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THE URBAN WASTE-WATER TREATMENT DIRECTIVE:

OBSERVATIONS ON THE WATER QUALITY OF WINDERMERE, GRASMERE, DERWENT WATER AND BASSENTHWAITE LAKE, 2001

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CONFIDENTIALITY STATEMENT

CONTENTS

EXECUTIVE SUMMARY

1. The results of biological and chemical analyses undertaken on samples collected during 2001 from either basin of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake are summarised and interpreted in the context of the provisions of the Urban Waste Water Treatment Directive in respect to Windermere and Bassenthwaite Lake.

2. To varying extents, water quality was influenced by the normality of stratification and the magnitude of phosphorus carried forward from the previous, very wet autumn.

3. Phosphorus carry-over was least in the well-flushed Grasmere and Bassenthwaite Lake and greatest in the large volume of Windermere. Access to phosphorus in deep water and isolated there during the spring was assisted by storm-mixing during July, which event was followed by the production of a large desmid biomass in the late summer (actually, the greatest on record in terms of the chlorophyll content).

4. Winter wash-out and then early and stable stratification in Grasmere together constrained the exploitation of new phosphorus loading by phytoplankton.

5. Winter wash-out, thermal stability and weak P-recirculation together constrained phytoplankton development in Bassenthwaite Lake.

6. Low phosphorus availability at all times constrained the development of phytoplankton of Derwent Water. This is the only one of the five basins in which the pelagic production may be conducted predominantly via a functional microbial loop.

7. In a synthesis section, the environmental regulation of biological water quality in the four lakes is compared.

8. In relation to the provisions of the UWWTD, environmental variability sometimes disguises the impact of remedial measures applied to secure acceptable water quality in lakes.

1. INTRODUCTION

This report continues a series of annual reviews of the water quality, as indicated by the dynamics of their phytoplankton, in a series of Lake District lakes nominated by the client. These include the two lakes (Windermere and Bassenthwaite Lake) that are subject to the provisions of the Urban Waste water Treatment Directive. Grasmere, which feeds into Windermere, is nominated on account of concerns over a deterioration in its water quality over the last thirty years or so; Derwent Water, which feeds into Bassenthwaite Lake, is included partly as "a control" against which the vicissitudes in the quality of Bassenthwaite may be judged and partly because of its importance as the sole refuge of a healthy, surviving population of the vendace, *Coregonus albulus*. The present series is linked contractually with CEH annual reports on the status of sensitive populations in both UWWTD lakes (the latest being Winfield *et al.*, 2002a,b). Every second year, an overview of the progress in implementing the Urban Waste Water Treatment Directive in respect of Windermere and Bassenthwaite Lake is issued. The next is due as a sequel to the current reports (Reynolds & Winfield, 2002).

Owing to the serious outbreak of foot-and-mouth disease in Cumbria during February, 2001, access to all agricultural land was immediately curtailed. With the knowledge and agreement of the Agency, the sampling programmes on Bassenthwaite Lake, Derwent Water and Grasmere were suspended (not so Windermere, where access is direct). Sampling at Derwent Water and Grasmere was resumed in April, after a gap of two months, but it was mid-June before clearance was granted for access to Bassenthwaite Lake. The gaps in the respective records are unfortunate and the interpolation of the intermediate biotic responses is, accordingly, more speculative.

The present report retains the approximate format of its predecessors, in order to facilitate ready comparison.

2. GENERAL REMARKS ABOUT THE PERIOD COVERED

The sensitivity of biological water quality in the English Lake District, especially to the effects of summer drought, stable stratification, high rainfall and strong winds, is well rehearsed (see, for instance, IFE, 1997, pp.11 - 13). The variability in the efficacy of the selective filters influencing the growth and composition of the phytoplankton relates most to the severity, intensity and frequency of atmospheric forcing (Reynolds, 1997). Following what is now an established precedent, we open with an outline of the weather patterns as a first guide to the hydrographic behaviour of the lakes during the year 2000.

In the wake of the very wet preceding autumn, the calendar year opened with the lakes in an extremely flushed condition. Not unexpectedly, very low levels of phytoplankton obtained in Grasmere and Bassenthwaite Lake, the two most sensitive lakes in this respect. The very wet autumn led to frequent episodes of high waste-water discharges. As has been established in previous investigations (Reynolds, 1999; Reynolds *et al.*, 2001a), tertiary-treated effluents become very dilute with respect to their organic carbon and nutrient concentrations but, cumulatively, lead to a larger proportion of the phosphorus content penetrating the works, resulting in a higher load to the receiving water. The longer is the hydraulic retention time of the latter, the higher is the concentration of nutrients likely to be. This effect had already been picked up in raised total phosphorus levels in the South Basin of Windermere at the end of 2000 (Reynolds *et al.*, 2001b; see also "SBAS" in Fig. 1) and residual effects of increased fertility were anticipated in the current monitoring.

