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The Environment Agency (North West Region)

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THE URBAN WASTE-WATER TREATMENT DIRECTIVE:

OBSERVATIONS ON THE WATER QUALITY OF WINDERMERE, GRASMERE, DERWENT WATER AND BASSENTHWAITE LAKE, 2000

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CONFIDENTIALITY STATEMENT

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EXECUTIVE SUMMARY

1. The results of biological and chemical analyses undertaken on samples collected during 2000 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 has been influenced by above-average precipitation and its effect upon hydraulic flushing and upon nutrient loads.

3. Effects were least in the large volume of Windermere, where water quality was marginally better than in any year since the 1992 implementation of remediation, and in Derwent Water where the primary constraint on water quality remains the severe nutrient deficiency.

4. Flushing continued to influence the behaviour of the increasingly enriched waters of Grasmere. However, mixing and entrainment of the hypolimnion during July led directly to the stimulation of a substantial summer phytoplankton crop. Once considered to have a probability of 0.1, 2000 was the fourth consecutive year that this has happened. In contrast with the previous years, investment in the biomass of bloom-forming Cyanobacteria (notably *Anabaena* spp.) was prevalent.

5. Flushing also regulated the standing-crop biomass of phytoplankton in Bassenthwaite, although biomass during less wet periods depleted the available soluble phosphorus. Resuspension of fine sedimentary material continues to generate turbidity and to interfere with typical ecosystem function.

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

7. In relation to the provisions of the UWWTD, compliance has manifestly secured an acceptable water quality in Windermere but not yet in Bassenthwaite Lake, where further remedial measures may be needed.

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. 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.*, 2001a,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 most recent was Reynolds *et al.* (2000). The next is due to be submitted at the end of calendar year 2002.

The present report retains the approximate format of its predecessors 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.

The mild, wet and windy weather of the preceding autumn gave way to what was a fairly sunny and, but for the fact that most of the rain fell in just two days late in the month, fairly dry January. February was also sunny but it was often wet and windy too, with above-average monthly rainfall. March was very mild but heavy rain, especially at the start of the month, kept the rainfall near average.

April had near-normal temperatures and rainfall was also near-average, though fairly well dispersed through the month. Some dry and, at times, very warm weather gave a summery feel to the first half of May but the second half of the month was cooler and more blustery. Unsettled weather persisted into June: there was a warmer, drier spell in the second half of the month but a return to the unsettled conditions left the monthly temperatures and rainfall close to the long-term average.

Cool and cloudy weather dominated during July, with some wet and stormy days, especially around 9 and 10 July. August was a little warmer, drier and sunnier than the long-term average. Summer did not persist far into September before cool and wet conditions returned; indeed, heavy precipitation was brought in on a warm, south-westerly air stream in the second part of the month.

Heavy rain associated with a series of intense depressions was prevalent during October, making it one of the wettest of the century. The pattern was maintained into November and on into early December, by which time, almost all rainfall was immediate runoff. Given the sustained period of cyclical depressions experienced, it was of little surprise to learn that they had contributed the wettest autumn for 200 years. Yet the mildness persisted until the very last week of the year, when heavy snow was followed by a cold snap brought by northerly air. It was too late and too brief to divert the year 2000 from continuing a three- or four-year series of milder and wetter years in north-west England.

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 a similar level to that observed in recent years, with a maximum of 0.014 mg P l^{-1} in April. The soluble fraction (same panel, broken line, right-hand scale) varied between 0.009 mg l^{-1}, during the winter months, and the limits of its analytical detection, during the summer. The 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 maximum sustainable level (~23 µg l^{-1}) predicted by Reynolds' (1992) regression. Indeed, as inspection of Fig.2 reveals, the phytoplankton chlorophyll concentration in NBAS was generally weaker than in any of the three preceding years.
The acceptable water quality and clarity of the North Basin has been maintained.

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 in late April and late August. In spring, diatoms dominated, *Asterionella formosa* (maximum observed, 2 800 cells ml^{-1}) and *Aulacoseira islandica* (370 cells ml^{-1}) being the most conspicuous forms. In summer, nanoplankters (notably *Chlamydomonas*, *Chrysochromulina*) were relatively abundant. The oligotrophic "feel" to the assemblage was mitigated somewhat by a substantial population of the small-celled colonial Cyanobacterium, *Aphanothece clathrata* (observed maximum, 140 colonies ml^{-1}).

