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Commissioned Report No.262

Loch Leven 2004-2006: trends in water quality and biological communities

(ROAME No. F05LH01/2)

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COMMISSIONED REPORT

Summary

Loch Leven 2004-2006: trends in water quality and biological communities

Commissioned Report No.262 (ROAME No.F05LH01/2)
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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 biological 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 2004-06 monitoring data show no strong evidence of any further improvement from previous years in all three key water quality parameters. Comparison of the annual mean total phosphorus (TP) and chlorophyll concentrations and Secchi depth readings from the last three years shows that the recovery that appeared to be establishing in 2000 and 2001 has not been sustained.

- Chlorophylla and TP concentrations both exceeded the respective statutory target concentrations set by the Loch Leven Area management Group (LLAMAG). Phosphorus concentrations have, however, shown a large improvement over time, with a clear movement towards the TP target set by LLAMAG, whereas both chlorophyll and water clarity have shown little improvement.

- A strong spring clear-water phase did, however, establish in May and June in all three years. Maximum recorded rooted growing depth was also particularly deep in 2006 (>4.5 m) compared with previous records from the loch. This is evidence of some further recovery in the ecological quality of the loch, which should lead to improvements in food and habitat quality of invertebrates, fish and birds.

The following conclusions were reached:

- The phytoplankton data suggest that toxin-producing cyanobacteria are possibly becoming less dominant than in previous decades, and that the phytoplankton community is returning to a predominantly diatom-dominated flora. A shift from cyanobacteria to diatoms should also be having favourable implications for the fish

community in Loch Leven and also the bird communities that feed on the large populations of benthic invertebrates and swan mussels found in the loch.

- Daphnia grazers clearly play a pivotal role in driving the water quality of Loch Leven with strong evidence from analysis of the long-term dataset that reductions in chlorophyll and improvements in water clarity are associated with increased Daphnia densities. Densities in 2004-2006 were relatively low compared with the good water quality years of 2000-2002, although spring Daphnia densities were higher over the 2004-06 period than the long-term average. Analysis of the long-term datasets, suggests that the trend towards warmer springs observed at Loch Leven is having a significant, positive effect on spring Daphnia densities, and may, in part be responsible for the more defined spring clear water phase and deeper rooted-macrophyte growing depth observed in recent years.

- There is clearly a need for continued lake and catchment management at Loch Leven to improve water clarity further and enhance the ecological recovery. Despite the large reductions in external phosphorus loadings that have been achieved so far, current loadings do not yet appear to be delivering nitrogen and phosphorus concentrations sufficiently low enough to limit phytoplankton growth. Catchment management should, therefore, continue to identify and reduce significant sources of both nitrogen and phosphorus.

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1 INTRODUCTION

Loch Leven is the largest loch in lowland Scotland. It is also one of the most important sites in the UK for waterfowl, with the largest population of breeding ducks and thousands of migratory ducks, geese and swans resident over winter (Scottish Natural Heritage, 2007). In recognition of its nature conservation importance both nationally and internationally, it is designated as a Site of Special Scientific Interest (SSSI), a National Nature Reserve (NNR), a Special Protection Area (SPA) and a Ramsar site. The loch is also an internationally-renowned brown trout fishery. The loch has, however, suffered water quality problems, with dense cyanobacterial blooms occurring periodically in summer 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. Toxic cyanobacteria blooms can also impact directly on invertebrate (particularly filter feeding bivalves) and fish communities in the loch.

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).

This report analyses monitoring data from the years 2004-2006 and is one of a series that has described and interpreted physical, chemical and biological information from Loch Leven (e.g. Carvalho and Kirika 2005). 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.

2 METHODS

During the period of study, water samples were collected at least at monthly and generally at fortnightly intervals. Three 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 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). 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, sample depths varied from 3.0 to 3.5 metres. Phytoplankton samples were sub-sampled from these water samples, with the Reed Bower sample used in preference. Phytoplankton counting procedures followed UK standard guidance (Brierley & Carvalho, 2007) with taxonomy following John *et al*. (2003).

Open water crustacean zooplankton samples were collected and concentrated with a plankton net (mesh size 120 µm), which was drawn slowly to the water's surface from a depth of 4.5 m (i.e. vertical net tow) at the South Deeps and from a 4 m (angled net tow) at the Reed Bower site. At the sluices, surface samples were normally taken with a bucket and, subsequently, concentrated by passing the sample through the plankton net. All samples were preserved in formaldehyde. In the laboratory the crustacean zooplankton samples were placed in a glass vessel and made up to a final volume of 250 ml with distilled water. Each sample was thoroughly mixed, to distribute the animals randomly, and then subsampled with a Stempel pipette (volume 5ml). The animals present in each subsample were identified (Dussart and Defaye 1995; Einsle 1996; Flößner and Kraus, 1986; Harding and Smith 1974; Scourfield and Harding 1966) and counted under a low power binocular microscope. In most cases, three subsamples were examined. The subsample counts were converted to numbers of individuals per litre using appropriate multiplication factors.

3 RESULTS

3.1 Physical factors

3.1.1 *Water temperature*

Variation in surface water temperature followed a generally simple pattern over all three years, although temperatures peaked at 20°C in August in 2004, compared with earlier peaks of 21 and 23°C in July 2005 & 2006 (Figure 1). Ice coverage was not recorded on any visit, over the three years, continuing the trend of milder winters over the most recent decade. 2004 was a particularly cool year with an annual mean water temperature of 8.9°C, compared with a 20-year average of 11.5°C.

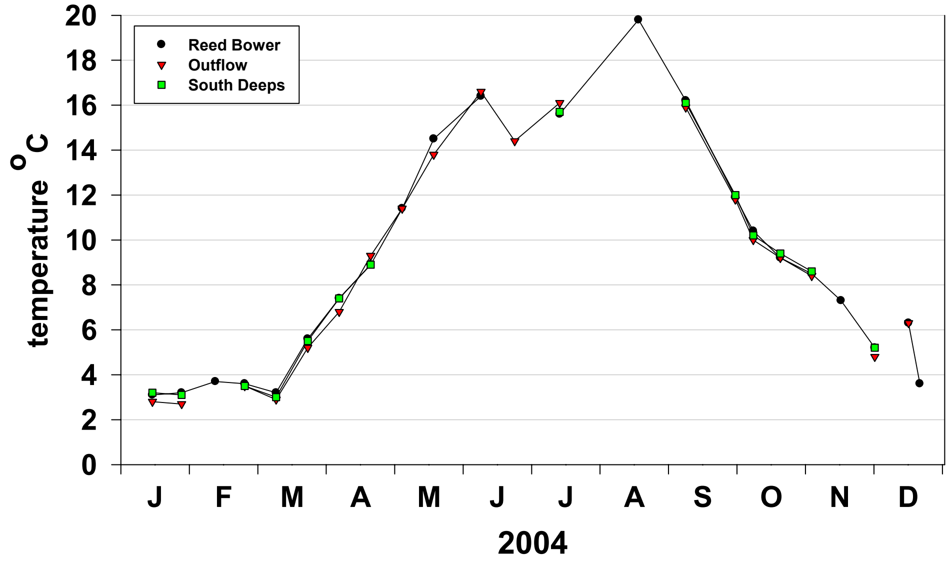
3.1.2 *Water level*

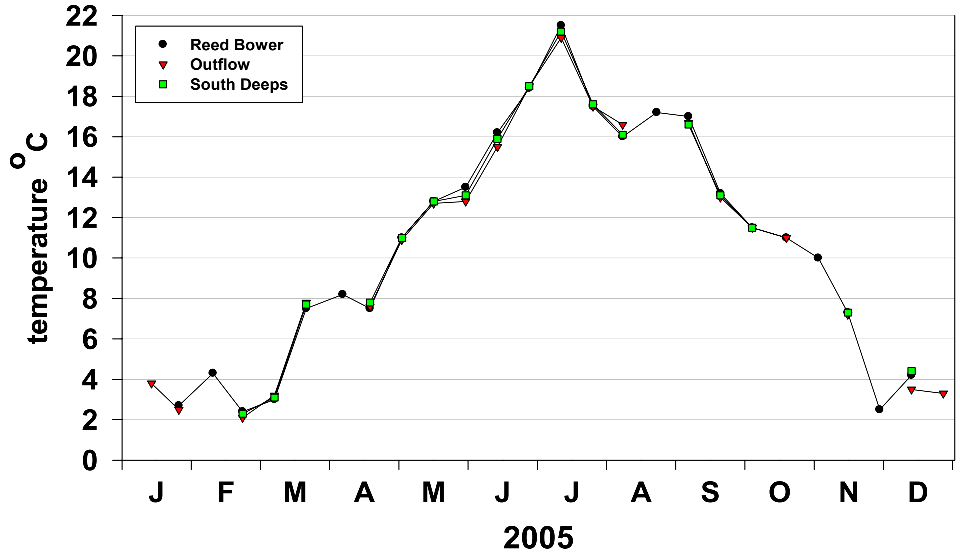
There was no regular seasonal pattern in water levels over the three years, although levels generally rose during spring and autumn periods and fell during summers (Figure 2). Records in 2004 were more sporadic. Lowest levels over the three years were recorded in January 2006 and highest levels in December 2006, a range of 1.25m over the year. This was the opposite pattern to that observed in 2003. The December 2006 peak level was one of the highest levels recorded during the past 40 years and was largely a result of sustained levels of high rainfall.

3.1.3 *Water clarity*

Water clarity showed a consistent seasonal pattern over the three years, with a clear-water phase in May and June, particularly well developed in 2004 and 2006 (Figure 3). More turbid waters, with Secchi depths of around 1m, were present throughout much of the rest of the year. Annual mean Secchi depths of 1.4, 1.3 and 1.4 m in 2004, 2005 and 2006 respectively, were similar to that recorded in 2003 (1.3 m) and slightly less than the average of 1.5 m over the last 10-years (1997-2006). Secchi depths do, however, remain lower than in 2000 (1.8 m) and 2001 (2.2 m), two of the clearest years on record.