The calendar year, 2001, opened with a cold, frosty spell but the second half of January saw a return to more normal temperatures and cloudiness and below-average rainfall. A pattern of relatively dry, calm and frequently sunny weather persisted well into March, before the onset of another spell of dull, wet but mild conditions.

The second half of April was dry, very sunny with above-average temperatures but local windspeeds were close to the seasonal average for Ambleside. Warm, sunny weather persisted through much of May but it became cooler and windier at the month's end. Rainfall remained below- or close to average in June. However, the end of the month was again warm and sunny.

Hot and sunny weather continued into the first week of July but the next two became much cooler, wetter and there were several days of strong winds around the 16th and 17th days of the month. Normality was restored towards the end of the month, August temperatures and rainfall (despite some intense showers) being close to average, with above-average sunshine levels. During September rainfall was above average and there were several windy days but temperatures remained generally above the seasonal average.

Benign temperatures and reducing rainfall made October a pleasant, if rather dull month. Mild weather persisted well into November, temperatures falling to normal only at the month's end, when heavy rains and occasional strong winds emphasised the overdue transition to typical autumnal weather. However the transition was brief as the predominant December weather was anticyclonic - cold and frosty, but dry and often very sunny. A return to wet and windy Atlantic weather was short before snowfalls heralded a cold and frosty end to the year.

3. WINDERMERE NORTH BASIN

The North Basin of Windermere (NBAS) has the largest volume of the water bodies concerned and is, thus, the relatively least responsive to hydrological variability. The total phosphorus content (Fig.1, top panel, solid line, left-hand scale) continued at slightly elevated levels with respect to recent years (maximum: 0.016 mg P l^{-1} in April). The soluble fraction (same panel, broken line, right-hand scale) varied between 0.011 mg l^{-1}, during the winter months, and the limits of its analytical detection, during most of the summer. This behaviour is, of course, symptomatic of a system capable of assimilating the entire soluble phosphorus pool. The observed maximal phytoplankton biomass yield in this basin, analogised to chlorophyll-*a* concentration (Fig.2, top panel: 14 μg chl*a* l^{-1}) is comfortably within the supposed maximum carrying capacity of the phosphorus available (Reynolds, 1992: 29 μg chl*a* l^{-1}). With Secchi-disc readings consistently greater than 3 m, an acceptable water quality and clarity persisted throughout the year.

According to the routine plankton counts (submitted to EA by separate transfer, copies retained on CEH database), the seasonal distribution of phytoplankton was also quite typical, with maximal crops coming at the beginning of May and in mid-August. The spring bloom was dominated, as in most of the past 50 years, by the diatom *Asterionella formosa* (maximum observed, 4 500 cells ml^{-1}) but, rather unusually compared with recent years, with only small numbers of *Aulacoseira.* Indeed, a relative abundance of *Cyclotella* (just over 1 000 cells ml^{-1}) recalled the spring flora recorded by Lund forty-to-fifty years ago (Macan, 1970). *Cryptomonas* spp. and *Rhodomonas* were briefly abundant after the onset of near-surface stratification and the collapse of the spring bloom (top panels of Figs 3 and 4) and before *Pseudosphaerocystis* and *Coenochloris* dominated the modest mid-year plankton, together with the colonial but non-buoyant cyanobacterium, *Aphanothece clathrata.* Epilimnetic deepening in July stimulated a modest growth of diatoms (including of *Urosolenia* and a small-celled *Synedra*) but, in general, dominance passed to desmids. The most abundant of these was identified as *Staurastrum cingulum*, reaching 80 cells ml^{-1} during August.

Other algae constituted a high on going species richness but few were ever numerous. Small numbers of *Anabaena circinalis* were noted during June and early July, when there were even some modest blooms; *Aphanizomenon* and *Woronichinia* were present in autumn. Small numbers of *Tychonema bourrellyi*, the cyanobacterium notorious for its abundance in Windermere prior to the restoration, was present during the late summer, peaking during October.

Overall, the trophic condition of NBAS gave no cause for concern – despite the slightly elevated phosphorus and chlorophyll levels with respect to 2000, the plankton performance shows no significant difference in behaviour from the three previous years (Fig. 2, top panel). Hypolimnetic oxygen demand (Fig. 3) was also typically modest in 2001,despite the evidently late onset of full-column overturn.

