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THE URBAN WASTE-WATER TREATMENT DIRECTIVE:

OBSERVATIONS ON THE WATER QUALITY OF WINDERMERE, GRASMERE, DERWENT WATER AND BASSENTHWAITE LAKE, 2002

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This report has been independently checked for consistency, scientific rigour and presentational quality, and amended where appropriate. Final responsibility for the report remains with the author(s).

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Executive summary

1. The results of biological and chemical analyses undertaken on samples collected during 2002 from the North and South Basin of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake are presented and interpreted in this report.

2. The North Basin of Windermere, South Basin of Windermere and Bassenthwaite Lake are all responding, to lesser or greater extents, to remediation by reduction of point-source phosphorus load from Wastewater Treatment works. The extent of this response varies with the lake and is also influenced by the weather in a particular year.

3. The main weather event which influenced lake function during 2002 was the relatively dry late summer and autumn. This had little discernible effect on the North and South Basin of Windermere and Derwent Water with relatively long retention times. In contrast, in Grasmere and Bassenthwaite Lake where algal populations are usually constrained by hydraulic loss, relatively large autumn populations developed.

4. In Bassenthwaite Lake the autumn peak was dominated by the cyanobacterium *Anabaena solitaria* which was largely responsible for a maximal chlorophyll *a* concentration of 40.4 mg m^{-3} in the centre of the lake. This is not exceptional for the lake but, because this alga is buoyant, unlike many maxima in previous years, it is susceptible to aggregation in downwind bays and lake shores. This is likely to be the cause of the concern over water quality in Bassenthwaite, particularly in the River Derwent downstream of the lake.

5. While Grasmere and Derwent Water show no evidence of any long-term change, there is some evidence for a continued decline in average total phosphorus in Bassenthwaite Lake. In contrast, there is still cause for concern over water quality in the two basins of Windermere where conditions in 2002 appear to have been slightly worse than in previous years.

6. Continued monitoring is essential to ensure that any improvements in water quality are documented and any deterioration is detected so that management strategies can be implemented.

CONTENTS

1. INTRODUCTION

This report continues a sequence of annual reviews of water quality in Windermere and Bassenthwaite Lake that are subject to the provisions of the Urban Waste Water Treatment Directive. Grasmere, which feeds into Windermere is also included because of concerns over a deterioration in water quality over the last, approximately 30 years and Derwent Water is included, partly as a comparison with Bassenthwaite Lake and partly because it is the sole refuge of a healthy, population of the vendace, *Coregonus albulus*. Linked reports on the status of populations of arctic charr in Windermere and vendace in Bassenthwaite Lake and Derwent Water are given in Winfield et al. 2003a,b.

Previous reports in the series were prepared by C.S. Reynolds who retired in May 2002. This report has been prepared by S.C. Maberly but follows the general format of the earlier reports for consistency of presentation.

2. GENERAL FEATURES OF THE STUDY LAKES

The five lake basins experience the same day-to-day and year- to-year fluctuations in weather. However, the influence of this varies because of physical differences among the lake basins (Table 1). Thus Grasmere and Bassenthwaite Lake, on average, have short retention times which reduces the build up of phytoplankton under normal discharge, and can produce rapid loss of phytoplankton during high discharge. In contrast, the North Basin of Windermere has a relatively long average retention time which makes its biology less susceptible to changes in rainfall. The shallow lakes Bassenthwaite and Derwent Water are less strongly stratified as the energy from wind-induced surface mixing can readily break down transient thermal structures.

Table 1. General physical features of the study lake basins, largely from Talling (1999) and Reynolds & Irish (2000)

Lake Basin	Altitude (m)	Area (km^2)	Max. depth (m)	Mean depth (m)	Volume (10^6 m^3)	Area of drainage basin (km^2)	Average retention time (d)
Grasmere	62	0.64	21.5	7.7	50	27.9	28
Bassenthwaite Lake	69	5.28	19	5.3	27.9	347.4	19
Derwent Water	75	5.35	22	5.5	29.0	82.7	67
Windermere North Basin	39	8.05	64	25.1	201.8	174.7	168
Windermere South Basin	39	6.72	42	16.8	112.7	55.8	94
Windermere total lake	39	14.77	64	21.3	314.5	230.5	263

The study lakes fall roughly in the middle of the Pearsall series from Wastwater to Esthwaite Water. Derwent Water has the lowest alkalinity, conductivity and concentration of all the plant nutrients of the study lakes, while Bassenthwaite Lake and South Basin of Windermere tend to have the highest.

Table 2. General chemical features of the study lakes based on Lakes Tour data from January 2000 (Parker et al. 2001).

Lake Basin	Alkalinity (mEquiv m^{-3})	Conductivity (μS cm^{-1})	Total P (mg m^{-3})	Dissolved inorganic nitrogen (mg m^{-3})	Silica (mg m^{-3})
Grasmere	90	56.1	10.7	590	2040
Bassenthwaite Lake	116	67.8	15.9	450	2130
Derwent Water	65	55.7	6.3	313	1710
Windermere North Basin	201	72.7	11.1	548	2040
Windermere South Basin	262	81.0	14.8	646	1910

3. WINDERMERE NORTH BASIN

Seasonal changes in the concentration of total phosphorus are relatively small and the concentrations in 2002 were very similar to the average in the preceding seven years (Fig. 1). Seasonal changes in soluble reactive phosphate (here ascribed to phosphate, PO_4-P) were also similar to previous years with an annual maximum of 0.009 g m^{-3} and a minimum below the level of detection of 0.0006 g m^{-3}. The concentration of phytoplankton chlorophyll *a* was slightly higher than in previous years (Fig. 2) with an annual maximum of 17.1 mg m^{-3} in early August produced by a mixed population of cyanobacteria such as *Anabaena lemmermannii, A. circinalis, Aphanothece clathrata, Aphanizomenon flos-aquae* and *Planktothriz mougeotii* as well diatoms such as *Cyclotella comensis* and green algae such as *Micractinium* sp., *Oocystis* sp. and *Pseudosphaerocystis* sp. (data submitted to EA by separate transfer, copies retained on CEH database). *Aphanothece clathrata* was also present last year (Reynolds et al. 2002) but produced a much larger population this year (971 compared to 140 colonies mL^{-1}).

There is a small, but just statistically significant ($p= 0.04$), increase in the annual average phytoplankton chlorophyll *a* in the North Basin (Figs 2 & 5). Linked to this, the minimum secchi depth declined from 3.5 to 2.5 m (Figs 2 & 5). The oxygen concentration at depth was also lower in 2002 at 5.65 g m^{-3} than in any of the succeeding seven years when the average minimum was 6.66 g m^{-3} (Figs 3 & 5). Surface water temperature in the North Basin was slightly cooler than in succeeding years in early summer but the water temperature at depth was very close to the long-term seasonal average(Fig. 4) Apart from average phytoplankton chlorophyll *a*, noted above, there were no time-trends in any of the other variables over these eight years.

