Spatial pattern of recent sediment and diatom accumulation in a small, monomictic, eutrophic lake

N.J. Anderson
Palaeoecology Research Unit, University College London, 26, Bedford Way, London WC1H OAP;
Present address: Danish Geological Survey, Thoravej 8, DK-2400 Copenhagen NV, Denmark

Abstract

Spatial variability of sediment and diatom deposition was assessed in a small monomictic, eutrophic lake in Northern Ireland (Lough Augher, Co. Tyrone) using measurements from 17 sediment cores. Loss-on-ignition profiles in water depths > 6 m showed good repeatability, while littoral cores were more variable with localised profiles. Dry mass accumulation rates, derived by biostratigraphic correlation to a ^{210}Pb dated master core, were variable and not correlated with water depth. Basin mean dry mass accumulation rate was 0.068 g cm^{-2} yr^{-1} (range 0.036–0.09) prior to 1900, and 0.19 g cm^{-2} yr^{-1} (range 0.11–0.3) after 1974. Post-1940 cumulative fluxes were estimated for dry mass (range 3.49–9.16 g cm^{-2}) and diatoms (range 16.9–113.8 × 10^7 frustules cm^{-2}). Cumulative dry mass was inversely correlated ($r = -0.64$) with distance from the inflow, indicating its localised influence. No variable was correlated with water depth except frustules of planktonic diatoms ($r = 0.66$). However, high cumulative fluxes of diatoms and dry mass away from the inflow suggest that the expansion of the littoral macrophyte community may be responsible for decreased resuspension in shallow water, and together with increased sediment trapping, has enhanced sediment accumulation in shallow water over recent time periods.

Introduction

The heterogeneity of lake sediment accumulation, due to the variability of depositional processes in space and time, is well known (Davis, 1976; Bloemendal *et al.*, 1979; Evans & Rigler, 1980; Dearing *et al.*, 1981; Davis & Ford, 1982). This variability has implications for the interpretation of microfossil assemblages (Battarbee, 1978a, b; Davis *et al.*, 1986), calculation of catchment erosion rates (Foster *et al.*, 1985), mineral cycling (Engstrom & Swain, 1986), and the contribution of sediment microbial activity to whole lake carbon metabolism (Jones, 1980). Despite this

importance, knowledge of the basic mechanisms causing variability is still rudimentary, and what is known has been largely inferred from either sediment-core studies (Kimmel, 1978; Evans & Rigler, 1980; Davis & Ford, 1982) or sediment trapping (e.g. Flower, 1980; Bloesch & Uehlinger, 1986). Sediment trap and core data provide different information about sediment accumulation, as a result of the different timescales over which they operate (Hilton, 1985). While trap data can be difficult to interpret, core data provide only an integrated record of lake sediment accumulation, and in the absence of individual dating of cores, there is the problem of accurate core correlation

(Anderson, 1986b; Dearing, 1986), and bio-turbation (Robbins, 1982; Moeller *et al.*, 1984). As such, process inferences have been largely conjectural.

The assessment of deposition patterns through the use of sediment cores has been the subject of a number of detailed studies (e.g. Davis *et al.*, 1986; Hilton, 1985; Hilton *et al.*, 1986; Dearing, 1986; Dearing *et al.*, 1981; Foster *et al.*, 1985); although only Hilton has been directly concerned with depositional processes. Dearing's work has been concerned with the problems caused by variability of sediment accumulation patterns for inferring past rates of catchment erosion. In contrast, both Davis (Davis, 1973; Davis & Brubaker, 1973; Davis & Ford, 1982) and Anderson (1989; 1990) have been primarily concerned with the influence of sediment deposition processes on the microfossil record, pollen and diatoms respectively.

Sediment distribution is a function of external (to the lake) factors, such as topography, shelter, and climate, which influence physical limnological processes (e.g. thermocline depth, time of turnover, wave action). Hilton (1985) has provided a conceptual framework within which future sediment distribution studies might be considered. Hilton *et al.* (1986) suggested that the most important processes for a monomictic lake (Esthwaite, English Lake District) were probably peripheral wave attack, random redistribution, intermittent complete mixing, and slump-sliding on slopes.

Before a more predictive approach can be established, two criteria need to be fulfilled; firstly, more detailed studies of sediment distribution in a range of lake types in relation to a range of easily measurable and quantifiable parameters (e.g. fetch, shelter, stratification periods); and secondly, direct process studies. The former can be fulfilled relatively easily if time and the necessary funding are available; unfortunately the second requires technological changes, and may still be someway away, although there have been some recent advances (e.g. Lemmin & Imboden, 1987). Håkanson's approach (Håkanson & Jansson, 1983) has limited applicability, because his models

have been derived from work on large lakes in Sweden. The scale of processes controlling sediment accumulation in such lakes is different from those operating in small lakes (<100 ha), i.e. those generally chosen for finescale (temporal and spatial) palaeolimnological projects (e.g. Engstrom *et al.*, 1985).

This study describes the distribution of recent sediment and diatoms in a small monomictic eutrophic lake. It examines the different patterns of accumulation shown by bulk sediment, planktonic and periphytic diatoms, and considers the observed pattern in relation to Hilton's (1985) model.

Study site

Augher Lough is a small (area 9.25 ha, maximum depth 14.2 m, mean depth 5.5 m) eutrophic lake in Co. Tyrone, N. Ireland. It has a simple bathymetry (Fig. 1) and a single inflow situated at the southern end of the lake. The lake is monomictic, stratifying annually from about May until September, and has an anoxic hypolimnion with a mean thermocline depth of 5 m (Rippey, 1983). The lake level was raised sometime prior to 1800 by the cutting of an artificial inflow (Anderson & Rippey, 1988). Because of the creation of this broad shelf (<2 m depth; Fig. 1) the lake has extensive fringing macrophytes; submarginal stands of *Carex* spp. and *Typha latifolia*, with the dominant submerged species, *Potamogeton natans* and *Myriophyllum spicatum*, occupying much of the littoral area <2 m water depth. A local creamery profoundly altered the ecology of the lake by disposing of its effluent into the lake between 1900 and 1979; the diatom stratigraphic record of this eutrophication is described by Anderson (1986a; 1989).