4. WINDERMERE SOUTH BASIN

Total phosphorus levels in the South Basin during 2001 were augmented by relatively high winter loadings from Tower Wood WwTW, reaching a maximum of between 0.035 and 0.040 mg P l^{-1}. With more than half of this in the dissolved fraction, this represents a considerable increase in fertility of the water with respect to the previous year (Fig. 1, SBAS). However, the peak of the spring bloom, during April, did not exceed 14 µg chl*a* l^{-1}, despite the depletion of the soluble (PO_4-P) fraction to the limits of its analytical detection. Following the July storms, the phytoplankton chlorophyll built to a record level for the lake of just under 100 µg chl*a* l^{-1}. Only after the September maximum was soluble phosphorus again detected.

Nevertheless, the yield of chlorophyll *a* for the phosphorus invested is impressive. The overwhelming dominant was the desmid, *Staurastrum cingulum*, the maximum recorded concentration of which was 1100 cells ml^{-1}. This represented only a modest increase over the standing population of one month earlier (840 cells ml^{-1}) when the chlorophyll was barely over 20. Thus, the unusually high chlorophyll in the water was mainly attributable to a high cell-specific chlorophyll-*a* content than to an exceptional biomass. Even so, desmid concentrations of this order are rare (though not unrecorded) in the English Lake District (Brook, 1981).

The spring bloom featured only modest levels of *Asterionella* (1140 cells ml^{-1}) and *Aulacoseira* (*A. islandica,* 170 cells ml^{-1}) – the dominant alga was *Cyclotella comensis*, numbering over 5000 cells ml^{-1} in April. This was followed by an early summer period of nanoplankton abundance (*Rhodomonas*, *Ochromonas*, then *Chrysochromulina* were conspicuous) and *Cryptomonas* spp. achieved up to 200 cells ml^{-1}. Colonial chlorophytes (*Coenochloris*, *Pseudosphaerocystis*) were present during June and *Fragilaria* numbers responded slightly to the July mixing, but nothing, least of all the modest growths of *Anabaena*, *Aphanocapsa* , *Aphanizomenon*, *Woronichinia* or even *Tychonema*, was to detract from the summer of *Staurastrum.*

Despite the higher phytoplankton biomass observed in South Basin during 2001, hypolimnetic oxygen depletion was no worse than in previous years. The increased phosphorus loading is disquieting but the consequences, in terms of the production of noxious or nuisance algae, have not been serious.

5. GRASMERE

Grasmere is much smaller in volume than Windermere but it has a relatively large catchment area (28 km^2) and the latter receives a high annual precipitation (> 2 m). The lake is thus very sensitive to episodes of heavy rainfall and to the hydrological flushing it engenders. The wet autumn of 2000 had left the phytoplankton in a very washed-out condition but the circumstances in 2001 were favourable to a rapid recovery. When sampling resumed during April, the chlorophyll-*a* concentration had reached 13 µg chl*a* l^{-1} (Fig. 2, GRAS). The phytoplankton at that time was dominated by nanoplankton (almost 50 000 cells ml^{-1} of *Chlorella*) with only small numbers of diatoms and colonial chlorophytes. Within one month, the algal biomass had been reduced by about 90%, having succumbed to an abundant herbivorous zooplankton, featuring the ciliate *Nassula*, the rotifer *Keratella cochlearis* (220 l^{-1}) and the cladoceran *Daphnia* (20 l^{-1}).

By late June, a *Cryptomonas*-dominated phytoplankton had recovered to15 µg chl*a* l^{-1}. The July storm stimulated a brief resurgence of diatoms, followed by a more typical summer succession involving nanoplankton (*Chrysochromulina, Rhodomonas, Micractinium* and *Chlorella*), larger chrysophytes (*Dinobryon divergens*), small dinoflagellates (*Peridinium umbonatum*), small numbers of *Anabaena* and dominant *Cryptomonas*. The latter reached over 900 ml^{-1} in September, coinciding with the maximum chlorophyll of 26 µg chl*a* l^{-1}. This was gradually diluted out during the autumn but the fine, mild weather in November was such to support renewed development of *Chlorella*, *Chrysochromulina* and *Rhodomonas*.

Overall, Grasmere's plankton followed established trends, once it had recovered from the autumnal rains of the previous year. Diatoms fared poorly in 2001, possibly as a consequence of stock depletion but, over the last 20 –30 years, cryptomonads have become firmly installed as the most typical algae in the plankton of Grasmere. The eutrophic character of the water, if not of the plankton is enduring as ever, the hypolimnetic oxygen depletion being as rapid and complete as ever (Fig.3).

