Centre for Ecology and Hydrology
Lancaster Environment Centre,
Library Avenue, Bailrigg
Lancaster
LA1 4AP

March 2007

THE URBAN WASTE WATER TREATMENT DIRECTIVE:

OBSERVATIONS ON THE WATER QUALITY OF WINDERMERE, GRASMERE, DERWENT WATER AND BASSENTHWAITE LAKE, 2006

Prepared by:
S.C. Maberly, M.M. De Ville, J.A. Elliott, J.M. Fletcher, J.B. James, S.J. Thackeray and C. Vincent.

Project Leader: S.C. Maberly
Contract Start Date: 1 April 2001
Report date: March 2007
Report to: Environment Agency (North West Region)
CEH Project: C01752NEW, Task 1
CEH Report Ref: WI/C01752/17

Executive summary

1. The results of biological, chemical and physical analyses undertaken on samples collected fortnightly during 2006 from the North and South Basin of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake are presented and interpreted in this report. Summary meteorological data from Ambleside for 2006 are presented to help understand the patterns found. The main meteorological feature of the year was the high temperatures in July and also in autumn.
2. In the North Basin of Windermere, 23.7ºC was measured at the end of July: the highest temperature recorded since records began in 1947. The minimum concentration of oxygen at depth was 3.5 g m^{-3}, the lowest recorded since the tertiary P-removal started in 1992 and part of a statistically-significant trend of reducing oxygen concentrations at depth. The annual average concentration of total phosphorus (TP) has shown a steady increase since 1997 to the value in 2006 of 15.8 mg m^{-3} and there is now worrying evidence that the water quality in the lake is deteriorating. Further evidence comes from the tendency for phytoplankton chlorophyll *a* to increase and for the significant decline in Secchi depth. Currently, the North Basin has moderate ecological status under the Water Framework Directive (WFD) and would, therefore, require a directed Programme of Measures to improve ecological status.
3. The South Basin of Windermere had a maximum water temperature of 24.1ºC, the highest ever recorded. The minimum oxygen concentration at depth was 2.2 g m^{-3}, slightly higher than in some earlier years, but there are no clear long-term trends. Alkalinity is increasing in the lake (and many other lakes in the area) with an annual mean of 14.7 g $CaCO_3$ m^{-3} and a peak pH of 9.55 during the summer phytoplankton bloom. There have been no statistically significant changes in the concentration of TP or phytoplankton chlorophyll a: the annual average for the latter was 7.5 mg m^{-3}. However, there has been a statistically significant decrease in Secchi depth from about 4.7 m in 1995 to 4 m in 2006. In terms of the WFD the South Basin has poor ecological status for both chlorophyll a and TP and urgent work is needed to improve the condition of the lake.
4. Grasmere water temperatures were also high in July but of more ecological impact was the partial destratification in August that caused temperatures at depth to rise, but resupplied oxygen to depth. Overall there is a statistically significant increase in oxygen concentration at depth. There is a slight, not significant, tendency for concentrations of TP to increase since 1995. Although there is also no significant increase in phytoplankton chlorophyll *a*, the trend is upwards and the late summer peak of 54 mg m^{-3} is the second largest recorded since records began in 1971. There has been a significant decline in annual average Secchi depth. Grasmere fails good ecological status for the WFD: in terms of chlorophyll *a* it is on the moderate: poor boundary.
5. In Derwent Water seasonal changes responded to meteorological forcing similarly to other lakes, however stratification only reformed weakly after breakdown in late summer resulting in elevated temperatures at depth but higher than usual oxygen concentrations. The have been no significant trends in oxygen concentration at depth. There are indications that the concentration of soluble reactive phosphorus (SRP) is increasing. There is an indication of an upward trend in concentration of TP and the annual average in 2006 was 12.1 mg m^{-3}, the highest recorded since records began in 1990. This is matched by the highest concentration of chlorophyll *a* recorded, 25.7 mg m^{-3}, and there is a significant trend for increasing chlorophyll. Although the ecological status based on TP is good, based on chlorophyll *a* it is just below the good: moderate

boundary and declining. Point sources of phosphorus to Derwent Water have been identified in another report and these inputs should be reduced.

6. Bassenthwaite Lake also had high water temperatures in July 2006 and an early breakdown of stratification in August with very little indication of reforming later in the summer. This helped reduce the extent and duration of oxygen depletion at depth. Although there has been a statistical reduction in concentration of TP since 1995, there has been very little change since 1998. Similarly there has been little change in concentration of SRP suggesting that improvements in water quality have stalled. This is supported by the lack of change in chlorophyll concentration or depth of the Secchi disc. While Bassenthwaite is at good ecological status for TP, it is only moderate for phytoplankton chlorophyll. Future work will need to identify why this is the case.
7. The long-term monitoring, started in 1945 in some lake basins, is an essential resource to diagnose change and its likely cause. Consistency of monitoring is essential in order that these valuable datasets are not compromised.

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*., 2007a,b. The location in Cumbria of the lakes included in this report are shown in Figure 1.

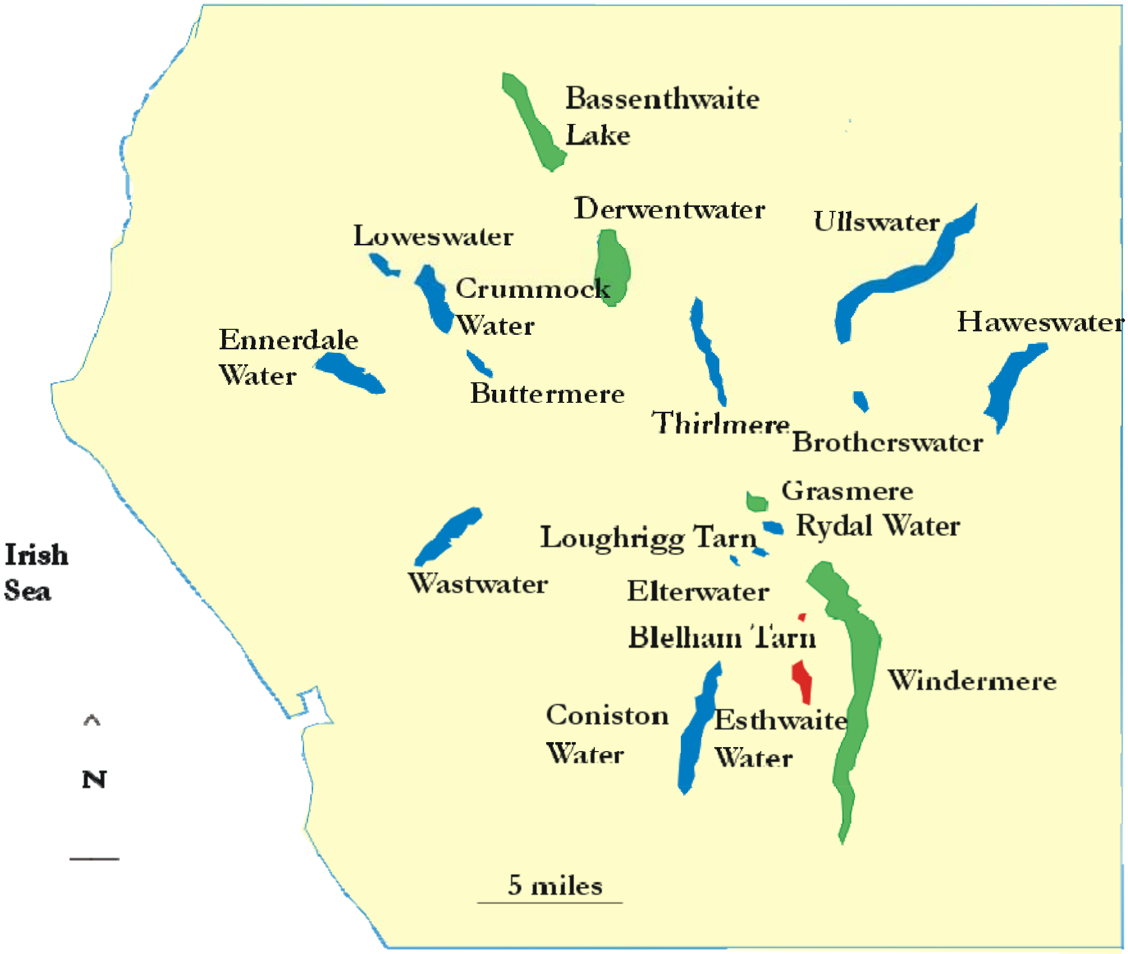

Figure 1. Location of major lakes of the English Lake District (after Pickering, 2001). Lakes included in this report are coloured green, lakes also monitored by CEH but not included in this work are coloured red.

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 (Fig. 2d) and Bassenthwaite Lake (Fig. 2e), 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 resulting from high rainfall. In contrast, the North Basin of Windermere (Fig. 2a) has a relatively long average retention time which makes its biology less susceptible to changes in rainfall. The shallow lakes Bassenthwaite and Derwent Water (Fig. 2c) 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). Also given are the Water Framework Directive typologies for these lakes: LA-S = Low alkalinity, shallow; MA-S = Medium alkalinity, shallow; MA-D = Medium alkalinity, deep.

Lake Basin	Altit -ude (m)	Area (km^2)	Max. depth (m)	Average depth (m)	Volume (10^6 m^3)	Area of drainage basin (km^2)	Average retention time (d)	WFD classif-ication
Grasmere	62	0.64	21.5	7.7	50	27.9	28	LA-S
Bassenthwaite Lake	69	5.28	20	5.3	27.9	347.4	19	MA-S
Derwent Water	75	5.35	22	5.5	29.0	82.7	67	LA-S
Windermere North Basin	39	8.05	64	25.1	201.8	174.7	168	MA-D
Windermere South Basin	39	6.72	42	16.8	112.7	55.8	94	MA-D
Windermere total lake	39	14.77	64	21.3	314.5	230.5	263	MA-D

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, and is mesotrophic in status, while Bassenthwaite Lake and South Basin of Windermere (Fig. 2b) tend to have the highest and are eutrophic. A comprehensive assessment of the status of these and other major lakes in the English Lake District in 2005 was made by Maberly *et al*. (2006).

Figure 2. Photographs of the study lakes: a) North Basin of Windermere, b) South Basin of Windermere, c) Derwent Water, d) Grasmere and e) Bassenthwaite Lake.

3. BRIEF METHODS

The methods used are briefly noted here, more detail is available in Parker *et al*. (2001) and the reference given below.

Each of the five lake basins was visited fortnightly. At each basin, samples were collected or measured at the deepest point. Oxygen and temperature depth-profiles were measured with a WTW 340i oxygen meter and thermistor. Secchi disc transparency was measured with a white painted disc, 30 cm in diameter, which was lowered into the water and the depth at which it disappeared from view was noted, as was the depth at which it reappeared when the disc was then raised. The recorded depth was the average of these two depths.

