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ISSN 1366-7300

ENVIRONMENTAL CHANGE RESEARCH CENTRE

University College London

RESEARCH REPORT

No. 22

A study of recent environmental change within selected standing waters proposed as special areas of conservation in Wales

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A Report to the Countryside Council for Wales by ENSIS Ltd.

Contract No: FC 73-01-131

March 1996

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WC1H 0AP

Countryside Council for Wales Report Distribution

Report Number: 130
Publication Date: March 1996
Contract Number: FC 73-01-131
Nominated Officer: C. Duigan
Report Title: A study of recent environmental change within selected waters proposed as Special Areas of Conservation (SAC) in Wales - Llyn Idwal, Llyn Cwellyn, Llyn yr Wyth Eidion, Llyn Safadden (Llangorse Lake).
Author: Ed. H. Bennion
Restrictions: None

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Executive Summary

1. This is the final report to the Countryside Council for Wales under contract FC 73-01-131: A study of recent environmental change within selected waters proposed as Special Areas of Conservation (SAC) in Wales - Llyn Idwal, Llyn Cwellyn, Llyn yr Wyth Eidion, Llyn Safadden (Llangorse Lake).

2. The report employs palaeolimnological techniques to evaluate the ecological implications and extent of acidification and/or eutrophication for four Welsh lakes: Llyn Idwal, Llyn Cwellyn, Llyn yr Wyth Eidion, Llyn Safadden (Llangorse Lake).

3. The report describes the lithostratigraphies, and presents results of Spheroidal Carbonaceous Particle analysis, and diatom analysis of three levels from a sediment core from each site.

4. The appropriate diatom-based transfer functions are applied to the core data to generate quantitative reconstructions of pH and/or TP based for each site, following taxonomic harmonization between the training set and core species data. The pH reconstructions are calculated using the Surface Water Acidification Programme (SWAP) calibration set of 167 lakes from the UK and Scandinavia (Stevenson *et al.*, 1991), and the TP reconstructions are calculated using a Northwest European calibration set of 152 lakes (Bennion *et al.*, in press).

5. The report interprets the findings with reference to the documented history of the four sites.

6. The study shows that:

- i) Llyn Cwellyn has acidified by *c.*0.7 pH units since the late 1800s but there is no evidence of change in the trophic status of the site;
- ii) Llyn Idwal has not experienced any overall change in lake-water chemistry between the mid 1800s and 1995;
- iii) Llyn yr Wyth Eidion has not experienced any enrichment since at least 1980;
- iv) Llangorse Lake has experienced a decline in TP concentrations since 1984, following sewage diversion in 1981.

7. By reconstructing quantitatively the past water chemistry of the lakes, realistic targets can be set for the possible amelioration of acidification and/or eutrophication. The findings of this project will be important in the development of the management plans which the CCW is committed to produce for these Special Areas for Conservation, and as part of the UK Biodiversity Action Plan.

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1 Objectives

Acidification and eutrophication are the major threats to the freshwater conservation resource in Wales. Previous research has shown that the two upland lakes, Llyn Idwal and Llyn Cwellyn, occur in areas susceptible to acid deposition. In particular, Llyn Cwellyn is exposed to the combined acidification effects of atmospheric deposition and extensive areas of coniferous plantation within its catchment. The continued survival of its native Arctic charr population is a particular cause for concern. Based on the findings of previous research, it is considered likely that Llyn Cwellyn has acidified, with associated chemical and biological effects. The possibility of a degree of nutrient enrichment at Llyn Cwellyn is also a consideration. Some acidification is believed to have occurred at Llyn Idwal, with ecological changes occurring in sensitive communities, but an acid neutralising capacity above zero has been maintained. It is therefore evident that further palaeolimnological research is required to carry out diatom-based pH and total phosphorus (TP) reconstructions at these two important conservation sites to assess the extent of acidification and nutrient enrichment.

In the lowlands, the occurrence of artificial enrichment at Llangorse Lake is undisputed by a large number of independent researchers and a number of strategies have been implemented to tackle the problem. Relatively little is known about the active marl-producing system of Llyn yr Wyth Eidion on Anglesey. The site is located within the Cors Erddreiniog NNR and this type of natural freshwater habitat is extremely rare in Wales. The objective of this study was to perform diatom-TP reconstructions to provide quantitative estimates of the degree of nutrient enrichment which has occurred at these two sites.

The aim was to use these palaeolimnological techniques to evaluate the ecological implications of the acidification and eutrophication scenarios. This study aims to establish the onset and extent of these processes with reference to the documented history of the four sites. In addition, by reconstructing quantitatively their past water chemistry, realistic targets can be set for the possible amelioration of these problems. The findings of this project will be important in the development of the management plans which the CCW is committed to produce for these Special Areas for Conservation, and as part of the UK Biodiversity Action Plan.

2 Methods

2.1 Coring and Lithostratigraphic Analyses

Long cores were taken from the deepest point in all four sites using either a Mackereth or a Glew corer, operated from an inflatable boat. The cores were extruded in the laboratory and sliced at 0.5 cm vertical intervals to a depth of 20 cm and subsequently at 1 cm intervals to the core base.

The percentage dry weight (%dw) for each sample was calculated by weighing approximately 1g of wet sediment in a pre-weighed crucible, from each pre-homogenised sediment layer, drying the sediment at 105°C for at least 16 hours, then reweighing the crucible. Approximate organic matter content was then determined (as a percentage loss on ignition %loi) by placing the crucible containing the dried sediment in a muffle furnace at 550°C for two hours and then reweighing.

2.2 Spheroidal Carbonaceous Particle (SCPs) Analyses

Analysis for Spheroidal Carbonaceous Particles (SCPs) followed the procedure described in Rose (1994) involving the removal of unwanted sediment fractions by selective chemical attack. HNO3, HF and HCl were used to remove the organic matter, mineral and biogenic silicates and carbonate minerals respectively. A sub-sample of the resulting concentrate was evaporated onto a coverslip, mounted onto a microscope slide and counted at 400 x magnification using a light microscope.

Primarily SCP profiles in lake sediments in the United Kingdom show three main characteristics that enable approximate dates to be allocated to previously undated cores: the start of the record (linked to the start of high temperature fossil fuel combustion), the rapid increase in concentration (following increases in energy demand after the Second World War), and the peak in SCP concentration (changes in the trends in energy production). The approximate dates assignable to these characteristics are the 1850s, the 1950s and 1978 +/- 2 respectively.

For a full account of the historical arguments and the techniques used for dating using SCP profiles refer to Rose *et al.* (1995).

2.3 Diatom-based Transfer Functions

In the absence of long-term historical water chemistry data, the sediment accumulated in lakes can provide a record of past events and past chemical conditions (e.g. Smol, 1992). Diatoms (unicellular, siliceous algae) are particularly good indicators of past limnological conditions, for example lake pH, nutrient concentrations and salinity. In recent years, quantitative approaches have been developed, of which the techniques of weighted averaging (WA) regression and calibration, developed by ter Braak (e.g. ter Braak & van Dam, 1989), are currently the most statistically robust and ecologically appropriate. WA has become a standard technique in palaeolimnology for reconstructing past environmental variables. The methodology and the advantages of WA over other methods of regression and calibration are well documented (e.g. ter Braak & van Dam, 1989; ter Braak & Juggins, 1993; Line *et al.*, 1994).

Using the technique of WA, a predictive equation known as a transfer function can be generated that enables the inference of a selected environmental variable from fossil diatom assemblages, based on the relationship between modern surface-sediment diatom assemblages and contemporary environmental data for a large training set of lakes. This approach has been successfully employed in recent years to quantitatively infer lake pH (e.g. Birks *et al.*, 1990) and lake total phosphorus (TP) concentrations (e.g. Anderson *et al.*, 1993; Bennion, 1994; Bennion *et al.*, in press), whereby modern diatom pH and TP optima are calculated for each taxon based on their distribution in the training set, and then past pH and TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. These models are able to provide estimates of baseline pH and TP concentrations in lakes, and coupled with dating of sediment cores (radiometric or SCPs), enable the timing, rates and possible causes of acidification and enrichment to be assessed for a particular site. This information can be used to design lake classification systems and can be incorporated into lake management and conservation programmes.

In this study, three levels from each core were prepared and analysed for diatoms using standard techniques (Battarbee, 1986). At least 300 valves were counted from each sample using a Leitz research quality microscope with a 100 x oil immersion objective and phase contrast. The data were expressed as percentage relative abundance.

The appropriate transfer functions were applied to the core data to generate quantitative reconstructions of pH and/or TP for each site, following taxonomic harmonization between the training set and core species data. The pH reconstructions were calculated using the Surface Water Acidification Programme (SWAP) calibration set of 167 lakes from the UK and Scandinavia (Stevenson *et al.*, 1991), and the TP reconstructions were calculated using a Northwest European calibration set of 152 lakes (Bennion *et al.*, in press). The pH results presented in this report are based on simple WA with classical deshrinking, and the TP results are based on simple WA with inverse deshrinking on log-transformed annual mean TP data. The reconstructions were implemented using CALIBRATE (Juggins & ter Braak, 1993).

3 Llyn Cwellyn (SH 560 550)

3.1 Lithostratigraphy and Dating

A 27 cm core was taken from Llyn Cwellyn (CWEL2) on 5-7-95 using a Glew gravity corer. The core was obtained from 36 m of water, the deepest point of the basin.

The %loi diagram (Figure 1) indicates a fairly constant sediment accumulation rate throughout the core, except in the top 3.5 cm where there is a higher percentage organic content - evidence of an increasing accumulation rate over this recent period.

The SCP profile (Figure 2) clearly shows that the end of the particle record lies between 24.5 and 27.5 cm. The actual end is likely to be closer to the lower limit of this range, as the record does not appear to be truncated. Using this to calculate the accumulation rate for the last 140 years, an approximate rate of 2 mm yr^{-1} was estimated. The SCP peak was identified at 4.25 cm to 4.75 cm. Taking this feature as 1978 +/- 2 years, the average accumulation rate for the last 17 years (up to 1995) was approximated at 2.5 and 2.8 mm yr^{-1}.

The most difficult dating point to identify was the rapid increase in SCP concentration. Initially it might appear that 13.5 cm marks this characteristic, however this would give an accumulation rate of 3.4 mm yr^{-1} for the 1950's to the present day. The SCP peak would then be expected to lie closer to 5.5 cm (which is plausible) but would also shift the expected start of the record to around 47 cm. This hypothesis is inconsistent with the observed SCP record, and the %loi profile provides little support for such a marked change in accumulation rate, required to explain the shortness of the profile. The rapid increase in SCP concentration is therefore most likely positioned at between 8.5 and 9.5 cm, giving an average accumulation rate of between 2.1 and 2.4 mm yr^{-1} from the 1950s until the present, being entirely consistent with the other dating points.