4. WINDERMERE SOUTH BASIN

The concentration of total phosphorus in the South Basin of Windermere is about 1.5 times greater than in the North Basin (range of 0.014 to 0.029 g m^{-3} rather than 0.009 to 0.018 g m^{-3}), as is the maximum concentration of PO_4-P (0.014 vs 0.009 g m^{-3}) although the minimum concentration of PO_4-P is similarly below the level of detection in summer (Fig. 1).The average concentration of TP and PO_4-P were marginally lower than 2001 but there are no significant changes in concentration of either phosphorus form over the last eight years, although the direction of change is for a decline (Fig. 6).

Seasonal changes in phytoplankton chlorophyll *a* concentration was rather similar to previous years (Fig. 2) with two nearly equal maxima of about 22 mg m^{-3}, one at the end of May and the other at the beginning of September. The spring peak comprised a typical diatom assemblage of *Asterionella formosa* (5617 cell mL^{-1}) and *Aulacoseira subarctica* (262 cell mL^{-1}). The late summer peak comprised a mixed assemblage of thirty-seven species including *Aphanizomenon flos-aquae*, *A. formosa*, *Chlorella* sp. and *Geminella* sp. The average and maximum concentration of chlorophyll *a* were both below the exceptional values of 2001 reinforcing the belief that the high values in 2001 resulted from the particular weather in that and the previous year. There are no statistically significant changes in long-term (last eight years) concentrations of the maximum, average or minimum concentration of chlorophyll in the South Basin (Fig. 6).

Although the concentration of phytoplankton chlorophyll *a* has remained relatively unchanged, the secchi disc depth was shallower between April and August than in the previous seven years and there has been a significant ($P < 0.001$) long-term decline in average secchi depth over the last eight years, the reason for which is unclear. It could result from changes in phytoplankton assemblage towards smaller species or it could represent an increase in non-algal dissolved and particular material in the lake. Further work would be necessary to understand the reasons behind this trend.

As in the North Basin, spring and early summer water temperature was slightly cooler than in previous years (Fig. 4). The hypolimnetic oxygen concentration fell to 0.6 g m^{-3} (Fig. 3), the first time it has fallen below 1 g m^{-3} since the phosphate stripping procedure began. This may be related in part to the slightly higher hypolimnetic temperature in 2002, presumably increasing respiratory oxygen demand, since there is a negative, but not quite significant relationship between oxygen minimum and water temperature at depth ($r = -0.64$, $P = 0.09$).

5. GRASMERE

In contrast to the two basins of Windermere, Grasmere is much more susceptible to heavy rain events because of its relatively short average retention time (Table 1). In 2002, the seasonal pattern of total phosphorus was similar to previous years but with slightly lower concentrations in summer and an annual maximum of 0.037g m^{-3} in mid October (Fig. 1). Concentrations of PO_4-P ranged from below the limit of detection of 0.0006 g m^{-3} and a maximum of 0.0095 g m^{-3} also in October. The high phosphorus concentration in October is consistent with a large input as a result of high rainfall. There are no statistically significant long-term trends in either total P or PO_4-P in Grasmere over the last eight years.

Phytoplankton chlorophyll *a* varied between a minimum of 0.7 mg m^{-3} in December 2002 and a maximum of 35.8 mg m^{-3} at the end of September (Fig. 2). Although both the minimal or maximal values are within the range recorded in previous years, the annual maximum coincided with a particularly dry late summer and early autumn giving the phytoplankton a chance to develop during a period of low hydraulic loss as modelled by Reynolds *et al.* (2001). This assemblage was dominated by *Cryptomonas* sp. with a population of over 900 cell mL^{-1}, along with smaller biovolumes of *Chlorella* sp. *Asterionella formosa*, and *Rhodomonas* sp. There are no statistically significant changes in phytoplankton chlorophyll *a* or secchi depth in Grasmere (Fig. 7) and the lake appears to be at a stable trophic state.

Temperature in the surface and bottom of Grasmere was very similar to previous years (Fig. 4) and the minimum concentration of oxygen at depth at 0.08 g m^{-3} (Fig. 3) was similar to previous years and there was no evidence of long-term change.

6. DERWENT WATER

Derwent Water is a mesotrophic lake where the water quality is strongly controlled by the availability of phosphorus (Hall *et al.* 2000). The seasonal pattern of change is similar to the average pattern in previous years (Fig. 1). The maximal concentration of total phosphorus in 2002 at 0.0174 g m^{-3} was higher than in 2001, but the annual average concentration was similar and there has been a statistically significant decline in average total phosphorus concentration ($r = -0.85$, $P<0.01$) over the last eight years (Fig. 8). The concentration of PO_4-P ranged from less than the detection limit of 0.006 g m^{-3}, as is typical in most years, to a maximum in October of 0.0085 g m^{-3}. This latter value is higher than has been recorded before and, although it occurred at about the time the lake de-stratified and hence phosphorus from depth may become available, could represent contamination because it is a single point and the difference between total phosphorus and PO_4-P is small. There is a tendency (even when this point is excluded) for the average concentrations of PO_4-P to have increased over the last eight years, but this is not statistically significant.

Concentrations of phytoplankton chlorophyll *a* reached a maximum of 7.8 mg m^{-3}, even lower than 2001, (Figs 2, 8) and the average concentration was 4.4 mg m^{-3}. The seasonal pattern was very similar to previous years (Fig. 2) and there have been no significant long-term changes over the last eight years. The annual maximum chlorophyll in early March was dominated by the diatoms *Asterionella formosa* (1064 cell mL^{-1}) and *Aulacoseira ambigua* 850 cell mL^{-1}), along with *Chlorella* spp. (5300 cell mL^{-1}) and *Rhodomonas* sp. (1060 cell mL^{-1}). Summer dominants, albeit at low concentration, comprised the cyanobacterium *Anabaena lemmermannii*, along with smaller amounts of a mixed population of the green alga *Chlorella* spp., the haptophyte *Chrysochromulina parva*, the diatom *Cyclotella comensis*, and the chrysophyte *Urosolenia* sp.

Secchi depth ranged between 2.9 and 6.4 m, following a similar seasonal pattern to previous years (Figs 2, 8). There is a weak, but statistically insignificant, tendency for secchi depth to have increased in the last 8 years (Fig. 8). The oxygen at depth fell to a low concentration (0.13 g m^{-3}; Fig. 3) which is typical of previous years and there is no indication of a long-term trend.

7. BASSENTHWAITE LAKE

The status of Bassenthwaite Lake has been a cause for concern in recent years despite the implementation of a tertiary treatment plant at the Keswick WwTW in 1995. The main conservation concern is over the state of the population of the rare fish the vendace (e.g. see Winfield et al. 2003a), but there are also issues over water quality and production of algal blooms (e.g. Maberly & Elliott 2002, Maberly 2003).