An integrated water sample was taken on each occasion using a weighted plastic tube. The depth of integration was 7 m on the North and South Basin of Windermere, and 5 m at the three other sites. Replicate water samples from the tube were used to fill a previously rinsed 5 dm^3 plastic bottle. After mixing, the water was sub-sampled into:

a) a small glass bottle with a ground glass stopper. The bottle was completely filled and stoppered with no trapped air-bubbles. This was used to determine pH and alkalinity. Note that on Grasmere, Bassenthwaite and Derwent Water, these samples were taken from a sub-surface 'dip', not an integrated sample.
b) A disposable, previously rinsed, 500 cm^3 plastic bottle for chemical analysis.
c) An acid-cleaned, previously rinsed, 500 cm^3 glass bottle, for phosphate analysis.
d) A 1 dm^3 plastic bottle containing 5 cm^3 of Lugol's iodine for subsequent enumeration and identification of the phytoplankton (on Grasmere, bottle volume and volume of Lugol's iodine was half these volumes).

Alkalinity and pH. Alkalinity was measured by Gran titration and pH was measured with a calibrated combined pH-electrode (Mackereth *et al*., 1978).
Phytoplankton chlorophyll a was determined using a boiling methanol extraction of cells filtered onto a Whatman GF/C glass-fibre from a known volume of water. The pigments were quantified spectrophotometrically.
Phytoplankton species were counted after sedimenting a known volume of the iodine preserved sample. Counts were made in a Lund counting chamber with a microscope at a magnification of x100 and x400 for microplankton and nanoplankton respectively.
Total phosphorus (TP) and soluble reactive phosphorus (SRP) were measured using the molybdate-blue method, the former following digestion, (Mackereth *et al*., 1978).

4. METEOROLOGICAL CONDITIONS FOR 2006

Year-to-year and seasonal changes in the weather are known to affect the performance of lakes, and lakes are also know to be sensitive to climate change (George *et al*. 2004). For this reason, this section provides a background to the meteorological conditions for the year in comparison to the average over the previous fifteen years. The data presented are from Ambleside and may not completely reflect the weather for the more northerly Derwent Water and Bassenthwaite Lake, particularly for wind and rainfall which can be localised, but is likely to give a good approximation to the conditions experienced when averaged over a week as done here.

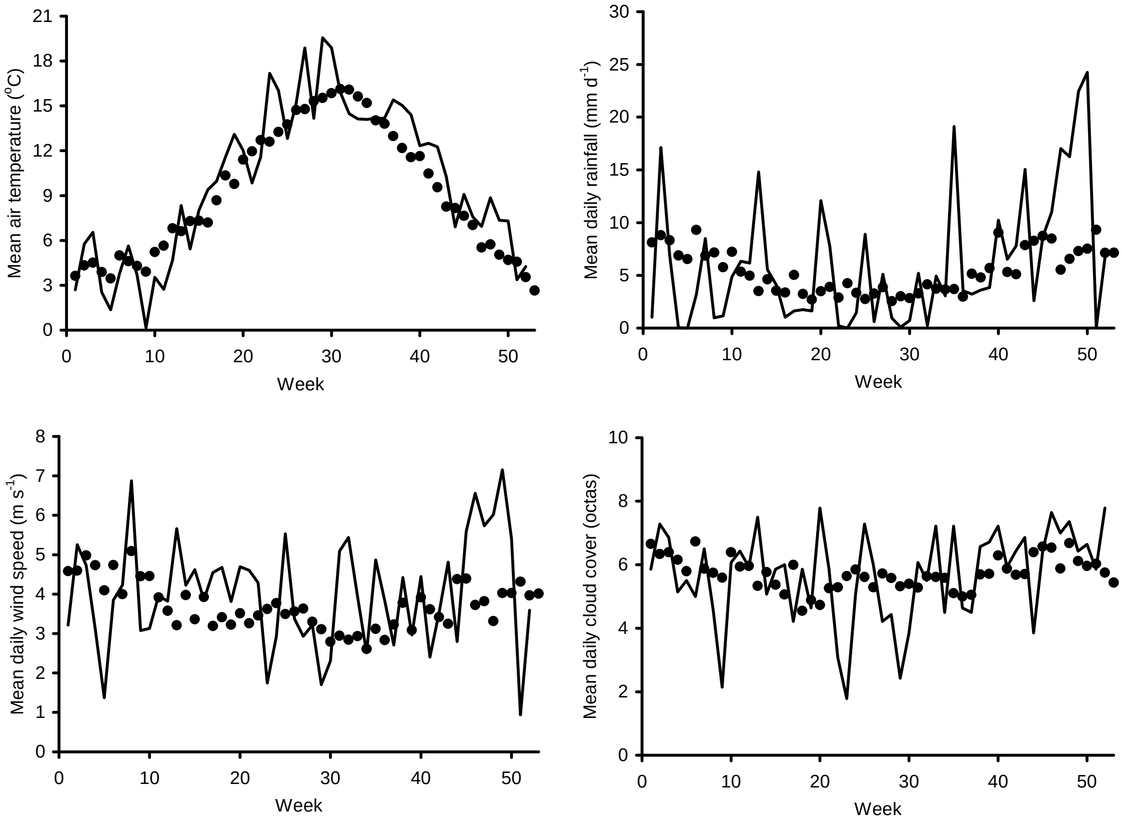

Figure 3. Meteorological data from Ambleside collected by Mr Bernard Tebay. Weekly averages between 1990 and 2005 (●) compared to weekly averages for 2006 (─). Diane Hewitt of the Freshwater Biological Association is thanked for her help in compiling these data.

The main meteorological feature for 2006 in this region was the high air temperatures in early summer with many weeks warmer than the long-term average. Following a cooler and windy spell of weather in mid-summer, autumn temperatures were again above the long-term average. Winter, in contrast, was relatively cold and also calm and dry. The end of the year concluded with high wind speeds and high rainfall.

5. WINDERMERE NORTH BASIN

The surface water temperature in the North Basin of Windermere was several degrees above the 12-year average in mid June and late July (Fig. 4). On the 25 July, 23.7°C was recorded in the early morning which is the highest reading ever recorded in the previous 12 years or indeed in similar records extending back to 1947. The previous highest value was 23.3°C recorded in July 1976. For comparison, average surface temperatures in July over the last 12 years are about 5°C lower than the peak measured in 2007 at 18.5°C. In contrast, temperatures in the spring were slightly below, and temperatures in autumn slightly above, the 12-year average which follows the pattern for air temperature (Fig. 3). Stratification began around mid-April, which is slightly later than usual, and water temperatures at around 60 m were very similar to previous years, reaching a maximum value of 6.9°C just before stratification broke down again at the end of November, probably aided by a spell of windy weather (Fig. 3).

Oxygen depletion at depth is a key indicator of lake status, has potentially negative effects on fish and macroinvertebrate populations, can lead to release of phosphorus from the sediment to the water and is a supporting element in the Water Framework Directive. In the North Basin of Windermere in 2006 the minimum concentration of oxygen at depth was 3.5 g m^{-3} (Fig. 5), the lowest recorded since the tertiary P-removal started in 1992. There has been a clear, statistically significant, reduction in average and, more importantly, minimum oxygen concentration at depth since 1995 (Fig. 6, Table 2).

The average concentration of total phosphorus (TP) has shown a steady increase since 1997 (Fig. 6) and although the long-term change since 1995 is not quite statistically significant (Table 2) the value in 2006, 15.8 mg m^{-3}, is the second highest since records began in 1970, only being exceeded in 1981. The concentration of TP during the growing season was noticeably higher than the average for the previous 12-years (Fig. 7). As has been noted in previous reports, there is a worrying lack of effect of the phosphorus stripping in the North Basin of Windermere and clear indications that the lake is deteriorating. Concentrations of soluble reactive phosphorus (SRP) had a similar seasonal pattern to previous years with a winter maximum of 6.3 mg m^{-3} and summer minimum below the limit of detection at about 0.6 mg m^{-3} (Fig. 7). There are no significant long-term trends in SRP (Table 2).

Seasonal changes in concentration of phytoplankton chlorophyll *a* comprised a spring bloom of 9.6 mg m^{-3} at the start of May (Fig. 8), slightly later than usual, which was dominated by the diatom *Asterionella formosa* with smaller amounts of the diatom *Aulacoseira subarctica*, the green alga *Chlorella* sp. and the cryptophyte *Rhodomonas* sp. There was an early-summer peak at the end of July, and an annual maximum of 18.6 mg m^{-3} (Fig. 8). This was dominated by the colonial cyanobacterium (blue-green alga) *Aphanothece clathrata* but there was also substantial densities of *Chlorella* sp., the cyanobacterium *Pseudanabaena limnetica*, *Rhodomonas* sp., the diatom *Nitzschia/Synedra* (unable to distinguish by light-microscopy) and *Microcystis* sp. There is a tendency for the annual average and maximum concentration of phytoplankton chlorophyll *a* in the North Basin of Windermere to increase (Fig. 6, Table 2) but these are not statistically significant although the increase in average chlorophyll was significant last year (Maberly *et al*., 2006). The depth of the Secchi disc varied between 2.9 and 5.5 m over the year. A statistically significant decline in Secchi depth was recorded as was noted in 2004 although it was not quite significant in 2005. This indicates that water clarity is tending to deteriorate in the North Basin of Windermere.