In summary:-

Depth	Approx. Date	Approx. Acc. Rate
4.5 cm	1978+/-2	2.6 mm yr^{-1}
9 cm	1950s	2.2 mm yr^{-1}
27 cm	1850s	1.9 mm yr^{-1}

Figure 1 **Lithostratigraphic data for Llyn Cwellyn**

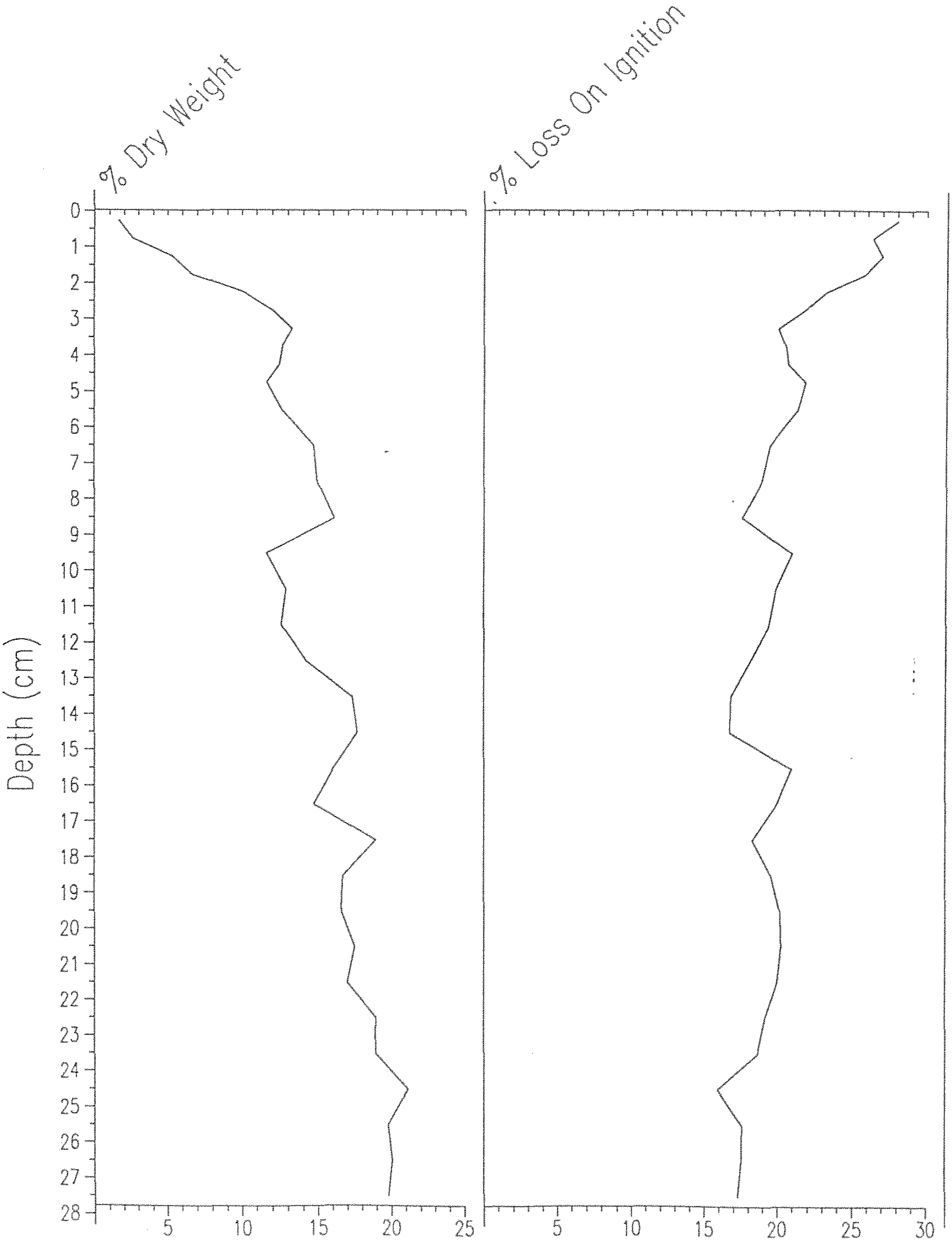
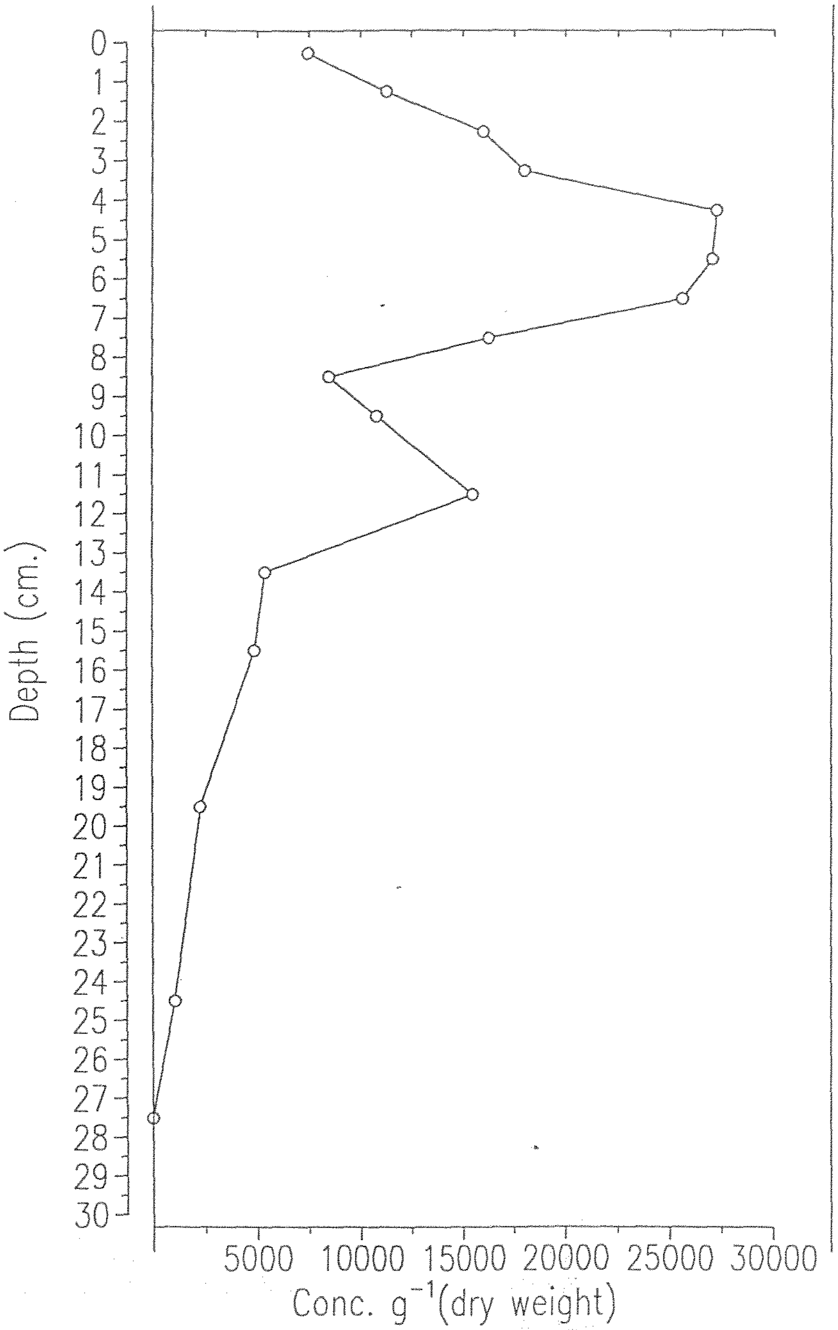


Figure 2 **Spherical Carbonaceous Particle profile for Llyn Cwellyn**



3.2 Diatom Stratigraphy

The three stratigraphic levels selected for diatom analysis from the Llyn Cwellyn core (CWEL2) were 0-0.5 cm, 9-10 cm and 24-25 cm. These levels were selected to cover the period since the late 1800s, the 24-25 cm level representing approximately 1860-1870 (see SCP chronology). A summary diatom diagram is shown in Figure 3.

The diatom assemblage at 24-25 cm is dominated by planktonic *Cyclotella* taxa, particularly *C. comensis* and *C.* [*krammeri/rossii*]. The latter species is part of the group of taxa formerly assigned to *C. kuetzingiana* Thwaites (Håkansson, 1990). Other common *Cyclotella* taxa in the assemblage include *C. krammeri*, *C. glomerata* and *C.* [sp. 1]. Although the assemblage is dominated by these planktonic taxa, high abundances of the periphytic *Achnanthes minutissima* also occur. Other periphytic taxa occur in lower abundances, but include *Tabellaria flocculosa* and *Brachysira vitrea*. The assemblage is indicative of nutrient-poor, circumneutral waters.

The planktonic *Cyclotella* taxa are also common in the 9-10 cm level (1950s), although in reduced abundances compared to the lower level. The assemblage here is dominated by two species; *Achnanthes minutissima* and *Cyclotella* [*krammeri/rossii*]. Other common taxa include *Tabellaria flocculosa*, *Brachysira vitrea* and *Fragilaria virescens* var. *exigua*. In comparison to the 24-25 cm level, abundances of *Cyclotella comensis* and *C. krammeri* are low, and *C. glomerata* and *C.* [sp. 1] are absent.

The assemblage of the 0-0.5 cm level (1995) is dominated by periphytic taxa, particularly the circumneutral *Achnanthes minutissima* and the acidophilous *Tabellaria flocculosa*. Other acidophilous taxa are common, including *Fragilaria virescens* var. *exigua* and *Peronia fibula*. *Eunotia exigua* is also present, a taxon indicative of more acidobiontic conditions. *Cyclotella* taxa are almost completely absent, with only a few valves of *C.* [*krammeri/rossii*] being recorded. The assemblage is indicative of nutrient-poor, slightly acid waters

