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Quantitative reconstructions of the nutrient histories of three Anglesey lakes

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SUMMARY

The quantitative reconstructions of the three studied lakes indicate that:

1. All three lakes have been eutrophic throughout the period represented by the sediment cores. Llyn Penrhyn has the highest total phosphorus (TP) levels, followed by Llyn Coron and then Llyn Dinam.

2. Llyn Coron and Llyn Dinam experienced a gradual, steady increase in TP concentrations (core base to 20 cm), followed by a marked, rapid increase in TP concentrations from the time represented by 20 cm (early 1970s), most probably associated with agricultural intensification.

3. Llyn Coron and Llyn Dinam have recently experienced a decline in TP concentrations (10-0 cm), but current levels are still considerably higher than those at the base of the cores [Llyn Dinam: current = 112 $\mu g\ l^{-1}$; base = 65 $\mu g\ l^{-1}$, and Llyn Coron: current = 156 $\mu g\ l^{-1}$; base = 70 $\mu g\ l^{-1}$]. Therefore, reductions in external phosphorus (P) loading are resulting in a gradual decrease in epilimnetic TP concentrations, although the probable occurrence of internal P recycling suggests that without sediment removal, it is unlikely that TP concentrations in these waters will return to levels prior to the major eutrophication phase.

4. Llyn Penrhyn experienced no clear changes in lake productivity over the period represented by the sediment core (0-23 cm). However, poor diatom preservation and the possibility that the sediment record was disturbed, suggest that the reconstructions for this lake might not be reliable.

5. The diatom assemblages of Llyn Penrhyn are very similar to those of the other two lakes, despite the fact that the measured annual mean TP concentrations are an order of magnitude higher (hence the under-estimation of TP concentrations by the model). This indicates that top-down control is more important than bottom-up mechanisms in this lake, and therefore it is crucial to maintain the present system, so as to prevent a switch to a phytoplankton dominated community and turbid water conditions.

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OBJECTIVES

A previous study of the diatoms preserved in the sediments of three Anglesey lakes: Llyn Penrhyn, Llyn Coron and Llyn Dinam, reported shifts in species composition which indicated that there had been significant changes in the trophic status of these waters (Haworth *et al.*, 1994). Therefore, the aim of this study was to apply weighted averaging (WA) transfer functions to the diatom data in order to quantitatively reconstruct the total phosphorus (TP) concentrations for each lake, thus providing an estimate of background, pre-enrichment nutrient levels, and enabling an assessment of the onset, causes and extent of eutrophication at each lake to be made.

METHODS

Palaeolimnology and the transfer function approach

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 are particularly good indicators of past limnological conditions, for example lake pH, salinity and trophic level. Until recently, only a qualitative interpretation of species changes in the sediments of eutrophic lakes has been possible (e.g. Bradbury, 1975; Anderson *et al.*, 1990), and some early attempts at semi-quantitative inferences of past lake nutrient levels had either limited applicability or have been time consuming to perform (e.g. Stockner & Benson, 1967; Battarbee, 1978). In the last few 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 (usually > 30). This approach has been successfully employed in recent years to quantitatively infer lake total phosphorus (TP) concentrations (e.g. Hall & Smol. 1992; Anderson *et al.*, 1993; Bennion, 1994; Bennion *et al.*, in press), whereby modern diatom TP optima are calculated for each taxon based on their distribution in the training set, and then past TP concentrations are derived from the weighted average of the TP optima of all diatoms present in a given fossil sample. Such models have generally been concerned with reconstructing phosphorus rather than nitrogen concentrations as an indicator of lake trophic status, largely because phosphorus is commonly the major limiting nutrient in temperate, freshwaters. Studies have shown that annual mean TP provides the most reliable single estimate of lake phosphorus levels, as it incorporates both winter data (when TP is usually at its maximum in stratifying lakes) and summer data (which is equally important in shallow waters where TP often peaks due to sediment phosphorus release). Furthermore TP is generally the most important nutrient variable in explaining the variation in the diatom data (e.g. Anderson *et al.*, 1990; Bennion, 1994). These models are able to provide estimates of baseline TP concentrations in lakes, and coupled with radiometric dating of sediment cores, enable the timing, rates and causes of 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.