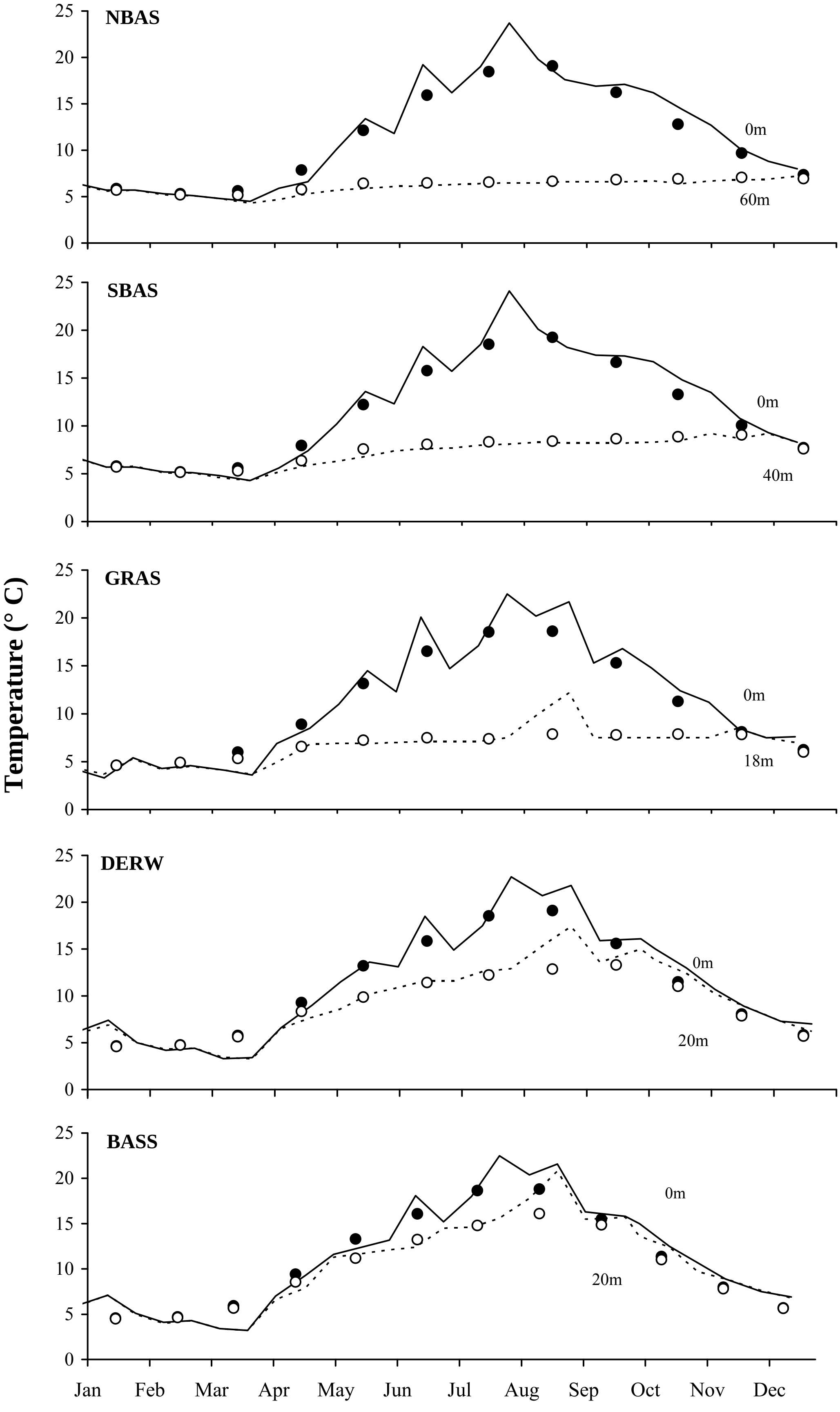

Fig. 4. Temperature at the surface (__) and maximum depth (---) measured in five lake basins in 2006. Monthly average (1995-2006) surface (closed circles) and bottom temperature (open circles) also shown.

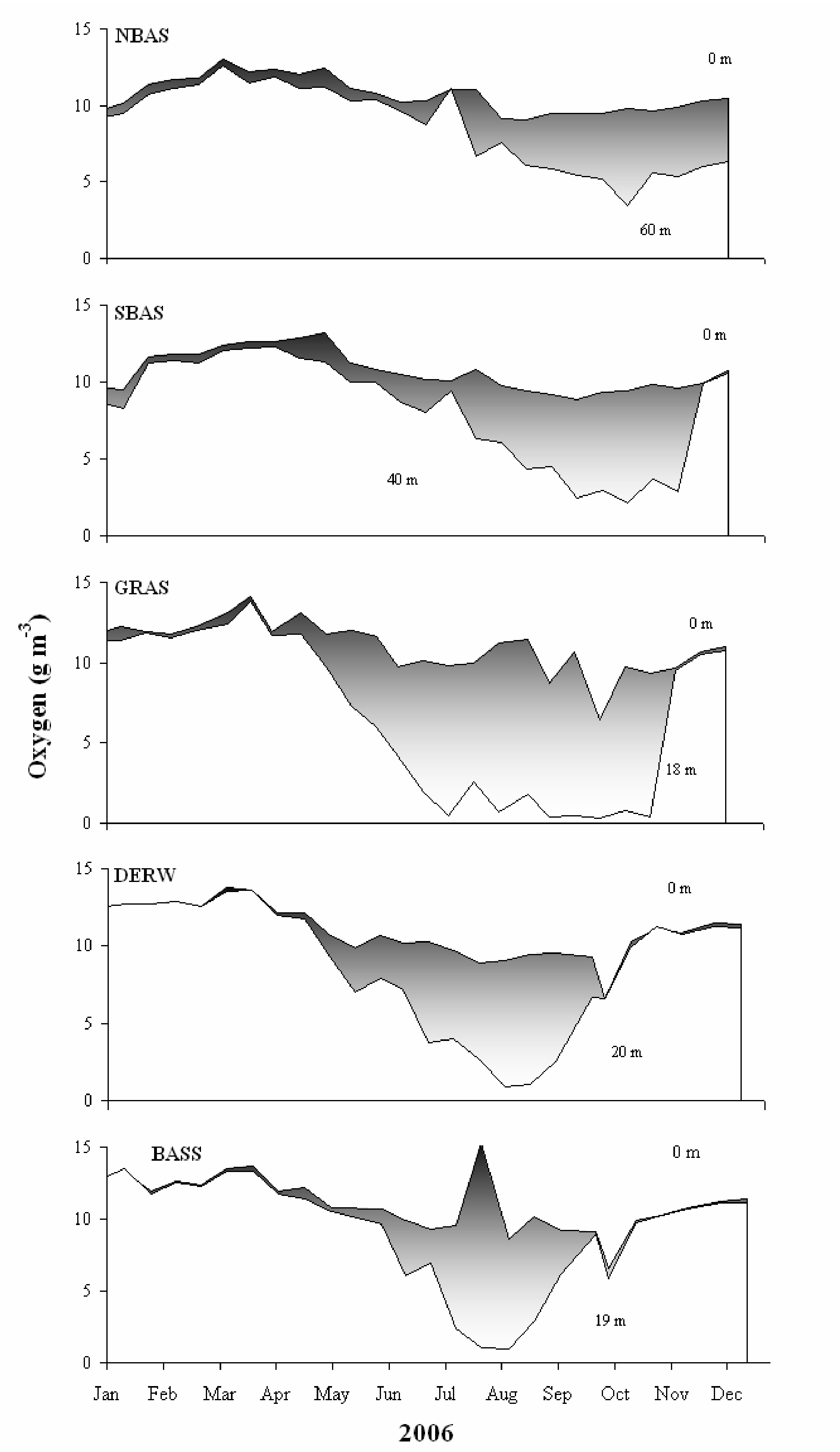

Fig. 5. Oxygen concentrations measured at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake during 2006.

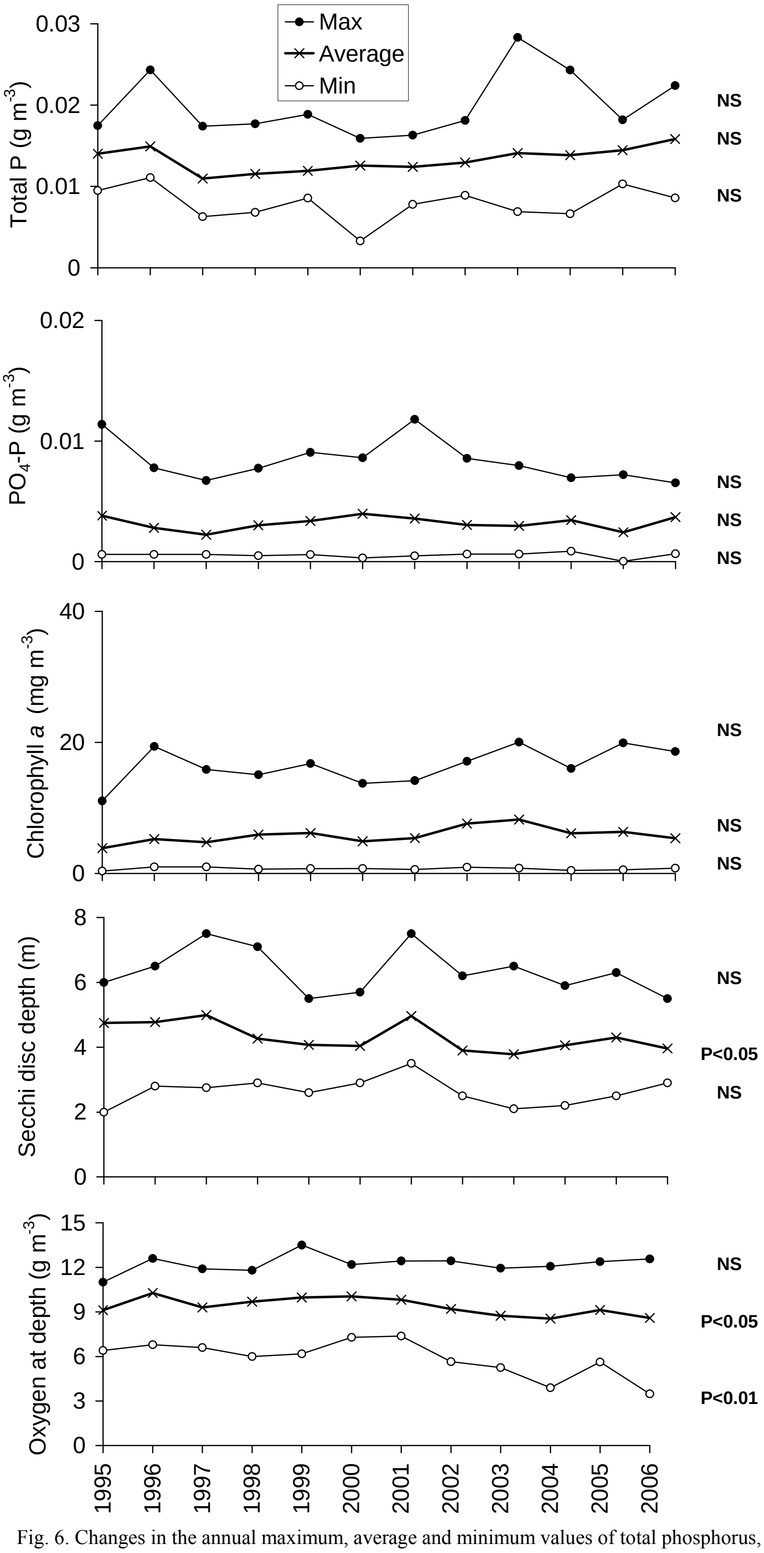

Fig. 6. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll a, Secchi depth, and oxygen concentration at depth between 1995 and 2006 in the North Basin of Windermere. Statistical significance of any long-term trends are shown on right-hand side of each panel.

