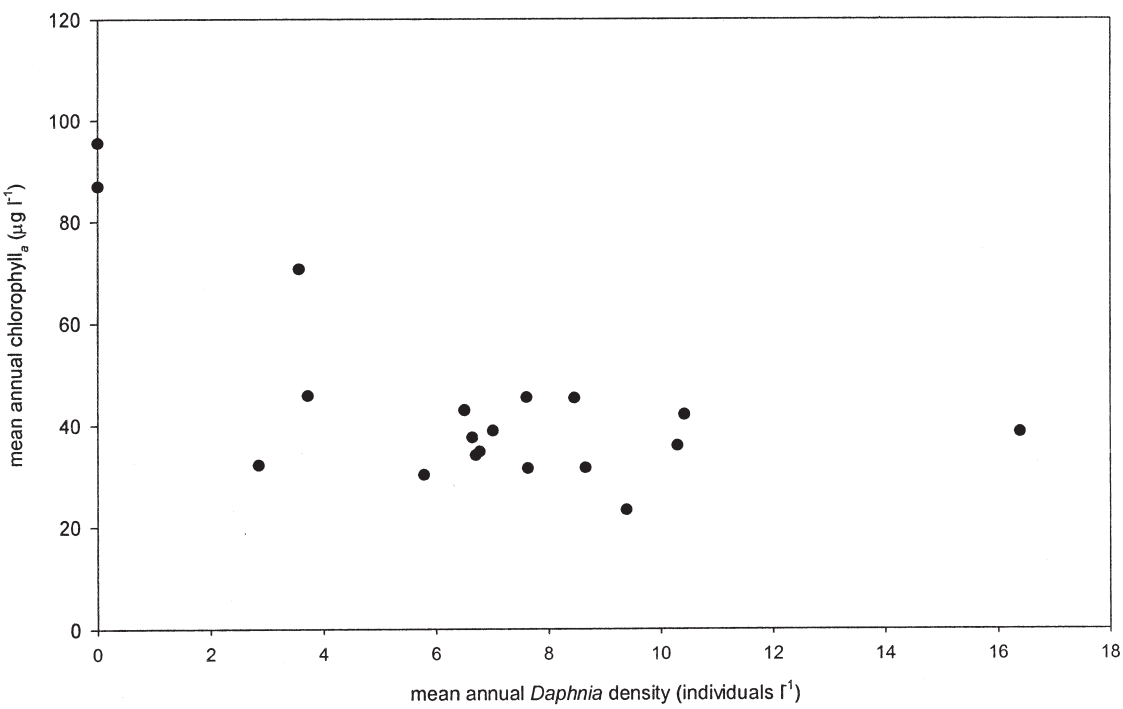


Figure 27 Scatter plot of chlorophyll$_a$ against *Daphnia* density 1968–1998

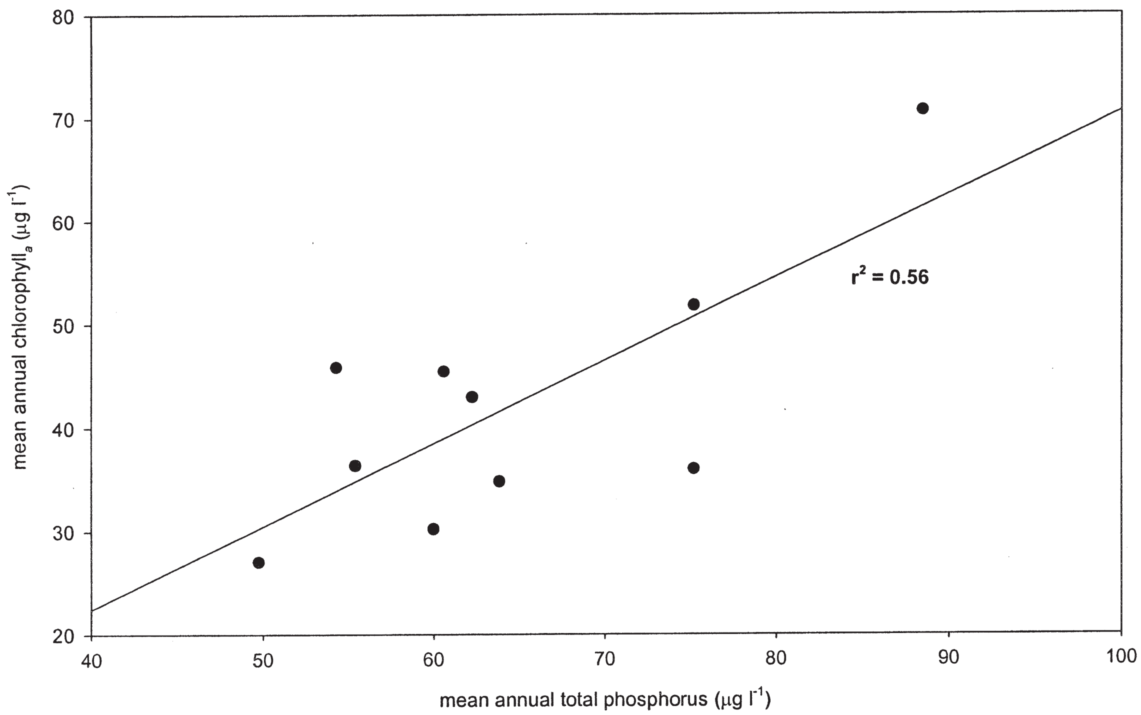


The impact of *Daphnia* is even more apparent in the first ten years (1968–77), with a very strong negative correlation (r = –0.97). This is largely driven by the first two years when *Daphnia* were absent, where the lack of grazer control on phytoplankton biomass is clearly apparent (Figure 27). Omitting these two points gives only a modest correlation (r = –0.46), although the years with the highest *Daphnia* density, such as 1980, have some of the lowest annual mean chlorophyll$_a$ concentrations. There appears to be a threshold annual mean *Daphnia* density of around 3 l^{-1}, above which there is little further impact on phytoplankton biomass. Sufficient zooplankton data is currently unavailable for the last 5 years to carry out any statistical analysis of recent recovery.

In the last 10 years (1992–2001), the relationship between chlorophyll$_a$ and TP concentrations appears to be becoming increasingly strong (r = 0.75) (Figure 28).

It is difficult to determine the precise effect of just one of these factors as they often have opposite effects and are also, themselves, correlated to a varying extent. For example, the declining TP concentrations over the last 10 years should result in decreasing algal biomass, but this could be counteracted by the observed increasing trend in temperatures or any decrease in *Daphnia* densities. There is some evidence that the warmer years in the last decade have improved the recovery signal through positive effects on zooplankton densities in spring (Carvalho & Kirika, 2003).

Figure 28 Scatter plot of TP against chlorophyll$_a$ (1992–2001)



3.2 Macrophytes

Changes in the submerged macrophyte assemblage are documented in Table 3, with species ranked in order of increasing Trophic Rank Score (Palmer, 1989). *Nitella opaca* is now generally considered synonymous with *Nitella flexilis* and many surveyors had difficulty distinguishing *Potamogeton pusillus* from *Potamogeton berchtoldii*. Both are, therefore, considered as single entities in the records.