Despite the concerns over water quality, the annual maximum and average concentration of total phosphorus at 0.0277 and 0.0199 g m^{-3} respectively are the lowest recorded in the last eight years (Figs 1, 9) and average total phosphorus concentration has declined significantly over that time ($r = -0.90$; $P< 0.01$). The concentration of PO_4-P ranged between 0.0068 g m^{-3} and below the detection limit at <0.0006 g m^{-3}. There has been a statistically significant decline in the annual maximum concentration of PO_4-P since 1995 ($r = -0.77$; $P<0.05$).

In the early part of the year the phytoplankton chlorophyll *a* followed a similar seasonal pattern to previous years (Fig. 2) with a small spring peak of 15.9 mg m^{-3} in mid April but otherwise slightly lower phytoplankton chlorophyll than before. The spring peak comprised the typical vernal diatoms *Aulacoseira ambigua* (3010 cell mL^{-1}) and *Asterionella formosa* (1650 cell mL^{-1}) along with *Chlorella* spp (4340 cell mL^{-1}). In early autumn, following a dry late summer, a large chlorophyll *a* concentration built up reaching 35.7 mg m^{-3} on 2 October 2002 and a maximum of 40.4 mg m^{-3} on 16 October 2002 before falling to 12.7 mg m^{-3} on 30 October (Fig. 2). The maximum mainly resulted from a dense population of *Anabaena solitaria* which reached 108 mm filaments mL^{-1} with some representation by *Aulacoseira ambigua* and *Chlorella* spp. *A. solitaria* is a filamentous species which produces gas vesicles (Fig. 10) and so can be buoyant allowing it to be carried by wind and waves to produce large accumulations in downwind bays and lake shores. This autumn this population produced a major concern, particularly in the water quality of the River Derwent leaving Bassenthwaite. This size of chlorophyll maximum is not unusual in Bassenthwaite and in 1999, 94 mg m^{-3} was produced. However, this maximum was produced largely by non-motile species such as *Dictyosphaerium* and *Aulacoseira* which are not susceptible to down-wind accumulation (Maberly 2003).

Overall there is no evidence for long-term changes in phytoplankton chlorophyll *a* or secchi depth, although in this lake the latter is controlled more by the amount of suspended solids than the amount of algae (Maberly 2003). Seasonal patterns of water temperature and oxygen depletion at depth in 2002 were typical for Bassenthwaite (Figs 3, 4, 9).

8. SYNOPSIS AND CONCLUSIONS

This report details the results for 2002 of part of a monitoring programme which is able to assess lake functioning, water quality and provide data to interpret the causes of the patterns and responses observed. As in previous reports a major aspect of the work is to distinguish between long-term changes that result, for example, from changed nutrient loading in the catchment, or from point sources such as WwTW, from those that result from the weather in a particular year and lake sensitivity to a particular weather driver. For any nutrient loading there will be an 'envelope' of outcomes depending on the weather. This was well illustrated this year in Bassenthwaite Lake, where a relatively large population of *Anabaena solitaria* developed in late autumn because of a spell of dry weather: the relatively rapidly flushed nature of this lake (Table 1) normally prevents these populations of slow growing phytoplankton from developing. Although the maximum biomass as chlorophyll *a* was not particularly exceptional for the lake, the buoyant nature of this particular species allows it to accumulate downwind and this characteristic probably accounts for the perceived poor water quality in late autumn, particularly in the river draining the lake, the River Derwent. This also underlines the necessity of knowing which species are present rather than relying solely on chlorophyll *a* concentration.

The studied lakes responded rather similarly in 2002 to previous years. In the North Basin of Windermere there is some weak evidence that the lake is not improving further and showing some signs of regressing: since 1995 the annual average phytoplankton chlorophyll *a* has increased, the minimum secchi depth has declined and the oxygen depletion at depth was greater than in previous years. This may just represent a response to the particular weather in 2002, but it is important to continue the monitoring programme to detect any further deterioration in water quality.

In the South Basin of Windermere, the concentrations of total phosphorus and phytoplankton chlorophyll *a* appear to be stable but there is an apparent decline in secchi depth which will have a knock-on effect on macrophyte populations in the lake, particularly at depth. The reason for this decline are unclear. The greater extent of hypolimnetic oxygen depletion noted in 2002 probably results from the greater hypolimnetic water temperature and therefore results from weather patterns. Nevertheless, continued monitoring is essential to provide an early warning of a deterioration in water quality.

Grasmere shows no long-term changes and the water quality appears to be stable. The dry late summer and early autumn resulted in a large autumn population of phytoplankton developing, for the same reason as in Bassenthwaite Lake.

The concentration of total phosphorus in Derwent Water is declining but there is little evidence for changes in phytoplankton chlorophyll *a* concentration or oxygen depletion. This lake also appears to be stable and there are no causes for concern over its water quality.

These lakes should continue to be monitored to ensure that any deterioration in water quality if noted rapidly and to document and quantify any improvement in water quality resulting from management of the loads of nutrient to the lake.

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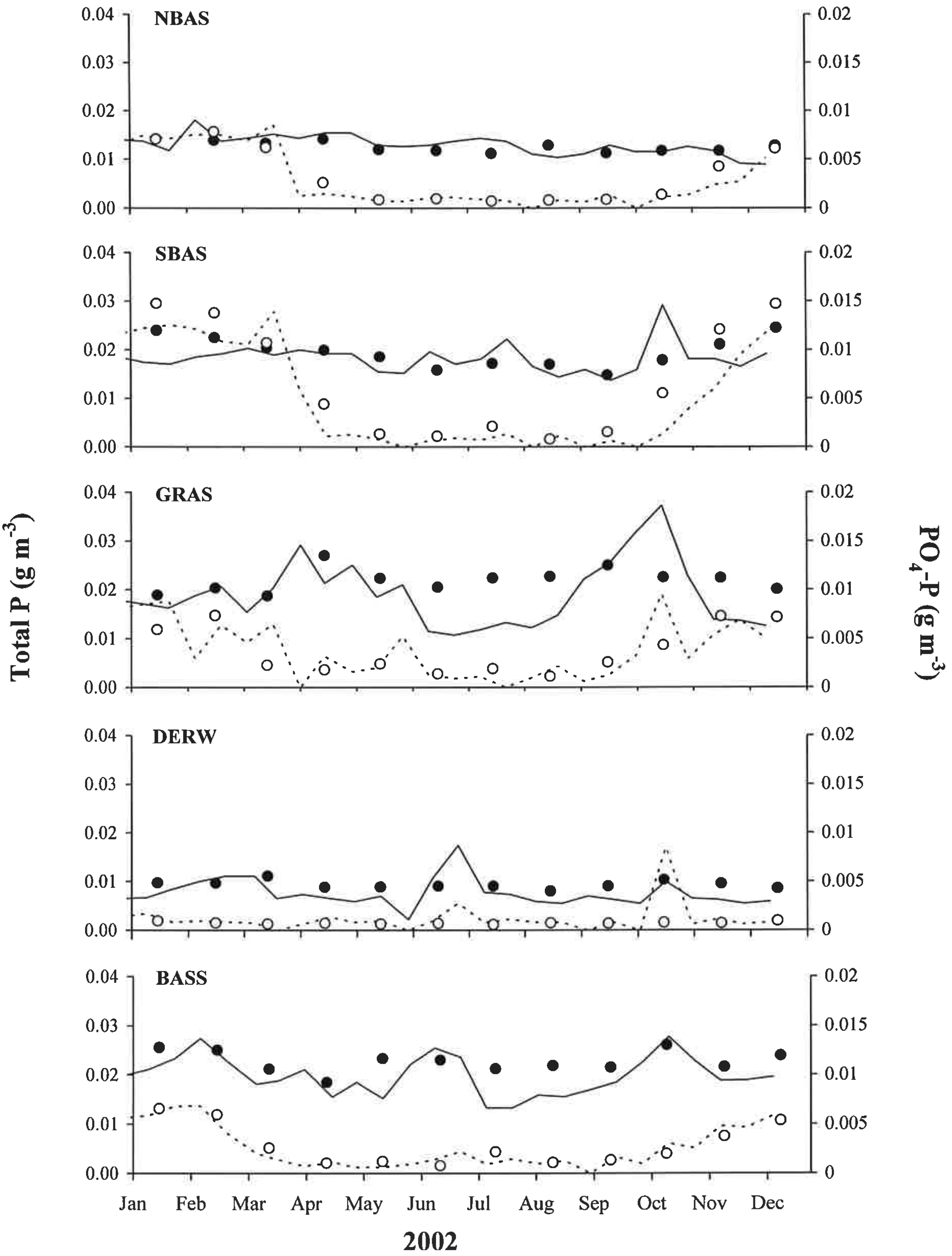