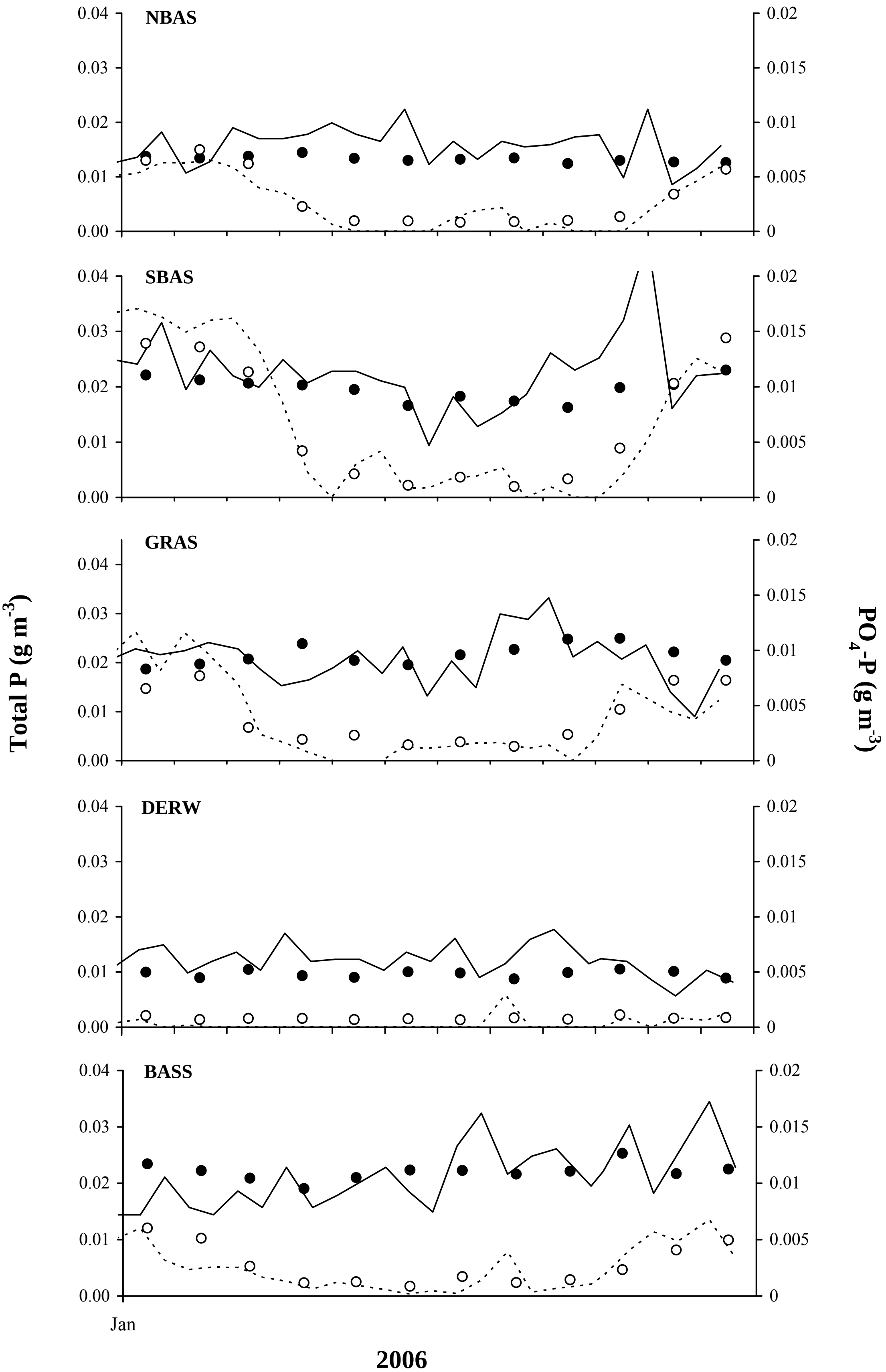

Fig. 7. Total phosphorus (__) and PO_4-P (---) concentrations measured in five lake basins in 2006. Monthly average (1995-2006) Total P (closed circles) and PO_4-P (open circles) also shown.

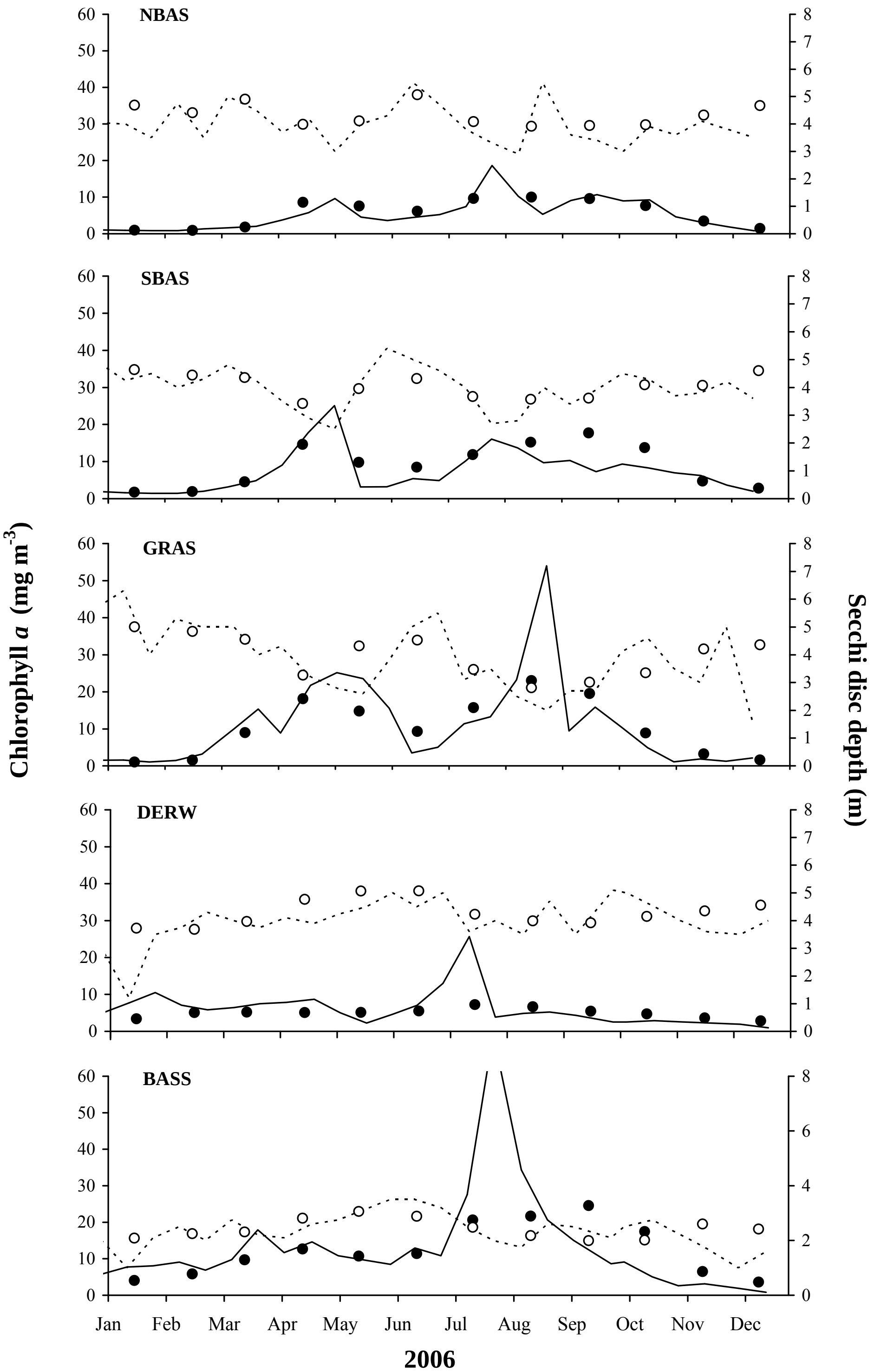

Fig. 8. Chlorophyll *a* concentration (__) and Secchi disc depth (---) measured in five lake basins in 2006. Monthly average (1995-2006) chlorophyll *a* (closed circles) and Secchi depth (open circles) also shown. NB the peak value of chlorophyll a in Bassenthwaite Lake was 71.7 mg m^{-3} (not shown).

Table 2. Correlation coefficient (r) for long-term trend between 1995 and 2006 for stated variables in the five lake basins. Negative correlations are shown in blue, positive correlations in black. The cell shading denotes the significance of the correlation: NS- no shading; P<0.05, green; P<0.01, yellow; P<0.001, orange (none in this table).

Variable	Annual statistic	North Basin of Windermere	South Basin of Windermere	Grasmere	Derwent Water	Bassenthwaite Lake
	Max	0.317	0.195	-0.532	-0.244	-0.606
TP	Mean	0.442	-0.085	-0.307	0.108	-0.681
	Min	-0.053	-0.207	-0.098	0.102	-0.350
	Max	-0.402	-0.642	-0.371	0.277	-0.656
SRP	Mean	0.051	0.107	0.515	0.393	-0.275
	Min	-0.109	0.584	0.394	-0.427	-0.451
	Max	0.530	0.021	-0.200	0.709	0.204
Chlorophyll a	Mean	0.545	0.223	-0.197	0.469	-0.105
	Min	-0.101	-0.318	-0.060	-0.178	-0.463
	Max	-0.315	-0.533	-0.733	0.098	0.419
Secchi disc	Mean	-0.626	-0.761	-0.401	0.206	0.180
	Min	-0.011	-0.559	-0.156	0.118	0.206
	Max	0.302	0.130	0.664	0.198	-0.020
Oxygen at depth	Mean	-0.616	-0.395	0.060	0.169	-0.114
	Min	-0.696	-0.377	0.664	-0.030	0.087

6. WINDERMERE SOUTH BASIN

Seasonal changes in surface water temperature in the South Basin of Windermere broadly followed that in the North Basin (Fig. 4). In mid June surface temperature was 18.3°C, about 2.5°C higher than the 12-year average for June. A maximum temperature of 24.1°C was recorded on 25 July, slightly higher than that in the North Basin, about 4.8°C above the 12-year average for July and the highest recorded since records began in 1947. The previous record, like in the North Basin, was recorded in July 1976 at 23. 5°C. Water temperature at depth, about 40 m, were unaffected by the very warm surface water and were very similar to the 12-year average. The maximum temperature at depth was 9.2°C, recorded at the end of October towards the end of stratification.

In the South Basin of Windermere, the minimum concentration of oxygen at depth was 2.2 g m^{-3}. This is slightly higher than that recorded in 2002, 2003 and 2004 but there are no clear trends with time and a large amount of unexplained year-to-year variation that may be partly associated with weather conditions.

The average alkalinity in the South Basin of Windermere in 2006 was 14.7 g $CaCO_3$ m^{-3} (i.e. about 0.294 equiv m^{-3}). This is higher than has been recorded in any previous year. The seasonal pattern is typical for lakes of this type with a maximum in late summer and minimum in winter (Fig. 9). Peaks in pH coincided with maxima in phytoplankton chlorophyll *a*: the spring bloom (see below) produced a pH of 8.84 at the start of May and the summer bloom produced the annual maximum pH of 9.55 at the end of July. The reason for the association between phytoplankton and pH is because photosynthesis removes carbon dioxide and bicarbonate ions and this causes the carbonate equilibria to shift towards higher pH.

As reported in previous years, there have been no statistically significant changes in total phosphorus concentration in the South Basin of Windermere (Fig. 10, Table 2). Concentrations of SRP varied between a winter maximum of 17.1 mg m^{-3} and summer concentrations that were below the limit of detection (Fig. 7). There is a weak statistical trend for decreasing maximum concentrations of SRP since 1995 although a slight tendency for an increase since 2002 (Fig. 10).

The annual average concentration of phytoplankton chlorophyll *a* in 2006 was 7.5 mg m^{-3} which is similar to previous years and there have been no long-term trends in concentration since 1995 (Fig. 10. Table 2). The seasonal pattern was for a large spring bloom of 25.1 mg m^{-3} in early May (Fig. 8). This was dominated by a high density of the diatom *Asterionella formosa* and lesser densities of the cryptophyte *Rhodomonas* sp., the cyanobacterium *Pseudanabaena limnetica* and another diatom *Fragilaria crotonensis*. Summer phytoplankton peaked early in late July at 16.1 mg m^{-3} and there was an unusually small late summer phytoplankton population as was noted for 2005. The July population was similar to that in the North Basin and dominated by the cyanobacterium *Aphanothece clathrata* but there was also substantial densities of *Chlorella* sp., *Rhodomonas* sp., and two other cyanobacteria *Pseudanabaena limnetica* and *Anabaena spiroides*.

