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Transport Mechanisms and rates for the  
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The results of this work will be used in the formulation of Government Policy, but views expressed in this report do not necessarily represent Government Policy.

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## Executive Summary

A programme of work has been carried out to determine the various transport rates and mechanisms of Chernobyl radionuclides moving from catchment areas to rivers, reservoirs, lakes and sediments. In so doing the potential for Cs to be retained by and remobilised from sediments was assessed, along with the amount of deposited radioactivity which was in soluble form and hence was available in drinking water.

Only a limited Ru-103 data set was obtained before it had decayed away below detection limits. However, results from this period showed that Ru mirrored Cs in its behaviour as it was measurable in the sediments at the same time after the deposition and it was trapped in the bottom waters of the lake. A substantial Cs data set was obtained for two lakes, Windermere and Esthwaite Water and it could be interpreted, with the aid of mathematical models developed during this study, to indicate the major processes and pathways operating in the transport of Cs through lake catchments.

During the initial period after the deposition a maximum of 27% of the Cs in the water column was found in the particulate form and rapidly (months) reduced to 10-15% of the total. Total water column concentrations had reduced to half their initial measured values within 15 days in Esthwaite Water and 70 days in Windermere. Cs-134 was observed in surface sediments within 7 days in Esthwaite Water (15.5 m deep) and 30 days in Windermere (65 m deep) which, from a knowledge of mixing regimes of the lakes can be interpreted in terms of similar settlement velocities of 1-2 m per day. A small proportion of Chernobyl material was rapidly moved into the sediment as shown by small concentrations of Cs-134 being found at a depth of 8 cm after one year. This indicates that a non-diffusional transport mechanism, such as bioturbation, may be important for the transport of particulate caesium in sediments.

A model was developed assuming that: i) either the epilimnion or the epilimnion and the metalimnion were completely mixed; ii) direct transport of soluble caesium to sediment was minimal; iii) after the initial deposition event no Cs entered the lake via the inflow; iv) the transfer factor to particulate material remained constant. It showed that 34-60% of the Cs was lost via the outflow of Esthwaite Water with 40-66% accumulating in the sediments. In Windermere 26-38% went out the outflow and 62-74% to the sediments. The data are consistent with Cs being transported to the sediments on algal particles at settling velocities of about 1.5 m per day. This velocity is very close to the value estimated directly from the delay before Cs was observed in the sediments. The time dependence and total loads of Cs accumulation in the sediments-estimated from the model prediction of water column losses, assuming no catchment input, agreed well with measured values.

Deposition loads estimated from rainfall data were I-131 11200 Bqm<sup>-2</sup>, Cs-137 2030 Bqm<sup>-2</sup>, Cs-134 1270 Bqm<sup>-2</sup>. Initial lake water Cs concentrations estimated from these fluxes agreed with concentrations estimated by extrapolation of the measured concentration in the water column to the time of maximum Chernobyl deposition. In 1986 Cs was trapped in the isolated bottom waters as deep water concentrations remained approximately constant after thermal stratification had developed in May until the lake completely mixed in the autumn, when concentrations reduced rapidly to the low values observed in the surface water by this time. In Esthwaite Water Cs was released from the sediments in the summer of 1987, into the bottom waters which were devoid of oxygen reaching a mean concentration of 8.3 Bqm<sup>-3</sup>. The total amount released was equivalent to only 1% of the sedimentary store.

The following conclusions can be drawn:-

- 1) For a given atmospheric deposition flux the initial lake concentration will be inversely related to the mean depth or to the mixed layer depth in a stratified lake.
- 2) Epilimnetic concentrations decline quickly due to a combination of flushing and settling.
- 3) Remaining Cs is mainly (90%) in the solution phase.
- 4) Very little Cs was remobilised from the clay catchments studied in this work.
- 5) Only a small proportion of the sedimentary Cs was remobilised into the water column although significant concentrations were developed therein.
- 6) Cs was probably transported to the sediments by phytoplankton.

## SCHEDULE 1 - PROGRAMME OF RESEARCH

## TRANSPORT MECHANISMS AND RATES FOR THE LONG LIVED CHERNOBYL DEPOSITS

Objectives

To determine the various transport rates, and mechanisms for Chernobyl radionuclides moving from catchment areas to rivers, reservoirs and lakes.

To assess possible retention and re-mobilisation of Cs in sediments.

To assess the fraction of deposited radioactivity that will remain in sediments.

## SCHEDULE 1 - WORK PROGRAMME

(i) Assessment of the rate and extent of removal of Cs and Ru from surface waters to lake/reservoir sediments and the relative amounts which can escape lake/reservoir systems via river outflows.

(ii) Quantification of the inputs associated with (a) direct deposition onto the lake/reservoir, and (b) deposition on and subsequent transport from the catchment to the lake/reservoir.

(iii) Assessment of the possible redistribution and remobilisation of sediment-bound Cs and Ru.

(iv) Determination of the main mechanisms of Cs/Ru removal from lake/reservoir waters to sediments.

(v) Measurement of solid/solution distribution coefficients (i.e.  $K_d$ ) in lake/reservoir waters of various types.

## Introduction

The Chernobyl reactor accident has led to increased levels of radionuclides in the environment, principally Cs-137. This contamination provides an opportunity to better understand transport mechanisms and rates of Cs movement from the catchment areas to rivers, reservoirs, lakes and the sea. There is an opportunity to distinguish between direct deposition on to the lakes and reservoirs and the contribution from the catchment areas.

Three sampling strategies were devised to determine both the various transport rates, and mechanisms for Chernobyl radionuclides moving from catchment areas to rivers, reservoirs and lakes, and to assess possible retention and re-mobilisation of Cs-137 in sediments.

### Sampling strategies

Because the objectives were interlinked a series of different but interdependent sampling strategies was developed.

#### a) Sediment profiles + water column

Starting from the 13th May (7 days after the major deposition of Chernobyl derived material) water samples were collected at a gradually decreasing rate (Table 1) from two lakes, Esthwaite Water and Windermere North Basin, which run parallel to, and within 2 miles of each other, in the same Silurian slate bedrock. The two lakes were chosen because of their different morphological and trophic status. Esthwaite Water is a relatively shallow (15.5 m max depth; 5.3 m mean depth), small (total surface area 1.004 km<sup>2</sup>), eutrophic lake which stratifies annually and develops anoxia in the hypolimnion during the summer and early autumn. The North Basin of Windermere (the north and south basins of Windermere can be considered as two separate lakes) on the other hand is a deep (max depth 64 m; mean depth 25 m), large (surface area 8 km<sup>2</sup>), mesotrophic lake which, although it stratifies annually, does not lose all the oxygen in the hypolimnion.

On each sampling date starting from the 8th May (Table 1) a sediment core was taken with a Jenkin Corer from the deepest point of both lakes. On returning to the laboratory, cores were sliced into one cm sections, dried at 60°C to obtain the percentage water content and then transported to ITE Merlewood for  $\gamma$ -spectroscopy on each section. All sedimentary Cs concentrations are reported relative to the dry weight of sample. During the same sampling trip 10 l samples were taken using a peristaltic pump from the upper water layer (Esthwaite 3 m, Windermere 3 m) and from the lower water layer (Esthwaite 13.5 m, Windermere 45 m). In the laboratory these samples were filtered through 0.45  $\mu$ m Millipore filters. Hypolimnetic samples from Esthwaite were not filtered prior to evaporation when strongly anoxic conditions were prevalent as large quantities of ferric oxide floc formed on contact with the air. Subsamples were taken for quantifying suspended solids and analysis of carbon and nitrogen using a Carlo Erba CHN analyser. Particulate material and water were transported to the Department of Environmental Science at Lancaster University where they were counted separately. Particulate material was counted directly on the filter. Water samples were evaporated to 100 ml and counted after addition of EDTA to redissolve precipitated iron.

Gamma spectra in the range 60-1800 keV were obtained using 40% relative efficiency hyperpure germanium detectors, counting into 4096 channel MCAs. Spectral analysis was performed using Camberra Apogee software, running on a microVAX computer. The detector was calibrated using standards of appropriate density and geometry, prepared from a mixed radionuclide standard solution supplied by NPL. Analysis of appropriate IAEA reference materials showed the results to be acceptably accurate.

#### b) Sediment Grids

Black Beck, the major inflow to Esthwaite Water, enters at a narrow, shallow part of the lake (Fig. 1). At less frequent intervals than outlined in

(a), (Table 1), sediment samples were taken in a grid pattern (Fig. 1) from 16 sites which were located using a 'Geodimeter' equipped with a laser range finder. In the laboratory the top two centimetres were removed as one sub-sample and dried at 60°C to obtain the percentage water content. The -spectroscopic analysis of each subsample was carried out at ITE, Merlewood.

#### c) Water Profile

On 27 August 1986, 10 l water samples were taken from the deepest point of Esthwaite Water at intervals of 0.5 or 1 metre throughout the whole water column. Samples were filtered in the field through 0.45 µm membrane filters in a specially designed high volume sealed flow unit which excluded oxygen from anoxic samples and prevented oxidation of iron during the 20 minute filtration procedure. -spectroscopy was carried out as in a) to obtain values for particulate and soluble Cs-134 and Cs-137. Oxygen and temperature were measured in situ at the time of sampling. Subsamples from each depth were analysed for soluble iron, manganese, zinc, copper, cadmium, lead, humic substances and dissolved organic carbon. Particulate material was analysed for iron, manganese, carbon and nitrogen. A similar profile was taken on 9.9.87 but with a reduced number of samples in the epilimnion.

## Results

### Ruthenium-103

As ruthenium-103 has a short half-life (40 d) it was only possible to quantify concentrations if samples were counted before the end of November '86 at the latest. During this period counting facilities were overloaded with Chernobyl samples and priority was generally given to those samples from research with confirmed contracts. However, the importance of the Ru-103 results was appreciated by the research team and efforts were made to obtain data for a limited number of the early sediment samples up to and including

2/7/86 (Figure 2). These samples suggest that the transport processes to the sediment are the same for both Ru and Cs (Table 4, 5) as the time of transport and deposition patterns are the same for both elements. Difficulties in keeping iron in solution in evaporated water samples were not solved until it was too late to obtain many Ru counts (Table 1). Therefore there is virtually no information about Ru in the waters of the lake. Counts of Ru-103 on the soluble fraction of the water from the Esthwaite profile taken on 27/8/86 gave similar values,  $10.7 \pm 1.25$  and  $8.7 \pm 1.3$  mBq  $l^{-1}$  at 0.5 and 13.5 metres depth respectively, in contrast with counts of Cs-134 which doubled at the deep water site. Neither Cs-134 nor Ru-103 were detectable in the particulate fraction. The literature contained so little data for Ru concentrations in rainfall in Cumbria that it was not possible to estimate direct deposition to the lake or the catchment.

#### Caesium-134 and Caesium-137

Water data are given in tables 2 (Esthwaite) and 3 (Windermere) and plotted in figures 3-6. Cs-134 and Cs-137 both show similar patterns in the two lakes. The majority of the Cs was found in the soluble form with a maximum of 27% in particulate form in Esthwaite at the start of the programme reducing to generally 10-15% later. In both lakes deep water concentrations are initially slightly lower than near surface samples, but, while surface concentrations rapidly decreased, deep water samples remained relatively constant until the autumn, when they too decreased to the same concentration as surface samples. In surface water, concentrations had reduced to half the calculated initial concentration within 15 and 70 days in Esthwaite and Windermere respectively.

The overall pattern of these observations can be explained by considering the physical processes occurring in lakes. During the winter, wind induced turbulence is sufficiently strong to ensure that the water is completely mixed in three dimensions. However as spring progresses the heat of the sun warms

the surface layers of water making them less dense than the colder bottom layers. Eventually the density difference between the top and the bottom becomes so large that the lake separates into two sections, one above the other, which are effectively isolated from one another. Although vertical mixing is relatively slow there are strong horizontal currents. The bottom waters - the hypolimnion - are cold and dark and the oxygen which they contain is not replenished as it is used by bacterial decomposition processes and respiration, so that, in productive lakes, all the oxygen can be removed producing anaerobic conditions with ensuing release of  $\text{Fe}^{2+}$ ,  $\text{NH}_4^+$ ,  $\text{S}^{2-}$  and other ions into the hypolimnion. Surface waters - the epilimnion - are warm and completely oxic as oxygen enters through the air-water interface as normal and is supplied by photosynthesis. In autumn, wind induced turbulence increases and heat inputs decline, so that eventually the wind mixing "overturms" the stratification producing a fully mixed lake again.

Chernobyl derived deposition arrived in May, during the onset of thermal stratification immediately before the bottom waters become isolated. Hence the surface deposition can be considered to have mixed rapidly throughout both lakes. In fact the concentration differences between surface and bottom samples suggest that mixing was not quite complete, but that the assumption of complete mixing is a reasonable first approximation. For reasons which will be discussed later concentrations began to fall immediately in the completely mixed system until thermal stratification was established. At this point epilimnetic concentrations continued to fall while hypolimnetic concentrations remained static. In the autumn, destratification again produced a completely mixed system with equal surface and bottom concentrations.

Sediment concentrations are given in Tables 4 and 5 for Esthwaite and Windermere respectively and are plotted in figures 7-10. Particulate material from the water column settles to the lake bottom accumulating on previously deposited sediment. As the majority of the particulate material is algae, it

is produced in the surface water, and a delay would be expected between the observation of, say, Cs in surface water particulates and its appearance in the surface sediments due to the length of time required for the particles to settle. Cs had reached the sediments within 7 days and 1 month in Esthwaite and Windermere respectively. Although Esthwaite data is confused by two large peaks which will be discussed later (page 21), both lakes show a similar pattern of increasing deposition until about the end of 1986 as Cs continues to be transported via particles to the sediments. In the simplest situation, new material would collect on top of older sediments to form discrete layers. Hence, the Chernobyl material would only be expected to be measurable in the top slice of a sediment core. However, Cs is observed to move down into the sediments with time suggesting that more complex sedimentary processes are present.

#### Quantification of direct deposition onto the lakes and their catchments

Mean concentrations of radionuclides in precipitation in Cumbria were obtained from the literature (Dept. Agric. N. Ireland et al. 1986). In the period 3-20 May, data was available for 13 days for I-131, 10 days for Cs-137, 9 days for Cs-134 and 4 days for Ru-103 (Table 6).

Rainfall data were available from four sites in the locality (Table 6). Although these are generally incomplete they do indicate the gross variability of the rainfall over a very small area. Cumulative total rainfall for Foldgate and Wray Mires, about 1 mile apart on opposite sides of Esthwaite Water, differ by a factor of 2. Similar comparisons of the Ambleside data (about 5 miles away from Esthwaite) with the two former sites, for the days on which data are available at all these sites, show between 5 and 10 times more rain at Ambleside. On the other hand comparison of the Ambleside data with the Merlewood data (approx 20 miles south of Ambleside) from 3-9th May only differed by a factor of 2. As the Ambleside data is the most complete it has

been used to calculate deposition fluxes but the local variability in the rainfall suggests that estimates are unlikely to be better than within a factor of two of the actual mean deposition.

By the 20th May concentrations of Chernobyl derived radionuclides in rainfall were markedly reduced to levels near to their limits of detection. The total deposition was estimated by scanning all fluxes, from 3-20th May inclusive (Table 6), without attempting to estimate missing values. Deposition was I-131  $11200 \text{ Bq m}^{-2}$ ; Cs-137,  $2030 \text{ Bq m}^{-2}$ ; Cs-134,  $1270 \text{ Bq m}^{-2}$ . There was insufficient data to estimate Ru-103 deposition. I-131 fluxes are likely to be under estimates of the true flux as a large proportion of this nuclide is deposited by dry deposition mechanisms.

Estimates of Cs deposition are corroborated by measurements made on a bulk rainwater sample for 3rd-9th of May at Merlewood. In 347 ml of sample Cs-137 and Cs-134 concentrations were  $44.2$  and  $22.2 \text{ Bq l}^{-1}$  respectively. The collector was  $14.5 \text{ cm}$  in diameter so that the total deposition during this period was  $929$  and  $466 \text{ Bq m}^{-2}$  Cs 137 and 134 respectively. Summation of the appropriate daily deposition estimates for Merlewood calculated in the same way as the Ambleside estimates, gives deposition of  $1098$  and  $706 \text{ Bq m}^{-2}$ . They agree with the direct measurement to well within the minimum estimated error of a factor of two. Estimates of total deposition onto the surface of Esthwaite Water and Windermere and onto their catchments are given in Table 7.

#### Mathematical modelling of Water Concentrations

Any pollutant which enters lakewater can do one of three things a) remain in the lake for a period of time then move on through the outflow, b) stay in the lakewater increasing lake concentrations; c) be transported to the lake sediments and be removed, at least temporarily, from the system. Both (a) and (b) are applicable to particulate and soluble forms of pollutant, but both the rate of transport of soluble pollutants to the sediments, and direct removal

mechanisms by the sediments are very slow processes, so significant mass transport of pollutants to the sediments will only take place by the settling of particulate bound material.

At any point in time after the assumed instantaneous deposition of Chernobyl material onto the lake surface and instantaneous mixing within the lake volume the system can be visualized in terms of Fig. 11. A mass balance for the lake can be constructed assuming that transport of soluble Cs direct to the sediments is minimal.

$$- \frac{V.d(C_s + C_p)}{dt} = F(C_s + C_p) + A.u.C_p - F.C_i \quad (1)$$

Where:

V = volume of completely mixed region of the lake ( $m^3$ )

$C_s$  = instantaneous concentration of soluble caesium in the lake ( $Bq\ m^{-3}$ )

$C_p$  = instantaneous concentration of particulate caesium in the lake ( $Bq\ m^{-3}$ )

$C_i$  = instantaneous concentration of caesium in the inflow ( $Bq\ m^{-3}$ )

F = hydraulic flow through the lake ( $m^3\ d^{-1}$ )

A = surface area of the lake ( $m^2$ )

u = deposition velocity of particulate caesium ( $m\ d^{-1}$ )

t = time from the initial event (d)

It is not possible to integrate this equation in its present form. If we assume that  $C_p$  (in  $Bq.m^{-3}$ )  $\ll$   $C_s$  (fig. 5,6), then equation 1 reduces to

$$- V \frac{dC_s}{dt} = FC_s + AuC_p - F C_i \quad (2)$$

$C_p$  and  $C_s$  are related by the distribution coefficient (Kd) which is assumed constant and defined by:

$$Kd = \frac{C_p}{SS C_s} \quad (3)$$

where SS = concentration of suspended solids ( $m^{-3}.kg$ ).

substitution of equation 3 in 2 gives:

$$-V \frac{dC_s}{dt} = FC_s + AuK_d SS C_s - F C_i$$

Separating variables

$$\begin{aligned} -V \frac{dC_s}{dt} &= C_s (F + AuK_d SS) - F C_i \\ &= (F + AuK_d SS) \left( C_s - \frac{F C_i}{F + AuK_d SS} \right) \end{aligned}$$

$$\frac{dC_s}{(C_s - k_2)} = \frac{-(F + AuK_d SS)}{V} dt \quad (4)$$

$$\text{where } k_2 = \frac{F \cdot C_i}{(F + AuK_d SS)}$$

integrating equation 4 from  $t=0$  to  $t=t$  when  $C_s=C_0$  and  $C$  respectively;

$$\ln \frac{(C_s - k_2)}{(C_0 - k_2)} = \frac{-(F + AuK_d SS)t}{V}$$

$$\text{or } C_s = C_0 \exp \frac{-(F + AuK_d SS)t}{V} + \left( 1 - \exp \frac{-(F + AuK_d SS)t}{V} \right) \frac{F C_i}{(F + AuK_d SS)} \quad (5)$$

In this study only a limited number of samples were collected from the inflows to Esthwaite or Windermere during the period of rapid concentration change within the lake (Table 8). Data for rivers anywhere in Britain are extremely limited but other work (Jones and Castle, 1987) suggests that concentrations in rivers upstream of lakes fell extremely rapidly, i.e. within a few days, to levels which were not significant. Rivers downstream of lakes contained elevated values due to the lake output but this would probably be rapidly diluted by other inflows. Assuming  $C_i = 0$  equation 5 can be simplified to:

$$C = C_0 e^{\frac{-(F + AuK_d SS)t}{V}}$$

There is insufficient independent data available from which to estimate  $u$  and  $K_d$ , and suspended solids data for this work are incomplete. Hence the modelling will be carried out in terms of a multiple parameter variable  $Z$  ( $= u.K_d SS$ ) which has units of velocity and will be referred to as the areal removal coefficient i.e.

$$C = C_0 e^{-\frac{(F+Az)t}{V}} \quad (6)$$

Initially estimates of the effects of hydraulic flushing alone were made by setting  $z = 0$ .

Flow data for Eel House Bridge (downstream of Esthwaite) and the River Levens (outflow of Windermere, South Basin) were purchased from the North West Water Authority and appropriate catchment area ratios (Esthwaite = 0.9119; Windermere = 0.7318) were used to correct the data to give lake and basin outflow from Esthwaite and Windermere respectively. The most difficult component in the model to estimate is the appropriate lake volume. Chernobyl material was deposited when both lakes were just beginning to stratify. We need to estimate the volume of water in the upper mixed layer. Unfortunately the natural systems do not conform to a simple 2 box model and rather than an abrupt change at some depth from the hypolimnion to the fully mixed epilimnion there is an intermediate region, called the metalimnion, where a limited amount of mixing takes place. This region can be quite small in terms of depth, but, because it is in a relatively shallow region of the lake, it is often equivalent to a large volume of the lake. In order to put extreme bounds on this region the upper limit of the hypolimnion and the lower limit of the epilimnion were determined from the point of intersection of the vertical temperature profile in the fully mixed region with the sloping temperature profile of the metalimnion (Fig. 12). The time dependence of concentrations were then calculated from equation 6 using either the epilimnion volume or the epilimnion and metalimnion combined, and assuming complete mixing in this volume (Fig. 13,14) (Cs-137 and Cs-134 are sufficiently alike that only Cs-137 data are given).

In Figure 13 for 3 m samples in Esthwaite the measured data lies close to but just below the lower curve indicating that hydraulic flushing is probably responsible for the basic shape of the data, but that another loss mechanism may also be occurring. 3 m data from Windermere (Fig. 14), however, show a considerable difference from the hydraulic flushing curves, at least in the early period. This suggests that sedimentation is more important in Windermere as might be expected for a lake with such a long retention time (1986 mean 0.4 y).

Assuming that all residual losses can be attributed to sedimentation, summation of the masses estimated to have been lost by the hydraulic processes and sedimentation over the period from the first measurements to the end of 1987 shows that between 51-70% of the total Cs-137 load in Esthwaite and 40-58% of the total Cs-137 load in Windermere can be accounted for. The difference from 100% represents the amount lost before the first measurements were taken. Estimates of initial lake concentrations suggest that only about 70% and 50% of the original direct atmospheric input to Esthwaite and Windermere respectively would be left in the water column by the time the first measurements were taken (see page 16). Results from the model show that between 34-60% of the Cs-137 in Esthwaite was lost via the outflow with 40-66% being deposited on the sediments. In Windermere between 26-38% were lost from the outflow and 62-74% deposited to the sediments. The reduced losses via the outflow of Windermere are to be expected given the much longer hydraulic retention time (e.g. 1986 mean retention times Windermere NB 0.4 y; Esthwaite 0.2 y).

Hypolimnetic Cs concentrations in Windermere are essentially constant during stratification (Fig. 4), suggesting that no release from the sediments occurs. Initial observation of a detailed profile in the water column of Esthwaite water taken on 27.8.86 (Table 11a, Fig. 15a) showed high concentration ( $72 \text{ m Bq l}^{-1}$  Cs-137) below 11.5 m compared to concentrations above that depth (mean =  $39 \text{ m Bq l}^{-1}$  Cs-137). This was initially interpreted

as evidence for considerable remobilisation of Cs from bottom sediments. However, the time series data for the 13.5 m water sample (Fig. 3 & 6) show that high hypolimnetic concentrations were present all through the stratified period indicating that the initially deposited Cs was simply isolated by stratification. Although a small increase in concentration with time can be seen in Esthwaite, changes in the hypolimnion volume during this period are large preventing any reliable estimate of recycling fluxes for 1986.