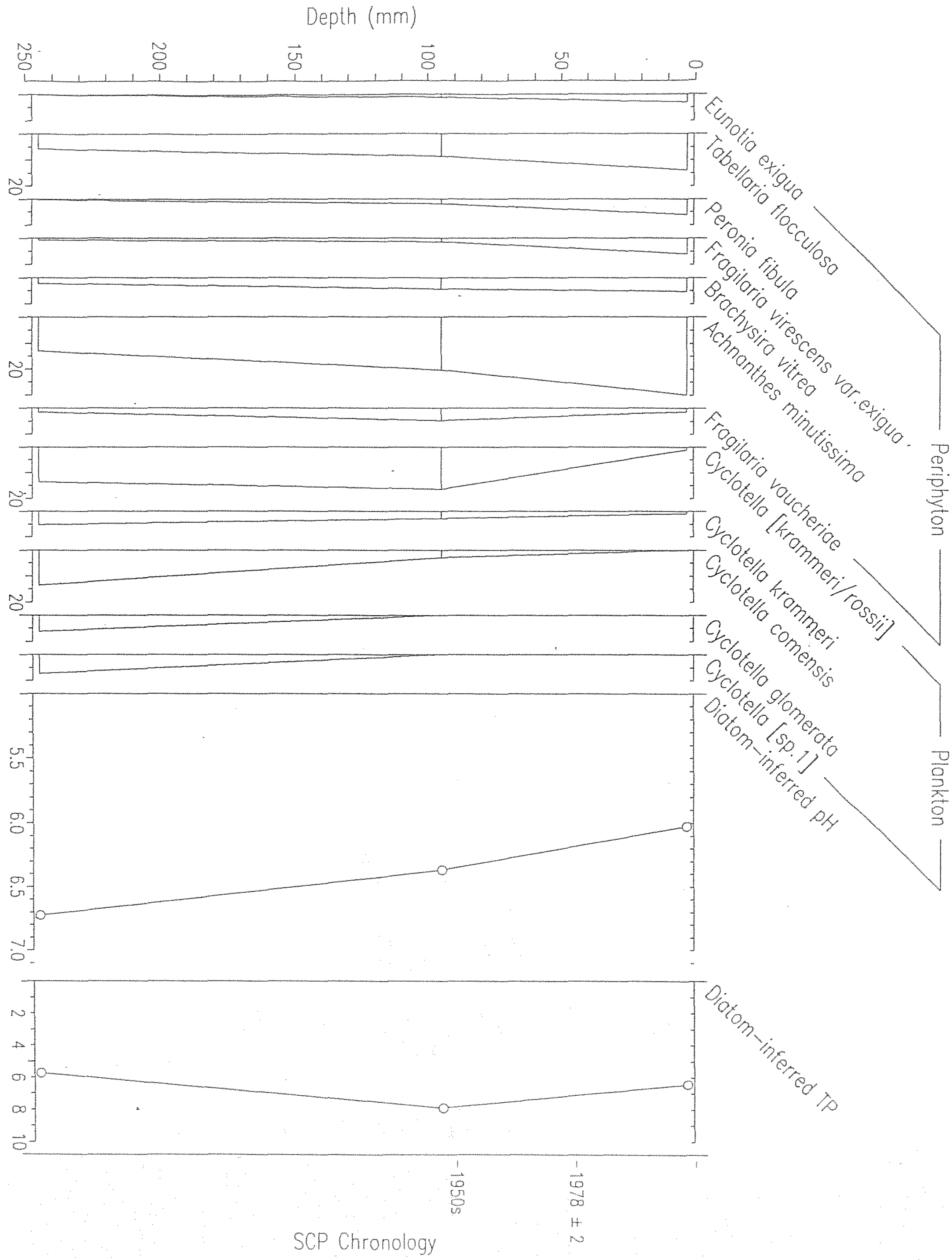
3.3 pH Reconstruction

The diatom-inferred pH values (DI-pH) are indicated in Figure 3. They show a pattern of decreasing pH through the period represented by the core. The DI-pH at 24-25 cm (*c.*1860-1870) is 6.73, DI-pH at 9-10 cm (1950s) is 6.37, and at 0-0.5 cm (1995) is 6.03. This indicates an overall decline in pH of 0.7 units since the late 1800s. These trends in diatom-inferred pH reflect the shift in diatom assemblages from dominance by circumneutral, planktonic *Cyclotella* species at the base of the core, to the more acidophilous periphytic assemblage in the surface sample. The DI-pH value of the surface sample (6.03) somewhat under-estimates the mean measured lake-water pH of 6.35 (Allott *et al.*, 1994).

3.4 TP Reconstruction

The diatom-inferred TP values (DI-TP) are shown in Figure 3. These are uniform at 6-8 μg TP l^{-1}, indicating stable, oligotrophic conditions throughout the period represented by the core. The DI-TP for the surface sample (6.4 μg TP l^{-1}) corresponds closely to the mean annual lake-water TP concentrations of 7.1 μg TP l^{-1} (Allott *et al.*, 1994).

Figure 3 Summary diatom diagram and pH and TP reconstructions for Llyn Cwellyn



3.5 Discussion

The SCP chronology indicates that the core contains a continuous stratigraphic record covering the period since *c.*1850. The three diatom assemblages analysed indicate a clear floristic change over this period from dominance by planktonic *Cyclotella* species in the late 1800s, to an assemblage containing reduced abundances of *Cyclotella* species in the 1950s, to dominance by circumneutral and acidophilous, periphytic species in the surface sediments. These changes are consistent with acidification of Llyn Cwellyn, as reflected in the diatom-inferred pH values. A decline or disappearance of oligotrophic *Cyclotella* species is often the first floristic response to acidification in low alkalinity lakes (e.g. Battarbee, 1984). Similar declines in planktonic *Cyclotella* floras have also been observed due to changes in water turbidity associated with increased sediment inputs into lake systems (e.g. Stevenson *et al.,* 1990). However this latter mechanism is unlikely to account for the changes in Llyn Cwellyn as the lithostratigraphic record shows relatively uniform sediment composition, indicating little change in sediment sources. The increased abundance of acidophilous and acidobiontic periphytic diatoms (e.g. *Peronia fibula*, *Eunotia exigua*) in the surface sample is also consistent with a shift to more acid conditions.

The data suggest that Llyn Cwellyn has acidified by *c.*0.7 pH units since the late 1800s. With the limited data available it is difficult to be more precise about the timing or rate of acidification. The period over which the lake has acidified correlates with the contamination of the sediments by SCPs (see 3.1). This coincidence between atmospheric contamination and diatom-inferred pH change suggests that acid deposition is the cause of the acidification. This conclusion reflects the findings of other palaeolimnological studies of acid-sensitive sites in Wales (e.g. Battarbee *et al.,* 1988, Fritz *et al.,* 1990) which indicate lake acidification dating from the mid to late 1800s.

Llyn Cwellyn currently supports biological communities typical of a deep, low-alkalinity, nutrient-poor lake (Allott *et al.,* 1994). Additionally the Llyn supports a population of Arctic charr, and was designated an SSSI largely on the conservation interest of this species. An acidification of *c.*0.7 pH units is likely to have impacted biological communities, particularly those biological groups most sensitive to changes in lake-water pH such as algae, zooplankton, and benthic macroinvertebrates (see Muniz, 1990). It is less likely that the inferred acidification has had significant impacts on salmonid fish populations, as current lake-water pH remains above 6, mean alkalinity levels are well above zero (29 $\mu eq\ l^{-1}$) and levels of labile (toxic) aluminium are low (Allott *et al.,* 1994). However, with the exception of the diatom record there is limited historical biological data for Llyn Cwellyn, and without more detailed study the biological effects of acidification at Llyn Cwellyn are largely unknown.

Two further issues are important in assessing the impact of acidification on the conservation status of the site;

(i) the influence of catchment afforestation;

(ii) the extent to which the acidification trend is continuing.

A significant area of the south-eastern shores of the Llyn were afforested with conifers during the mid 1940s. In areas of high acid deposition, afforestation can exacerbate problems of acidification due to increased 'scavenging' of acid deposition (e.g. Kreiser *et al.,* 1990). It is therefore possible that the afforestation has contributed to the inferred acidification of Llyn Cwellyn. The extent of this impact could be evaluated by more detailed analysis of the diatom record. This would allow the response of the lake chemistry to the past afforestation to be evaluated, permitting assessment of the likely impacts of future catchment forestry practice (e.g. impacts of felling and/or replanting).

Although the diatom data indicate that since the late 1800s Llyn Cwellyn has acidified, the data are not detailed enough to reveal if this trend is continuing. In the UK emissions of sulphur dioxide have declined by *c.*35% since 1970 (UKRGAR, 1990) and this has led to a reduction in acid deposition. In several regions, acidified surface waters have responded to this change in deposition inputs, and reversals of the acidification trend have been observed (e.g. Allott *et al.,* 1992). However, such response is highly variable between both sites and regions (Patrick *et al.,* 1995). At Llyn Cwellyn it is possible that the trend to more acid conditions has ceased, or even been reversed. Current loadings of acid deposition in the region, however, still exceed the critical load for Llyn Cwellyn (Allott *et al.,* 1994), implying that unless loadings are reduced further the site will continue to acidify. Recent (post-1970) trends in lake-water acidity could be evaluated by more detailed diatom analysis of the recent sediments (see Allott *et al.,* 1992).

Although the diatom data indicate a trend of acidification, there is no evidence of change in the trophic status of the site. Diatom-inferred TP concentrations indicate that lake-water TP has remained between 6-8 µg TP l^{-1} since the late 1800s, suggesting stable, oligotrophic conditions.

4 Llyn Idwal (SH 646 595)

4.1 Lithostratigraphy and Dating

A 28 cm core was taken from Llyn Idwal (IDWA2) on 4-7-95 using a Glew gravity corer. The core was obtained from a depth of 9 m in the main basin of the lake.

The %loi profile for Llyn Idwal (Figure 4) indicates that there is a considerable increase in the percentage organic content at 7-14 cm, peaking between 11 and 13 cm. The mechanism causing this broad peak in percentage organic content is uncertain and therefore it is unclear as to how this has affected the sediment accumulation rate in the lake.

The SCP peak is clearly observed at 5.5 cm (Figure 5), although it could potentially occur slightly higher at 4.75 cm. However a date of 1978+/-2 years can clearly be assigned to this feature. Consequently, the calculated average accumulation rate from this depth to the surface lies in the range 2.8 to 3.2 mm yr^{-1}. Given the comparatively smooth transition from very low levels of SCPs to the peak in SCP concentration at 5.5 cm, and the changes in %loi between 7-14 cm, it is very difficult to assign a particular date to this part of the core. However we can still be reasonably confident that the 1950s lies between 8 and 12 cm.

The end of the SCP record is quite clearly indicated between 19 and 21 cm. Due to the low concentrations of SCPs observed in the 16.5 and 18.5 cm samples, however, and because of the apparent rapid tailing off of the profile as a whole, there could be a problem with reaching the limits of detection, and the profile potentially extends a few centimetres below the last level in which SCPs are known to be present. However, we can be reasonably certain from the very low concentrations of SCPs that the sediment at around 20 cm dates to the late 1800s.

In summary:-

Approx. Depth	Year	Approx. Acc. Rate
5 cm	1978+/-2	3 mm yr^{-1}
8 - 12 cm	1950s	?
20 cm	late 1800s	?