Over the year the depth of the Secchi disc varied between 5.4 and 2.5 m, the annual minimum coinciding with the annual maximum concentration of phytoplankton chlorophyll *a* (Fig. 8). As in the North Basin, there has been a marked, statistically significant decrease in the average depth of the Secchi disc from about 4.7 m in 1995 to about 4 m in 2006 (Fig. 10, Table 2).

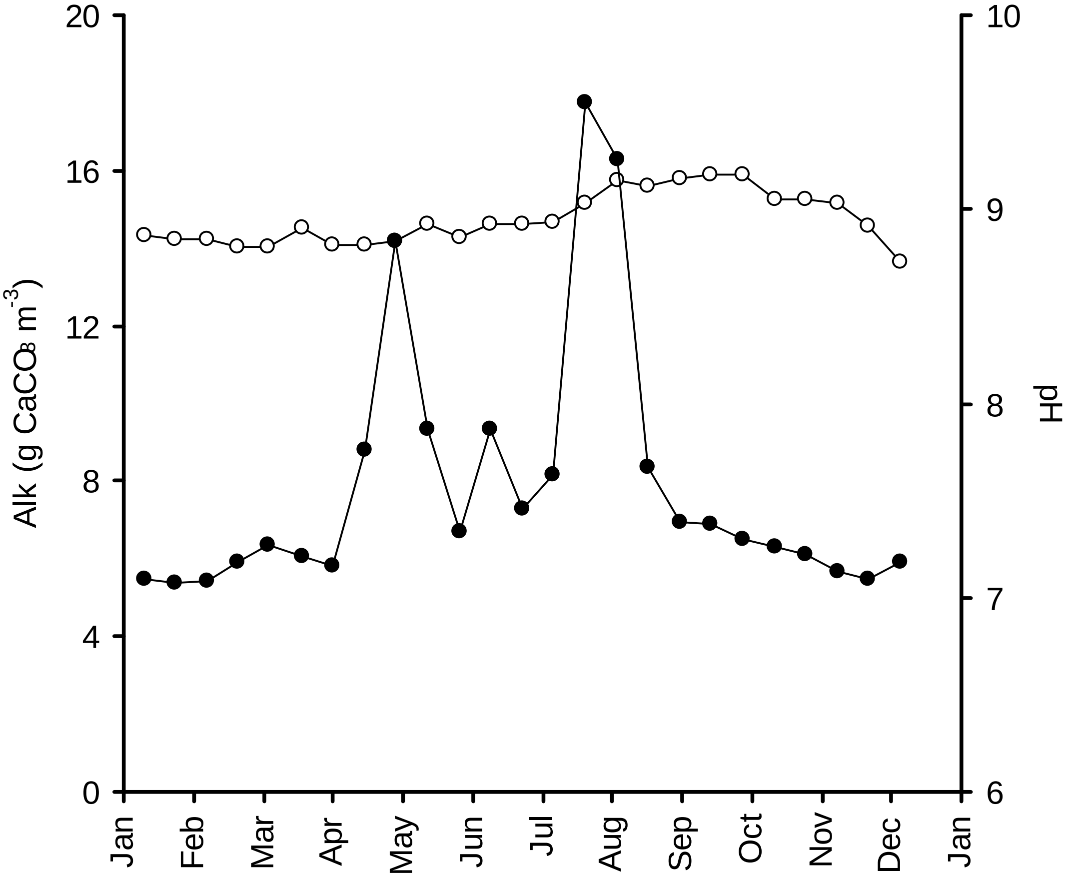

Figure. 9 Alkalinity (○) and pH (●) in the South Basin of Windermere during 2006.

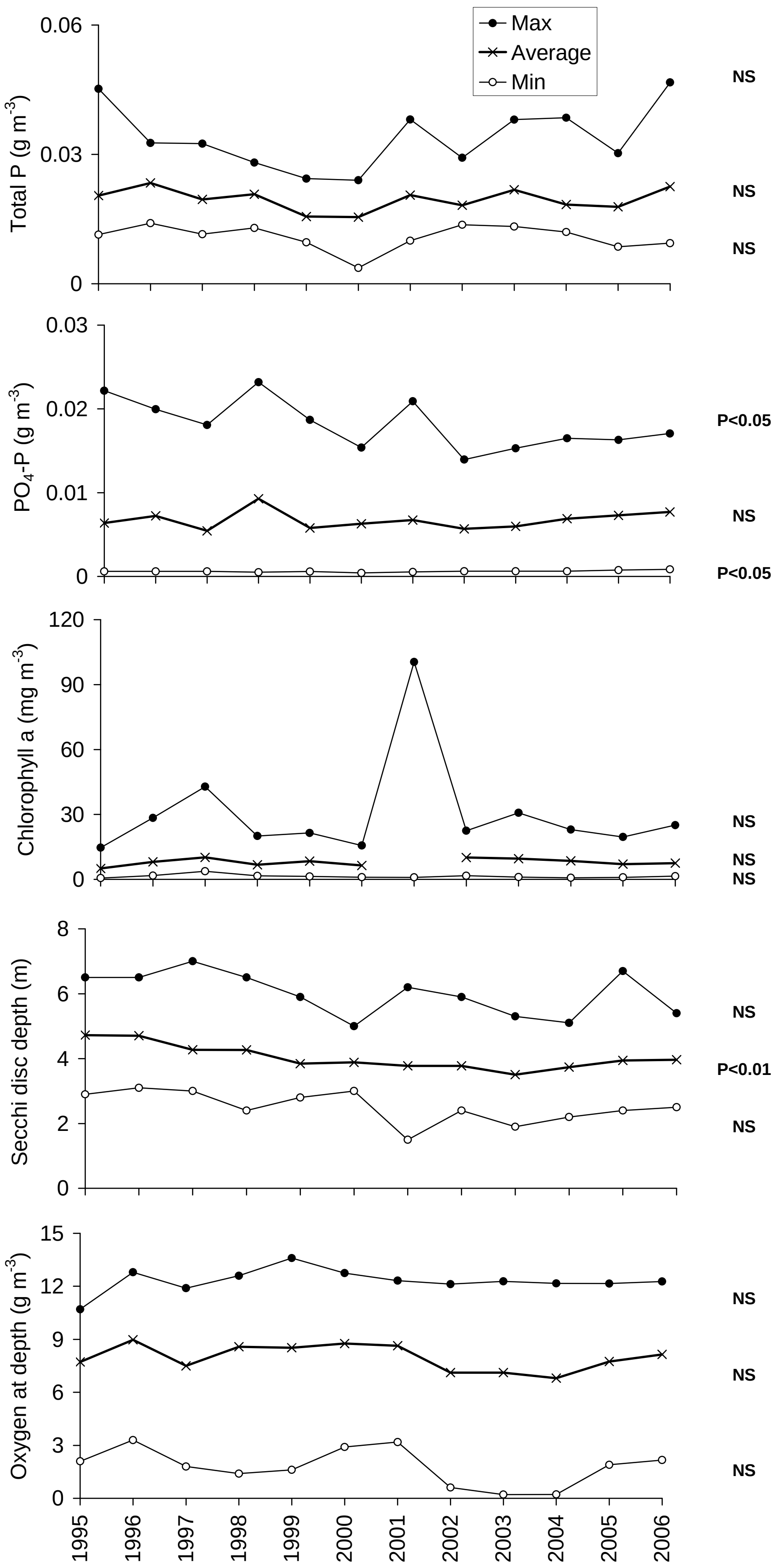

Fig. 10. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a* , Secchi depth, and oxygen concentration at depth between 1995 and 2006 in the South Basin of Windermere. Statistical significance of any long-term trends are shown on right-hand side of each panel.

7. GRASMERE

Surface water temperature at Grasmere reached a maximum of 22.5°C on 24 July and a second high value of 21.7°C on 23 August 2007 (Fig. 4). These are slightly lower than the maximum surface values recorded: 23°C on 31 July 1995, but nevertheless are very high values for an English lake. The overall seasonal pattern was broadly similar to the two basins of Windermere with cooler than usual spring temperatures and higher than average autumn temperatures. Water temperature at depth, about 18 m, was largely unaffected by the higher surface temperature during the stratified period apart from on 23 August when stratification had weakened and the temperature at 18 m had risen to 12.2°C compared to the seasonal average of about 7.9°C. On the next sampling date the stratification had strengthened again and the water temperature at depth had fallen back to 7.5°C. This transient breakdown in stratification may have been linked to the lower air temperatures and the high rainfall at about this time (Fig. 3).

Of all the lakes reported on here, Grasmere has the most extreme oxygen depletion at depth during stratification (Fig. 5). The period of time that oxygen was depleted below 1 g m^{-3} was less than in 2005 and less than at any time in the period from 1995. While this may be caused in part by the weather condition and the transient breakdown of stratification in the summer this is an encouraging reversal of the trend for increased duration of oxygen depletion. This is supported by a statistically significant increase in oxygen concentration at depth (Fig. 11 Table 2).

The concentration of TP is highly variable with maxima and minima of 33 and 9 mg m^{-3} respectively (Fig. 7). There is a general trend for decreasing concentrations of TP in Grasmere since 1995, but none of these are statistically significant (Fig. 11, Table 2). Concentrations of SRP ranged from a winter maximum of 11.7 mg m^{-3} to early summer minima which were below the limit of detection (Fig. 7). There are no statistically significant long-term trends in concentration of SRP (Fig. 11, Table 2) although there is a possible upward trend for average SRP concentration.

Grasmere produced a spring phytoplankton chlorophyll *a* concentration of 25.2 mg m^{-3} in early May (Fig. 8). This is slightly later than usual, as has been noted for other lakes, and slightly larger than usual, although similar to 2005. It comprised small unicells such as the green alga *Chlorella* sp., the cryptophyte *Rhodomonas* sp., the prymnesiophyte *Chrysochromulina parva* plus the spring-blooming diatom *Asterionella formosa*. Following a clear-water phase with low concentrations of chlorophyll *a* in early summer, there was an extremely large phytoplankton bloom that reached 54 mg m^{-3} in late August (Fig. 8). This is the second largest population recorded since our records began in 1971, the largest being 57 mg m^{-3} in 1999. The 2006 population comprised a mixed population dominated by the chrysophyte *Syncrypta* sp. and the cyanobacterium *Anabaena circinalis/flos-aquae*, *Chlorella* sp., and lesser amounts of the colonial green alga *Eudorina* sp., *Rhodomonas* sp., the cyanobacteria *Pseudanabaena limnetica* and *Aphanothece clathrata* plus *Chrysochromulina parva* and *Chlamydomonas* sp. There have been no long-term trends in concentration of chlorophyll *a* since 1995 although there is some indication that maximum concentrations are higher in the last ten years compared to earlier years if the whole of the data series is examined (data not shown).

Secchi depth had a minimum of 1.6 m in early December at a time of low concentrations of phytoplankton chlorophyll *a* (Fig. 8). This coincided with wet weather (Fig. 3) and is probably caused by inflow of suspended material from the catchment. The clearest water as measured with the Secchi disc occurred in the previous January with a value of 6.3 m. This is the lowest value recorded in the period from 1995. There has been a statistically significant decline in annual maximum water clarity over the years 1995 to 2006 (Fig. 11, Table 2), as noted in previous reports, although this is caused in part by exceptionally clear water in 1995, there is now evidence that this is not the only cause of the reduction: the change is still significant if this year is excluded from the analysis.

