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AN ASSESSMENT OF THE USE OF RESERVOIR SEDIMENTS IN THE SOUTHERN PENNINES FOR RECONSTRUCTING THE HISTORY AND EFFECTS OF ATMOSPHERIC POLLUTION

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Summary

Palaeoecological techniques developed and previously applied to natural lake sediments have been extended to reservoirs in the southern Pennines in an attempt to assess water quality and atmospheric pollution histories at these sites.

Reservoirs have complex and heterogeneous sediment accumulation patterns and sediments can be extensively eroded and re-worked, causing hiatuses and subsequent loss of stratigraphic conformity. In the Pennines this variability in the sediment record is compounded by the very high rates of sediment accumulation which results from erosion of peat deposits on the surrounding moors.

Sediment hiatuses, high accumulation rates and extensive re-working of fine organic fractions determine that some of the assumptions that underpin the use of ^{210}Pb dating are invalidated.

Although a number of reservoirs are sufficiently old to cover the increase in 19th century atmospheric pollution, the history of regular drawdown suggests that suitable stratigraphic records will seldom exist. The identification of suitable sites, if they exist, would require very thorough and detailed coring or a large range of sites.

Where suitable sites are found, problems associated with diatom preservation and distribution determine that further work is first required to construct a calibration set, before the problem of pH reconstruction can be assessed from the sedimentary diatom assemblage in reservoirs.

A detailed history of pollution from atmospheric sources may be documented from an analysis of the chemistry and carbonaceous particle record in reservoir sediments. The major limitation to such reconstruction will be the availability of relatively undisturbed sediments.

Given the availability of reasonable water quality data for reservoir raw water since the mid-1970s a more favourable approach may be the analysis of short cores in conjunction with Water Authority pH records in an attempt to identify possible signs of pH increase.

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1.0 Introduction

Surface water acidification is recognised as one of the most important environmental problems in Europe and North America. In earlier papers (Flower and Battarbee 1983, Battarbee et al. 1985, Jones et al. 1986) we established that lakes on granitic rocks in Galloway, south-west Scotland, were strongly acidified and that the most probable cause of acidification was acid deposition. Our enquiries have now been extended to acid lakes in other parts of the UK to test the general hypothesis that clearwater lakes with pH values less than 5.5, occurring within areas of high acid deposition, are acidified owing to an increase in acid deposition over recent decades.

In this report we consider surface waters in the English Pennines. If our conclusions about the main source of atmospheric pollutants and the timing of lake acidification are correct (eg. Flower and Battarbee 1983, Battarbee et al. 1985), then susceptible surface waters in and around the major industrial areas of Yorkshire, Lancashire and the northern Midlands should have acidified earlier and more rapidly than sites geographically distant from these industrial source areas. Since the southern Pennines is an area of few natural lakes preliminary investigations have been made of a number of reservoirs in the area.

The methodology used at natural lake sites (Stevenson et al. 1987a) has allowed the reconstruction of acidification and of atmospherically derived contamination (eg. Fritz et al. 1986, 1987, Kreiser et al. 1986, Patrick et al. 1987a, b, Stevenson et al. 1987b, c). However, in reservoirs the sediment record can be distorted by disturbance processes associated with reservoir management practice, most notably drawdown effects (Stott 1984).

There have been few, if any, attempts to reconstruct the history of atmospheric pollution from reservoir sediments in the UK. This study was therefore undertaken to assess their suitability for diatom-based pH reconstructions and to identify problem areas in the light of previous research, particularly that of Stott (1984). This report presents preliminary investigations of a number of Pennine reservoirs in areas of high atmospheric deposition and more detailed results from one in particular-Watersheddles (Fig. 1).

2.0 The southern Pennine reservoirs

The southern Pennine area investigated in this study is shown in Figure 1. Although it is an area of few natural lakes there are several hundred reservoirs scattered through the southern Pennines. Initially their construction was associated with river regulation schemes for the canal system which served the growing textile industry in the late 18th and early 19th centuries. Somewhat later, as a result of industrial expansion and urban population growth, reservoirs were constructed for the provision of public water-supply.