Figure 4 **Lithostratigraphic data for Llyn Idwal**

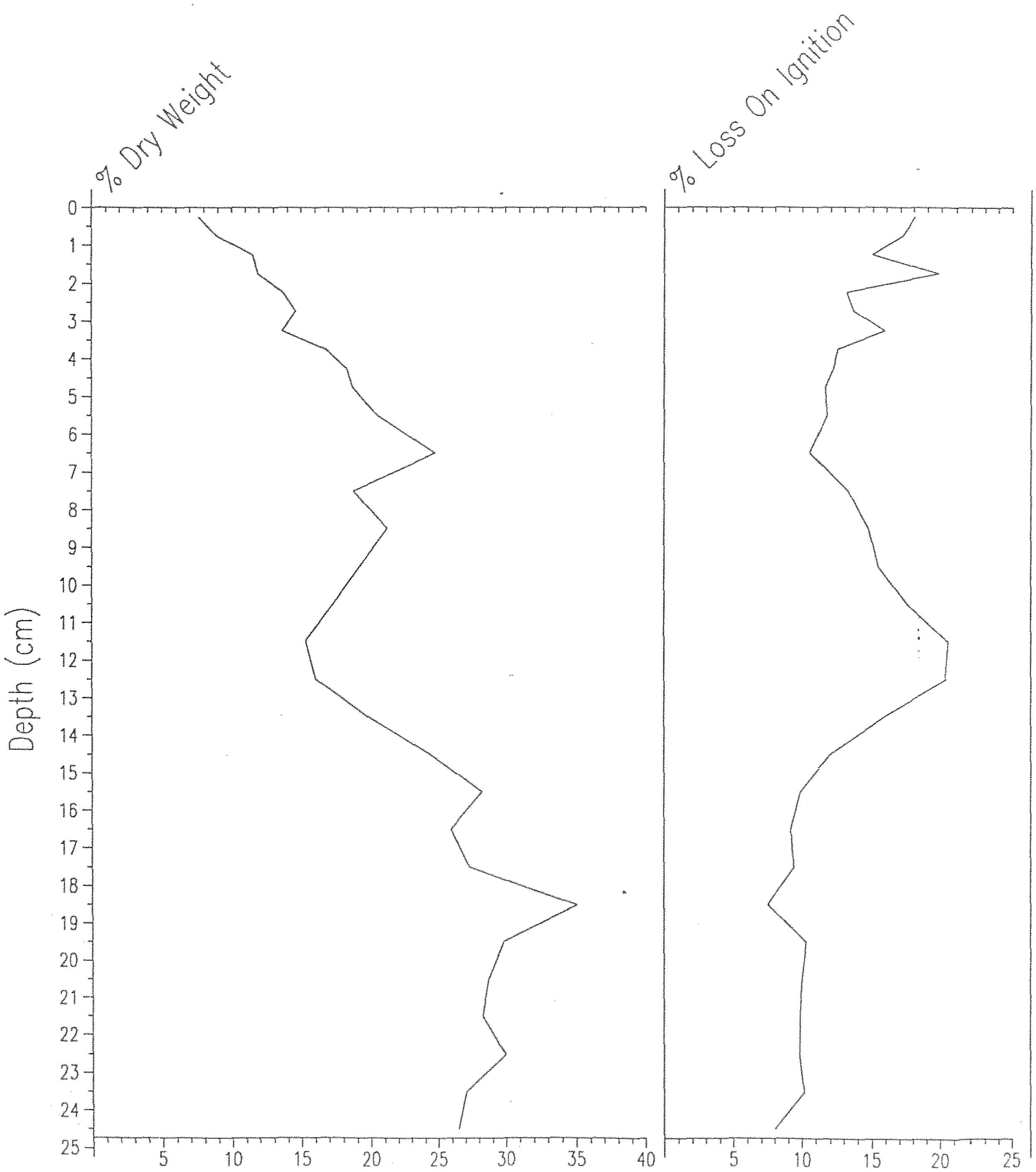
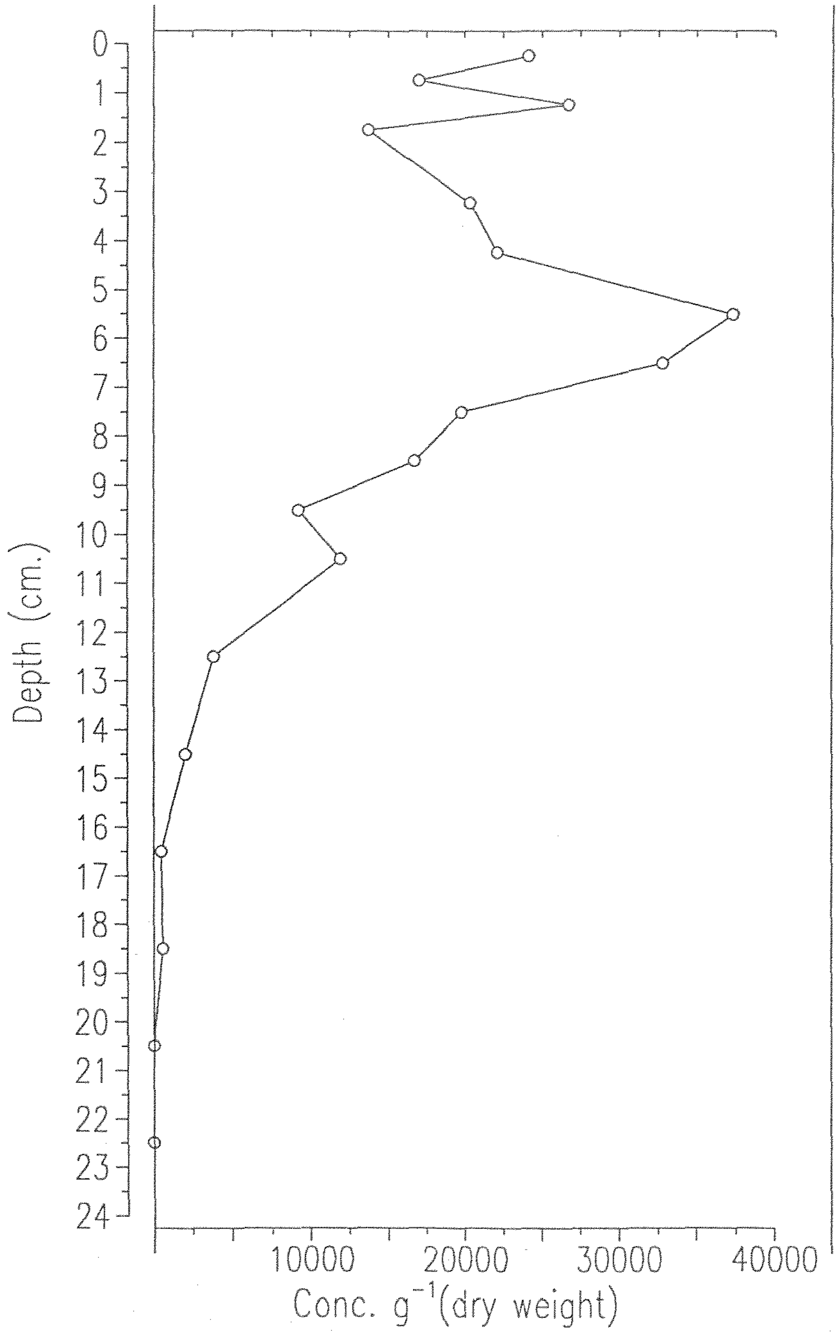


Figure 5 Spherical Carbonaceous Particle profile for Llyn Idwal



4.2 Diatom Stratigraphy

The three stratigraphic levels selected for diatom analysis from the core (IDWA2) were 0-0.5 cm, 9-10 cm and 24-25 cm. These levels were selected to cover the period since the mid-1800s (see SCP chronology). A summary diatom diagram is shown in Figure 6.

The assemblage of the 24-25 cm level (mid 1800s) is dominated by the circumneutral, periphytic *Achnanthes minutissima* (27%), with *Brachysira vitrea* and the planktonic *Cyclotella comensis* also common. Other taxa are only present in abundances <5%, but include *Cymbella minuta* and *Fragilaria virescens* var. *exigua*.

In the 9-10 cm level (1950s), *C. comensis* becomes co-dominant (28%) along with *A. minutissima*. However, there is a reduction in the abundance of *A. minutissima* compared to the lower level. *B. vitrea* is also common. Other taxa present in the assemblage include *Nitzschia perminuta* and *Cymbella microcephela*, although their abundances are low (<4%).

The surface sediment assemblage (1995) is dominated by a single taxon, *A. minutissima*. *B. vitrea*, *N. perminuta* and *F. virescens* var. *exigua* are also common. *C. comensis* is absent.

Comparison of the assemblages indicates a high degree of general similarity, with most species present in the core showing stable abundances. The only major floristic variation is the fluctuation in the abundance of the planktonic *C. comensis*. All three of the assemblages analysed are indicative of nutrient-poor, circumneutral conditions.

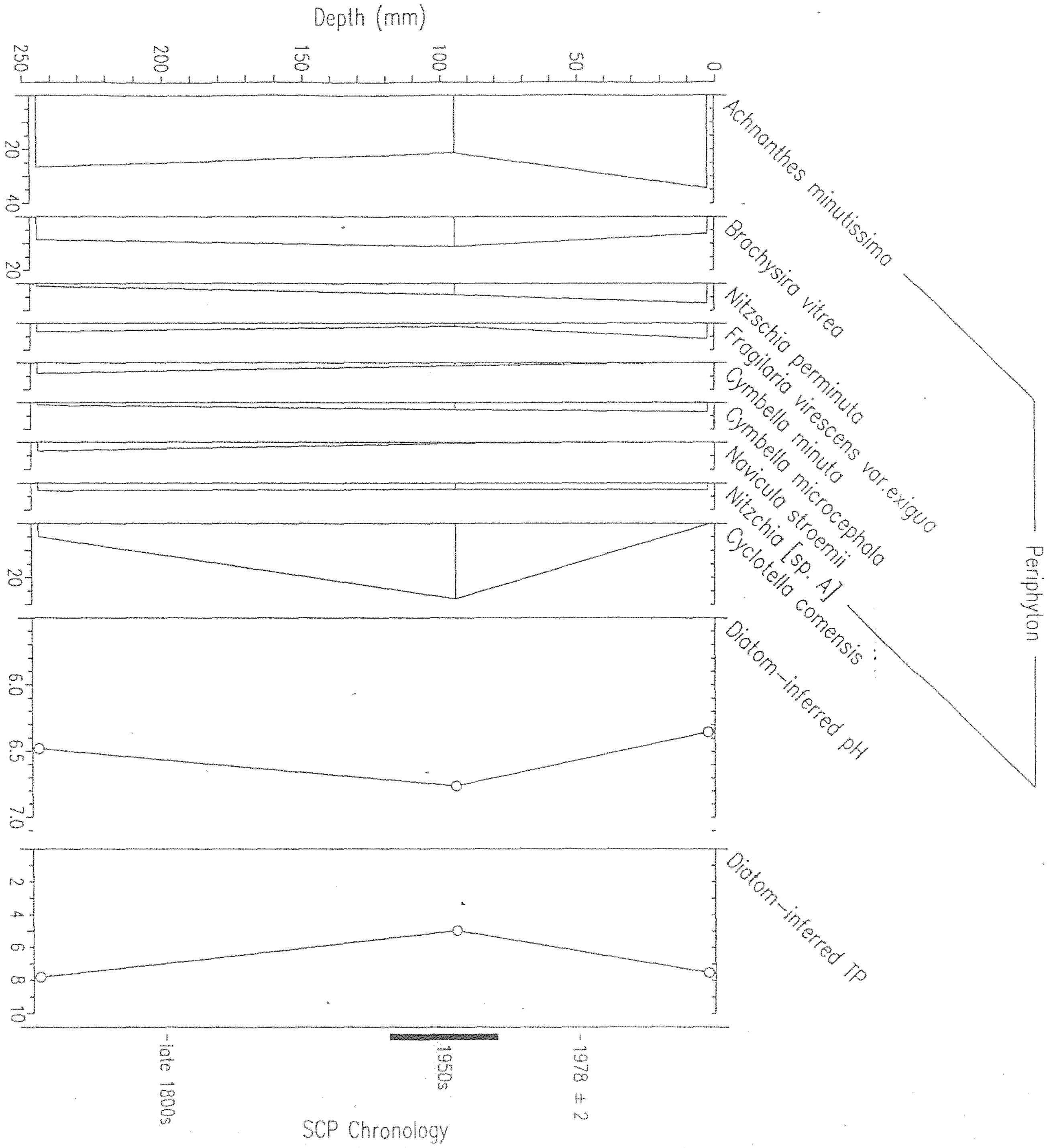
4.3 pH Reconstruction

The DI-pH results are shown in Figure 6. The DI-pH values vary between 6.35 and 6.77. However, there is no consistent, linear trend in pH between the three levels, and the highest value is recorded in the 9-10 cm level (1950s). This pattern of DI-pH is due to the fluctuation in the abundance of *C. comensis*. In the SWAP training set (Stevenson *et al.*, 1991) this taxon has a pH optimum of 6.7. *A. minutissima*, the other dominant taxa in the core, has an optimum of 6.3 (Stevenson *et al.*, 1991).