6. DERWENT WATER

During 2001, the phytoplankton in Derwent Water remained severely constrained by the availability of phosphorus (Fig. 1, DERW: TP < 9 μg P l^{-1}, throughout, soluble phosphorus ≤ 1 μg P l^{-1}). The maximum chlorophyll content noted during the year was < 9 μg chl*a* l^{-1}, observed in February, when *Asterionella* dominated with 5 500 cells ml^{-1}). When sampling resumed in April, *Asterionella* was still dominant (4 640 cells ml^{-1}) but now with significant numbers of *Cyclotella comensis*, *Aulacoseira ambigua* and *Chlorella*. Diatom dominance gave way during May to a phase of dominance by *Coenochloris* and *Dinobryon bavaricum* as well as to small population of *Anabaena flos-aquae*. During June, the nanoplankton performed most impressively, showing relative abundances of *Chrysochromulina*, the picoalga, *Chlorella* cf. *minutissima*, together with the unmistakeable components of an active microbial loop (the heterotroph, *Ochromonas*, the ciliate *Strombidium* and a calanoid-dominated zooplankton).

The summer storm impacted slightly in stimulating *Chlorella*, *Rhodomonas* and *Bicosoeca* in the nanoplankton, *Cyclotella*, *Stephanodiscus* and *Tabellaria* among the diatoms and *Dinobryon* and *Anabaena lemmermannii* among the conventional netplankton. In aggregate, the chlorophyll concentration was restored to ~7 μg chl*a* l^{-1}.

Desmids (*Cosmarium*, *Spondylosium* and the beautiful *Staurodemus glabrus*) and diatoms *Tabellaria flocculosa*) gradually gained dominance over nanoplankton into the autumn, although, as observed in Grasmere, a surge of nanoplankton growth was noted during September.

During 2001, Derwent Water remained true to its mesotrophic character. The oxygen depletion of its hypolimnion (Fig. 3) is considered atypical of such lakes but, of course, its relatively small volume in this generally shallow lake gives a distorted impression of the overall biological oxygen demand.

7. BASSENTHWAITE LAKE

The very low phytoplankton biomass present in Bassenthwaite Lake at the start of the year is considered typical of this well-flushed lake at the conclusion of a very wet autumn. The good growing conditions in January and February led to the quick establishment of an *Asterionella*-dominated phytoplankton, which had achieved almost 15 μg chl*a* l^{-1} by the time that the sampling programme was truncated and at the expense of the 0.008 mg of soluble P l^{-1} present at the start of the year ("BASS" in Figs. 1 and 2).

Sampling could not be resumed until mid-June, by which time, a small (~9 μg chl*a* l^{-1}) but rather mixed phytoplankton population was obtaining, featuring *Asterionella* and *Tabellaria*, cryptomonads and significant numbers of Cyanobacteria (*Anabaena circinalis* and *An. flos-aquae*). The total phosphorus content was the lowest measured in the lake during 2001 (0.014 μg P l^{-1}) of which the soluble fraction was beyond the lower analytical detection limits, confirming an ongoing phosphorus constraint on the biomass capacity. The July storm provided some relief – with a sharp increment in the total phosphorus content and an increase in the standing phytoplankton, with the largest relative investment going into nanoplankton and diatoms (especially of *Aulacoseira ambigua*). Large numbers of ciliates (including *Nassula*) and rotifers capitalised upon the food availability but, when eventually *Daphnia* numbers had built sufficiently to make a difference, the refuge was quickly lost. During September, a now-weakly grazed plankton, dominated by cryptomonads, the diatom *Fragilaria* and substantial numbers of *Dictyosphaerium pulchellum*, built to the year's largest recorded biomass (37 μg chl*a* l^{-1}). During the autumn, numbers of all species dropped steadily, but there was a mini-revival of nanoplankton during November, pending the onset of a wet and windy period. The latter caused some resuspension of bottom material, though this was nowhere as intense as corresponding events in recent preceding years.

In the context of the long-term behaviour of the lake and the progress of its anticipated restoration, the relatively modest, plainly P-limited plankton biomass during 2001 is to be welcomed. However, compared to recent years, there was much less rainfall in the summer and fewer instances of P-penetration of surcharged waste-water treatment. This observation, alone, supports the high rainfall runoff-high P loading theory put forward by Reynolds (1999). The longer hydraulic retention time favours greater opportunity for bloom-forming Cyanobacteria to persist and this, too, was a feature of the plankton development in Bassenthwaite Lake during 2001.