By the winter of 1986 and spring 1987 concentrations in the epi- and hypolimnion had fallen to unmeasurable levels. Epilimnetic levels then stayed at these low levels while hypolimnetic levels increased again providing reasonable evidence that the increase was due to release of sedimentary Cs. An alternative explanation is that Cs on settling particulate material was remobilised before reaching the bed. A second profile was taken on 9th Sept. 1987 (Table 11b, Fig. 15b). The high concentrations immediately above the bed indicate that the sediment is probably the source, but it is not conclusive. The mean concentration of Cs-137 on 9.9.87 in the hypolimnion, i.e. below 8 m, was  $8.35 \text{ Bq. m}^{-3}$ . The volume enclosed by this contour is  $1.279 \times 10^6 \text{ m}^3$  giving a total quantity of  $10.68 \times 10^6 \text{ Bq}$  in the hypolimnion. This is equivalent to 1-2% of the total Cs-137 stored in the top 5 cm of the sediments below a depth of 8 m of water. We can conclude that any remobilisation is small compared to the total quantities of Cs in the sediments but it can produce significant concentration increases in the water column.

If the areal removal coefficient remained constant over the initial period and the input of Cs via the inflow was insignificant, a plot of log concentration against time will be linear. Figs 16 and 17 are reasonably linear during May and June supporting these assumptions. By extrapolation the initial soluble concentrations can be estimated: 182(Cs-134), 275(Cs-137), in Esthwaite and 72(Cs-134) and 135(Cs-137)  $\text{Bq m}^{-3}$  in Windermere respectively, compared with 200, 318, 51, 81  $\text{Bq m}^{-3}$  respectively estimated from deposition data assuming complete mixing. As only the soluble fraction was used in the

model calculation the former estimates are likely to be a little on the low side (about 30%) but they are still well within a factor of 2 of the concentrations calculated from deposition estimates. The higher values obtained by extrapolation from Windermere data imply that the assumption of instantaneous complete mixing is not completely valid and this is corroborated by differences in the measured epilimnetic and hypolimnetic concentrations at the start of sampling. However the errors introduced into the model by this assumption do not appear to be significant compared with the variability in the estimates of initial deposition fluxes.

### Sediments

Figs 2 and 3 indicate that Ru-103 and Cs-134 had reached the surface sediments of Esthwaite water within 7 days of the major deposition. Cs-134 was not observed in the sediments of Windermere until the 3rd June, i.e. 27 days after the event (Fig. 4), although samples from 20th May indicate that Cs 137 could have increased slightly above background levels at that time. From the depth of each lake it is possible to calculate settling velocities of  $1.8 \text{ m d}^{-1}$  and  $2.3 \text{ m d}^{-1}$  respectively for Esthwaite and Windermere assuming particles settle from 3 m depth to the bottom (Table 12). However, hydraulic mixing will rapidly move particles well down into the water column, reducing the distance they have to settle to the bed. Therefore these estimates are likely to be greater than the true settling velocities and are referred to as the maximum velocity in Table 12. An estimate of the minimum velocity can be obtained by assuming instantaneous mixing of particles down to the bottom of the epilimnion and subsequent settlement from this depth (Table 12). The minimum velocity calculated in Windermere is within a factor of 2 of the maximum velocity in both Esthwaite and Windermere. However the minimum velocity in Esthwaite is an order of magnitude lower than the other three estimates and probably represents an unrealistic assumption. The former speeds are typical of settling velocities for natural particles in lakes (Reynolds 1984).

Although data are limited a mean  $K_d$  (Figure 11) of 171 (SD = 81)  $\text{m}^3 \text{kg}^{-1}$  can be estimated from Esthwaite Cs-137 and Cs-134 data. By substituting this value, and the suspended solids concentration into the equation for  $z$  ( $= u \cdot K_d \cdot \text{SS}$ ) it is possible to estimate the settling velocity independently (Tables 9 and 10). Model derived velocities range from 0.08 - 6.3  $\text{m d}^{-1}$  with a mean of 1.5  $\text{m d}^{-1}$  which is very close to the mean of 1.8  $\text{m d}^{-1}$  estimated from the delay before Cs-134 appearance in the sediments. The very low velocities estimated from the model in some instances probably result from either an injection of Cs from the hypolimnion or violation of the assumption of no inputs via the inflow. There are obvious violations of these simplifications on occasions when the concentration at one sampling date is greater than the concentration on the previous date. Small injections of Cs would have the effect of apparently reducing  $u$ . Hence, the very low velocities can probably be ignored.

Assuming quiescent-settling, spherical particles, with diameters ranging from 11.8-20.3  $\mu\text{m}$  and having the mean density of lake sediment (Table 12) of 1.6  $\text{g cm}^{-3}$ , would have appropriate settling velocities. However, lake sediment is not made up of particles of uniform mean density. The density is more nearly bimodal with many heavier silicate mineral and quartz particles with density about 2.6  $\text{g cm}^{-3}$ , and other lighter organic particles of mainly algal origin with a density 1.1  $\text{g cm}^{-3}$ . Spherical particles with appropriate settling velocities range from 4.4-7.6  $\mu\text{m}$  for clay particles and 70-122  $\mu\text{m}$  for algal cells without silica skeletons. Tipping (1982) has shown that low density iron floc has an equivalent Stokes diameter of typically 0.3-0.5  $\mu\text{m}$  and so would sink very slowly.

In May 1986 the North Basin of Windermere was dominated by the alga Asterionella (disc-like colonies 1  $\mu\text{m}$  thick, 150  $\mu\text{m}$  diameter with a silica skeleton). Settling velocities for Asterionella colonies have been measured by Reynolds (1984) at 0.6-0.9  $\text{m d}^{-1}$  depending on the colony size. This is the same order as the velocities we observed. Esthwaite Water had a mixed

population of Anabaena, Dinobryon and several species of small cryptophytes and flagellates. Anabaena contains gas vacuoles which help it to stay in suspension. It would be unlikely to sink and reach the bottom before the autumn. The small cryptophytes and flagellates would be eaten by zooplankton and depending on the zooplankton species, excreted either as faecal pellets which are about 150  $\mu\text{m}$  in size, quite compacted and settle very quickly ( $> 400 \text{ m d}^{-1}$  i.e. within a day), or as a diffuse mass with a similar sinking rate to normal phytoplankton. Dinobryon was observed to have disappeared from the upper 5 m of water column by the 21st of May and was likely to have reached the bed either as algal cells or encysted cells. A peak in sediment concentrations of Cs was observed at this time.

The initial data are consistent with particulate transport of Cs and Ru to the sediments by association with algae, Asterionella in Windermere and Dinobryon in Esthwaite but further work is required to corroborate this pathway. In particular, it is not known whether the Cs is adsorbed onto the algae or whether there is a specific uptake mechanism. All freshwater organisms are required to osmoregulate and consequently potassium is pumped through their bodies. Cs could be involved as an alternative to K and so osmoregulation could provide a specific uptake mechanism. However, the similar sediment recruitment rates for Cs and Ru, which would not be directly involved in osmoregulation, argue against such a possibility.

Total loads of Cs accumulating in the sediments can be calculated by summing all the Cs-134 and Cs-137 in any core. A constant correlation factor was estimated from a frequency distribution of individual Cs-137 concentrations in slices from the top 5 cm of cores taken prior to 31.12.86 and which contained no Cs-134, fig 18a,b. The factor was subtracted from Cs-137 concentrations to remove the effects of bomb caesium: Esthwaite =  $157 \text{ Bq kg}^{-1}$ ; Windermere =  $190 \text{ Bq kg}^{-1}$ . Total loads are tabulated in Tables 13 and 14 and plotted in figures 19 and 20. An estimate of the sediment contribution from material deposited directly onto the water surface can be calculated from

the water column model (Table 9). By starting the model with the concentration at the beginning of a sampling interval, the amount of radio caesium lost due to hydraulic effects can be calculated. Subtraction of the remaining Cs load at the end of the sampling interval from the amount which would have been present if hydraulic processes alone had been operating gives the load transported to the sediments.

An estimate of the amount of Cs being transported to the sediment on the first sampling date was made by taking a proportion (c. 70%) of the total Cs lost during the first few measured periods. A delay, equivalent to the length of time taken in each lake for Cs-134 to reach the sediments, was added to each water column measurement date to allow for the time taken to settle through the water column. Either 62 (epi) or 74 (hypo) % of the initial loss in Windermere and 40 or 66% in Esthwaite were considered to have settled to the sediments (Fig. 20).

In both Esthwaite and Windermere the accumulation of material in the sediment estimated using epi and epi+meso volumes straddle the general trend (Figs 19 and 20) suggesting that the early increases in sediment concentrations are due solely to transfer of a proportion of the material originally deposited on the surface of the lake. The fit is better for Windermere than Esthwaite, but evidence from the grid sampling (Fig. 24) suggests that samples taken at the deepest point of Esthwaite were not typical as the large peaks in July and October '86 are not apparent in most cores. In September/October 86 there appears to be a sudden increase in Cs concentrations in the sediments of both lakes, presumably due to the rapid demise of the summer algal populations.

Concentrations in fish flesh did not follow the pattern expected from models (MAFF, unpublished). Instead of a rapid rise coincident with water concentration rises, followed by a slow fall, concentrations rose steadily for 1 y to 18 months before starting to fall, and occasional fish contained very high concentrations of Cs. There is some conjecture that the sediments may be a previously unrecognised link in the transfer of radionuclides into freshwater

fish via invertebrate food sources living in the sediments. Hence it is of interest to observe the "mixing depth" of Chernobyl material into the sediments. In an ideal sedimentary situation pollutants will settle on the surface of the sediment and become covered by new sedimenting material forming a discrete layer. However other processes, e.g. turbulent water mixing, bioturbation or diffusion, can cause the input material to be mixed over a finite depth from the sediment surface, smearing the recorded deposition pattern. The base of the detectable Cs-134 record is plotted in figure 21. Within 2 months of the Chernobyl deposition Cs-134 was present to a depth of at least 5 cm in the Esthwaite sediments, whereas in Windermere it had only penetrated to about 2½ cm. It is unlikely that this effect is an artifact of the slicing technique used during sample preparation, when Cs could be transferred down the core by smearing of the edge material on the tube surface, because cores from the two lakes were treated identically and there was no evidence of a relationship between penetration depth and the maximum Cs concentration (Fig. 22). Further work is required to elucidate the cause of this phenomenon, either within lake or during sample preparation, as the vertical stability of Cs within the core is important both because of its use as a dating tool and, particularly because an increase in the mixing depth reduces the mean concentration of Cs available to invertebrates and is an important parameter in any model of radionuclide transfer into the food chain via freshwater fish.

On the assumption that much of the material entering the lake from a clay rich catchment could be transported as aggregates in the bed load along river bottoms and be missed by normal sampling, a grid of sites were sampled in Esthwaite Water where the lake narrows drastically towards the outlet of the main feed river - Black Beck, Fig. 1. Data are given in Table 15 and concentrations plotted with time in Figure 23. It is immediately apparent that data at different sites are extremely variable and the central buoy data fall into a group represented by violent changes in concentration rather than the

smoother changes observed in many other cores. However there is a general trend in all cases of higher concentrations at the start of the work compared to the data at the end of the period. Distribution maps of the mean concentration of the first four samples and the last two samples at each site are given in figure 24a and b respectively. Fig. 24a shows a heterogeneous distribution. An interesting feature is the high concentration of Cs around the smaller inflows but low concentrations around the mouth of Black Beck. This can be rationalised as follows. The small streams are ephemeral, disappearing in dry spells, but in wet weather they can be seen to have large contributions from overland run-off, transporting surface soil rich in Chernobyl fallout, to be deposited close to the stream outlet. Black Beck, on the other hand, is the main drainage channel from the catchment. Much of the pasture in the lowland area of the catchment has been improved by subsurface drainage (J.W.G. Lund, personal communication) so that Black Beck has a high contribution from sub-surface sources which contain low concentrations of Cs. At the end of the sampling period redistribution and dilution by newly accumulated sediment had reduced the concentration range from 244-1400 Bq kg<sup>-1</sup> to 193-544, excluding one slightly higher concentration sample at the outlet of one beck. The general pattern of concentration follows that of an independent map of sediment deposition rate, (fig. 24c, Hilton et al., 1986) with low concentrations in low deposition regions and vice versa.

#### Conclusions and Recommendations

i) A simple model has been used to show that hydraulic washout is not the only loss process. Incorporation into particles and subsequent deposition can be an important loss process, particularly in lakes with long retention times. The relative importance of the two processes will depend on the depth, hydraulic residence times, the degree of stratification of a lake and the amount of primary productivity. The latter gives a seasonal dependence as does the importance of algae as the main source of particulate material. More work

is required on the uptake of Cs by both phytoplankton and other natural particles. Information is also required on their sinking rates before a reliable predictive model can be produced.

ii) The initial concentration in the water column in lakes within clay catchments depends simply on the surface deposition and the surface area to volume ratio.

iii) In clay catchments only a very small amount of the material deposited on the catchment is remobilised into the aquatic system. It is probable that this is not the case in organic catchments in upland areas where many reservoirs are found and further work is required on this important aspect.

iv) Chernobyl Cs has moved rapidly down the sediment profile. This has the effect of reducing the average concentration of radiocaesium in the food of sedimentary invertebrates. Further investigation of the processes involved is required before reliable models can be developed for the transfer of radionuclides into the food chain via freshwater fish.

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Table 1. Sampling dates for water samples and sediment profiles in Esthwaite and Windermere, sediment grid samples from Esthwaite and water profiles from Esthwaite.

Date	Esthwaite		Windermere		Esthwaite	Esthwaite
	Water Samples	Sediment Profiles	Water Samples	Sediment Profiles	Sediment Grid	Water Profile
8/5/86	-	X	-	X	-	-
12/5/86	-	-	-	-	X	-
13/5/86	X	X	-	X	-	-
20-21/5/86	X	X	-	X	-	-
28/5/86	-	-	-	-	X	-
3-4/6/86	X	X	X	X	-	-
16/6/86	X	X	-	-	X	-
17-18/6/86	-	-	X	X	-	-
1-2/7/86	X	X	X	X	-	-
14-15/7/86	X	X	X	X	X	-
29-30/7/86	X	X	X	X	-	-
11/8/86	X	X	-	-	-	-
14/8/86	-	-	X	X	X	-
27/8/86	-	-	-	-	-	X
1-3/9/86	X	X	X	X	-	-
22/9/86	X	X	-	-	X	-
23-24/9/86	-	-	-	X	-	-
7/10/86	-	-	X	-	-	-
20-21/10/86	X	X	X	X	-	-
3/11/86	-	X	-	-	X	-
18-19/11/86	X	X	X	X	-	-
9/12/86	-	-	X	X	-	-
15/12/86	X	X	-	-	X	-
2/3/87	-	-	-	-	X	-
2-3/4/87	X	X	X	X	X	-
1-3/6/87	X	X	X	X	X	-
24-25/8/87	X	X	X	X	X	-
9/9/87	-	-	-	-	-	X
30/11/87	X	X	-	-	X	-
1/12/87	-	-	X	X	-	-

Table 2. Data from samples collected at 3 m and 13.5 m in the water column of Esthwaite Water at the deepest point

Date	Sample volume	Carbon $\mu\text{g/l}$	Particulate Nitrogen $\mu\text{g/l}$	Suspended solids $\text{mg/l}$	Particulate Csl34 $\text{mBq/l}$	Particulate Csl37 $\text{mBq/l}$	Soluble Csl34 $\text{mBq/l}$	Soluble Csl37 $\text{mBq/l}$	Soluble Ru103 $\text{mBq/l}$	Total Csl34 $\text{mBq/l}$	Total Csl37 $\text{mBq/l}$	Kd factor $\text{m}^3 \text{kg DW}^{-1}$
Depth = 3.0 m												
13/05/86	5.8	-	-	-	31.93	73.96	96.09	203.34	9.6	128.02	277.30	-
21/05/86	10.5	-	-	-	16.66	37.34	70.44	151.50	7.0	87.10	188.84	-
04/06/86	10.1	299.19	79.780	0.7*	2.95	14.47	44.55	81.50	-	47.50	95.97	254
16/06/86	9.9	173.13	23.040	0.4*	3.79	7.61	32.10	64.34	4.0	35.89	71.95	295
02/07/86	10.1	387.34	61.950	0.9*	2.93	14.47	24.18	61.41	-	27.11	75.88	135
14/07/86	19.8	-	-	-	<2.70	6.00	23.65	50.43	-	23.65	56.43	-
30/07/86	9.7	1783.34	349.065	4.2*	8.95	17.16	16.27	34.30	-	25.22	51.46	131
11/08/86	10.0	1449.08	260.280	3.4*	3.98	11.66	13.53	34.35	-	17.51	46.01	100
01/09/86	9.9	814.82	147.720	1.9*	5.42	7.13	15.52	42.26	-	20.94	49.39	184
22/09/86	-	-	-	-	3.27	8.82	7.99	24.84	-	11.26	33.66	-
20/10/86	-	1226.32	229.100	2.9*	<1.81	<2.15	<2.64	<2.81	-	3.77	11.45	-
19/11/86	-	-	-	-	<2.19	2.72	3.77	8.73	-	-	-	-
15/12/86	-	-	-	-	<2.30	<2.39	<2.75	<3.51	-	-	-	-
02/04/87	-	828.22	139.370	3.70	-	-	<2.10	<2.60	-	-	4.48	-
01/06/87	-	791.27	153.780	1.10	-	-	<2.19	4.48	-	-	-	-
24/08/87	-	652.52	122.760	3.05	<1.17	<1.87	<2.28	<2.88	-	-	-	-
30/11/87	-	383.50	68.230	1.25	-	-	<1.81	<3.23	-	-	-	-
Depth = 13.5												
13/05/86	5.8	-	-	-	-	-	91.19	189.20	8.4	91.19	189.20	-
21/05/86	10.7	-	-	-	17.23	37.66	57.75	132.10	-	74.98	169.76	-
04/06/86	9.8	444.42	55.260	1.0*	4.40	11.26	46.23	99.98	-	50.63	111.24	113
16/06/86	10.6	444.42	68.840	1.0*	6.24	10.63	42.27	85.20	-	48.51	95.83	148
02/07/86	10.4	1357.40	182.665	3.2*	-	-	-	-	-	-	-	-
14/07/86	10.6	-	-	-	-	-	-	-	-	-	-	-
30/07/86	9.3	564.94	62.255	1.3*	-	-	-	-	-	46.10	92.38	-
11/08/86	9.8	1582.73	196.280	3.7*	-	-	-	-	-	40.89	99.51	-
01/09/86	9.9	1088.90	165.490	2.5*	-	-	-	-	-	36.06	94.67	-
22/09/86	-	-	-	-	-	-	-	-	-	26.98	66.00	-
20/10/86	-	1451.60	267.300	3.3	<1.57	<1.58	5.21	25.85	-	5.21	25.85	-
19/11/86	-	-	-	-	<2.32	<2.24	<2.74	6.06	-	-	6.06	-
15/12/86	-	-	-	-	<2.35	<2.51	-	-	-	-	-	-
02/04/87	-	855.59	126.600	3.60	-	-	<2.22	<2.67	-	-	-	-
01/06/87	-	456.39	38.135	1.30	-	-	<2.22	7.21	-	-	7.21	-
24/08/87	10.3	-	-	-	-	-	<2.52	8.08	-	-	8.08	-
30/11/87	-	275.60	42.040	1.15	-	-	<1.68	03.15	-	-	-	-

\* estimated from previously established particulate C:suspended solids relationships

Table 3 Data for samples collected at 3 m and 45 m in the water column of Windermere (North Basin) at the deepest point

Date	Sample volume l	Depth = 3.0 m												
		Carbon µg/l	Particulate Nitrogen µg/l	Suspended solids mg/l	Particulate Cs134 mBq/l	Particulate Cs137 mBq/l	Soluble Cs134 mBq/l	Soluble Cs137 mBq/l	Soluble Ru103 mBq/l	Total Cs134 mBq/l	Total Cs137 mBq/l			
04/06/86	10.4	679.16	81.250	1.58*	-	-	30.98	64.97	-	30.98	64.97	-	30.98	64.97
17/06/86	11.1	229.10	33.460	0.52*	-	-	19.75	47.56	-	19.75	47.56	-	19.75	47.56
01/07/86	10.9	131.83	26.710	0.3*	-	-	15.03	45.07	-	15.03	45.07	-	15.03	45.07
15/07/86	10.3	-	-	-	-	-	16.77	39.07	-	16.77	39.07	-	16.77	39.07
29/07/86	10.2	192.52	34.445	0.44*	-	-	12.78	37.58	-	12.78	37.58	-	12.78	37.58
14/08/86	10.0	542.68	41.650	1.26*	-	-	8.50	24.89	-	8.50	24.89	-	8.50	24.89
03/09/86	10.1	381.79	57.620	0.88*	-	-	12.37	28.61	-	12.37	28.61	-	12.37	28.61
07/10/86	-	-	-	-	-	-	6.73	16.83	-	6.73	16.83	-	6.73	16.83
21/10/86	-	265.07	44.970	0.61*	-	-	10.41	22.10	-	10.41	22.10	-	10.41	22.10
18/11/86	-	-	-	-	-	-	6.28	20.26	-	6.28	20.26	-	6.28	20.26
09/12/86	-	-	-	-	-	-	5.18	16.26	-	5.18	16.26	-	5.18	16.26
02/04/87	-	288.72	37.560	1.10	-	-	<2.30	<2.83	-	<2.30	<2.83	-	<2.30	<2.83
03/06/87	-	341.62	44.230	1.10	-	-	<2.01	6.34	-	<2.01	6.34	-	<2.01	6.34
25/08/87	-	697.09	119.110	1.73	-	-	<2.23	<2.80	-	<2.23	<2.80	-	<2.23	<2.80
01/12/87	-	171.91	28.010	0.90	-	-	<2.03	<2.98	-	<2.03	<2.98	-	<2.03	<2.98
Depth = 45.0 m														
04/06/86	10.4	284.750	21.570	-	-	-	19.15	42.50	2.6	19.15	42.50	2.6	19.15	42.50
17/06/86	10.8	182.765	17.820	-	-	-	15.30	38.81	-	15.30	38.81	-	15.30	38.81
01/07/86	10.2	203.780	24.765	-	-	-	18.17	42.49	-	18.17	42.49	-	18.17	42.49
15/07/86	10.0	-	-	-	-	-	-	-	-	-	-	-	-	-
29/07/86	10.0	94.390	14.920	-	-	-	15.08	39.59	-	15.08	39.59	-	15.08	39.59
14/08/86	10.2	238.920	11.910	-	-	-	16.34	37.73	-	16.34	37.73	-	16.34	37.73
03/09/86	10.1	166.740	32.250	-	-	-	19.26	45.59	-	19.26	45.59	-	19.26	45.59
07/10/86	-	-	-	-	-	-	17.82	36.42	-	17.82	36.42	-	17.82	36.42
21/10/86	-	224.340	23.670	-	-	-	14.27	37.60	-	14.27	37.60	-	14.27	37.60
18/11/86	-	-	-	-	-	-	13.14	35.28	-	13.14	35.28	-	13.14	35.28
09/12/86	-	-	-	-	-	-	3.65	17.65	-	3.65	17.65	-	3.65	17.65
02/04/87	-	-	-	0.90	-	-	<2.25	5.41	-	<2.25	5.41	-	<2.25	5.41
03/06/87	-	154.020	15.600	0.80	-	-	<2.06	5.65	-	<2.06	5.65	-	<2.06	5.65
25/08/87	-	104.540	18.270	0.15	-	-	<2.42	<2.96	-	<2.42	<2.96	-	<2.42	<2.96
01/12/87	-	220.450	31.540	0.75	-	-	<2.12	<3.11	-	<2.12	<3.11	-	<2.12	<3.11

\*estimated from previously established C : suspended solids relationships

Table 4. Concentrations of radionuclides in the top 5 cm of sediments in Esthwaite Water.