Overall, the trophic condition of NBAS reached its highest quality since the remediation programme commenced in 1992. It is interesting to note that, against the "metabolic milestone" charts, commissioned and devised by EA (Reynolds, 1995; see also Reynolds & Irish, 2000), the performance is close to the predicted threshold for the likelihood of Cyanobacterial blooms. Moreover, the hypolimnetic oxygen demand in North Basin (Fig. 3) has also declined as predicted, although this might be attributable, in part, to a slightly lower hypolimnetic heat content (see Fig.4). Nevertheless, it is gratifying that the observations are consistent with the model predictions. This does not mean that recovery is complete, so much as the behaviour of the biota in 2000 conform to the lower variability limit surrounding the approximate steady state that has been struck since the 1992 remediation.

4. WINDERMERE SOUTH BASIN

Though pitched at a slightly higher level than those in the North Basin, total phosphorus concentrations in Windermere's South Basin (Fig.1, SBAS) had also stabilised at a reasonably steady state (mean: 0.016 mg P l^{-1} ; range: 0.011 – 0.020 mg P l^{-1}). However, a small but sustained rise was noted during the autumn, culminating in a concentration of ~0.022 mg l^{-1} by the year end. That this accommodated an increase of some 0.015 mg l^{-1} in the soluble fraction points to an increased load of SRP rather than eroded particulates and to a suspicion that the increment might be coming through the main sewage works. In view of deductions about the performance of tertiary treatment plants elsewhere in the district (Reynolds, 1999), it is suggested that the effect is similarly explained by poorer net P removal under conditions of high surcharges of storm water to the foul drainage. In this way, the rise may be symptomatic of the wet conditions during 2000: it remains to be seen whether the production of phytoplankton responds positively during 2001.

During 2000, however, chlorophyll concentrations remained close to the steady state condition that has developed in the late 1990s, achieving maxima in April, June and August, not exceeding 16 µg chl*a* l^{-1}. These have again occurred at the expense of the bioavailable phosphorus (see Fig.1, second panel, broken line), although the crop sizes have been well within the theoretical maximum supportive capacity (~ 26 µg chl*a* l^{-1}: Reynolds, 1992). Diatoms dominated the April maximum, *Asterionella formosa* (observed maximum, 4 400 cells ml^{-1}) re-establishing its usual pre-eminence after its relatively poor performance in 1999 (noted in Reynolds *et al.*, 2000). However, it is interesting that *Aulacoseira islandica* achieved its maximum of ~ 400 cells ml^{-1} earlier in the same month and while its biomass exceeded that of *Asterionella*. However *Aulacoseira* does not grow as fast as *Asterionella*; as discussed elsewhere (Reynolds & Irish, 2000), the better early showing of *Aulacoseira* may be a function of its more effective perennation and re-infection strategy but, in Windermere, the superior recruitment dynamics of *Asterionella* continue to exclude *Aulacoseira*-dominated vernal blooms; see Fig 2).

The June maximum in SBAS was unusual in featuring quite large populations of nanoplanktic flagellates (*Plagioselmis, Chrysochromulina, Chlamydomonas*) together with a moderate population of *Planktothrix mougeotii*. This filamentous Cyanobacterium used to be common in the South Basin but it is one of the species which diminished during the recent enrichment of the lake. It will be interesting to follow its future development in Windermere's post-restoration state.

In the August maximum, the prominent species were the flagellate *Cryptomonas*, the colonial chlorophyte *Radiococcus* and the small-celled colonial Cyanobacterium, *Aphanothece clathrata*. There was also a modest presence of *Tychonema bourrellyi*, the filamentous Cyanobacterium that was so adversely symptomatic of the enriched, pre-restoration condition of Windermere.

Hypolimnetic oxygen depletion occurred at a slightly slower rate than in past years (less of the annual production was eliminated through sedimentation). The minimum (1.6 mg O_2 l^{-1} in late October) was near-normal for the post-restoration years.

5. GRASMERE

Grasmere is much smaller in volume than Windermere but it has a relatively large catchment area and the latter receives a high annual precipitation. The lake is thus very sensitive to episodes of heavy rainfall and to the hydrological flushing it engenders. Following the wet autumn of 1999, the plankton of the lake started the year in a very washed-out condition. Chlorophyll-*a* concentrations were extremely low (see Fig. 2, GRAS), reflecting the sparsity of live algae. However, population recruitment was strong during January with nanoplankton (especially *Chlorella*) and vernal diatoms (*Asterionella*) emerging as dominant types. Wet weather during February and March led to severely increased flushing losses and it was not until mid-March that anything approaching a spring bloom began to develop. The late-April maximum (with a highest recorded chlorophyll-a concentration of 24 $\mu g\ l^{-1}$) was dominated by a population of *Chlorella* of over 10^5 cells ml^{-1}.