Fig. 1. Total phosphorus (__) and PO_4-P (---) concentrations measured in five lake basins in 2002. Monthly average (1995-2001) Total P (closed circles) and PO_4-P (open circles) also shown.

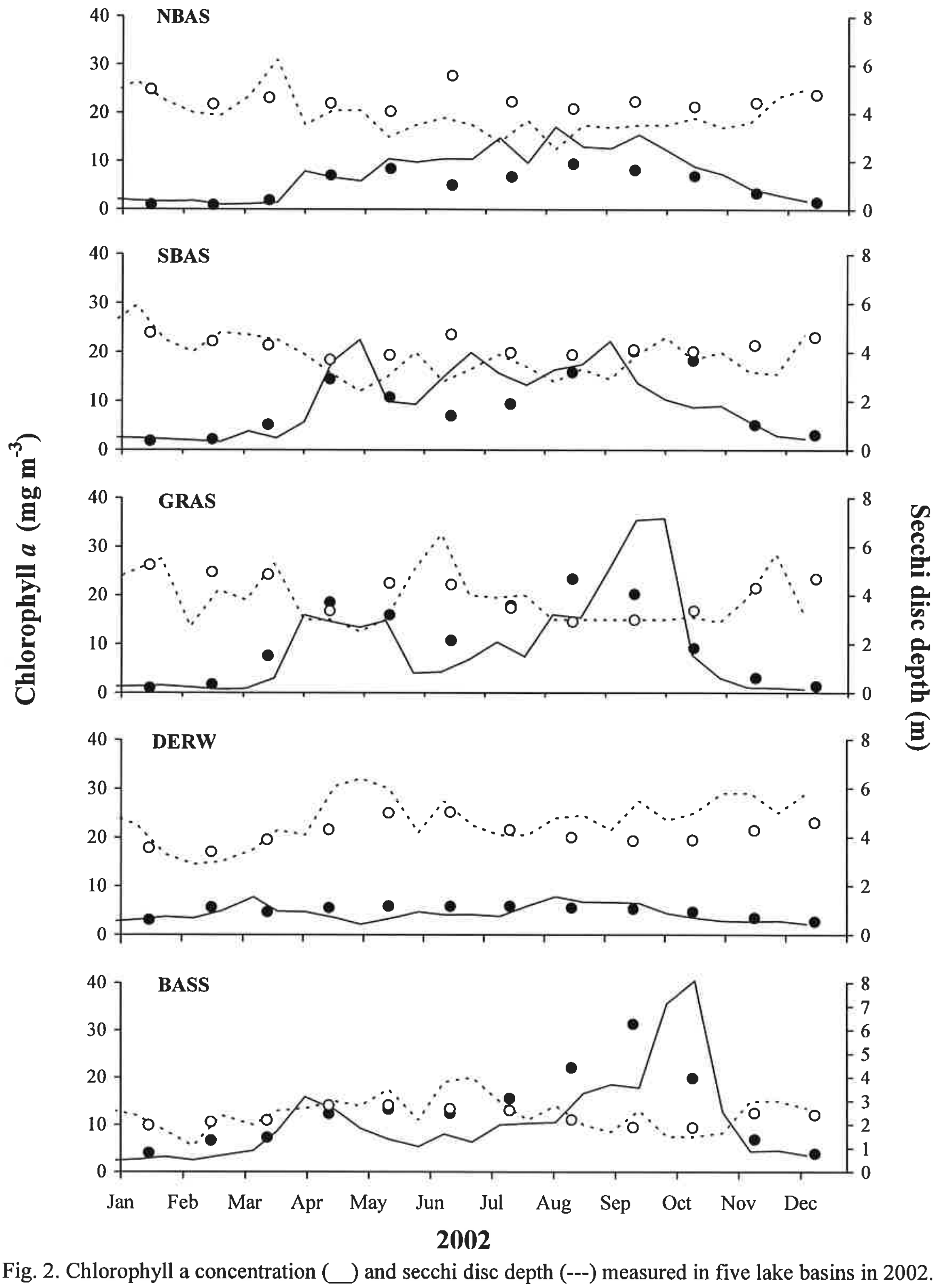

Fig. 2. Chlorophyll a concentration (__) and secchi disc depth (---) measured in five lake basins in 2002. Monthly average (1995-2001) chlorophyll a (closed circles) and secchi depth (open circles) also shown.