There have been a number of changes in the submerged macrophyte assemblage of the loch that can be viewed largely as responses to eutrophication. The oligotrophic macrophyte species (low TRS values), *Isoetes lacustris* and *Lobelia dortmanna*, were last recorded in the 1820/30s (Balfour, 1894, Hooker, 1821). The survey carried out by West at the start of the 20th century (West, 1910) was the first comprehensive survey of the submerged macrophyte community and can be used as a baseline for comparison with later surveys. West (1910) reported 20 submerged macrophyte species, including eight *Potamogeton* and five charophyte taxa. Macrophyte changes since 1910 can largely be associated with eutrophication, indicated by the increasing site TRS value, and include the loss of five *Potamogeton* and four charophyte taxa and the establishment of two characteristic eutrophic species, *Potamogeton pectinatus* and *Zannichelia palustris*.

The survey period covered by Jupp *et al.* (1974), appears to be a transitional period, with small traces of low TRS species, such as *Myriophyllum alterniflorum*, *N. opaca* and *Potamogeton obtusifolius*, previously recorded by West (1910) and others earlier in the century, and, the first appearances of high TRS species, such as *P. pectinatus* and *Z. palustris*. The establishment of abundant crops of nuisance macroalgae, such as *Cladophora* spp. and *Enteromorpha intestinalis*, by 1972 (Jupp *et al.*, 1974) was another sign of progressing eutrophication. At this point, however, Loch Leven still retained a relatively low TRS compared with later years.

The small fluctuations in richness and TRS over recent years are largely due to changes in recording of rare species. For example, *Tolypella glomerata* is particularly under-recorded as it only appears to be present in small quantities in a restricted distribution and is only obvious for a short period in early summer, before most surveys take place. One qualitative change, that is clear from recent surveys, is in the charophyte composition, with the complete disappearance of the once abundant *N. opaca* after 1990 and the replacement of *Chara aspera*, which dominated up to 1972, by *Chara contraria* by 1990 (Robson, 1990). The only sign of recovery is in localised species richness reported in the latest macrophyte survey (Griffin and Milligan, 1999), which showed that there was significantly greater species richness in 1999 for individual sectors within the loch, compared with the previous survey (Murphy and Milligan, 1993).