Date	Cs-134					Cs-137				
	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm
08/05/86	<11.1	-	-	-	-	159.0	118.0	122.0	107.0	100.0
13/05/86	77.7	-	-	-	-	407.0	137.0	130.0	111.0	115.0
21/05/86	1088.0	24.7	-	16.0	-	2479.0	189.0	122.0	144.0	137.0
04/06/86	496.0	33.3	<11.1	<11.1	<11.1	1225.0	174.0	130.0	141.0	174.0
16/06/86	242.0	20.9	11.0	<11.1	8.8	685.0	159.0	144.0	130.0	159.0
02/07/86	955.0	67.0	24.0	34.8	28.1	2357.0	263.0	211.0	207.0	215.0
14/07/86	1690.0	1280.0	177.0	51.3	70.2	3730.0	2810.0	455.0	202.0	232.0
30/07/86	1620.0	1020.0	195.0	33.2	40.4	3480.0	3080.0	487.0	182.0	193.0
11/08/86	1040.0	191.0	40.5	19.6	16.5	2360.0	490.0	192.0	152.0	161.0
03/09/86	71.3	401.0	145.0	32.9	-	151.0	922.0	431.0	209.0	179.0
22/09/86	190.0	40.7	<11.1	<11.1	<11.1	520.0	193.0	138.0	139.0	140.0
20/10/86	683.0	144.0	24.6	<11.1	24.3	1550.0	394.0	161.0	140.0	163.0
03/11/86	483.0	647.0	127.0	30.6	26.4	1060.0	1460.0	358.0	157.0	159.0
19/11/86	298.0	92.4	29.9	14.0	<11.1	751.0	312.0	174.0	157.0	142.0
15/12/86	315.0	183.0	39.7	<11.1	<11.1	751.0	477.0	184.0	140.0	<11.1
02/04/87	185.0	181.0	-	-	-	433.0	555.0	202.0	155.0	145.0
01/06/87	83.0	120.0	66.0	41.0	52.0	399.0	331.0	224.0	179.0	206.0
24/08/87	273.0	250.0	154.0	79.0	-	619.0	595.0	392.0	256.0	185.0
30/11/87	114.0	172.0	279.0	165.0	37.0	351.0	505.0	668.0	426.0	183.0

Date	Ru-103					Ru-106				
	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm
08/05/86	-22.2	-	-	-	-	-	-	-	-	-
13/05/86	677.0	-	-	-	-	-	-	-	-	-
21/05/86	4995.0	-	-	-	-	1343.0	-	-	-	-
04/06/86	2146.0	<29.6	<29.6	<29.6	<29.6	477.0	-	-	-	-
16/06/86	1129.0	115.0	62.9	<29.6	29.6	-	-	-	-	-
02/07/86	3885.0	148.0	<29.6	159.0	170.0	984.0	-	-	-	-
14/07/86	-	-	-	-	-	2180.0	1240.0	-	-	-
30/07/86	-	-	-	-	-	1550.0	688.0	-	-	-
11/08/86	-	-	-	-	-	1330.0	-	-	-	-
03/09/86	-	-	-	-	-	-	605.0	-22.2	481.0	-
20/10/86	-	-	-	-	-	1160.0	-	-	-	-
03/11/86	-	-	-	-	-	737.0	749.0	-	-	-
19/11/86	-	-	-	-	-	392.0	-	-	-	-
15/12/86	-	-	-	-	-	371.0	218.0	-	-	-

Table 5. Concentrations of radionuclides in the top 5 cm of sediments in Windermere.

Date	Cs-134					Cs-137				
	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm
08/05/86	<11.1	<11.1	<11.1	-	-	81.4	137.0	137.0	167.0	192.0
13/05/86	<11.1	<11.1	<11.1	-	-	152.0	170.0	196.0	229.0	215.0
20/05/86	-	-	-	-	-	311.0	155.0	137.0	159.0	174.0
03/06/86	492.0	39.0	<11.1	<11.1	<11.1	1162.0	266.0	138.0	148.0	174.0
17/06/86	696.0	115.0	<11.1	<11.1	<11.1	1728.0	359.0	144.0	152.0	148.0
01/07/86	339.0	48.0	<11.1	<11.1	<11.1	966.0	281.0	137.0	174.0	178.0
15/07/86	675.0	146.0	-	-	-	1560.0	452.0	179.0	144.0	174.0
29/07/86	1620.0	217.0	-	-	-	3690.0	521.0	234.0	221.0	219.0
14/08/86	403.0	101.0	-	-	-	1020.0	329.0	168.0	155.0	156.0
03/09/86	524.0	<11.1	48.4	<11.1	<11.1	1180.0	402.0	188.0	127.0	122.0
23/09/86	303.0	-	-	-	-	725.0	126.0	122.0	210.0	230.0
21/10/86	935.0	638.0	122.0	-	-	2080.0	1480.0	407.0	230.0	233.0
18/11/86	854.0	797.0	386.0	63.3	-	1870.0	1737.0	959.0	267.0	195.0
09/12/86	732.0	450.0	73.2	-	-	1710.0	1070.0	277.0	227.0	250.0
02/04/87	676.0	344.0	28.0	-	-	1540.0	856.0	171.0	155.0	184.0
03/06/87	722.0	428.0	106.0	-	-	1711.0	962.0	319.0	156.0	158.0
25/08/87	483.0	486.0	211.0	44.0	-	1110.0	1099.0	582.0	327.0	294.0
01/12/87	184.0	192.0	135.0	-	-	885.0	861.0	636.0	239.0	172.0

Date	Ru-103					Ru-106				
	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm	Bq kg 0-1cm	Bq kg 1-2cm	Bq kg 2-3cm	Bq kg 3-4cm	Bq kg 4-5cm
08/05/86	<22.2	<22.2	<22.2	-	-	-	-	-	-	-
13/05/86	<22.2	<22.2	<22.2	-	-	-	-	-	-	-
03/06/86	4144.0	278.0	<22.2	<22.2	<22.2	-	-	-	-	-
17/06/86	7474.0	1232.0	125.0	<29.6	<29.6	910.0	-	-	-	-
01/07/86	2897.0	492.0	<22.2	<22.2	<22.2	640.0	-	-	-	-
29/07/86	-	-	-	-	-	2550.0	557.0	-	-	-
03/09/86	-	-	-	-	-	483.0	-	-	-	-
21/10/86	-	-	-	-	-	992.0	793.0	-	-	-
18/11/86	-	-	-	-	-	1090.0	1000.0	515.0	-	-
09/12/86	-	-	-	-	-	-	729.0	-	-	-
02/04/87	-	-	-	-	-	739.0	626.0	-	-	-
03/06/87	-	-	-	-	-	966.0	-	-	-	-

Table 6. Rainfall data and radionuclide deposition estimates.

Date	Concentration Bq/l			Ru-103	Ratio 134/137	Rainfall mm		Wraymires
	I-131	Cs-137	Cs-134			Foldgate	Wraymires	
3/5/86	772.00	87.00	61.00	147.00	0.70	2.40	2.00	
4/5/86	NR	NR	NR			NR	NR	
5/5/86	44.00	9.00	<6.00		<0.67	NR	NR	
6/5/86	141.00	78.00	44.00		0.56	0.40	0.10	
7/5/86	140.00	53.00	34.00	82.00	0.64	0.00	0.00	
8/5/86	13.00	<3.00	<3.00			Tr		
9/5/86	no rain at Merlewood					1.50	0.70	
10/5/86	13.00	9.00				0.00	0.00	
11/5/86	18.00					NR	NR	
12/5/86	8.00	1.40	<1.40		<1.00	NR	NR	
13/5/86	no rain at Merlewood					0.00	0.00	
14/5/86	16.00	3.90	2.90	3.80	0.74	0.00	0.00	
15/5/86	NR	NR	NR			0.00	0.00	
16/5/86	<1.00	<0.80	<1.00			1.70	1.10	
17/5/86	NR	NR	NR			0.00	0.00	
18/5/86	NR	NR	NR			NR	NR	
19/5/86	NR	NR	NR			NR	NR	
20/5/86	<0.90	1.10	<0.90	2.60	<0.82	7.00	2.90	

Date	Rainfall mm		Daily flux Bq/m <sup>2</sup>		Daily flux I-131	Daily flux Cs-137	Daily flux Cs-134
	Ambleside	Merlewood	I-131	Cs-137			
3/5/86	11.10	5.80	8569	966	448	505	354
4/5/86	8.60	6.20					
5/5/86	5.10	9.00	224	46	396	81	54
6/5/86	7.90	6.20	1114	616	874	484	273
7/5/86	6.10	0.15	854	323	21	8	5
8/5/86	1.30	6.50	17	<4	85	20	20
9/5/86	21.80						
10/5/86	6.90		90	62			
11/5/86	18.30		329				
12/5/86	0.30		2	0			
13/5/86	1.80						
14/5/86	1.80		29	7			
15/5/86	0.00		0	0			
16/5/86	0.00						
17/5/86	16.30						
18/5/86	0.20						
19/5/86	9.70						
20/5/86	1.50		<1	2			<1

NR = no reading

Tr = trace

Table 7. Total deposition of Chernobyl radionuclides onto lakes and catchments.

	Esthwaite	Windermere North Basin
Lake area (km <sup>2</sup> )	1.004	8.046
Lake area (m <sup>2</sup> )	1.004 x 10 <sup>6</sup>	8.046 x 10 <sup>6</sup>
I-131 load (Bq)	1.244 x 10 <sup>10</sup>	0.997 x 10 <sup>11</sup>
Cs-137 load (Bq)	2.035 x 10 <sup>9</sup>	1.631 x 10 <sup>10</sup>
Cs-134 load (Bq)	1.278 x 10 <sup>9</sup>	1.024 x 10 <sup>10</sup>
Catchment area-lake (km <sup>2</sup> )	16.1	160
Catchment area-lake (m <sup>2</sup> )	16.1 x 10 <sup>6</sup>	160 x 10 <sup>6</sup>
I-131 load (Bq)	1.995 x 10 <sup>11</sup>	1.982 x 10 <sup>12</sup>
Cs-137 load (Bq)	3.263 x 10 <sup>10</sup>	3.243 x 10 <sup>11</sup>
Cs-134 load (Bq)	2.571 x 10 <sup>10</sup>	2.037 x 10 <sup>11</sup>
Total catchment area (km <sup>2</sup> )	17.1	168.3
Total catchment area (m <sup>2</sup> )	17.1 x 10 <sup>6</sup>	168.3 x 10 <sup>6</sup>
I-131 load (Bq)	2.119 x 10 <sup>11</sup>	2.085 x 10 <sup>12</sup>
Cs-137 load (Bq)	3.466 x 10 <sup>10</sup>	3.411 x 10 <sup>11</sup>
Cs-134 load (Bq)	2.177 x 10 <sup>10</sup>	2.142 x 10 <sup>11</sup>

Table 8. Radio caesium analysis of river waters. R. Leven = outflow from Windermere south basin; Cunsey Beck = outflow from Esthwaite Water; Black Beck = major inflow to Esthwaite Water.

River	Date	Activity mBq/l	
		Cs-134	Cs-137
R. Leven	25.07.86	11.11 ± 1.98	22.58 ± 3.04
Cunsey Beck	25.07.86	18.54 ± 2.62	37.63 ± 3.82
Cunsey Beck	17.03.87	<2.04	3.27 ± 1.52
Cunsey Beck	24.04.87	<2.35	<2.74
Cunsey Beck	22.05.87	<2.23	4.61 ± 1.75
Cunsey Beck	14.07.87	<2.11	3.12 ± 1.55
Black Beck	06.10.86	<3.51	7.96 ± 2.14
Black Beck	17.03.87	<2.00	<2.63
Black Beck	24.04.87	<2.31	3.61 ± 1.62
Black Beck	22.05.87	<2.30	4.75 ± 1.76
Black Beck	14.07.87	<2.15	<2.64

Table 9a Modelled Cs-137 data for Windermere (3 m depth)

Date	Days	Cs137 mBq/1	Epi vol $\times 10^6$ $\frac{3}{m^3}$	Hypo vol $\times 10^6$ $\frac{3}{m^3}$	Flow $\times 10^3$ $\frac{3}{m}$	Conc		Deposition velocity ( $\text{m d}^{-1}$ )		Hydr epi $\times 10^6$ Bq	Cum loss $\times 10^6$ Bq	Hydr hypo $\times 10^6$ Bq	Cum loss $\times 10^6$ Bq	Settle epi $\times 10^6$ Bq	Cum loss $\times 10^6$ Bq	Settle hypo $\times 10^6$ Bq	Cum loss $\times 10^6$ Bq	
						epi mBq/1	hypo mBq/1	epi	hypo									
04/06/86	29	64.97	143.00	164.00	32886													
17/06/86	42	47.56	115.00	146.00	9823	59.65	60.74	2.8	3.8	686.2	686	655.3	655	1559.7	1560	2043.3	2043	
01/07/86	56	45.07	120.00	148.00	4257	45.90	46.21	0.4	0.6	194.8	881	198.2	854	97.8	1657	167.8	2211	
15/07/86	70	39.07	40.00	139.00	995	43.96	44.75	-	-	88.6	970	46.1	900	391.4	2049	814.9	3026	
29/07/86	84	37.58	50.00	139.00	1302	38.07	38.71	0.08	0.5	45.2	1015	50.6	950	21.9	2071	156.5	3182	
14/08/86	100	24.89	45.00	132.00	17044	25.73	33.03	0.05	1.3	562.8	1578	616.8	1567	40.0	2111	1102.7	4285	
03/09/86	120	28.61	50.00	145.00	10465	20.19	23.16	-	-	223.3	1801	240.0	1807	0.0	2111	0.0	4285	
07/10/86	154	16.83	71.00	145.00	5508	26.47	27.54	-	-	129.2	1930	154.6	1962	583.5	2694	1553.5	5839	
21/10/86	168	22.10	94.00	147.00	4631	16.02	16.31	-	-	66.7	1997	76.2	2038	0.0	2694	0.0	5839	
18/11/86	196	20.26	139.00	174.00	61981	14.15	15.48	-	-	926.2	2923	1063.0	3101	0.0	2694	0.0	5839	
09/12/86	217	16.26	202.00	202.00	53795	15.52	15.52	-	-	807.6	3731	890.5	3991	0.0	2694	0.0	5839	
02/04/87	331	<2.83	202.00	202.00							3731		3991	0.0	2694	0.0	5839	
03/06/87	393	6.34	145.00	164.00							3731		3991	0.0	2694	0.0	5839	
25/08/87	476	<2.80	50.00	245.00							3731		3991	0.0	2694	0.0	5839	
01/12/87	574	<2.98	202.00	202.00							3731		3991	0.0	2694	0.0	5839	

Table 9b Modelled Cs-134 data for Windermere (3 m depth)

Date	Days	Cs134 mBq/l	Epi vol x10 <sup>6</sup>	Hypo vol x10 <sup>6</sup>	Flow x10 <sup>3</sup>	C		Deposition velocity (m d <sup>-1</sup> )		Hydr epi x10 <sup>6</sup>	Cum loss x10 <sup>6</sup>	Hydr hypo x10 <sup>6</sup>	Cum loss x10 <sup>6</sup>	Settle epi x10 <sup>6</sup>	Cum loss x10 <sup>6</sup>	Settle hypo x10 <sup>6</sup>	Cum loss x10 <sup>6</sup>
						epi mBq/l	hypo mBq/l	epi	hypo								
04/06/86	29	30.98	143.00	164.00	32886												
17/06/86	42	19.75	115.00	146.00	9823	28.44	28.96	4.5	46.0	327.2	327	312.5	312	1121.5	1121	1428.2	1428
01/07/86	56	15.03	120.00	148.00	4257	19.06	19.19	4.7	6.3	80.9	408	82.3	395	473.7	1595	611.5	2040
15/07/86	70	16.77	40.00	139.00	995	14.66	14.92	-	-	29.5	438	15.4	410	0.0	1595	0.0	2040
29/07/86	84	12.78	50.00	139.00	1302	16.34	16.61	1.4	4.3	19.4	457	21.7	432	160.2	1755	532.9	2573
14/08/86	100	8.50	45.00	132.00	17044	8.75	11.23	0.05	1.3	191.4	648	209.8	642	11.9	1767	370.2	2943
03/09/86	120	12.37	50.00	145.00	10465	6.89	7.91	-	-	76.2	725	82.0	724	0.0	1767	0.0	2943
07/10/86	154	6.73	71.00	145.00	5508	11.45	11.91	-	-	55.9	781	66.9	790	285.4	2053	750.9	3694
21/10/86	168	10.41	94.00	147.00	4631	6.41	6.52	-	-	26.7	807	30.5	821	0.0	2053	0.0	3694
18/11/86	196	6.28	139.00	174.00	61981	6.66	7.29	-	-	436.3	1244	500.7	1322	44.8	2097	162.2	3856
09/12/86	217	5.18	202.00	202.00	53795	4.81	4.81	-	-	250.3	1494	276.0	1598	0.0	2097	0.0	3856
02/04/87	331	<2.30	202.00	202.00							1494		1598	0.0	2097	0.0	3856
03/06/87	393	<2.01	145.00	164.00							1494		1598	0.0	2097	0.0	3856
25/08/87	476	<2.23	50.00	145.00							1494		1598	0.0	2097	0.0	3856
01/12/87	574	<2.03	202.00	202.00							1494		1598	0.0	2097	0.0	3856

Table 10a Modelled Cs137 data for Esthwaite (3 m depth)

Date	Days	Cs137 mBq/1	Epi vol $\times 10^6$	Hypo vol $\times 10^6$	Flow $\times 10^3$	C		Deposition velocity ( $\text{md}^{-1}$ )		Hydr epi $\times 10^6$	Cum loss $\times 10^6$	Hydr hypo $\times 10^6$	Cum loss $\times 10^6$	Settle epi $\times 10^6$	Cum loss $\times 10^6$	Settle hypo $\times 10^6$	Cum loss $\times 10^6$
						epi mBq/1	hypo mBq/1	epi	hypo								
13/05/86	7	203.34	5.86	6.43	770												
21/05/86	15	151.50	5.05	6.40	620	179.84	184.56	-	-	128.2	128	120.5	120	154.6	155	212.1	212
04/06/86	29	81.50	1.76	5.45	1118	80.20	123.40	-	1.3	242.7	371	166.5	287	0.0	155	248.2	460
16/06/86	41	64.34	2.87	5.05	648	65.04	71.69	0.04	0.7	38.1	409	51.5	338	1.6	156	38.6	499
02/07/86	57	61.41	3.20	6.10	369	57.33	60.56	-	-	21.3	430	21.1	360	0.0	156	0.0	499
14/07/86	69	50.43	2.50	6.25	77	59.54	60.65	-	-	5.3	436	4.7	364	26.0	182	63.1	562
30/07/86	85	34.30	2.60	6.25	161	47.41	49.15	0.07	0.2	7.7	443	8.0	372	33.4	216	98.2	655
11/08/86	97	34.35	3.10	6.25	849	26.08	29.94	-	-	23.4	467	27.2	399	0.0	216	0.0	655
01/09/86	118	42.26	5.25	6.35	648	30.36	31.02	-	-	16.6	483	21.0	420	0.0	216	0.0	655
22/09/86	139	24.84	6.40	6.40	313	40.24	40.24	-	-	11.8	495	12.9	433	89.7	305	98.2	753
20/10/86	167	<2.81	6.40	6.40	374	23.43	23.43	-	-	9.0	504	9.0	442	149.9	455	149.9	903
19/11/86	197	8.73	6.40	6.40	5569	0.00	0.00			0.0	504	0.0	442	0.0	455	0.0	903
15/12/86	223	<3.51	6.40	6.40	5435	3.73	3.73			32.0	536	32.0	474	23.9	479	23.9	927
02/04/87	331	<2.60	6.40	6.40	11867	0.00	0.00			0.0	536	0.0	474	0.0	479	0.0	927
01/06/87	391	4.48	2.75	5.75	1932	0.00	0.00			0.0	536	0.0	474	0.0	479	0.0	927
24/08/87	475	<2.88	4.87	6.37	3852	2.03	2.45			9.3	545	12.3	487	7.7	487	14.8	942
30/11/87	573	<3.23	6.40	6.40	9528	0.00	0.00			0.0	545	0.0	487	0.0	487	0.0	942

Table 10b Modelled Cs-134 data for Esthwaite (3 m depth).