Such a large maximum of a highly edible food resource provided a stimulus for the development of a dense consumer population. Not for the first time after a wet winter, this constituted ciliates (*Strombidium, Halteria, Nassula*, Tintinnids) and rotifers (notably *Ascomorpha*); crustaceans were conspicuous for their rarity. However, the numbers of *Daphnia* built up strongly during May, to over 30 individuals l^{-1}. The filtration pressure that this population could exert is alone sufficient to explain the observed clearance of the nanoplankton and the collapse of the chlorophyll maintained.

The good growing conditions in June, together with the collapse by starvation of the *Daphnia*, saw the renewed build-up of phytoplankton, this time with cryptomonads in pole position. The strong winds and rain at the beginning of July increased the depth of the epilimnion, entraining nutrient-rich water from the metalimnion and sustaining the further increase of *Cryptomonas.* Rapid recruitment of *Pseudanabaena* and the potential bloom-forming *Anabaena lemmermannii* was also observed at this time. The maximum recorded chlorophyll-*a* concentration (43.6 $\mu g\ l^{-1}$) represented the annual production peak. This is not the highest recorded in the lake (the 57 $\mu g\ l^{-1}$ set in August 1999 remains unbroken) but its summer occurrence follows the precedent of the previous three years. In each case, failure of the stratification to isolate the hypolimnetic repository of phosphorus-rich sewage effluent until the autumn rains has provided the necessary stimulus for the development of a summer bloom. In previous years, the added production has been invested in algae other than cyanobacteria but, in 2000, the numbers of the potential scum-formers of the genera *Anabaena* and *Aphanizomenon* were considerably greater than in any other year since the metalimnetic sewage outfall was commissioned in 1982.

It is not known whether any nuisance blooms actually developed. *Anabaena* numbers were certainly maintained into September, though there was an attrition in the *Cryptomonas* population, mainly as a consequence of grazing losses to large ciliates and to poor recruitment after soluble phosphorus concentrations were returned to growth limiting levels (see Fig. 1: the broken line in GRAS) . Thereafter, washout and dilution dominated the plankton dynamics of the lake; by October, biomass levels had been restored to those observed at the year's dawn.

Heavy water renewal is the only redeeming feature of the sorry decline in water quality in this lake, which is now seriously eutrophied.

6. DERWENT WATER

During 2000, the phytoplankton in Derwent Water remained sparse, its abundance in this shallow lake having been almost continuously constrained by severe phosphorus deficiency (Fig.1 DERW). Total phosphorus stayed within the range 0.006 – 0.009 mgPm^{-3}; occasionally more after stormy weather; the concentration of soluble phosphorus was almost always 1 μg P l^{-1}. Growth to close < 1 μg to the carrying capacity achieved a vernal maximum with an observed peak chlorophyll-a concentration of 6 μg l^{-1}. The main components of this were Chlorellids and *Rhodomonas*: though several species of diatom were conspicuous in the plankton (including *Urosolenia eriensis, Cyclotella comensis, Asterionella formosa, Tabellaria flocculosa* and *Aulacoseira ambigua*), none achieved populations > 200 cells ml^{-1}).

The favourable conditions for growth during June allowed the development of another small maximum of phytoplankton (to about 7 μg chl*a* l^{-1}) in which a high diversity of species was dominated by *Ochromonas* and *Tabellaria.* By early August, the dominance had moved toward *Chrysochromulina, Peridinium* and Cryptomonads, with significant representation by *Anabaena lemmermanni*. *Dinobryon divergens* and *Ceratium hirundinella* also featured prominently in the late summer assemblage, which began to dissipate gradually through the autumn months.

During 2000, Derwent Water remained true to its mesotrophic character. The oxygen depletion of its hypolimnion (Fig. 3) is atypical of such lakes but, of course, its relatively small volume in this generally shallow lake gives a distorted impression of the overall redox demand.

7. BASSENTHWAITE LAKE

Windy and sometimes quite wet weather at the start of 2000 brought a sufficient mixture of turbidity and flushing to maintain a low plankton biomass in this shallow, well-flushed lake. The concentration of planktic chlorophyll *a* in Bassenthwaite Lake did not exceed 3 $\mu g\ l^{-1}$ until March (see BASS in Fig.2). Only after mid-March did net population growth contribute to net increase and vernal blooming. Even then, the main respondent was *Aulacoseira ambigua*: it dominated the observed maximum of 14.8 $\mu g\ l^{-1}$ chlorophyll *a* in early April. *Aulacoseira subarctica* was a relatively more abundant sub-dominant than it has been in recent years.