What is more evident in recent years is a recovery in the maximum observed depth of submerged macrophytes (Table 3). In 1910 it was recorded as being about 4.6m, declined to 1.5m in 1972, but then recovered, to 1.8m in 1990, 2.1m in 1993 and 3.6m in 1999.

3.3 Invertebrates

Table 4 lists presence/absence data for a range of littoral taxa compiled from the International Biological Programme (IBP) studies from 1967–73, surveys carried out by the Forth River Purification Board (FRPB) in 1993 and samples collected under the Environment Change Network (ECN) programme from 1998–2001.

From this data, it is apparent that there has been a general increase in species richness. In particular, it is encouraging to note the re-occurrence in recent years of a much richer assemblage of mayflies, stoneflies, water beetles and caddisflies than was the case during the IBP period. Further evidence of improvement is provided by consistently higher Biological Monitoring Working Party (BMWP) and Average Score Per Taxon (ASPT) scores from 1999 onwards.

The BMWP score system, although designed for assessing the biological quality of rivers, is a useful surrogate measure for reporting on the water quality of littoral lake habitats. In general, a higher BMWP score indicates higher water quality. The BMWP total score can, however, improve with increased sampling effort and so may be misleading. To overcome this problem the ASPT score is also shown as it is largely independent of sample size and is, therefore, regarded as a better and more reliable indicator of biological quality.

Table 3 Presence/absence data for submerged macrophytes in Loch Leven from six surveys
Individual macrophyte and whole survey date Trophic Rank Scores (TRS) are also provided, following Palmer (1989)

		1910	1974	1986	1990	1993	1999
Species	**TRS**	**West**	**Jupp et al.**	**Robson**	**Robson**	**Murphy & Milligan**	**Griffin & Milligan**
Isoetes lacustris	5.0						
Lobelia dortmanna	5.0						
Myriophyllum alterniflorum	5.5	1	1				
Nitella opaca/flexilis	5.5	1	1		1		
Littorella uniflora	6.7	1	1	1		1	1
Potamogeton gramineus	7.3	1					
Potamogeton obtusifolius	7.3	1	1				
Potamogeton perfoliatus	7.3	1	1	1	1	1	1
Potamogeton praelongus	7.3	1					
Callitriche hermaphroditica	8.5	1	1	1	1	1	1
Chara globularis var virgata	8.5				1		
Eleocharis acicularis	8.5	1	1	1	1	1	1
Elodea canadensis	8.5	1	1	1	1	1	1
Potamogeton crispus	8.5		1	1			*1
Potamogeton pusillus/berchtoldii	8.5	1			1	1	1
Persicaria amphibium	9.0	1	1	1	1	1	1
Myriophyllum spicatum	10.0	1					
Potamogeton filiformis	10.0	1	1	1	1	1	1
Potamogeton lucens	10.0	1					
Potamogeton pectinatus	10.0		1	1	1	1	1
Zannichelia palustris	10.0		1	1	1	1	1
P. x zizii (P. gramineus x lucens)		1					
Chara aspera		1	1				
Chara contraria					1	1	1
Chara fragilis		1					
Chara vulgaris		1					
Chara sp.				1			
Tolypella glomerata		1			1	1	
Fontinalis antipyretica			1	1			
Species richness		20	15	12	13	12	12
Site TRS		7.99	8.10	8.70	8.58	8.70	8.68
Maximum recorded growing depth (m)		4.6	1.5		1.8	2.1	3.6
							*ECN record
Nuisance macroalgal species							
Cladophora sp.			1	1	1	1	1
Enteromorpha intestinalis			1	1	1	1	1

Table 4 Presence/absence data for littoral macro-invertebrates in Loch Leven from six survey periods

		1967–73 (IBP)	1993 (FRPB)	1998 (ECN)	1999 (ECN)	2000 (ECN)	2001 (ECN)
TRICLADIA (flatworms)	*Polycelis* sp.	X	X	X	X	X	X
NEMATODA (roundworms)	Nematoda	X		X	X	X	X
GASTROPODA (snails)	*Valvata piscinalis*	X	X		X	X	X
	Potamopyrgus jenkinsi	X	X	X	X	X	X
	Lymnaea peregra	X	X	X	X	X	X
	Lymnaea truncatula		X				
	Physa fontinalis	X	X	X	X	X	X
	Bathyomphalus contortus			X	X	X	X
	Gyraulus albus	X		X	X	X	X
	Planorbis carinatus				X	X	X
	Planorbis laevis		X				
	Armiger crista				X	X	X
	Ancylus fluviatilis	X					
BIVALVIA (mussels)	*Anodonta* sp.	X			X		X
	Sphaeriidae	X	X	X	X	X	X
OLIGOCHAETA (segmented worms)	Oligochaeta	X	X	X	X	X	X
HYDRIDAE (hydras)	Hydridae	X		X	X	X	X
HIRUDINEA (leeches)	*Piscicola geometra*					X	X
	Glossiphonia complanata	X	X	X	X	X	X
	Glossiphonia heteroclita	X		X			
	Helobdella stagnalis	X	X	X	X	X	X
	Theromyzon tessulatum	X	X	X	X	X	X
	Erpobdella octoculata	X	X	X	X	X	X
HYDRACARINA (water mites)	Hydracarina	X	X	X	X	X	X
CRUSTACEA (crustaceans)	Ostracoda	X		X	X	X	X
	Cladocera	X		X	X	X	
	Copepoda	X			X	X	
	Asellus aquaticus	X	X	X	X	X	X
	Gammarus pulex	X	X	X	X	X	X