Date	Days	Cs137 mBq/1	Epi vol $\times 10^6$	Hypo vol $\times 10^6$	Flow $\times 10^3$	C		Deposition velocity ( $\text{m d}^{-1}$ )		Hydr epi $\times 10^6$	Cum loss $\times 10^6$	Hydr hypo $\times 10^6$	Cum loss $\times 10^6$	Settle epi $\times 10^6$	Cum loss $\times 10^6$	Settle hypo $\times 10^6$	Cum loss $\times 10^6$
						epi mBq/1	hypo mBq/1	epi	hypo								
13/05/86	7	96.09	5.86	6.43	770												
21/05/86	15	70.44	5.05	6.40	620	84.98	87.21	-	-	60.6	61	56.9	57	79.3	79	107.6	108
04/06/86	29	44.55	1.76	5.45	1118	37.29	57.37	-	0.8	112.8	173	77.4	134	0.0	79	76.0	184
16/06/86	41	32.10	2.87	5.05	648	35.55	39.19	0.4	1.2	20.8	194	28.2	163	8.0	87	37.2	221
02/07/86	57	24.18	3.20	6.10	369	28.60	30.21	0.2	0.5	10.6	205	10.5	173	13.4	101	33.6	254
14/07/86	69	23.65	2.50	6.25	77	23.44	23.88	-	-	2.1	207	1.8	175	0.0	101	1.4	256
30/07/86	85	16.27	2.60	6.25	161	22.23	23.05	0.07	0.2	3.6	211	3.8	179	15.2	116	42.4	298
11/08/86	97	13.53	3.10	6.25	849	12.37	14.20	-	0.04	11.1	222	12.9	192	0.0	116	4.2	302
01/09/86	118	15.52	5.25	6.35	648	11.96	12.22	-	-	6.6	228	8.3	200	0.0	116	0.0	302
22/09/86	139	7.99	6.40	6.40	313	14.78	14.78	-	-	4.3	233	4.7	205	39.5	155	43.3	346
20/10/86	167	<2.64	6.40	6.40	374	7.54	7.54			2.9	235	2.9	207	48.2	204	48.2	394
19/11/86	197	3.77	6.40	6.40	5569	0.00	0.00			0.0	235	0.0	207	0.0	204	0.0	394
15/12/86	223	<2.75	6.40	6.40	5435	1.61	1.61			13.8	249	13.8	221	10.3	214	10.3	404
02/04/87	331	<2.10	6.40	6.40	11867	0.00	0.00			0.0	249	0.0	221	0.0	214	0.0	404
01/06/87	391	<2.19	2.75	5.75	1932	0.00	0.00			0.0	249	0.0	221	0.0	214	0.0	404
24/08/87	475	<2.28	4.87	6.37	3852	0.00	0.00			0.0	249	0.0	221	0.0	214	0.0	404
30/11/87	573	<1.81	6.40	6.40	9428	0.00	0.00			0.0	249	0.0	221	0.0	214	0.0	404

Table 11a Chernobyl - Esthwaite Profile 27 August 1986

Depth in metres	Temp °C	O <sub>2</sub> mg.l <sup>-1</sup>	Soluble (1)		Part (2)		Total (3)		Sol (1)		Part (2)		Trace Metals (1)-Soluble-µg.l <sup>-1</sup>					Colour (4)		DOC (4) mg.l <sup>-1</sup>
			Fe mg.l <sup>-1</sup>	Fe mg.l <sup>-1</sup>	Fe mg.l <sup>-1</sup>	Mn mg.l <sup>-1</sup>	Zn mg.l <sup>-1</sup>	Cu mg.l <sup>-1</sup>	Pb ND	Cd ND	Abs at 340nm 4cm									
0.5	14.1	8.15	0.208	0.234	0.001	0.181	0.112	0.051	0.187	0.170	0.181	0.063	0.8	0.63	ND	ND	0.051	0.051	2.08	
1.5	14.0	8.02	0.229	0.293	0.240	0.187	0.143	0.043	0.187	0.170	0.181	0.063	1.1	0.53	ND	0.27	0.043	0.043	2.05	
2.5	14.0	8.00	0.269	0.161	0.242	0.170	0.062	0.042	0.170	0.170	0.181	0.063	1.0	0.65	ND	0.01	0.042	0.042	1.58	
3.5	14.0	8.00	0.333	0.170	0.239	0.181	0.063	0.043	0.181	0.170	0.181	0.063	0.8	0.69	ND	0.18	0.043	0.043	1.53	
4.5	14.0	8.00	0.361	0.251	0.233	0.174	0.112	0.039	0.174	0.174	0.181	0.063	1.0	0.81	ND	0.46	0.039	0.039	1.72	
5.5	13.95	8.00	0.017	0.124	0.232	0.197	0.042	0.043	0.197	0.197	0.181	0.063	1.0	0.69	ND	0.50	0.043	0.043	1.50	
6.5	13.9	8.00	0.256	0.261	0.226	0.171	0.113	0.044	0.171	0.171	0.181	0.063	1.3	0.51	ND	0.04	0.044	0.044	2.36	
7.5	13.9	7.85	0.195	0.227	0.224	0.162	0.093	0.041	0.162	0.162	0.181	0.063	0.8	0.51	ND	0.39	0.041	0.041	2.19	
8.5	13.85	7.60	0.253	0.128	0.233	0.153	0.043	0.041	0.153	0.153	0.181	0.063	0.8	0.55	ND	0.15	0.041	0.041	1.91	
9.5	13.8	7.50	0.370	0.293	0.253	0.200	0.108	0.044	0.200	0.200	0.181	0.063	1.0	0.57	ND	0.10	0.044	0.044	2.18	
10.5	13.8	7.20	0.222	0.269	0.300	0.232	0.098	0.045	0.232	0.232	0.181	0.063	-	-	-	-	0.043	0.043	1.96	
11.0	13.8	7.20	0.310	0.199	0.301	0.231	0.062	0.047	0.231	0.231	0.181	0.063	1.0	0.74	ND	0.17	0.047	0.047	1.99	
11.5	13.3	3.65	0.393	0.221	0.287	0.223	0.066	0.045	0.223	0.223	0.181	0.063	-	-	-	-	0.045	0.045	-	
12.0	12.9	3.35	0.519	0.433	0.416	0.417	0.083	0.041	0.417	0.417	0.181	0.063	1.6	1.09	0.024	0.30	0.041	0.041	2.12	
12.5	12.9	2.00	0.613	0.710	0.963	0.860	0.033	0.041	0.860	0.860	0.181	0.063	-	-	-	-	0.050	0.050	1.98	
13.0	12.5	3.05	0.678	1.263	1.412	1.405	0.042	0.041	1.405	1.405	0.181	0.063	1.5	0.57	ND	0.09	0.048	0.048	1.91	
13.5	11.8	0.75	3.242	0.268	2.219	2.176	0.017	0.041	2.176	2.176	0.181	0.063	-	-	-	-	0.156	0.156	2.24	
14.0	11.5	0.80	4.082	0.201	2.270	2.263	0.014	0.041	2.263	2.263	0.181	0.063	1.6	0.50	0.042	0.27	0.101	0.101	2.48	
14.5	11.2	0.65	4.129	0.238	2.298	2.255	0.017	0.041	2.255	2.255	0.181	0.063	-	-	-	-	0.085	0.085	2.30	
15.0	11.2	0.75	4.695	0.068	2.370	2.300	0.009	0.041	2.300	2.300	0.181	0.063	1.8	1.40	0.013	2.00	0.111	0.111	3.46	

(1) Measured by AA after filtration (0.45 µm Millipore). (2) Acid dissolution of material on filter  
(3) After acidification (1M HCl). (4) Filtered (GFF), acidified to 0.0009 M H<sub>2</sub>SO<sub>4</sub>.  
(5) Carlo Erba analysis of filter.

Table 11a Cont'd

Depth in metres	C mg C l <sup>-1</sup>	N <sup>(5)</sup> mg l <sup>-1</sup>	C:N <sup>(5)</sup> at ratio	Dissolved Activity mBq/l		Particulate Activity mBq/l	
				Cs-134	Cs-137	Cs-134	Cs-137
0.5	1.649	0.245	6.73	21.08 ± 3.09	46.87 ± 5.97	<3.70	<5.52
1.5	1.535	0.242	6.35	16.99 ± 2.61	33.46 ± 4.51	<3.28	<4.38
2.5	1.717	0.252	6.80	24.00 ± 3.34	42.39 ± 5.72	<2.53	<2.64
3.5	1.677	0.217	7.73	17.22 ± 2.58	43.74 ± 4.91	<3.02	<2.81
4.5	1.547	0.248	6.23	14.26 ± 2.33	32.33 ± 4.36	<2.98	<2.85
5.5	1.619	0.244	6.63	14.88 ± 2.72	36.47 ± 5.67	<3.27	3.85 ± 1.91
6.5	1.622	0.216	7.51	13.20 ± 2.36	44.56 ± 5.21	<3.07	<3.07
7.5	1.569	0.208	7.56	21.65 ± 3.19	39.94 ± 5.64	<2.80	<2.65
8.5	1.498	0.190	7.88	13.89 ± 2.45	41.29 ± 5.34	<2.91	<3.04
9.5	1.467	0.173	8.48	21.22 ± 2.77	39.32 ± 4.56	<3.06	<2.75
10.5	1.586	0.172	9.22	24.53 ± 3.39	38.94 ± 5.58	<2.75	<2.81
11.0	1.164	0.158	7.36	17.28 ± 2.79	33.07 ± 5.16	<2.59	<2.55
11.5	1.604	0.239	6.80	19.86 ± 2.83	41.45 ± 4.96	<3.60	<3.41
12.0	1.822	0.189	9.66	21.33 ± 3.15	48.15 ± 5.99	<3.36	<2.97
12.5	1.336	0.106	12.57	23.80 ± 3.04	60.08 ± 5.67	<3.25	<3.16
13.0	1.424	0.125	11.40	29.49 ± 3.27	57.68 ± 5.36	<3.14	<4.00
13.5	1.267	0.079	16.06	41.36 ± 5.01	87.12 ± 8.74	<2.63	<2.52
14.0	1.621	0.117	13.80	35.92 ± 4.37	86.19 ± 8.04	<3.13	<2.93
14.5	1.996	0.144	13.84	36.52 ± 3.67	79.70 ± 6.16	<2.61	<2.59
15.0	1.547	0.116	13.33	28.52 ± 3.03	85.15 ± 5.90	<2.71	<2.50

Table 11b. Esthwaite profile 9.9.87

m	Temperature		oxygen		Depth m	Activity mBq/l	
	°C	%	mg l <sup>-1</sup>	µM		Cs-134	Cs-137
0	16.1	108	10.6	331			
1	16.1	108	10.6	330	1.0	<2.26	<3.08
2	16.0	107	10.5	329			
3	15.9	104	10.2	319			
4	15.9	103	10.2	318	4.0	<2.39	<3.06
5	15.8	102	10.1	316			
6	15.6	70	7.0	218	7.0	<2.13	<2.66
7	14.4	22	2.2	68			
8	12.4	<1	<0.1	1	8.0	<2.20	8.25 ± 1.94
9	11.7	<1	<0.1	1		<2.51	8.00 ± 2.13
10	11.2	<1	<0.1	1		<2.97	6.76 ± 2.24
11	10.4	<1	<0.1	1		<2.74	5.28 ± 2.03
12	10.2	<1	<0.1	1		2.56 ± 0.88	6.85 ± 2.19
13	10.0	<1	<0.1	1		2.28 ± 0.74	6.30 ± 1.90
14	9.9	<1	<0.1	1		<2.08	9.68 ± 2.07
14.7	9.9	<1	<0.1	1		2.67 ± 0.80	15.64 ± 2.47

15.0 = bottom

S. Disc = 1.6 m

Table 12. Settling velocities and equivalent Stokes diameters for particles transporting Cs to the sediments.

	Esthwaite		Windermere	
	Maximum <sup>1</sup> velocity	Minimum <sup>2</sup> velocity	Maximum <sup>1</sup> velocity	Minimum <sup>2</sup> velocity
Time to first appearance in sediments (d)	7	7	27	27
Depth of travel (m)	(15.5-3)	(15.5-14)	(64-3)	(64-28)
velocity (m d <sup>-1</sup> )	1.8	0.2	2.3	1.3
Equivalent spherical particle diameters (μm)				
density = 1.6 g cm <sup>-3</sup>	15.9	1.8	20.3	11.8
density = 2.6 g cm <sup>-3</sup>	6.0	0.7	7.6	4.4
density = 1.1 g cm <sup>-3</sup>	96	10.6	122	70.6

1 distance travelled = maximum depth - 3 m

2 distance travelled = maximum depth - epilimnion base

Table 13 Sums of Cs-134 and (Cs-137 - background Cs-137) for top 5 cm of sediment in Esthwaite Water

Date	Cs-134 Bq m <sup>-2</sup> x 10	Cs-137 Bq m <sup>-2</sup> x 10
08/5/86		-20.023
13/5/86	4.185	-1.936
21/5/86	41.232	74.390
04/6/86	32.473	62.572
16/6/86	23.866	36.543
02/7/86	67.855	148.254
14/7/86	145.332	284.942
30/7/86	140.010	327.514
11/8/86	31.565	42.648
03/9/86	41.591	75.867
22/9/86	16.935	21.911
20/10/86	53.316	89.345
03/11/86	102.737	183.946
19/11/86	39.818	65.316
15/12/86	49.450	61.143
02/4/87	27.694	56.319
01/6/87	35.311	48.419
24/8/87	108.777	182.304
30/11/87	81.554	141.404

Table 14 Sums of Cs-134 and (Cs-137 - background Cs-137) for the top 5 cm of sediment in Windermere

	Cs-134 Bq m <sup>-2</sup> x 10	Cs-137 Bq m <sup>-2</sup> x 10
08/5/86		-9.494
13/5/86		5.891
20/5/86		-6.394
03/6/86	8.643	8.773
17/6/86	22.787	37.552
01/7/86	14.972	27.830
15/7/86	23.615	40.843
29/7/86	45.480	100.068
14/8/86	20.272	30.287
03/9/86	22.429	36.076
23/9/86	32.775	49.120
21/10/86	72.923	153.616
18/11/86	103.224	199.375
09/12/86	66.626	140.068
02/4/87	63.078	114.071
03/6/87	73.802	128.026
25/8/87	72.903	154.853
01/12/87	25.607	91.800

## ----- Site=1 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	137.0	373.0
08/05/86	162.0	436.0
16/06/86	56.2	165.0
14/07/86	123.0	366.0
11/08/86	23.9	66.8
02/09/86	90.1	271.0
03/11/86	56.6	271.0
15/12/86	95.5	313.0
02/03/87	.	263.0
02/04/87	114.0	349.0
01/06/87	106.0	349.0
24/08/87	124.0	363.0
30/11/87	93.1	293.0

## ----- Site=2 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	20.3	134
08/05/86	35.5	132
16/06/86	78.6	265
14/07/86	59.9	231
11/08/86	221.0	523
02/09/86	156.0	421
03/11/86	200.0	503
15/12/86	107.0	275
02/03/87	.	.
02/04/87	107.0	281
01/06/87	83.6	294
24/08/87	.	145
30/11/87	84.4	257

## ----- Site=3 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	.
08/05/86	35.9	129
16/06/86	60.7	179
14/07/86	84.0	217
11/08/86	118.0	320
02/09/86	111.0	313
03/11/86	119.0	330
15/12/86	125.0	351
02/03/87	.	.
02/04/87	61.6	156
01/06/87	79.9	235
24/08/87	56.8	176
30/11/87	65.6	210

## Esthwaite Water Grid Samples

## ----- Site=4 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	212	433
08/05/86	677	1540
16/06/86	514	1130
14/07/86	78	250
11/08/86	300	728
02/09/86	329	811
03/11/86	213	561
15/12/86	153	415
02/03/87	141	371
02/04/87	114	301
01/06/87	140	367
24/08/87	118	309
30/11/87	108	294

## ----- Site=5 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	191.0	478
08/05/86	136.0	407
16/06/86	508.0	1180
14/07/86	291.0	756
11/08/86	375.0	863
02/09/86	423.0	1023
03/11/86	138.0	403
15/12/86	278.0	720
02/03/87	.	203
02/04/87	178.0	453
01/06/87	239.0	680
24/08/87	156.0	428
30/11/87	91.1	325

## ----- Site=6 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	185	488
08/05/86	242	648
16/06/86	313	893
14/07/86	301	789
11/08/86	561	1310
02/09/86	369	922
03/11/86	287	738
15/12/86	372	921
02/03/87	250	667
02/04/87	292	828
01/06/87	256	667
24/08/87	313	786
30/11/87	164	565

## Esthwaite Water Grid Samples

## ----- Site=7 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	135	414
08/05/86	430	972
16/06/86	345	834
14/07/86	410	1006
11/08/86	381	936
02/09/86	350	858
03/11/86	233	570
15/12/86	235	571
02/03/87	169	437
02/04/87	144	393
01/06/87	144	381
24/08/87	.	132
30/11/87	182	488

## ----- Site=8 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	144.0	377
08/05/86	276.0	640
16/06/86	347.0	727
14/07/86	326.0	824
11/08/86	257.0	619
02/09/86	156.0	447
03/11/86	263.0	655
15/12/86	177.0	457
02/03/87	154.0	457
02/04/87	92.9	299
01/06/87	116.0	320
24/08/87	165.0	425
30/11/87	143.0	327

## ----- Site=9 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	128
08/05/86	126.0	363
16/06/86	184.0	482
14/07/86	.	133
11/08/86	264.0	650
02/09/86	272.0	672
03/11/86	239.0	589
15/12/86	295.0	747
02/03/87	209.0	490
02/04/87	227.0	592
01/06/87	144.0	390
24/08/87	170.0	485
30/11/87	91.5	343

## Esthwaite Water Grid Samples

## ----- Site=10 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	54.2	182
08/05/86	346.0	834
16/06/86	.	211
14/07/86	255.0	665
11/08/86	108.0	352
02/09/86	255.0	688
03/11/86	285.0	756
15/12/86	296.0	784
02/03/87	320.0	832
02/04/87	194.0	507
01/06/87	261.0	717
24/08/87	.	336
30/11/87	162.0	501

## ----- Site=11 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	130
08/05/86	184	553
16/06/86	152	502
14/07/86	287	982
11/08/86	588	1450
02/09/86	531	1310
03/11/86	509	1210
15/12/86	393	996
02/03/87	129	459
02/04/87	106	306
01/06/87	.	145
24/08/87	187	508
30/11/87	163	515

## ----- Site=12 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	223
08/05/86	269.0	734
16/06/86	193.0	576
14/07/86	193.0	623
11/08/86	335.0	926
02/09/86	489.0	1150
03/11/86	128.0	504
15/12/86	303.0	799
02/03/87	286.0	720
02/04/87	411.0	939
01/06/87	287.0	739
24/08/87	93.8	440
30/11/87	201.0	647

## Esthwaite Water Grid Samples

## ----- Site=13 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	177
08/05/86	175	484
16/06/86	184	481
14/07/86	147	453
11/08/86	458	1151
02/09/86	147	460
03/11/86	147	453
15/12/86	518	1230
02/03/87	.	.
02/04/87	148	417
01/06/87	303	763
24/08/87	178	477
30/11/87	222	591

## ----- Site=14 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	263
08/05/86	208	551
16/06/86	114	380
14/07/86	1405	3090
11/08/86	379	905
02/09/86	283	646
03/11/86	589	1319
15/12/86	232	579
02/03/87	.	.
02/04/87	183	509
01/06/87	107	356
24/08/87	264	610
30/11/87	145	435

## ----- Site=15 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	.
08/05/86	173	491
16/06/86	257	668
14/07/86	240	647
11/08/86	343	869
02/09/86	350	856
03/11/86	266	706
15/12/86	245	624
02/03/87	.	.
02/04/87	195	488
01/06/87	.	.
24/08/87	206	572
30/11/87	198	507

## Esthwaite Water Grid Samples

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----- Site=16 -----

Date	Cs134 Bq/Kg	Cs137 Bq/Kg
02/05/86	.	.
08/05/86	91.8	298
16/06/86	393.0	900
14/07/86	270.0	697
11/08/86	355.0	824
02/09/86	960.0	2120
03/11/86	431.0	1030
15/12/86	375.0	914
02/03/87	.	.
02/04/87	239.0	594
01/06/87	.	.
24/08/87	147.0	437
30/11/87	245.0	602

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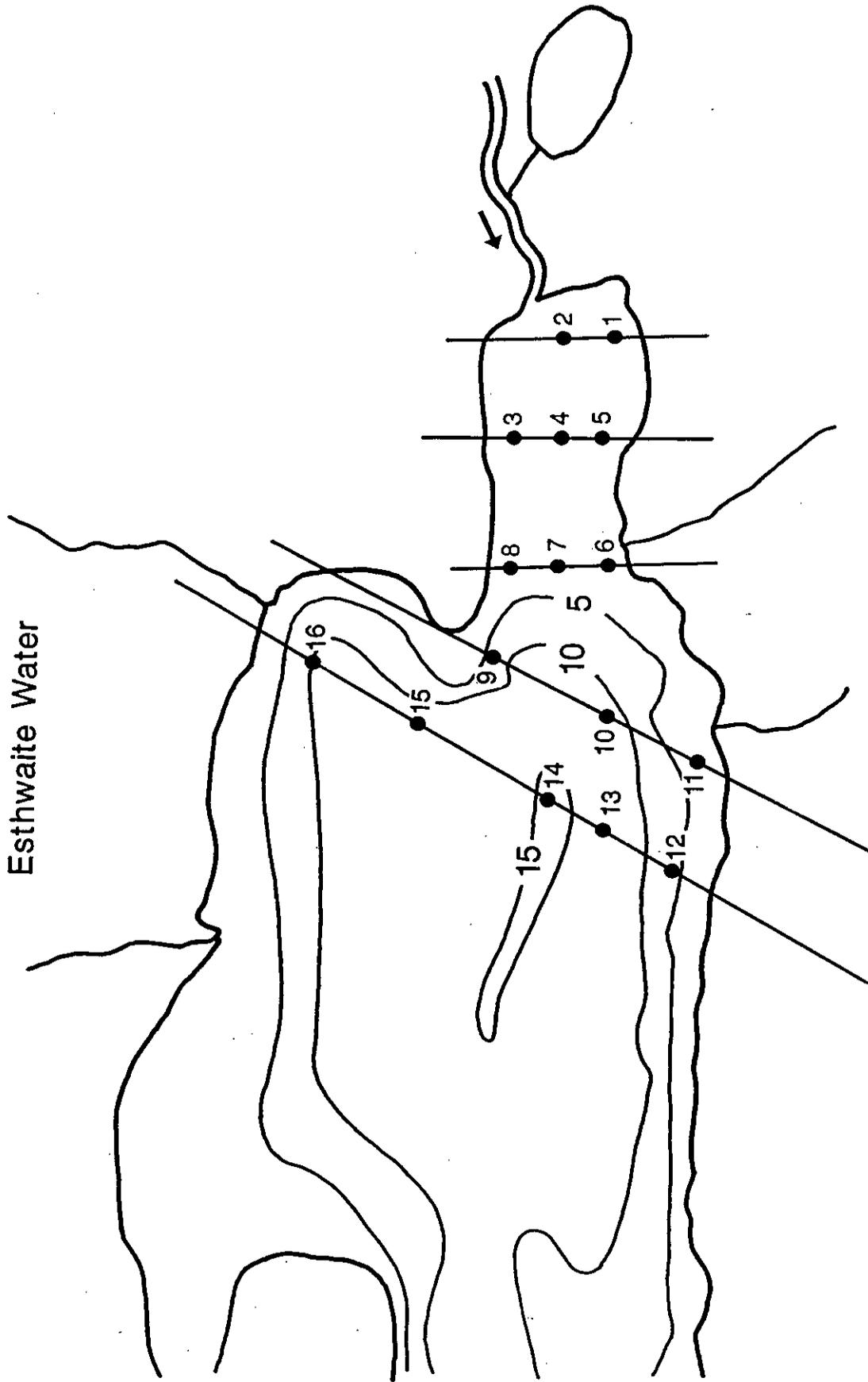


Fig 1 A map of the layout of sampling points at the mouth of Black Beck

Fig 2 Ruthenium 103 concentrations in the surface centimetre of Esthwaite and Windermere sediments

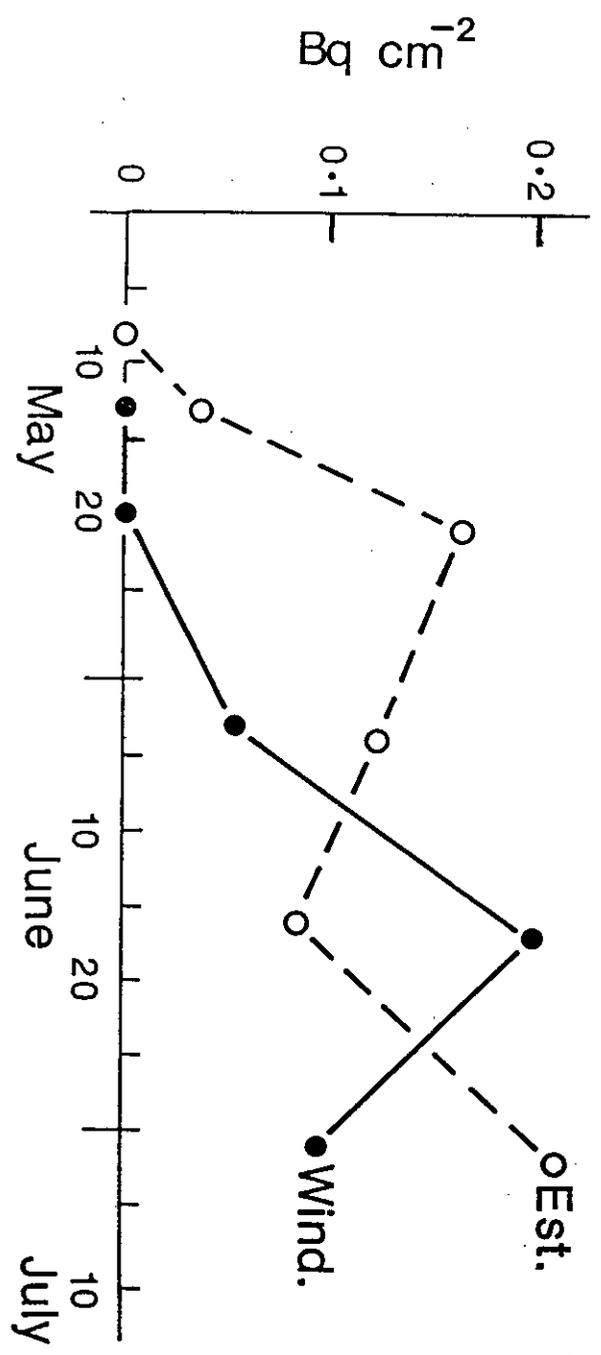


Fig 3. Change in the total concentration of radiocaesium with time in water from Esthwaite