The other persistent problem in this lake, the recurrent episodes of fine-sediment resuspension and turbidity, seems not to have been experienced during 2001. Again, the amelioration is to be welcomed but it is likely to relate more to benign weather during much of the year rather than to any prospect that the sedimentary material itself may have diminished or stabilised.

8. SYNTHESIS AND RECOMMENDATIONS

The main function of the monitoring programme that has been continued with only detailed modifications since the early 1990s is manifestly intended to document lake-water quality and the behaviour of the main biota. The function of the reporting exercise is to sort out the sources of the inevitable year-to-year variability in the data among random climatic fluctuations and genuine long-term trends. During 2001, the dominating features have been the effects carried over from the extremely wet autumn of 2000 and what were generally near-normal weather conditions and rainfall distribution during 2001. The latter has favoured rather normal stratification and phases of typical phytoplankton succession, interrupted by a single significant storm event. The real interest, then, is to contrast among the various lakes, the combination of a deep-mixing event and a high winter nutrient loading in a deep, long-retention lake like Windermere and a shallow, well-flushed example like Bassenthwaite Lake. The former retained a large proportion of its inflated winter P-load, some of which was re-used in the support of a large summer crop of desmids. The effect is much more pronounced in the richer South Basin than the more rarefied North Basin. In Bassenthwaite Lake, the phase of availability of persistent dissolved phosphorus was rapidly truncated by phytoplankton growth, while significant wet-weather phosphorus penetration of the WwTW was minimal and internal recycling was correspondingly suppressed.

In Grasmere, winter flushing and summer stratification constrained the ability of the phytoplankton to exploit the phosphorus load, at least until July. The stimulus of the storm mixing was not as great as observed in this lake in recent years. In Derwent Water, the severe phosphorus limitation is hardly eased throughout the year and variations in flushing and thermal stability do not overcome the overriding constraint.

The outcome of events in 2001 seem, at first sight, to counter past views expressed about the relative effectiveness of the Urban Waste Water Treatment Directive in securing an acceptable water quality in Windermere but not in the case of Bassenthwaite Lake. However, the large chlorophyll concentration in Windermere South Basin owes more to the wet autumn of 2000 than to the failure of the restoration strategy, while the improved quality of Bassenthwaite Lake emphasises the potential for success of the strategy of P-load reductions, once the wet weather penetration of Keswick WwTW by phosphorus can be truncated and the magnitude of the P-recycling problem is reduced.

Monitoring of the condition of the lakes should be continued. This has been recognised by both the Centre and by the Agency through the conclusion of new partnership agreements covering the years 2001–04 and beyond.

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Fig. 1. Total Phosphorus (__) and PO_4-P (...) concentrations measured in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1998 - 2001.

