Institute of Freshwater Ecology

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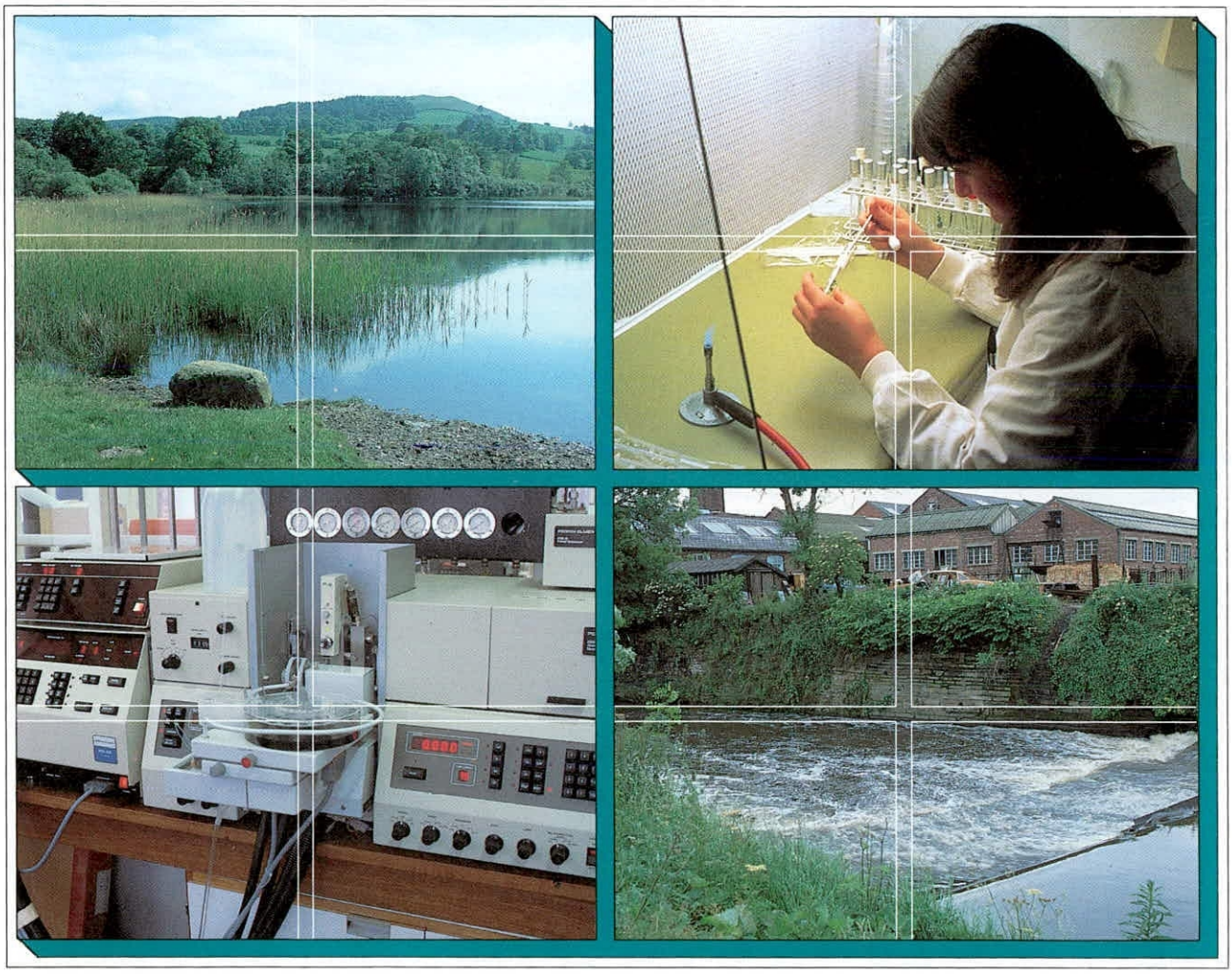

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INTRODUCTION

Bassenthwaite Lake and Derwentwater are two of the larger Cumbrian lakes, and are both situated in the northern region of the English Lake District.

Bassenthwaite Lake has considerable conservation status, being designated a Site of Special Scientific Interest in 1983 by the Nature Conservancy Council under the provisions of the Wildlife and Countryside Act of 1981. Such status was related to the vegetation in the lake and also the presence of the rare vendace fish (*Coregonus albula*). The remaining populations of vendace in Central Europe have been listed as endangered due to eutrophication (Lelek, 1987).

Bassenthwaite Lake has no major developments around its shores, but it does receive the sewage effluent, via its main inflow, from one of the largest tourist resorts in Cumbria, namely Keswick. Unlike other Cumbrian lakes, it has an unusually high catchment area feeding into a small lake volume. Combined with a mean depth of only 5.3 m, this leads to a relatively short retention time of approximately 24 days (Atkinson et al., 1989). The lake basin has a deep central region up to 19 m, enclosed by a large area of shallow water; 64 % of the lake volume is less than 5 m deep. Compared to other lakes in the region, the vertical temperature range in the deep region is relatively small. In summer the lake appears to be weakly stratified and there is some evidence for mixing to the deep water (Atkinson et al., 1989; Jaworski et al., 1991, 1992).

Up until 1990 the lake had not been the subject of any long-term study, but more scattered data exist which date back to the 1920's. Most studies formed part of a broader lakes survey (Pearsall & Pearsall 1925; Pearsall 1932 and Gorham et al., 1974). Similar intermittent studies were

carried out at the Freshwater Biological Association between the years 1949 and 1984. A survey of the major ions in the near surface water in the years 1954-56 and 1974-76 was carried out by Carrick & Sutcliffe (1982). In a detailed study Mubamba, (1989) looked at the main phytoplankton composition and related chemistry of the lake at monthly intervals between 1987-88. A general assessment of the biological features was presented by Atkinson et al., (1989) for the North West Water. In this, extensive use was made of the data generated in the studies cited above, in particular those of Mubamba. In a recent report to the NRA, Hilton et al (1993) fed data from the period January to August 1993 into a dynamic model. In this they discuss the effect of phosphate removal from the Keswick STW effluent, the effects of flushing and the role of sediments in the development of algal peaks.

Derwentwater is a more accessible lake which lends itself to tourist activities. Keswick is situated on its northern perimeter, other development around the shores is limited. The sewage effluent enters the outflow from the lake (R. Derwent), and since Derwentwater lies within the drainage basin of Bassenthwaite Lake, this is also one of the main inflows to the latter. Both lakes are remarkably similar in their physical features and the presence of vendace. Derwentwater has a central region which is 22 m deep but its mean depth is only 5.4 m so there is a large area of shallow water. It does differ considerably by having a retention time of 73 days, due to its having a substantially smaller drainage area.

Derwentwater has not previously been studied at length, although it was included in the broader surveys of Cumbrian lakes referred to above for Bassenthwaite Lake. Mubamba (1989), for his work on the vendace, carried out a comprehensive survey for the water quality of the lake.

A scientific programme to investigate the water quality of both lakes over a period of at least 5 years was initiated by the Institute of Freshwater Ecology in 1990. This project was part-funded by the National Rivers Authority, North West Region (NRA). Data have been presented annually in the form of a report to NRA (Jaworski et al., 1991, 1992, 1993).

2. METHODS

The sampling programme was carried out, conditions permitting, at fortnightly intervals. Samples were collected from the deepest point of either lake.

A weighted PVC tube, 5 m long and capacity 1 litre, was used to collect *ca* 5 litres of water from the 0-5 m vertical column. One litre of this was preserved *in situ* with Lugol's iodine and later used for the algal enumeration. The remainder of the fresh sample was used for chemical analysis, including chlorophyll *a* measurement.

A surface dip, which excluded air bubbles, was collected in a 100 ml glass bottle for alkalinity and pH determinations. By hauling a 50 µm mesh net through the 0-7 m water column, a concentration of phytoplankton was collected. In the laboratory, this sample underwent a further concentration on a Whatman no 541 filter before bring preserved in formalin and archived for possible future reference. Dissolved oxygen concentrations and the temperature of the water were measured with a YSI model 57, combined oxygen/temperature meter and probe. Measurements were taken throughout the 0-20 metre profile at regular intervals of 1 or 2 metres depending on the stratification. The point of light extinction was measured with a Secchi disc.

In the laboratory, phytoplankton was enumerated on an inverted microscope following sedimentation of the preserved material (Utermöhl 1958, Lund et al., 1958). A Lund chamber was used to count the nanoplankton in a concentrated sample at a higher magnification (Lund 1959, Youngman 1971). Procedures based on those of Mackereth et al., (1978) and Hilton &

3. RESULTS: BASSENTHWAITE LAKE

3.1 Algae and Chlorophyll *a*

Figure 1 shows the peaks and troughs of chlorophyll *a* which reflect on the algal growth between August 1990 and December 1993. Over the few years sampled the chlorophyll *a* concentration has increased significantly both in terms of its maximum and annual mean values (Table 1).

Table 1

Year	Chlorophyll *a* Concentration µg/L		
	mean	mean (Aug-Dec)	Maximum
1990	9.06 ± 3.64 (n = 10)	9.06 ± 3.64 (n = 10)	13.58
1991	9.73 ± 5.88 (n = 21)	9.70 ± 4.86 (n = 10)	21.49
1992	15.73 ± 12.68 (n = 23)	19.94 ± 17.51 (n = 9)	44.81
1993	13.85 ± 10.04 (n = 24)	13.43 ± 10.93 (n = 10)	36.52

In 1990 the sampling period covered the latter half of the year only, when the mean chlorophyll *a* concentration was 9.06 µg l^{-1} and varied from 13.58 to 2.63 µg l^{-1}. In spite of a large number of chlorophycean species, the main algae which contributed to the peaks belonged to the Bacillariophyceae (diatoms). In the late summer, the lake supported a large species composition dominated by an increasing population of *Fragilaria crotonensis* Kitton together with *Sphaerocystis schroeteri* Chodat and the nanoplankton species *Ankyra judayi* (GM Smith) Fott, *Rhodomonas minuta* Skuja, *Cryptomonas* spp. and *Monodus* sp. A small peak in autumn was attributed chiefly to *F. crotonensis* (1240 cells ml^{-1}) and *Aulacoseira ambigua* (Grunow)

Simonsen (780 cells ml^{-1}), with numerous other species such as *Anabaena flos-aquae* Brébisson and *Cryptomonas* making minor contributions.