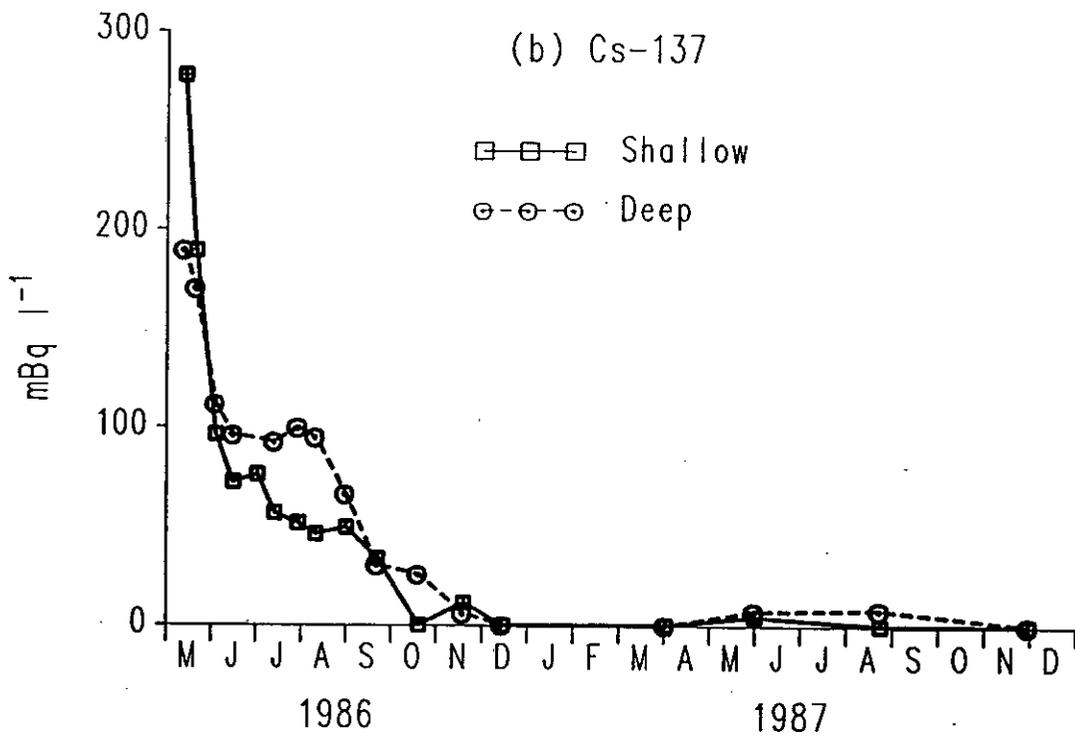
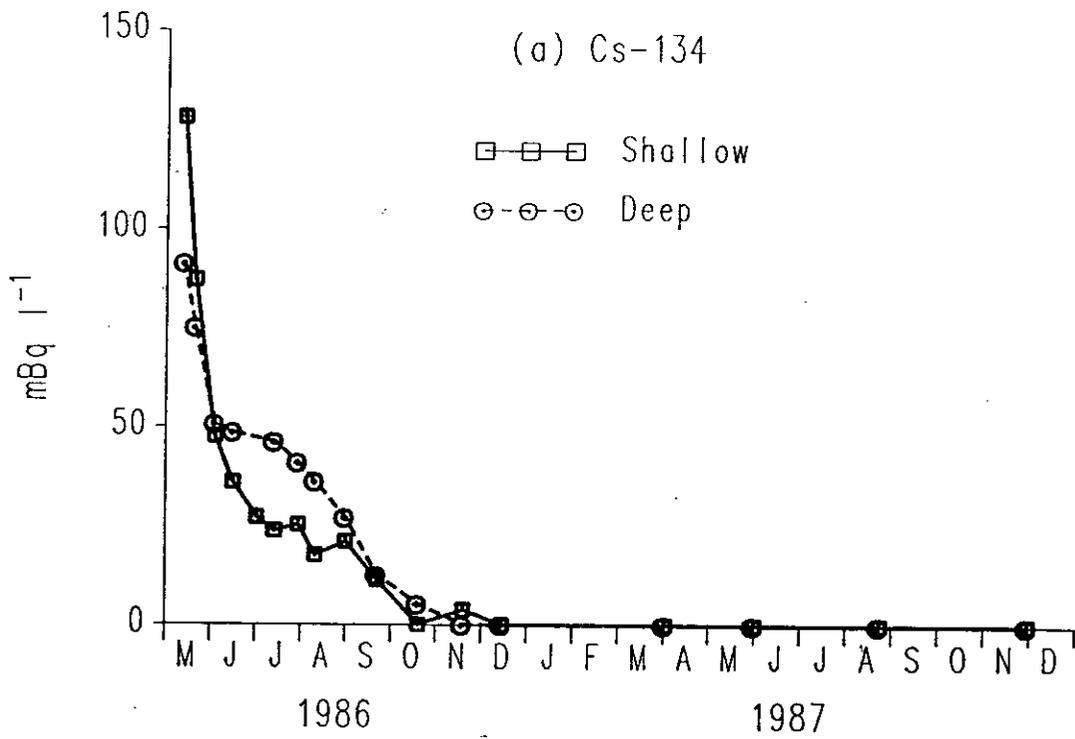


Fig 4. Change in the soluble concentration of radiocaesium with time in water from Windermere

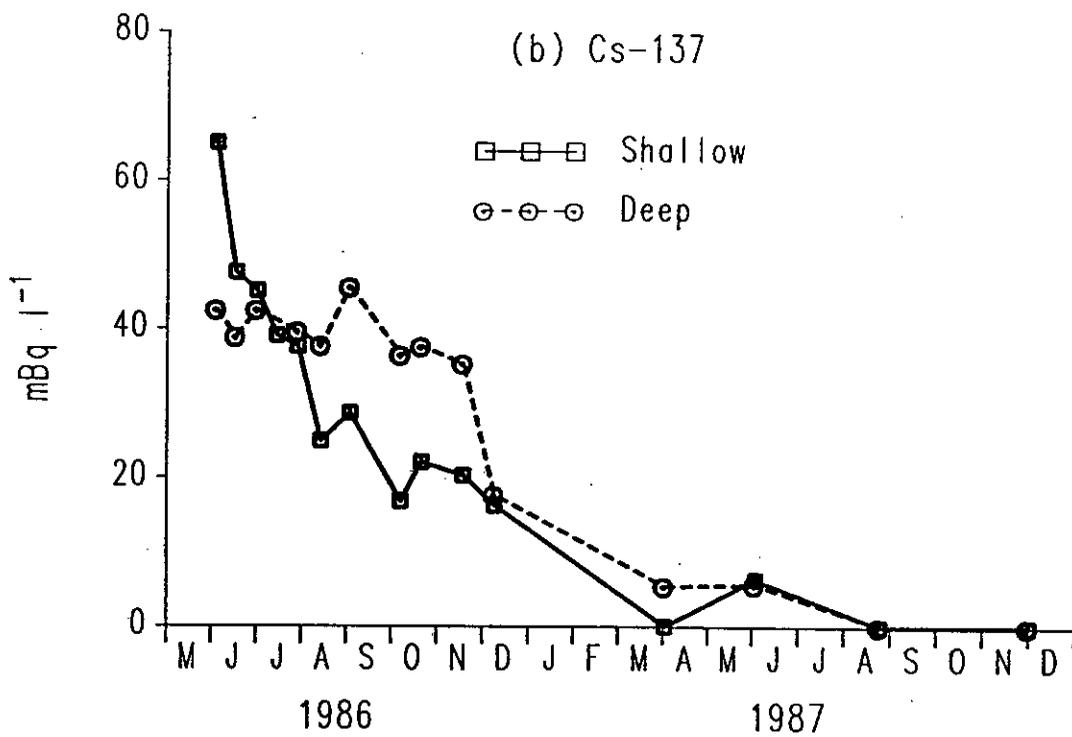
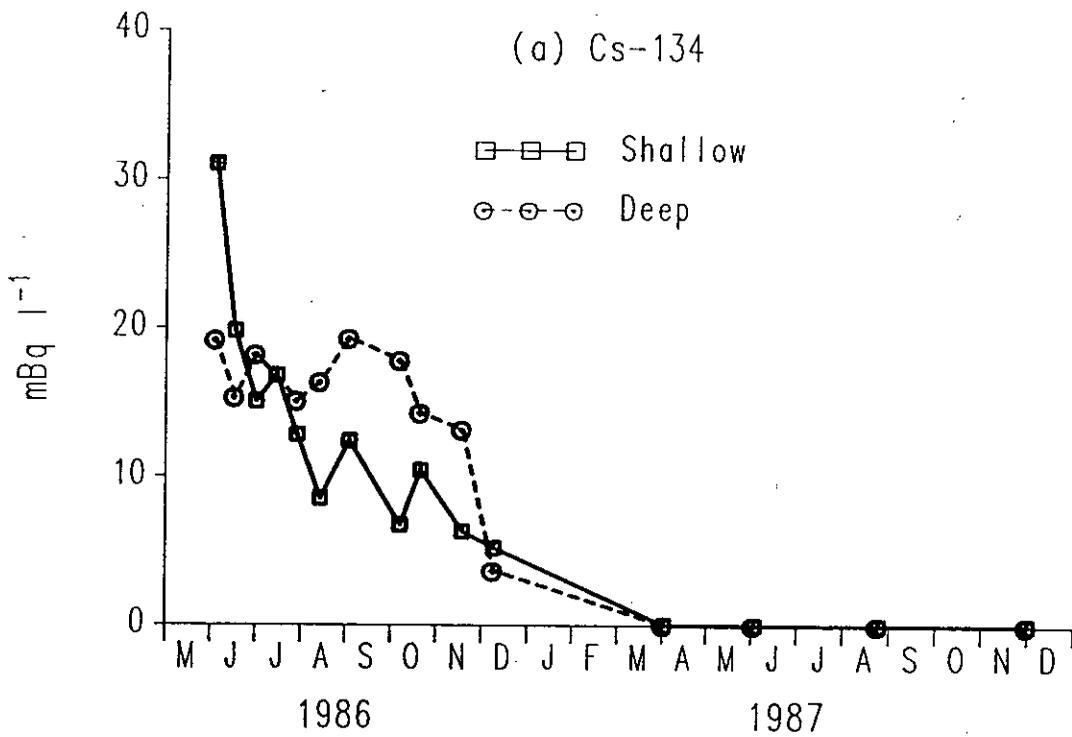


Fig 5. Temporal changes in the soluble and particulate concentrations of radiocaesium in the surface waters (3m) of Esthwaite

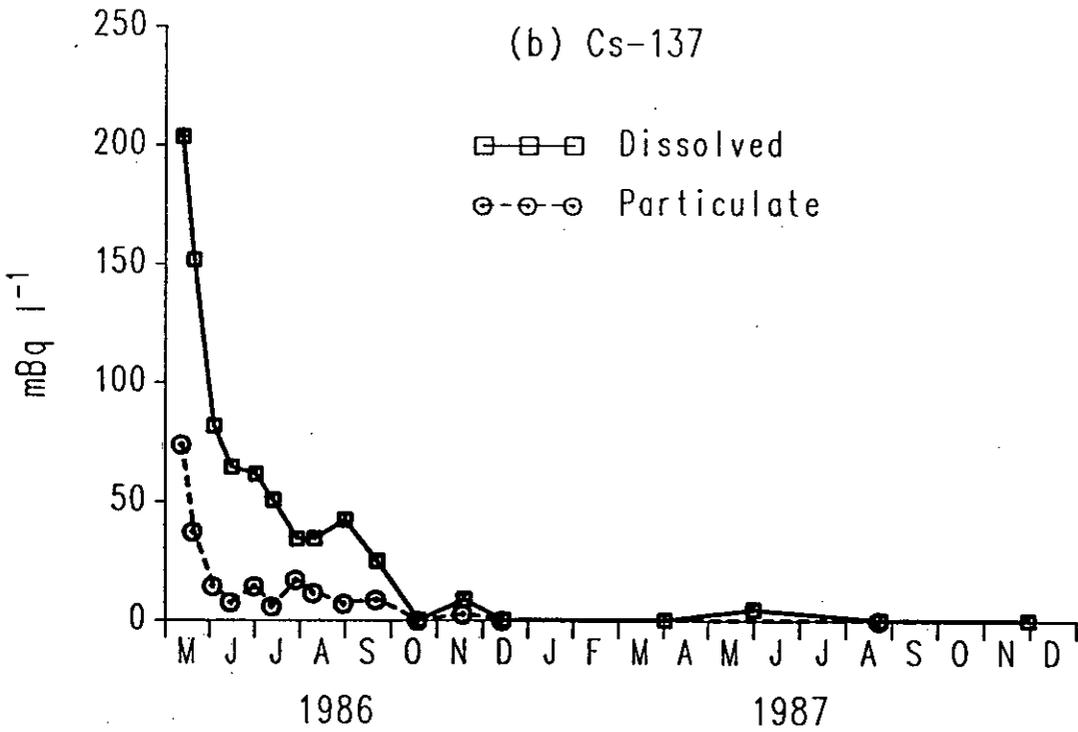
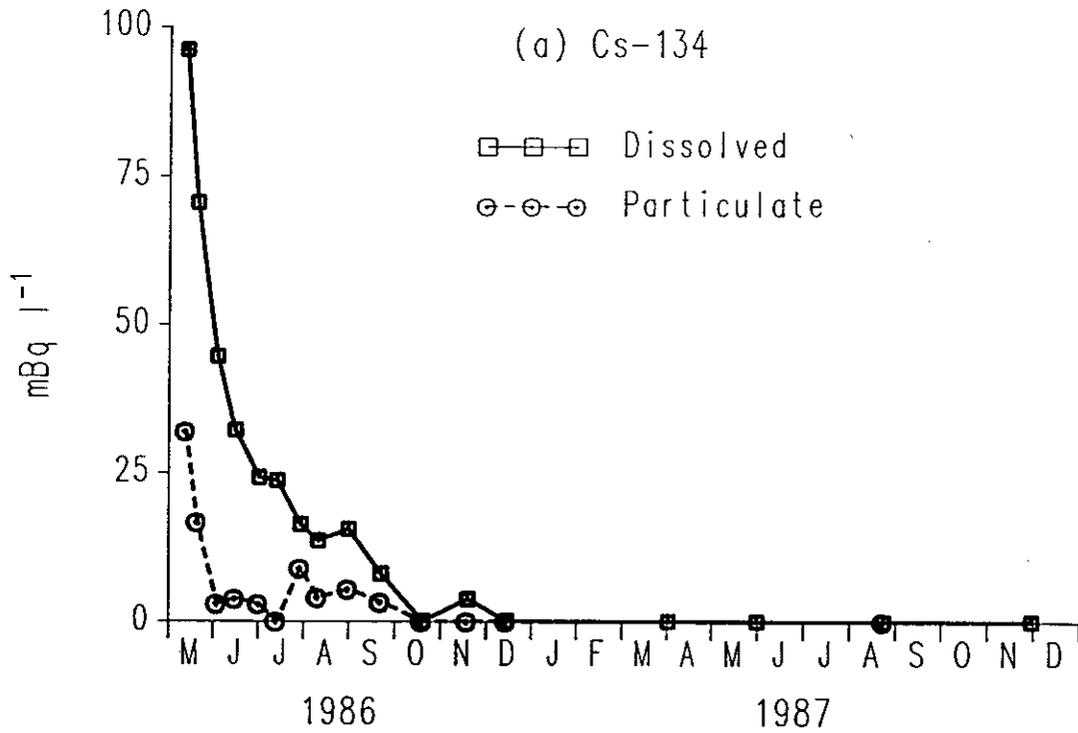


Fig 6. Temporal changes in soluble and particulate concentrations of radiocaesium in the bottom waters (13.5m) of Esthwaite

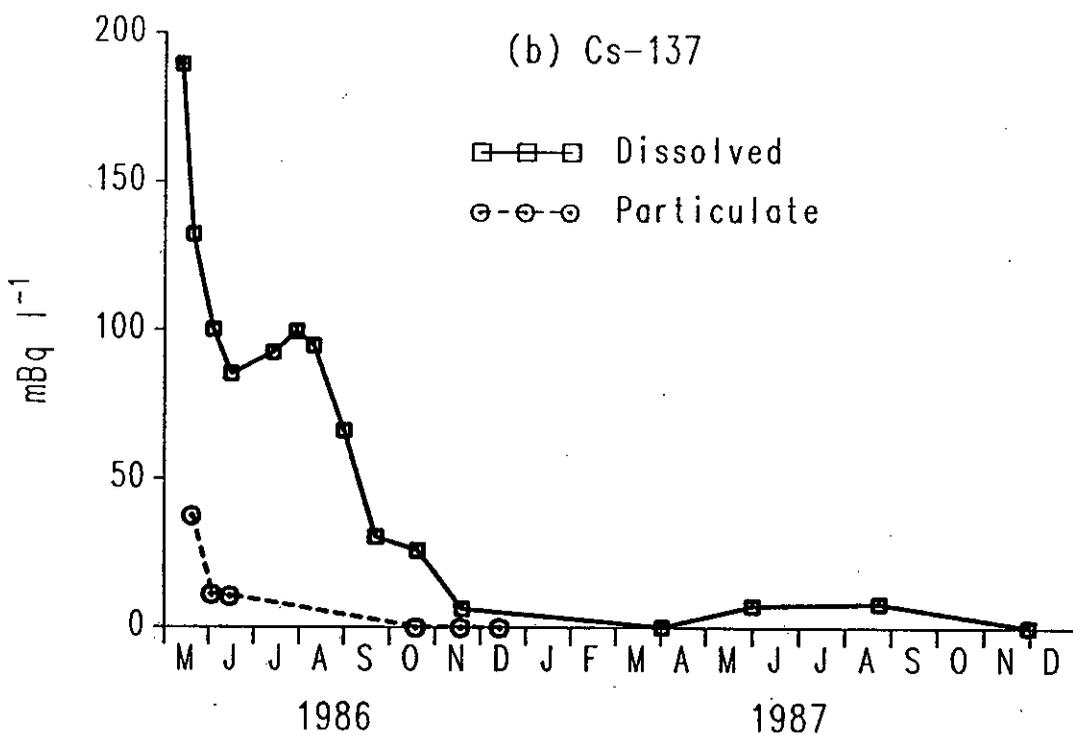
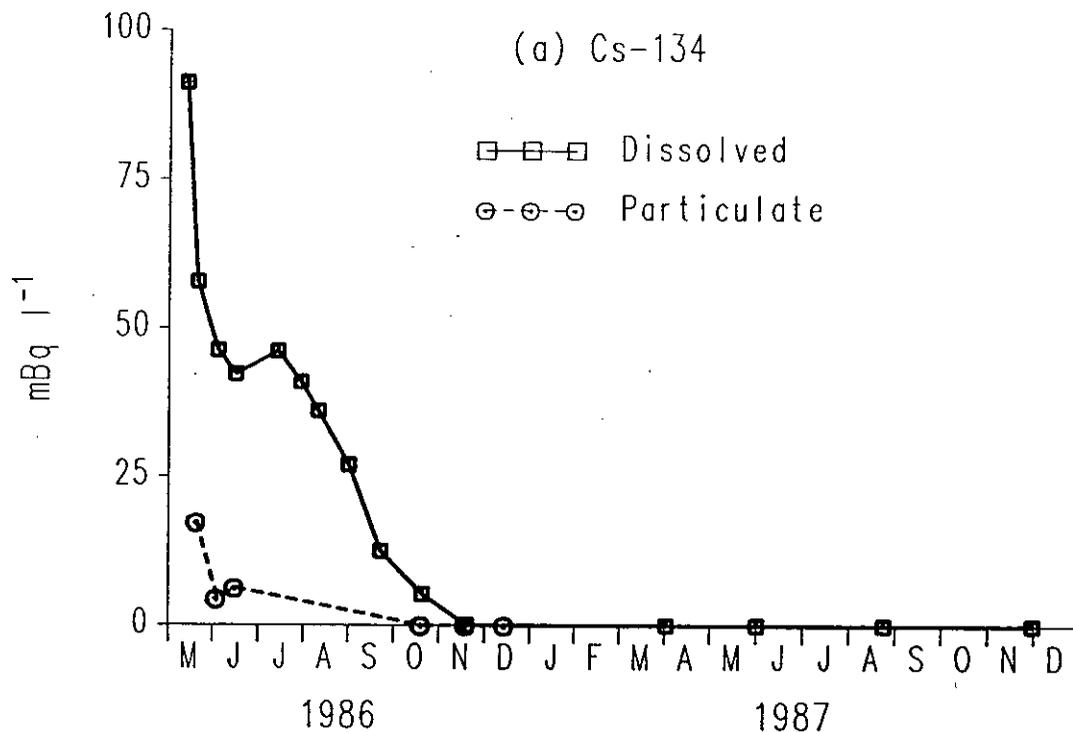




Fig 8. Variation in the concentrations of Cs-134 in the top five centimetres of Esthwaite sediments

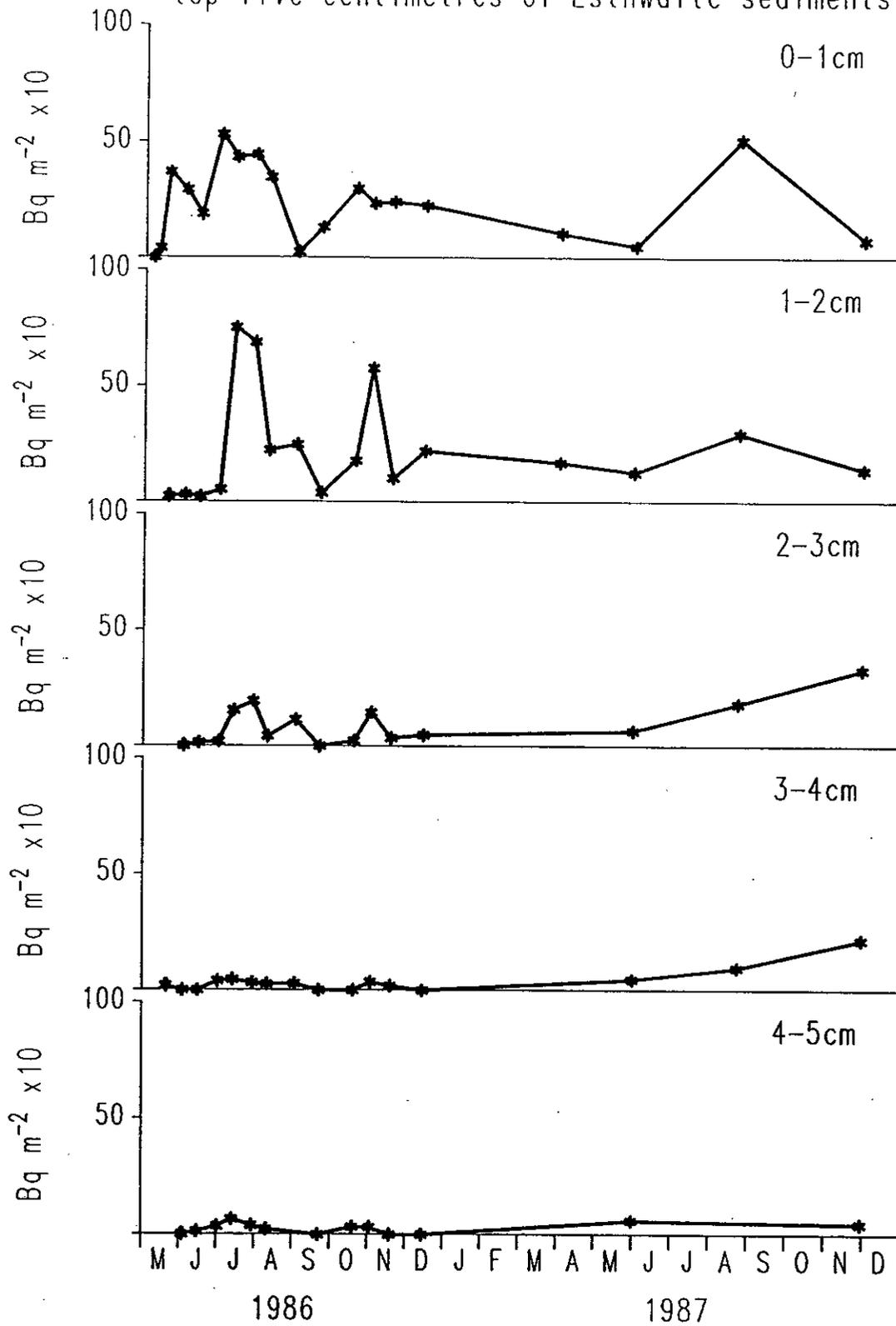
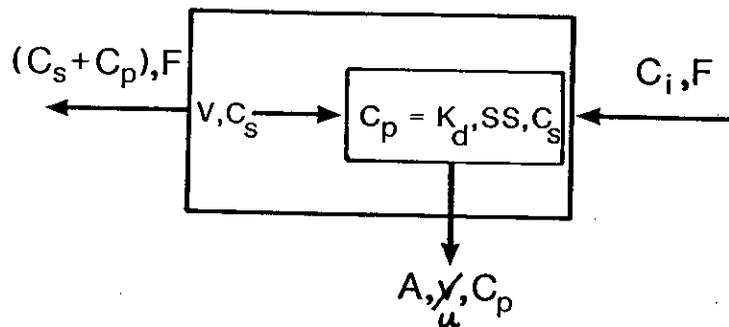