Table 4 *(continued)*

		1967–73 (IBP)	1993 (FRPB)	1998 (ECN)	1999 (ECN)	2000 (ECN)	2001 (ECN)
EMPHEMEROPTERA (mayflies)	*Cloeon simile*		X				
	Siphlonurus lacustris		X	X			
	Ecdyonurus sp.		X	X	X	X	X
	Ephemerella ignita			X	X		
	Caenis horaria	X	X	X	X	X	X
	Caenis luctuosa group		X	X	X	X	X
PLECOPTERA (stoneflies)	*Nemovra cinerea*		X				
	Leuctra hippopus		X				
	Leuctra geniculata					X	
	Capnia bifrons		X				
	Diura bicaudata		X	X	X	X	X
	Chloroperla torrentium	X			X		
HEMIPTERA (water bugs)	Gerridae	X					
	Callicorixa praeusta	X					
	Callicorixa wollastoni	X					
	Arctocorisa germari			X			
	Micronecta poweri	X		X	X	X	X
	Sigara concinna		X				
	Sigara dorsalis	X	X	X	X		X
	Sigara falleni	X		X		X	X
COLEOPTERA (beetles)	*Haliplus lineolatus*				X	X	X
	Haliplus sp.	X		X		X	X
	Dytiscidae		X	X	X	X	X
	Ilybius fuliginosus	X	X				
	Nebrioporus depressus/elegans			X	X	X	X
	Platambus maculatus						X
	Oreodytes sanmarkii					X	X
	Oreodytes septentrionalis				X		
	Hydrophilidae			X	X		
	Elmis aenea				X	X	X
	Limnius volckmari	X					
	Oulimnius tuberculatus	X		X	X	X	X

Table 4 *(continued)*

		1967–73 (IBP)	1993 (FRPB)	1998 (ECN)	1999 (ECN)	2000 (ECN)	2001 (ECN)
TRICHOPTERA (caddis flies)	*Rhyacophila dorsalis*		X				
	Cyrnus trimaculatus			X			
	Polycentropus flavomaculatus		X	X	X	X	X
	Tinodes waeneri	X	X	X	X	X	X
	Agraylea multipunctata		X	X	X	X	X
	Anabolia nervosa		X		X	X	X
	Chaetopteryx villosa				X		
	Limnephilus centralis		X		X		
	Limnephilus lunatus		X	X	X	X	X
	Limnephilus vittatus		X		X	X	X
	Limnephilidae		X		X	X	X
	Goera pilosa				X		
	Athripsodes cinereus		X	X	X	X	X
	Mystacides sp.				X	X	X
	Oecetis ochracea	X			X	X	X
DIPTERA (true-flies)	Tipulidae		X	X	X	X	X
	Ceratopogonidae	X		X	X	X	X
	Chironomidae	X	X	X	X	X	X
	Number of Taxa	39	41	44	55	51	52
	BMWP Score	113	169	153	172	141	138
	ASPT Score	4.71	5.63	5.46	5.55	5.04	4.93

3.4 Fish

Table 5 lists all fish species recorded in Loch Leven for five time periods. Arctic charr (*Salvelinus alpinus*) and Atlantic salmon (*Salmo salar*) were both lost following modifications of the outflow carried out between 1829 and 1832. North Atlantic eel (*Anguilla anguilla*) was lost in the 1930s but appears to have successfully returned to the site. Of particular note is the introduction of non-native rainbow trout from 1993, which has included annual re-stocking with large numbers (around 30,000 per year) of fish up to 2lbs in weight. The native brown trout stocks are supplemented by the introduction of fry, reared from eggs taken from adult fish entering the Camel Burn to spawn. The numbers of fry involved vary but are well in excess of the rainbow trout, with over 250,000 being introduced in 1994 alone. Details on stocking and fish catches can be found at: http://www.kinrosshouse.com/projectfishing.html