<u>Training set description and transfer function performance</u>

A diatom-phosphorus transfer function has been generated from 147 lakes in five regions of Western Europe (Southeast England, the Cheshire and Shropshire meres, Northern Ireland, Denmark and Sweden). The lakes are mostly lowland, small, shallow, alkaline waters with agricultural activity in the catchments, and the training set covers an annual mean TP range of 5 to 1190 μg l^{-1} (although most lakes have TP concentrations > 40 μg l^{-1} and would be classified as eutrophic to hypertrophic according to OECD, 1982). Many of the lakes in the training set are chemically and physically similar to the three Anglesey lakes, and have similar diatom floras, and therefore the model was considered appropriate for reconstructing the nutrient histories of the selected sites. This model is as yet unpublished but further details of the smaller regional data sets from which it is comprised are provided in Anderson *et al.* (1993), Anderson & Odgaard (1994), and Bennion (1994). The results presented in this report are from WA based on inverse deshrinking on log-transformed annual mean TP data, implemented using WACALIB version 3.3 (Line *et al.*, 1994).

The relationship between diatom-inferred and measured TP has a high R^2 correlation coefficient of determination of 0.80, and low errors of prediction with a root mean squared error of prediction (RMSE) of 0.244 and a cross validated RMSE ($RMSE_{boot}$) of 0.266 (log values), indicating that the model performs well. It is this latter value which is used to indicate the standard error of prediction for each reconstructed value in the presented figures. Further details concerning assessment of model performance and bootstrapping procedures are outlined in Birks *et al.* (1990).

This model was applied to the fossil diatom data of the three Anglesey lakes, expressed as relative abundance data (refer to Haworth *et al.*, 1994 for full details of the diatom profiles), following taxonomic harmonization between the training set and core species data.

RESULTS

Llyn Dinam

The TP reconstruction for Llyn Dinam (Fig. 1) is based on 20 levels (0-70 cm). There were no analogue problems, with over 95% of the diatom taxa in each fossil sample being present in the training set. Llyn Dinam is the least enriched of the three studied lakes. There is a close agreement between the diatom-inferred annual mean TP for the surface sample of 125 $\mu g\ l^{-1}$ and the current measured annual mean TP concentration of 112 $\mu g\ l^{-1}$ (Allott *et al.*, 1994), confirming that the model performs well.

The TP reconstruction shows that the lake has had relatively high TP concentrations for the whole time period represented by the core. The model provides an estimate of approximately

65 μg l^{-1} for the base of the core, which would place the lake in the eutrophic category (i.e. > 40 μg l^{-1}) according to the OECD (1982) classification. The lake experienced a very gradual increase in TP levels over the time period represented by 70 cm to 20 cm, with values steadily rising to 84 μg l^{-1} at 20 cm. However, the most marked changes occurred in the period represented by the upper 20 cm of the core, with a sharp increase in TP values to a peak of 160 μg l^{-1} at 10 cm, associated with the appearance of *Stephanodiscus parvus* in the lake, a species commonly found in highly enriched waters. TP values have fluctuated since this time but show a general decrease in the uppermost levels to concentrations of 120-130 μg l^{-1}, placing the lake in the hypertrophic category (i.e. > 100 μg l^{-1}). Therefore, current TP concentrations are approximately double those prior to the period of significant enrichment.

Llyn Coron

The TP reconstruction for Llyn Coron (Fig. 2) is based on 19 levels (0-80 cm). There were no major analogue problems, with greater than 90% of the taxa in each fossil sample being present in the training set. However, two diatom taxa present in the core, *Ellerbeckia arenaria* (present in the central core section especially from 70 to 15 cm) and *Thalassiosira* spp. (present in the upper core section from 15 to 5 cm), were absent from the training set. Llyn Coron is the intermediate of the three lakes with TP values higher than Llyn Dinam but lower than Llyn Penrhyn. As for Llyn Dinam, there is a close agreement between the diatom-inferred annual mean TP for the surface sample of 166 μg l^{-1} and the current measured annual mean TP concentration of 156 μg l^{-1} (Allott *et al.*, 1994), further confirming that the model performs well.