Following minimal winter growth, the onset of spring 1991 led to a maximum chlorophyll *a* value of 21.44 $\mu g\ l^{-1}$. Thereafter, the concentration fluctuated between 8.80 and 17.29 (mean 12.77) $\mu g\ l^{-1}$ until it collapsed in November. The annual mean concentration was 9.73 $\mu g\ l^{-1}$.

Within the lake there was a wide species diversity, particularly throughout the summer when many chlorophyceae were present. However, only a few species made a major contribution to the chlorophyll peaks. Spring populations were dominated by *Aulacoseira subartica* (O. Müller) Haworth and *Uroglena americana* Calkins with maxima of 2793 and 2633 cells ml^{-1} respectively. Several small nanoplankton species were conspicuous, some more so after the collapse of *A. subartica*. Most noteworthy were *Chlorella spp.* (11047 cells ml^{-1}), *Chrysochromulina parva* Lackey, *Koliella longiseta* (Vischer) Hindak, *Stichococcus minutissimus* Skuja and Cryptomonads, including the smaller *Rhodomonas*. It should be noted that the majority of nanoplankton species are $\leq$ 20 µm long and as such account for a small input to the algal biomass even when present in substantially large quantities. Summer assemblages were remarkable for the large number of species present which en masse rather than individually influenced the chlorophyll concentration. An early peak featured a declining population of *Uroglena americana*, a mixture of re-establishing diatoms and the emergence of *Anabaena flos aquae*. These were eclipsed by the numbers for the nanoplankton; *Aphanothece clathrata* W et GS West 24363 cells ml^{-1}, *Chlorella* spp. 5750 cells ml^{-1}, *Chrysochromulina parva* 5069 cells ml^{-1}, *Stichococcus minutissima* 3647 cells ml^{-1} and *Rhodomonas minuta* 1120 cells ml^{-1}. The diatom assemblage rallied to produce a late summer peak, with concentrations of *Asterionella formosa* Hassall and

conditions, the most successful species *Uroglena americana* attained a maximum 2285 cells ml^{-1} and also maintained a strong presence over several weeks. The final component in the spring flora was *Cryptomonas* spp. and *Rhodomonas minuta*. In early summer assemblages, a strong presence of *Fragilaria crotonensis* (4736 cells ml^{-1}) was observed. At the same time, there was an abundance of the several smaller species, *Chlorella* spp. (16170 cells ml^{-1}), *Monoraphidum contortum* (1736 cells ml^{-1}), *Stichococcus minutissima* (2642 cells ml^{-1}), *Chrysochromulina parva* (1835 cells ml^{-1}) and *Rhodomonas minuta* (3315 cells ml^{-1}), which collectively contributed towards an early peak in the chlorophyll *a* concentration. From mid- to late-summer, a rich flora persisted and steady growth was observed. The main participants had changed, *Aulacoseira* spp. were established as the dominant species supported to a lesser extent by *Asterionella formosa* and *Fragilaria crotonensis*. Amongst the Chlorophyceae the colonial *Dictyosphaerium tetrachotomum* Printz flourished (1675 cells ml^{-1}), while cell numbers for those species present earlier declined but remained plentiful and were supported by a host of other small green algae. The blue-green alga *Aphanothece clathrata* reached a maximum of 17971 cells ml^{-1} in mid-summer before entering into a steady decline. The population of *Aulacoseira* spp. grew at a steady rate and had reached 11050 cells ml^{-1} by mid-autumn, which was represented by the very large chlorophyll *a* peak in Fig. 1a.

A series of peaks in the chlorophyll *a* concentration during 1993 reflected the upward trend observed in the previous year. The uppermost values occurred during spring (36.52 $\mu g l^{-1}$), early and late summer 27.60 and 30.20 $\mu g\ l^{-1}$ respectively) and mid-autumn (27.62 $\mu g\ l^{-1}$); periods more or less in agreement with previous years. The major spring component was the *Aulacoseira* spp. (4180 cells ml^{-1}) with the smaller *Cyclotella pseudostelligera* Hustedt (3676 cells ml^{-1}), *C. comensis* (1617 cells ml^{-1}) and *Uroselenia erieneis* (1230 cells ml^{-1}) in the more supportive roles.

More diatoms were present in the plankton at much lower concentrations. An abundance of any other type of algae was lacking; only *Chlorella* spp. (1669 cells ml^{-1}), *Rhodomonas minuta* (756 cells ml^{-1}), *Koliella longiseta* (483 cells ml^{-1}) offered a hint of growth. Diatoms were still well represented, albeit somewhat reduced in number, in the summer assemblages. Another interesting feature was an emergence of certain species of blue green algae. In the early summer populations, the *Aulacoseira* spp. (1216 cells ml^{-1}) once again provided the main diatom content, while *Cyclotella commensis* and the large *Synedra ulna* added weight to the biomass. Three other algae were fairly numerous, *Chlorella* spp. (4916 cells ml^{-1}), *Rhodomonas minuta* (1532 cells ml^{-1}) and the small filamentous cyanophyte *Pseudanabaena limnetica* (Lemmermann) Komarek (7558 cells ml^{-1}) (formerly known as *Oscillatoria limnetica* Lemmermann). By late summer *Aulacoseira subartica* (1292 cells ml^{-1}) and *A. ambigua* (724 cells ml^{-1}) has recovered after a mid-season collapse. *Chlorella* spp. maintained their position throughout and were supported by *Monoraphidium contortum* and *Dictyosphaerium tetrachotomum* as the main chlorophycean species, *Rhodomonas minuta* was ever present but by now its concentration had fallen drastically. On the other hand, species of Cyanophyceae were at their most prolific and *Pseudanabaena limnetica* had grown steadily to a maximum 44,414 cells ml^{-1}. Other blue greens of note were *Aphanothece clathrata* (7704 cells ml^{-1}) and *Anabaena flos-aquae* (1525 cells ml^{-1}), while *Tychonema bourrellyi* (Lund) Anagnostidis et Komárek (formerly known as *Oscillatoria bourrellyi* Lund) was observed in the lake for the first time (*ca* 1200 cells ml^{-1}). After a decrease in numbers, *Aulacoseira ambigua* and *A. subartica* recovered to more or less the previous concentrations and together with *Fragilaria crotonensis* were major components of the autumn peak. The other algae present in appreciable numbers were *Aphanothece clathrata* (3362 cells ml^{-1}), *Chlorella* (941 cells ml^{-1}), *Uroglena americana* (574 cells ml^{-1}) and *Rhodomonas minuta* (421 cells ml^{-1}).

exception of a short-lived increase maintained this state well into the summer. A sharp input of NH_4-N in September led to a maximum concentration of 89 $\mu g\ l^{-1}$ then quickly disappeared, afterwards measurements were very variable.

3.2c Silicon

Soluble reactive silica (SiO_2) concentrations from August 1990 until December 1992 shown in Figure 4a, had for the most part annual cycles with a similar appearance. From September 1990 the SiO_2 concentration climbed to > 2 mg l^{-1} and was more or less stable throughout winter. This was quickly depleted from the maximum 2.49 to 0.25 mg l^{-1} in response to the spring growth of diatoms in 1991. Through to autumn the concentration remained below 1 mg l^{-1} and underwent some fluctuations which led to diatom growth when in excess of 0.5 mg l^{-1}. After the breakdown of stratification the amounts of SiO_2 in the lake gradually rose to > 2 mg l^{-1}. The next cycle in 1992 had a similar appearance, high concentrations (2.65 mg l^{-1}) were reduced to < 0.5 mg l^{-1} in spring, values then fluctuated *ca* 0.5 mg l^{-1} into late autumn, during which time it was interesting to note a lack of diatom growth. By the end of the year the concentration had advanced to > 2 mg l^{-1} and remained so throughout winter. In response to spring diatom growth, the SiO_2 concentration in 1993 was depleted to 0.28 mg l^{-1}. In the period that followed up until autumn the SiO_2 concentration was more variable than in previous years. Such changes led to concentrations above 0.5 mg l^{-1} and supported diatom populations; as was earlier reported diatoms flourished throughout the year. When the SiO_2 recovered in winter its concentration was < 2 mg l^{-1}.

3.2d Dissolved Oxygen

Comparison of the dissolved oxygen concentration (DO) at depths 0 m and 20 m is shown in Figure 5a. The greatest differences in the DO occurred during the summer months. Early in August 1990, the water column gave the appearance of being well stratified and the DO at 0 m and 20 m was 8.55 and 0.075 mg l^{-1} respectively. A short time later, measurements (not shown) provided evidence for mixing into the deeper layers, followed by a weakened DO re-stratification. The process leading to a uniform concentration throughout the water column began in September and was complete by mid-October, when an increase in the DO became apparent. Small differences at 0 m and 20 m in the DO were observed from an early stage in 1991 and 1992 but the most significant change occurred with the stratification in May. Throughout the summer there was a strong indication that the water column was unstable, with periods of mixing into the deeper layers interchanged with those of stratification (figure 5a). The maximum vertical DO difference was 10.28 and 8.52 mg l^{-1} in July 1991 and June 1992 respectively. In 1992 the overturn was delayed into November. The stability of the DO in the water column was stronger throughout summer 1993, with only a slight hint of mixing to 18 m during August. A small difference in the DO through the water column was seen during May but this proved to be unstable. However, by June and onwards, significant differences were observed, the maximum vertical DO difference was 9.87 mg l^{-1} in August. The breakdown of the DO stratification has been almost completed in September.