Water-column stagnation and bright sun at the start of May induced the classic symptoms of photoreaction in the *Aulacoseira* which include an abrupt increase in sinking rate. However, the diversity of the assemblage rose rapidly as many other algae increased in number. By late May, the low, apparently phosphorus-constrained biomass was dominated by nanoplankton and *Anabaena circinalis*. Modest further growth followed the cool blustery interlude in May, with the diatoms *Asterionella*, *Fragilaria* and *Tabellaria* flourishing briefly, in the company of an increasing stock of *Cryptomonas*. The latter continued to increase through June and July to well over 1 000 cells ml^{-1}. Eventually, *Cryptomonas* dominated an assemblage in which the dinoflagellate *Peridinium willei* and, notably, the desmid *Gonatozygon* were major participants.

By mid-August, when the highest chlorophyll-*a* concentration of the year (46.4 $\mu g\ l^{-1}$) was noted, the plankton was augmented again by *Aulacoseira ambigua*, together with significant quantities of *Anabaena* and *Aphanizomenon* spp.

Although washout events and dilution were responsible for the steady attrition of the phytoplankton through the late summer and autumn, several re-suspension events also restored *Aulacoseira* crops from the sediment: over 11 000 cells ml^{-1} were recorded in late September.

Total phosphorus concentrations in the lake (fig.1 BASS) continued to be erratic during 2000, but mostly fell within a range peaking at 0.027 – 0.028 mg P l^{-1}. Occasional measurements of >0.03 mg l^{-1} occurred during the summer, yet, for long periods, values < 20 μg P l^{-1} were obtained. It is difficult to determine whether this is a consequence of reduced P loadings or increased P dilution but it is encouraging to note that, except at the very start and end of the year, SRP measurements remained close to detection limits. This is a sure sign that the phytoplankton is living at the limits of ready availability. Supposing Reynolds' (1992) regression holds, an endogenous phytoplankton maximum of 40 – 46 μg chlorophyll *a* l^{-1} represents an approximate minimum investment of 23 – 29 μg biologically available phosphorus l^{-1}. Unlike the corresponding calculations carried out in respect of events in 1999, these seem to fit well with the observations.

Brief episodes of total anoxia of the small hypolimnetic volume continue to be observed (Fig.4).

8. COMMENTARY

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. In this context, it is possible to deduce that three of the sequences (Windermere North, Windermere South and Derwent Water) have continued to conform to some recognisable norm, but that the other two (Grasmere, Bassenthwaite) are beset by much less predictable behaviours, challenging the ability to diagnose contingent patterns.

Starting with Derwent Water, changes in the land use are relatively minor, and interannual variability in this shallow lake should be expected to be driven by physical forcing (sun, wind and rainfall) but in reality, its consistently low phosphorus supply places an overriding productive ceiling upon its productivity (Reynolds, 1997). The annual pattern of production and standing biomass is remarkably consistent, remaining close to the carrying capacity of the available phosphorus through the year. Variability extends mostly as far as which species dominate the standing crops. The prominence of diatoms during the spring of 2000 is considered normal. A higher diversity of species making up the summer plankton has been noted but the species assemblage was also one that has been well represented in the past.

In the case of Windermere, the lake has been subject to a remarkable anthropogenic enrichment (between 1965 and 1991) and then to remediation based upon the tertiary treatment of the effluents from the two main sewage works discharging into the lake. As the most recent reports make clear (e.g., Reynolds *et al.*, 2000; see also Reynolds & Irish, 2000), both basins have been restored to a condition comparable to that last seen in the late 1970s, which state has been maintained since. The size of the lake provides a sort of hydrological and nutrient-load damping so that productivity now tends to be similar from year to year. The species composition also remains fairly similar from year to year but there are small but significant interannual differences which appear to be driven essentially by differences in the weather. Conditions in 2000 were not universally conducive to large standing crops. Thus, the pleasing suggestion of a better water quality in the last year than any since the tertiary treatment was first implemented may simply reflect the weather variability.

In the case of Grasmere, interannual variability in wind and rainfall intensity dominates the annual plankton cycle to the extent that the long-term trends have sometimes been difficult to discern. However, a progressive increase in fertility has been disguised by feeding the supposedly mineralised sewage effluent to a disposal point deep within the lake. This has denied the phosphorus to the phytoplankton during summer, whereas flushing has removed most of this at autumnal overturn. In other words, flushing has protected against the planktic symptoms of eutrophication, though not those of hypolimnetic carbon metabolism and redox. A latent danger, identified in contemporaneous reports to the (then) NRA, was that cool or windy conditions in summer might lead to the entrainment of enriched hypolimnetic water into the epilimnion and thus stimulate unacceptable growths of phytoplankton in the lake during the late summer months. "Wolf" may seem to have been cried but precisely this scenario has been realised in consecutive years from 1997 to 2000. Worse still, in the last year, the additional summer crops comprised large populations of bloom-forming Cyanobacteria, including the potentially toxic *Anabaena*. The irony is that the present disposal arrangements were intended to mitigate against bloom development. The sadness is that the condition of this once high-quality water now seems to be so severely impaired.