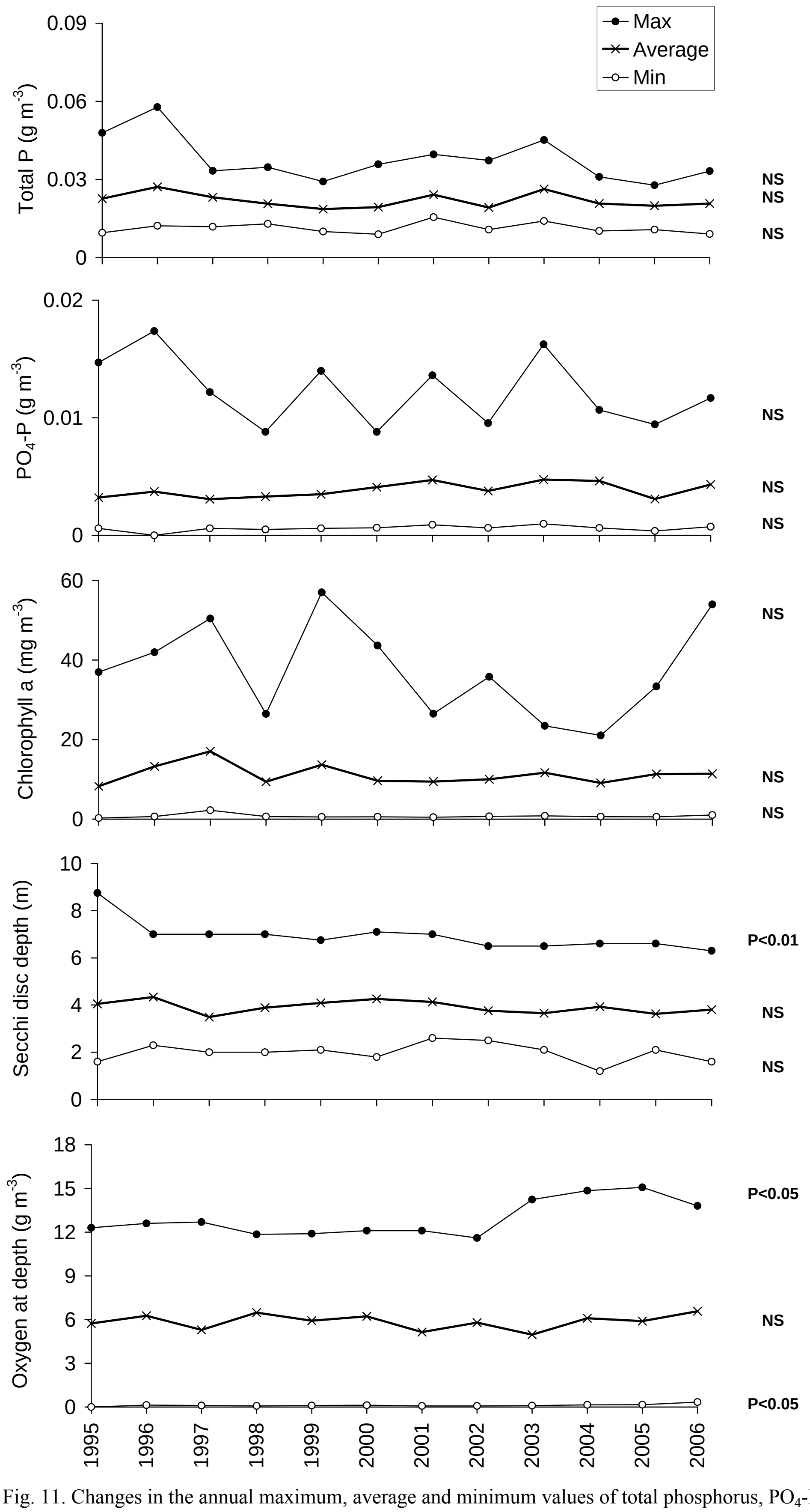

Fig. 11. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a* , Secchi depth, and oxygen concentration at depth between 1995 and 2006 in Grasmere. Statistical significance of any long-term trends are shown on right-hand side of each panel.

8. DERWENT WATER

Seasonal changes in water temperature in Derwent Water responded to meteorological forcing in a similar way to the other lakes in the area (Fig. 4). Spring water temperature was over 2°C cooler than usual, and the temperature at the end of July reached 22.7°C, the second highest recorded here. As in Grasmere, water temperature at depth was similar to previous years until a substantial warming episode at the end of August when temperatures increased to 17.4°C , the highest temperature ever recorded at depth as stratification partially broke down, which is probably linked to a spell of relatively cool, wet weather. Unlike the smaller and more sheltered site at Grasmere where stratification reformed, in Derwent Water stratification remained weak for the rest of the summer and temperature at depth remained elevated above the long-term average.

The concentration of oxygen at depth fell to just below 1 g m^{-3} in early August and only for one sampling fortnight (Fig. 5). The duration of oxygen depletion is shorter than in many previous years. This is possibly because of the partial breakdown in stratification at the end of August that probably led to some entrainment of oxygen to depth. There have been no statistically significant trends in the concentration of minimum oxygen concentration at depth (Fig. 12, Table 2).

Concentrations of TP have been relatively stable for the last 12 years although there is some indication of a slight upward trend (Fig. 12). The annual average concentration in 2006 was 12.1 mg m^{-3} which is the highest recorded since records began in summer 1990. In 2006, the concentration of TP varied between 17.7 and 5.7 mg m^{-3} and was generally above the 12-year average in the first part of the year (Fig. 7). There is therefore a slight worry that concentrations of TP are increasing in this mesotrophic lake. It is also noteworthy that the average concentration is above the target of 10 mg m^{-3} set by the Environment Agency's Habitats Directive Technical Advisory Group WQTAG (WQTAG, 2005) for the second year in a row. Maberly Elliott & Thackeray (2006) evaluated known loads of TP to the lake and estimated that a significant improvement to the water quality of Derwent Water could be made by reducing the discharge concentrations from the know wastewater treatment works in the catchment to 1 g TP m^{-3}. In contrast to TP, the concentration of SRP remained low for most of the year, apart from a small peak of 2.9 mg m^{-3} on 10 August which may have resulted from a slight destratification (Fig. 7). There are no long-term trends in the concentration of SRP in Derwent Water.

Over 2006, the concentration of phytoplankton chlorophyll *a* varied between a minimum of 2.3 mg m^{-3} in mid May and a maximum of 25.7 mg m^{-3} in early July (Fig. 8). This is the highest concentration recorded in Derwent Water: the last three years have been successively the three highest chlorophyll maxima in the record for this lake. This trend is statistically significant (Table 2) and extremely worrying. The peak bloom was diverse, comprising 32 taxa, but was dominated by the diatom *Urosolenia* sp., the green alga *Chlorella*, the prymnesiophyte *Chrysochromulina parva*, the raphidophyte *Gonyostomum semen*, the cyanobacterium *Anabaena circinalis/flos-aquae* and the cryptophyte *Rhodomonas* sp. This is the first time that *Gonyostomum* has been recorded in Derwent Water.

The depth of the Secchi disc varied between 1.2 m in early January, the lowest recorded in this lake (probably the result of suspended solids since there was very heavy rainfall in the two previous days (Fig. 3) and the concentration of chlorophyll *a* was low), and a maximum of 5.1 m in late September (Fig. 8). There are no significant long-term trends in the depth of the Secchi disc (because of the very low minimum value recorded in 2006) in contrast to the slight improvement in minimum Secchi depth reported previously (Maberly *et al*. 2005; Fig. 12, Table 2).

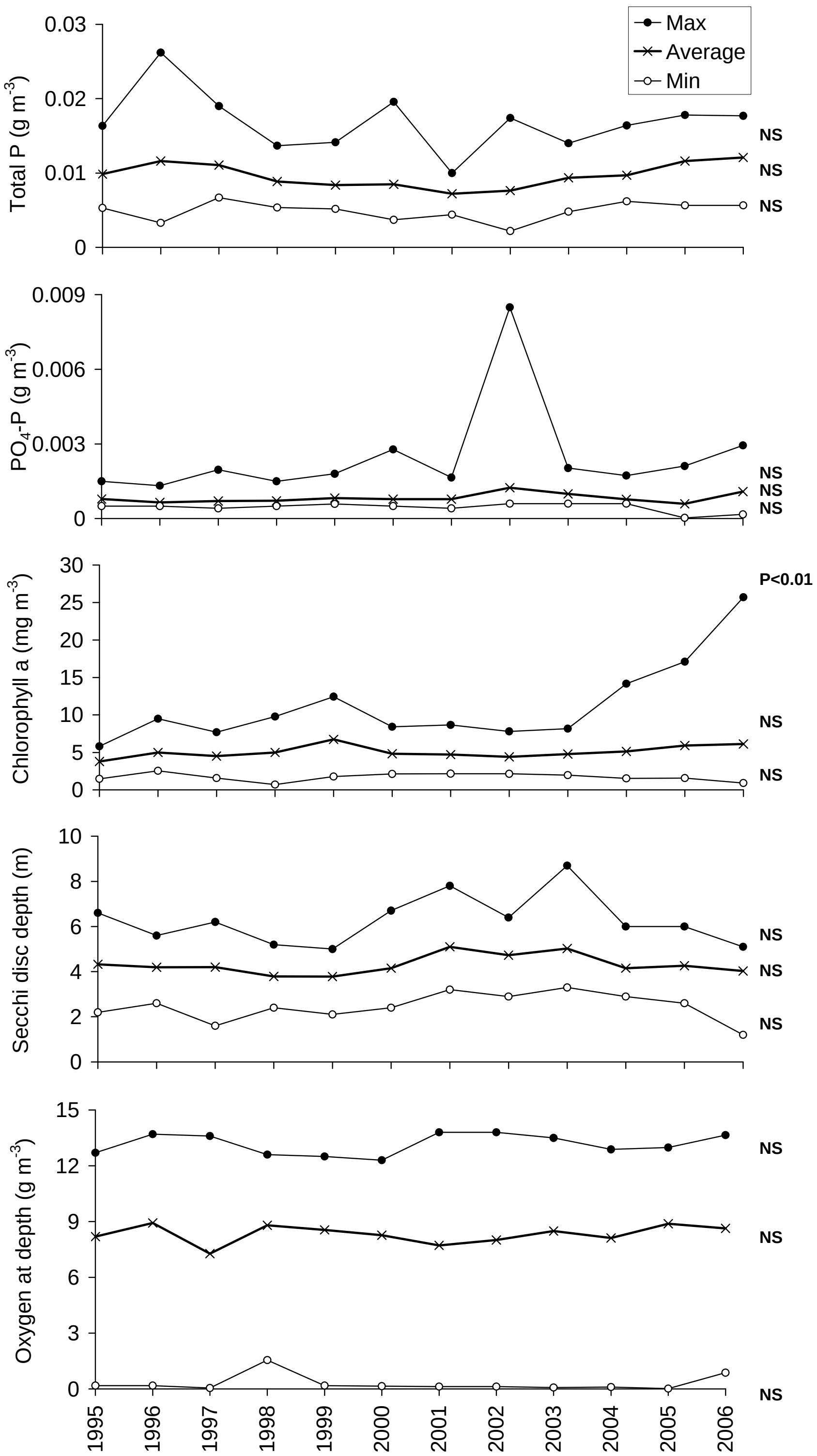

Fig. 12. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a* , Secchi depth, and oxygen concentration at depth between 1995 and 2006 in Derwent Water. Statistical significance of any long-term trends are shown on right-hand side of each panel.