3.2c pH and Alkalinity

Four yearly cycles of pH measurements are shown in Figure 6a. The annual trends after 1990 showed much similarity with values consistently < 7 throughout winter and early spring. In the second half of 1990 changes to the pH were small with values between 6.72 and 7.03. In the

years following, the pH measurements increased significantly during spring and throughout summer, showed some variations at values > 7 before they decreased in the autumn, except in 1993 when higher values extended into December. The maximum and minimum measurement during this period were 8.22 and 6.50 respectively.

The changes in alkalinity, expressed as mg l^{-1} $CaCO_3$, are shown in Figure 6. Excluding 1993, the alkalinity tended to rise in spring, peak around mid-summer and decrease gradually into autumn before a more rapid fall in winter. Values dropped from over 11 mg l^{-1} in August 1990 to *ca* 6 mg l^{-1} throughout the winter and spring 1991. A significant rise led to a peak in June of 12.1 mg l^{-1}, followed by relatively stable values into the autumn. The pattern was the same in 1992, a maximum alkalinity of 12.6 mg l^{-1} was observed during July. From the beginning of 1993 the alkalinity rose gradually in a series of peaks to reach a maximum value of 11.9 mg l^{-1} in late October.

3.3 Temperature and Light

Water temperature measurements at 0 m and 20 m show that the maximum vertical difference was small and consistently *ca* 6°C after the commencement of stratification. Recorded temperatures in 1990 were made over a short period of the summer through to winter. Surface temperatures varied from 19.1°C in August to 3.3°C in December, during this time the maximum vertical difference was 4.3°C. The breakdown of stratification began in September. The surface water temperature in 1991 ranged between 1.1°C and 19.6°C, and the maximum vertical difference was 5.3°C. The lake began to stratify in May, showed several mixing events through summer and had finally overturned in September. The surface water temperature in 1992 varied between 1.9°C

and 18.6°C, and the maximum vertical difference was 5.6°C. The lake stratified in May, showed signs of mixing in summer and overturned in October. This pattern also applied to temperatures in 1993, when the variation was 1.9°C to 21.5°C and the maximum vertical difference 5.9°C. To a lesser extent there was evidence for some summer mixing.

Throughout the sampling period annual values for the light penetration showed much similarity. The minimum and maximum values were 1.0 m and 4.4 m, while the mean light penetration (1990-93) was 2.5 ± 0.4 m (m = 77).

4. RESULTS: DERWENTWATER

4.1 Algae and chlorophyll *a*

Derwentwater supported an algal flora which contained a rich diversity of species. The greatest number were of nanoplankton which belonged to the groups Chrysophyceae and Chlorophyceae. Few species were sufficiently abundant to make worthwhile contributions to the algal biomass. Chlorophyll *a* concentration (Figure 1b) did not change significantly during the period monitored, only differences in seasonal peaks were observed. Between 1991 and 1993 (the years with a complete sampling programme), the mean chlorophyll *a* concentrations were 4.84, 5.48 and 5.57 $\mu g\ l^{-1}$.

The mean concentration of chlorophyll *a* during 1990 (August-December) was 6.18 $\mu g\ l^{-1}$, and highest values were observed prior to October. Algal populations in this period were relatively small, the only noteworthy algae present were *Anabaena flos-aquae* (577 cells ml^{-1}), *Dinobryon divergens* Imhof (588 cells ml^{-1}) and *Uroglena americana* (700 cells ml^{-1}) in the phytoplankton together with *Chrysochromulina parva* (1727 cells ml^{-1}), *Chlorella* spp (1698 cells ml^{-1}), *Monoraphidium* sp (799 cells ml^{-1}), *Uroselenia eriensis* (941 cells ml^{-1}) and to a lesser extend *Rhodomonas minuta* (481 cells ml^{-1}) from the nanoplankton community.

The chlorophyll *a* peak of 14.11 $\mu g\ l^{-1}$ in May 1991 resulted from the growth of *Uroglena americana* (12,000 cells ml^{-1}). Minor contributors present at the same time were *Anabaena flos-aquae, Chrysochromulina parva, Chlorella* sp. and *Monochrysis* sp. Much smaller peaks were observed in summer and autumn, the more dominant algae at these times were *Aphanothece*

clathrata (10,000-19,000 cells ml^{-1}), *Dinobryon divergens*, *Uroglena americana* and *Sphaerocystis schroeteri*.

The plankton in Derwentwater during 1992 produced two peaks in spring and early summer which were substantial for the lake. However, a much higher concentration of chlorophyll *a* was observed at the end of summer (13.52 $\mu g\ l^{-1}$). *Uroglena americana* featured highly during all three peaks but its maximum concentration occurred in the spring (8246 cells ml^{-1}) when there was scant support from *Chlorella* spp and *Aphanothece clathrata*. In early summer, the blue-greens *Anabaena circinalis* Rabenhorst and *Aphanothece clathrata* played a supporting role to the *Uroglena*. The late summer peak was associated with a mixed population of algae, in which the *Uroglena* was once again the major species. The other algae which offered valuable additions to the chlorophyll *a* concentration were *Aphanothece clathrata*, *Dictyosphaerium tetrachotomum*, *Kirchneriella* spp., *Monoraphidium* spp., *Paulschulzia pseudovolvox* (Schulz im Teiling) Skuja, *Dinobyron* spp., *Kephyrion* spp. and *Uroselenia eriensis*. The largest algal populations in each year since 1991 appear to have been progressively later, as demonstrated by an autumn peak in 1993. During this period *Uroglena americana* (4671 cells ml^{-1}) and *Aphanothece clathrata* (7409 cells ml^{-1}) were the two most abundant species and they maintained a high profile until the end of November. Smaller contributions to the autumn chlorophyll were offered by *Chlorella* spp., *Asterionella formosa* and *Uroselenia eriensis*. Earlier growth was limited to several lower pulses, the first in spring was confined mainly to a large number of sparsely concentrated nanoplankton species, in particular the Chrysophyceae of which *Chrysochromulina parva* was the most common (1160 cells ml^{-1}).

In terms of numbers of species the nanoplankton continued to dominate in the summer community, however the smaller Chrysophyceae had been replaced by Chlorophyceae, whose contribution was also collective. On the other hand larger colonial chrysomonads grew well, *Uroglena americana* (1251 cells ml^{-1}) and *Dinobryon sertularia* Ehrenberg (970 cells ml^{-1}) were a major part of the assemblage together with *Cyclotella comensis* (1230 cells ml^{-1}) and *Aphanothece clathrata* (6415 cells ml^{-1}).

As a rough guide to the species diversity in Derwentwater over recent years, the nanoplankton: phytoplankton ratio in 1993 was 53:21, the greatest diversity being within Chyrsophyceae where the ratio was 23:3.

4.2 Chemical Analysis

4.2a Phosphorus

The annual cycles of soluble reactive phosphorus (PO_4P) and total phosphorus from August 1990 to December 1993 are shown in Figure 2b. Up until the mid-summer of 1993 the PO_4P concentrations were very predictable, that is summer concentrations were below the level of detection and overwintering concentrations were < 2 $\mu g\ l^{-1}$ and rarely maintained for any length of time. Small quantities of PO_4P were detected prior to the massive (by Derwentwater standard) rise to 13.2 $\mu g\ l^{-1}$ in 1993, the concentration fell away quickly but not immediately and there was a small increase to 3.6 $\mu g\ l^{-1}$ in September. There was no clear pattern to the annual cycles in total phosphorus, concentrations appeared to fluctuate in an irregular manner and did not necessarily show direct correlation to the chlorophyll *a* concentration. However, it did hint to

possible phosphorus enrichment; mean annual concentrations in the earlier years ranged between 9.1 and 11.1 $\mu g\ l^{-1}$ and were followed in 1993 by a significant rise to 15.7 $\mu g\ l^{-1}$.

4.2b Nitrogen

Figure 3b shows the concentrations of nitrate nitrogen (NO_3N) and ammonium nitrogen (NH_4N) in the years 1990-1993. The annual NO_3N cycle followed a similar pattern during the period in which it was monitored. From a maximum position in spring the concentration fell sharply to a minimum in summer, then immediately grew to a near maximum value by the end of the year. From a mid year starting point of 23 $\mu g\ l^{-1}$ in 1990 the concentration of NO_3N increased to 221 $\mu g\ l^{-1}$. The maximum and minimum concentrations respectively were 389 and 70 $\mu g\ l^{-1}$ in 1991, 331 and 20 $\mu g\ l^{-1}$ in 1992 then finally 254 and < 14 $\mu g\ l^{-1}$ in 1993. In the last year mentioned the cycle showed a slight variation to those described earlier, once the concentration reached a minimum it then proceeded to move up and down with values < 100 $\mu g\ l^{-1}$, and only in the last days of the year rose significantly.

The NH_4N concentration in 1990 varied between 5 $\mu g\ l^{-1}$, the limit of detection, and 11 $\mu g\ l^{-1}$. Early detected concentrations in 1991 were depleted by the spring, then made some considerable gains to > 20 $\mu g\ l^{-1}$, and once to 41 $\mu g\ l^{-1}$ in the summer as the amounts fluctuated widely. For long periods in 1992-93 the concentration was beyond the limit of detection or only slightly higher. Occasional measurements in both years showed values significantly above 10 $\mu g\ l^{-1}$.