Finally, we come to Bassenthwaite Lake and its responses to a complex set of driving variables. Logic suggests that its natural behaviour should be close to the morphometrically-similar Derwent Water, whence a large proportion of its volume is derived. In fact, the catchment area is very much larger and its aggregate hydraulic load is sufficient to reduce its average hydraulic retention time to 30 days. Thus, the plankton ecology of Bassenthwaite Lake naturally shares some of the characteristics of Grasmere in being subject to irregular episodes of flushing and community restructuring.

In addition, the lake has been subject to the enhanced nutrient loading from Keswick Waste Water Treatment Works. The short retention time was demonstrably a factor mitigating the usual symptoms of eutrophication, but poor water quality in the early nineties combined with deteriorating fishing and concern for the condition of the vendace population led ultimately to a decision to apply tertiary treatment to the sewage effluent from Keswick WWTW. This commenced in 1995 but, in contrast to the experiences in Windermere, the extent of recovery has been disappointing and, as the latest report if Winfield et al (2001a) confirms, the plight of the vendace in Bassenthwaite Lake remains parlous. Several reasons for the slow rate of response have been proposed and investigated, including the supposed efficiency of internal nutrient recycling. According to Reynolds' (1999) critical review, two main factors are implicated. One is that the efficiency of phosphorus stripping at Keswick declines in wet weather, owing to severe dilution of foul water by run-off and the resultant shortened contact times, and substantial phosphorus loads continue to be supplied during wet weather. The other is the presence in the lake of a fine, allochthonous silt material, of unverified provenance, which, apart from smothering the nursery areas of the vendace, has limited binding affinity for phosphate and, thus, fails to immobilise the sedimentary P-flux in the way that occurs in most other lakes. It is difficult to see how either of these adverse factors can be mitigated quickly, without incurring very high capital expenditure.

In the meantime, the behaviour of Bassenthwaite Lake remains contingent on the interactions among flow-sensitive variations in short-term nutrient loadings and their elimination from the lake, the opportunities for planktic growth and accumulation, and the weather-mediated mobility of allochthonous materials.

9. RECOMMENDATIONS

It is generally clear that compliance with the provision of the Urban Waste Water Treatment Directive has secured an acceptable water quality in Windermere but not, or not yet, in the case of Bassenthwaite Lake. The difference is partly anticipated on grounds of differential limnologies but measures to further reduce the phosphorus loading to Bassenthwaite Lake and to overcome the mobility of allochthonous sediments would now seem to be desirable goals.

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 –03 and beyond.

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Fig. 1. Total Phosphorus (__) and PO_4-P (...) concentrations measured in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1997 - 2000.