4.4 TP Reconstruction

The DI-TP results are shown in Figure 6. The values are indicative of oligotrophic conditions, falling in the range 5-8 μg TP l^{-1}. The DI-TP value for the surface sample is 7.5 μg TP l^{-1}, which slightly over-estimates the mean annual lake-water TP concentration of 5.3 μg TP l^{-1}. The DI-TP of the 9-10 cm level (1950s) is 5.0 μg TP l^{-1}, somewhat lower than that of the other two assemblages. This is due to the high abundance of *C. comensis*, a taxon with a lower TP optimum in the training set than the other taxa abundant in the core (Bennion *et al.*, in press). However, the significance of this variation must be viewed with caution as it is well within the error of the technique.

Figure 6 **Summary diatom diagram and pH and TP reconstructions for Llyn Idwal**



4.5 Discussion

The SCP chronology indicates that the core contains a continuous stratigraphic record covering the period since the mid 1800s. Over this period there have been some changes in diatom assemblages, but there is no clear evidence of either acidification or nutrient enrichment. The assemblages analysed from the mid 1850s and from the surface sediments (1995) are floristically similar, indicating circumneutral (pH *c.*6.5), oligotrophic (TP *c.*8 μg TP l^{-1}) conditions.

The diatom assemblage from the 1950s level indicates slightly higher pH conditions (*c.*6.8) than in the other assemblages due to higher abundances of the planktonic *Cyclotella comensis*. This coincides with the period of elevated %loi values in the lithostratigraphic record (see Figure 4). The causes of these trends are difficult to ascertain. They may be related to catchment specific processes, such as an increase in the intensity of catchment erosion. The catchment is under significant recreational pressure, with a number of heavily eroded footpaths, and thus changes in the supply of sediment from the catchment to the lake are feasible. The catchment geology includes several areas of base-rich rocks (Allott *et al.*, 1994), and erosion of base-rich mineral material from such areas into the lake might provide an explanation for increased lake-water pH. However, this type of erosion would be reflected in an increase in the mineral content of the lake sediments, the converse of the observed pattern (Figure 4). Alternatively, the increase in %loi values might indicate an erosion of catchment peats, but it is difficult to cite a link between this form of erosion and an increase in lake-water pH. The cause of the high abundance of *Cyclotella comensis* in the assemblage from the 1950s is therefore unclear.

In summary, the data suggest that between the mid 1800s and 1995 there has been no overall change in lake-water chemistry at Llyn Idwal. However, there may have been a period of higher lake-water pH in the 1950s, possibly due to catchment specific processes. Improved data on catchment history and more detailed analysis of the diatom record would allow more complete evaluation of this period in the lake's history.

5 Llyn Yr Wyth Eidion (SH 474 819)

5.1 Lithostratigraphy and Dating

A 28 cm sediment core (WYTH1) was taken from the deepest part of the lake in a water depth of 9.2 m using a Glew gravity corer on 22-11-95.

The %dw and %loi profiles (Figure 7) suggest continual and gradual change in the organic content of the sediment. The %loi increases from approximately 16% at the bottom to 34% at the surface. This trend appears to be broken into three more subtle phases: there is a marked increase in the %loi between the bottom of the core and *c.*19 cm; values remain reasonably constant with a very slight decline between 19 and 10 cm, followed by a further increase in the percentage organic content in the upper 10 cms.

The SCP profile shows an obvious peak in concentration at 8.5 cm (Figure 8), although it appears slightly truncated. This could be the effect of the sampling interval as contiguous samples were not analysed. Consequently the actual peak could lie between the extremes of 7.25 and 9.25 cm. Taking 1978+/-2 as the dating point for this feature the calculated accumulation rate falls between 4.3 and 5.4 mm yr^{-1} (averaged for the last 17 years), but is likely to be nearer the midpoint of 4.9 mm yr^{-1}. Using the intercept method described in Rose *et al.* (1995) to locate the start of the rapid increase in SCP concentration, a narrow region can be identified between 12.5 and 13.5 cm where the dating point for the 1950s is centred. The associated average accumulation rate for the period 1950-1978 is therefore estimated at 3.2 - 3.4 mm yr^{-1}.

As the core was not long enough to enable the end of the SCP record to be identified (the bottom sample still contained SCPs), it is necessary to extrapolate from the data. Using the calculated accumulation rates from the other dating features, the start of the record is estimated at 68 cm (from the peak) and 46 cm (from the start of the rapid increase in SCP concentration), both of which seem unlikely from the appearance of the profile. The changes seen in the %loi throughout the core suggest that the accumulation rate was lower at the core base than at the top. It is likely, therefore, that the actual end of the record occurs at a *c.* 30 cm, thus dating the core base to the late 1800s.

In summary :-

Approx. Depth	Year	Approx. Acc. Rate
7.75 cm	1978+/-2	4.9 mm yr^{-1}
13 cm	1950s	3.3 mm yr^{-1}
28 cm	late 1800s	1.4 mm yr^{-1}?

Figure 7 Lithostratigraphic data for Llyn yr Wyth Eidion

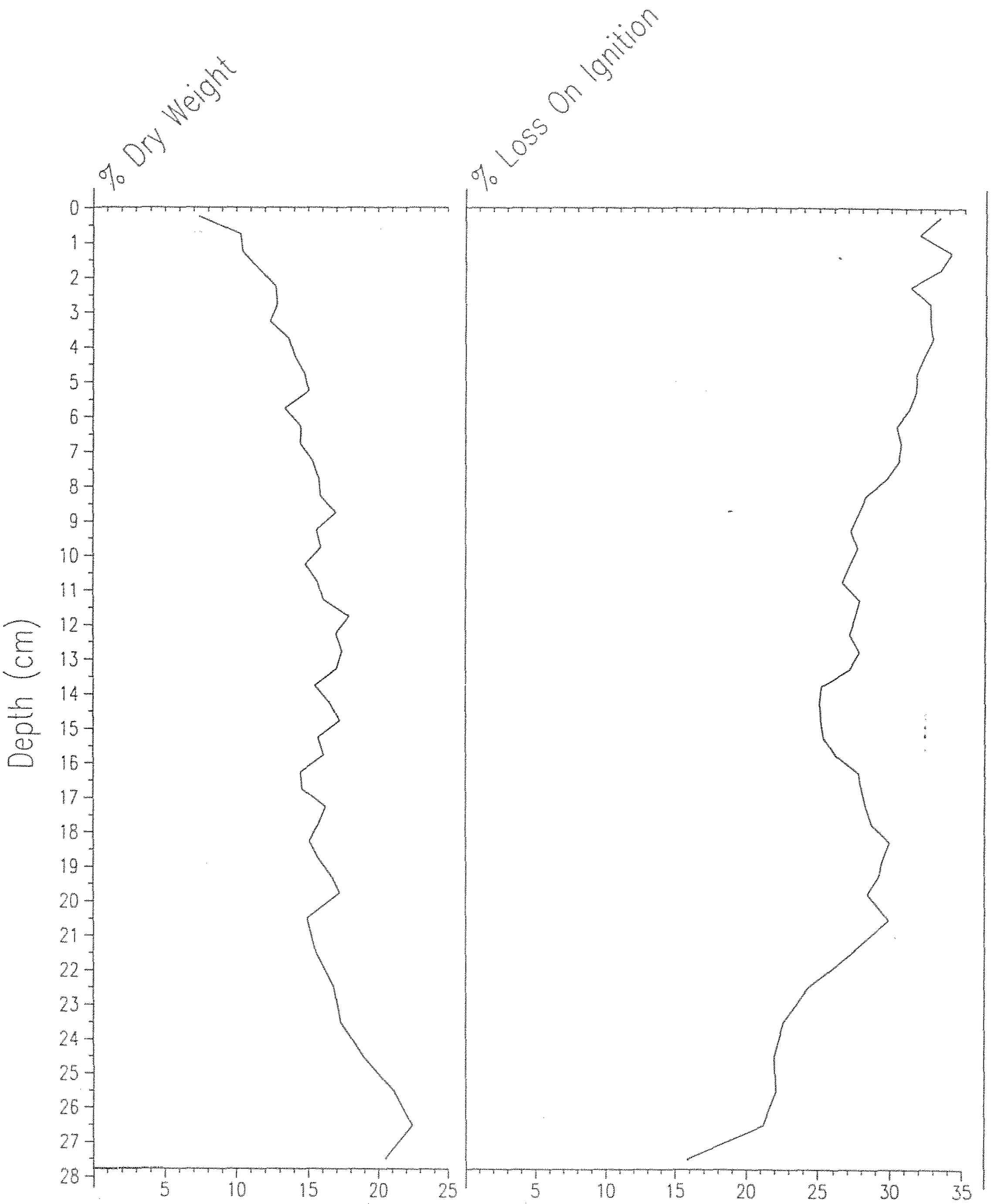
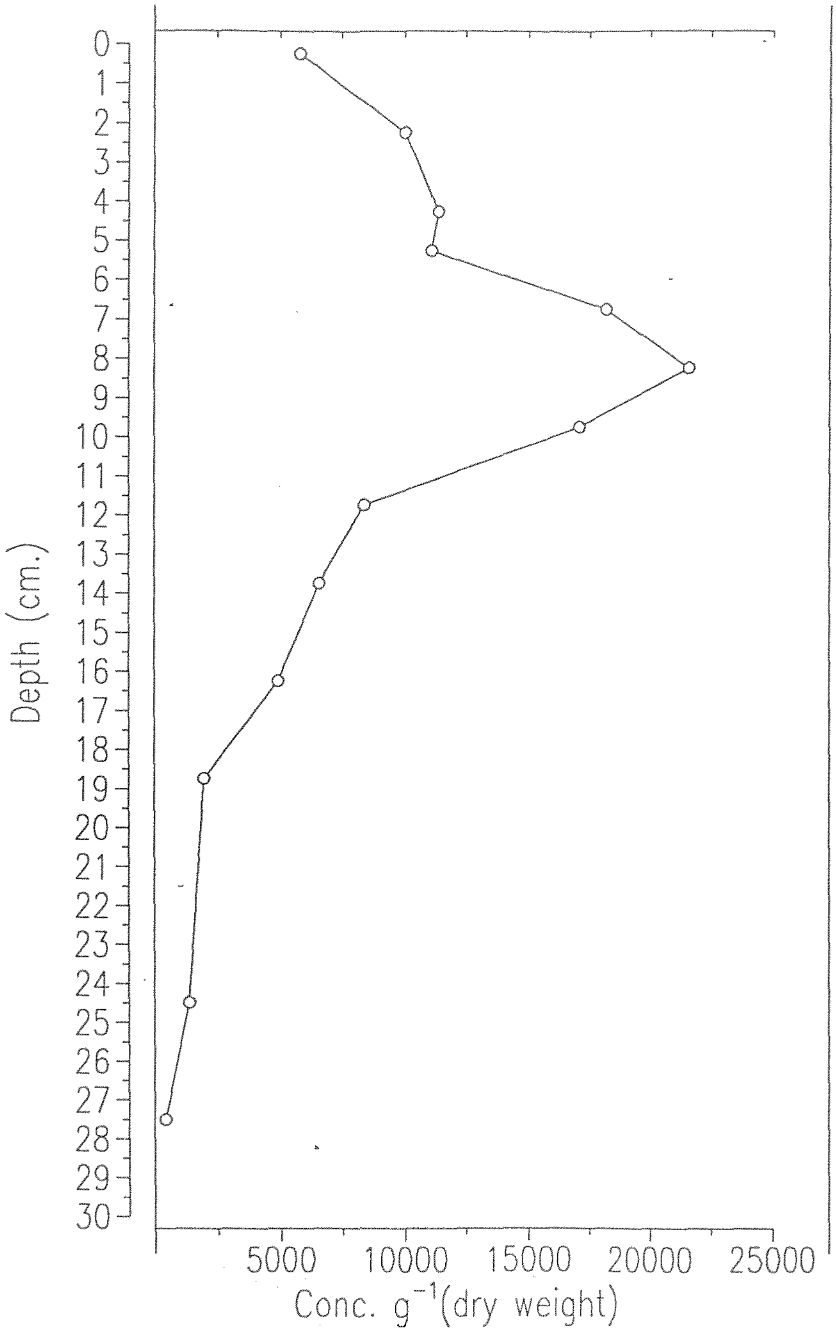