The TP reconstruction shows that the lake has been eutrophic for the whole of the period represented by the core. The model provides an estimate of approximately 70 μg l^{-1} for the base of the core, similar to that for Llyn Dinam. However, Llyn Coron appears to have experienced a slightly faster rise in TP levels than Llyn Dinam with values rising to 107 μg l^{-1} by the 20 cm level. Similarly to Llyn Dinam, the period represented by the upper 20 cm of the core is the time of most significant change. There is a gradual rise in TP values to a peak of 244 μg l^{-1} at 10 cm, and as for Llyn Dinam this is associated with the appearance and sharp increase in *Stephanodiscus parvus*, and here also *S. hantzschii* and an unidentified

Thalassiosira spp., at the expense of *Cyclotella radiosa* and the benthic *Fragilaria* taxa, which experience a marked relative decline. The model indicates that TP levels have decreased over the period represented by the upper 10 cm to concentrations of around 165 μg l^{-1}, although there was a second peak of 211 μg TP l^{-1} at 2 cm, associated with a high abundance of *Aulacoseira granulata*, a species commonly found in enriched waters.

Therefore, although annual mean TP concentrations appear to be declining in recent years, they are still considerably higher (more than double) than those in the past, and Llyn Coron would be currently classified as hypertrophic according to the OECD (1982) system.

Llyn Penrhyn

The TP reconstruction for Llyn Penrhyn (Fig. 3) is based on only 11 levels (0-23 cm), owing to the minerogenic nature of the sediment, poor diatom preservation and the broken condition of the diatom material below this level. Although there were no major analogue problems with over 80% of the taxa in each fossil sample being present in the training set, analogues were on average lower than for Llyn Dinam and Llyn Coron. For example, as for Llyn Coron, *Ellerbeckia arenaria* and *Thalassiosira* spp. were present in relatively high amounts (as much as 10%) in several fossil samples but were absent from the training set. Llyn Penrhyn is the most enriched of the three lakes.

The model appears to significantly under-estimate TP values for this site, as the diatom-inferred annual mean TP for the surface sample is only 180 μg l^{-1}, compared with a measured annual mean of 1085 μg l^{-1} (Allott *et al.*, 1994). The reconstructed TP values fluctuate between 130 and 200 μg l^{-1} over the period represented by the 23 cm core section (which is estimated as a period of approximately 80 years according to the radiometric dating results presented in Haworth *et al.*, 1994) indicating that the lake has been hypertrophic throughout this period. There is however no clear trend in lake productivity changes, despite marked changes in the diatom flora (Haworth *et al.*, 1994).

The possible error sources of the under-estimated TP concentrations and the absence of a trend in the reconstructed values for Llyn Penrhyn are listed below:

a) The sediment record may be disturbed, as indicated by problematic radiometric dating. The lack of a clear ^{137}Cs peak in the profile suggests that there is some degree of sediment mixing.

b) The diatom material in the core was extremely poor. Diatom preservation was generally poor throughout the whole core, and in the lower core section even the few specimens that were observed were badly broken. For example, in the 20 cm level, only 186 specimens were found. Dissolution can also result in under-representation of lightly silicified taxa, and therefore the relative abundance diatom data may be misleading.

c) The absence of *Ellerbeckia arenaria* and *Thalassiosira* spp. from the training set may introduce further errors, as only 80% of the total fossil diatom assemblage data was being used in the core levels where these taxa were present in relatively high amounts.

d) The common diatom taxa are similar to those in the other two lakes (i.e. benthic *Fragilaria* spp. and *Stephanodiscus parvus*), whereas one might expect a plankton-dominated assemblage in a lake with such high TP concentrations. This could be due to the shallow nature of the site and its extensive vegetation cover, providing habitats for benthic and epiphytic communities, rather than supporting large planktonic taxa (cf. Bennion, 1994). Haworth *et al.* (1994) suggest that the good zooplankton population in Llyn Penrhyn keeps the phytoplankton population low enough to maintain a good macrophyte cover.