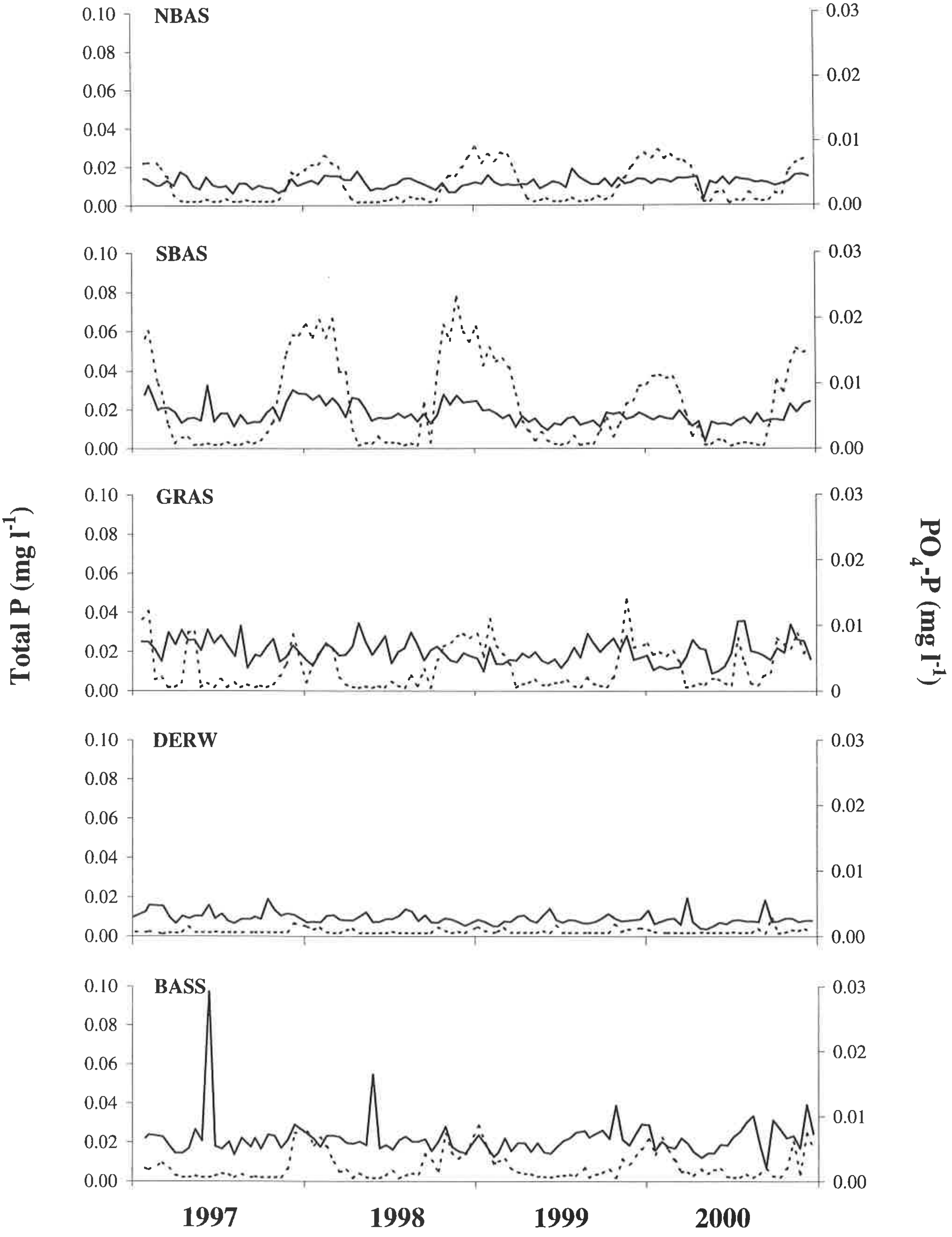


Fig. 2. Chlorophyll *a* concentrations (__) and Secchi disc depths (...) measured in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1997- 2000.