Methods

A number of short cores were taken with a 1 m Mackereth corer (Mackereth, 1969), on three coring trips (A: 1980, AA: 1981, and AB: 1983).
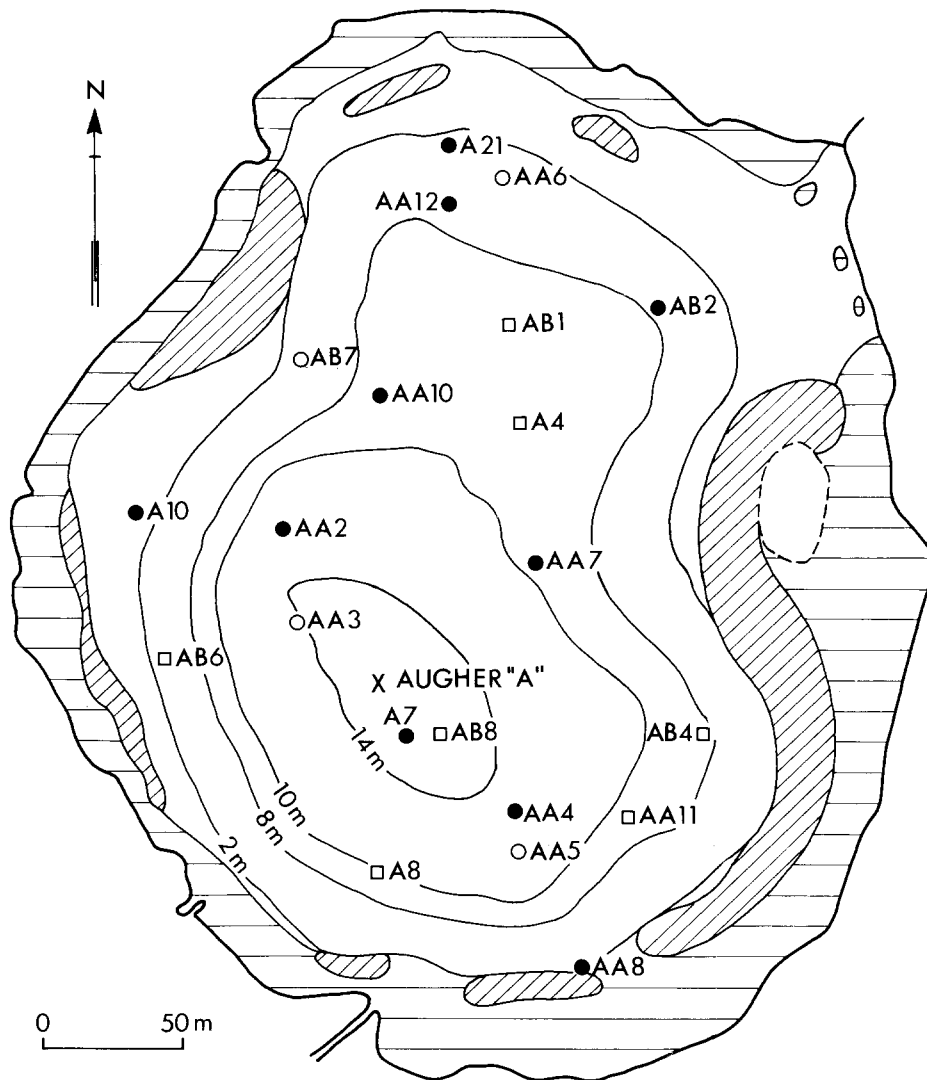
Fig. 1. Bathymetry and core locations. Approximate distribution (based on a qualitative survey) of the dominant submersed and emergent macrophytes is shown; diagonal hatching: *Myriophyllum spicatum* and *Potamogeton natans*; horizontal shading: *Typha latifolia* and *Carex* spp.. Analyses made on the cores are indicated by different symbols: x Augher 'A', ^{210}Pb dated master core; ●, cores with full core biostratigraphy, temporal dry mass and cumulative flux estimates, LOI; □, partial biostratigraphy, cumulative flux estimates, LOI; o LOI only.

Cores were accurately located using shore based surveying equipment (Battarbee *et al.*, 1983), and cover a range of water depths and locations within the basin (Fig. 1). Cores were sealed in the field, transported vertically, and stored in a constant temperature room prior to extrusion. They were extruded at 1 cm intervals, except for core AB8, at 2 cm intervals below 20 cm depth.

Dry weight (DW) (overnight at 105 °C), wet density, and loss-on-ignition (LOI) at 550 °C and 1000 °C, to estimate organic content and carbonates respectively (Dean, 1974), were determined for all cores (Anderson, 1986a). Sediment wet density was estimated by packing sediment in to a brass vial of known volume, and the bulk density (g [DW] cm^{-3}) derived using the percentage dry weight. Lithostratigraphic analyses were on consecutive samples over the surface 20 cm, and at every second cm below that.

Diatom analysis followed standard methods

(Battarbee, 1986), and concentrations were determined using the microsphere method (Battarbee & Kneen, 1982). The error of this method has been estimated to be ca. 10% (Anderson, 1990). Full details of the diatom methodology employed in this study are given in Anderson (1986a).

Core analyses

All dates have been derived by core correlation and transfer of a ^{210}Pb chronology (cf. Battarbee, 1978a; Dearing, 1986; Anderson, 1986b) from a centrally located master core Augher 'A' (core taken, 1976; Anderson, 1989). These correlations were used to create time-depth diagrams from which the sediment accumulation rate (cm yr^{-1}) was estimated. Dry mass accumulation rates (g cm^{-2} yr^{-1}) were calculated for depth intervals using the sediment accumulation rate and the bulk density (g [DW] cm^{-3}) for that level.

10 cores (Fig. 1) with full biostratigraphic analyses (i.e. to sediment depths prior to the start of the creamery effluent disposal; Anderson [1989]) were used for calculation of dry mass accumulation rates. For biostratigraphic time zones (Anderson, 1989, 1990) a whole-basin mean dry mass accumulation rate was calculated. This estimate was not area weighted (cf. Engstrom & Swain, 1986) because of the poor relationship between accumulation rate and water depth, and because deposition patterns have changed with time (see below). The arithmetic mean was used, therefore, to calculate a relative accumulation rate for each time zone, which can be used to assist in the interpretation of changes in accumulation patterns (Engstrom & Swain, 1986).

Post-1940 cumulative fluxes

In core-based sediment distribution studies it is usual to plot accumulation rate against water depth (A–D plots in the terminology of Hilton, 1985; e.g. Kimmel, 1978; Evans & Rigler, 1980). Given possible problems with core correlation and the transfer of the ^{210}Pb chronology across the basin it was considered useful to use a method with as few errors as possible, to reduce ambiguity in the results. Therefore, a cumulative flux (dry mass, g cm^{-2}; diatoms, frustules $\times$ 10^7 cm^{-2}) above an unambiguous marker horizon (the *Stephanodiscus parvus* increase, ca. 1940; Anderson, 1989) was used, and these results used to assess the relationship between medium-term ($\sim 10^1$–10^2 yr) sediment accumulation and water depth. For 5 cores (Table 1) up to 8 consecutive levels were analysed to identify the *S. parvus* increase. In total 17 cores were used for the cumulative dry mass estimates and 13 for the diatom cumulative flux estimates.

For core AB8, for which no diatom analyses have been made, the depth was estimated from a mineral magnetic parameter horizon – the 'S-Ratio' decline – that has been identified to be approximately synchronous with the *S. parvus* increase in all cores for which both parameters have been analysed (Anderson, 1986b). For AB-cores taken in 1983, the surface 1–2 cm, depending on estimated accumulation rate, were excluded from the cumulative flux estimate to make them comparable to the early cores.

Because not all levels were analysed for diatom concentrations or bulk densities below 20 cm, the cumulative dry mass and diatom totals for the period 1940–1980 were estimated by trapezoidal integration (Swinborne, 1971). While using a clear stratigraphic marker horizon assists in minimumising error associated with between core correlation, error still results due to mixing. Resolution of the biostratigraphy and the inferred depth of mixing varies with core location and linear sediment accumulation rate (Anderson, 1990). However, the placement of the 1940 horizon varies by ± 2 cm, and with average bulk density of 0.2 g cm^{-2} at ca. 30–40 cm depth, the maximum associated error will be ca. ± 0.4 g cm^{-2} in any core.

The post-1940 cumulative flux results (which were based on a higher core density than the 10 cores used for temporal dry mass estimates; Fig. 1) were contoured using the programme Surfer (Golden Software Inc., Golden, Colo-

Table 1. Post-1940 cumulative fluxes for selected parameters.