Although predominantly uniform in terms of construction, the reservoirs vary greatly in size. The largest generally comprise part of valley systems at low altitude, while the small headwater systems are often used for water balancing purposes. Many of the upland reservoirs are situated on Millstone Grits, locally derived tills and to a lesser extent, coal measures, geologies susceptible to acidification (Fig. 2, Table 1). Catchment soils are dominated by peats. Acid deposition is high (0.04 - >0.05 g H^{+} m^{-2} wet deposited acidity - Barrett et al. 1987) and many reservoirs are very acid (Appendix 1). Extensive peat erosion occurs in the area (Tallis 1981) and this is a cause for concern both for the water authorities because of increased water treatment costs (Austin and Brown 1982) and loss of reservoir capacity, and with environmental bodies because of the loss of vegetation communities (eg. Phillips et al. 1981).

Table 1 Categories adopted for classification of the solid geology of the UK, according to sensitivity to acidification (Kinniburgh and Edmunds 1986)

Category	Buffer capacity and/or impact on groundwaters	Rock type
1	Most areas susceptible to acidification, little or no buffer capacity, except where significant glacial drift.	Granite and igneous rock, most metasediments, grits, quartz sandstones and decalcified sandstones, some Quaternary sands and drift.
2	Many areas could be susceptible to acidification. Some buffer capacity owing to traces of carbonate and mineral veining.	Intermediate igneous rocks, metasediments free of carbonates, impure sandstones and shales, coal measures.
3	Little general likelihood of acid susceptibility except very locally.	Basic and ultrabasic igneous rocks, calcareous sandstones, most drift and beach deposits, mudstones and marlstones.
4	No likelihood of susceptibility, infinite buffering capacity.	Limestones, chalk, dolomitic limestones and sediments.