Table 5 Presence/absence data for fish in Loch Leven for five periods

	pre-1830	1834/35	1968–73	1993	2000
Native					
Atlantic salmon	1				
Salmo salar					
Arctic charr	1				
Salvelinus alpinus					
trout (sea/brown)	1	1	1	1	1
Salmo trutta					
perch	1	1	1	1	1
Perca fluviatilis					
pike	1	1	1	1	1
Esox lucius					
minnow	1	1	1	1	1
Phoxinus phoxinus					
stickleback	1	1	1	1	1
Gasterosteus aculeatus					
North Atlantic eel	1	1		?	1
Anguilla anguilla					
stone loach	1	1	1	1	1
Noemacheilus barbatulus					
brook lamprey	1	1	1	1	1
Lampetra planeri					
Native species richness	**10**	**8**	**7**	**7**	**8**
Introduced					
rainbow trout				**1**	**1**
Salmo gairdneri					

4 DISCUSSION

4.1 Physics, chemistry and plankton

The 34-years of monitoring cover a period of great environmental variability and directional change. This includes:

1. a large reduction in phosphorus loading from the catchment by the control of point-sources of pollution (woollen mill and STWs)
2. a general trend of increasing water temperatures, particularly within the last decade
3. the re-appearance of *Daphnia* in 1970, following at least a 4-year period of absence

Frequent monitoring over a long-time period is essential to establish the impact of these changes, particularly to distinguish the ecological impact of the point-source controls from other potential driving forces.

The LLAMAG report (1993) set specific targets for three aspects of water quality: water clarity, nutrient concentrations and extent of algal bloom development. The targets set were:

- annual mean Secchi disc depth of 2.5m
- annual mean total phosphorus concentration of $40\mu g l^{-1}$
- annual mean chlorophyll$_a$ concentration of $15\mu g l^{-1}$

These targets were based on simple mathematical models and aimed to improve water clarity sufficiently to allow *Chara* to grow to a depth of 4m (LLWGWG, 1996), a feature of the loch recorded by West (1910). It must be noted, however, that more recent studies suggest that, in general, submerged macrophytes will grow to a depth of two to three times the Secchi depth (Canfield *et al.*, 1985, Chambers and Kalff, 1985). This suggests that an annual mean Secchi depth of 2.0m may be an acceptable and more achievable target. The following discussion of ecological recovery will focus on patterns of change in these three indicators and the role that other factors may have played in their overall trends.

4.1.1 Water clarity

In terms of Secchi depth, the statistical trend analysis provided no evidence of a monotonic trend. The only significant result was for a decline in water clarity for the month of August. Despite this result, and the strong inter-annual variability, a slight improving trend is apparent, with annual minimum, mean and maximum Secchi depth values all generally increasing over the 34-year period. An annual mean of 2.0m was attained in 2001.

The LLAMAG (1993) target Secchi disc depth of 2.5m has not been achieved in any year, although water clarity during the summer has been exceptionally good for the last two years, peaking at over 3.5m in both years. The seasonal light requirements for *Chara* growth are not currently known, but its maximum recorded growing depth is a feature that should be closely monitored (see Section 4.3). *Charophyte* distributions with depth, may not be just a simple response to water clarity, but could also be related to other factors, such as epiphyte or macro-invertebrate grazer abundances (Van den Berg, 1999). It may, therefore, be more appropriate to set a more specific ecological target of 4m maximum recorded growing depth of *Chara*.

Unlike the Secchi depth target, this value would be based on actual historical data and only requires a single summer survey along a number of depth transects to obtain, compared with regular and frequent Secchi depth measurements throughout the year (although these measurements are important in interpretation of the cause of ecological changes).

The very strong negative relationship between Secchi depth and chlorophyll$_a$ highlighted in the correlation analysis, suggests that phytoplankton abundance is the main driver of water clarity. The strength of the relationship is surprising, as it would be expected that, given the shallow and exposed nature of the loch, wind-induced re-suspension of bottom sediments would have a significant effect on water clarity. The extent and frequency of physical disturbance of the bottom sediments of the loch by wind is unknown, although increases as wind speed increases (Smith, 1974). Wind speed is, perhaps, only strongly related to water clarity during shorter periods of high wind speeds.

4.1.2 Total phosphorus

The statistical trend analysis provided conclusive evidence of a highly significant declining trend in TP concentrations, with particularly low annual mean concentrations in recent years (50µgl^{-1} in 2001). What is apparent is that the improving trend in in-loch TP concentrations is not simply a direct response to reductions in external nutrient load. The SRP data suggest that there has also been a big reduction in internal load from the sediments. The evidence for this comes from the magnitude and timing of peak SRP concentrations, which normally occur between August and October, but have declined dramatically over the last seven years. Wider research on lake recovery suggests that the decline in primary production, associated with external load reduction, is the principal driving force behind this gradual decrease in internal sediment release (Sas, 1989).