Core	Water depth (m)	Dry mass (g cm^{-2})			Diatoms (frustules × 10^7 cm^{-2})		
		Total	Organic	Inorg.	Total	Plank.	Peri.
A7	14.5	5.28	1.64	3.64	69.4	26.6	42.8
AB8	14.5	5.55	*	*	*	*	*
AA2	12.5	4.40	*	*	54.6	16.3	38.3
AA4	12.4	9.16	2.36	6.80	113.8	39.8	73.9
A8	10.0	7.00	1.91	5.08	*	*	*
AA7	9.2	4.34	1.21	3.14	49.1	14.2	34.9
AA11	8.6	7.07	1.78	5.29	*	*	*
AA10	8.4	4.45	1.36	3.09	65.5	16.8	48.6
A4	8.0	3.49	0.94	2.55	37.1	8.9	28.2
AB4	8.0	4.21	0.97	3.24	16.9	2.9	13.9
AB1	8.0	3.78	1.06	2.72	48.3	*	*
AB2	7.5	4.18	1.21	2.98	35.0	9.4	25.6
AA12	6.8	4.60	1.41	3.19	56.0	11.9	44.2
AB6	4.5	3.81	1.10	2.71	*	*	*
A21	3.5	5.20	1.66	3.54	56.5	11.6	44.9
AA8	3.2	7.24	1.69	5.55	44.4	6.9	37.5
A10	1.5	5.25	1.98	3.27	44.4	10.4	34.1
Mean		5.24	1.49	3.79	53.2	14.6	38.9
SD		1.54	0.42	1.27	22.7	9.9	14.6
CV%		29.4	28.2	33.5	42.7	67.6	37.5
Weighted means:							
i. Depth area		5.3	*	*	53.8	*	*
ii. Isopleth		3.8	*	*	39.0	9.4	23.1
% difference#		−27%	*	*	−27%	−36%	−41%

* Not determined
# Compared to arithmetic mean.

rado). Whole-lake mean cumulative fluxes were determined by area weighting (using bathymetric intervals, cf. Battarbee *et al.* [1983]), and isopleth weighting using the contouring results, and these results compared to the arithmetic mean.

The post-1940 cumulative fluxes were correlated with various parameters to assess possible causal relationships. Slope was estimated from a detailed bathymetric map (Anderson, 1986a; Battarbee *et al.*, 1983). Perpendicular distance from shore to core site was used as a possible measure of the influence of macrophytes and distance from the inflow to core site was measured as a straight line.

Results

Loss-on-ignition profiles (Fig. 2)

LOI profiles can be split into four clear groups: three profundal groups, (i.e. cores in water depths >6 m), and littoral cores (water depths <6 m). Type I profundal cores (Fig. 2a) have LOI increases (to ca. 30%) towards the top of the core, with a series of clearly repeatable oscillations over the surface 20 cm. Type II profundal cores consists of a small subset of cores in the SE part of the basin with a characteristic decline in LOI values at ca. 10–20 cm depth (Fig. 2b). Type III
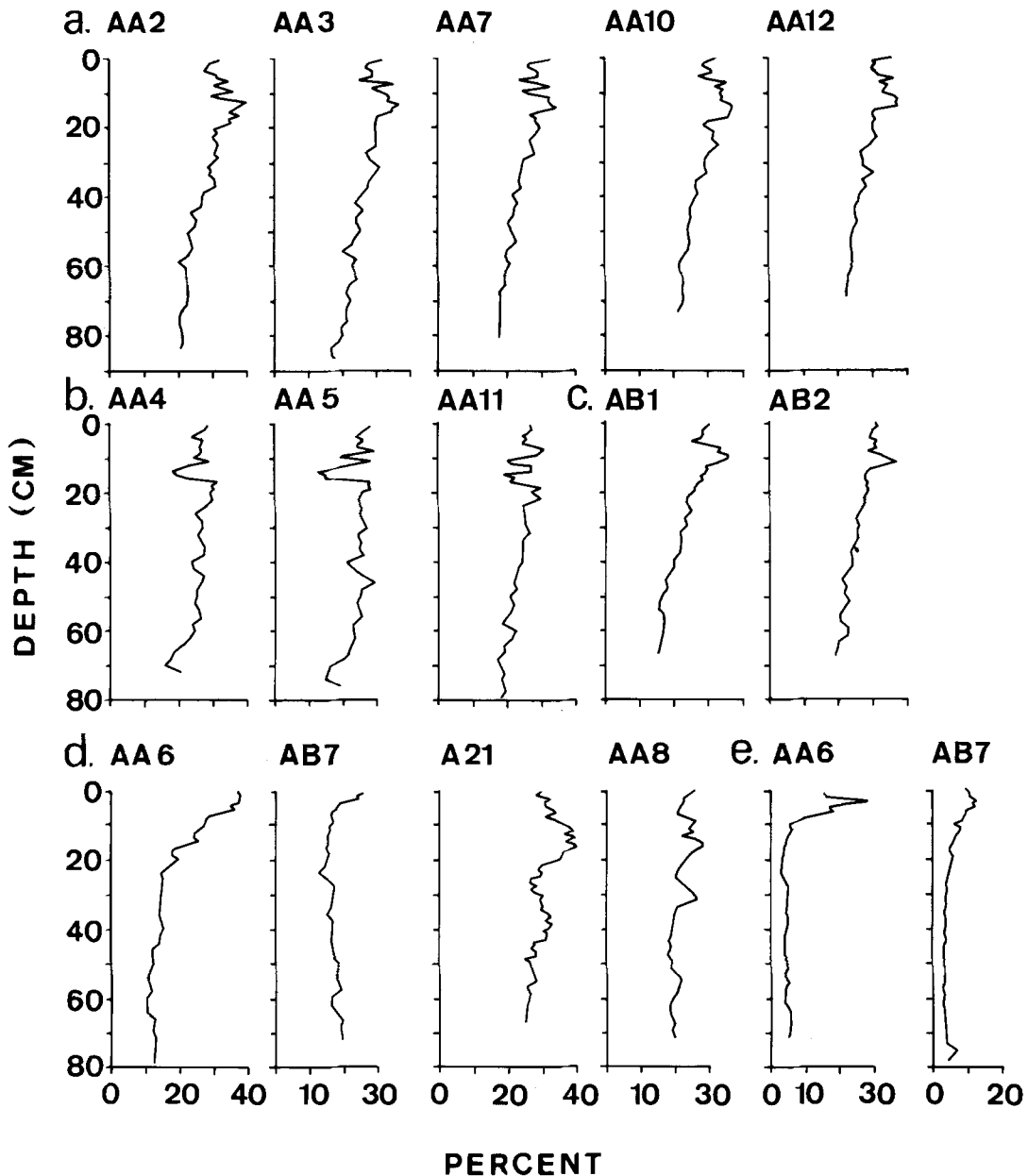
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Fig. 2. Loss-on-ignition (550 °C and 1000 °C) profiles for selected groups of cores. a–c profundal cores (550 °C): a, Type I; b, Type II; c, Type III; d, littoral cores (550 °C); e, littoral cores with increased carbonate (1000 °C) at core surface.

cores have a similar upcore increase, but with only one clear peak, and generally smoothed profiles (Fig. 2c). LOI profiles of littoral cores are more variable, with heterogenous profile trends and values compared to the deeper water cores (Fig. 2d).