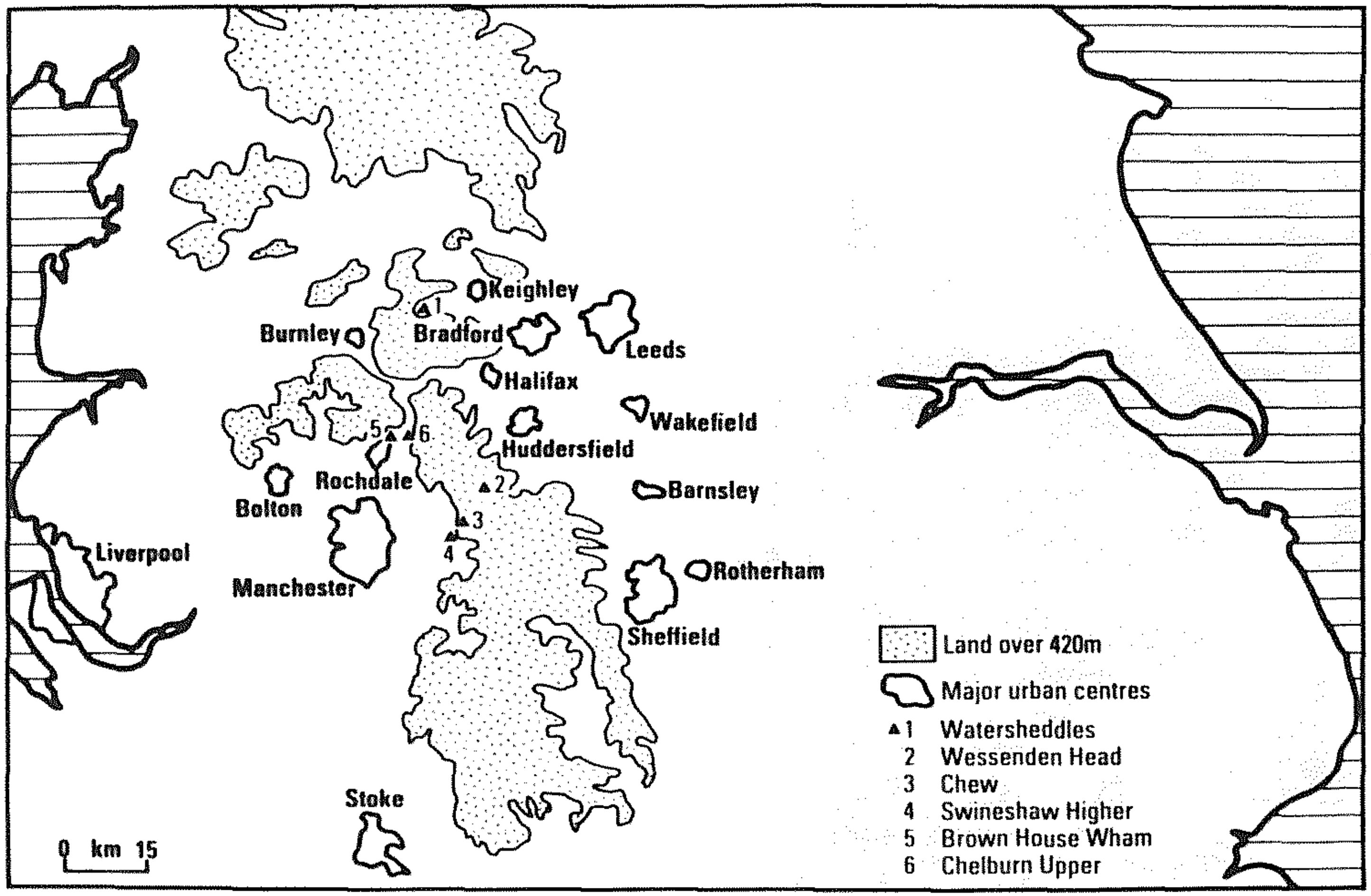


Figure 1. The southern Pennines

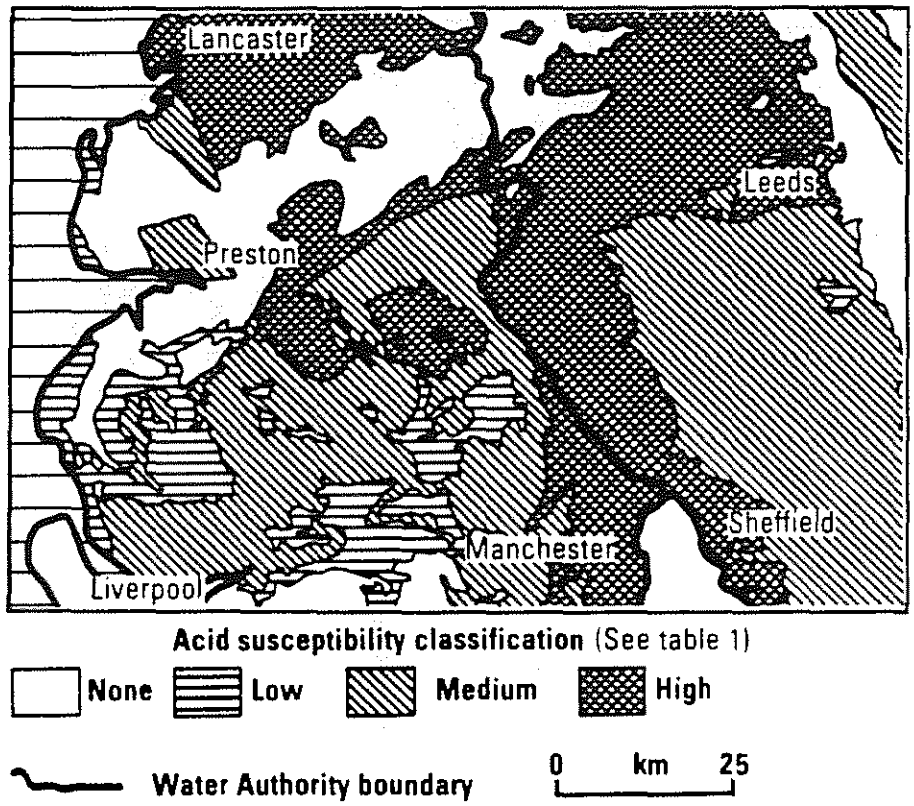


Figure 2. Acid susceptibility of geologies in the southern Pennines (Kinniburgh and Edmunds 1986)

3.0 Reservoir sediments

3.1 Introduction

The majority of sediment-based reservoir studies have been concerned with the loss of capacity resulting from high catchment erosion rates (eg. Austin and Brown 1982, Le Roux and Ross 1982) and the implications this has for water quality and water demand. High sediment accumulation rates and rapid infilling result primarily from the high catchment area : reservoir volume ratios and from poor land management practices (Gottschalk 1964). The economic implications of capacity loss have been studied in detail in the mid-west of the USA, where sediment yields tend to be high. It is apparent that recent increased rates of peat erosion in the southern Pennines have resulted in substantial losses of capacity (Tallis 1981).

Water supply engineers dealing with capacity loss have mainly studied those parameters affecting rates of infill, namely trap efficiency, deposit density and land use as it effects rates of soil erosion and hence sediment accumulation rates. The engineering implications of reservoir infilling have resulted in various attempts to derive empirical models describing sediment infill pattern and process (eg. Gottschalk 1964, Matyas and Rothenberg 1986). However, because there has been only limited use of reservoir sediments as a basis for palaeoenvironmental reconstruction in the UK, there have been few attempts to assess the problems which may limit their usefulness, an exception being Stott (1984).

The main sedimentary features of headwater reservoirs are summarised in Figure 3 (Stott 1984).

3.2 Primary sedimentation processes and deposits

As most reservoir systems are formed from existing river systems, primary sediments are mainly deltaic. These form extensive lobate, predominantly coarse-grained deposits in the upstream area of the reservoir. Scouring of the main delta and the formation of sub-delta lobes occurs with drawdown.