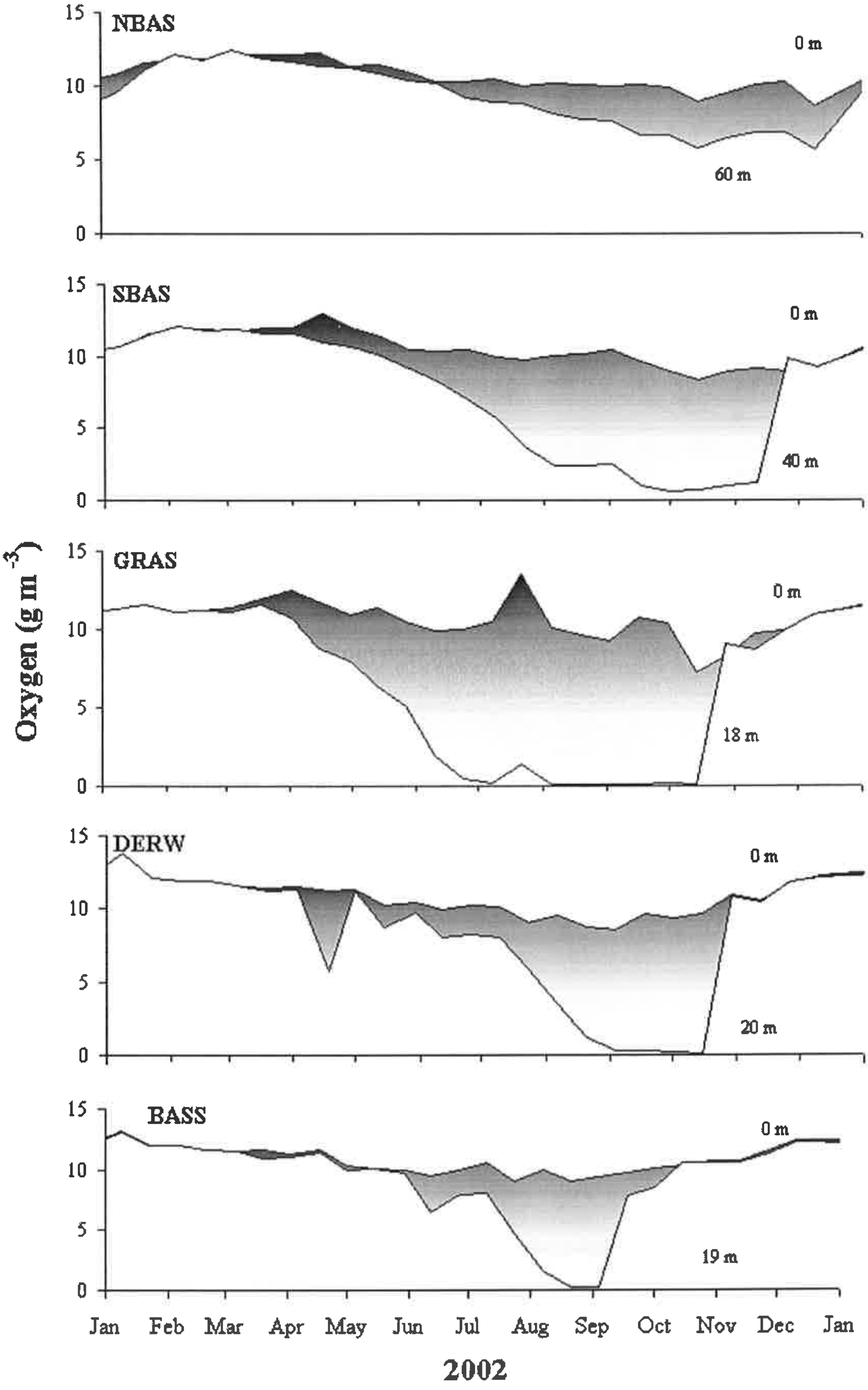

Fig. 3 Oxygen concentrations measured at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake during 2002.

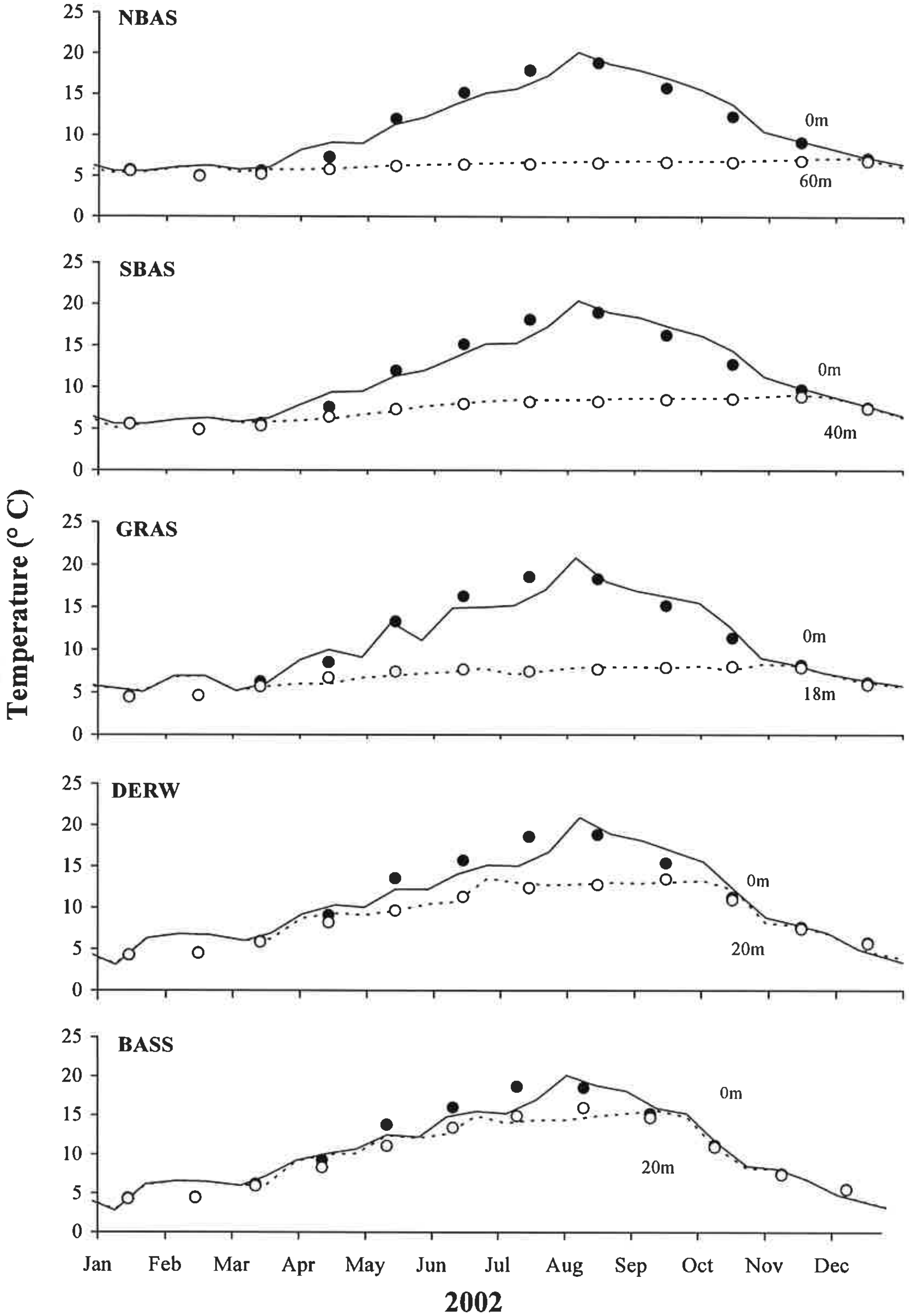

Fig. 4. Temperature at the surface (__) and maximum depth (---) measured in five lake basins in 2002. Monthly average (1995-2001) surface (closed circles) and bottom temperature (open circles) also shown.