4.2c Silicon

Figure 4b shows the soluble reactive silica (SiO_2) over the monitored period. From similar high winter amounts, *ca* 1.68 to 1.83 $mg\ l^{-1}$, SiO_2 decreased gradually to a minimum (0.32 to 0.37 mg

l^{-1}) during the first week in July and then ascended at a similar rate towards the winter peak, except in 1993 when the concentration remained more or less stable at *ca* 0.69 to 0.87 mg l^{-1} between August and November.

4.2d Dissolved Oxygen

In each year the minimum dissolved oxygen concentration at 20 m reached < 0.5 mg l^{-1} in the summer, when it was > 9.5 mg l^{-1} at the surface (Figure 5b). Stratification usually started in May and ended in October; however, in 1992 the mixing to deeper layers began during July but was not completed until October. There was an indication of mixing to the deeper layers in June 1991 before the lake had strongly stratified.

4.2e pH and Alkalinity

Winter alkalinity tended to rise from the start of the year into the autumn and then declined. Values over the complete period investigated ranged from 2.6 mg l^{-1} $CaCO_3$ in winter to 6.85 mg l^{-1} $CaCO_3$ in autumn (Figure 6b). pH values were higher in summer, lower in winter and ranged from 6.26 to 7.41 showing much similarity in each of the years (Figure 6b). Annual means were very comparable, and the overall mean was 6.78 ± 0.06.

4.3 Temperature and Light

Although the thermal stratification process began earlier, the lake did not become strongly stratified until May (figure 7b). In 1990 the range in surface temperatures was from 19.9°C in summer to 3.3°C in winter and the maximum vertical temperature difference recorded was 6.8°C. Surface temperatures in 1991 ranged from 0.7°C in February to 18.9°C in September, the

maximum vertical difference was 6.8°C in July. The lake became more or less isothermal in September. In 1992, the surface water temperature range varied from 2.8°C in February to 19.1°C in July, the maximum vertical difference was 8.6°C in June. The breakdown in thermal stratification began as early as August but was not completed until October. Finally, in 1993 the range in the surface water temperature was from 3.2°C in March to 20.0°C in June, however, summer temperatures were lower than in previous years. The maximum vertical difference was 6.3°C in July, and the end of stratification came in September.

The light penetration varied between 1.5 and 4.1 m during the period August to December 1990. The mean value was 3.4 ± 0.8 m. During the following years the fluctuations in the light penetration were similar (Figure 1b), measurements ranged between 2.5 and 6.1 m and the calculated annual mean values were between 3.9 and 4.5 m.

5. DISCUSSION

Although Bassenthwaite Lake contains a considerable number of algal species, conditions in the lake appear to be ideally suited for diatom growth. Diverse populations of diatoms in spring develop in response to the high overwintering concentrations of both phosphorus and silica. With the depletion of both these nutrients and the onset of summer stratification diatom growth is temporarily halted. Such conditions are not normally conducive to active diatom growth. However, in Bassenthwaite Lake where a combination of a large expanse of shallow water and frequent strong winds favoured a sequence of the mixing events to the deeper layers, which are essential to diatom growth. Under these conditions diatoms, particularly those in the marginal regions, could be returned to the upper water layers and take advantage of any nutrients similarly made available.

Some of the crops of larger diatoms observed from July onwards would certainly have had a requirement for PO_4P and SiO_2 in excess of the concentrations measured. Since the total phosphorus remained at a relatively constant level throughout the year, it is likely that internal nutrient loading due to mixing supplied the necessary amounts (Hilton et al. 1993)

Minor fluctuations in PO_4P appeared sufficient to support a large and diverse summer flora, consisting mainly of nanoplankton species of Chlorophyceae. Cell numbers could be extremely high, but by comparison the biomass was small, hence nutrient demands were not excessive.

Mixing and flushing, particularly in summer, does not create the ideal conditions for slow-growing gas vacuolate blue-green algae. Few opportunities for sizeable populations are provided, hence

there is a paucity of such species in the phytoplankton. *Anabaena flos-aquae* was the sole species showing some consistent growth, with populations annually reaching into the lower thousands of cells per ml, but still comparatively low compared to more eutrophic waters. Surface blooms of this alga have been reported, mainly within sheltered bays where wind swept material from other regions of the lake most probably accumulated. A *flos-aquae* is a nitrogen-fixing alga, and as such was able to grow in both lakes during periods of low nitrogen concentration.

In contrast the smaller-celled species of blue-green algae, *Aphanothece clathrata* and, more recently, *Pseudanabaena limnetica* have produced large populations. The small mucilaginous colonies of *Aphanothece* are said to overwinter on the sediments where they escape winter flushing (Starmach 1966) so in a large shallow lake they ought to be successful, as has been observed. Both are non gas-vacuolate so mixing will be advantageous. Concentrations of both total and soluble reactive phosphorus in 1993 were higher than in the preceding years. However, it is too soon to speculate whether or not this is an upward trend, or merely due to climactic conditions at the time.

During this survey, some species new to Bassenthwaite Lake have been observed, notably *Aulacoseira ambigua* (Canter & Haworth, 1991) and *Tychonema bourrellyi*. The former is now a well-established contributor to the diatom flora. *Tychonema* appeared in 1993, it is a non-gas vacuolate blue-green alga which has often dominated the summer phytoplankton in Windermere. Fortunately, the lake has with a short retention time and a very large drainage basin, so both alga and nutrients can be diluted quickly. However, if a long period of dry weather in summer was combined with strong wind action, then the *Tychonema* could quite easily flourish.

Physical features of Derwentwater closely resemble those of Bassenthwaite Lake but its trophic status differs greatly. Derwentwater contains a flora which is typical for oligotrophic waters, and mean chlorophyll *a* concentrations are annually < 7 $\mu g\ l^{-1}$. The lake supports an algal population made up almost entirely of nanoplankton species of Chyrsophytes and Chlorophytes. Within the former are many interesting species not common to the richer lakes, including in 1993 seven species of *Dinobryon* (many non-colonial) and seven species of *Kephyrion/Pseudokephyrion*. The two main components of a small diatom community are *Cyclotella comensis* and *Uroselenia eriensis* both commonly associated with oligotrophic conditions.

Measurements revealed a paucity of soluble reactive phosphorus in the epilimnion, for very long periods it was undetectable. As a result, growth was poor and except in 1993 no correlation was seen between phosphorus and algal growth. Total phosphorus by comparison was relatively high and constant throughout the year and could be a possible nutrient source. The situation appears to favour internal loading through recycling or recruitment from the large area of shallow sediments. In August 1993, there was an inexplicable and sudden rise in soluble reactive phosphorus to *ca* 14 $\mu g\ l^{-1}$, at the same time a sudden increase in the concentration was observed in Bassenthwaite Lake.

Another interesting feature was that of silica depletion. Concentrations in spring and autumn were more than sufficient to support substantial diatom crops, yet only a few hundred cells per ml were produced most probably due to phosphorus limitation. However, silica did decrease gradually to a low point in summer and then gradually rose again. One can only speculate that this loss in part was caused by benthic or epiphytic diatoms since these contribute 70 % to the

diatom community (Dr E.Y. Haworth, pers. comm.). Another cause may be dilution by loss through the outflow.

As was seen in Bassenthwaite Lake, the small blue-green alga *Aphanothece clathrata* formed substantial populations in terms of cell numbers. With extremely large areas of shallow water in both lakes, they make an ideal habitat for this alga. Colonies can overwinter on the sediments, where in shallower regions they will use the light and temperature more efficiently, before emigrating into deeper waters.

6. ACKNOWLEDGEMENTS

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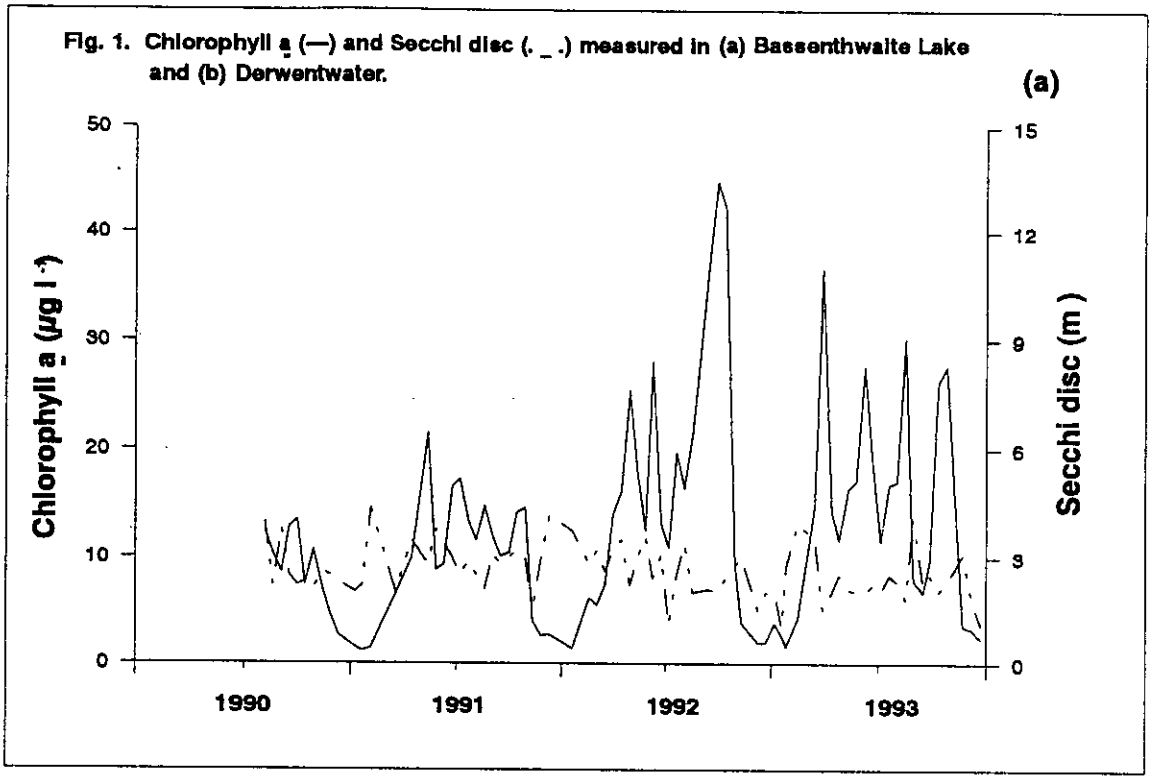
Fig. 1. Chlorophyll a (—) and Secchi disc (. _ .) measured in (a) Bassenthwaite Lake and (b) Derwentwater.