Primary sedimentation away from the delta front is governed by particle flocculation and settling. Because of low primary productivity deep water sediments are also largely allochthonous and high suspended sediment loads in inflowing streams can result in underflows. Where there is a sufficient range of particle size present in the suspended load of an inflow, bivariate modes of deposition associated with underflow activity can result in fine laminations (Stott 1984). These laminations comprise a light coloured well-sorted, medium to fine minerogenic fraction and a darker, more variable layer consisting of mainly organic matter with fine silts (Stott 1984). The presence of laminations in the sedimentary record presupposes no post-depositional re-working of the sediments (see below).

Resuspension processes in the marginal and shoreline areas cause the progressive re-working of side-slope sediments and their deposition in deeper water areas. Depending on the frequency and magnitude of drawdown, transient terraces may form (Duck and

McManus 1985). These processes may be exacerbated by drawdown. Slumping of marginal deposits, rill development and other surface erosion processes where slopes are sufficiently steep may occur. In many of the acid, upland reservoirs aquatic macrophyte development is usually minimal and has little influence on processes of sediment formation and re-working.

3.3 Secondary processes

A number of sedimentary processes are similar to those occurring in natural lakes (eg. sediment focusing, bioturbation) (cf. Sly 1978). However, reservoirs are prone to frequent alterations of water level and the associated processes can result in extensive re-working of the sedimentary sequence.

The exposure of sediment surfaces during drawdown can result in desiccation and as the sediment dries it cracks and flakes and becomes more readily eroded by sub-aerial processes. Eventually it may become colonised by algae and macrophytes.