Figure 8 **Spherical Carbonaceous Particle profile for Llyn yr Wyth Eidion**



5.2 Diatom Stratigraphy

The percentage relative frequencies of diatom species in only two levels of the sediment core were calculated (0-0.5 cm and 5-5.5 cm) and Figure 9 illustrates the results for the major taxa. Diatom preservation was extremely poor throughout the core, except for the surface sediment, with dissolution and breakage problems, and counting was difficult due to low concentrations and interference from mineral matter. Diatom (silica) dissolution is not uncommon in lime-rich waters and has been observed in other calcareous lakes in Britain, e.g. Semer Water and Malham Tarn in Yorkshire. Therefore, it was only possible to analyse the upper 5 cms of the core. A total of 48 taxa was observed, 46 of which were present in the TP calibration set. There were no species analogue problems, with greater than 98% of the fossil assemblage being used in the TP reconstructions. It was not possible to reconstruct pH owing to a lack of species analogues in the SWAP training set and given the high calcium content and base-rich nature of the site, it was not considered appropriate.

Figure 9 illustrates that there have been slight changes in the diatom species composition in terms of relative percentages over the period represented by the upper 5 cm of the core (*c.*1980-1995). Diatom dissolution was extremely bad in the 5 cm sample with presence of only very robust forms. The data may not therefore represent the true assemblage for this time and the observed changes in species composition may be more a reflection of the standard of preservation than any real species shifts. In view of these analogue problems, the reconstructions should be interpreted with caution.

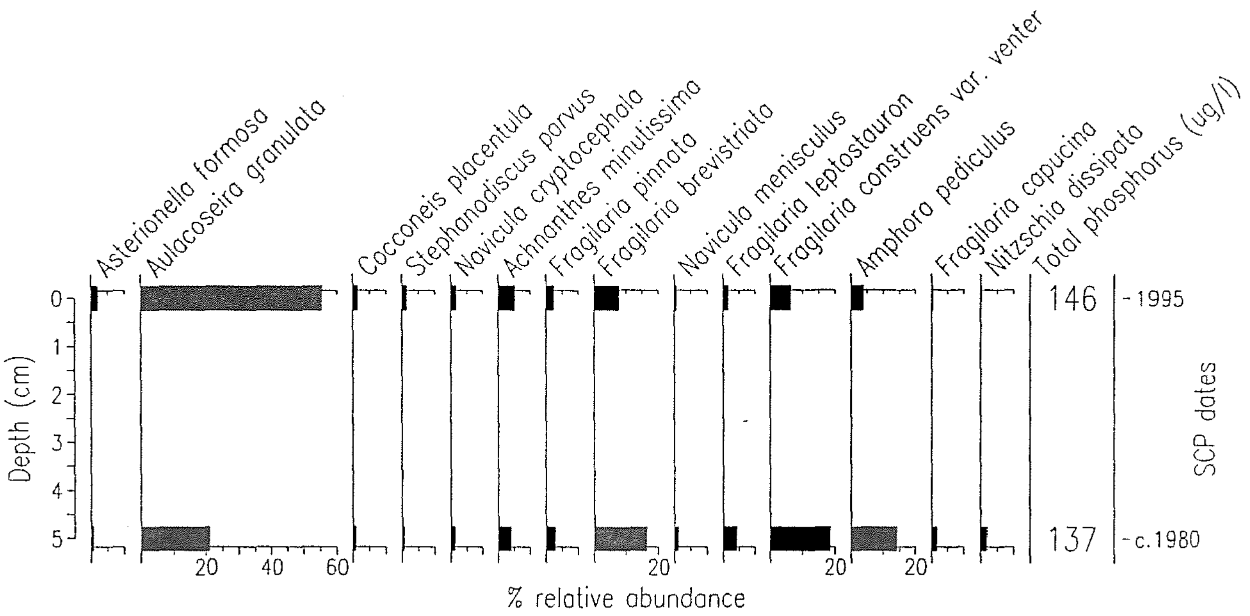
There has been no clear species replacement since 1980 and the assemblages have been dominated by the same major taxa throughout the core. The major taxa in the 5 cm sample were *Fragilaria brevistriata, Fragilaria construens* var. *venter*, *Amphora pediculus, Fragilaria leptostauron* and *Achnanthes minutissima*, all species commonly found attached to either the sediments, stones or macrophyte surfaces of shallow, alkaline waters, and a fine form of *Aulacoseira granulata*, generally observed in the phytoplankton of enriched waters (Bennion, 1994).

The same taxa were present in the surface sample, although the relative abundance of *Aulacoseira granulata* was 60% compared with 20% in the 5 cm level. The other notable changes were slight increases in *Asterionella formosa* and *Stephanodiscus parvus*, planktonic species commonly found in eutrophic lakes (Bennion, 1994: Bennion, 1995).

5.3 TP Reconstruction

The TP reconstruction shows that the lake has had high TP concentrations throughout the period represented by the sediment core (*c.*1980-1995), which would place the lake in the hypertrophic category (> 100 μg TP l^{-1}). The DI-TP concentrations were 137 μg TP l^{-1} for *c.*1980 (5 cm), increasing slightly to 146 μg TP l^{-1} by 1995. This increase, however, is not significant, given the errors associated with the TP model and the diatom dissolution effects.

Figure 9 Summary diatom diagram and TP reconstruction for Llyn yr Wyth Eidion



5.4 Discussion

The results suggest that Llyn yr Wyth Eidion has been a nutrient-rich lake since at least 1980 and has not experienced any major increase in TP concentrations since that time. However, these data must be viewed with caution in view of the chemistry of the lake-water and sediments. It is a highly alkaline, calcareous marl lake (240-250 mg l^{-1} $CaCO_3$), and silica dissolution is commonly a problem in such systems, causing problems with quantitative interpretations of the diatom data. A palaeolimnological interpretation of events is clearly limited by the poor diatom preservation.

The diatom flora is typical of an alkaline, nutrient-rich waterbody with both planktonic taxa and a high frequency of non-planktonic species. The development of epiphytic (attached to plant substrates) and epilithic (attached to stones) communities at the expense of planktonic ones may be regarded as one of the characteristics of a calcareous, eutrophic system and has been documented for Malham Tarn, a calcareous lake in Yorkshire (Round, 1953). Llyn yr Wyth Eidion is known to develop at least partial deoxygenation of the hypolimnion and the profundal fauna consists entirely of species which are tolerant of low oxygen conditions. The benthic invertebrate fauna is rich in gastropods and leeches, with a number of species typical of eutrophic waters (Ratcliffe, 1977). Therefore, the reconstructed TP concentrations, which would place the lake in the eutrophic/hypertrophic category (OECD, 1982), are consistent with these observations. Unfortunately, there are no available water chemistry data against which to validate the diatom-inferred values.

Given that the diatom data can only provide reconstructions dating back to *c.*1980 it is not possible to assess whether the lake is naturally eutrophic or whether it has been anthropogenically affected. The site is generally perceived to be "pristine" and relatively "undisturbed", buffered by the surrounding fen and peatland, and is considered to be a unique freshwater habitat in Wales. The findings of this study can neither confirm or reject this hypothesis. However, given the high DI-TP concentrations for the lake, it would be desirable to begin monitoring the water chemistry and lake biota.

6 LLyn Syfaddan or Llangorse Lake (SO 132 265)

6.1 Lithostratigraphy and Dating

An 80 cm sediment core (LLAN1) was taken from the deepest part of the lake at a water depth of 8 m using a Mackereth piston corer on 21-11-95.

The %loi profile (Figure 10) is remarkably featureless from top to bottom, remaining constant throughout, although there is a very slight increase in values from 25 cm to the surface. The SCP profile (Figure 11) is very difficult to interpret because the characteristic rapid change in SCP concentration followed by a clear peak is severely disrupted. The uniformity of the %dw and %loi profiles suggests that there have not been any marked changes in the sediment accumulation rate, and thus dilution or concentrating effects cannot explain the large fluctuations observed in the lower section of the SCP profile. These fluctuations are probably best considered as 'noise', being dependant on a variety of factors, the effects of which are very difficult to isolate.

In an attempt to clean the data and smooth the profile, a rolling two-point average system was employed (Figure 12). This worked well for the lower half of the core giving a smooth increase in SCP concentration from the bottom to approximately three-quarters of the way up. However, the obvious peak in the raw data was shifted upwards towards the surface. This seemed to be an effect of the nature of the surface data points themselves (i.e. little fluctuation) rather than an effect of the data smoothing. However, taking the 'cleaned' peak at 19.5 cm as 1978 the calculated accumulation rate would be *c.*11.5 mm yr^{-1}. It seems possible that the top 20 cm of the core may be smoother than the lower core section because of within-lake effects, whereby the surface sediment is continually remixed.