e) The measured TP concentration for Llyn Penrhyn of approximately 1000 $\mu g\ l^{-1}$ is at the upper limit of the TP gradient covered by the model, and only two sites in the training set have similarly high concentrations. Therefore, it is not expected that the model performs as well for Llyn Penrhyn as for the other two sites, whose range of TP values lie in the centre of the TP gradient represented by the training set. Furthermore, transfer functions based on inverse (as opposed to classical) regression deshrinking methods always tend to under-estimate at the upper extreme of the gradient, and thus the errors of the model are inherently greater at the higher TP values.

Figure 1 **Llyn Dinam - Total phosphorus reconstruction**

(line marked with filled circles represents the mean value and the single lines represent the upper and lower errors of prediction)

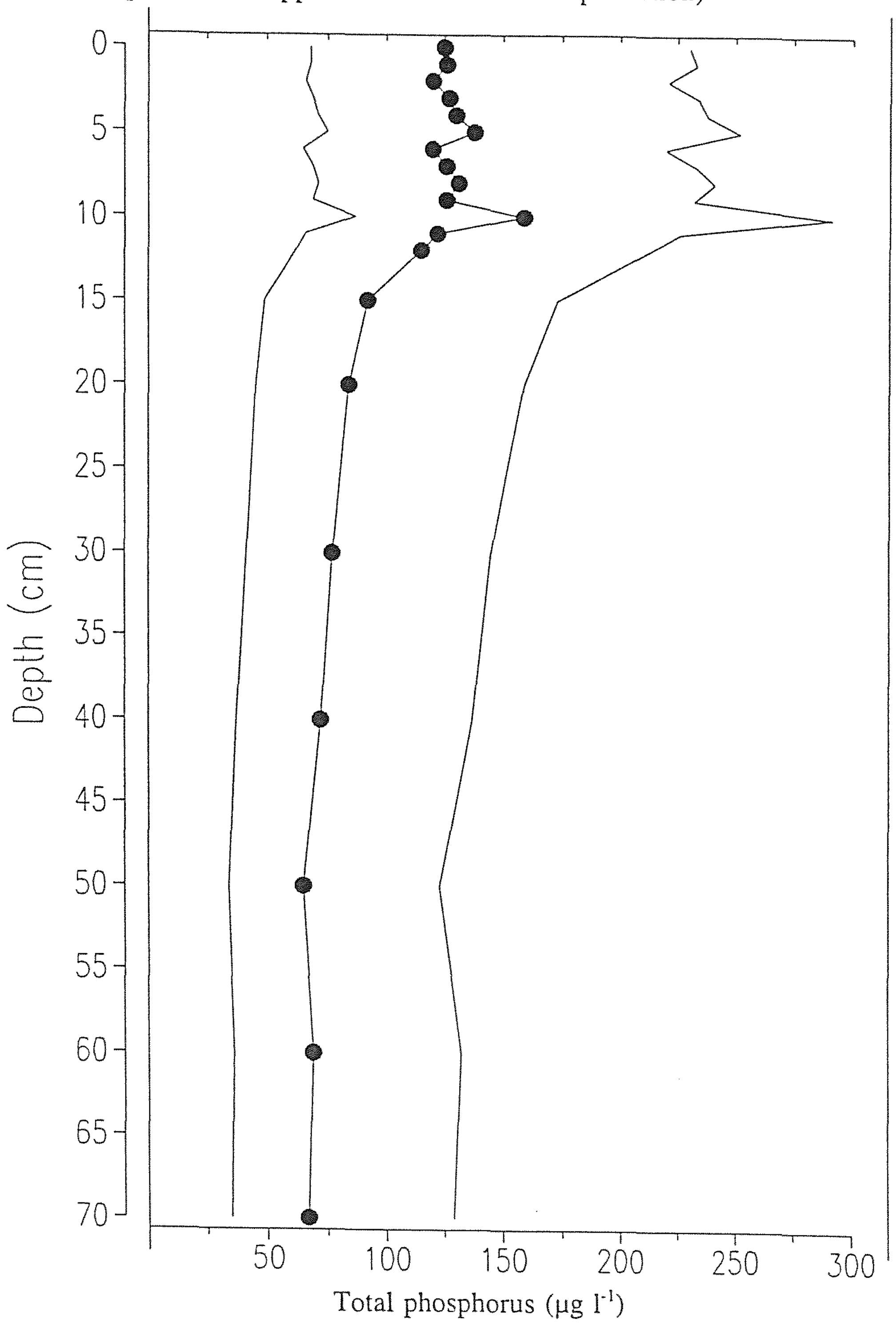


Figure 2 **Llyn Coron - Total phosphorus reconstruction**

(line marked with filled circles represents the mean value and the single lines represent the upper and lower errors of prediction)