Littoral core sites in water depths <3 m are also atypical in having carbonate surface maxima

of up to 30% (Fig. 2e). Carbonate values in profundal sediments increase above background levels with the eutrophication of the lake but are still low, ca. 8% (Anderson, 1989). The higher values in shallow waters result primarily from the high numbers of gastropods in the littoral zone (University of Ulster Freshwater Laboratory unpublished report); a conclusion supported by
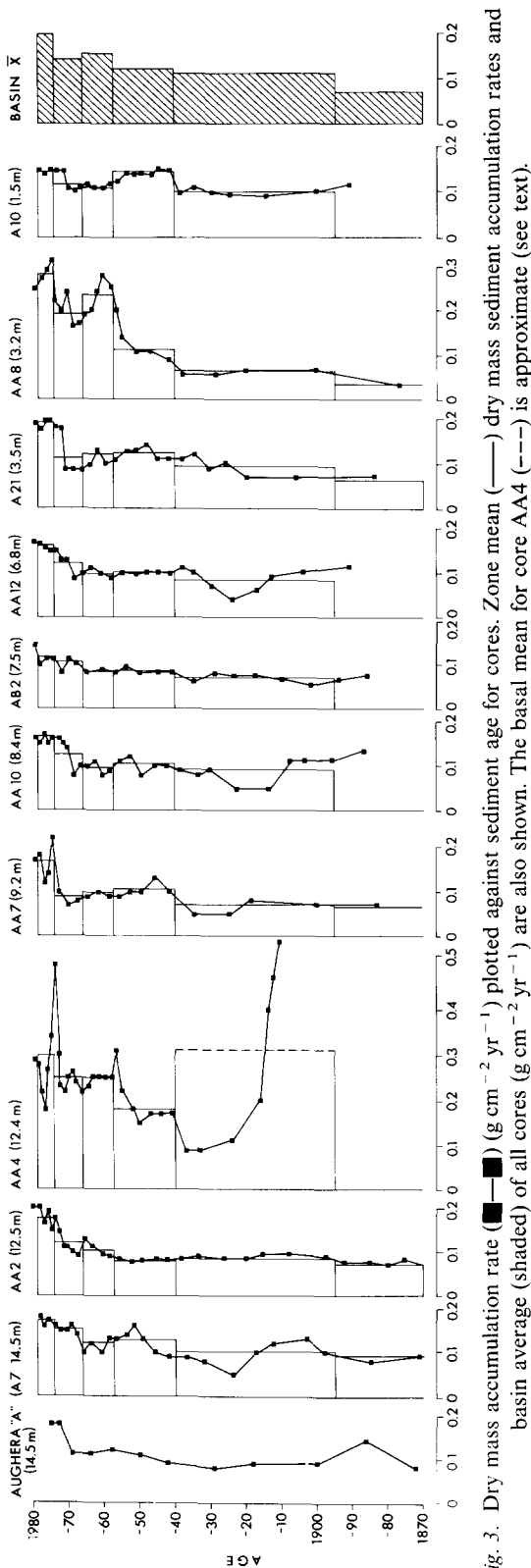
Fig. 3. Dry mass accumulation rate (■—■) (g cm⁻² yr⁻¹) plotted against sediment age for cores. Zone mean (——) dry mass sediment accumulation rates and basin average (shaded) of all cores (g cm⁻² yr⁻¹) are also shown. The basal mean for core AA4 (---) is approximate (see text).

observations of biogenic carbonate debris in the cores during extrusion.

Dry mass accumulation rates (DMAR) zone means, and average of all cores (Fig. 3)

All cores exhibit an increase of DMAR over successive time zones to surface maxima (after ca. 1970), apart from AA4 and AB2. A10 has a small increase between ca. 1940 and 1960, while A21 and AA8 show marked increases upcore, above low background levels. Despite some variability of profiles there is reasonable repeatability between nearby cores. For example, AA10 and AA12, two cores on the broad shelf at the north end of the lake, have similar profiles and rates. AA2 and A7 have a slight increase between 1900 and 1920.

AA4 is clearly distinguishable by its high values (after 1940, > 0.2 g cm⁻² yr⁻¹) and pronounced oscillations. However, the maximum values between 1895 and 1940 have to be considered tentative because the basal dates for the core were extrapolated: the high accumulation rate (> 0.8 cm yr⁻¹ over the length of the core) meant that core recovery did not include the *Aulacoseira ambigua* peak (ca. 1895) used to delimit the AU-1/2 biostratigraphic boundary (Anderson, 1989). Although high, these accumulation rates for the base of AA4 can be considered to be minimum estimates. In contrast, core AB2, at the edge of the 8 m shelf, and near the outflow, has DMAR rates below 0.1 g cm⁻² yr⁻¹ and the profile exhibits very little change.

The basin mean reflects these individual core trends, increasing from a mean of 0.068 g cm⁻² yr⁻¹ in the pre-creamery sediments (i.e. pre-1900) to ca. 0.2 g cm⁻² yr⁻¹ for the period 1974–1979, apart from a slight decrease between 1966–1974.

Relative accumulation rates (Fig. 4) show only small changes over time for a number of cores (e.g. AA2, AA10, AA12, AB2). There is no clear relationship with water-depth, which has important implications for process inference and core representativity. A number of cores are close
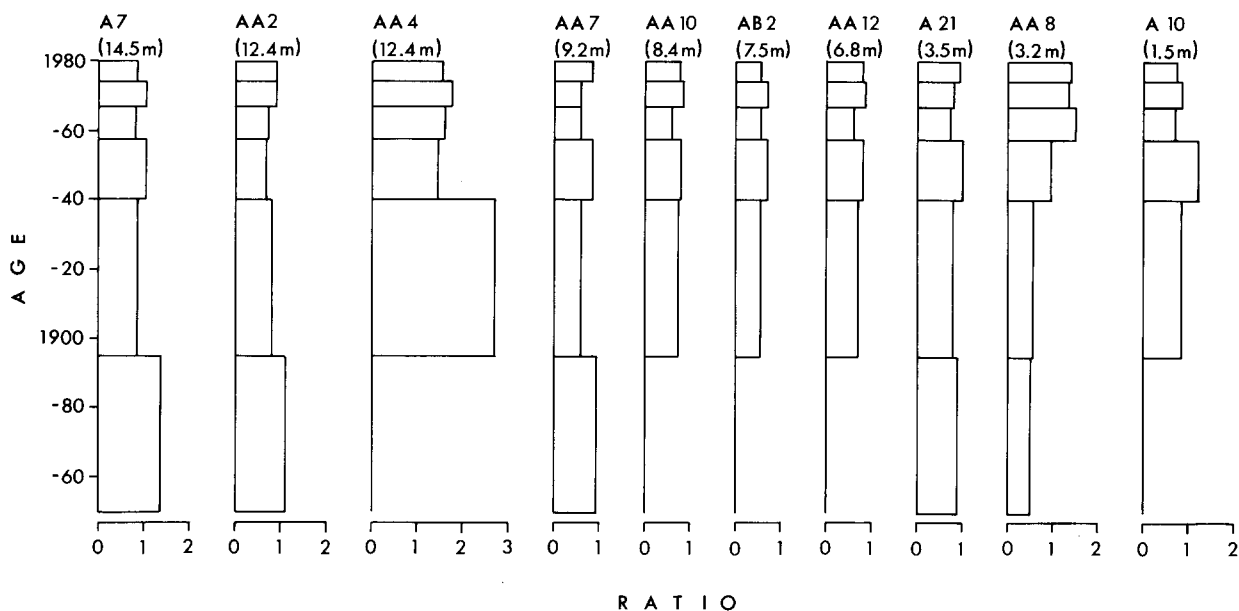
Fig. 4. Dry mass relative accumulation rates (RAR), see text for explanation. In RARs, 1 represents the basin mean, and they show, therefore, the extent to which individual cores over or underestimate the basin average.

to the average accumulation rate of all cores, e.g. AA2, (12 m), AA10 (10 m) and A21 (3 m). AB2 (8 m) has a relative accumulation rate < 0.5 of the average, while AA7 declines to ca. 0.5 in zones AU-4 and 5, despite a water depth of 8 m. A7 situated in the deepest part of the lake has a slight decline over the most recent time periods in its proportion of the mean sediment accumulation. AA8 (3.5 m) has a clear increase in the amount of sediment accumulating at that site. AA4 has an accumulation rate between 1.5 and 3 × that of the average.

Post-1940 cumulative accumulation (Table 1)

Dry mass, and inorganic and organic fractions (Fig. 5a & b)
Cumulative dry mass is not related to water depth (Table 2). The maximum, $9.16 \, g \, cm^{-2}$ at site AA4, occurs outside the deepest area of the basin. However, other cores analysed in the SE corner of the basin, A8 and AA11 also have higher than average values for cumulative dry mass (ca. $7.0 \, g \, cm^{-2}$ for both cores). The inorganic fraction

(Fig. 5b) shows a similar pattern to that of the total dry mass, while the organic fraction is more uniform between all core sites. Dry mass has relatively uniform spatial distribution, with cumulative rates $> 5 \, g \, cm^{-2}$ restricted to the S.E. part of the lake (Fig. 7a).