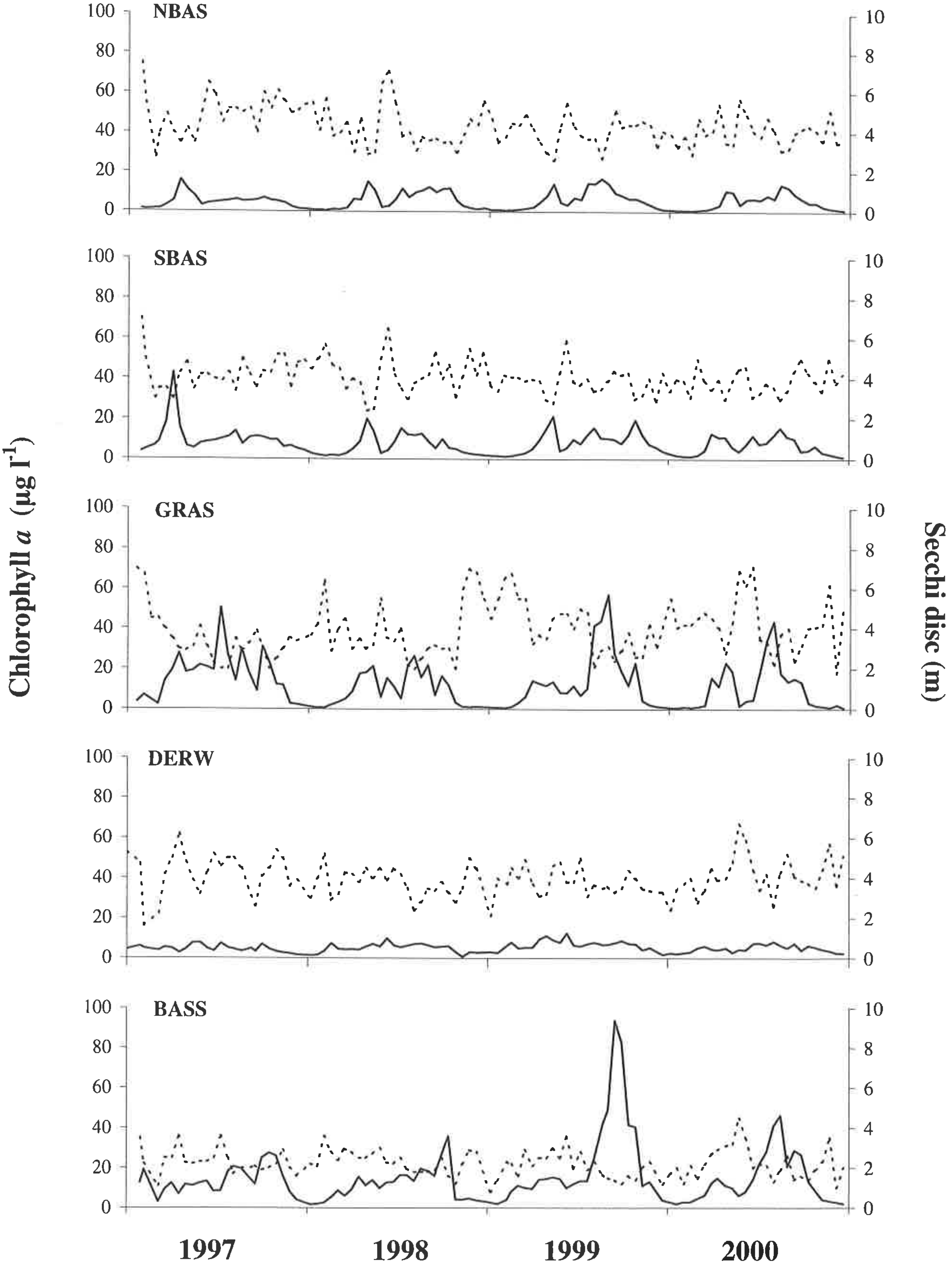


Fig. 3. Oxygen concentrations measured at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1997- 2000.