Figure 1   Spatial and temporal variation in surface water temperature





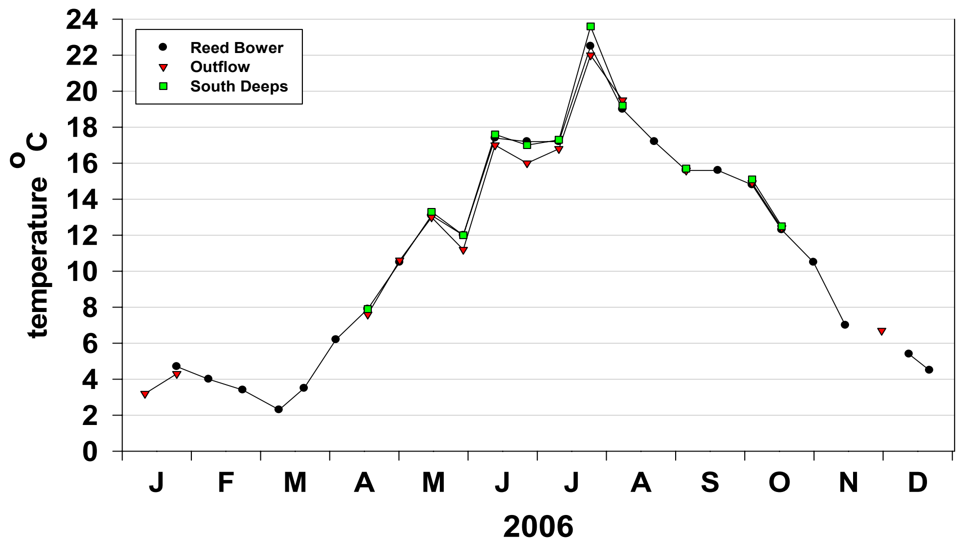
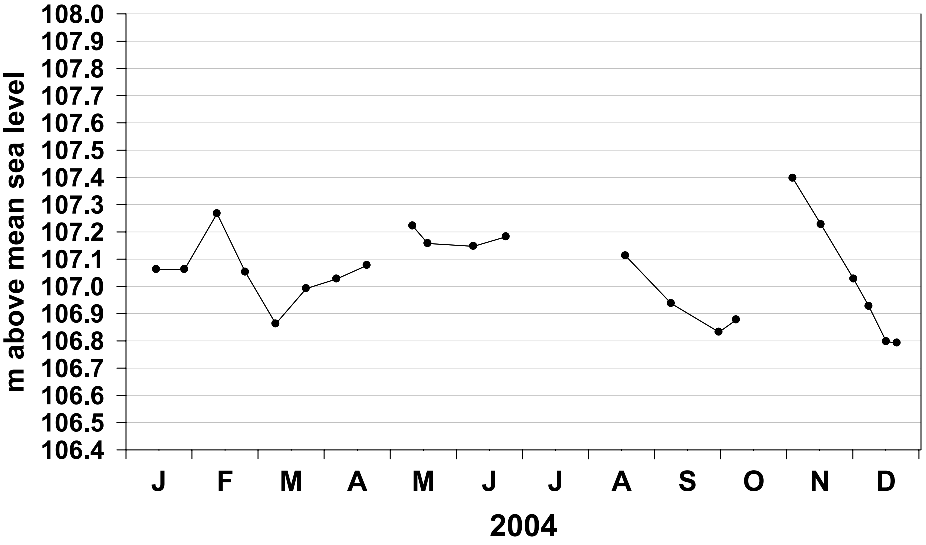
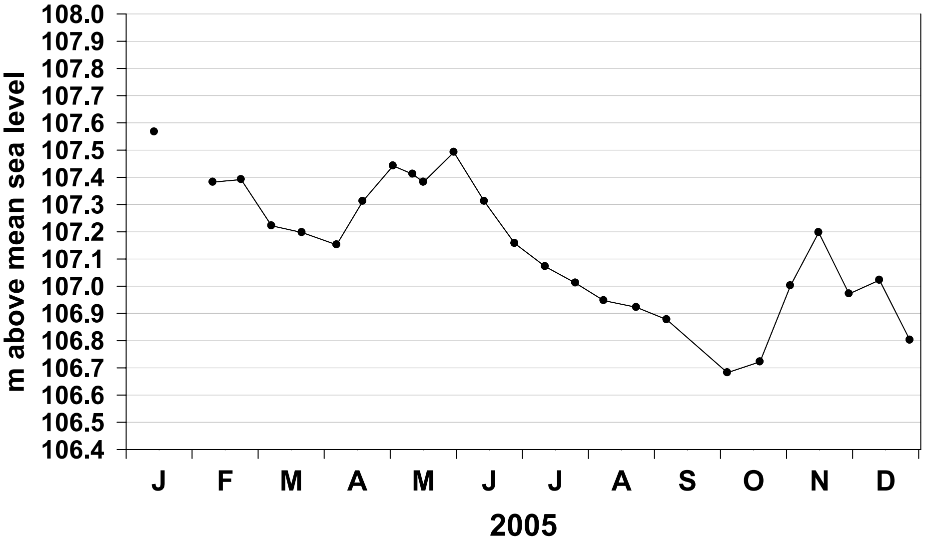


Figure 2 Water level fluctuation at the Harbour





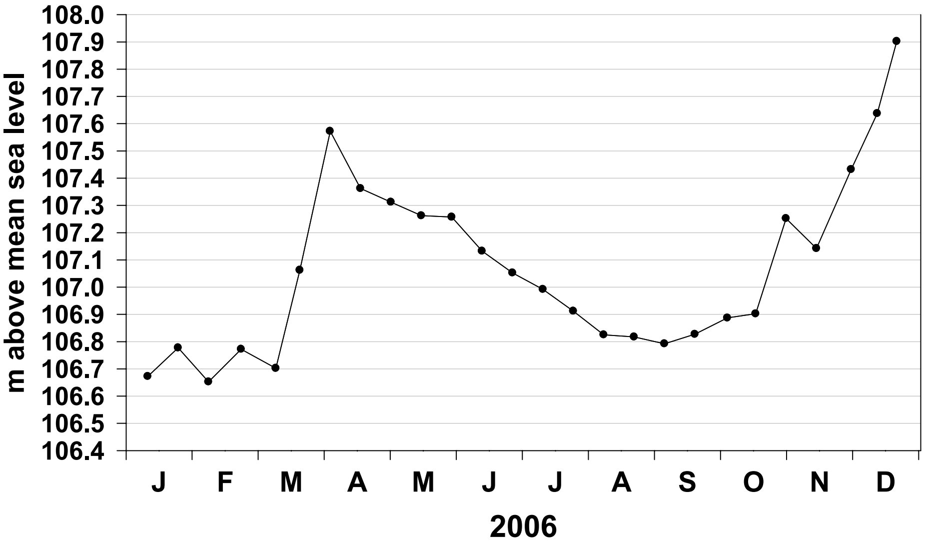
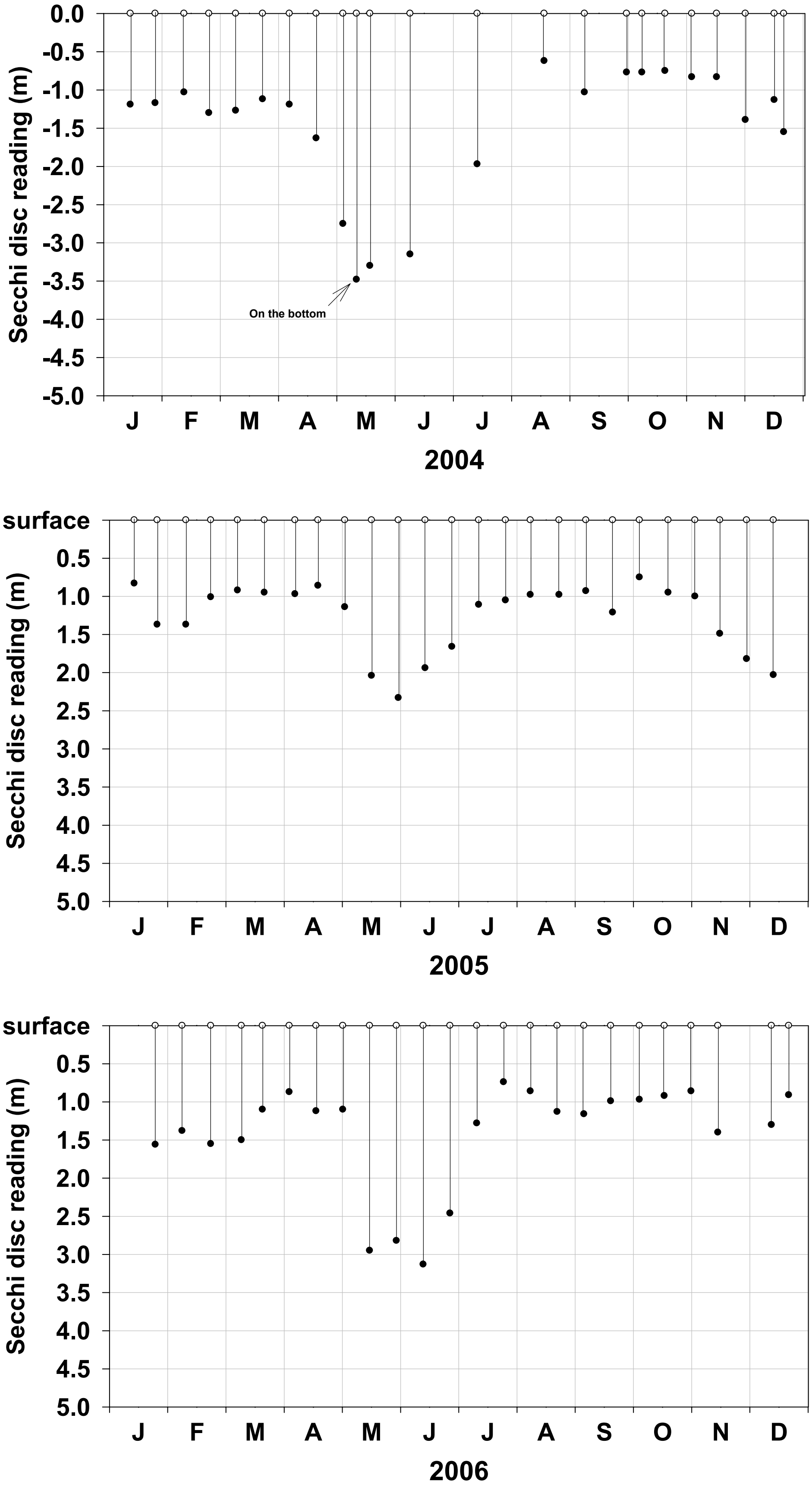


Figure 3 Water clarity (expressed as Secchi disc transparency) at the Reed Bower sampling site



3.2 Chemical factors

3.2.1 *Dissolved oxygen*

Measurements of dissolved oxygen (D.O.) concentration and saturation were not taken in 2004 due to faulty equipment (previously data have also been supplied by the Scottish Environment Protection Agency). Following purchase of a new D.O. probe in 2005, measurements began again. The values recorded in 2005 and 2006 suggest that, as in previous years, the surface waters of the loch are well-supplied with oxygen, with mean readings around 100% saturation at all three sites (Figure 4).

3.2.2 *Conductivity*

The conductivity values recorded at two sampling sites are shown in Figure 5. A seasonal pattern was most evident in 2004, with peaks in spring and minima in mid-summer. The values ranged between 210 µS cm^{-1} to 290 µS cm^{-1} and were typical for the loch.

3.2.3 *pH*

The range of pH values observed was fairly characteristic for the loch, ranging from just under pH 8 to pH 9.4. Peak values were recorded in summer and minima in winter (Figure 6).

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.

A fairly consistent seasonal pattern was observed in both $SRSiO_2$ and $TSiO_2$ over the three years. Concentrations start the year relatively high, declining over January and February, $SRSiO_2$ to undetectable levels, and then increasing again from May/June to peak during August and September. This is then followed by a sharp decline in late September followed by an increase in December. These changes are largely associated with diatom growth and losses from the water column, with silica limitation of diatom growth likely during Spring and Autumn periods. The exception to this was in autumn 2005, when concentrations did not decline to limiting levels.