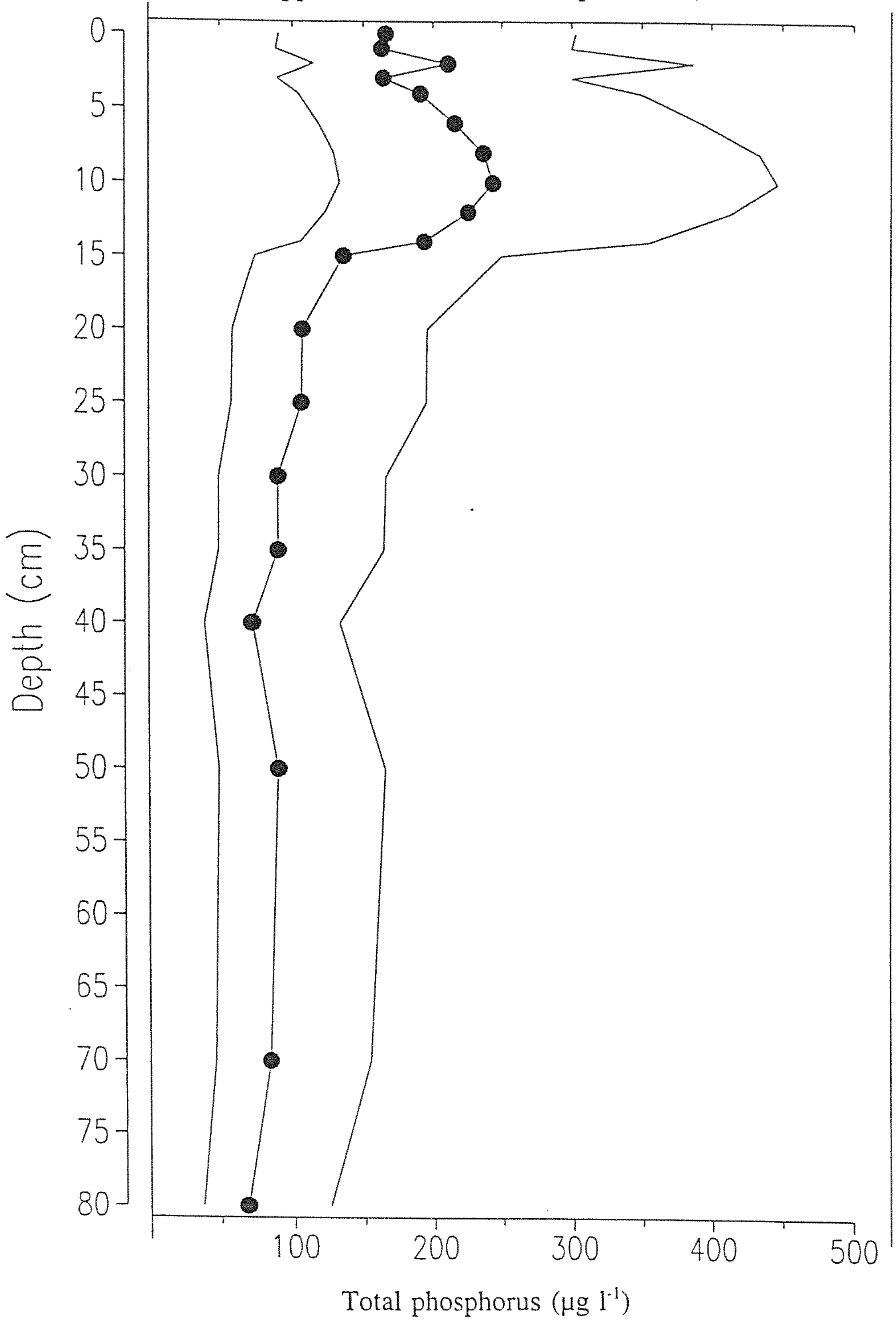