Table 2. Correlation coefficients for relationships between selected cumulative flux parameters and morphometric parameters assumed to influence sediment and microfossil deposition.

	Water depth	Slope	Distance from shore	Distance from inflow
Dry mass	0.17	0.19	− 0.12	− 0.64**
Organics	0.10	0.08	− 0.21	− 0.45*
Inorganics	0.26	0.22	− 0.09	− 0.68**
Total diatoms	0.46* 0.31#	− 0.12	0.35	− 0.31
Planktonic	0.66** 0.66*#	− 0.33	0.59*	− 0.42
Periphytic	0.30	− 0.02	0.25	− 0.21

Excluding AA4.
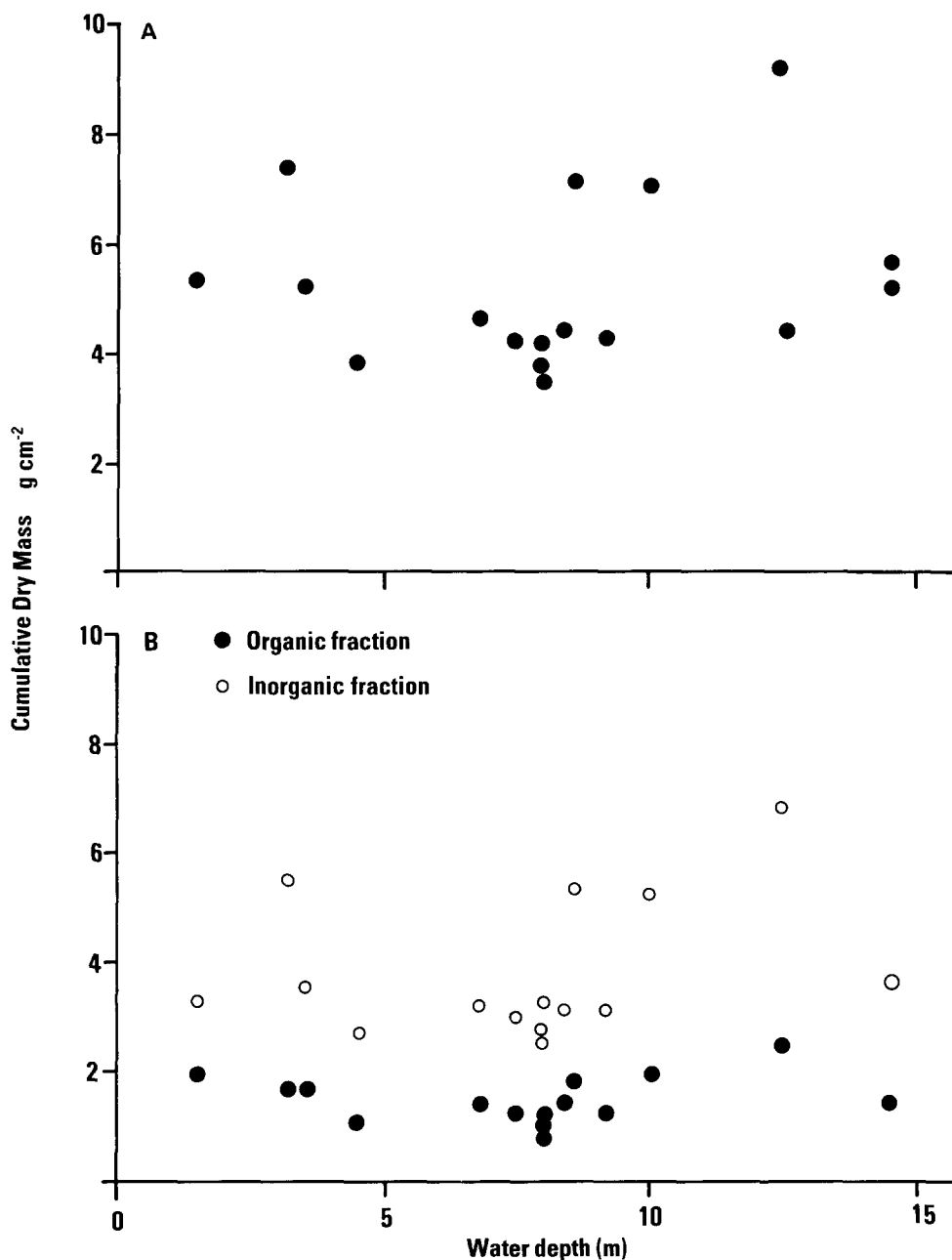Significance * $P < 0.05$; ** $P < 0.01$.

Fig. 5. Post-1940 cumulative flux plotted against water depth. A. Total dry mass. B. Inorganic and organic fraction.

Total diatoms, and plankton and periphyton components (Fig. 6a & b)

The total diatom – water depth relationship is poor ($r = 0.46$ Table 2). The plankton diatom – water depth relationship is, however, better ($r = 0.66$), as one would expect given the relation-

ship between plankton productivity and water depth. For all A-D relationships the r-value is influenced strongly by core AA4, which enhances the result. For the relationship between water depth and planktonic diatoms, however, the relationship is not altered by the removal of AA4,
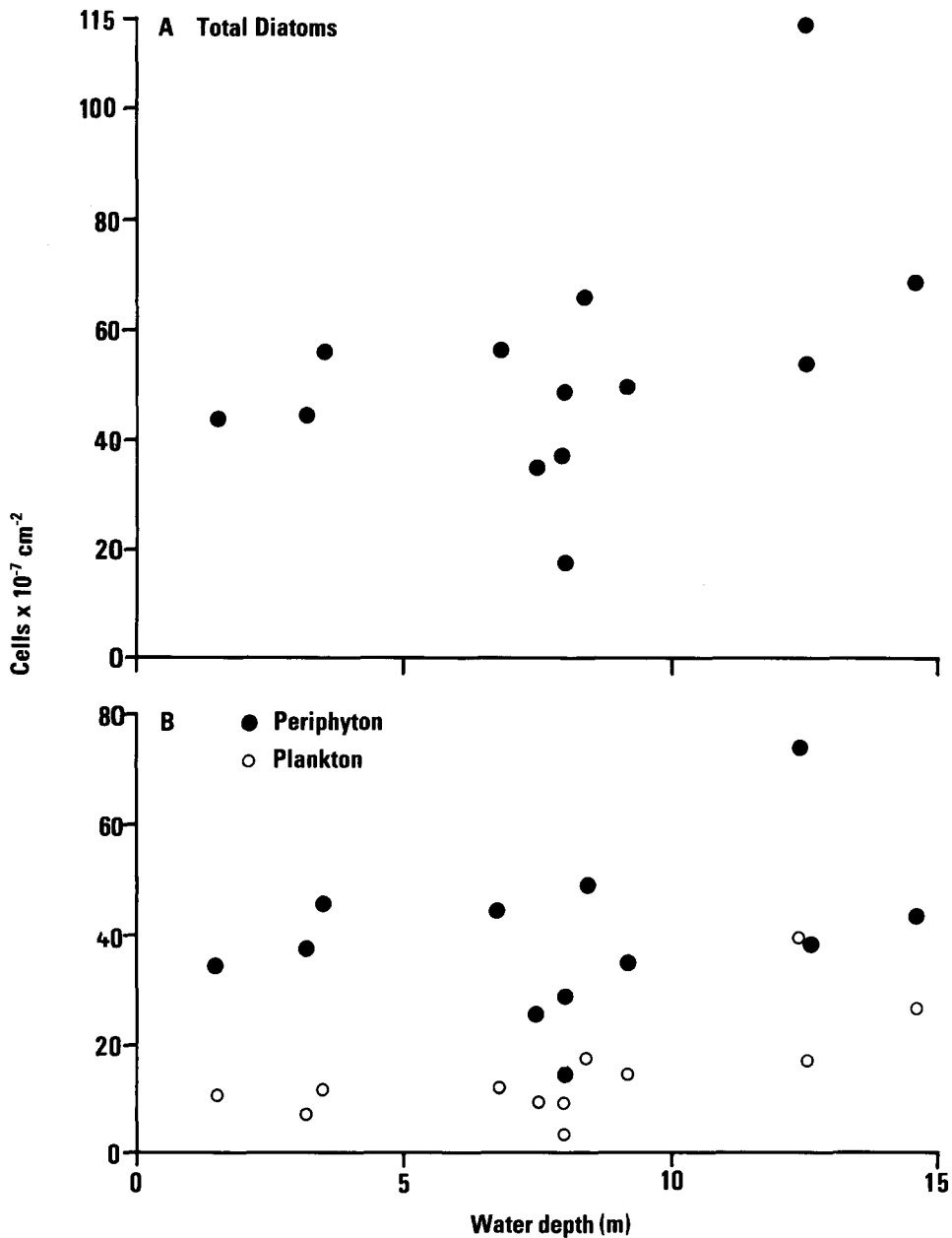
Fig. 6. Post-1940 cumulative flux plotted against water depth. A. Total diatoms B. Plankton and periphyton components.