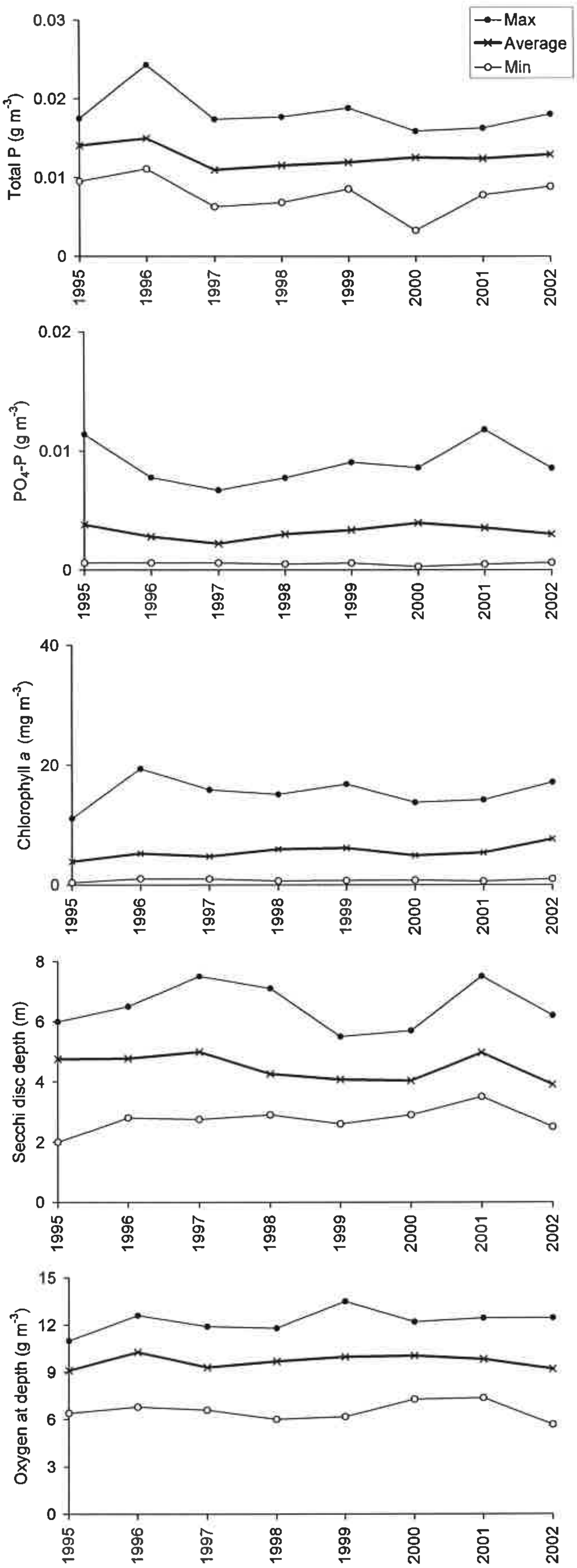

Fig. 5. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a*, secchi depth, and oxygen concentration at depth between 1995 and 2002 in the North Basin of Windermere.

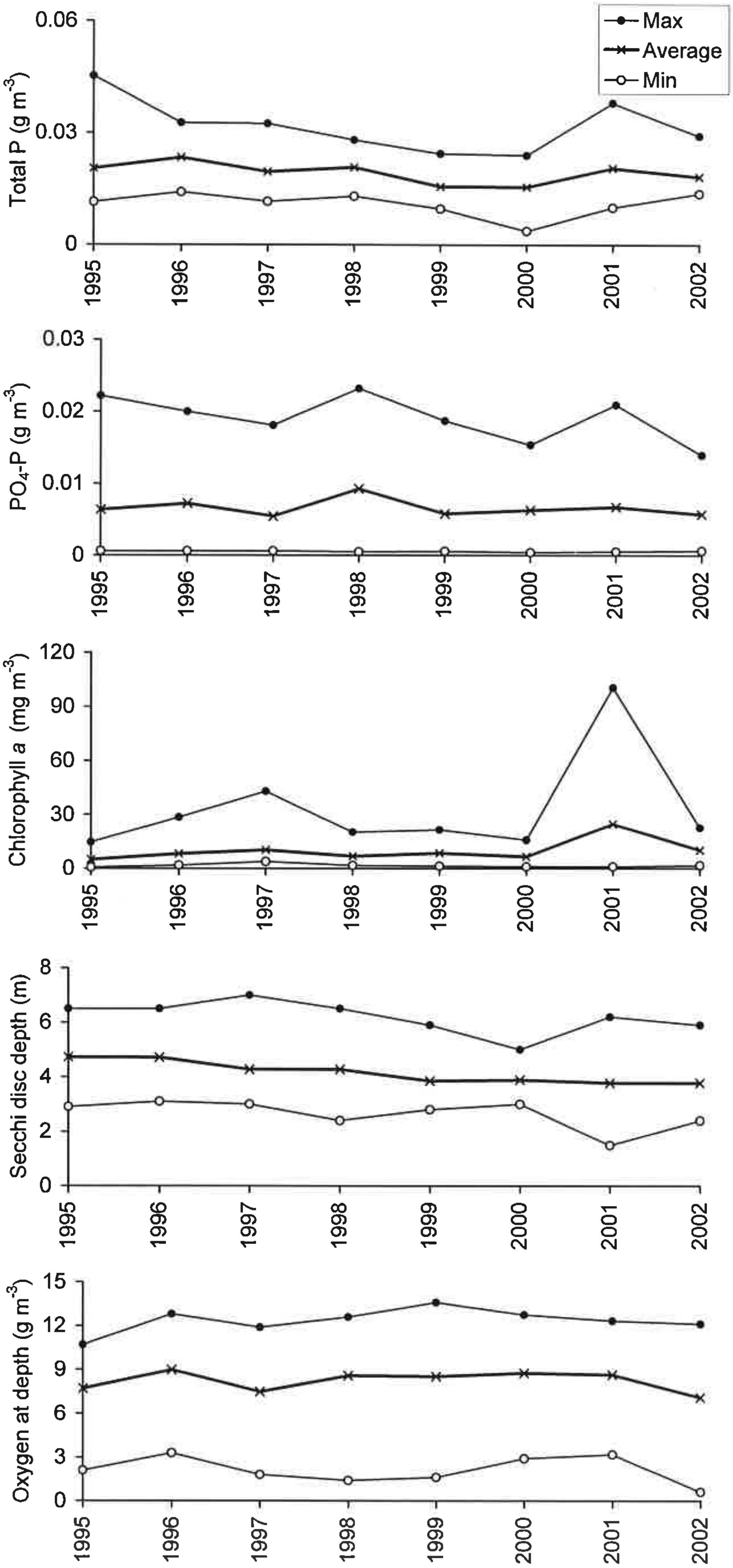

Fig. 6. Changes in the annual maximum, average and minimum values of total phosphorus, PO4-P, phytoplankton chlorophyll *a*, secchi depth, and oxygen concentration at depth between 1995 and 2002 in the South Basin of Windermere.