Figure 4 Dissolved oxygen saturation at ambient water temperatures

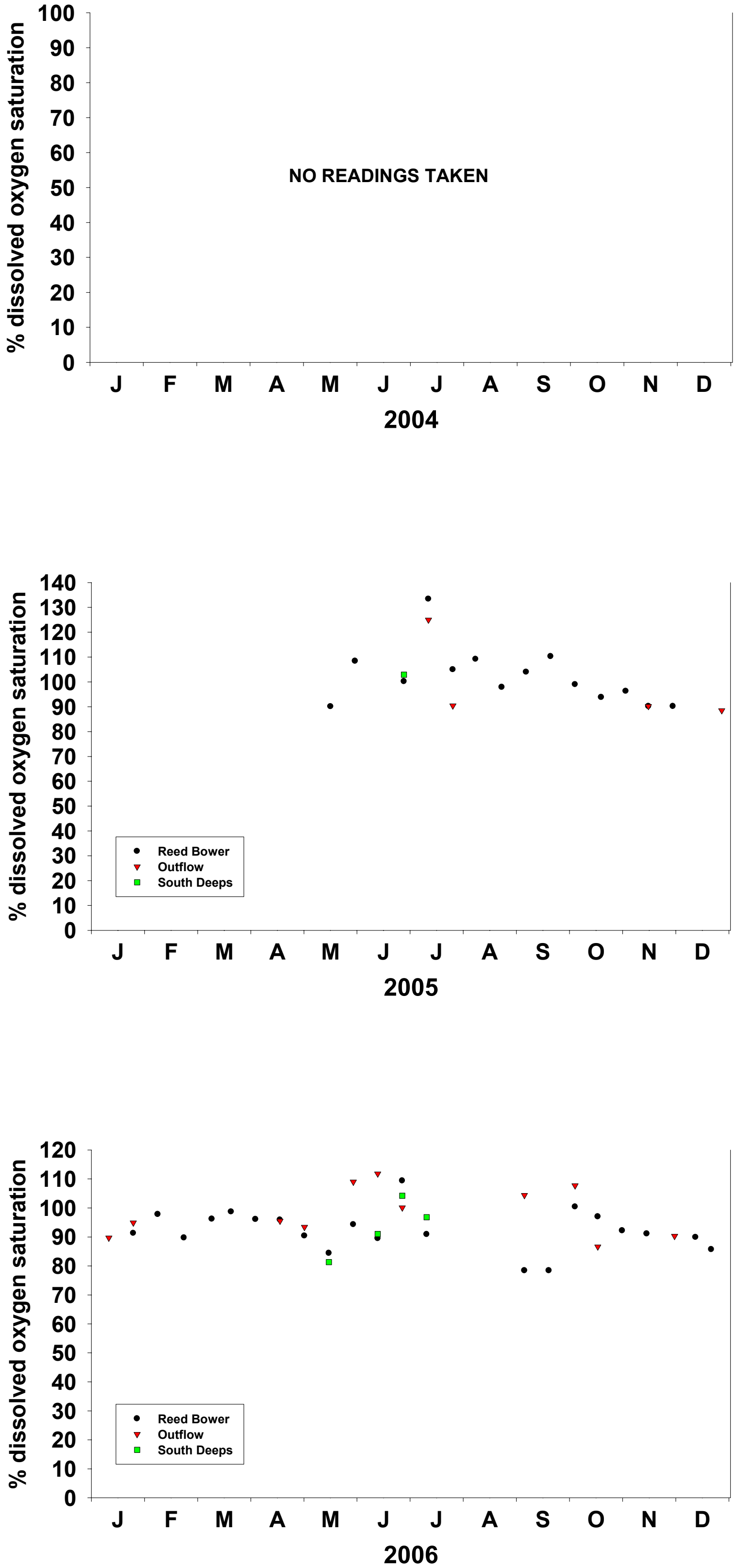
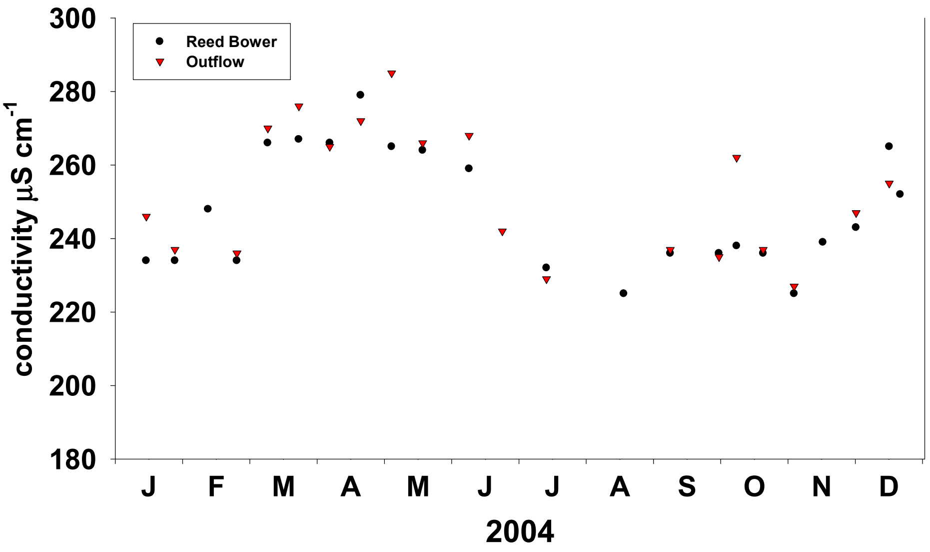
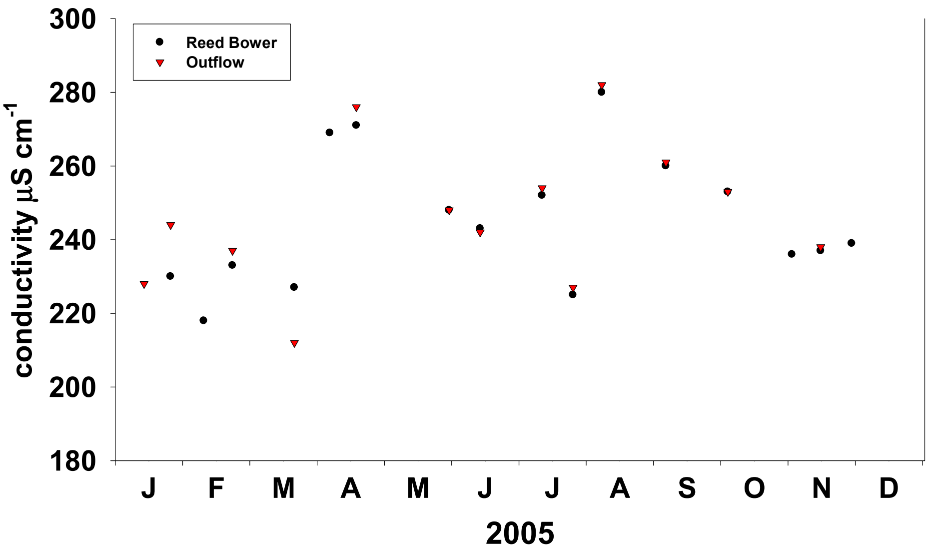


Figure 5 Electrical conductivity at ambient water temperature





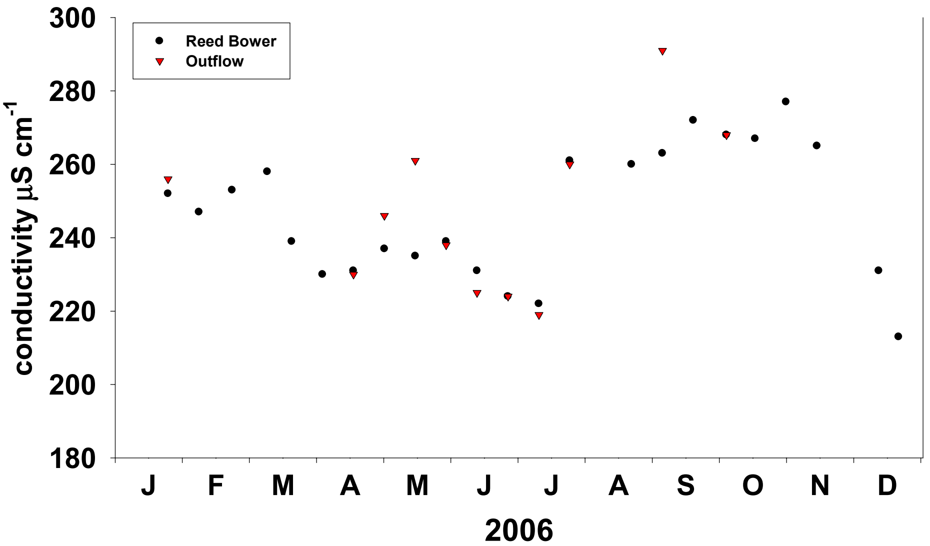


Figure 6 Temporal and spatial variation in pH at ambient water temperature

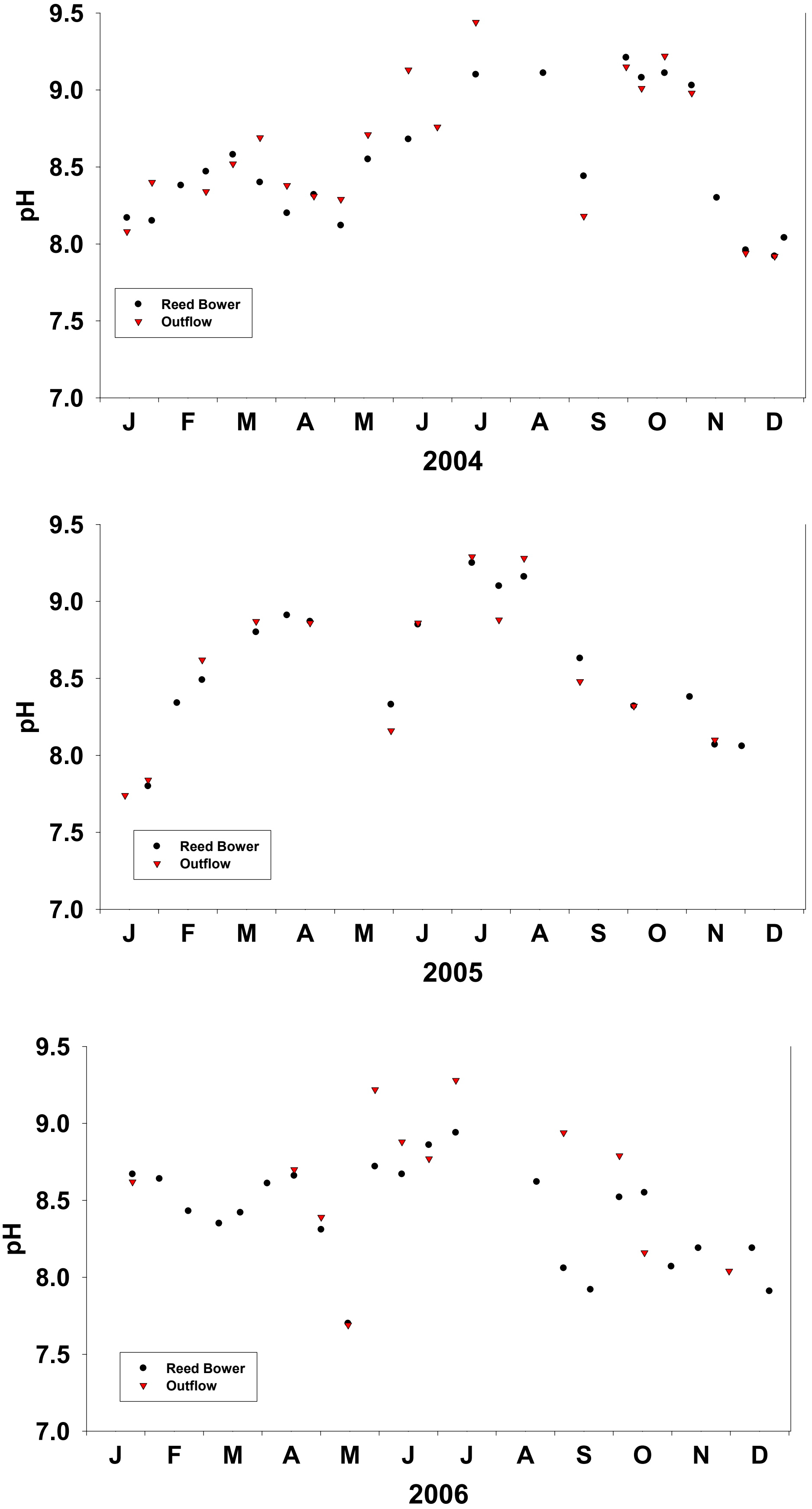
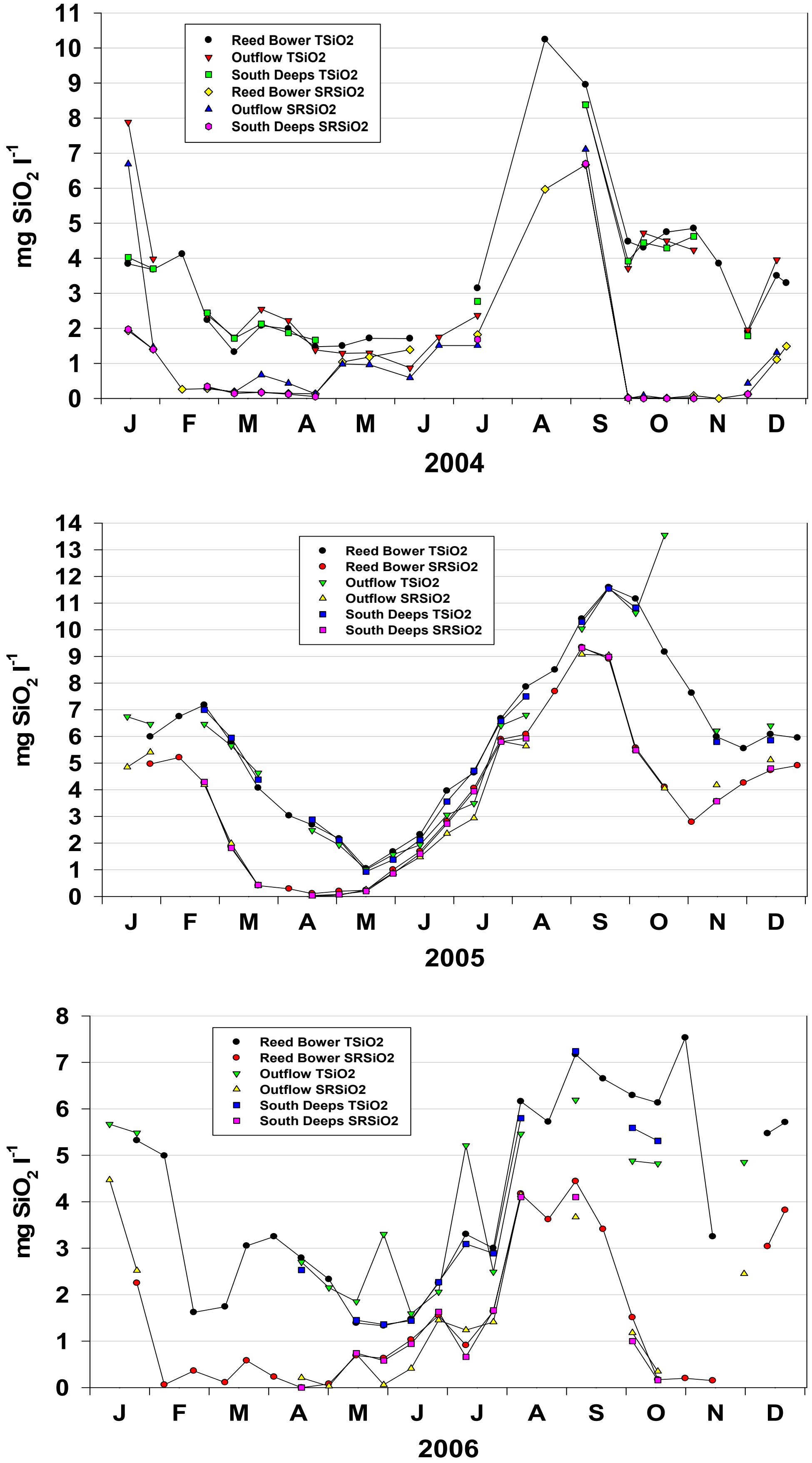