9. BASSENTHWAITE LAKE

Seasonal changes in surface water temperature in Bassenthwaite Lake were similar to Derwent Water. The temperature in mid-March was over 2°C below the seasonal average and the temperature at the end of July reached a maximum of 22.5°C, the second highest recorded since records began in 1990 (Fig. 4). As in Grasmere and Derwent Water, stratification broke down suddenly at the end of August and the temperature at depth, 20.8°C, was the highest recorded for this lake. Stratification was weak or non-existent for the rest of the year.

The concentration of oxygen at depth fell just below 1 mg m^{-3} in early August (Fig. 5) but had increased again on the next sampling date at the end of August as the stratification had weakened. The erosion of the stratification at the end of August, as recorded in other lakes and probably caused by a spell of cool, wet weather (Fig. 3) reduced the extent and duration of low oxygen concentrations at depth.

The average concentration of TP in Bassenthwaite Lake in 2006 was 21.5 mg m^{-3} and varied between 14.4 and 34.5 mg m^{-3} with no strong seasonal trends (Fig. 7). Although there is a statistically significant reduction in the maximum and average concentration of TP (Fig. 13, Table 2), this is wholly a result of a fall in concentration immediately after the P-stripping in 1995. There has been an essentially constant annual TP concentration in the nine years since 1998 with average values ranging between 19.9 and 21.9 mg m^{-3}. Long term trends in SRP are similar with essentially no change since 1997 and an annual average ranging from 2.1 to 3.0 mg m^{-3} (Fig. 13, Table 2). The phosphorus data therefore suggest that the improvement in water quality in Bassenthwaite Lake that was evident immediately after the implementation of the tertiary P-removal at the Keswick wastewater treatment works has now stalled.

Seasonal changes in concentration of phytoplankton chlorophyll *a* was fairly typical of previous years although the concentrations at the end of the year were lower than usual and there was an annual maximum of 17.8 mg m^{-3} recorded at the end of July. This comprised a diverse community of 45 taxa dominated by the raphidophyte *Gonyostomum semen*, the cryptophytes *Cryptopmonas* spp and *Rhodomonas* sp., the cyanobacterium *Aphanothece clathrata*, the diatom *Fragilaria crotonensis*, the prymnesiophyte *Chrysochromulina parva* and the green algae *Chlorella* sp., *Micratinium* sp. and *Paulschulzia tenera*. This is the first time that *Gonyostomum* has been recorded in Bassenthwaite Lake. There are no long-term trends in any of the annual chlorophyll *a* statistics (Fig. 13, Table 2).

The annual minimum Secchi depth of 1 m occurred in early January at a time of low chlorophyll *a* and coincident with the minimum value in nearby Derwent Water (Fig. 8). As in Derwent Water this was probably caused by high rainfall bringing in suspended sediments from the catchment since suspended sediment was very high on this data (unpublished CEH data). The annual maximum Secchi depth of 3.5 m occurred in mid June (Fig. 8). There is a slight tendency for Secchi depth to be improving but the change is not statistically significant (Fig. 13, Table 2).

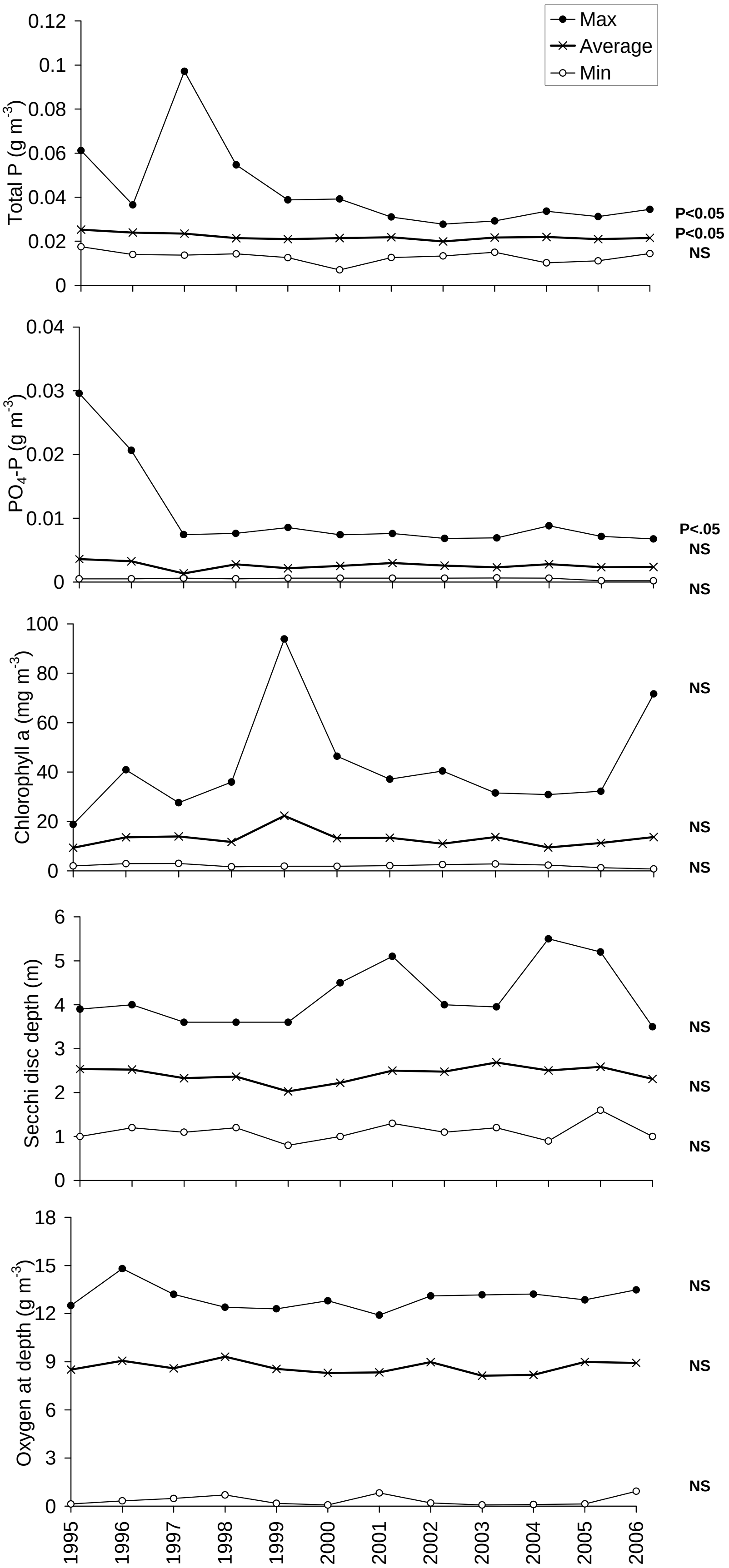

Fig. 13. Changes in the annual maximum, average and minimum values of total phosphorus, PO_4-P, phytoplankton chlorophyll *a* , Secchi depth, and oxygen concentration at depth between 1995 and 2006 in Bassenthwaite Lake. Statistical significance of any long-term trends are shown on right-hand side of each panel.

10. CONCLUSIONS, ECOLOGICAL ASSESSMENT AND FUTURE RESEARCH

Year-to-year and day-to-day changes in the weather can cause variations in the physical, chemical and biological factors reported on here and these have been noted in the various sections on the individual lake basins. However, the accumulating data on how these contrasting lakes operate gives a increasingly refined picture of the trends of improvement or deterioration in the status of each lake. These patterns are summarised on a lake-by-lake basin below. Each lake is also given a preliminary ecological status based on the current Water Framework Directive (WFD) classifications using the appropriate lake typology for each lake given in Table 1. The site specific boundaries for TP and chlorophyll *a* are as described in Maberly *et al.* (2006).

Ecological assessment

North Basin of Windermere

The initial modest improvement in the North Basin of Windermere seen following the implementation of tertiary wastewater treatment has now stalled and there are clear signs of deterioration. Good ecological status was last seen for TP in 2002 and for chlorophyll *a* in 1997 (Fig. 14). Currently the North Basin of Windermere is in the middle of the moderate ecological status for both features and will clearly need a Programme of Measures to improve the condition of the lake. Further evidence for deterioration in the condition of the lake is the statistically significant decrease in average Secchi depth and reduction in oxygen concentration at depth.

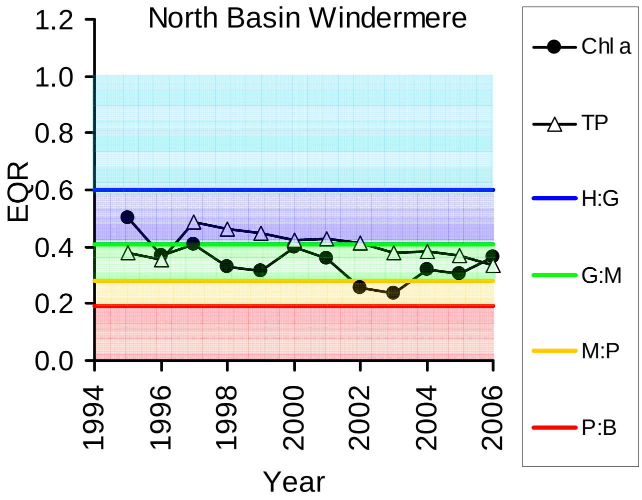

Figure 14. Long-term changes in the ecological status of the North Basin of Windermere in relation to the Water Framework Directive.

South Basin of Windermere

As for the North Basin, there was an improvement in the lake following the implementation of tertiary wastewater treatment in 1992, but the lake is currently very close to poor ecological status for both chlorophyll *a* and total phosphorus (Fig. 15). There are signs of continuing decline in the lake with statistically significant reductions in mean Secchi depth and the low hypolimnetic concentrations of oxygen.

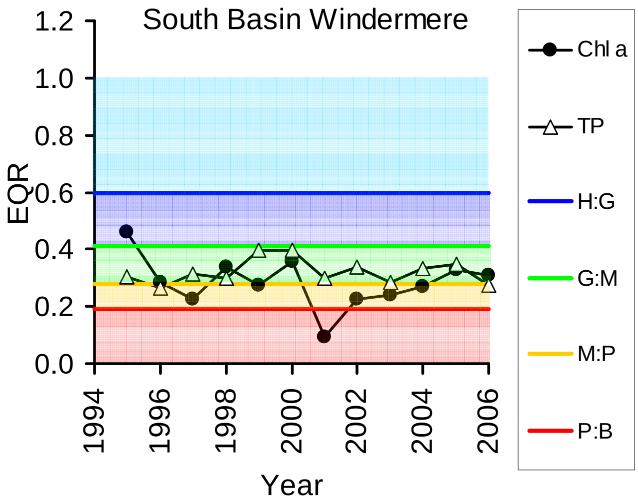

Figure 15. Long-term changes in the ecological status of the South Basin of Windermere in relation to the Water Framework Directive.