Drawdown causes deltas to be scoured, numerous sub-deltas to be formed and the re-deposition of the finer sediment further into the reservoir basin. As drawdown continues it may result in a major input of coarse grained sediment into deep water areas of the reservoir which form ripple-bedded sand lenses analogous to those formed in fluvial systems (Stott 1984).

The behaviour of the scour channel during drawdown is fundamental to any consideration of the usefulness of a particular reservoir for palaeoenvironmental reconstructions. The inflow/scour channel usually occupies a quasi-permanent position, particularly in those areas of the reservoir which are most frequently exposed. However, where exposure of the sediments is less frequent the channel may be filled in as water level rises and a new channel excavated at the next drawdown event. This episodic 'scour and fill' process (Stott 1984) results in the re-working of the deeper water sediments as the channel's position migrates both in space and time. Fine grained sediments (and microfossils - see Section 4.0) are also released by this process and accumulate in the deep water zone in front of the embankment which is only infrequently exposed. These deep water sediments (and their fossil assemblages) may therefore have no chronological relationship to their position in the stratigraphic record as they may have been re-worked numerous times since their initial deposition. Recognition of these processes led Stott (1984) to distinguish three characteristic sedimentary zones (Fig. 4):

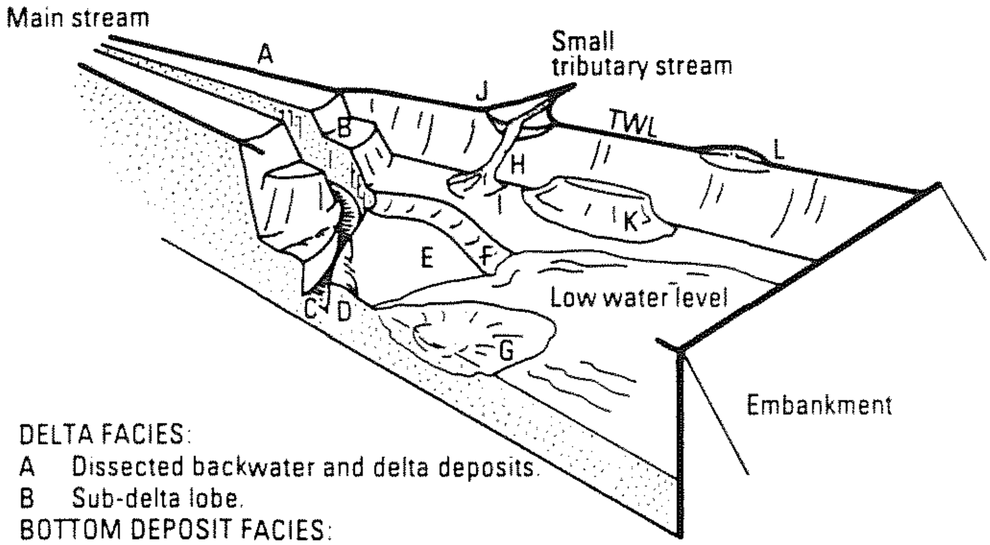
i. Shallow water zone (including deltaic deposits), characterised by high but spatially discontinuous rates of sedimentation and extensive re-working during drawdown.

ii. Intermediate zone of moderate exposure during drawdown. Re-working is confined to the scour channel which has temporary storage of coarse sediment. However, marginal sediments in this zone predominantly result from primary sedimentation with little erosion and re-working, although sedimentation may not be continuous.