Unfortuately, therefore, only a very basic level of interpretation is possible for Llangorse Lake. If one assumes that the level with the highest measured concentration of SCPs in the raw data (31-32cm) represents the actual peak, this feature represents a date of *c.*1978. This provides an accumulation rate of *c.*19 mm yr^{-1}. Assuming a constant accumulation rate throughout the core, the 1950s would occur close to the core base at *c.*76cm. Therefore, the accumulation rate is higher than at the other three study sites. These findings are consistent with the relatively lower SCP concentrations throughout the core which suggest dilution caused by fast accumulation of sediment, and with known site information.

In summary :-

Approx. Depth	Date	Approx. Acc. Rate
32 cm	1978	19 mm yr^{-1}
76 cm	1950s	19 mm yr^{-1}

Figure 10 **Lithostratigraphic data for Llangorse Lake**

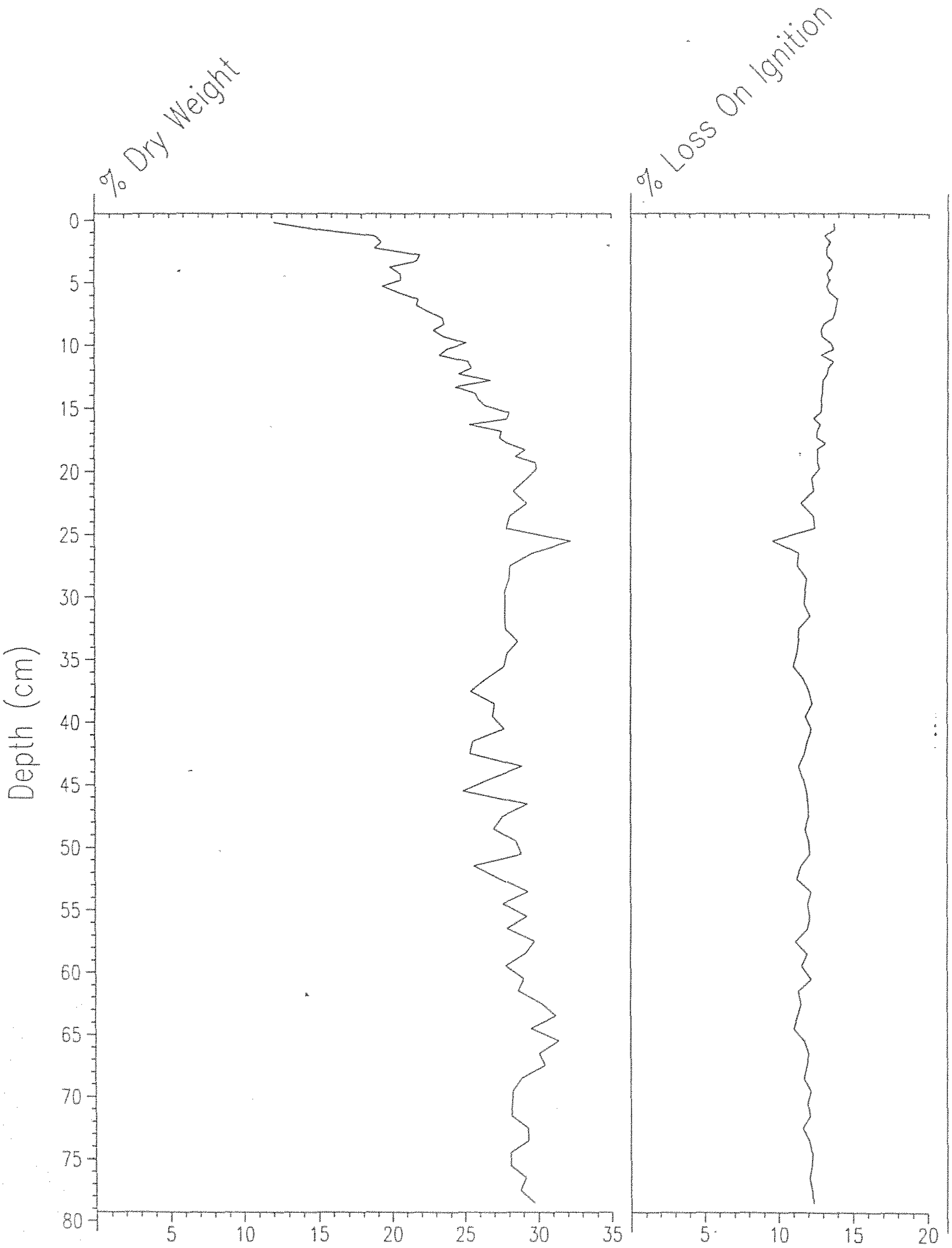


Figure 11 Spherical Carbonaceous Particle profile for Llangorse Lake

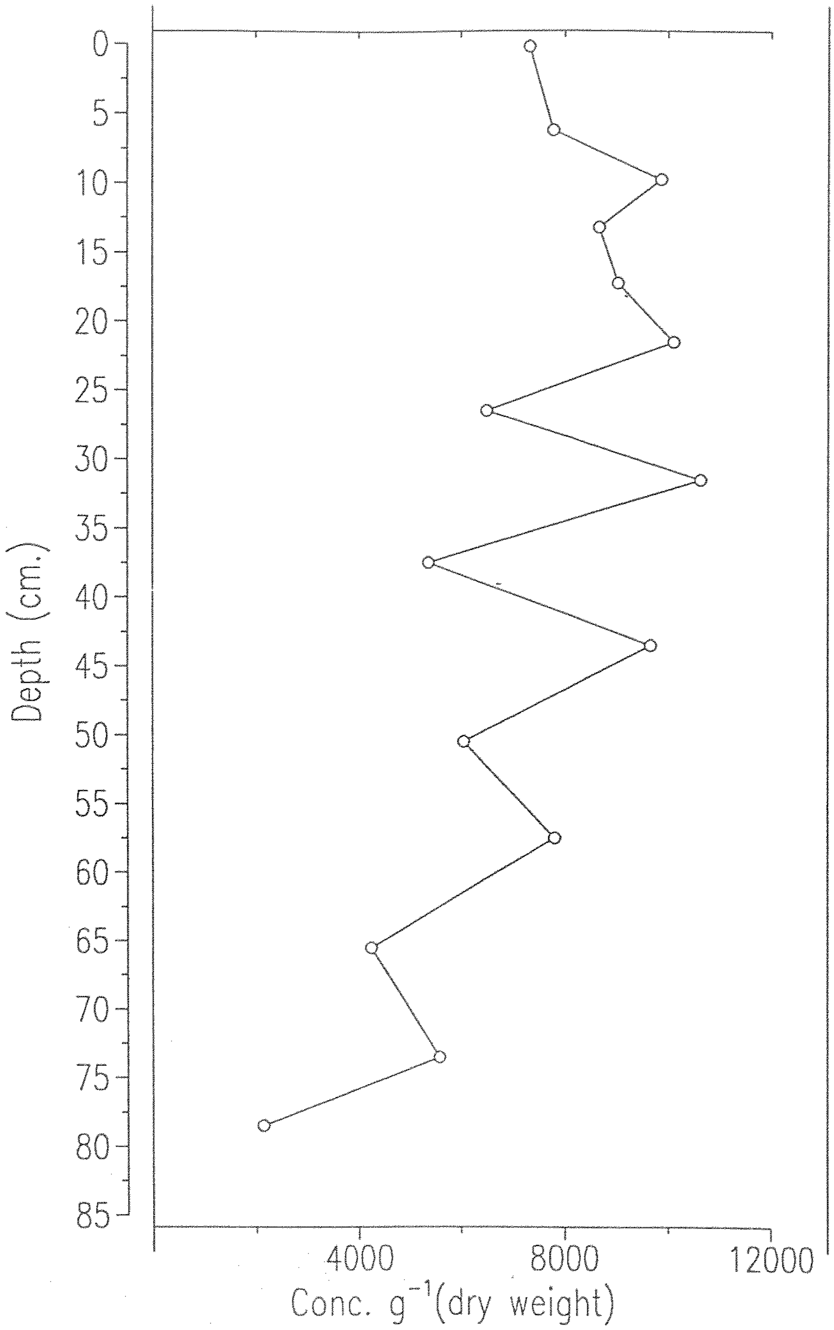
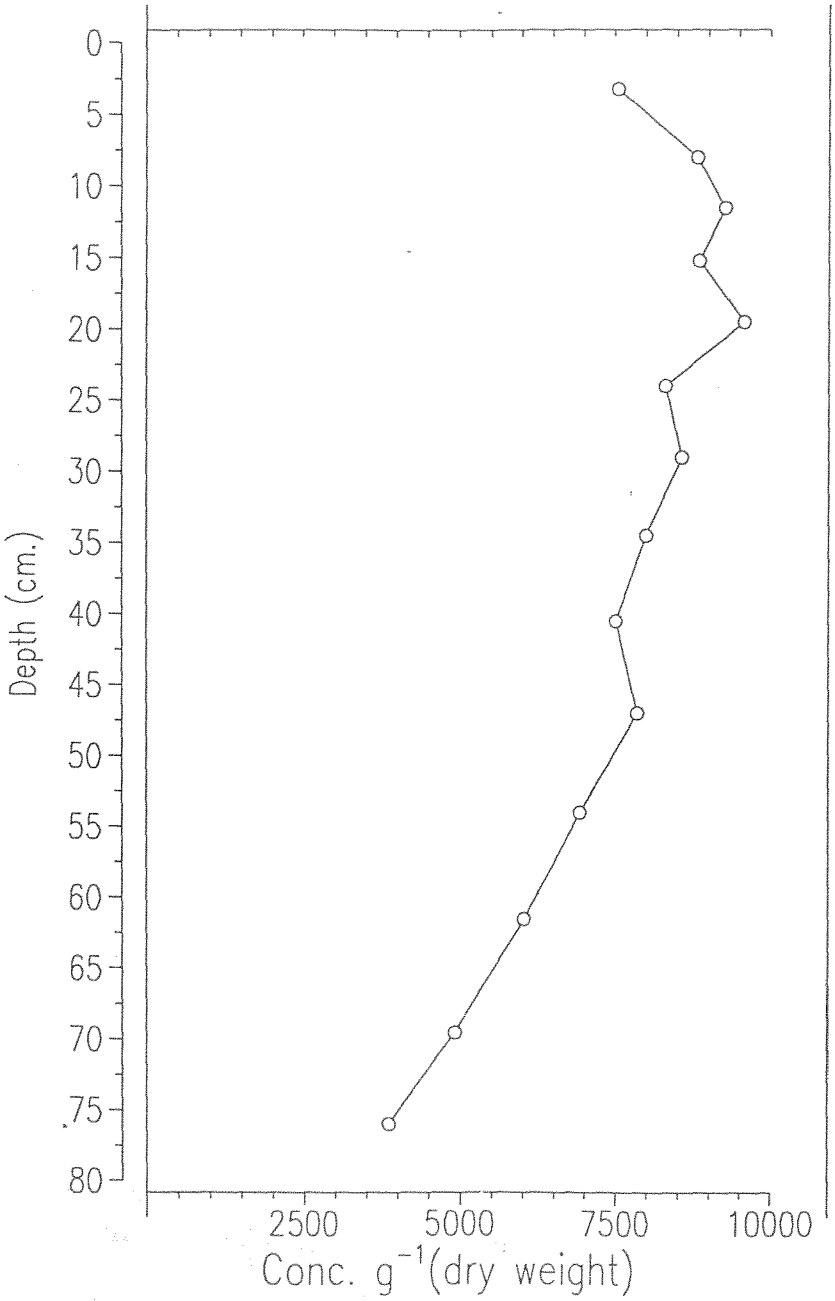


Figure 12 **Spherical Carbonaceous Particle profile for Llangorse Lake with a rolling two-point average**



6.2 Diatom Stratigraphy

The percentage relative frequencies of diatom species in four levels of the sediment core were calculated (0-0.5 cm; 20-21 cm; 40-41 cm; and 78-79 cm) and Figure 13 illustrates the results for the major taxa. Diatom preservation was generally poor throughout the core, with evidence of breakage and dissolution, especially of the lightly silicified centric, planktonic forms. A total of 79 taxa was observed, 71 of which were present in the TP calibration set. Species analogues were good with greater than 98% of the fossil assemblage being used in the TP reconstructions. As for Llyn yr Wyth Eidion, a pH reconstruction was neither valid or appropriate.