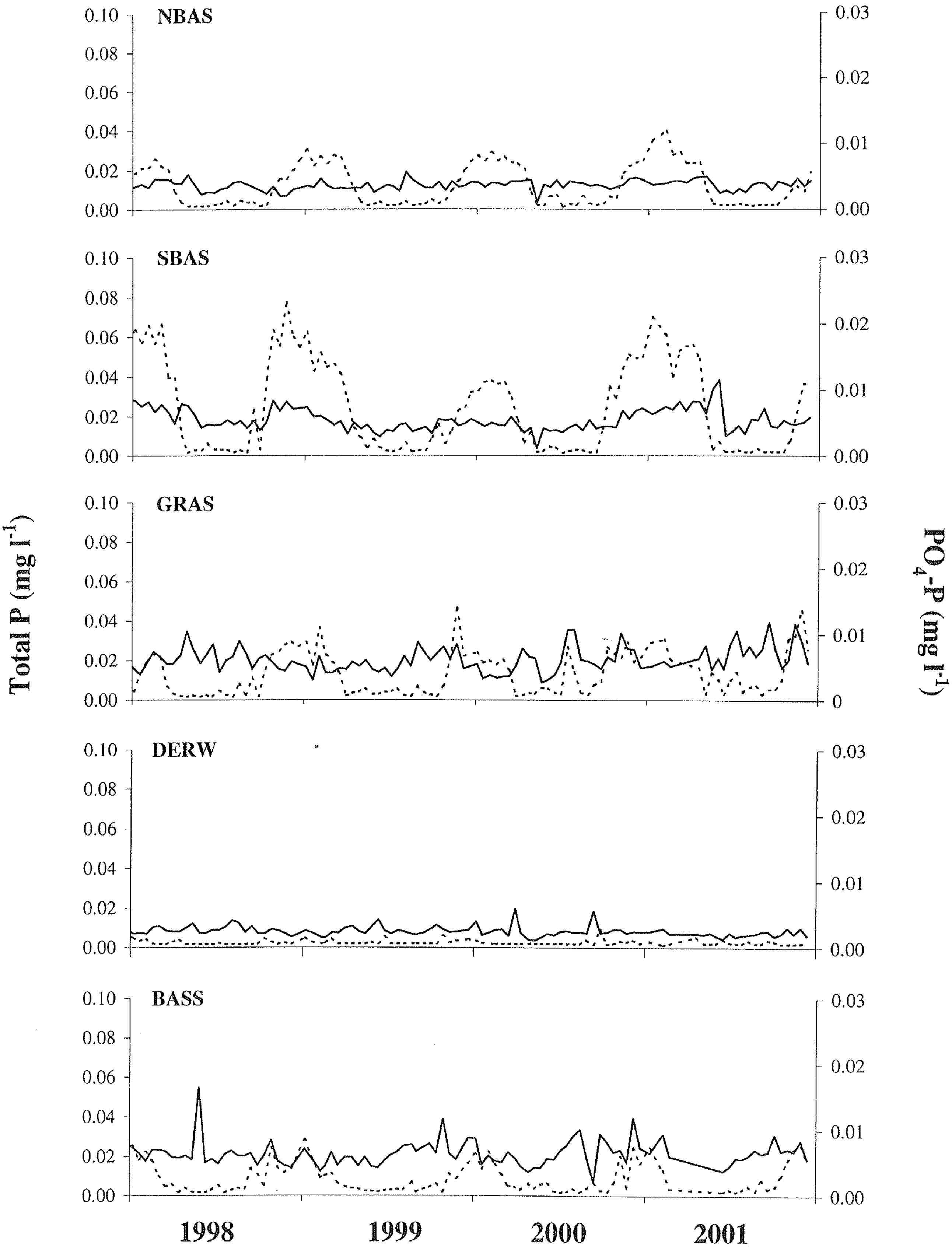


Fig. 2. Chlorophyll *a* concentrations (__) and Secchi disc depths (...) measured in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1998- 2001.