Despite the significant improvement, the target of an annual mean TP concentration of 40µgl^{-1} was not achieved in any year. The lowest values on record were 54, 55 and 50µgl^{-1} in 1998, 2000 and 2001, respectively. A baseline TP value of 45µgl^{-1} for Loch Leven has been estimated using palaeoecological methods (diatom-phosphorus transfer functions), although this is thought to be an over-estimate due to bias in the model (Bennion *et al.*, 2001). The PLUS model, which uses export-coefficients and past catchment land-use, estimated a baseline of 20µgl^{-1} for Loch Leven (Bennion *et al.*, 2001), although this approach may under-estimate catchment inputs. Interim WFD guidance on phosphorus targets for UK lakes (Carvalho *et al.*, 2003) estimates a reference target of 29µgl^{-1} for a high alkalinity lake, such as Loch Leven, with a doubling of this concentration indicating a site moving out of "good status". We would recommend that the target value of 40µgl^{-1} remains as it could possibly be achieved in the long-term with reductions in internal loading and further catchment management aimed at tackling diffuse sources of phosphorus from agriculture and household septic tanks.

4.1.3 Chlorophyll$_a$ concentration

The statistical trend analysis provided no conclusive evidence of a monotonic trend, with a result just above the significance level. A more discernible declining trend was, however, apparent in annual mean values, particularly in the 1970s, before any major reduction in nutrient loading or in-lake nutrient concentrations. The correlation analysis revealed that the decline in this period was strongly related to the re-appearance of *Daphnia*, and that phytoplankton biomass was significantly limited even at relatively low *Daphnia* densities (approx. >3 l^{-1}). The relationship with *Daphnia* was particularly driven by years when they were very scarce or completely absent (1968, 1969, 1994, 1998) and phytoplankton biomass reached very high levels, or when their numbers were high (1980 and 1992) and phytoplankton biomass remained low.

The influence of nutrient concentrations in driving chlorophyll$_a$ concentrations appears to have become more important in the last 5–10 years, highlighted by the strong correlation with TP concentrations for this period. This suggests that only in recent years have nutrient concentrations declined to levels that are beginning to limit phytoplankton biomass. Supporting evidence for this comes from the decline in SRP concentrations, where the annual mean concentrations for the last 5 years are the five lowest values in the 34-year dataset, and monthly mean values have been <10µgl^{-1} for 10 or more months of the year.

Despite all of these positive signs, the target of an annual mean chlorophyll$_a$ concentration of 15µgl^{-1} was not achieved in any year. The lowest values on record were 20, 23 and 27µgl^{-1} in 1985, 1980 and 2001, respectively. It may be that a target of 15µgl^{-1} is almost unattainable for a shallow, lowland loch, where phytoplankton growth is neither light- nor temperature-limited throughout much of the year. The increasing temperatures at Loch Leven in recent years, which are a response to the warmer winter temperatures experienced by the UK as a whole (http://www.met-office.gov.uk/research/hadleycentre/obsdata/CET.html), may have exacerbated this problem. The warmer springs in recent years, however, appear to be having a positive impact on *Daphnia* abundance (Carvalho & Kirika, 2003), which should result in reduced phytoplankton over this period. This is supported by the seasonal chlorophyll$_a$ data which shows, for the last 5 years, an earlier winter peak (February) and minimum phytoplankton concentrations in May and June, rather than in the colder winter months of December and January seen in earlier years. In fact, even though the formal seasonal Mann-Kendal test for trend showed no significant evidence of a trend in annual mean concentrations, April, May and June all showed significant downward trends. This may be critical for loch recovery, as clearer conditions during spring are thought to be important for healthy establishment of submerged macrophytes.

4.2 Macrophytes

Many of the changes in the submerged macrophyte assemblage of the loch can be viewed largely as responses to eutrophication. The losses of oligotrophic macrophyte species in the 1820/30s are thought to be a response to the combined effect of eutrophication of the loch and a major water level reduction following modifications of the outflow carried out between 1829 and 1831 (Morgan, 1970) and macrophyte changes since 1910 (West, 1910) are associated with an increasing site TRS value.

In terms of recovery, no improving trends in species richness are apparent. Griffin and Milligan (1999) did, however, show a significantly greater species richness in 1999 for individual sectors within the lake, compared with the previous survey (Murphy and Milligan, 1993). The most striking evidence for recent recovery is, however, in the maximum observed depth of submerged macrophytes, increasing from a low of 1.5m in 1972 to 3.6m recorded in 1999 (Griffin and Milligan, 1999).