r is 0.66 in both instances. Cumulative total diatom fluxes $> 50 \times 10^7$ frustules cm^{-2} are confined to a central north-south zone, with maximum rates offset from the deepest part of the lake (Fig. 7b). Planktonic diatoms have a pattern largely similar to that of total diatoms (Fig. 7c). Periphytic diatoms, however, have a more even accumulation pattern with cumulative fluxes

$> 40 \times 10^7$ frustules cm^{-2} occurring at both ends of the lake, but the maximum area is in a similar position to other variables (Fig. 7d), and reflects the influence of core AA4.

No cumulative flux estimates are correlated with slope, and only planktonic diatoms are correlated with distance from shore ($r = 0.59$), in part a result of the inter-relationships between
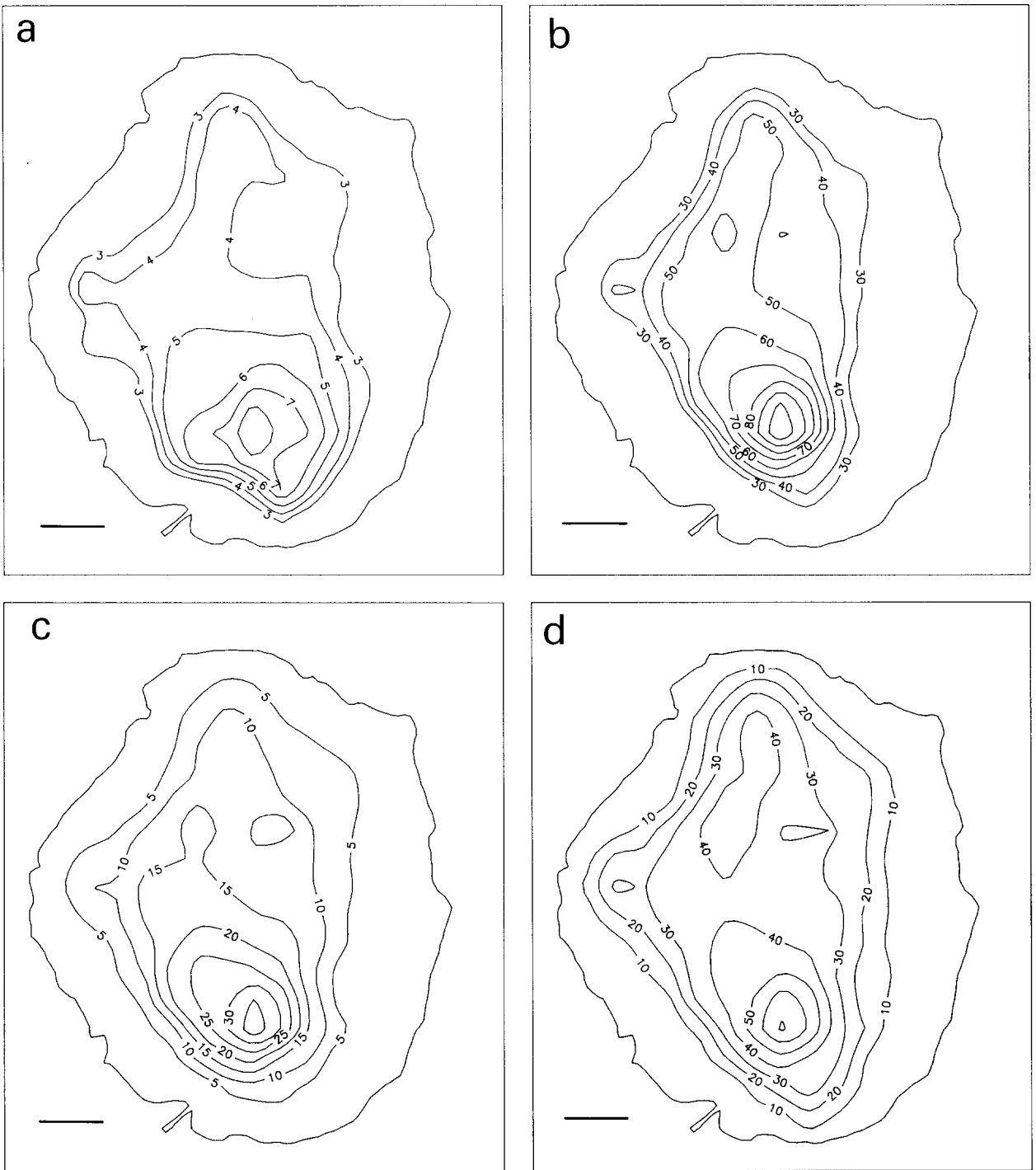
Fig. 7a–d. Results of contouring of the post-1940 cumulative flux data. a. total dry mass (g cm^{-2}), b. total diatoms, c. plankton, d. periphyton. (b–d frustules $\times$ 10^7 cm^{-2}). Scale bar represents 50 m.

depth and morphometry (Table 2). Dry mass and inorganic fractions are inversely correlated with distance from inflow ($r = -0.64$ & -0.68 respectively), and to a lesser extent so are organics and planktonic diatoms ($r = -0.45$ & -0.42 respectively; Table 2).

Whole-basin averages (Table 1)

The greater number of cores used for the post-1940 estimates permitted area weighted and isopleth means to be calculated, and these results compared to the arithmetic mean. For both dry mass and total diatoms there is good agreement between the area weighted and arithmetic estimates, but they are higher than the isopleth estimated mean. Area weighted means are 5.3 g cm^{-2} and 53.8 frustules $\times$ 10^7 cm^{-2} for dry mass and total diatoms respectively; compared to arithmetic means of 5.2 g cm^{-2} and 53.2 frustules $\times$ 10^7 cm^{-2}. Isopleth means of the four variables are between 26 and 41% lower than the arithmetic mean.

Discussion

Given Augher's morphometry and its seasonal stratification, Hilton's (1985) model predicts that sediment accumulation within the lake should be dominated by intermittent complete mixing (ICM) processes. However, the relationship between all post-1940 cumulative fluxes (except planktonic diatoms) and water depth is poor (Figs. 5 & 6; Table 2), certainly when compared to some previously published studies (Kimmel, 1978; Evans & Rigler, 1980; Davis & Ford, 1982; Hilton et al., 1986). Recent sediment accumulation rates in the littoral zone are high, with cores having both distinctive dry mass curves (Fig. 3) and post-1940 cumulative fluxes (Fig. 4; Table 1). Water depth accounts for little of the observed variability in sediment distribution, i.e. sediment focusing is not a dominant process.