Fig 11 A simple representation of a lake



$C_i$  = instantaneous concentration of Caesium in the inflow ( $\text{Bq.m}^{-3}$ )

$F$  = hydraulic flow through the system ( $\text{m}^3.\text{d}^{-1}$ )

$C_s$  = instantaneous concentration of soluble Caesium in the lake ( $\text{Bq.m}^{-3}$ )

$C_p$  = instantaneous concentration of particulate Caesium in the lake ( $\text{Bq.m}^{-3}$ )

$V$  = volume of completely mixed region of the lake

$K_d$  = distribution coefficient ( $\text{m}^3.\text{kg}^{-1}$ ) =  $\frac{C_p(\text{Bq.m}^{-3})}{SS(\text{kg.m}^{-3}).C_s(\text{Bq.m}^{-3})}$

$A$  = surface area of the lake ( $\text{m}^2$ )

$\nu$  = deposition velocity of particulate Cs ( $\text{m.d}^{-1}$ )

$SS$  = suspended solids concentration in  $\text{kg.m}^{-3}$

Fig 12 Definitions of the epilimnion, metalimnion and hypolimnion used in the model

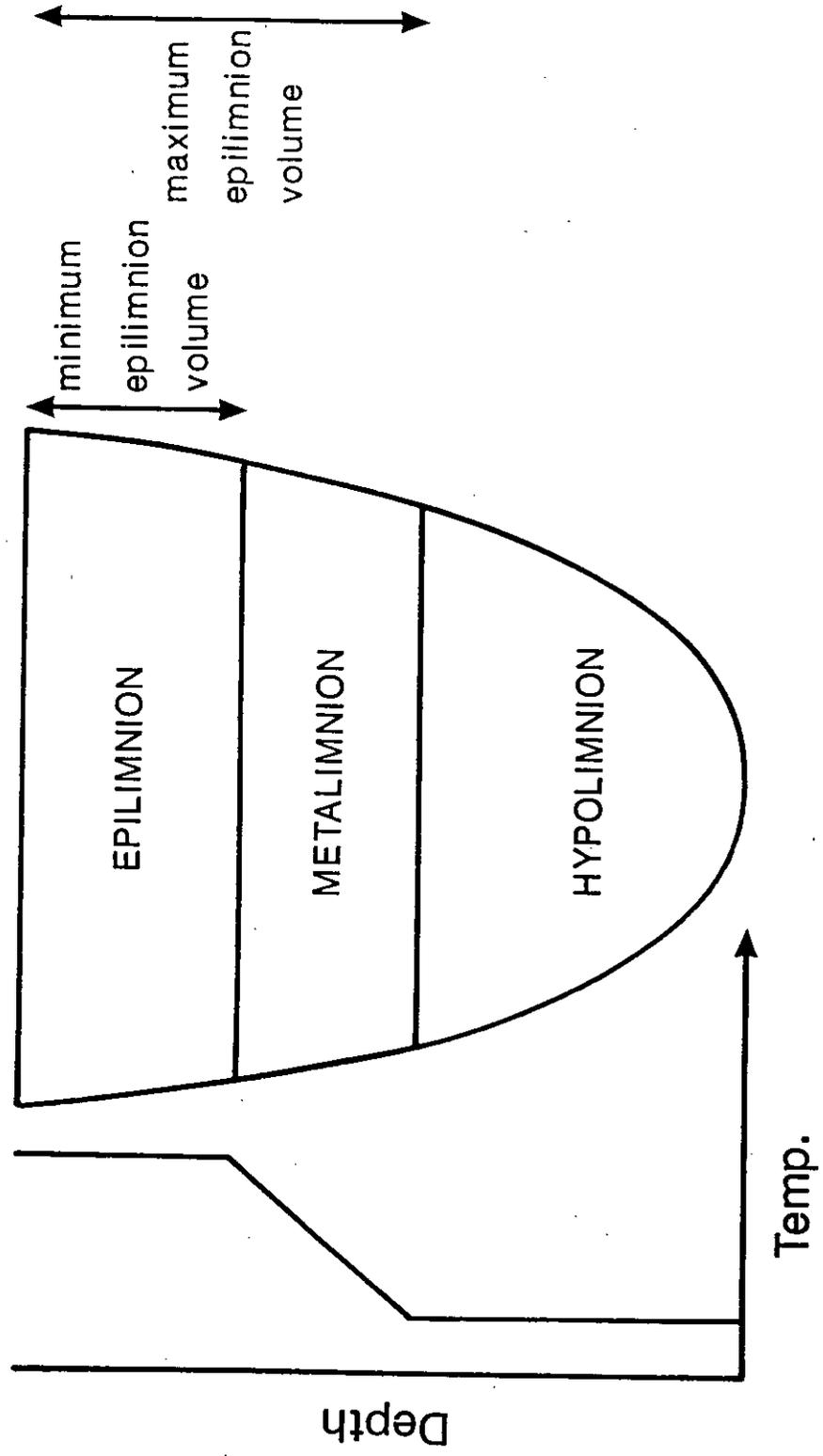


Fig 13. Estimated concentrations of Cs-137 in Esthwaite assuming hydraulic flushing losses only.  
(Dotted lines show model estimates; solid line shows measured values)

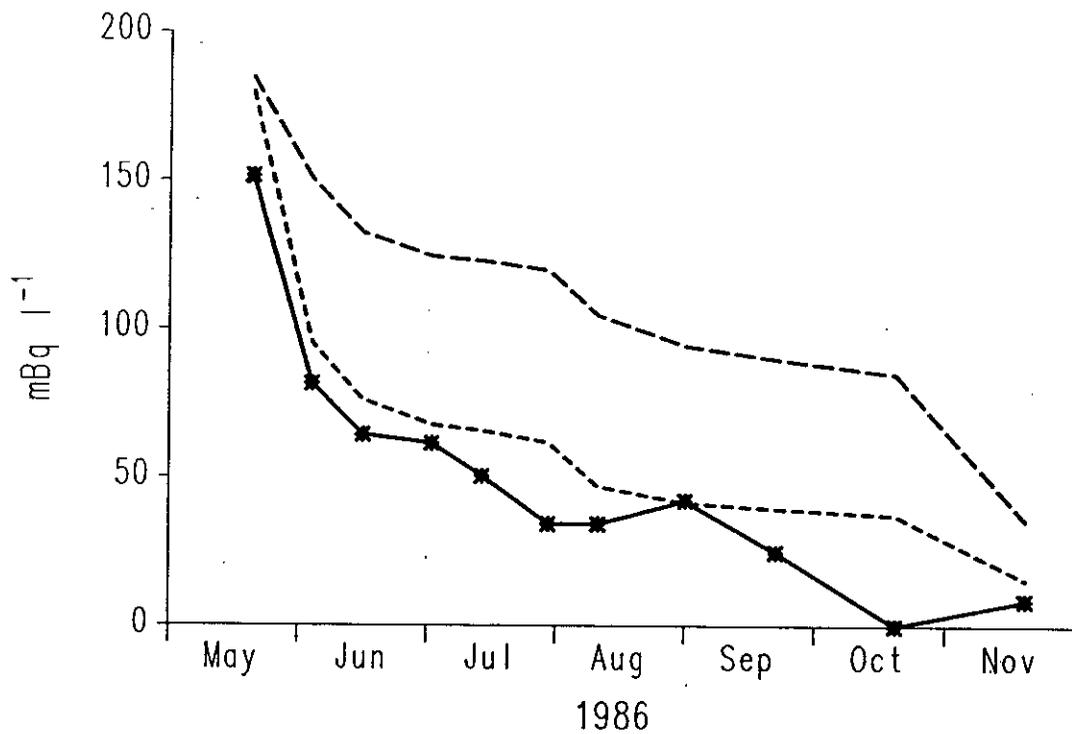


Fig 14. Estimated concentrations of Cs-137 in Windermere assuming hydraulic flushing losses only. (Dotted lines show model estimates; solid line shows measured values)

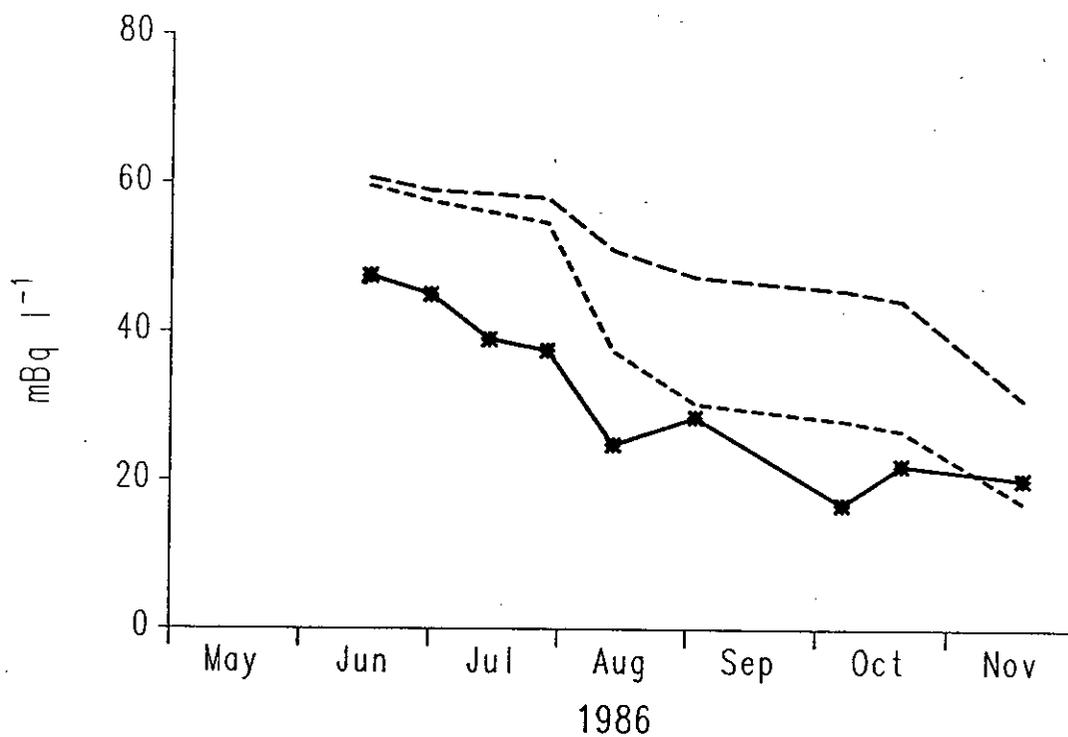


Fig. 15a  
Concentrations of soluble Cs-134, soluble Cs-137 and soluble Fe  
at various depths in Esthwaite Water on 27. 8. 1986

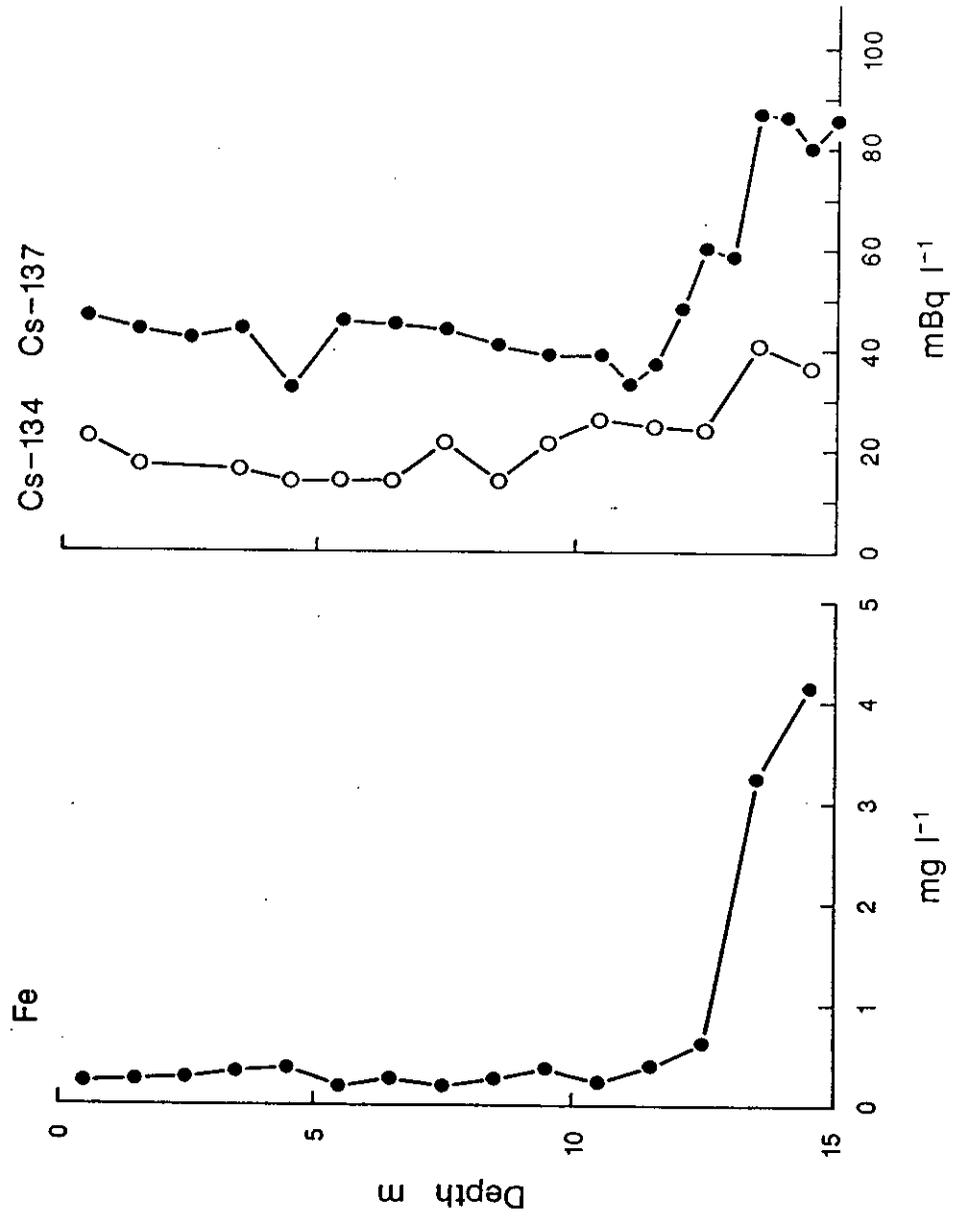


Fig 15b Concentration of Caesium 134 and 137 at various depths in Esthwaite Water on 9/9/87

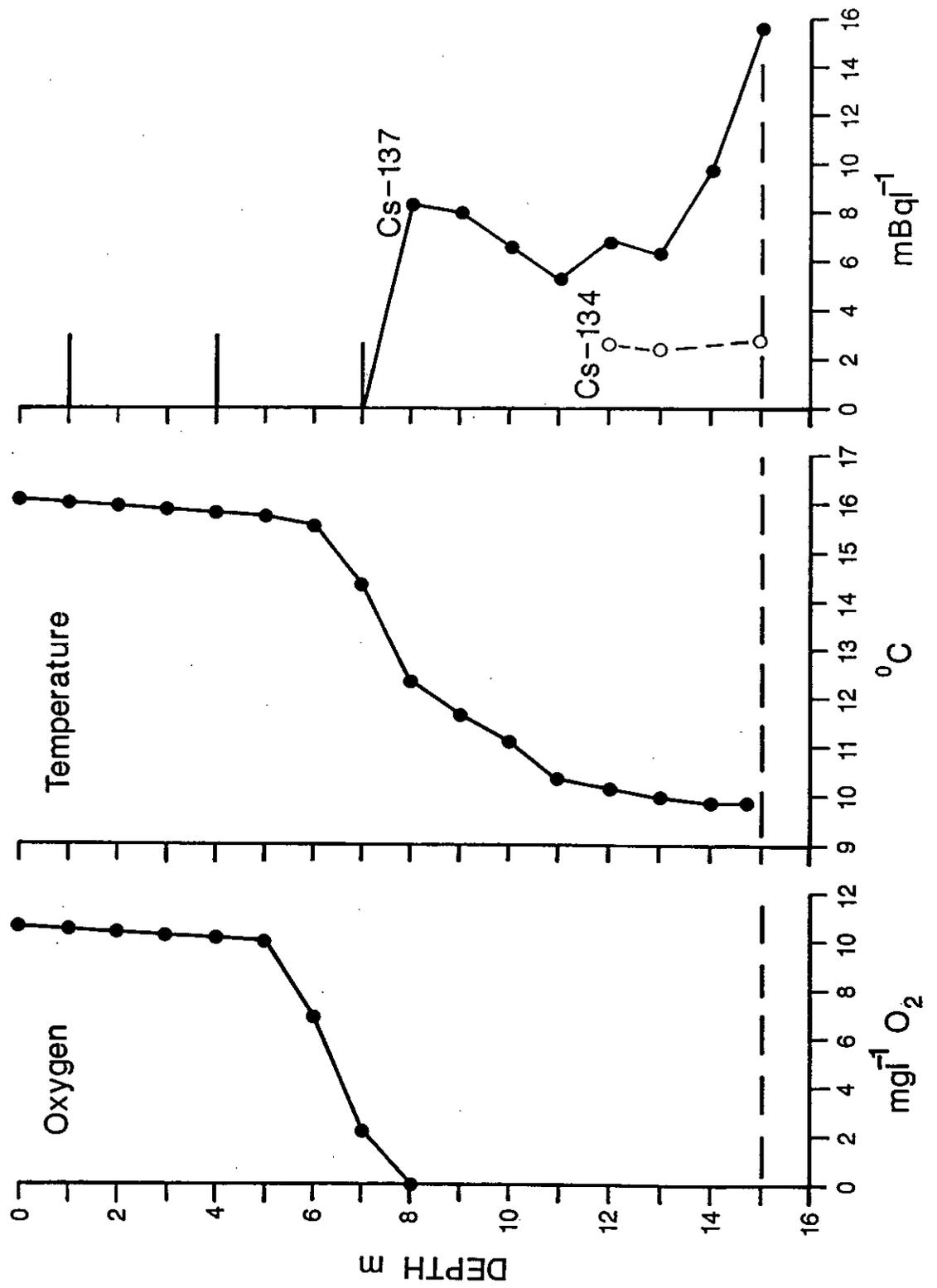


Fig 16. Log soluble and total concentrations of radiocaesium versus time in the surface waters (3m) of Esthwaite

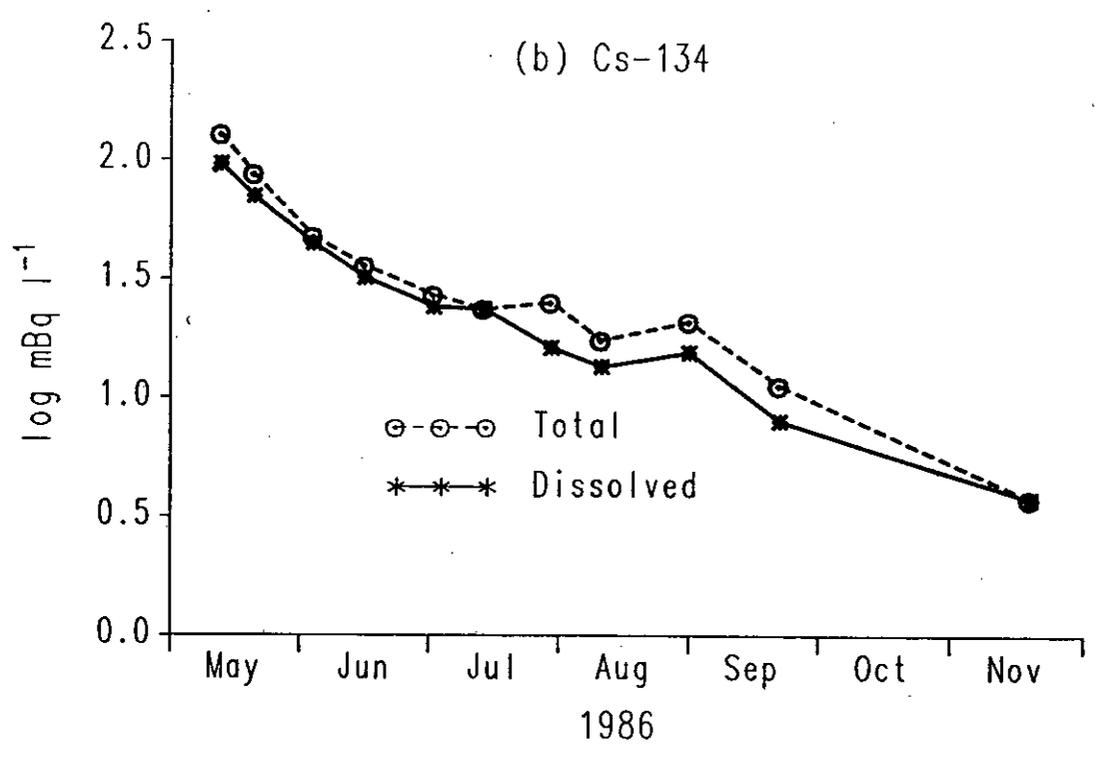
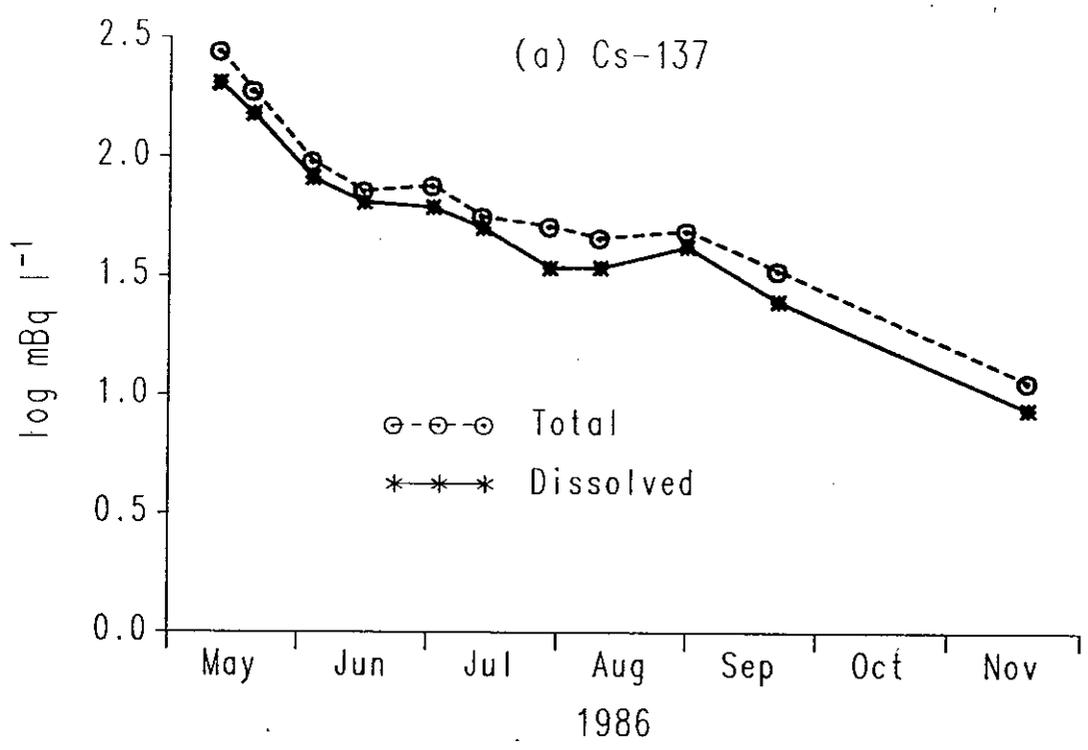