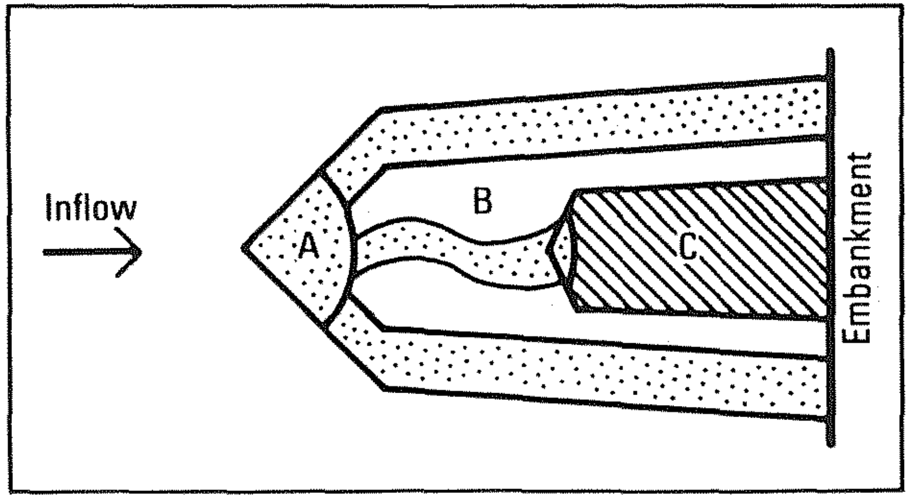
iii. Deep water zone rarely exposed by drawdown, with low rates of primary sedimentation but receiving extensive re-worked sediments from upstream, with occasional but major erosional hiatuses.

Consideration of these zones suggests that core location should be restricted to the more marginal areas of the intermediate zone away from the scour channel (cf. Stott 1984). Such a strategy was employed when determining core locations for the reservoirs studied in this paper.

Figure 3. Sedimentary features of headwater reservoirs (Stott 1984)



DELTA FACIES:
A Dissected backwater and delta deposits.
B Sub-delta lobe.
BOTTOM DEPOSIT FACIES:
C Scour channel.
D Levee type bank comprising lenses of fluvial/delta deposits.
E Laminated bottom deposits.
F Surface depression of infilled scour channel.
G Sub-delta lobe at low water level.
SLIDE-SLOPE FACIES:
H Gully eroded by small tributary stream.
I Fan/delta deposit at base of gully.
J Small delta at TWL.
K Sediment slump on sidé-slope.
L Wave erosion and beach terrace at TWL.



A Shallow water zone.
B Intermediate zone.
C Deep water zone.

Figure 4. Characteristic sedimentary zones in reservoirs (Stott 1984)

4.0 Diatoms in reservoirs

There have been comparatively few studies of diatoms in upland reservoirs, either in terms of their ecology as affected by continually varying water levels, or in their sedimentary record. Many of the problems associated with the interpretation of fossil diatom assemblages discussed by Battarbee (1986) for natural lakes apply equally to reservoir sediments. However, the effects of frequent drawdown impose additional restraints on diatom-based studies. In natural oligotrophic lakes diatoms grow profusely on stones, macrophytes and other substrata in the littoral zone. In reservoirs macrophytes are rare because of drawdown and only diatoms that can withstand repeated desiccation survive on stones and mud surfaces.

The combined effects of acidity, desiccation and substrate instability result in unusual communities and very low diatom productivity. This together with the high sediment accumulation rates resulting from increased catchment peat erosion (Tallis 1981) mean that the diatom content of reservoir deposits can be minimal and that existing models of pH reconstruction based on data from natural lakes may be invalid. In addition the low productivity of the diatoms in the reservoir itself may mean that diatoms derived from stream communities may be an important part of the fossil assemblage. Given the high peat content of many of the Pennine reservoirs, diatoms associated with inwashed peats may also be an important external source (cf. Battarbee and Flower 1984).

The low diatom content of reservoir sediments may also result from dissolution. Drawdown results in fluctuations of the local water table which has the effect of lowering interstitial silica concentrations to below saturating levels, thereby permitting continued dissolution.

Despite these general problems attempts have been made to find sites with relatively high diatom concentrations and the least disturbed pattern of sediment accumulation.