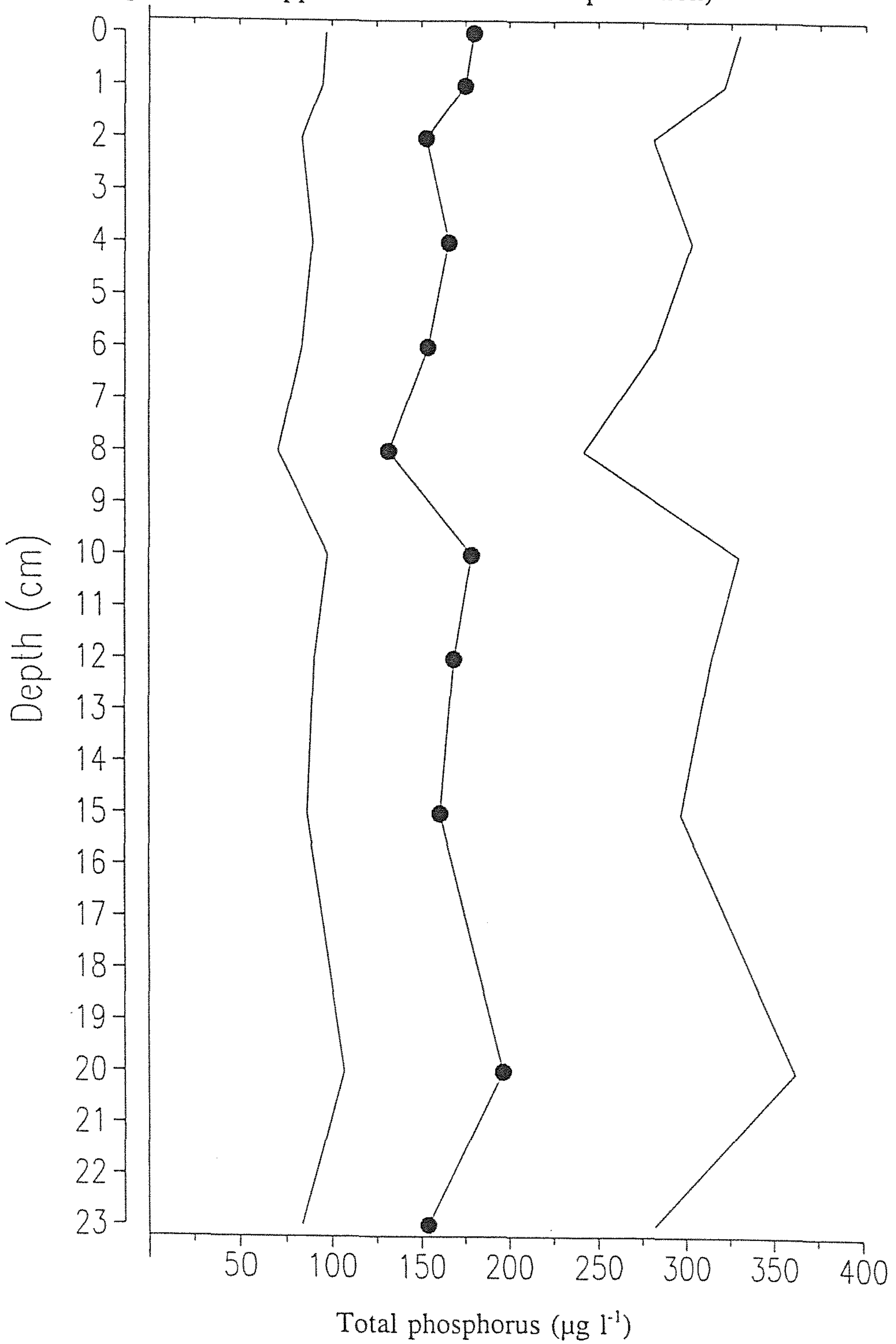