Fig 17. Log soluble concentration of radiocaesium versus time in the surface waters (3m) of Windermere

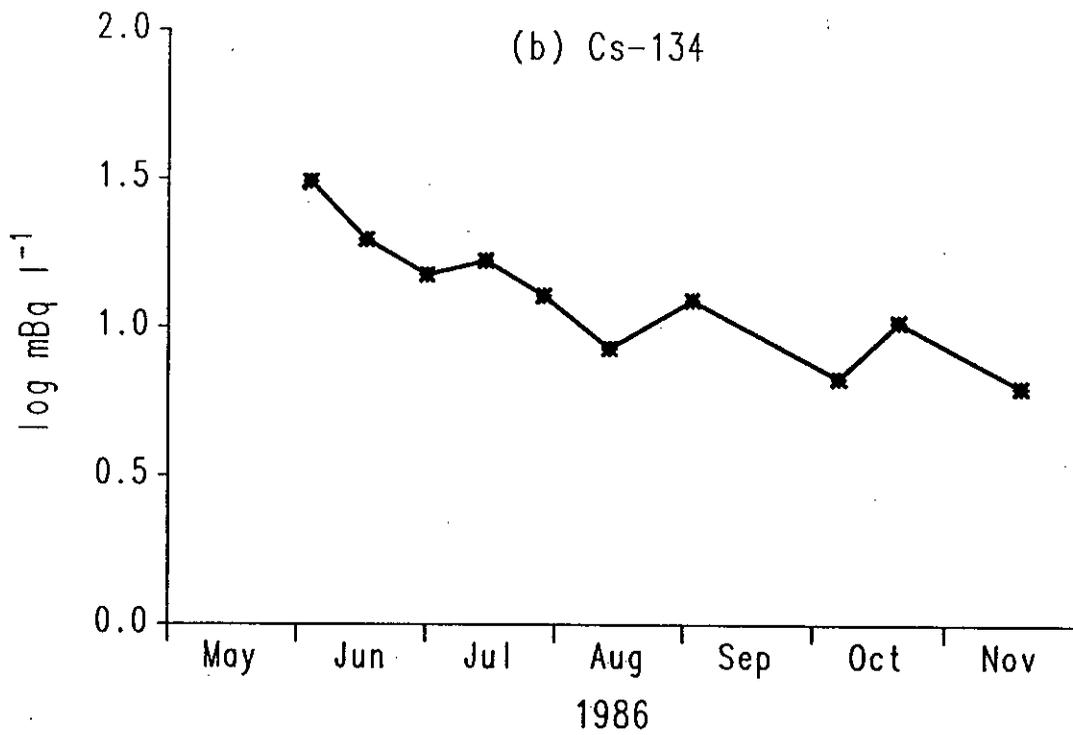
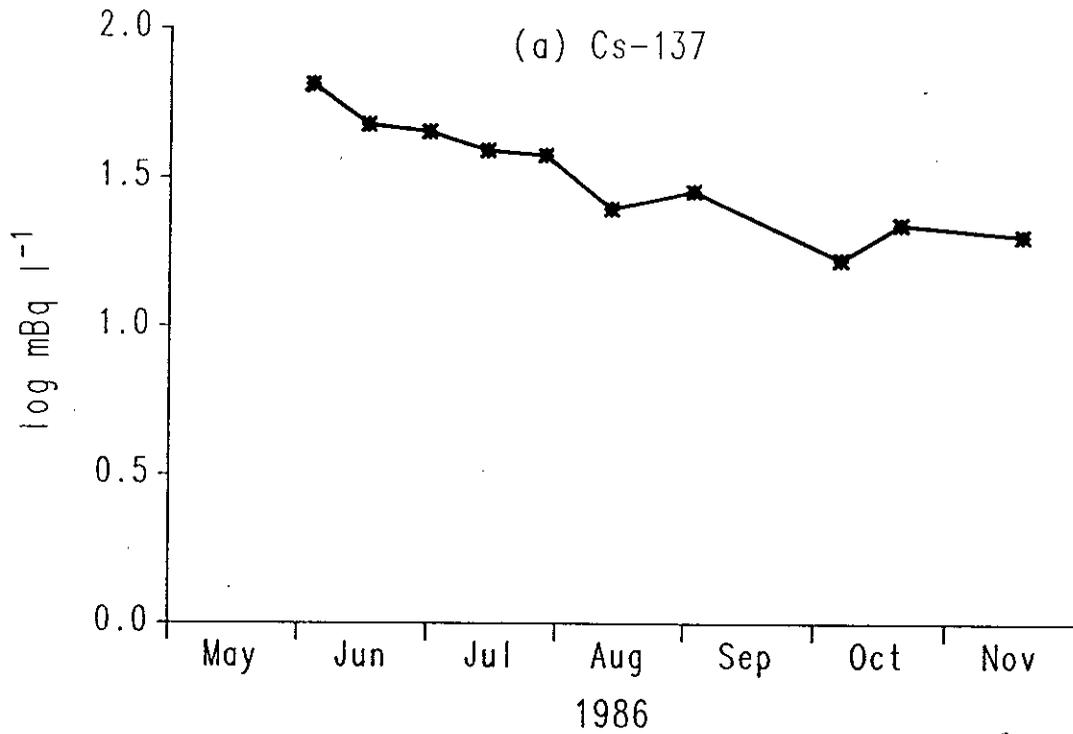


Fig 18. Frequency distribution of Cs-137 concentrations in samples not containing Cs-134  
(a) Esthwaite

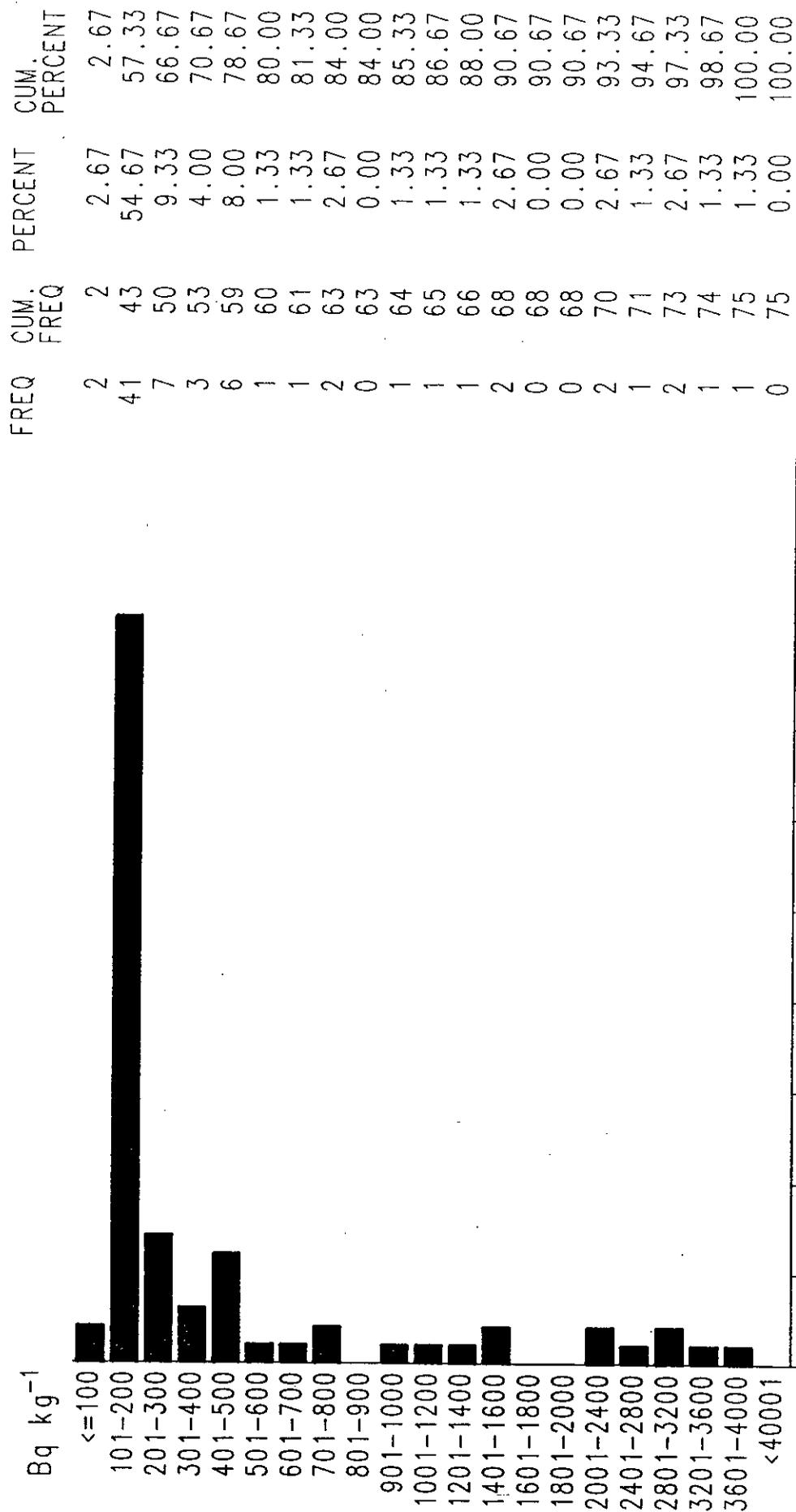
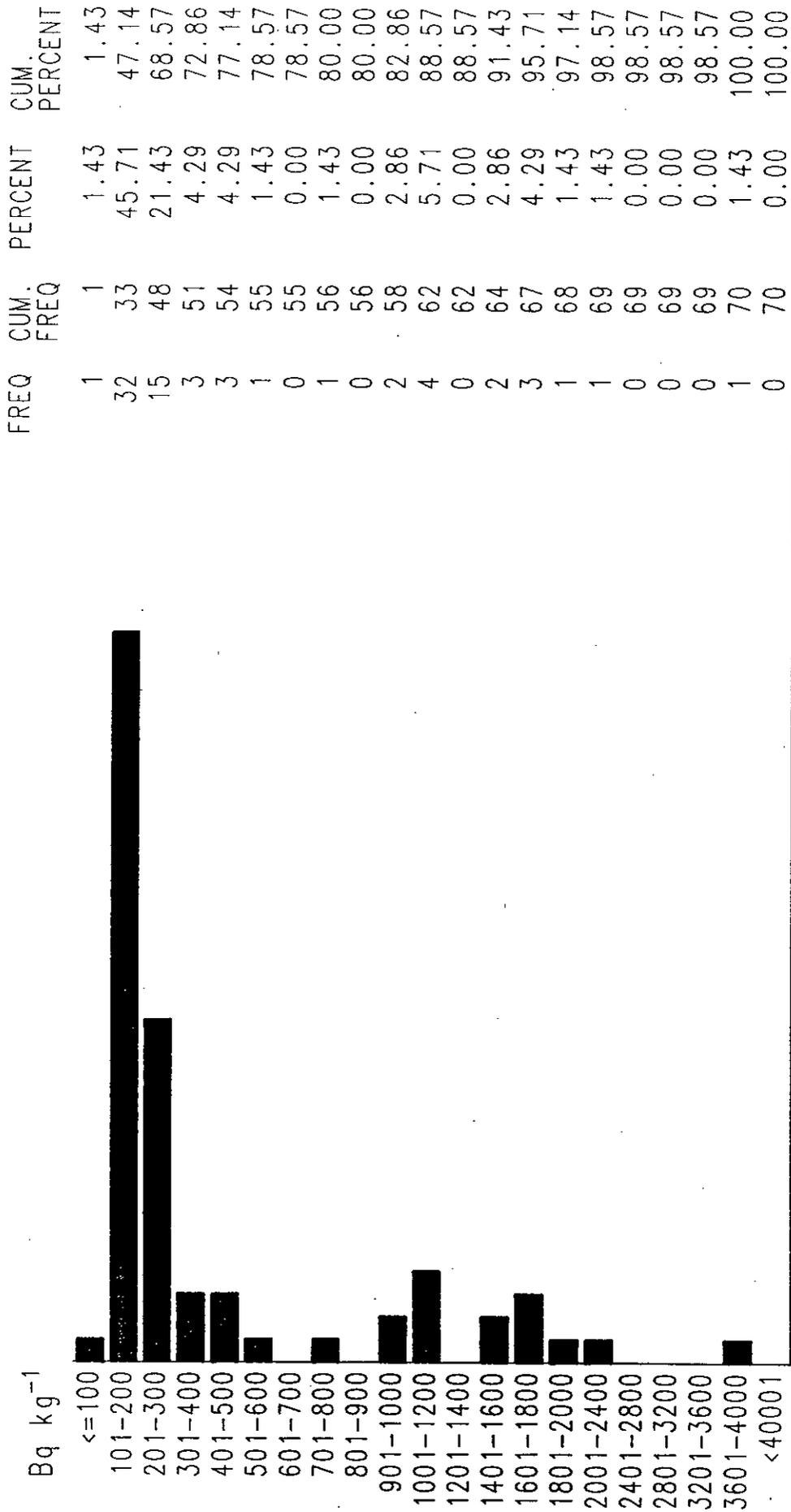


Fig 18. Frequency distribution of Cs-137 concentrations in samples not containing Cs-134  
(b) Windermere



Frequency

Fig 19. Total load deposited on the sediments of Esthwaite estimated from water column models. (Dotted lines show model estimates; solid lines show measured values)

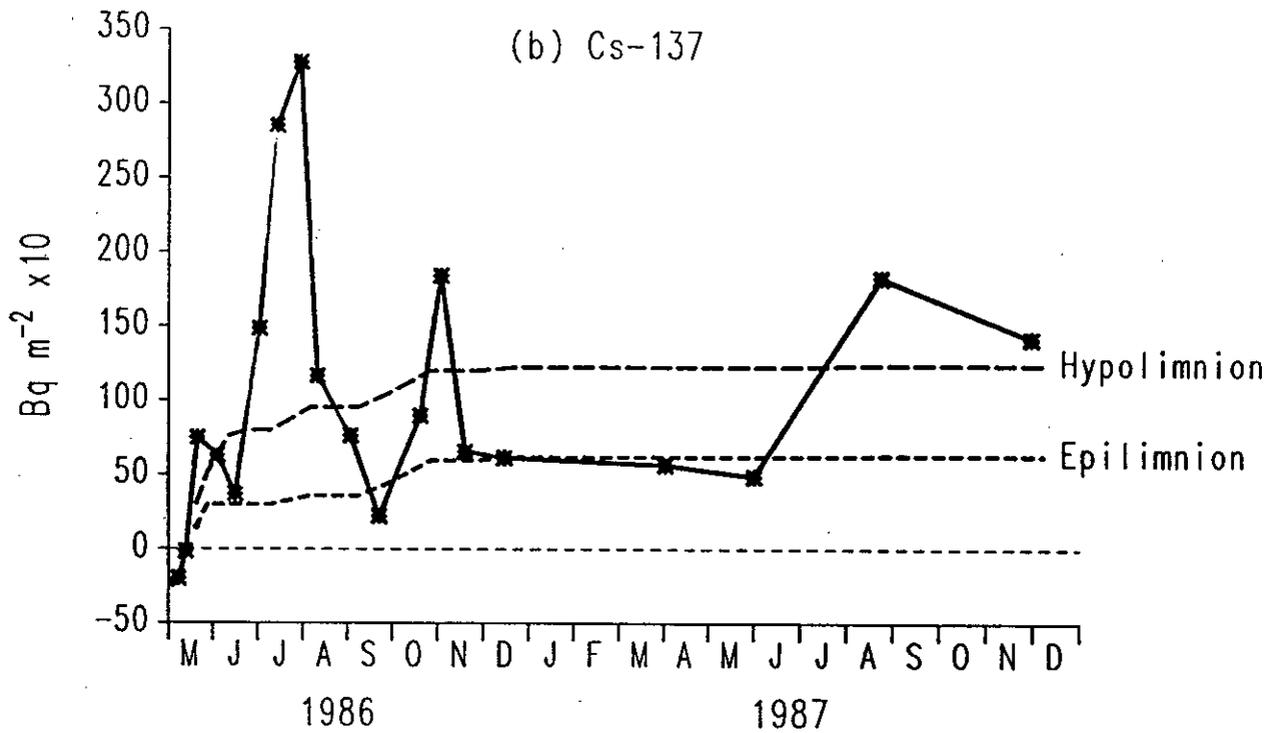
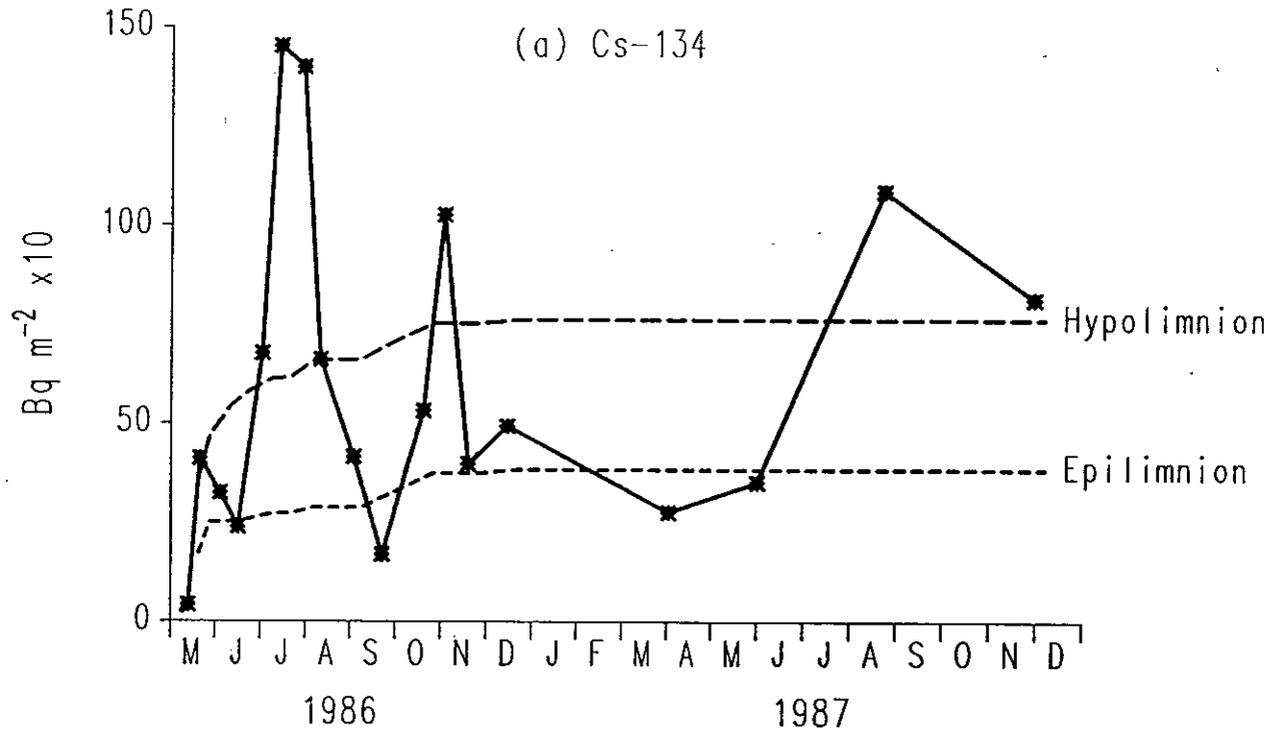
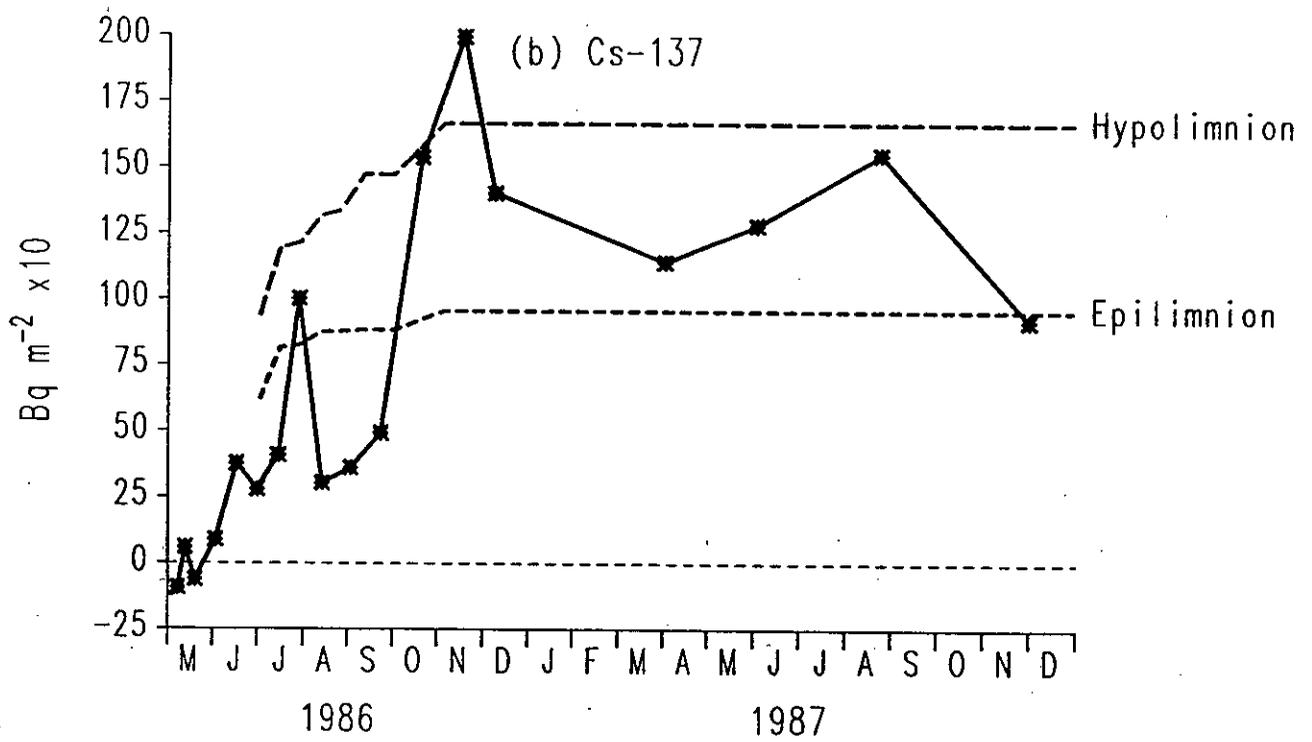
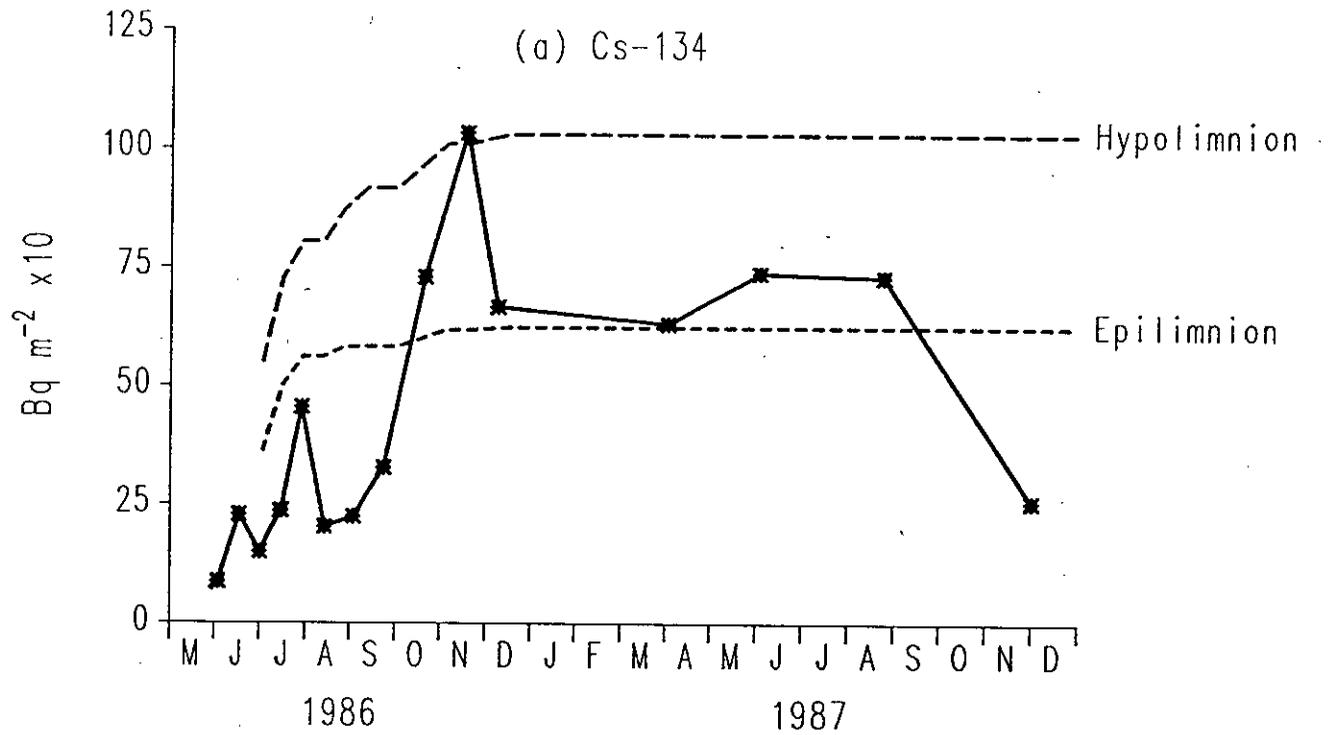