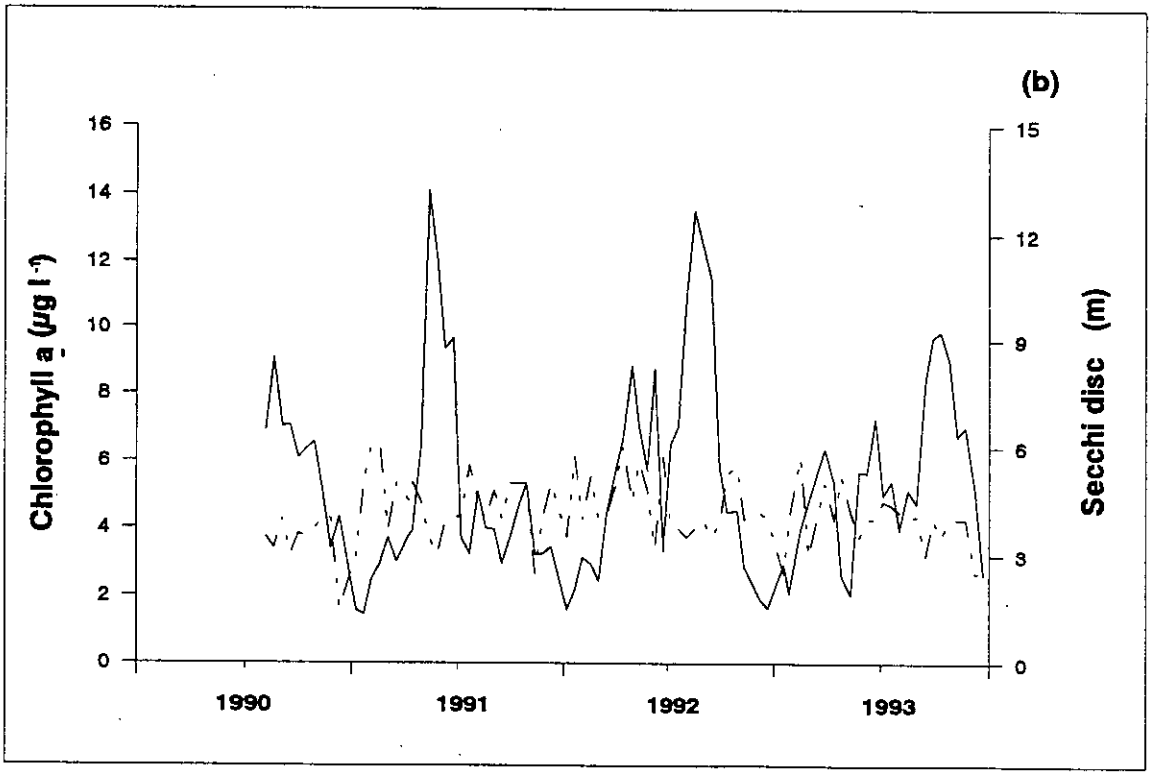
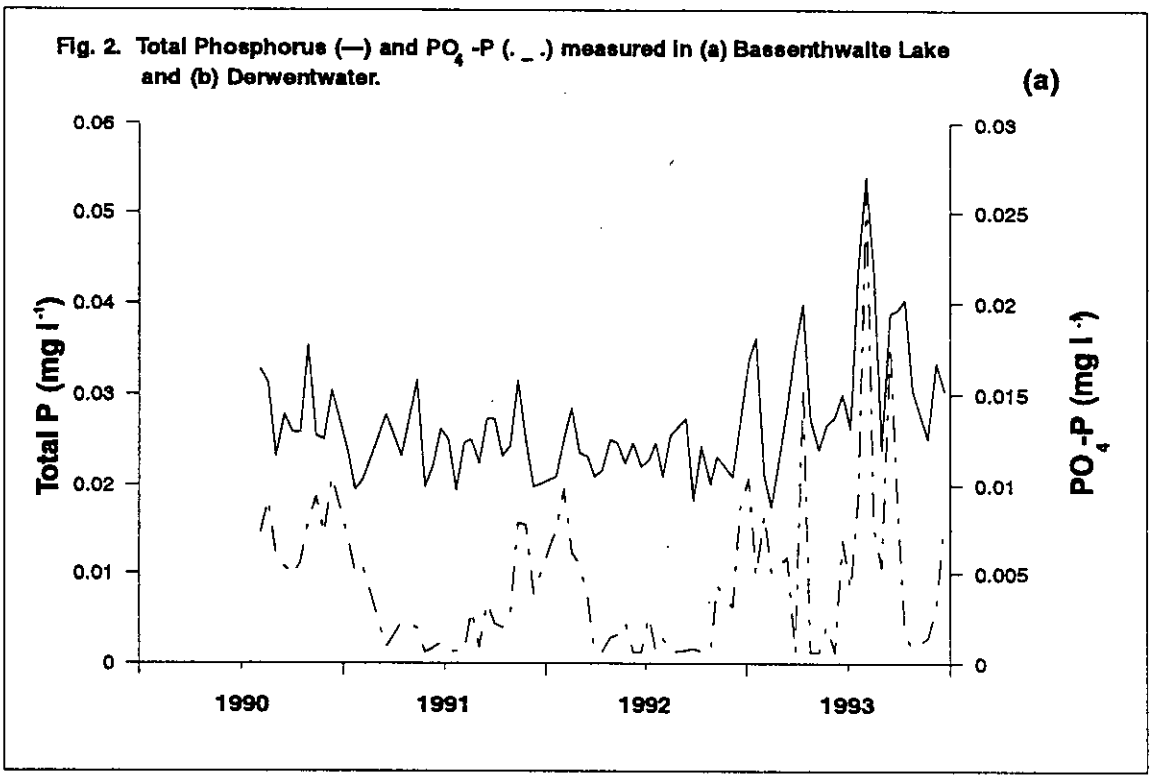


Fig. 2. Total Phosphorus (—) and PO_4 -P (. _ .) measured in (a) Bassenthwaite Lake and (b) Derwentwater.