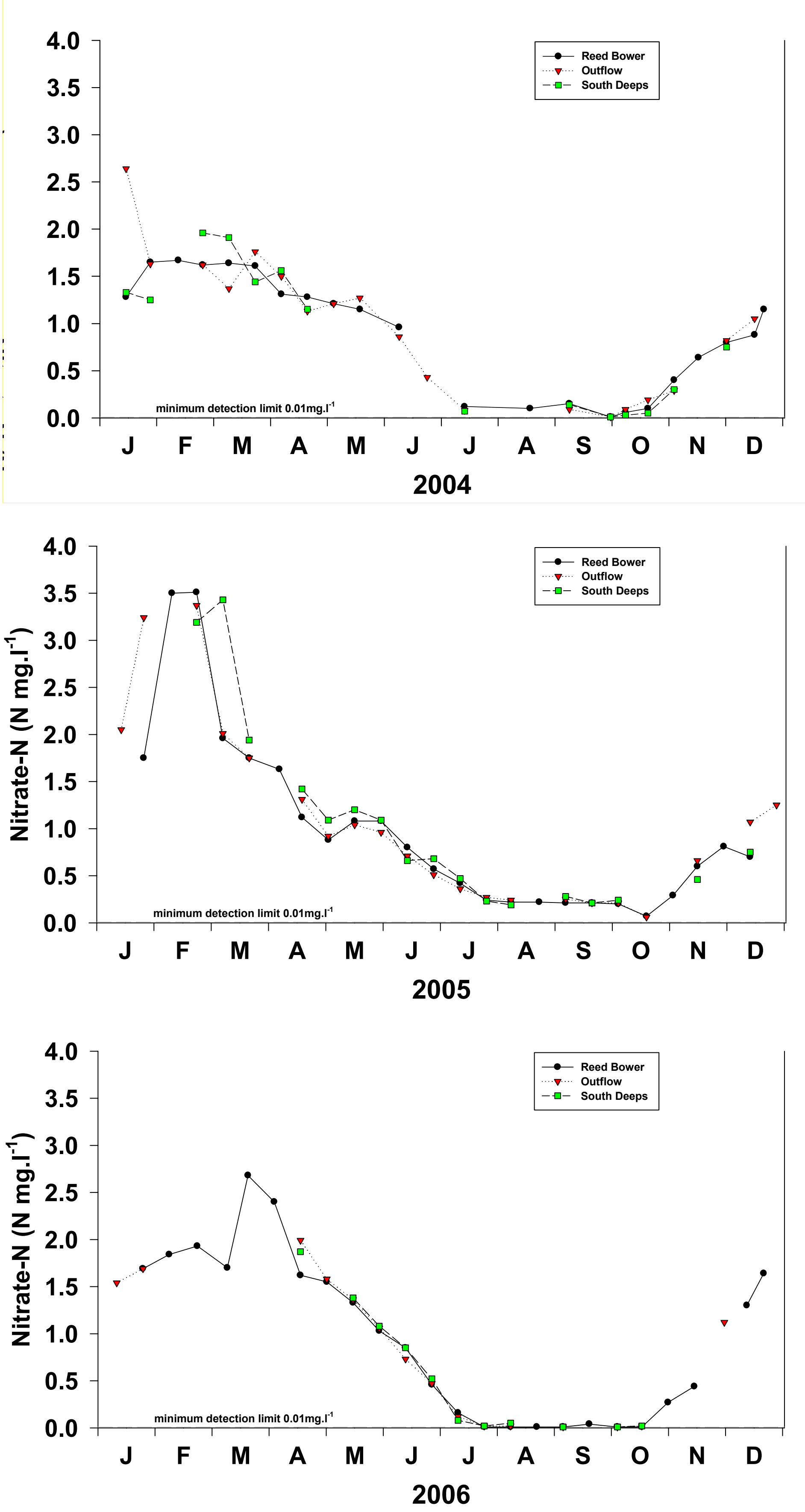
Figure 7 Spatial and temporal variation in concentrations of total silica ($TSiO_2$) and soluble reactive silica ($SRSiO_2$)



3.2.5 *Nitrate-nitrogen (NO_3-N)*

The seasonal pattern of change in nitrate concentrations tends to be similar each year, with the higher winter concentrations declining to levels near or below the detection limit by midsummer before rising again during autumn and the onset of winter (Figure 8). The limiting periods in 2004 and 2006 were very similar to that observed in 2003. Concentrations in 2005 were more similar to 2002, with slightly higher winter loadings and summer concentrations generally above the detection limit. There are no clear indications, however, that because of this, 2005 had higher phytoplankton crops and less dominance of N-fixing cyanobacteria, such as *Anabaena*; the latter were most abundant in July 2005 *(Figures 13 and 15)*.

Figure 8 Temporal variation in concentrations of Nitrate-nitrogen



3.2.6 *Soluble reactive phosphorus*

Soluble reactive phosphorus (SRP) concentrations showed a fairly consistent seasonal pattern over all three years, with concentrations generally very low (<10 µg l^{-1}) for much of the year, with a sharp increase during August and September (Figure 9). The exception to this was an increase during winter 2004/05 – a very atypical event in Loch Leven. The reason for this increase is not clear, but is unlikely to be an internal source at that time of the year. The SRP concentrations indicate that both internal and external sources of P remain much lower than in previous decades and that P-limitation of phytoplankton crops may be important during spring and autumn with concentrations sometimes declining below 5 µg l^{-1}. Internal loading still appears to be providing sufficient phosphorus to the water column during the summer months, when nitrogen-limitation appears to be more significant.

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 ranged between 3 µg P l^{-1} and 64 µg P l^{-1} over the years with a mean annual mean of 12 µg P l^{-1}, TSP levels were a little higher, ranging between 12 µg P l^{-1} and 84 µg P l^{-1}, with a mean annual mean of 28 µg P l^{-1}. There was, therefore, more soluble un-reactive P than reactive P in the water column.

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. As in previous years, there appears to be a distinctly increasing trend from June through to late October, which generally coincides with the trend in chlorophyll$_a$ shown in Figure 13, and hence with the growth of phytoplankton. There is, however, some discrepancy between the two during summer/autumn 2005, indicating high levels of re-suspension during that period.

3.2.9 *Total phosphorus*

Total phosphorus (TP) concentrations provide a simple index of loch trophic status. The data for 2004, 2005 and 2006 yield annual mean concentrations of 69 µg P l^{-1}, 74 µg P l^{-1} and 58 µg P l^{-1}, respectively (Figure 12). The annual mean for 2006 is particularly low relative to values recorded over previous decades.

The mean TP concentrations recorded are still 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).

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

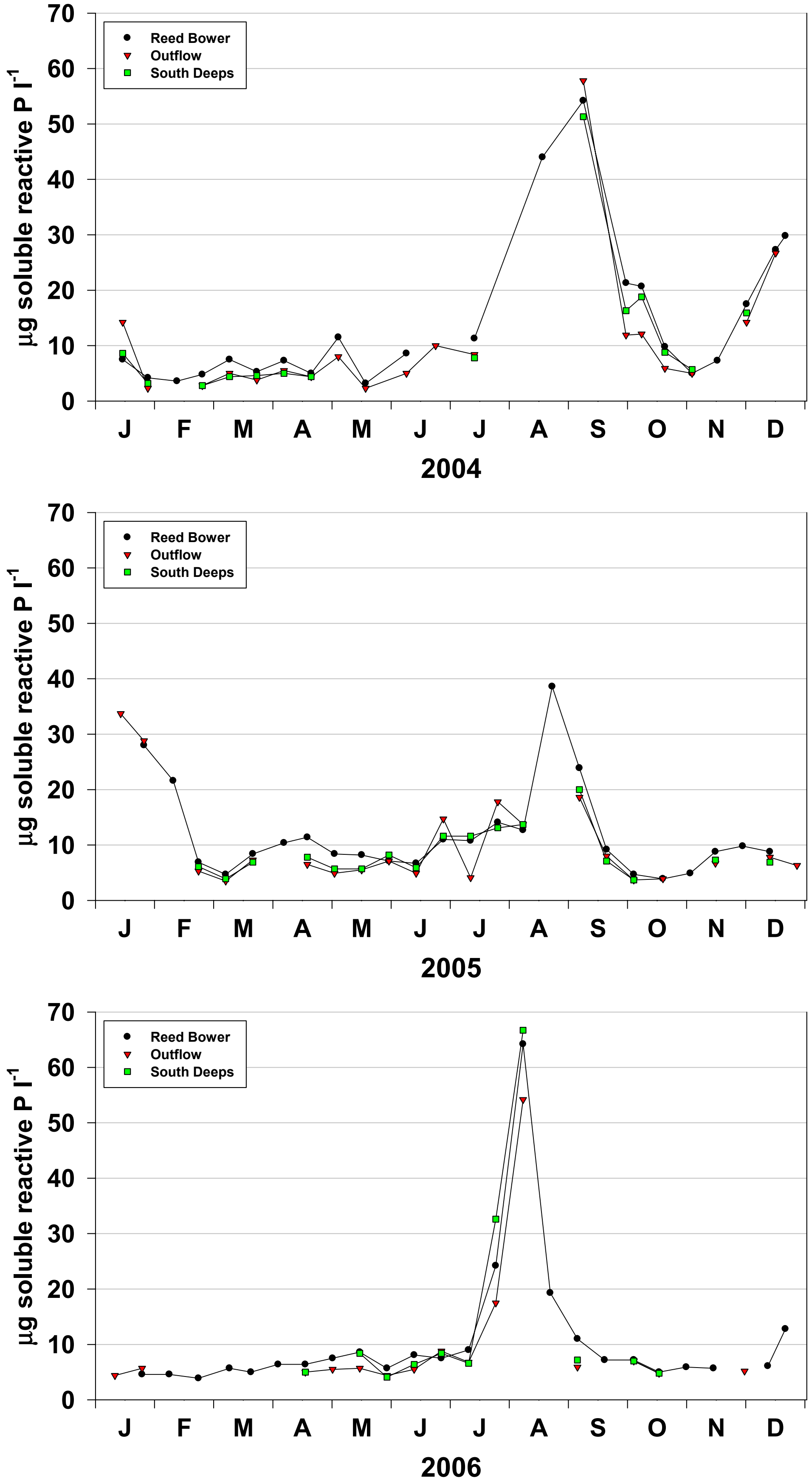


Figure 10   Temporal and spatial variation in concentrations of total soluble phosphorus