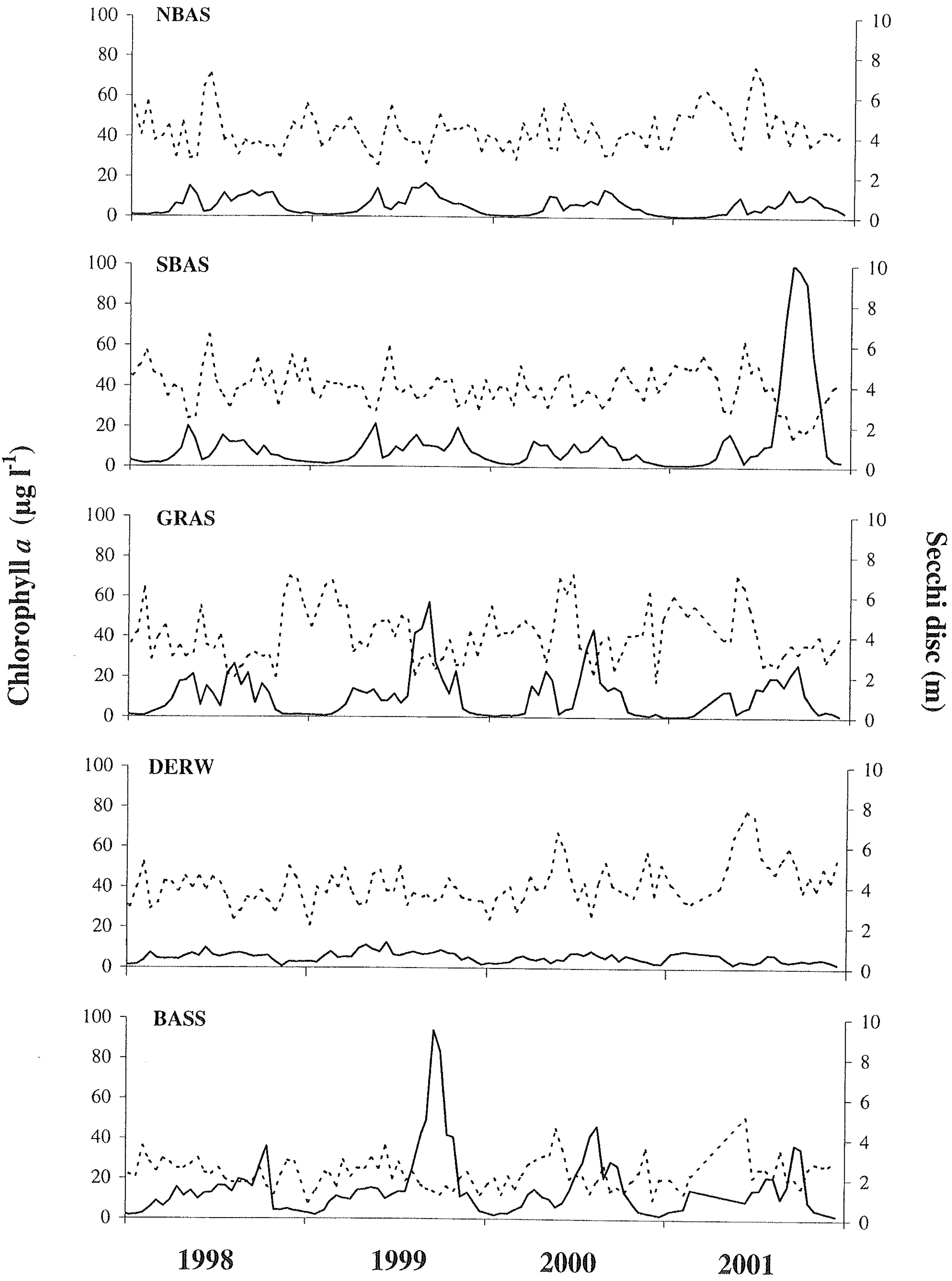


Fig. 3. Oxygen concentrations measured at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1998- 2001.