Fig 20. Total load deposited on the sediments of Windermere estimated from water column models. (Dotted lines show model estimates; solid lines show measured values)



Cs 134 penetration depth (cm)

Fig 21 Maximum penetration of Caesium 134 into sediments with time

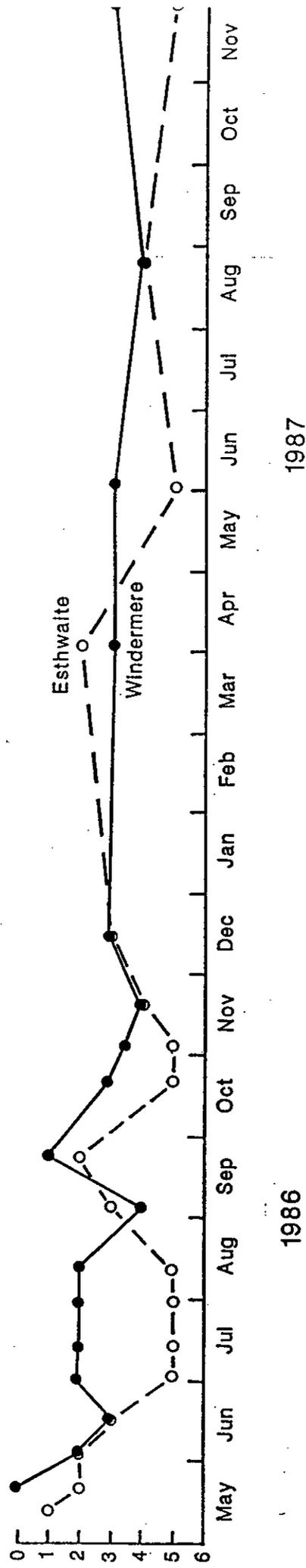
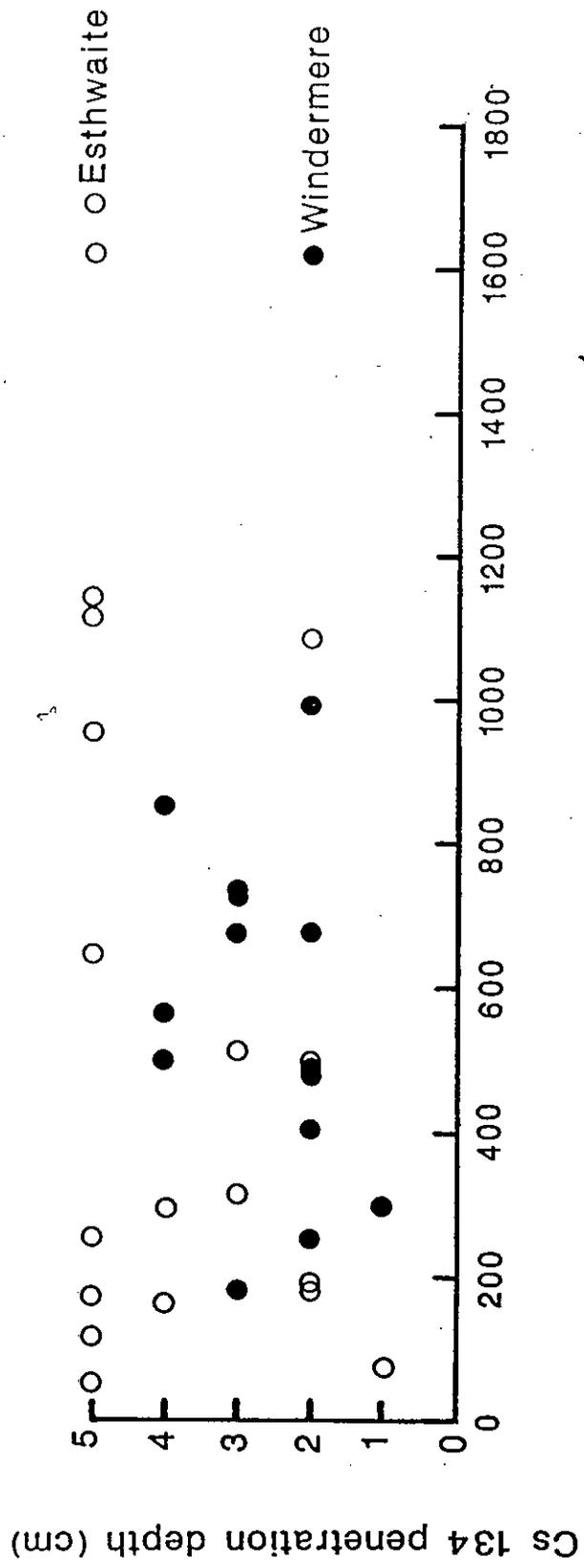


Fig 22 Caesium 134 penetration in surface 134 core



Cs 134 concentration on surface slice (Bq.kg<sup>-1</sup>)

Fig 23a. Cs-137 concentrations in the surface 2 cm of samples from a grid in Esthwaite Water

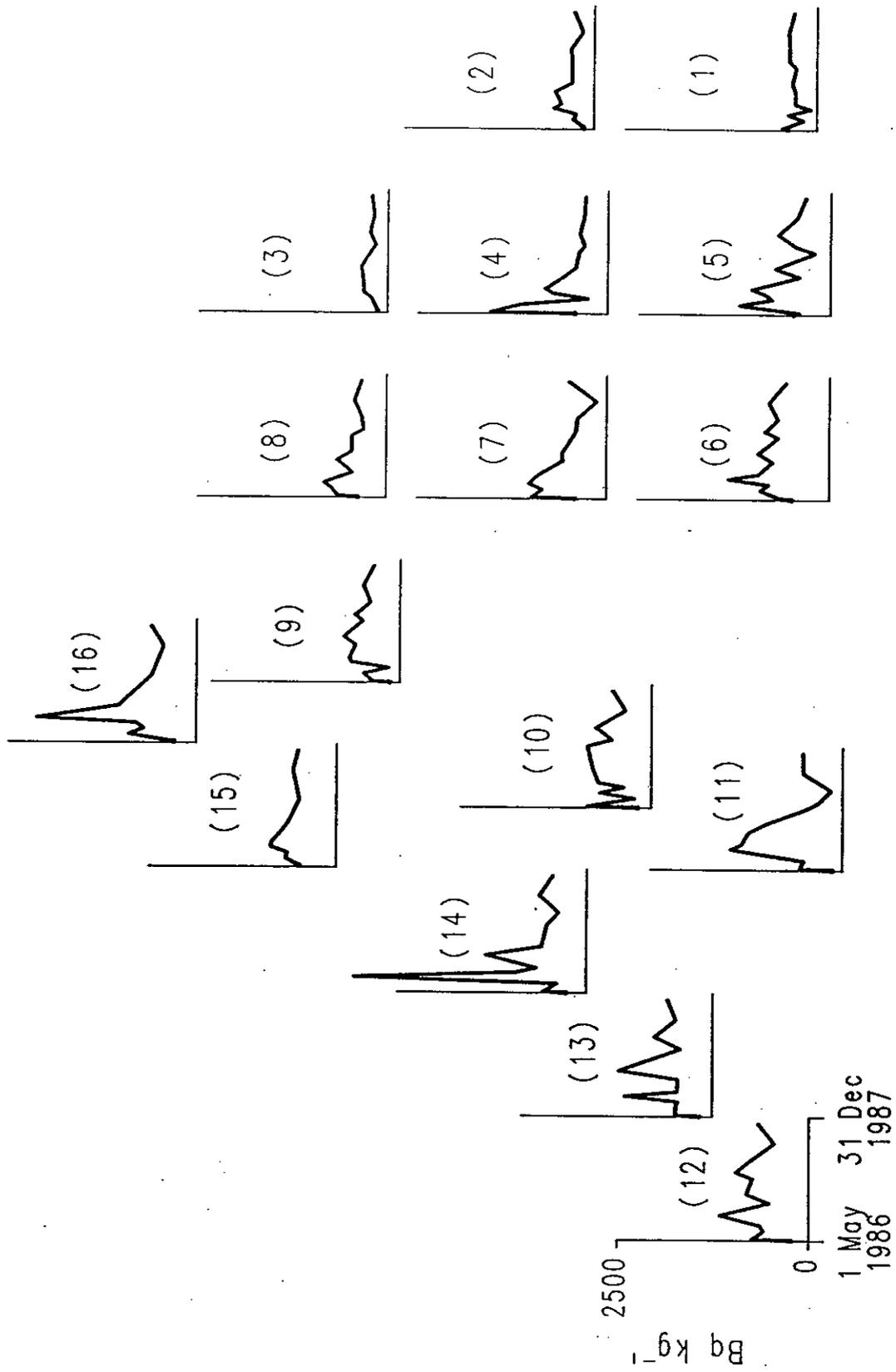


Fig 23b. Cs-134 concentrations in the surface 2 cm of samples from a grid in Esthwaite Water

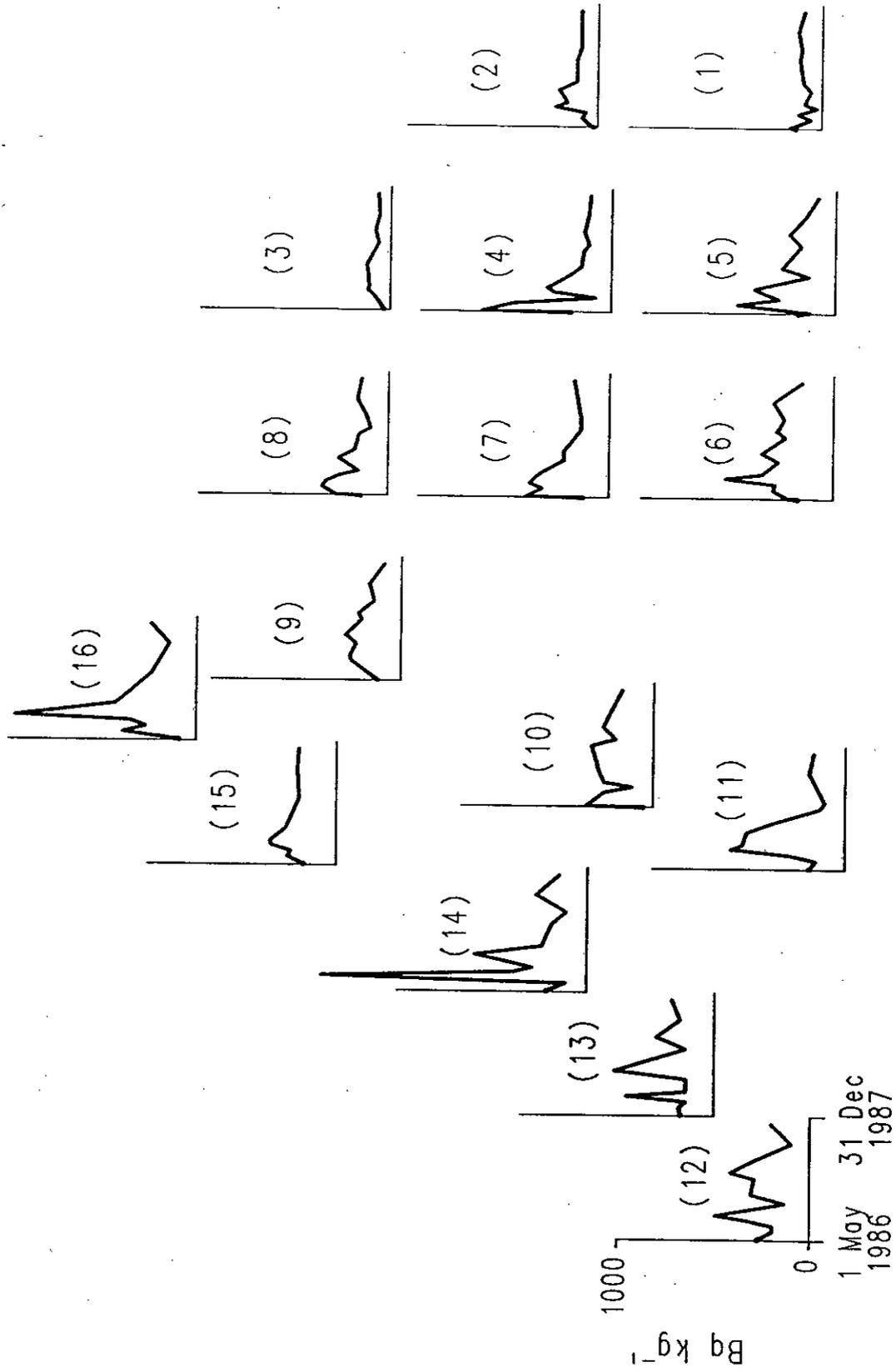


Fig 24a Mean of the first four samples at a each site

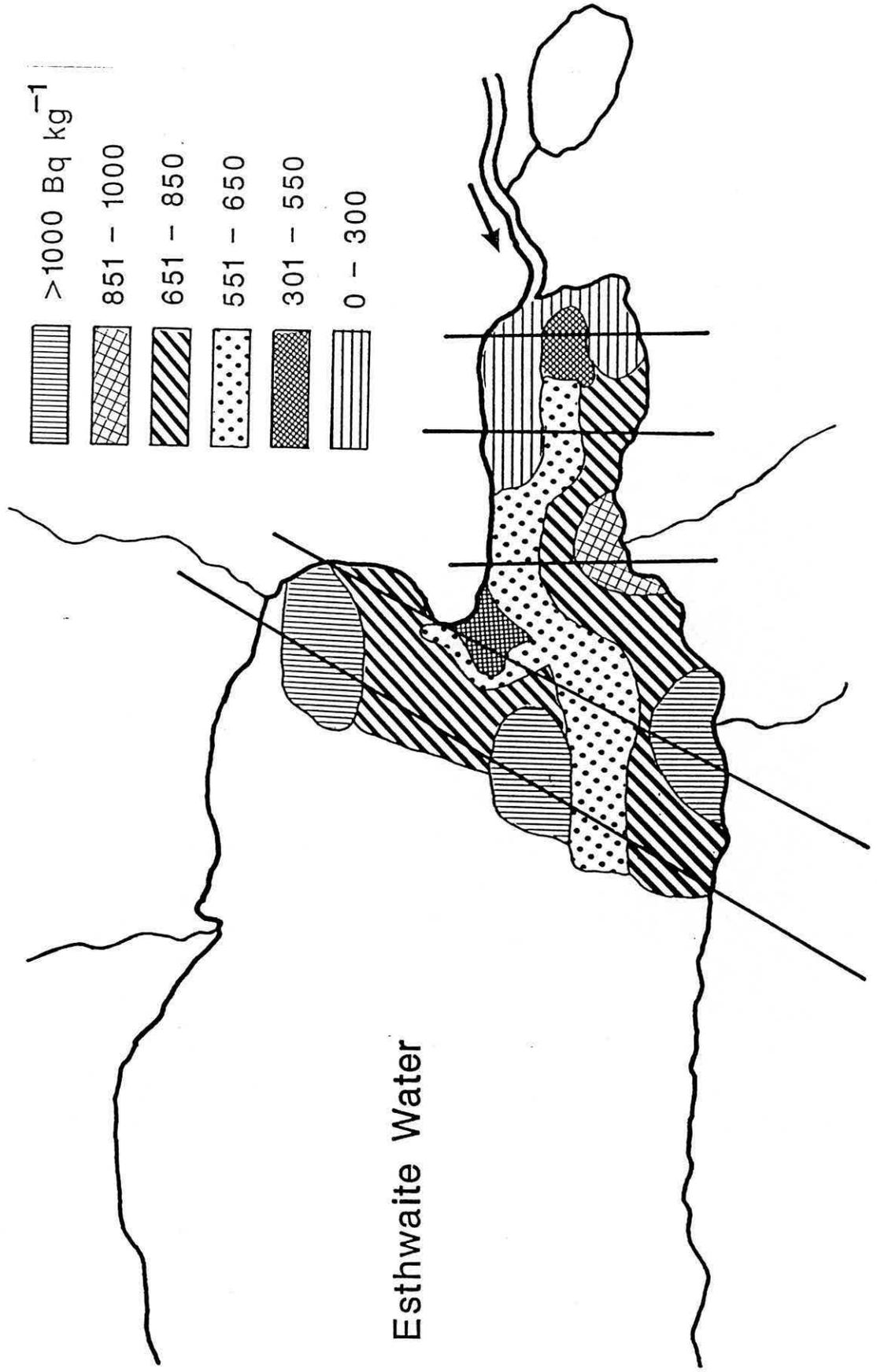


Fig 24b Mean of the last two samples taken at each site

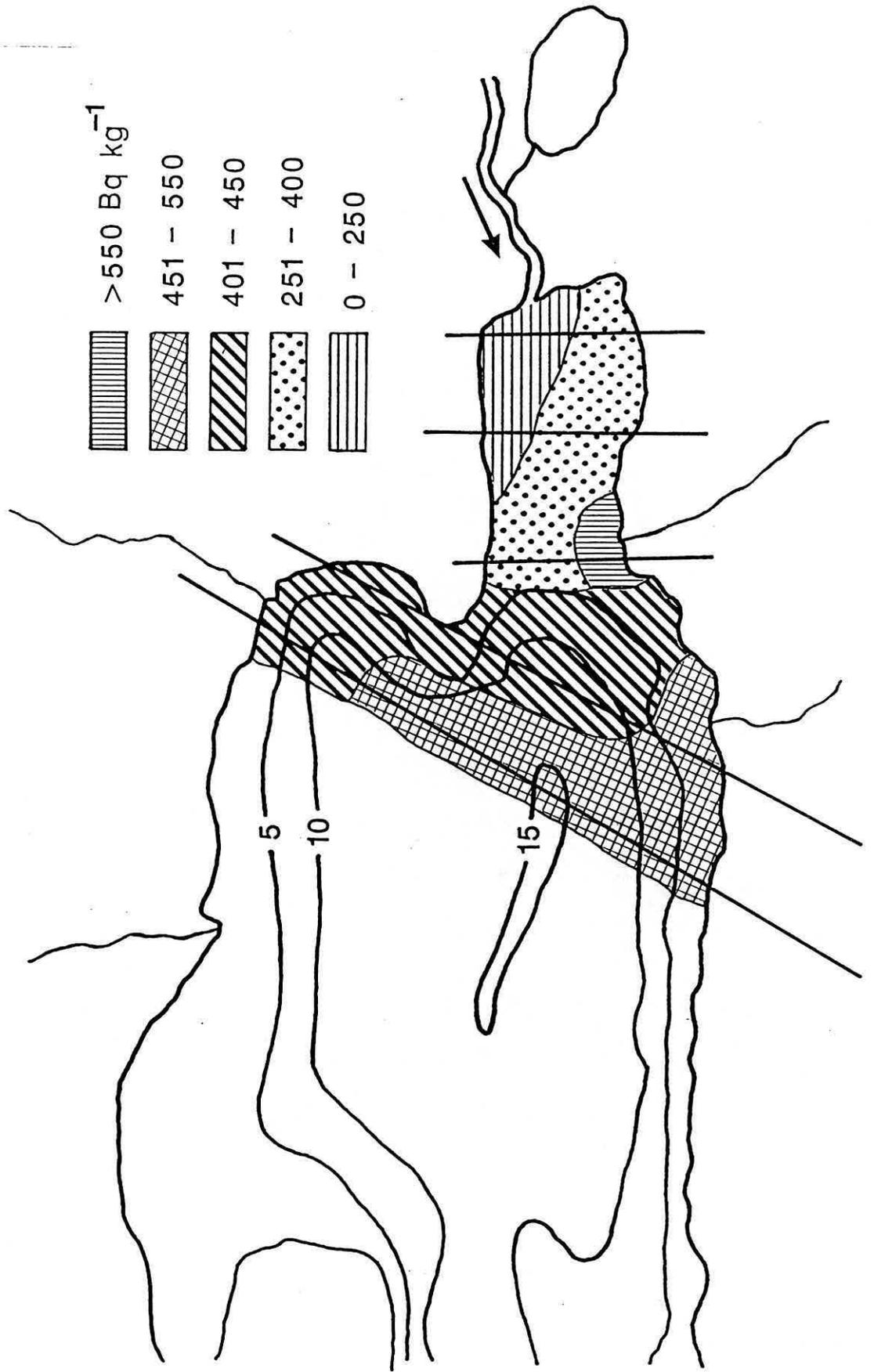


Fig 24c Deposition of sediment in cm since c. 1900 (from Hilton et al. 1986)