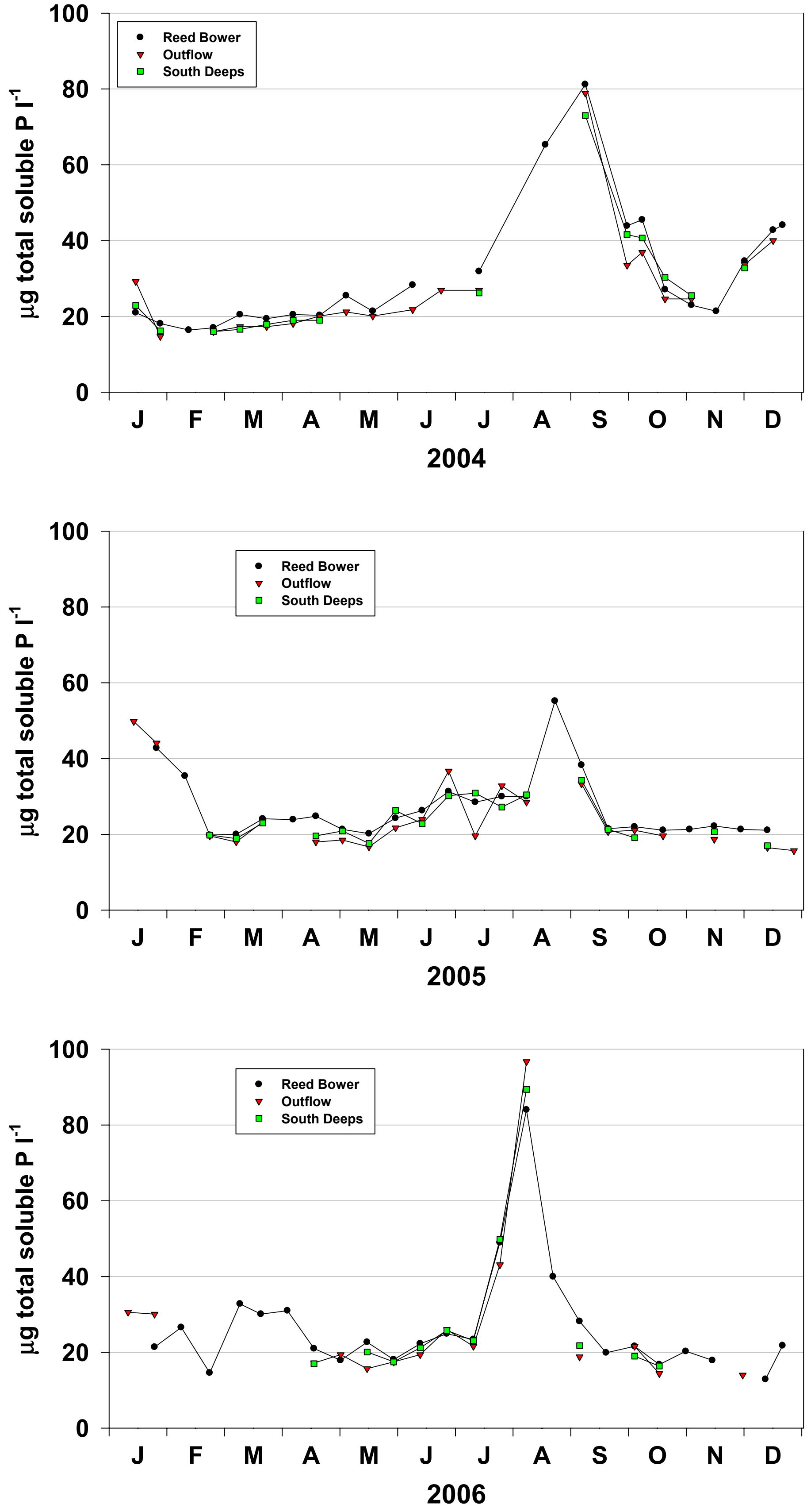


Figure 11 Temporal and spatial variation in levels of particulate phosphorus

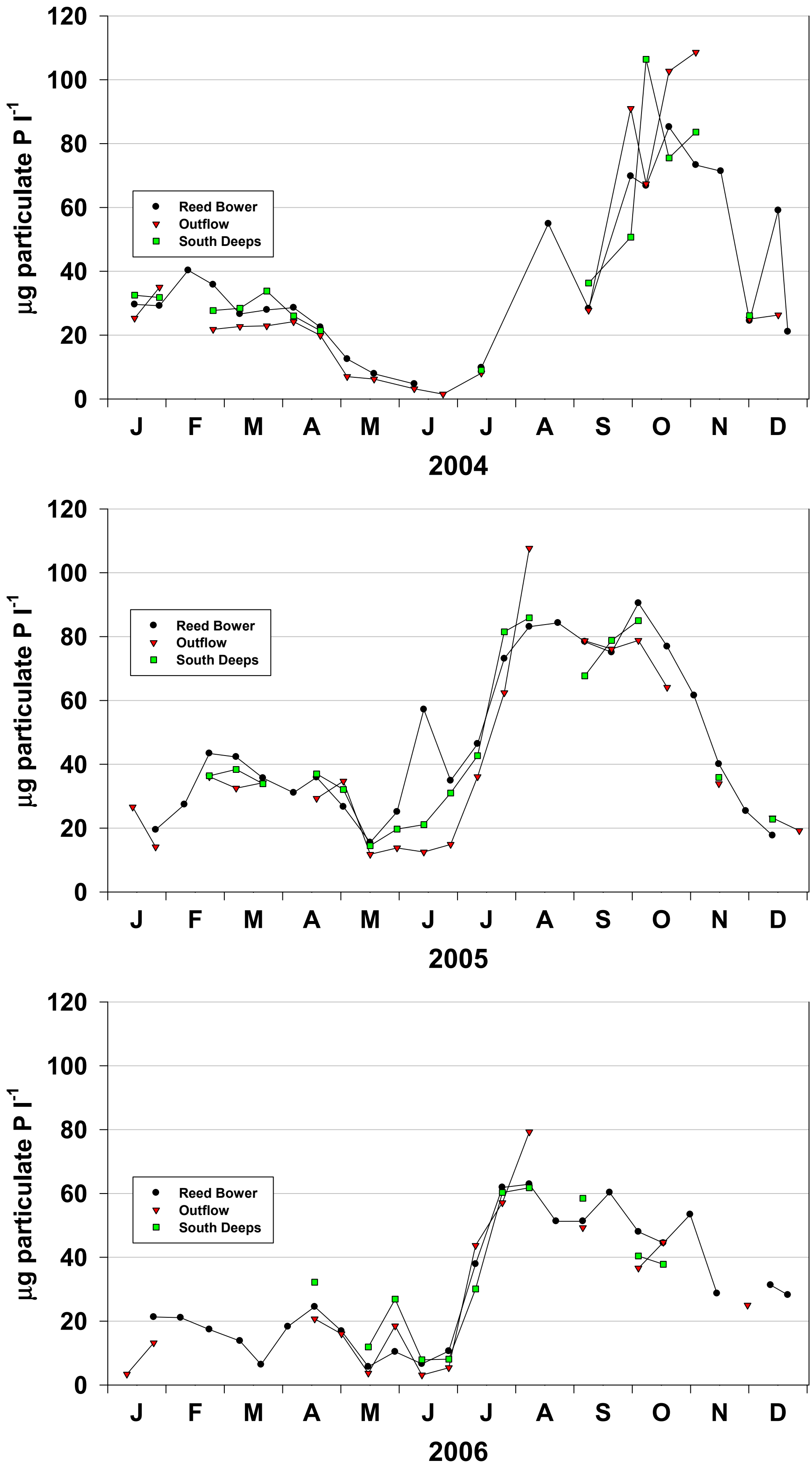
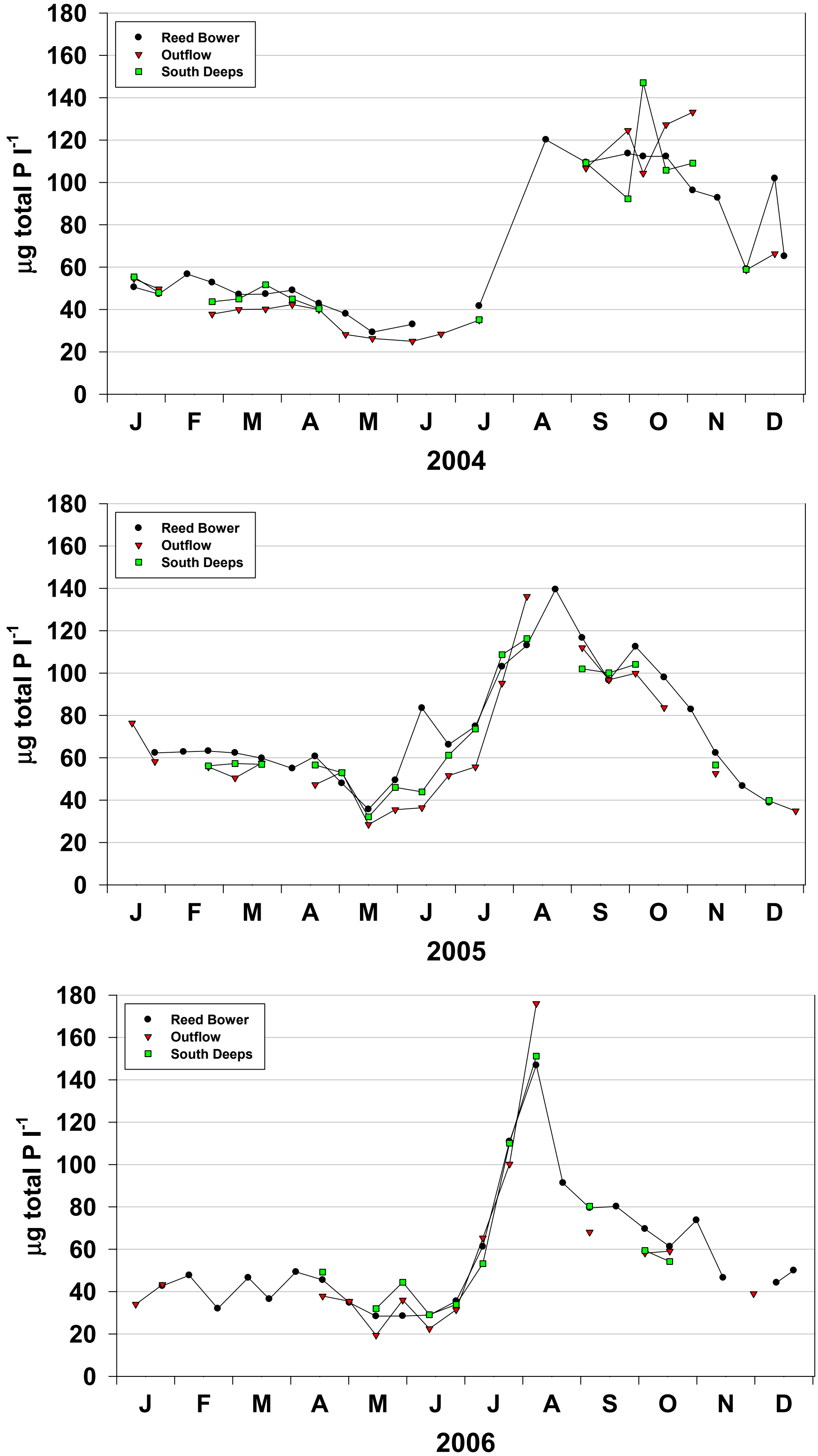


Figure 12 Temporal and spatial variation in concentrations of total phosphorus



3.3 Phytoplankton

3.3.1 *Chlorophyll$_a$*

With the exception of May and June, chlorophyll$_a$ concentrations frequently exceeded 20 µg l^{-1} (Figure 13). Annual mean concentrations for 2004, 2005 and 2006 of 48, 35 and 37 µg l^{-1}, respectively, were higher than the target mean annual chlorophyll concentration of 15 µg 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). The Water Framework Directive Good/Moderate status class boundary for chlorophyll for a high alkalinity, shallow lake, such as Loch Leven, has been agreed at a European level as 7.5 µg l^{-1}. The same target for a very shallow, high alkalinity lake (<3 m mean depth) is 16.5 µg l^{-1}. Loch Leven is near the lake type boundary, a site-specific target is, therefore, most appropriate and is likely to be closer to the value for a very shallow lake, of which it is functionally more equivalent too.