Grasmere

Grasmere also fails good ecological status and is in the middle of moderate ecological status for total phosphorus and on the moderate:poor boundary for chlorophyll a (Fig. 16). The lake is relatively stable although, as for the two Windermere basins, there is evidence for declining Secchi depth. A more detailed understanding of why this lake is failing good ecological status is needed.

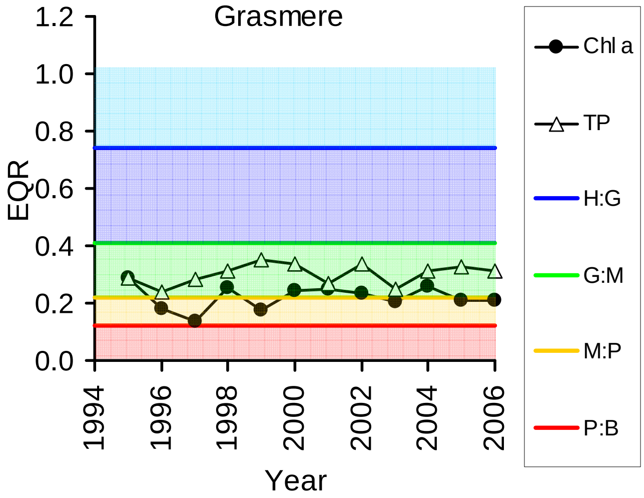

Figure 16. Long-term changes in the ecological status of Grasmere in relation to the Water Framework Directive.

Derwent Water

The ecological status of Derwent Water is high for total phosphorus, but there have been some recent increases in concentration of phytoplankton chlorophyll a so that ecological status for chlorophyll is now on or just below the good:moderate boundary (Fig. 17). There are also indications that the concentration of SRP is increasing: although the trend is not statistically significant. There are clear point sources providing phosphorus to this lake which gives relatively easy options for a successful Programme of Measures (Maberly Elliott & Thackeray 2006).

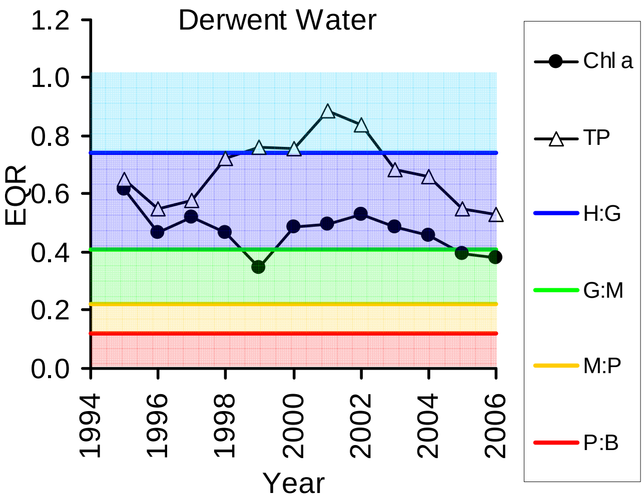

Figure 17. Long-term changes in the ecological status of Derwent Water in relation to the Water Framework Directive.

Bassenthwaite Lake
Bassenthwaite is at good ecological status for total phosphorus but in the middle of moderate status for phytoplankton chlorophyll a (Fig. 18). There are indications that TP is declining very slowly, but obviously not fast enough to improve water quality substantially. Future Programmes of Measures will need to identify why this is the case and be more proscriptive in reducing input of phosphorus from smaller WwTW and septic tanks.

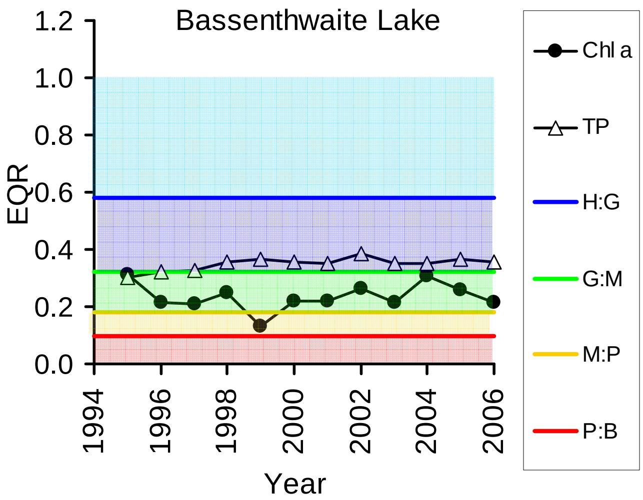

Figure 18. Long-term changes in the ecological status of Bassenthwaite Lake in relation to the Water Framework Directive.

Recommendations for further research
The long-term, detailed monitoring reported on here is a valuable exercise that provides further fundamental understanding of how lakes operate, a way of assessing the effectiveness of management procedures and warning of deterioration in lake ecological status. Specific topics that this study has highlighted as needing more attention are described below.

The two basins of Windermere initially responded positively to the implementation of the tertiary phosphorus removal at the two WwTw that feed directly into the lake. There have, for several years, been indications that the water quality in the lake has started to deteriorate again since around 2000. The cause of this decline, however, is far from clear and research is urgently needed to understand the cause so that appropriate management procedures can be put into place. This will anyway be needed since both basins currently fall below good ecological status for some criteria as described above. *We propose that initially a study is undertaken, using available long-term data, to describe and model the effects of various stress factors on the lake. This would not only include assessment of the effects of nutrient load, but also the effects of other possible factors such as climate change (which may, for example increase stratification and therefore promote greater oxygen depletion at depth) and the recent invasion of the roach (which may reduce zooplankton populations by feeding on them and so decrease the grazing pressure on the phytoplankton). **This suggestion needs to be considered with some urgency**.*

A second research recommendation for Windermere is to carry out a literature review. Windermere is perhaps the best studied lake in the world but a modern literature review is needed that includes both published work and the unpublished work that exist I many reports. This will produce a firm basis for future management decisions.

The ecological status at Grasmere is stable but close to poor. *An assessment is needed of what is contributing to the poor status and what programme of measures can be taken to remedy the situation.*

Derwent Water has shown signs of recent deterioration but ways of remediating this have recently been identified (Maberly *et al*., 2006). Of potentially greater long-term concern is the invasion of the non-native macrophyte *Crassula helmsii*. This could conceivably interfere with the spawning of the last healthy population of Vendace in The British Isles. *We suggest a baseline study is undertaken to identify the current distribution of* C. helmsii *so that any future changes in abundance or spread of this species can be assessed.*

On Bassenthwaite Lake the initial improvement in water quality following tertiary treatment has now stalled. *Further work is needed to understand what other sources of phosphorus, including internal loads of phosphorus from lake sediments, are driving continued productivity.*

11. REFERENCES

George D.G., Maberly S.C. & Hewitt D.P. (2004).The influence of the North Atlantic Oscillation on the physics, chemistry and biology of four lakes in the English Lake District. *Freshwater Biology* 49: 760-774.

Maberly S.C. (1996). Diel, episodic and seasonal changes in pH and concentrations of inorganic carbon in a productive English Lake, Esthwaite Water, Cumbria. *Freshwater Biology*, 35: 579-598.

Maberly S.C., Parker J.E., Dent M.M., Elliott J.A., James J.B., Fletcher J.M., Lawlor A.J., Simon B.M. & Vincent C. (2003) The Urban Waste-Water Treatment Directive: Observations on the water quality of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 2002. Final report commissioned by the Environment Agency. 20pp.

Maberly S.C., Parker J.E., Dent M.M., Elliott J.E., James J.B., Lawlor A.J., Simon B.M., Thackeray S.J. and Vincent C. (2004). The Urban Waste-Water Treatment Directive: Observations on the water quality of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 2003. Final report commissioned by the Environment Agency. 21pp.

Maberly S.C., De Ville M.M., Elliott J.A., Fletcher J.M., James J.B., Reynolds C.S., Thackeray S.J. & Vincent C. (2005). The Urban Waste Water Treatment Directive: Observations on the water quality of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 2004. Final report commissioned by the Environment Agency. 25 pp.

Maberly S.C., De Ville M.M., Elliott J.A., Fletcher J.M., James J.B., Reynolds C.S., Thackeray S.J. & Vincent C. (2006). The Urban Waste Water Treatment Directive: Observations on the water quality of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 2005. Final report commissioned by the Environment Agency. 26 pp.

Maberly S.C., De Ville M.M., Thackeray S.J., Ainsworth G., Carse F., Fletcher J.M., Groben R., Hodgson P., James J.B., Kelly J.L., Vincent C.D. & Wilson D.R. (2006). A survey of the lakes of the English Lake District: The Lakes Tour 2005. Final report to the Environment Agency, North West Region. 77pp + 87pp Appendices.

Maberly S.C., Elliott J.A. & Thackeray S.J. (2006). Options for the remediation of Ullswater and Derwent Water. Final Report to the Environment Agency. 63pp.

Mackereth, F.G.H., Heron, J. & Talling, J.F. (1978) Water analysis: some revised methods for limnologists. Freshwater Biological Association. Scientific Publication No. 36. Titus Wilson, Kendal.

Pickering, A.D. (2001) Windermere: Restoring the health of England's largest lake. Freshwater Biological Association. 122pp. Titus Wilson, Kendal.

Reynolds C.S. & Irish A.E. (2000) The phytoplankton of Windermere (English Lake District) 73 pp. Freshwater Biological Association, Titus Wilson, Kendal.

Talling, J.F. (1993). Comparative seasonal changes, and inter-annual variability and stability, in a 26-year record of total phytoplankton biomass in four English lake basins. *Hydrobiologia* 268: 65-98.

Talling, J.F. (1999). Some English Lakes as diverse and active ecosystems: a factual summary and source book. Freshwater Biological Association, Ambleside.

Thackeray S.J., Maberly S.C. & Winfield I.J. (2004). The present state of Bassenthwaite Lake: implication and opportunities for future management strategies. Final report commissioned by Unitied Utilities, English Nature and the Lake District National Park Authority. 94pp.

Thackeray S.J., Maberly S.C. & Winfield I.J. (2006). The Ecology of Bassenthwaite Lake (English Lake District). *Freshwater Forum* 25: 1-80.

UKTAG (2006). UK environmental standards and conditions (Phase 1): Draft provided to groups and organisations for review and comment (SR1-2006).

Winfield, I.J., Fletcher, J.M. & James, J.B. (2006a) The Urban Waste Water Treatment Directive: Monitoring the vendace populations of Bassenthwaite Lake and Derwent Water, 2005. Report to the Environment Agency, North West Region. CEH Lancaster.

Winfield, I.J., Fletcher, J.M. & James, J.B. (2006b) The Urban Waste Water Treatment Directive: Monitoring the arctic charr population of Windermere, 2005. Report to the Environment Agency, North West Region, CEH Lancaster.

WQTAG (2005). Guidance on the assessment of phosphorus in SAC/SPA lakes under the review of consents. Report by the Environment Agency's Habitats Directive Technical Advisory Group, WQTAG.