Figure 3 **Llyn Penrhyn - Total phosphorus reconstruction**

(line marked with filled circles represents the mean value and the single lines represent the upper and lower errors of prediction)



DISCUSSION

The quantitative reconstructions of the three Anglesey lakes indicate that all three lakes have been eutrophic throughout the period represented by the sediment cores. Llyn Penrhyn has the highest annual mean TP levels, followed by Llyn Coron and then Llyn Dinam.

Llyn Coron and Llyn Dinam experienced a gradual, steady increase in TP concentrations throughout the period represented by the core base to 20 cm, although the increase at Llyn Coron appears to have been a little faster and greater than that at Llyn Dinam, followed by a marked, rapid increase in TP concentrations from the time represented by the 20 cm level (early 1970s), associated with increases in *Stephanodiscus* spp. at both sites. This is most likely due to agricultural intensification in the lake catchments. The reconstruction for Llyn Penrhyn displays no clear trend in lake productivity.

Llyn Coron and Llyn Dinam have recently experienced a decline in TP concentrations from the time represented by the 10 cm level, but current levels are still considerably higher than those at the base of the cores, prior to the major eutrophication phase. For example, Llyn Dinam has a current measured annual mean TP concentration of 112 $\mu g\ l^{-1}$ compared with a core base TP concentration of 65 $\mu g\ l^{-1}$, and Llyn Coron has an even higher current measured annual mean TP concentration of 156 $\mu g\ l^{-1}$ compared with a core base TP concentration of 70 $\mu g\ l^{-1}$, similar to that for Llyn Dinam. Owing to the absence of radiometric dates for the cores from these two sites, it is not possible to state that these values represent pre-enrichment, 'baseline' levels. However, the reconstructed values for the base of the cores clearly provide estimates of concentrations prior to the major period of lake enrichment and thus provide realistic targets for lake restoration.

In the case of Llyn Coron, literature sources (Haworth *et al.*, 1994) indicate that this decrease in TP levels is most likely due to improved handling of agricultural waste in the catchment and a decline in the amount of P entering the lake from soils. Although the causes are not documented, similar improvements seem to have occurred at Llyn Dinam. Therefore, it appears that reductions in external P loading are resulting in a gradual decrease in epilimnetic TP concentrations in these two lakes, and thus continued control of external P loads is essential to prevent further increases in lake P concentrations. However, in shallow, enriched lakes such as these, internal P recycling from the P accumulated in the lake sediments is likely to be important (Bailey-Watts *et al.*, 1987; Boström *et al.*, 1988; Søndergaard *et al.*, 1992) and without sediment removal, it is unlikely that the TP concentrations in these waters will return to levels prior to the major phase of eutrophication.

The diatom assemblages in Llyn Penrhyn are similar to those in the other two lakes, despite the fact that the measured TP concentrations are an order of magnitude higher (hence the under-estimation of TP concentrations produced by the transfer function). This suggests that top-down control (grazing) is more important than bottom-up (nutrients) mechanisms in this lake, and therefore from a management perspective it is crucial to maintain the system with its high macrophyte cover and good zooplankton populations, so as to prevent a switch to a phytoplankton dominated community and turbid water conditions. Clearly, any possible reduction in external P loads from the local sewage works, and/or a reduction in the occurrence of sediment P release (either by stabilization or removal of the surface sediments) would contribute to an enhancement of clear water conditions in Llyn Penrhyn.

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