On a more positive note, low chlorophyll concentrations in May and June appear to be an established feature now at Loch Leven each year - with a typical "spring clear water phase". Recent analysis of Loch Leven's long-term datasets suggest this is in part a response to enhanced *Daphnia* grazer densities associated with warmer spring temperatures in recent years (Ferguson *et al*., 2007a; 2007b). The chlorophyll peak occurred in October in each year, associated with dense blooms of non-toxic diatom algae.

3.3.2 *Phytoplankton composition*

The phytoplankton community of Loch Leven was dominated by diatoms for much of the three year period (Figure 14). Composition showed a fairly consistent seasonal pattern over all three years, with biovolumes starting the year generally low, with a small diatom peak in late winter / early spring, followed by a low-biovolume clear-water period in May and June (the "spring clear water phase") when small cryptophytes dominated. Cyanobacteria start to increase in July, dominating in August and remaining abundant in September. Diatoms start to increase in abundance in autumn, peaking at very high densities in October in all three years, then declining in November and December. Crucially, the data suggest that toxin-producing cyanobacteria are less dominant than in previous decades, and that the phytoplankton community is returning to a predominantly diatom-dominated flora.

The 41 phytoplankton genera recorded over the three years in Loch Leven are listed in Table 1. The three most dominant genera were all diatoms (Table 1, Figure 15). Diatoms are a diverse group of algae, with intricate cell walls made of opaline silica (i.e. 'glass-like'). Many diatom species consist of only a single round (e.g. unicellular centrics) or oblong (e.g. *Synedra*) cell, although some form long chains of cells (e.g. *Aulacoseira*) or simple star-shaped colonies (e.g. *Asterionella*). A detailed analysis of the diatom species occurring in the plankton of Loch Leven over the last decade has recently been completed, with 22 species observed from 1996 to 2005 (Wischnewski, 2006). In terms of the dominant diatom species in Loch Leven over the past three years, three chain-forming species of *Aulacoseira* (*A. subarctica*, *A. ambigua* and *A. granulata*) and a number of small, unicellular centric diatoms (*Cyclotella*, *Cyclostephanos* and *Stephanodiscus*) were abundant, as well as *Asterionella formosa* and *Syndera acus*.

Three cyanobacteria genera are relatively abundant in Loch Leven (Table 1, Figure 15). *Anabaena*, a filamentous species, is typically the first to increase in abundance in early July. It is a nitrogen-fixing species and is commonly observed in Loch Leven with specialized nitrogen-fixing cells present, indicating nitrogen-limitation in the water column. Despite N concentrations remaining low through August and September too, *Anabaena* tends to be overtaken in August by large, slower-growing colonial cyanobacteria, *Microcystis* (*M. flos-aquae* and *M. aeruginosa*) and *Woronichinia naegeliana* (formerly called *Coelosphaerium naegelianum*). These colonial species do not fix nitrogen, but can regulate their buoyancy and are known to migrate down the water column to tap into sources of nitrogen and phosphorus released from sediments in the warmer summer months.

Other relatively abundant phytoplankton genera include readily grazed *Cryptomonas*, *Rhodomonas* and small *Gymnodinium* and *Scenedesmus* species (Table 1).

Table 1: Phytoplankton genera recorded in Loch Leven during the period 2004-2006, ordered by total biovolume (μm^3 ml) for the period 2004-2006

Taxon	Algal Class	Total Biovolume	Biovolume 2004	Biovolume 2005	Biovolume 2006
Aulacoseira	Diatom	145896659	21723819	16580272	107592568
Unicellular Centric Diatoms	Diatom	96781036	52473182	26075275	18232579
Synedra	Diatom	29477489	99851	7034476	22343162
Cryptomonas	Cryptophyte	19525218	3000987	8928624	7595607
Microcystis	Cyanobacteria	12236089	6193358	63522	5979209
Anabaena	Cyanobacteria	8673624	3636457	2867721	2169446
Asterionella	Diatom	7160858	4644358	514951	2001549
Woronichinia	Cyanobacteria	3707124	153917	3263345	289862
Gymnodinium	Dinoflagellate	3682294	692239	2235251	754804
Scenedesmus	Green	3636995	1509263	752550	1375182
Pediastrum	Green	3412582	883442	1459789	1069351
Rhodomonas	Cryptophyte	1139042	403218	172279	563545
Oscillatoria	Cyanobacteria	1030637	204420	826217	0
Chlamydomonas	Green	979928	17775	962153	0
Monoraphidium	Green	911291	296758	402155	212378
Tetrastrum	Green	759696	4454	645649	109593
Snowella	Cyanobacteria	488464	139759	31181	317524
Staurastrum	Green (desmid)	473428	401367	0	72061
Fragilaria	Diatom	425365	425365	0	0
Glenodinium	Dinoflagellate	401028	0	401028	0
Peridinium	Dinoflagellate	368231	0	368231	0
Oocystis	Green	300574	223014	77560	0
Diatoma	Diatom	262109	262109	0	0
Sphaerocystis	Green	238686	73741	164945	0
Closterium	Green (desmid)	218366	65397	143637	9332
Lagerheimia	Green	191355	14322	102228	74805
Ceratium	Dinoflagellate	166093	0	0	166093
Coelastrum	Green	162751	162751	0	0
Chroococcus	Cyanobacteria	157651	3985	0	153666
Closteriopsis	Green	152553	149975	2578	0
Dictyosphaerium	Green	144330	144330	0	0
Cosmarium	Green (desmid)	137168	88038	49130	0
Tetraedron	Green	87513	34888	3262	49363
Micractinium	Green	76114	47820	28294	0
Kephyrion	Green	56120	0	0	56120
Schroederia	Green	39694	0	6976	32718
Pseudokephyrion	Chrysophyte	19829	0	0	19829
Planktosphaeria	Green	18796	0	0	18796
Crucigenia	Green	10058	10058	0	0
Merismopedia	Cyanobacteria	4402	0	0	4402
Elakatothrix	Green	3587	3587	0	0