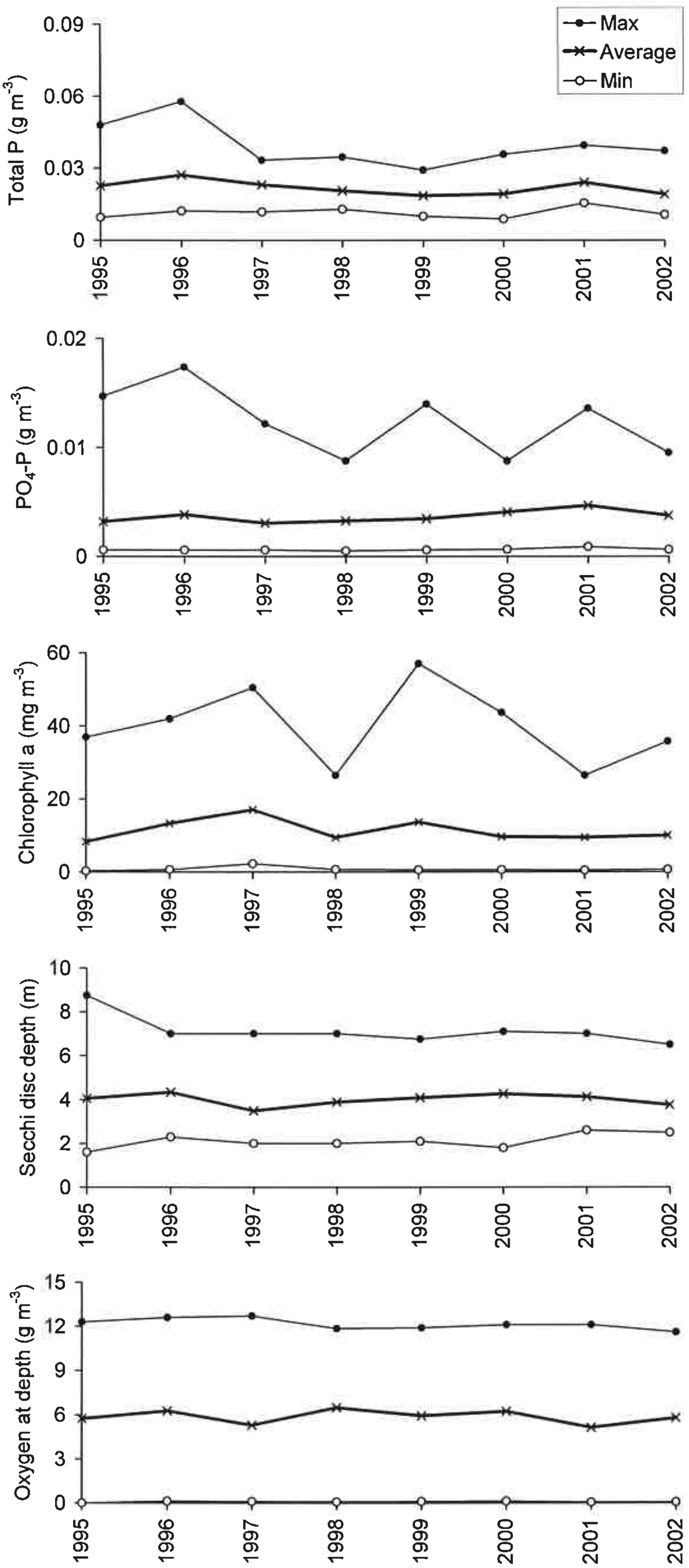

Fig. 7. Changes in the annual maximum, average and minimum values of total phosphorus, PO4-P, phytoplankton chlorophyll *a*, secchi depth, and oxygen concentration at depth between 1995 and 2002 in Grasmere.

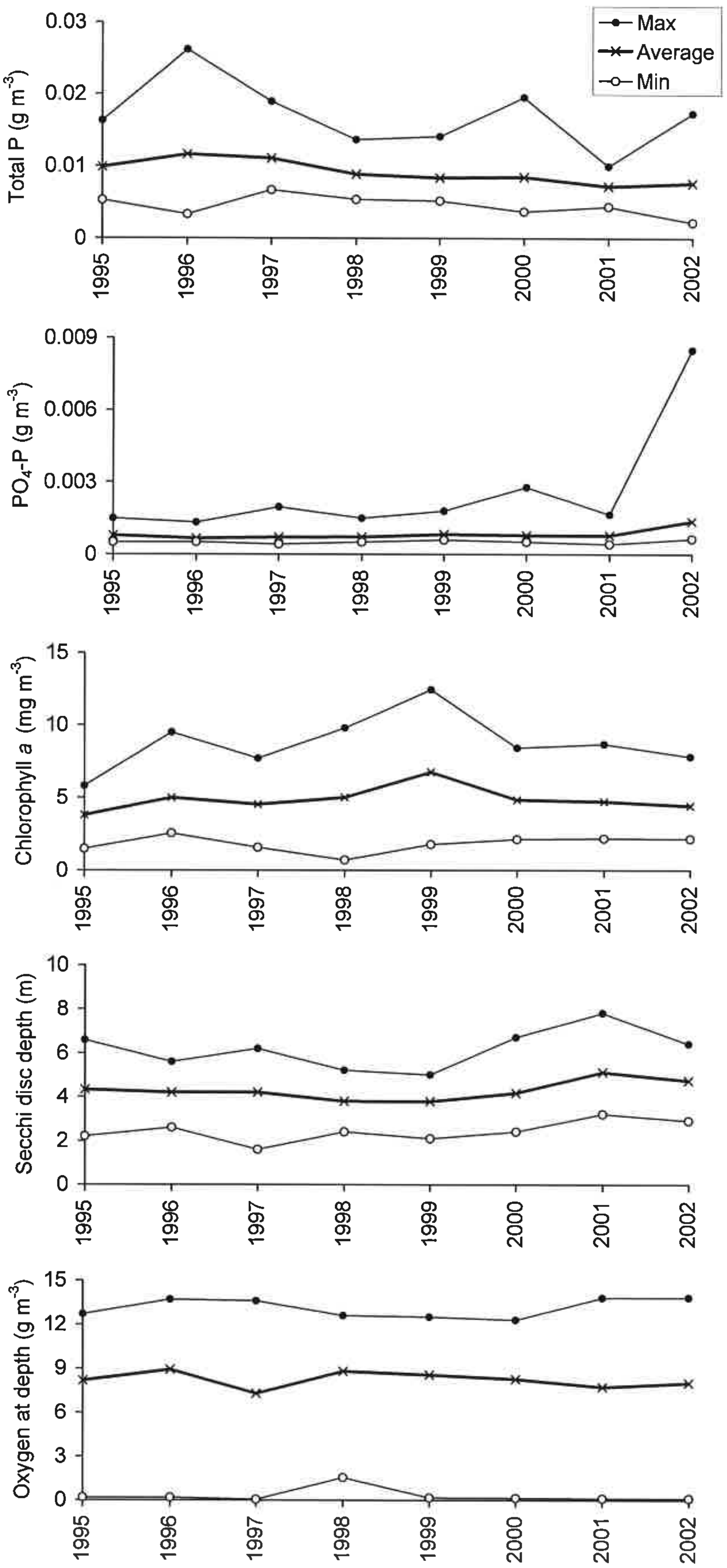

Fig. 8. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a* , secchi depth, and oxygen concentration at depth between 1995 and 2002 in Derwent Water.