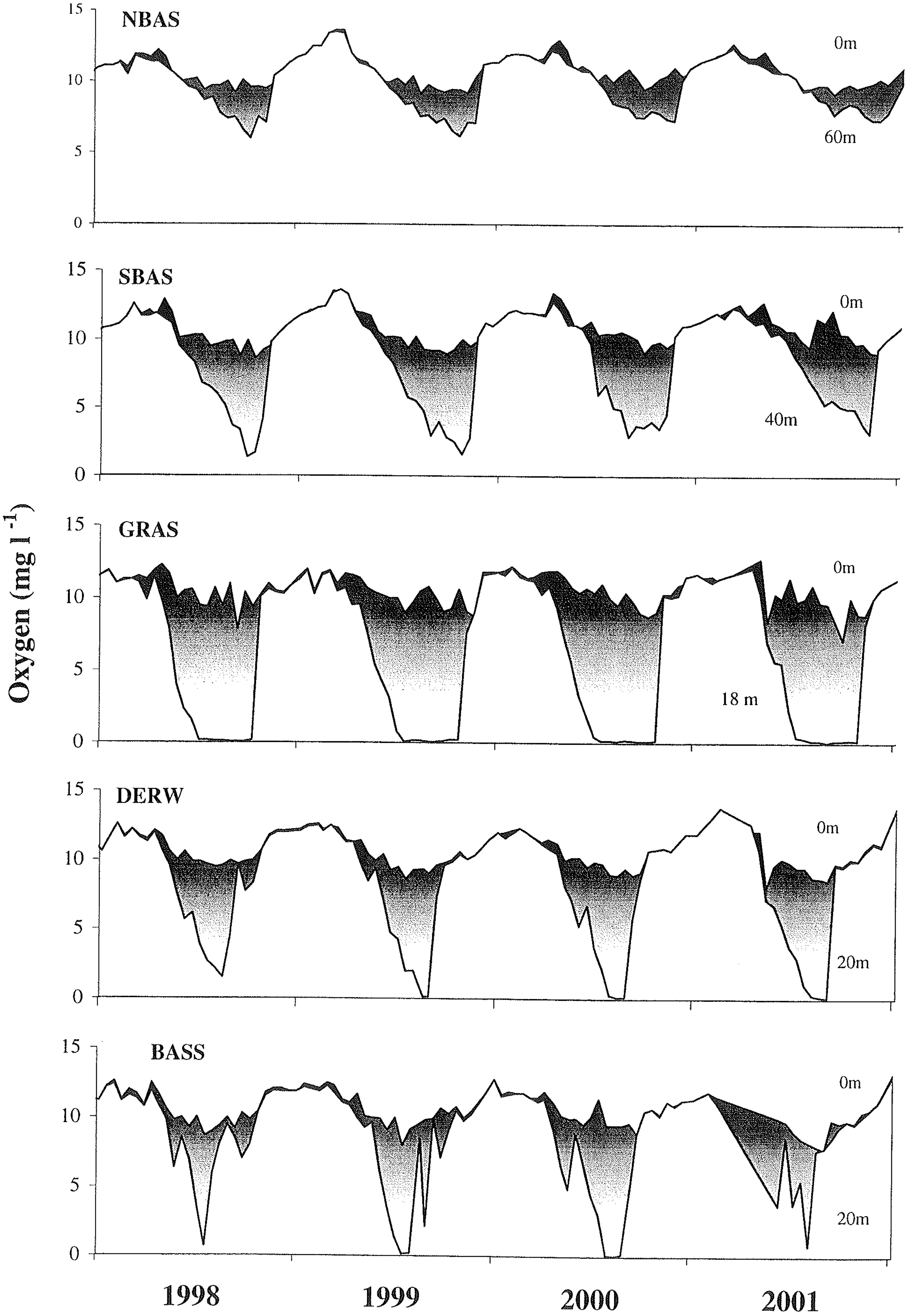
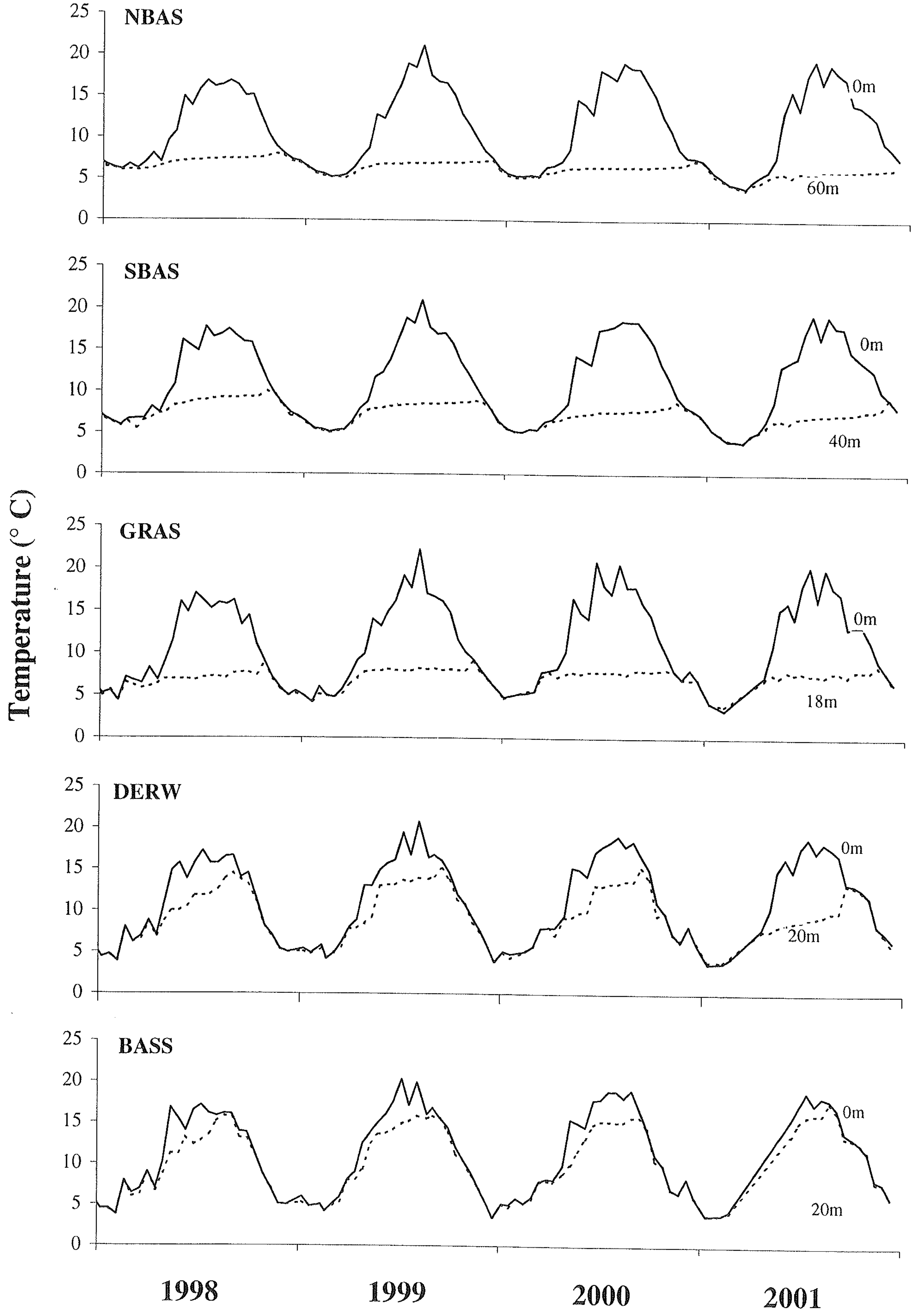


Fig.4 . Temperature measurements at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1998- 2001.



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