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

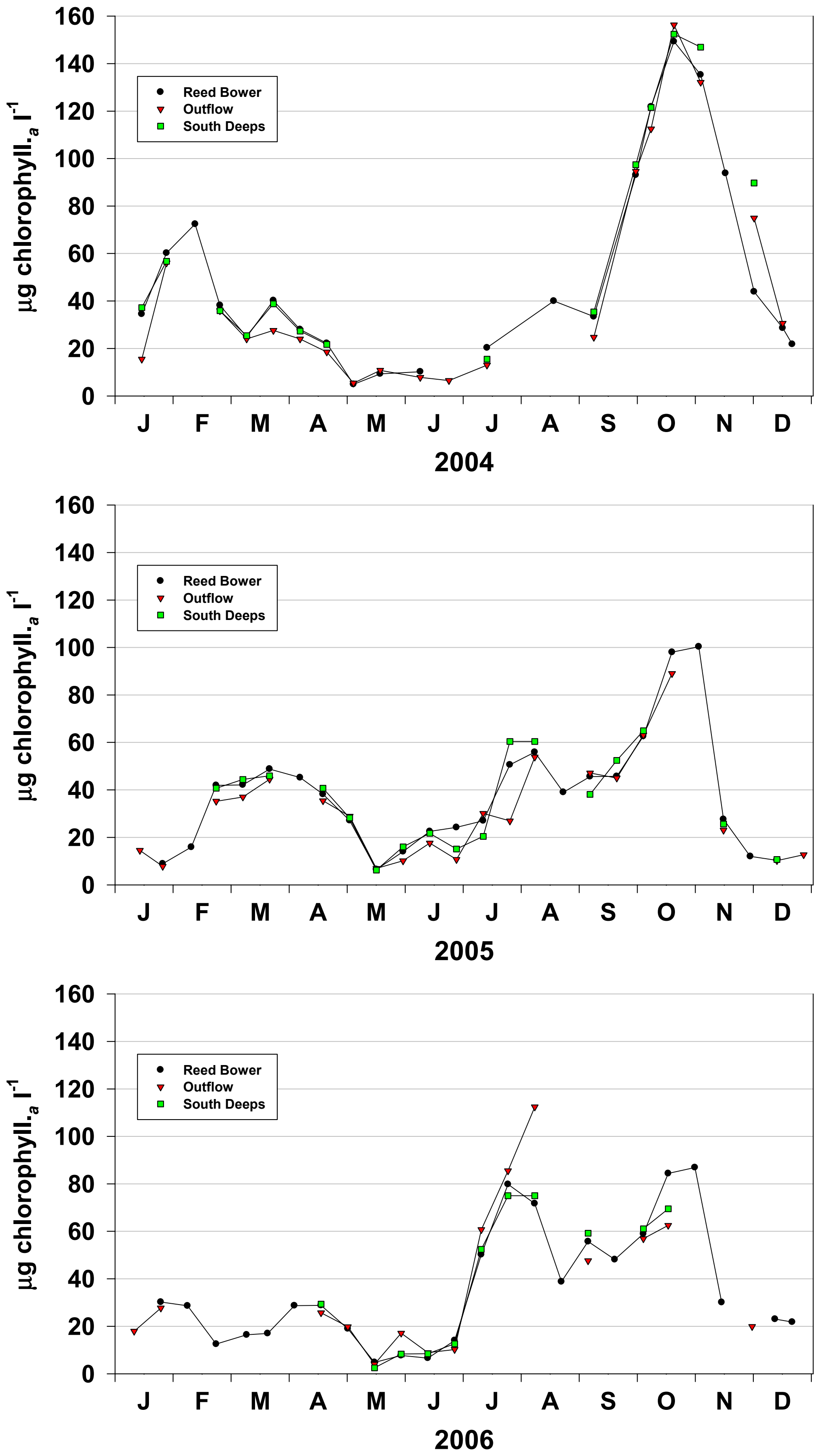


Figure 14 Temporal variation in phytoplankton classes

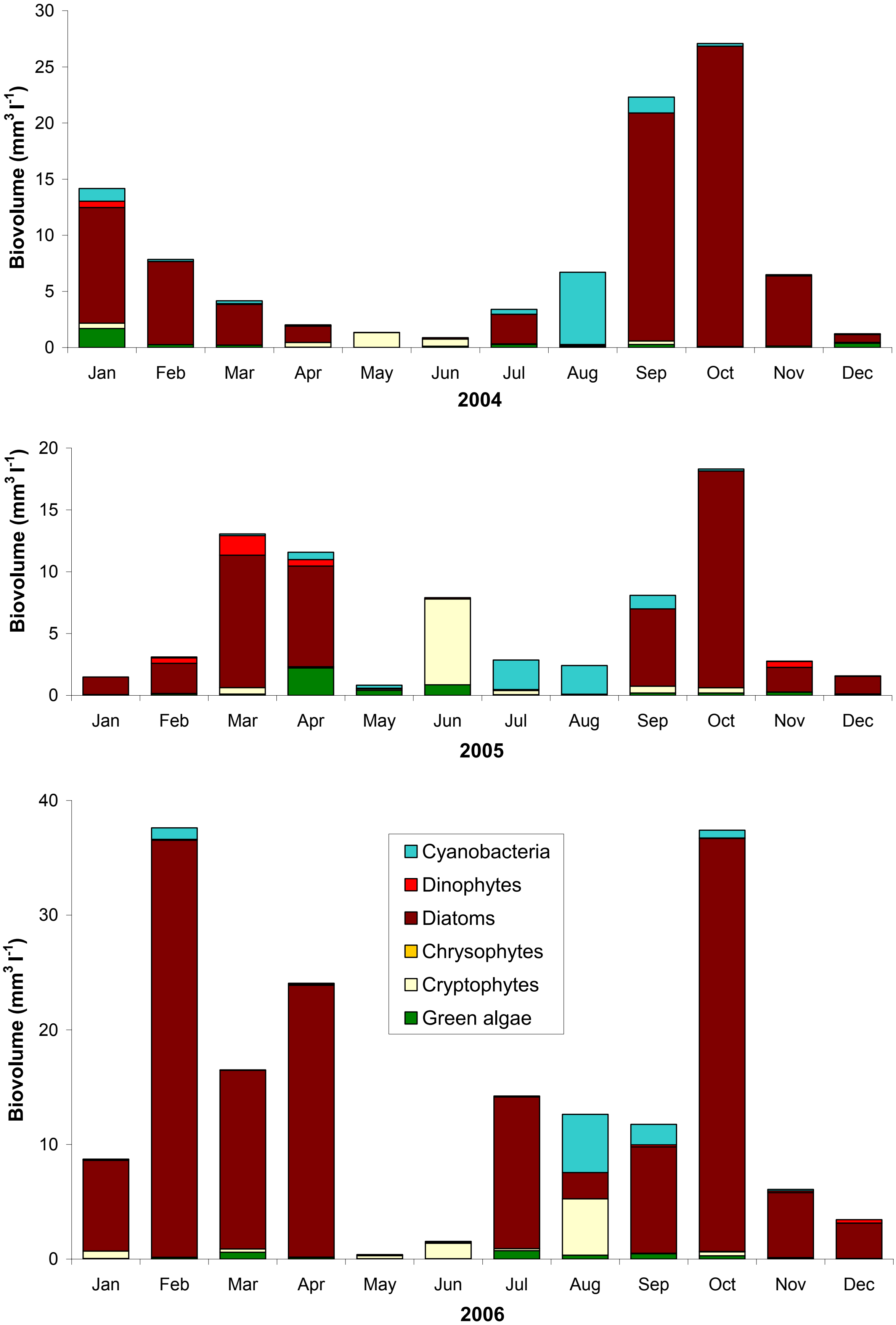
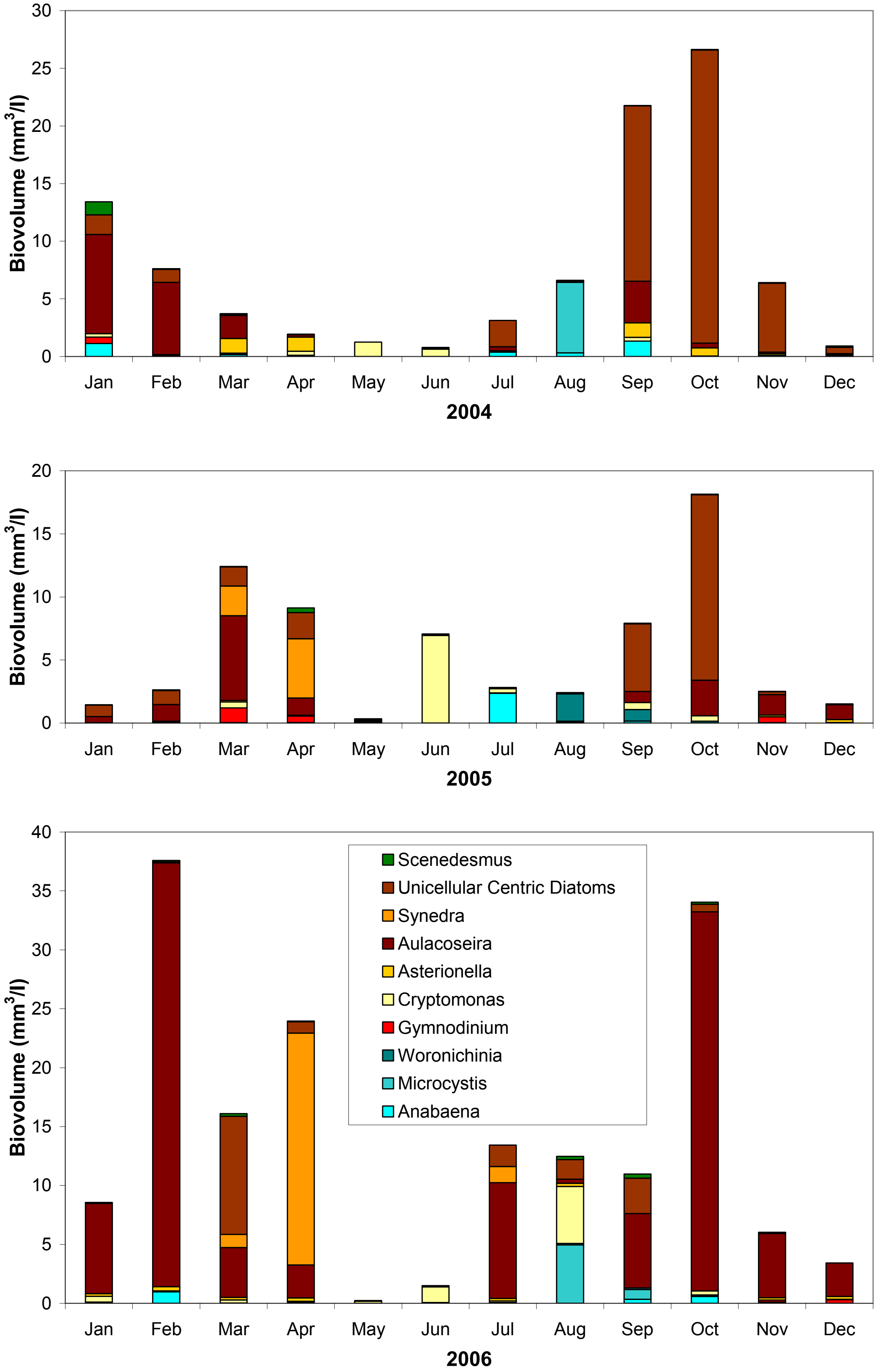


Figure 15 Temporal variation in dominant phytoplankton genera



3.4 Crustacean zooplankton

3.4.1 *Species list*

Eight crustacean species were found in Loch Leven during 2004-2006 (Table 2).

Table 2 Crustacean zooplankton species recorded from Loch Leven during 2004-2006

Cladocera (Branchiopoda)
Anompoda
Daphnia hyalina species-complex (formerly *D. hyalina var.lacustris* Sars)
Chydorus sphaericus (O.F. Müller)
Alona quadrangularis (O.F. Müller)
Halopoda
Leptodora kindti (Focke)
Onychopoda
Bythotrphes longimanus Leydig
Copepoda
Calanoida
Eudiaptomus gracilis (Sars) (formerly *Diaptomus gracilis* Sars)
Cyclopoida
Cyclops abyssorum Sars (formerly *Cyclops strenuous abyssorum* Sars)
Cyclops vicinus Uljanin

3.4.2 *Abundance*

The population dynamics of the main crustacean zooplankton species for 2004-2006 are shown in Figure 16. The principal taxa in all three years, as in earlier years, were the cyclopoid copepod *Cyclops*, the calanoid copepod *Eudiaptomus gracilis*, and the cladoceran referred to as the *Daphnia hyalina* species-complex (cf. May *et al*. 1993: Gunn *et al*. 1994). However, in 2006, unlike earlier years, the *Cyclops* population appears to be dominated by *Cyclops vicinus* rather than *Cyclops abyssorum*.

The general seasonal features of the population dynamics of each of the main crustacean zooplankton taxa over the period 2004-2006 can be summarised as follows:

(a) Population densities of *Daphnia* were very low (<4 ind.l^{-1}) during the first three months of each year, followed by a rapid increase in numbers to a peak in May/June (maximum of 31.8 ind. l^{-1} in May 2006). Numbers declined to relatively low densities thereafter with the exception of August 2005 where the *Daphnia* population increased again to a maximum peak of 39.5 ind.l^{-1} before declining rapidly back to over-wintering levels of about 2 ind.l^{-1}.

(b) The concentrations of the nauplii, copepodites and adults of *Cyclops* were low before reaching a maximum of around 50 ind.l^{-1} in late April/May/June period before declining rapidly over the summer months. In 2004, however, numbers rose again towards the end of the year reaching 29.4 ind.l^{-1} in December before returning to more normal over-wintering densities.

(c) *Eudiaptomus* densities generally remained at levels of less than 5 ind.l^{-1}, although numbers exceeded this in the latter half of 2005, reaching a population maximum of 14.1 ind.l^{-1} in July of that year.

(d) *Leptodora kindti* and *Bythotrophes longimanus* occurred in extremely low numbers (<0.4 ind.l^{-1}) over the summer months during 2004-2006.

Comparing the results from 2004-2006 with previous year's data indicates that the relative abundance, and seasonality of occurrence were broadly similar for *Cyclops, Daphnia* and *Eudiaptomus* although in terms of absolute concentrations *Daphnia* did exhibit a decline relative to 2000-2002 period.