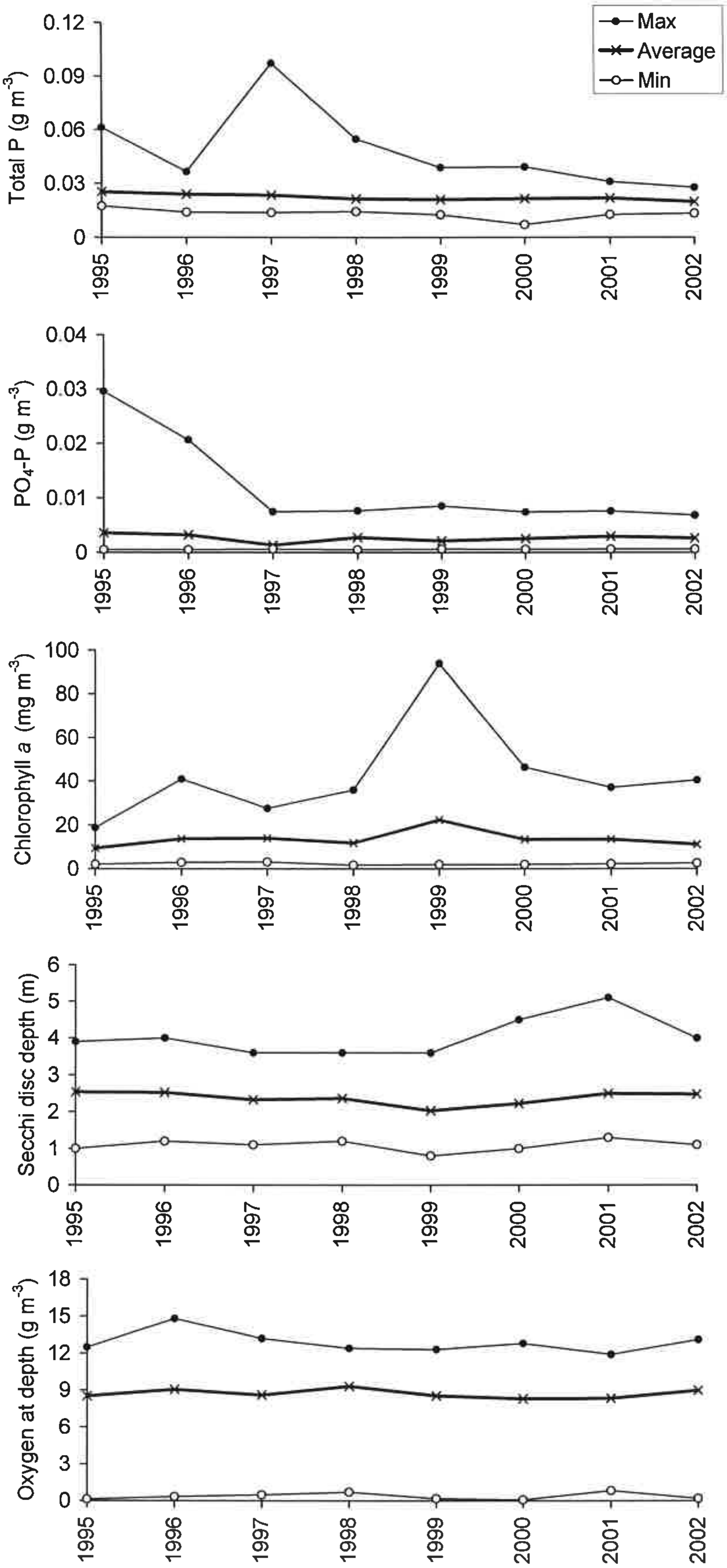

Fig. 9. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a*, secchi depth, and oxygen concentration at depth between 1995 and 2002 in Bassenthwaite Lake.

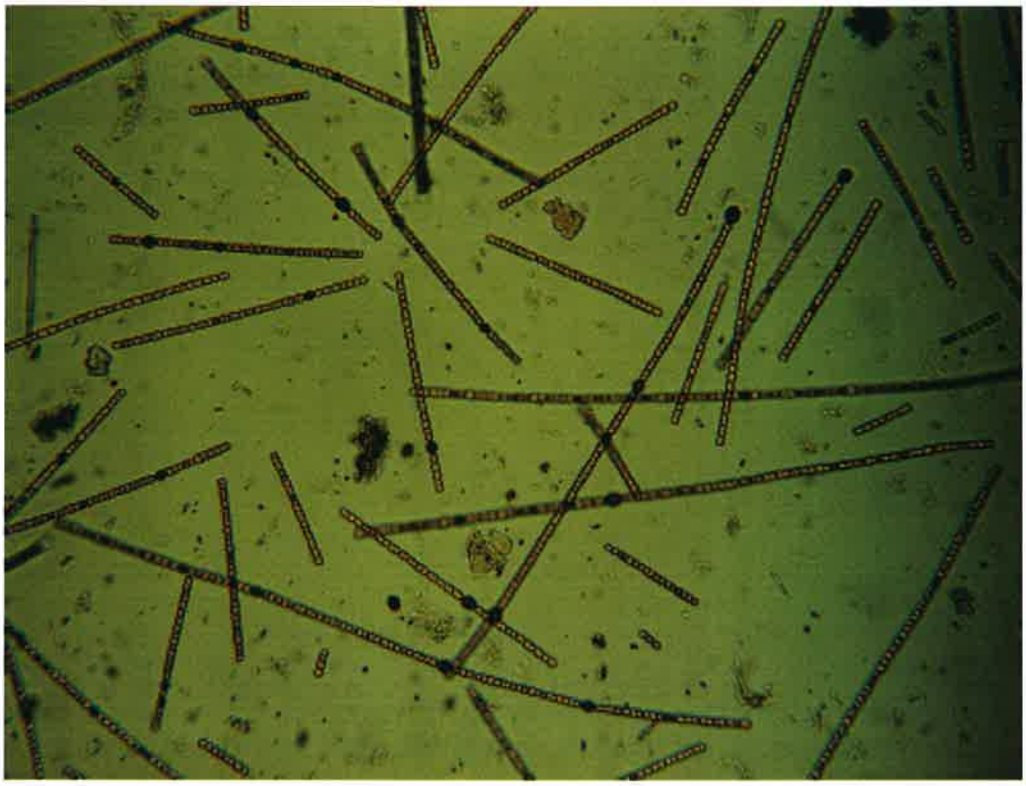

Fig. 10. Photograph of *Anabaena solitaria* from Bassenthwaite Lake after preservation in Lugol's iodine The filament width is approximately 6 μm.

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