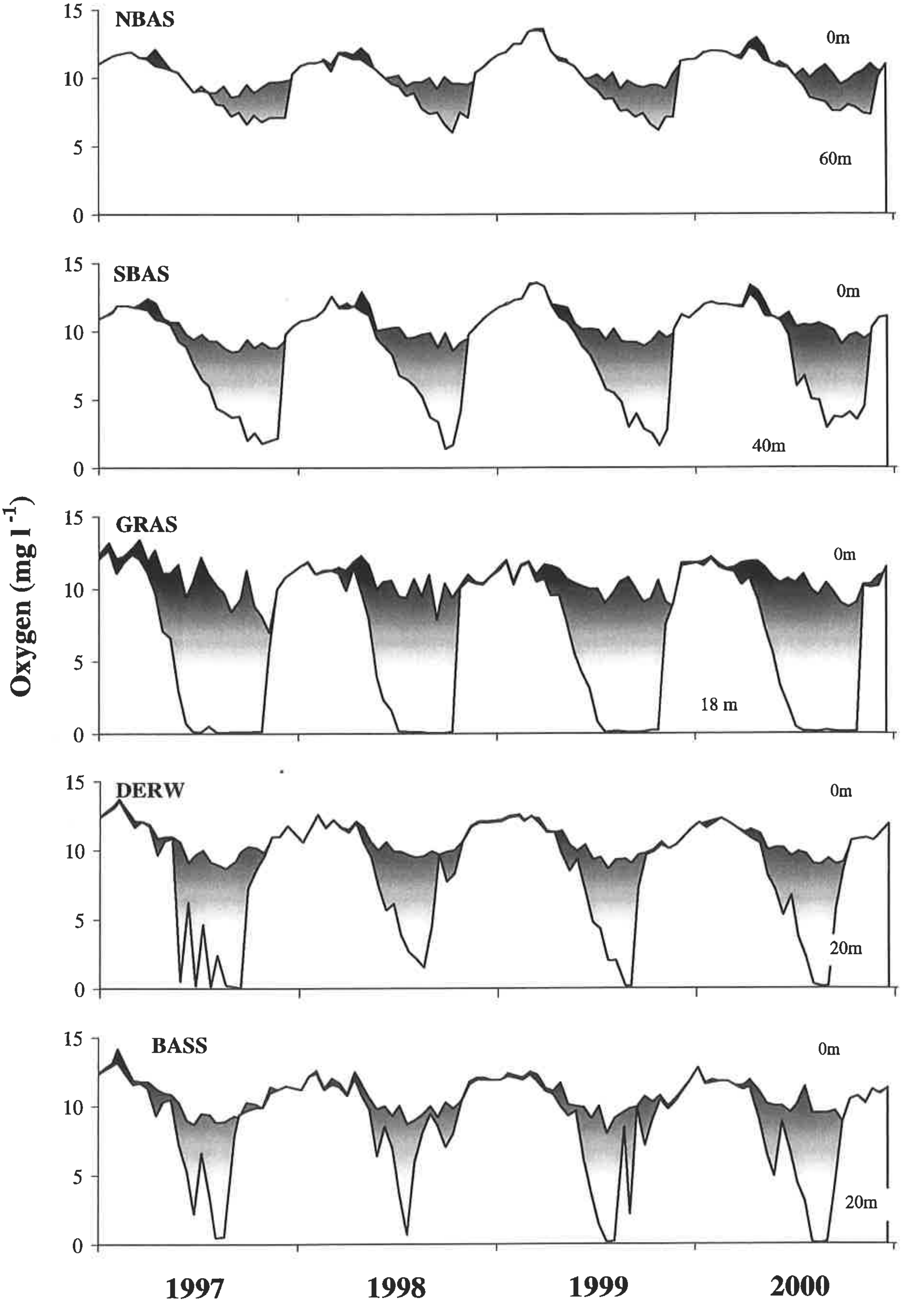
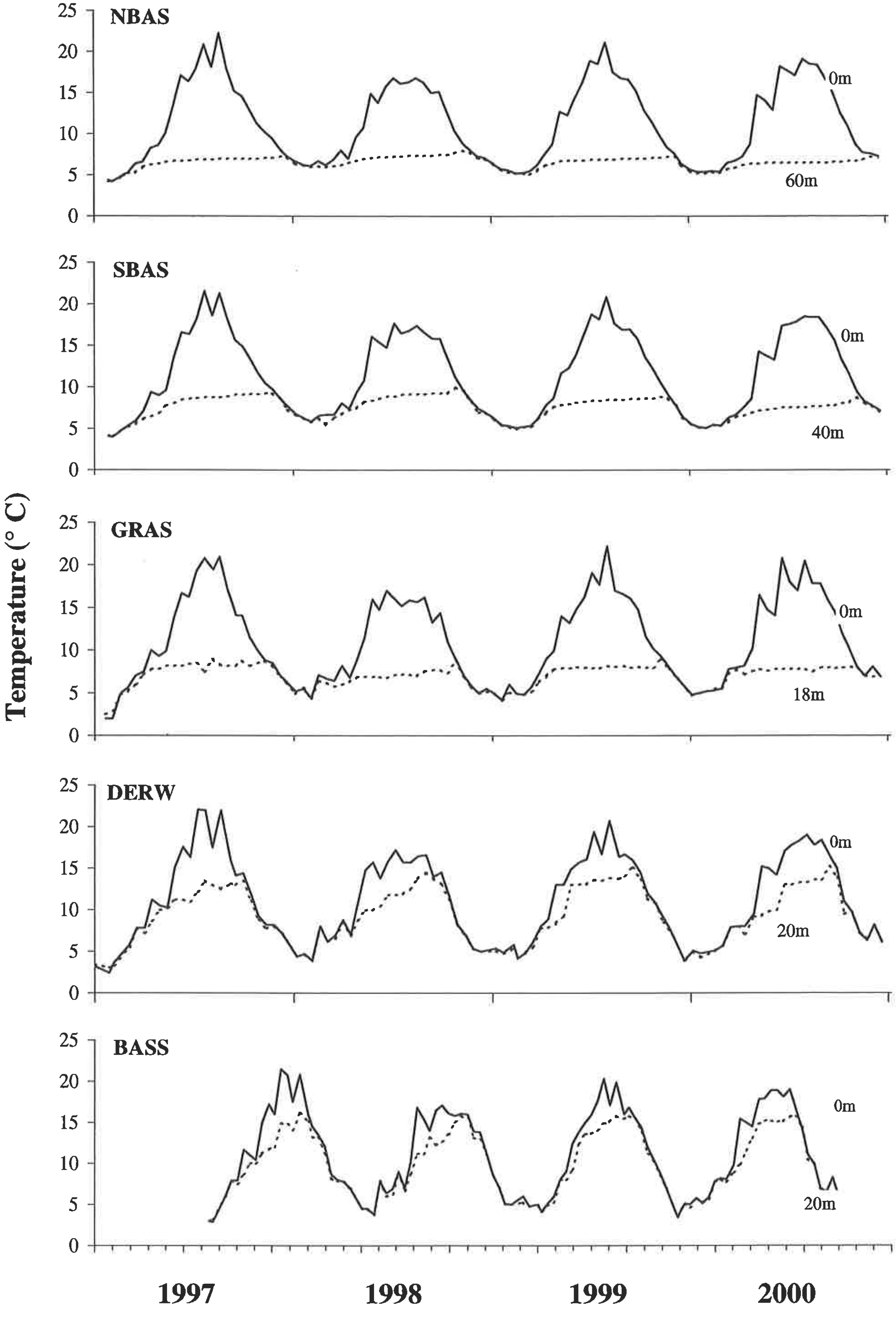


Fig.4 . Temperature measurements at the surface and at maximum depth in Windermere, Grasmere, Derwent Water and Bassenthwaite Lake, 1997- 2000.



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