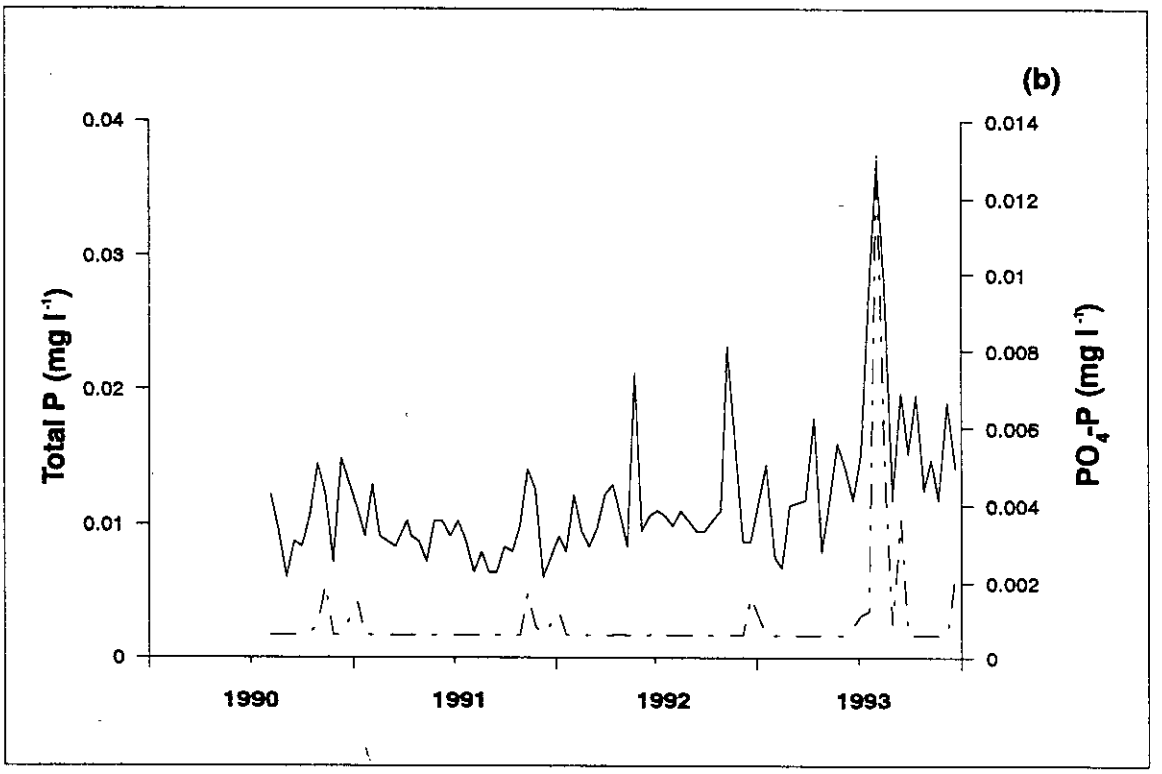
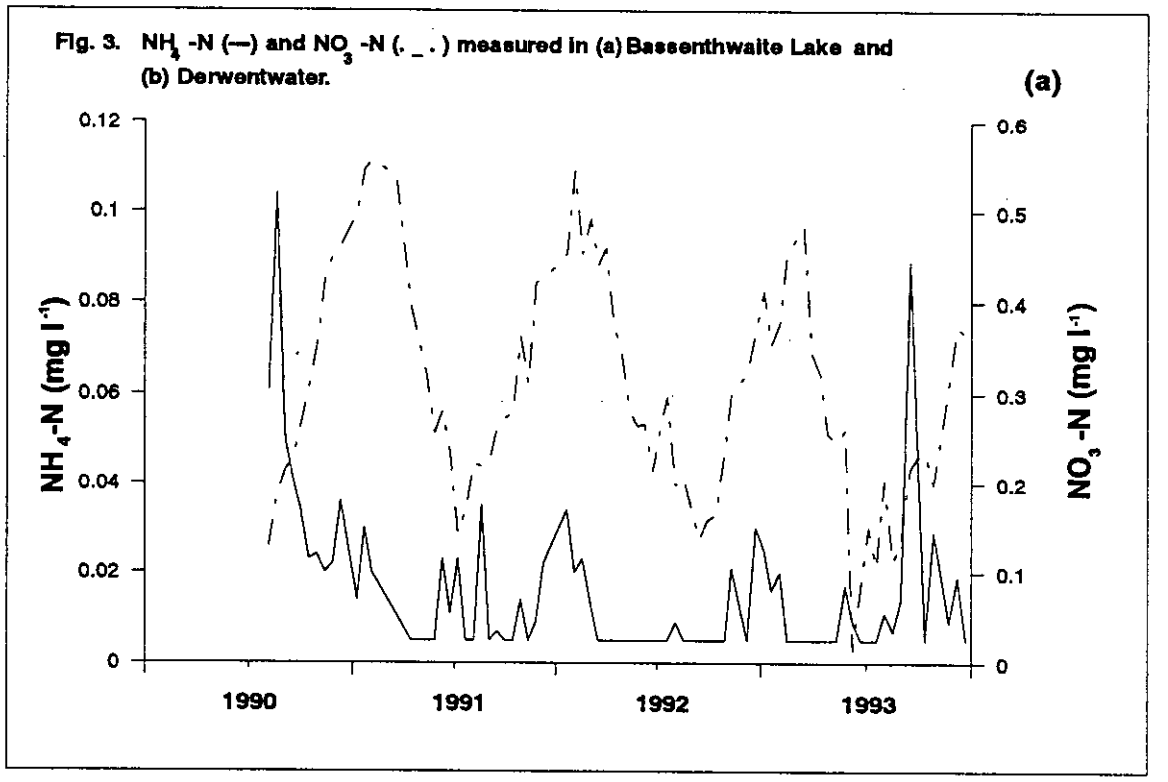


Fig. 3. NH_4 -N (—) and NO_3 -N (. _ .) measured in (a) Bassenthwaite Lake and (b) Derwentwater.



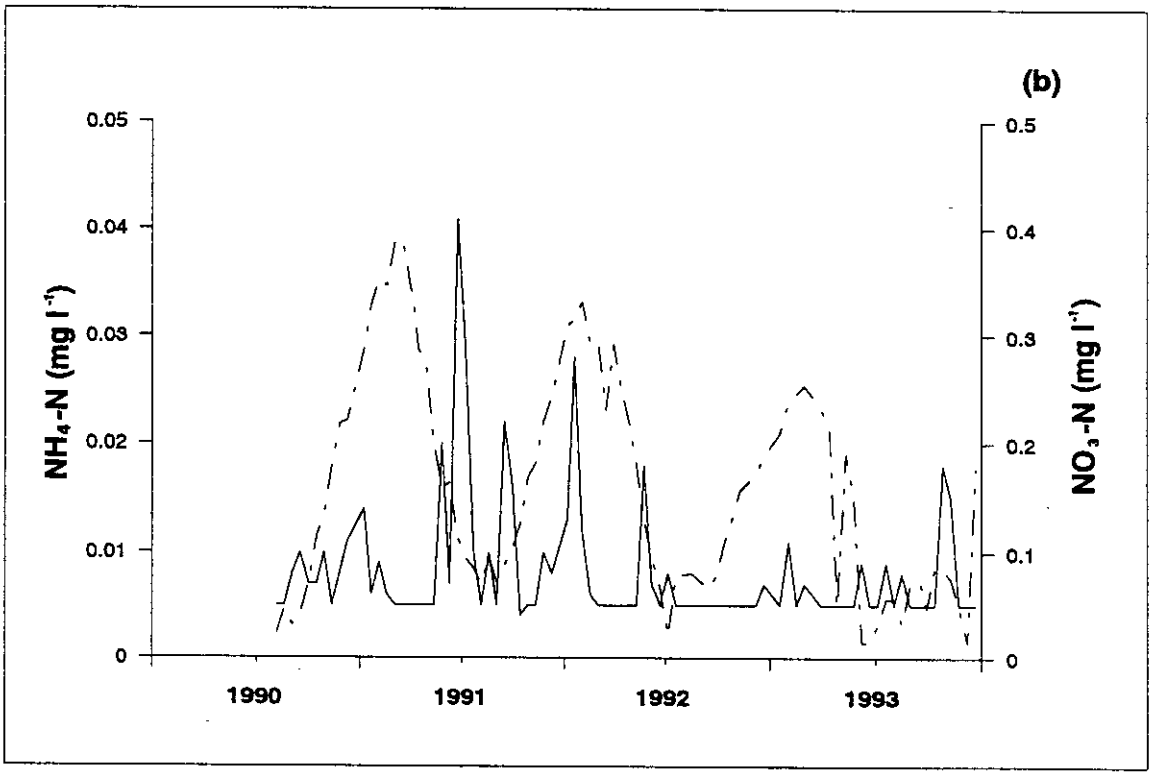
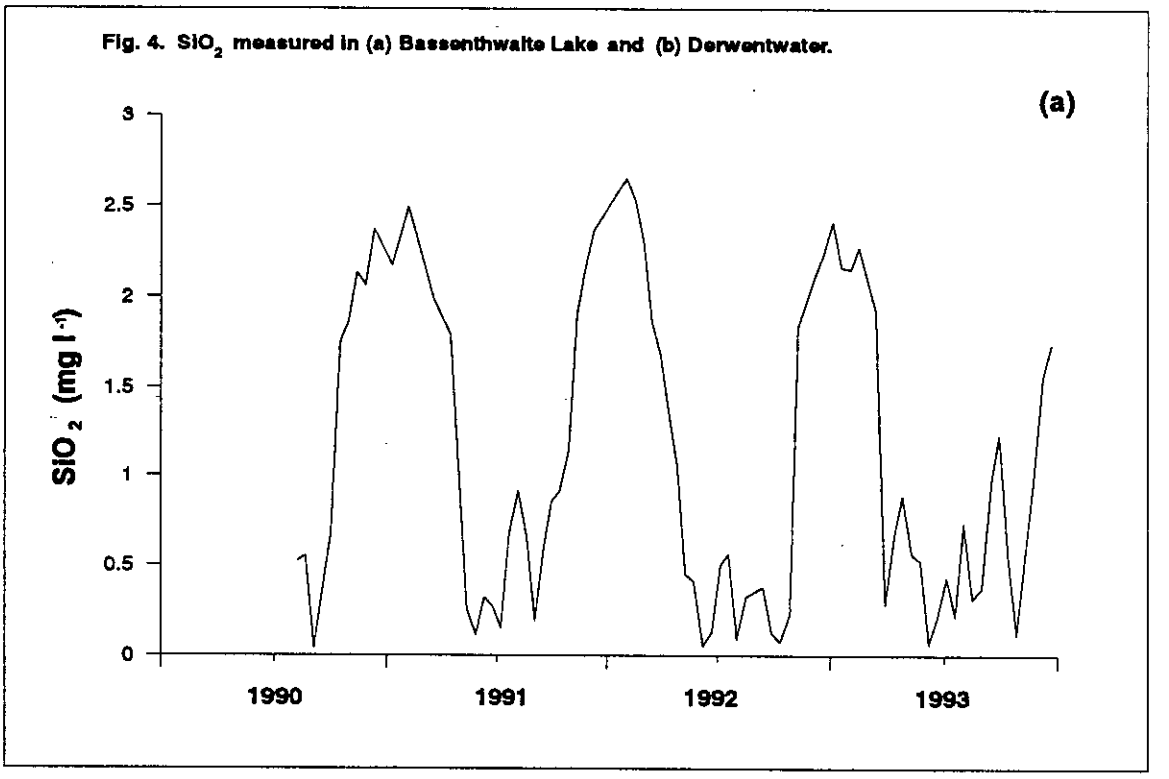


Fig. 4. SiO_2 measured in (a) Bassenthwaite Lake and (b) Derwentwater.