Figure 16a Mean densities of crustacean zooplankton in Loch Leven, 2004

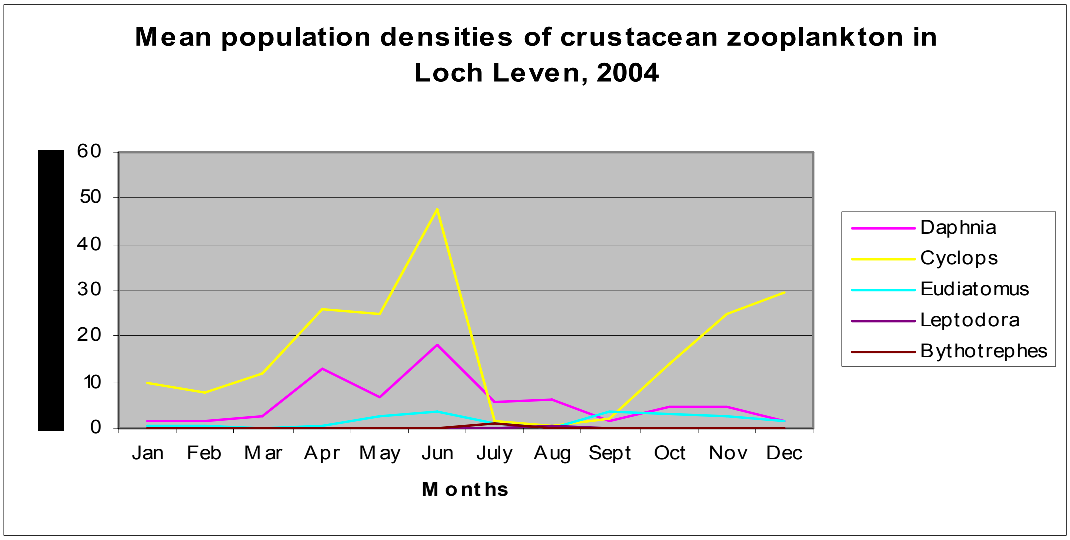


Figure 16b Mean densities of crustacean zooplankton in Loch Leven, 2005

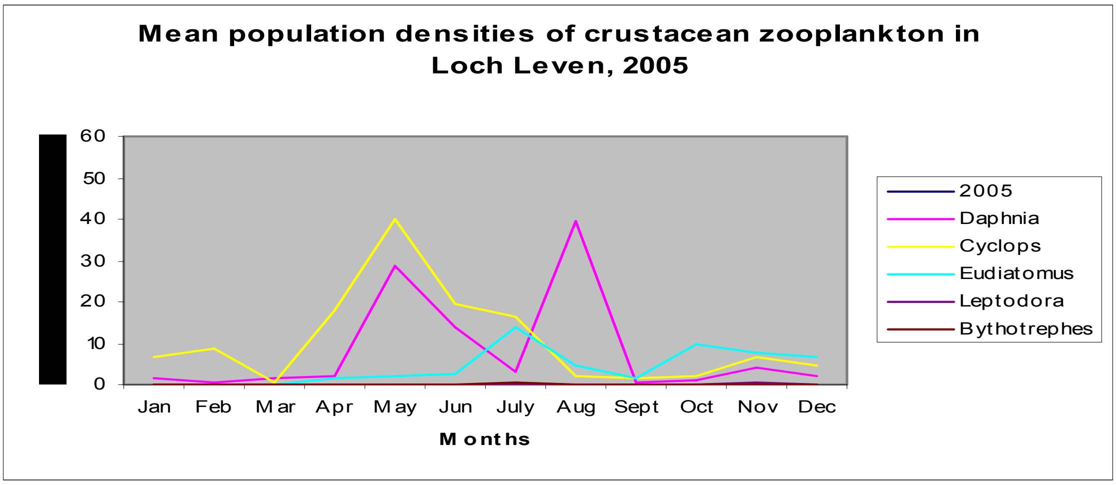
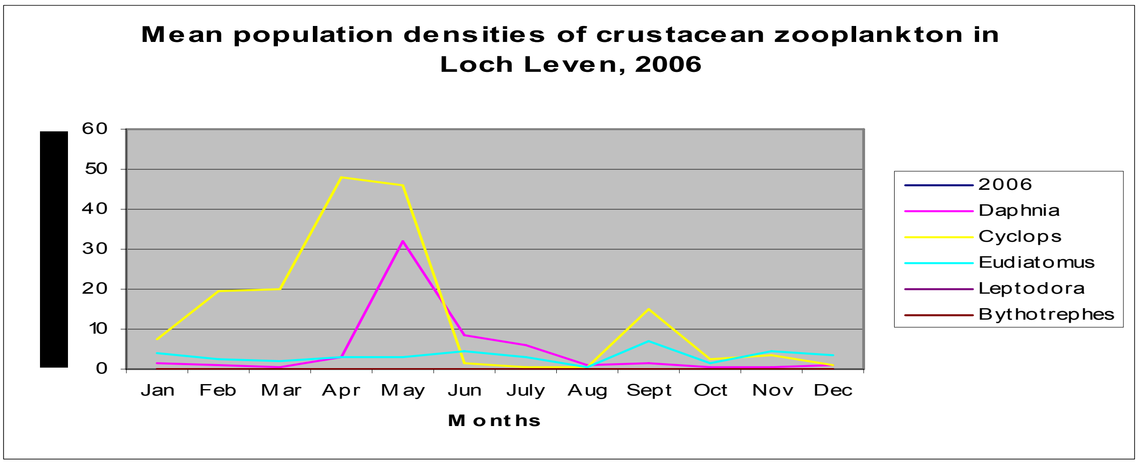


Figure 16c Mean densities of crustacean zooplankton in Loch Leven, 2006



4 DISCUSSION

4.1 Recent Trends in Water Quality & Plankton Dynamics

The 2004-06 monitoring data show no strong evidence of any further improvement from previous years in all three key water quality parameters. No obvious improving trend is visible over the past 10 years (Figure 17). Comparison of the annual mean TP and chlorophyll concentrations and Secchi depth readings from the last three years shows that the recovery that appeared to be establishing in 2000 and 2001 has not been sustained.

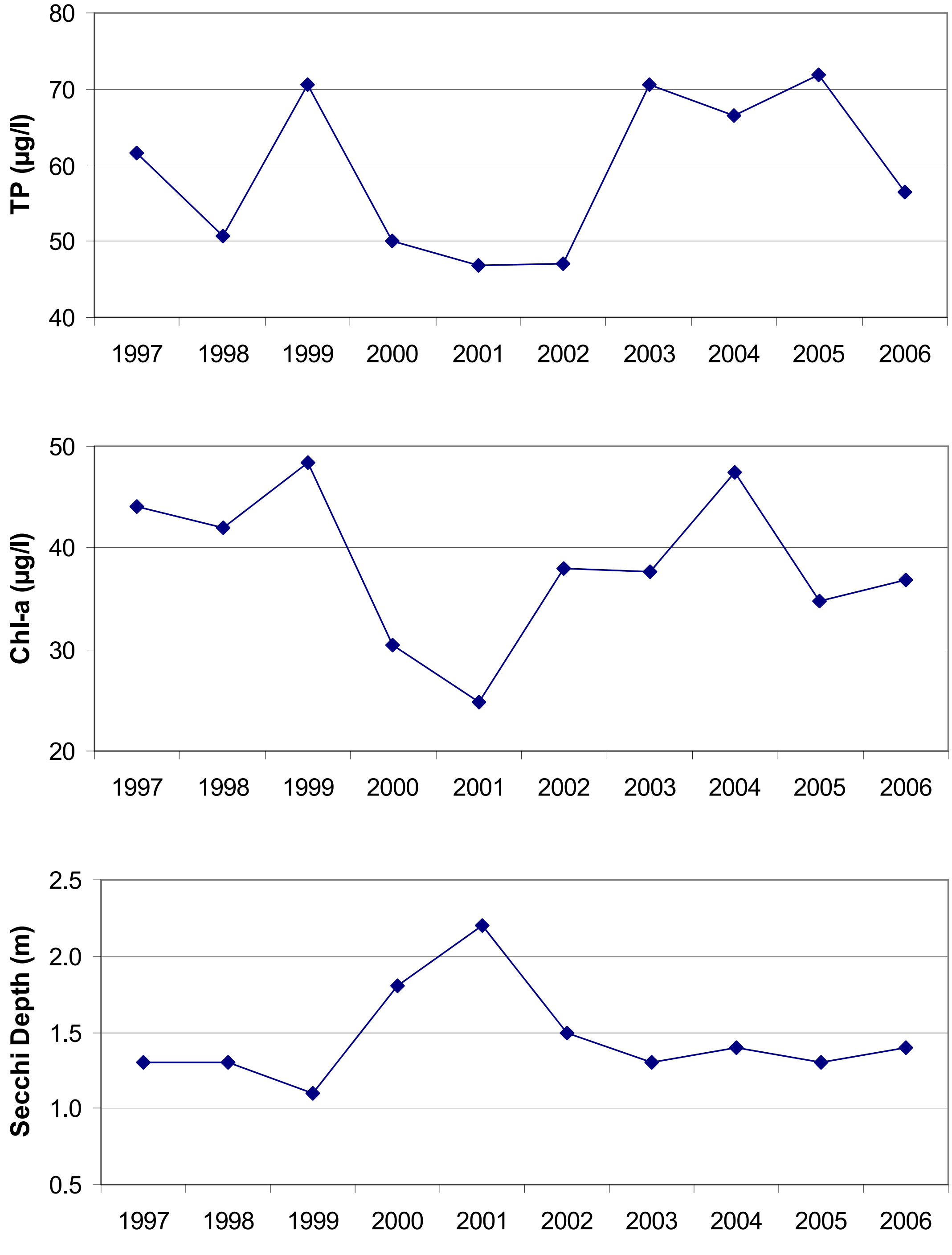
Chlorophyll$_a$ and TP concentrations both exceeded the respective statutory target concentrations of 15 µg l^{-1} and 40 µg l^{-1} set by the Loch Leven Area Management Group (LLAMAG) in 1993 (LLAMAG 1993) and endorsed in the Loch Leven Management Plan (Loch Leven Catchment Management Project 1999). Phosphorus concentrations, both bio-available forms (SRP) and total phosphorus, have, however, shown a large improvement over time, with a clear movement towards the TP target set by LLAMAG, whereas both chlorophyll and water clarity has shown little improvement.

Some positive news can be taken from the strong spring clear-water phase which established in May and June in all three years, particularly in 2004 and 2006. Maximum recorded rooted growing depth was also particularly deep in 2006 (>4.5 m) compared with all previous records from the loch. The 2006 rooted depths identified through grapnel tows were confirmed using underwater video. This is evidence of some further recovery in the ecological quality of the loch, which should lead to improvements in food and habitat quality of invertebrates, fish and birds.

The angling community at Loch Leven have raised some concerns regarding possible impacts of the dense diatom blooms on the fish community. The dominant phytoplankton in Loch Leven is the diatom *Aulacoseira*, which forms long chains of cells particularly in Spring and Autumn. Despite forming long chains, this type of alga is still a very good food source for zooplankton grazers, and in particular has been observed to be the preferential food of rotifers in Loch Leven (May *et al*., 2001). *Aulacoseira* cells have also been observed in other studies to be a major part of the diet of filter-feeding bivalve molluscs and benthic invertebrates after they sink down to the sediments following the spring and autumn blooms. On the other hand, toxic cyanobacteria, such as *Microcystis*, have been observed to reduce zooplankton grazing rates (Thompson *et al*., 1982) and also have direct negative impacts on filter-feeding bivalves and fish. No negative effects of freshwater diatom blooms on lake food webs have been reported in the published literature. The shift to diatoms in Loch Leven should, therefore, be having favourable implications for the fish community in Loch Leven, including young, zooplanktivorous brown trout, and also birds that feed on the large populations of benthic invertebrates and swan mussels found in the loch.

Daphnia grazers clearly play a very significant role in driving the water quality of Loch Leven with reductions in chlorophyll & improvements in water clarity associated with increased *Daphnia* densities (Ferguson *et al*., 2007a). *Daphnia* densities in 2004-2006 were relatively low compared with the 2000-2002 period, although spring densities were higher than the long-term average. Analysis of the long-term datasets, suggests that the trend towards warmer springs observed at Loch Leven is having a significant, positive effect on spring *Daphnia* densities, and may, in part be responsible for the more defined spring clear water phase observed in recent years (Ferguson *et al*, 2007b).

Figure 17 Temporal trends in annual mean TP and chlorophyll$_a$ concentrations and Secchi depth over the past 10 years



4.2 Lake and Catchment Management Implications

The reductions in phosphorus concentrations that have occurred at Loch Leven still appear to be insufficient to limit phytoplankton populations for much of the year. Phosphorus concentrations do get fairly close to limiting levels in Spring and Autumn, but clearly not low enough to have a strong limiting effect on the large diatom crops that dominate in these seasons. Further reductions in phosphorus loading should, therefore, be pursued. During the summer period, nitrogen-limitation of phytoplankton crops appears to be more important, so further reductions of nitrogen loading from the catchment is also strongly recommended. There is no evidence that increased N-limitation will encourage N-fixing cyanobacteria to dominate.

Recent research at CEH (Spears 2007, Spears *et al*, 2007) has shown that nutrient release from sediments ("internal loading") is still a significant source of nutrients to the water column at Loch Leven, particularly during the summer months when microbial breakdown is most active. This research has also shown that this release can be reduced significantly in the more oxygenated shallow water sediments (<5 m depth), thought to be due to the effects of benthic algae maintaining oxygenated sediments (Spears, 2007; Spears *et al*, 2007). The fact that improving light conditions in the loch are encouraging deeper growth of macrophytes, suggests that benthic algae are also able to colonise to deeper waters than previous decades, suggesting that internal loading although still very significant, may be reducing in magnitude. Studies of a number of long-term monitoring sites from around the world (Jeppesen *et al*., 2005) indicate this lag in recovery is typical following many years of enrichment. Long recovery times in shallow lakes are largely due to internal loading that can continue for many years or even decades following catchment measures (Scheffer, 1998).

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