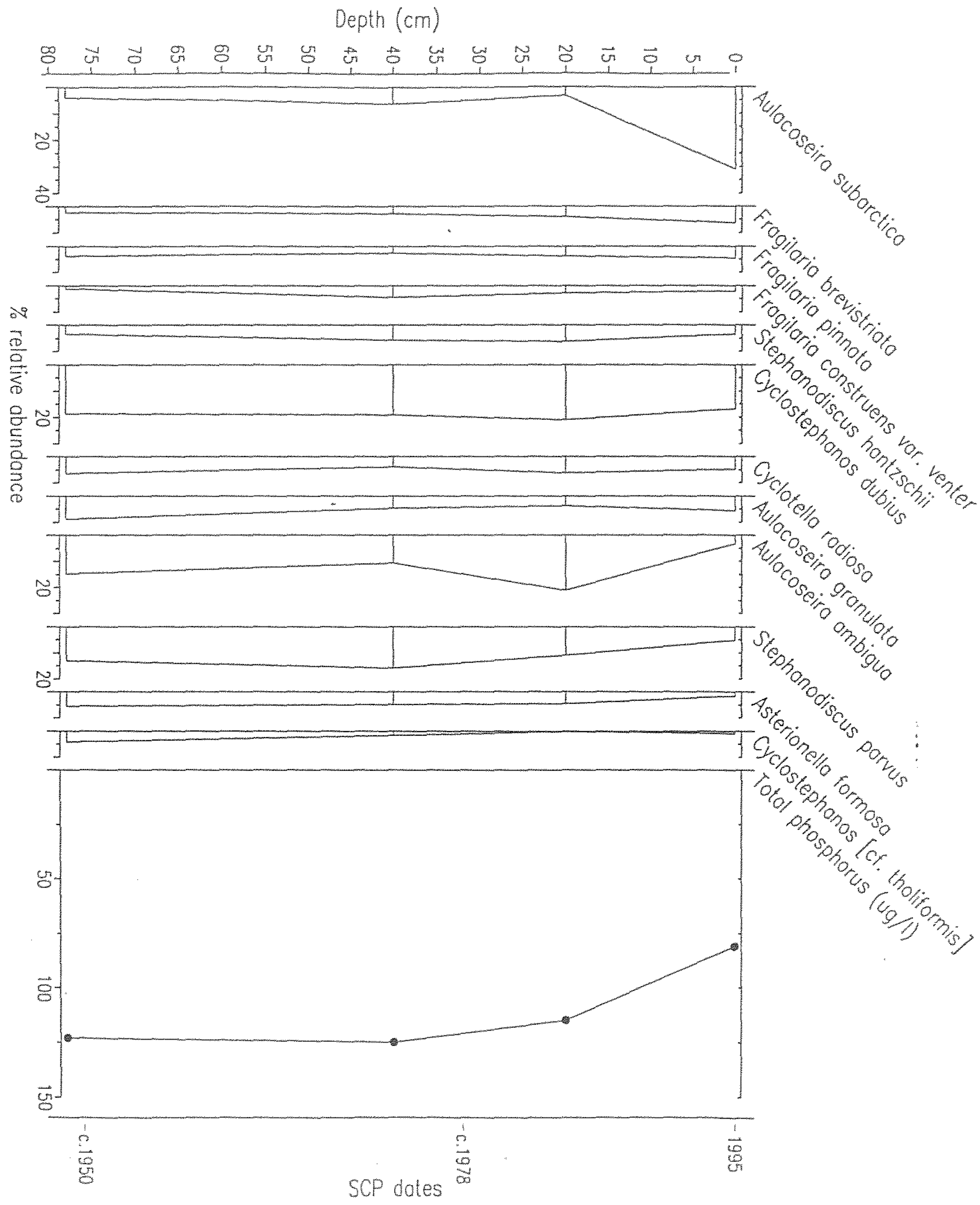
Figure 13 illustrates that there has been a marked change in the diatom species composition since the 20 cm level, dated to *c.*1984, following at least a 30 year period of relative stability. The three lower samples: 78 cm (*c.*1950s), 40 cm (*c.*1974) and 20 cm (*c.*1984) were all dominated by planktonic taxa typical of eutrophic waters, particularly *Cyclostephanos dubius, Aulacoseira ambigua, Stephanodiscus parvus, Aulacoseira granulata, Asterionella formosa, Stephanodiscus hantzschii* and *Cyclostephanos* [cf. *tholiformis*], as well as the non-planktonic *Fragilaria* spp., commonly found in base-rich waters across a wide range of TP concentrations (Bennion, 1995). The relative abundances of these major species remained remarkably similar over this period (*c.*1950-*c.*1984), except for a slight decrease in the importance of *Cyclostephanos* [cf. *tholiformis*].

The surface sample was markedly different from the 20 cm sample. The centric, planktonic taxa, associated with highly nutrient-rich waters decreased in relative abundance, particularly *Stephanodiscus parvus, Aulacoseira ambigua, Cyclostephanos dubius* and *Stephanodiscus hantzschii.* Conversely, the relative abundance of *Aulacoseira subarctica* , a species generally associated with mesotrophic waters and which has a lower TP optimum than most of the taxa of the genera *Stephanodiscus* and *Cyclostephanos,* increased to 30% from less than 5% in the lower section of the core.

6.3 TP Reconstruction

The TP reconstruction indicates that the lake has been eutrophic for the whole of the period represented by the sediment core. The model indicates that concentrations were relatively stable until *c.*1984 and have declined since that time to the present day. The DI-TP concentrations were 123 μg TP l^{-1} for *c.*1950 (78 cm), 125 μg TP l^{-1} for *c.*1974 (40 cm), decreasing slightly to 115 μg TP l^{-1} in *c.*1984 (20 cm), decreasing still further to 81 μg TP l^{-1} in 1995.

Figure 13 Summary diatom diagram and TP reconstruction for Llangorse Lake



6.4 Discussion

Llangorse Lake is described in the literature as a eutrophic lake (Ratcliffe, 1977). The DI-TP values also place the lake in the eutrophic category. When the DI-TP concentration for the 1995 sample is compared with mean TP data from a current water chemistry survey for CCW (ECRC, unpublished) it appears that the model is slightly under-estimating measured values, with concentrations of 81 μg TP l^{-1} and 134 μg TP l^{-1} for the modelled and measured data respectively. The two sets of data are not directly comparable, however, because the survey data are based on outflow readings, whilst the model is calibrated with in-lake concentrations.

The phosphorus budget of the lake is also complicated by the internal load. Evans (1990) concluded that much of the phosphate was being incorporated in the lake sediments and that at times of anoxia, this was released back into the water column. Phosphorus release is also enhanced by stirring up of the sediments (Böstrom *et al.*, 1988; Sϕndergaard *et al.*, 1992). Due to the shallowness of Llangorse Lake, a local mild breeze is strong enough to mix the water for the whole lake and undoubtedly this will cause some disturbance to the surface sediments. In addition, anthropogenic effects such as wash caused by power boats could increase the exchange of P between the water and sediments (ICOLE, 1993).

Unfortunately, the sediment core covers only the post 1950 history of the lake and it is therefore not possible to derive true, pre-anthropogenic impact baselines for TP. The reconstructions must also be interpreted with caution, in view of the uncertain core chronology. It is possible that the core may represent an even shorter time period than that estimated from the SCP profile or that the sediment has been mixed to such an extent that the temporal resolution is very low. The period represented by the core may post-date the start of significant enrichment. These factors may explain why the DI-TP values do not reveal the increase in lake productivity during the late 1960s that was observed in the lake. For example, a decline in the submerged macrophyte flora was recorded between 1961 and 1982, and an increase in the frequency of algal blooms was recognised in the 1960s and continued into the 1970s (Jones & Benson-Evans, 1974). These changes were attributed to an increase in agricultural productivity in the catchment, the entry of sewage effluent until 1981, and increased pressure on the lake from recreational activity, particularly power-boating (ICOLE, 1993). However, early references indicate that Llangorse Lake supported algal blooms even before the 1960s (Carter, 1957), suggesting that the lake has probably always been nutrient-rich.

The recent decline in lake productivity since *c.*1984, as inferred from the diatom model, is consistent with documented records of catchment events and water quality. The most obvious recent human impact on Llangorse Lake was Llangorse sewage treatment works and in 1981 the sewage was diverted from the lake, with a second smaller input from Bwlch sewage treatment works diverted in 1992. Macrophyte surveys demonstrated that the submerged flora began to recover in the mid 1980s and data on phytoplankton populations showed a species composition change reflecting an improvement in water quality following sewage diversion (ICOLE, 1993). Furthermore, low oxygen concentrations had been observed in the early 1980s but have increased since 1985 (ICOLE, 1993).

The changes in diatom species composition in LLAN1 since *c*.1984 are consistent with the above observations, with an increase in *Aulacoseira subarctica*, a species associated with mesotrophic conditions, and a concomitant decline in the importance of the eutrophic taxa. However, based on its current TP concentrations, Llangorse Lake would be classed as a eutrophic lake under the Vollenweider scheme (OECD, 1982).

Continued chemical and biological monitoring of the site is recommended in order to observe whether the improvement in water quality is maintained or indeed further improved upon. The effects of the chemical changes upon the recovery and stability of the lake's flora and fauna should be monitored. Further nutrient reductions are desirable but may not be feasible given the large internal P load already locked up in the lake sediments. Measures to reduce sediment phosphate release should be taken where they appear to represent significant additions to the water column.

7 Acknowledgements

The authors are grateful to CCW Regional staff for assistance with access to sites, and to the owners and occupiers of the sites for their co-operation. We would also like to thank Dan Bird and Simon Patrick for field assistance, and Ewan Shilland and Simon Dobinson for laboratory support.

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