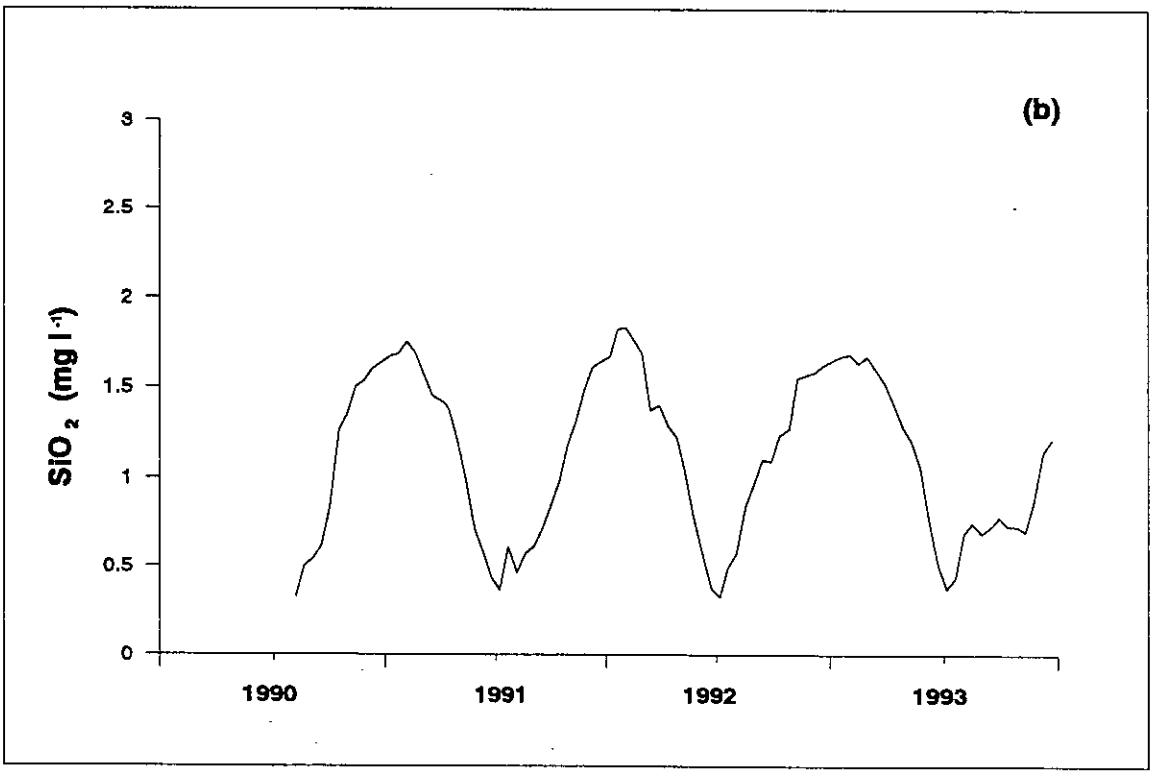
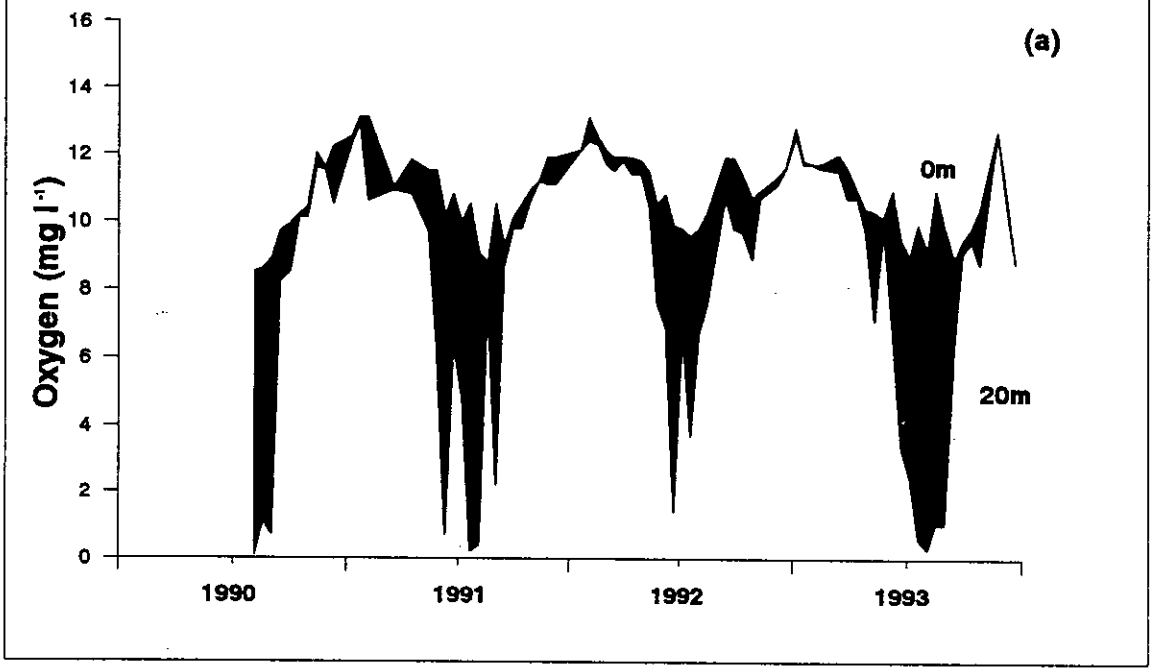
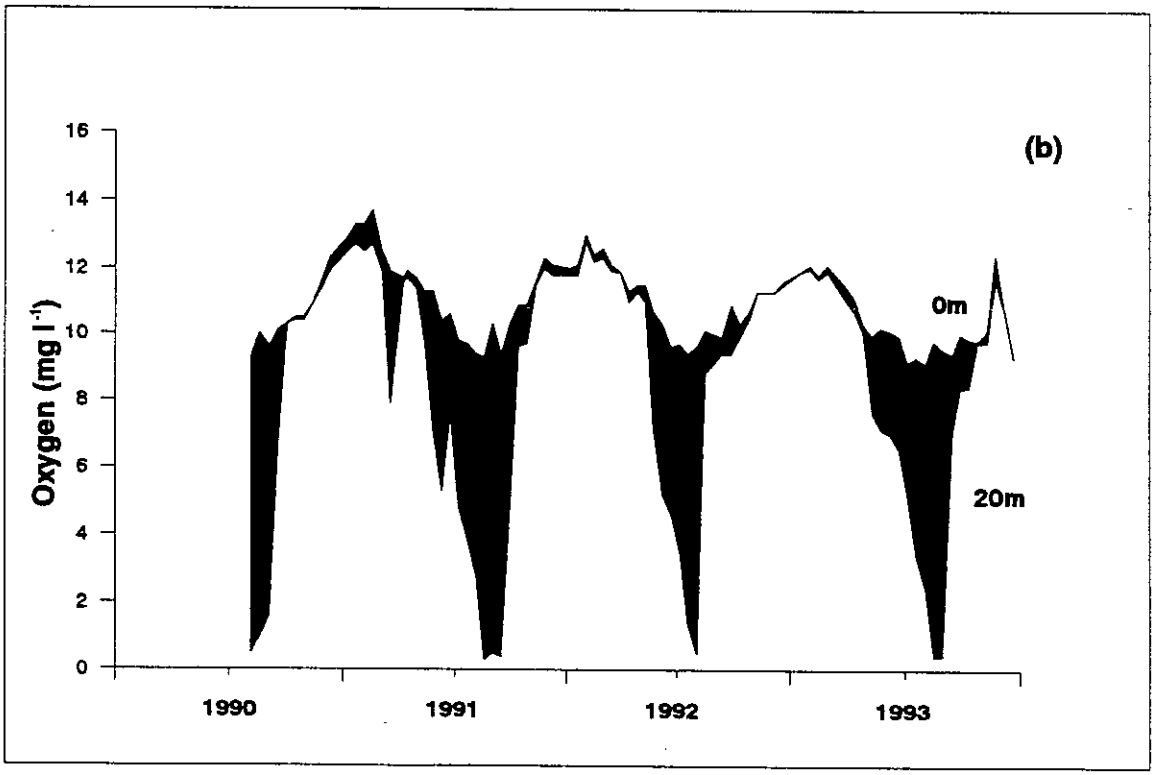


Fig. 5. Oxygen concentrations measured at 0m and 20m in (a) Bassenthwaite Lake and (b) Derwentwater.





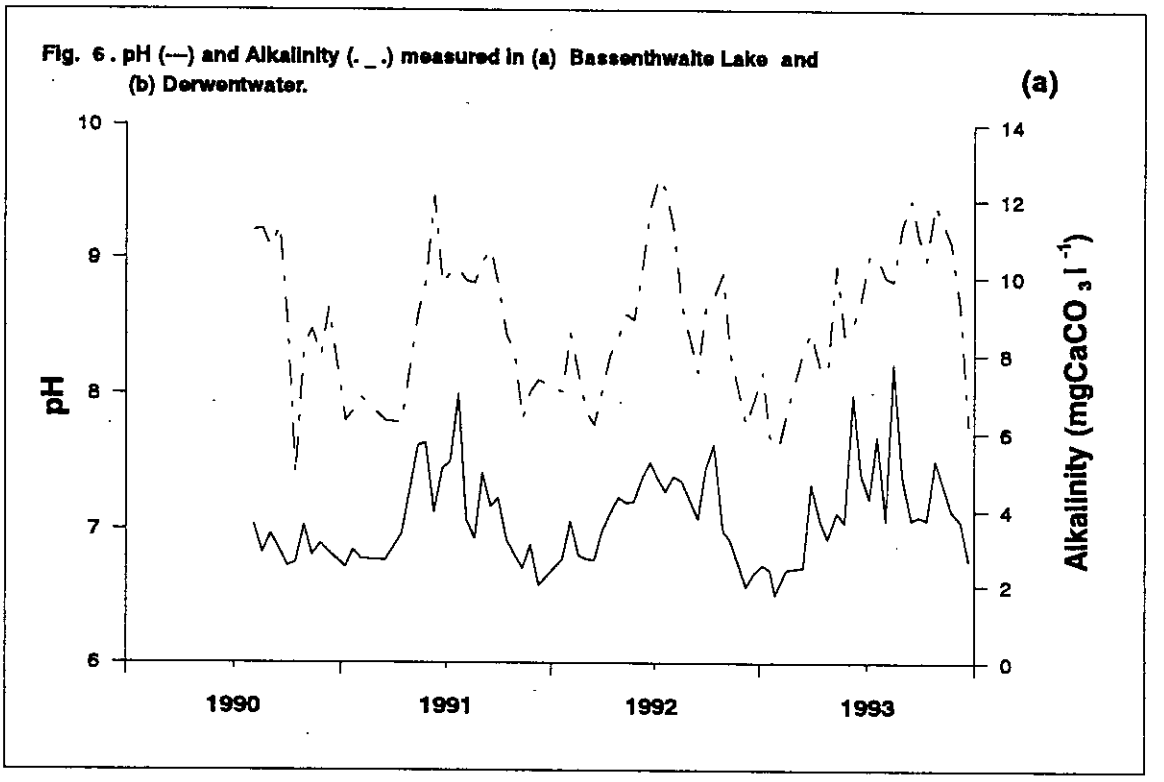


Fig. 6. pH (—) and Alkalinity (. _ .) measured in (a) Bassenthwaite Lake and (b) Derwentwater.