4.3 Invertebrates

Records from the late 19th century (Scott, 1891) and the first half of the 20th century (unpublished data of Professor Balfour Browne) indicate that during this period Loch Leven had a diverse and abundant invertebrate fauna including species of larval mayflies, stoneflies and caddisflies as well as numerous water beetles, snails and other taxa. However, by the time that detailed studies of the loch were carried out between 1967 and 1973, under the auspices of the International Biological Programme (IBP), the benthic invertebrate fauna had become relatively poor in terms of species diversity (Table 4). The macro-invertebrate communities were comprised mainly of oligochaete worms, chironomid midge larvae and a few other taxa with most of the formerly abundant mayfly, stonefly, caddisfly, Odonata and water beetle species absent (Maitland and Husdspith, 1974). The eutrophication of the loch, which had led to increased algal growths resulting in declines in higher plants and oxygen levels, was blamed for the absence of these macro-invertebrate taxa. In spite of subsequent efforts to reduce the inputs of nutrients into Loch Leven, a repeat survey of the benthos of the sandy and muddy loch sediments, carried out in 1994, showed that the fauna remained essentially the same as in the late 1960's and early 1970's (Gunn and Kirika, 1994).

In the ensuing decade there has been a greater emphasis on sampling the littoral (shoreline) areas of Loch Leven, including stony shores and macrophyte beds, thereby providing an opportunity to examine whether there is any evidence to suggest that there has been an improvement in the diversity of the macro-invertebate communities. The presence/absence data for a range of littoral taxa presented in Table 4 do highlight evidence of improvements in water quality and habitat conditions since the late 1960s/early 1970s in terms of overall taxa richness and richness of particularly sensitive groups (mayflies, stoneflies, water beetles and caddisflies). Further evidence is provided by higher Biological Monitoring Working Party (BMWP) and Average Score Per Taxon (ASPT) scores for the later data sets.

A word of caution has to given about drawing direct comparisons between the results of different surveys as sampling effort varied greatly, as did the number and type of littoral habitats sampled. For example, the ECN results are collated from three predominantly stony sample sites while the FRPB data is derived from a greater range of stony shores as well as from macrophyte beds. Nevertheless, despite these provisos, it is possible to derive some broad conclusions about the trends in the macro-invertebrate communities especially as we have the IBP data set available to act as a baseline for drawing comparisons.

The results of additional macro-invertebrate surveys of macrophyte beds in Loch Leven, carried out by the Scottish Environment Protection Agency in 1998 and 1999, also appear to lend support to a trend of improving conditions (Long, 2000).

The extent to which the macro-invertebrate fauna has recovered compared with the pre-eutrophication era is difficult to assess given the lack of comprehensive species lists for the earlier periods. Nevertheless, it may be possible, in future, to make direct comparisons with particular macro-invertebtrate groups for which there are detailed historical records, for example, Coleoptera (beetles).

4.4 Fish

Arctic charr and Atlantic salmon were both lost from Loch Leven following modifications of the outflow carried out in 1829 and 1830, although the former was declining in abundance before this, possibly in response to the onset of eutrophication at the site (Morgan, 1974). The loss of the North Atlantic eel (*A. anguilla*) in the 1930s may also be a response to eutrophication of the loch, but is more likely associated with declining water quality in the outflow, the River Leven. In recent years (date unknown), eels appear to have successfully returned to the site.

Of further importance in terms of conservation value, was the introduction of large numbers of specially-reared native brown trout (initially, in 1988, as juvenile fish but latterly as fingerlings or fry) and, since 1993, of non-native rainbow trout. This fish was introduced because of its greater tolerance of poor water quality. Its impacts on the ecology of the site are not known, although the stocking of large numbers of fry of both species should be managed extremely carefully because of their potential impact on zooplankton populations during spring and summer (see following section).

4.5 Recommendations for future monitoring and management

There are several good indications of recovery at Loch Leven. Nutrient concentrations have significantly declined and there are strong signs that phytoplankton biomass has declined in recent years in response to this. More significant, from a conservation perspective, is the fact that submerged macrophytes are showing an improving trend in terms of coverage into deeper water, and macro-invertebrate species richness has greatly increased. The evidence for recovery is strongest for the last few years, particularly the last two, which highlights the question of whether it is a true and sustained recovery. This question will only be answered by continued monitoring of key parameters over the next few years.

Research on shallow lake functioning does, however, help to identify key features of successful restoration and effective management actions that can help sustain them. It particularly highlights the key role of submerged macrophytes in stabilising clearer water over a turbid, phytoplankton-dominated state (Jeppesen *et al.*, 1998, Meijer *et al.*, 1999, Scheffer *et al.*, 1993). These features are:

- nutrient concentrations
- macrophyte coverage
- zooplankton grazer densities (or planktivorous fish abundance).