The scatter on the A : D plots (Figs. 5 & 6) suggests a strong random resuspension (RR) component (Hilton et al., 1986), but this itself is unlikely to a major factor. There are clear differ-

ences between littoral and profundal sediments, based on the lithostratigraphy (Fig. 2) and the biostratigraphy (Anderson, 1990), suggesting systematic differences between processes controlling sediment accumulation patterns within the lake. Dominance of ICM processes is not supported by the high resolution of the ^{137}Cs profile, which agrees very well with the theoretical fall-out for N.W. England (Anderson, 1986a): physical resuspension processes should, theoretically, result in a loss of stratigraphic resolution. Augher is a relatively deep-lake given its surface area, and it may be that ICM processes have reduced effectiveness in deep, sheltered systems. Smith (1975) suggested that resuspension may be reduced by a laminar layer at the sediment-water interface. Similarly, Bloesch & Uehlinger (1986) found little evidence for resuspension in the deepest areas of Lake Hallwill (Switzerland). There is an obvious need for more measurements of current speeds at the sediment-water interface, their ability to resuspend material in different lakes and at varying water depths.

Using Hilton's (1985) criteria, there are a number of possible explanations for the sediment accumulation patterns observed in this study: a.) non-uniform original sediment input, together with localised resuspension processes; b.) variable organic loadings and sources, together with the influence of macrophytes on circulation patterns; c.) localised stream inputs; d.) basin wide circulation processes (hydrodynamics) and stratification breakdown, and e.) sediment slumping from steep slopes.

Although slopes are locally quite steep within the basin, the conformity of the biostratigraphy, both for cores close to and on slope sites (e.g. A21 and AA12), strongly suggests that slumping is not an important process in this lake. Slumping may, however, account for the low cumulative fluxes of cores AB4 (slope > 15%) and AB6 (ca. 30%). However, a number of other cores have slopes > 15% (cf. Håkanson & Jansson, 1983) but have either conformable stratigraphy or high cumulative fluxes. Slumping can of course be catatrosphic, occuring intermittently over timescales of 10^2 yr, and not discernible from core data,

except as atypical biostratigraphy, as suggested by cores A4, AB6 and AB4 (Anderson, 1986a).

Influence of the inflow

Type II cores with high accumulation rates (AA4, AA11, AA5, A8) in the S E corner of the basin, are probably influenced by the inflow stream (Figs. 2b & 7a; Table 2). The decrease in LOI values around 12–16 cm in cores AA4 and AA5 (Fig. 2b) is caused by a large increase in % dry weight, probably due to a minerogenic 'inwash' associated with an isolated flood event. These depths have higher bulk densities (> 0.2 g cm^{-3}) than comparable depths in other cores (0.12 g cm^{-3}), and the increased allocthonous input diluted diatom concentrations (Anderson, 1986a, 1990). Removing the dry mass value of these levels from the post-1940 cumulative flux of AA4 gives a value of 8.22 g cm^{-2}, still considerably higher than both the average of all cores, and the flux for other individual cores from the profundal zone (e.g. A7, AB8). These data and their spatial distribution (Fig. 7a) support the supposition that this area of the lake is influenced by the inflow, and/or sediment focusing into a localised area.

While the influence of the stream is most obvious on the Type II deep-water cores, it may also affect nearby littoral accumulation (i.e. core AA8). The occurrence of high values for littoral cores away from the inflow (A21, A10), however, suggests that other mechanisms are also important (cf. macrophyte discussion below). Littoral cores at the north end of the basin have cumulative dry mass values of ca. 5.2 g cm^{-2}, the same as the average for all cores (Table 1; Fig. 6a), and greater than some cores in deeper water. Assuming an overt influence of the inflow on Type II cores, and excluding them from the A–D scatter plots, does not improve the cumulative dry mass – water depth relationship (Table 2).

The possible influence of the inflow on diatom flux is more difficult to assess. Core AA4 has very high cumulative fluxes of both periphytic and planktonic diatoms. Diatom concentration is inversely related to sediment accumulation in core AA4 ($r = -0.89$; cf. Anderson, 1990). If large numbers of diatoms are derived from the inflow an inverse relationship or dilution would not be expected. Repeatability of biostratigraphy between AA4 and other cores (Anderson, 1990) also suggest that the S.E. corner of the lake is not overly influenced by allochthonous diatom inputs. It is not known if the River Blackwater supports large phytoplankton populations as found in some small rivers (Swale, 1964; Lack, 1971). However, there have to be diatoms derived from the inflow (at least periphytic forms, e.g. Marker & Gunn, 1977), but without monitoring of the inflow, or some suitable diatom that grows only in the river/stream and which can be used as a natural tracer, it is not possible to assess critically this problem.

It may be that the cores in the SE corner of the basin represent both sediment focusing (to account for the high plankton accumulation rates) and, coincidentally, inflow effects on the cumulative dry mass. Equally, there may be some process by which the two are interrelated (i.e. increased retention associated with higher accumulation rates).

Macrophytes

Hilton et al. (1986) considered the influence of macrophytes on sediment distribution processes and patterns to be relatively unimportant. While this may be acceptable in a mesotrophic lake like Esthwaite Water where littoral macrophytes are few, in many eutrophic lakes in North-west Europe and North-East North America, littoral macrophytes are an important component of a lake's carbon budget and metabolism (Wetzel, 1979; Carpenter & Lodge, 1986; Moeller & Wetzel, 1988). Mirror Lake (Moeller & Wetzel, 1988), Bob Lake (Evans & Rigler, 1980) have erosional margins, contrasting with the accumulating and prograding littoral zones (Carpenter, 1981) of Lawrence Lake (Moeller & Wetzel, 1988) and Augher. Sediment accumulation models must be able to account for these differ-

ences. The high, and increased accumulation rates over the last 40 yr at littoral sites in Augher (Fig. 3) suggest that macrophytes may be of possible importance in determining sediment accumulation. Although cumulative fluxes were not correlated with distance from shore, the latter may not be a good measure of their influence.

The possible importance of macrophytes at this site may be due to two related factors. The lake level was raised in the 18th century (or earlier), and presumably provided an important area for submerged macrophytes to colonise when conditions permitted it: i.e. changes associated with the eutrophication of the lake. By utilising the littoral shelf created by the higher water level and the increased nutrient availability associated with the creamery effluent, *Myriophyllum spicatum* may have expanded rapidly (Carpenter, 1980a), and together with *Potamogeton natans* resulted in higher localised organic loads to the littoral sediments (cf. Moss *et al.*, 1986; Carignan, 1984), perhaps iniating a process of sediment accumulation and progadation (Carpenter, 1981). The increased DMAR in shallow water cores (Fig. 3), and the increased accumulation of periphytic diatoms associated with the habitat expansion provided by the macrophytes (Anderson, 1989) support this hypothesis.

The hypothesis is supported further by the known effects of macrophytes on changes in basin hydrodynamics, through velocity reduction and increased sediment trapping (Petticrew & Kalff, 1988), together with enchanced, localised organic loads (Carignan, 1984; Moss *et al.*, 1986; Carpenter & Lodge, 1986; Moeller & Wetzel, 1988).

If peripheral wave action had been important in the past any macrophyte expansion would have reduced its effectiveness. Process change associated with the expansion of the macrophytes may be one reason why patterns of diatom and sediment distribution have changed in more recent time-periods (Anderson, 1990). DMAR for the period 1870–1900 has a significant positive relationship with water depth (dry mass = 0.033 + 0.004 water depth; $r^2 = 80\%$, $n = 5$, $P < 0.05$). By retaining more sediment (and diatoms) at its initial deposition site, and adjacent

to it (Figs. 4 & 5), macrophytes may have decreased sediment focusing (cf. Anderson, 1990).