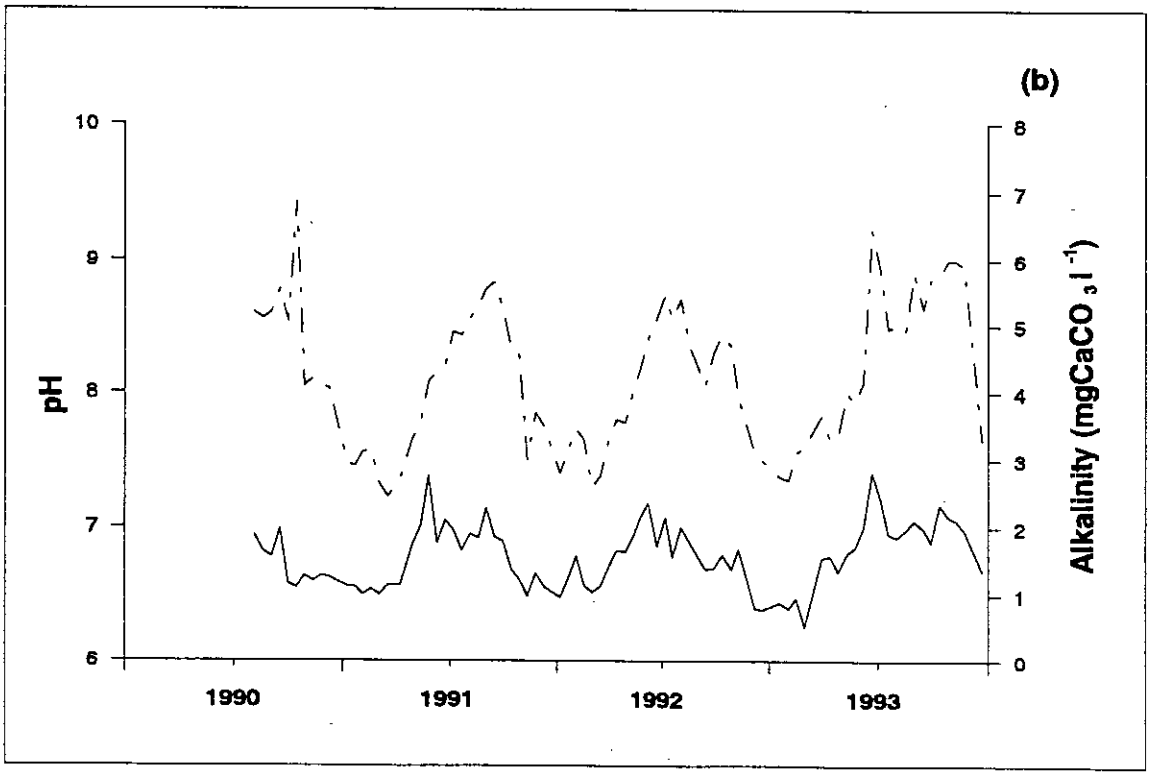
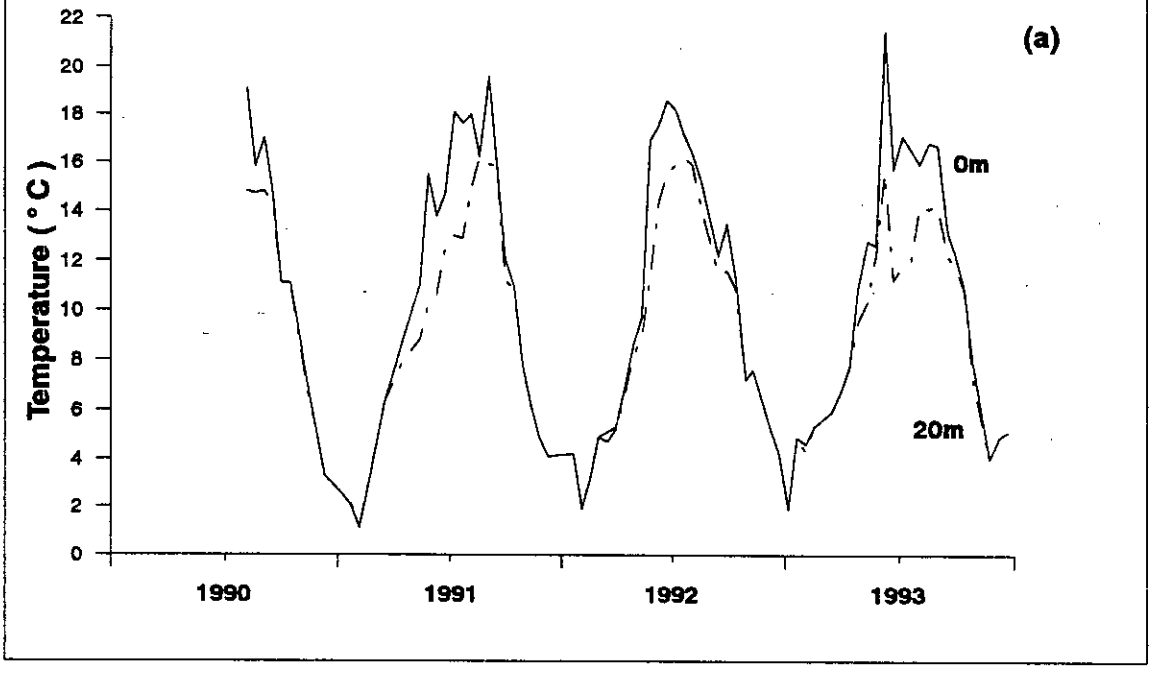
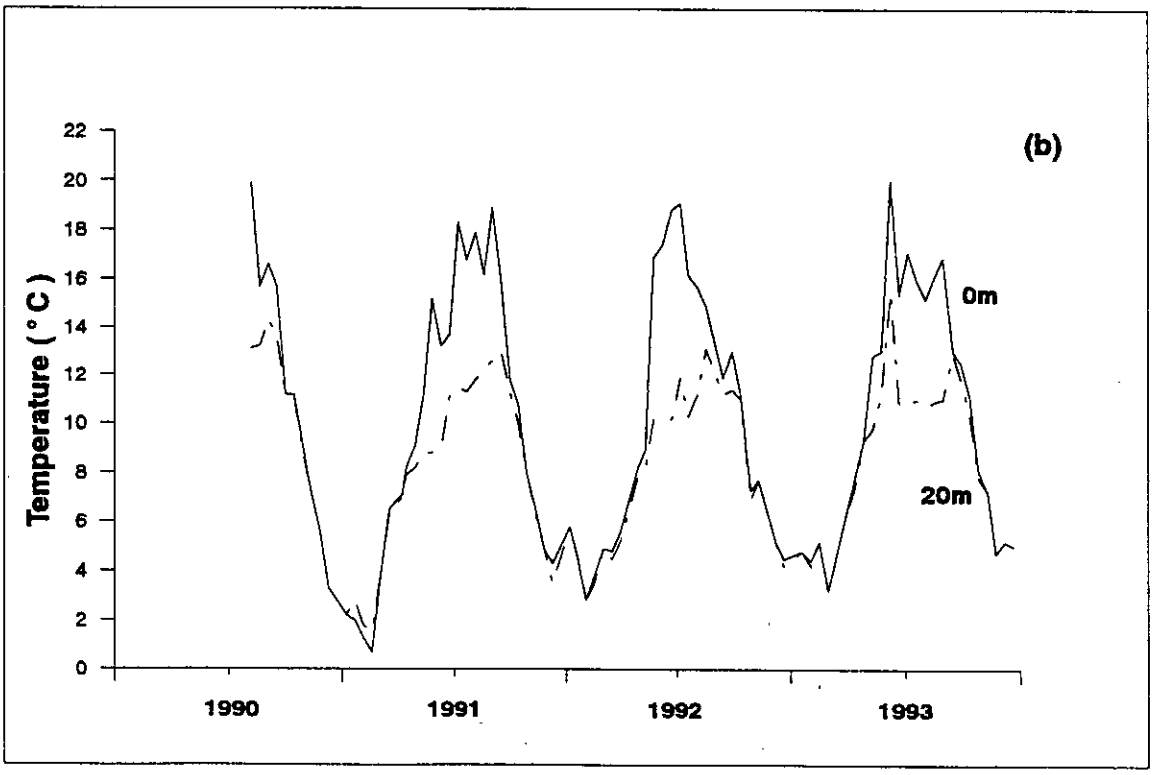


Fig. 7. Water Temperature measured at 0m and 20m in (a) Bassenthwaite Lake and (b) Derwentwater.



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