Critical nutrient levels for a stable clear state vary, depending on factors such as lake size and depth, but evidence collated from a large number of studies suggests mean annual TP concentrations of $<50 \mu g l^{-1}$ are important for long-term stability (Jeppesen *et al.*, 1998), a value that is just beginning to be achieved at Loch leven. Further reductions in nutrient concentrations, through careful management of diffuse nutrient sources (including septic tanks), are likely to be important in sustaining concentrations below $50 \mu g l^{-1}$ and the current target of $40 \mu g l^{-1}$ should be maintained as a long-term goal. The LLAMAG report (1993) discusses many of the catchment management options available.

In terms of macrophytes, an areal cover of >25% is recommended (Meijer *et al.*, 1999). Griffin and Milligan (1999) show that macrophyte coverage in Loch Leven in 1999 was extensive in areas of the loch that were less than 2.0m deep. This equates to approximately 45% areal cover (Linda May, personal communication). The current macrophyte coverage, therefore, appears to be more than sufficient. One note of caution must, however, be highlighted: submerged macrophyte beds are very sensitive to water level fluctuations. Extreme fluctuations should be discouraged during the macrophyte-growing season, as sudden increases in water level may reduce light availability, whilst a sudden lowered water level may damage plants through wave action or desiccation. Extreme fluctuations may even cause a shift between clear water, macrophyte-dominated and turbid, phytoplankton-dominated states (Wallsten & Forsgren, 1989). If used appropriately, however, water level management can be a useful management tool for lake restoration (Coops *et al.*, 2003).

In terms of what *Daphnia* densities are important to sustain clearer water, the correlation analysis suggests a threshold annual mean density of around 3 individuals l^{-1}. Above this level significant grazing limitation of phytoplankton biomass occurs, although this is dependent upon the composition of the phytoplankton population, with smaller algae being more readily consumed. It is recommended that this value be added as a key management target. The complete loss of *Daphnia* populations from Loch Leven has, in the past caused the most severe deteriorations in water quality. The reason for their disappearance is unclear, but it is known that between 1958–1964 the loch was polluted by a discharge of the insecticide dieldrin, used as a moth-proofing agent (Holden, 1964).

There is no strong evidence that stocking with rainbow trout and brown trout fry has had any significant impacts on *Daphnia* populations in Loch Leven. The stocking of very large numbers of brown trout in 1994 may have been an important factor in the low *Daphnia* densities and consequent poor water quality in that year, but more limited stocking in other years has less discernible effects. Young fish are particularly known to feed on *Daphnia*, but the scale of their impact is currently unknown. Research does indicate that stocking more fry than an 'optimal' level leads to fewer surviving parr, rather than more (Giles, 1994). Further research, aimed at identifying appropriate and sustainable stocking densities that are of benefit to water quality, and the reputation of the fishery, is, therefore, strongly recommended.

As discussed earlier, more appropriate conservation targets related to known historical accounts of the biology, such as maximum growing depth of *Chara* or gastropod richness, could also be developed. This does not rule out the need for frequent monitoring of more traditional water quality parameters, as information they provide is often essential to any understanding of the causes of environmental change. In fact, in order to assess more confidently that there is recovery it is critical to continue monitoring. Recommendations include:

- Maintaining fortnightly monitoring of key water quality parameters: water temperature, Secchi depth, nitrate, silica, SRP, TP and chlorophyll$_a$.
- Maintaining fortnightly monitoring of phytoplankton populations, particularly cyanobacteria, and re-introducing monitoring of zooplankton populations, particularly *Daphnia* densities.
- Annual measure of maximum growing depth of submerged macrophytes (particularly *Chara*) and from this an estimate of areal macrophyte coverage.
- Submerged macrophyte and littoral invertebrate surveys every 3 years to assess changes in species composition. Comparable survey dates, preferably within June or July, should be followed between years.
- In 2005, repeat of phosphorus loading survey following methodology carried out in 1985 and 1995 surveys (Bailey-Watts & Kirika, 1999), although recommend including a budget for total nitrogen.

Continuing collaborative funding from NERC, SNH and SEPA is key to maintaining the monitoring recommendations above. It must be stressed, however, that Loch Leven's extensive long-term dataset, covering climate, water chemistry, plankton and fisheries is almost unmatched world-wide. A dataset such as this offers unique insights into how pressures such as eutrophication and climate change impact on Scottish freshwater habitats.

This review has shown the difficulty in assessing ecological recovery even with such datasets. The magnitude of recovery at Loch Leven appears to be the result of conflicting responses to decreasing nutrient concentrations and increasing temperatures, with further strong interactive effects from internal processes such as *Daphnia* grazing and sediment release of phosphorus. It is possible that further analyses, using more sophisticated trend analysis techniques, such as Generalised Additive Models (GAMs), could be used to explore how much these factors are responsible individually and how their relative importance changes over the seasons. What is clear, however, is that Loch Leven is just beginning to show signs of recovery in both water quality and ecology, which can hopefully be sustained through continuing integrated lake and catchment management.

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