High cumulative dry mass in the littoral zone is due to high inorganic loadings to the sediments (Fig. 4a), including carbonate deposition (Fig. 2e). The littoral sediments have abundant molluscan debris, which is probably the main source of the carbonate, rather than biogenic precipitation associated with charophytes (Dean, 1981). The profundal cores also show some increase in carbonate content, the timing of which agrees well with other eutrophication indicators (e.g. LOI and *Stephanodiscus* profiles), suggesting that it may result from increased algal productivity (Anderson, 1989).

Post-1940 cumulative organic matter flux is relatively uniform at all core sites (Table 1; Fig. 7b); these results do not, however, distinguish between different organic sources (cf. Carpenter & Lodge, 1986). The clear repeatability of profundal (Type I) LOI profiles (Fig. 2a) strongly suggests a uniform input and/or diagenesis, probably from increased planktonic productivity in the post-war years (particularly cyanobacteria during the summer months). In contrast, the littoral cores, as well as initially receiving planktonic derived material, will also have high loads associated with the annual die-back of macrophytes within the basin, in particular *Myriophyllum spicatum* (e.g. Carpenter, 1980b; Barko & Smart, 1980; Carignan, 1984; Moss *et al.*, 1986). In the littoral zone, mineralization of the labile planktonic component in oxic eplimnetic water and surface sediments prior to burial may result in an increased importance of refactory macrophyte debris, mixed together with minerogenic material trapped by macrophytes (above).

Type III LOI profiles are interpreted as resolution loss resulting from either, the use of a standard sample interval (1 cm) on cores of a lower linear sediment accumulation rate, or increased sediment mixing as a result of the lower sediment accumulation rate. For example, AB2 in Fig. 2b, has a mean sediment accumulation rate (1900–1980) of 0.45 cm yr^{-1}, which can be compared to a basin mean of ca. 0.6 cm yr^{-1} (Anderson, 1990). As the cores are situated below the

thermocline, bioturbation will be reduced compared to littoral, oxic sediments, suggesting that a finer sample interval would have resulted in LOI profiles similar to the type I cores.

Although the relative fetch was not calculated, in a small lake such as Augher it is unlikely to vary much across the basin (cf. Hilton & Gibbs, 1984), suggesting that for this lake exposure is not an important influence on the variability of sediment accumulation. However, the low accumulation rates observed at site AB2 (Figs. 3 & 5; Anderson, 1990) are not easy to explain, but the core is at the theoretically wind stressed end of the lake, and near the outflow. The reasonably good resolution of the biostratigraphy at this core site does not support the idea of extensive resuspension, since the latter would result in reduced resolution due to interface mixing. The low cumulative flux perhaps indicates some mechanism of redistribution of the seston prior to deposition, independent of water depth. Sediment may be lost down-slope, but this process would theoretically influence sites A21 and AA12 more, but they have higher cumulative accumulations. Equally, the low fluxes at AB2 may be due to wash out down the outflow, which is situated close by.

Core representativity and whole-basin estimates

The use of an arithmetic basin mean is probably an overestimate because of the equal weighting it gives to the type II cores, which are confined to the S.E. part of the basin (Fig. 7). The difference between the different methods used to estimate the post-1940 mean, may not, however, be that significant in a small lake such as Augher, and the difference will decrease as more cores are used (Foster et al., 1985). Both the isopleth and bathymetric area weighted average extrapolate over the shallow littoral zone, from which no cores were taken. There is good reason to suspect that sediment accumulation actually increases in the macrophyte beds proper (Carpenter & Lodge, 1986), and any estimate for accumulation rates for this area based on cores from outside will be in error. However, the accuracy of these whole-basin mean estimates cannot be interpreted

without some independent measure of diatom or sediment production within the lake.

The change over time of the dry mass sediment accumulation pattern (Fig. 4) is not as great as that found by Engstrom & Swain (1986). Prior to 1900, however, sediment was more strongly focused into deep-water (above), as with the diatom accumulation rate data (Anderson, 1990). The error in the pre-1900 basin mean and RAR (Figs. 3 & 4) is probably greater than the post 1940 estimates because of the reduced number of cores used for the pre-1900 calculations. Without further cores to fully assess the pre-1900 sediment spatial distribution it was not considered justifiable to area weight the data prior to calculation of RARs. Strictly, therefore, the RAR diagram may not be an accurate representation of the whole basin (Engstrom & Swain, 1986).

The post-1940 cumulative flux data indicate the greater variability of diatom accumulation data (CV: 42.8%) compared to dry mass (CV: 29.4%). For diatoms, core AA2, situated to the western side of the basin (Fig. 1), approximates the mean rate very well (cf. Anderson, 1989). For dry mass, the profundal cores, A7 and AB8, are very close to the mean; a result not found by other studies (e.g. Dearing, 1986). However, the cumulative flux data do not indicate the degree to which the pattern of deposition is temporally variable (Fig. 4; Anderson, 1990). The deep-water cores would over estimate past accumulation rate (Fig. 4).

The differences between diatoms and dry mass accumulation are complicated further when planktonic and periphytic components are considered and demonstrate the complexity of selecting a single core site for extrapolating to the whole basin (cf. Anderson, 1990; Dearing, 1983, 1986; Engstrom & Swain, 1986). For the diatoms the changes over time (Anderson, 1990) and the poor relationship with water depth (Fig. 6) mean that it is difficult to indicate one core that is representative of basin wide accumulation rates. Although AA2 is quite close to the basin mean for both dry mass (Fig. 4) and diatoms (Anderson, 1989) it is not in a position normally chosen for core location (cf. Dearing, 1983).

The differences observed in the LOI profiles are to some extent indicative of the biostratigraphy of individual cores (cf. Anderson, 1986b). Littoral cores have both distinct LOI profiles, as well as strongly mixed biostratigraphic profiles; single peak LOI profiles (type III cores, Fig. 2c) also have reduced resolution in their biostratigraphy (Anderson, 1990). These relationships are sufficiently good that LOI profiles could be used diagnostically for any further cores taken within the basin; i.e. it would be possible to assess what type of biostratigraphy would result from any core obtained, and whether it warrants actual analysis. LOI analyses are quick to do, compared to time-consuming biostratigraphy, and if similar relationships are found to hold in other lakes then it may be possible to check variability of sediment accumulation patterns by LOI profiles, and consequently chose a 'representative site' on an *a priori* basis, rather than merely going to the deepest part of the lake.

Conclusions

The poor relationship of sediment parameters and water depth observed at this site suggest that sediment focusing is not the dominant process determining the sediment distribution, and contrasts with studies of other small lakes (Kimmel, 1978; Evans & Rigler, 1980). However, it is unlikely that random resuspension processes are dominant (cf. Hilton, 1985). The hypothesised role of littoral macrophyte beds offers a plausible explanation of sediment distribution away from the localised S.E. area influenced by the inflow, and to account for high sediment accumulation in shallow water. Macrophytes probably have both a direct and indirect influence on sediment retention in the littoral zone, through decreased efficiency of sediment resuspension processes, and higher organic loads (Carpenter & Lodge, 1986).

Augher does not fit well into Hilton's (1985) model for sediment accumulation in a small, but relatively deep lake, in terms of the dominant process predicted to control sediment distribution. Further data from different systems are re-quired to enhance the model. Also, the lack of a clear erosional-transport zone in Augher suggests the inapplicability of Håkanson's work (Håkanson & Jansson, 1983) to small, eutrophic lakes, with abundant macrophytes.

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