5.0 Sources and methods

5.1 Documentary sources

The historical record relating to such aspects as reservoir construction, water quality and water levels is generally poor. This is not because of any failure to record the salient contemporary information but is the result of data being lost or destroyed during successive water authority reorganisations.

5.2 Methods

Sediment cores were recovered using Mackereth, Livingstone and Russian corers. In general, analysis of core material was performed according to the standard techniques described in Stevenson *et al.* 1987a. Because of the large amount of sediment recovered at some sites and the relatively short deposition time, it was necessary to use homogenised 10 cm thick samples for analysis.

6.0 Study Sites

6.1 Introduction

Although many reservoirs in the Pennine area can be discounted for acidification studies because of their large size, catchment-reservoir area ratios, high pH, inappropriate catchments and the extreme nature of previous drawdown (cf. Stott 1984), a significant number of headwater reservoirs are still apparently suitable for core-based studies. Preliminary studies were made of a small number of reservoirs in an attempt to identify the range of depositional patterns and degree of diatom preservation. Various sampling strategies were used in this approach in an effort to indicate a possible site for more detailed study and to highlight the problems that might be encountered in such a study.

The following sections present results from sites that were not considered suitable for further palaeoecological investigation, together with the results of diatom analyses of samples obtained from other workers.

6.2 Drained sites

6.2.1 Chelburn Lower

Originally built to supply water for the local canal system, Chelburn Lower (Fig. 1) has recently been drained . Although not a valley head reservoir, the low water level provided a suitable opportunity to examine sediment deposition patterns at a site with high rates of peaty sediment accumulation. The scour channel is currently eroding a meandering course through old deposits to the current water level immediately in front of the embankment. This channel has exposed a number of sand lenses within the organic deposits, presumably resulting from previous alluvial deposition. Terrestrial vegetation is currently colonising the deltaic deposits around the inflow and surficial deposits around the perimeter of the reservoir.

A 3.5 m Livingstone core was taken in May 1986, above the level of permanent water and c. 30 m away from the scour channel, in an attempt to find a continuous sediment record. Attempts to core at other sites within the basin had indicated sub-surface minerogenic horizons, suggesting that organic sediment accumulation has been intermittent over large areas of the basin and deposition of coarse silts and sands resulted as the inflow scour channel meandered across the basin.

Dry weight and loss-on-ignition (LOI) profiles for the core are presented in Figure 5. Below 160 cm are a number of extensive sand horizons which are clearly indicated by the high (c. 80-90%) dry weight values and corresponding low LOI values, particularly at 170-180, 230-245 and 290-310 cm depth. These horizons probably represent alluvial deposition during periods of low water level (Stott 1984).

Between 170 and 130 cm dry weight decreases from c. 50% to 20-25% and remains relatively constant at that level to the core surface. LOI shows a corresponding increase from c. 170 cm to maximum values of 60-70%. The increase in the deposition of peaty sediments indicated by the higher LOI values may represent an increase of peat erosion in the catchment in the recent past.

The core lithology together with the examination of the bank side deposits of the scour channel, suggest that sediment accumulation in Chelburn Lower has been complex, with alternating fluvial and lacustrine deposition and heterogeneous, both in space and time, for a considerable period of its history.

Diatom samples were prepared from a number of organic samples over the length of the core. Concentrations and preservation were variable and diatoms were absent in some horizons. Because of this variability together with the extensive minerogenic horizons in the core and the suggestion of discontinuous deposition across the basin, no further analyses were made. The diatoms present in the upper part of the core were: *Eunotia exigua*, *E. pectinalis* v. *minor*, *Pinnularia subcapitata*, *P. microstauron* and *Frustulia rhomboides* v. *saxonica*; towards the base of the core: *Brachysira brebissonia*, *E. tenella* and *Tabellaria flocculosa*.

6.2.2 Brown House Wham

A small reservoir built in 1850 on the outskirts of Rochdale (Figure 1), Brown House Wham has now been drained for safety reasons. The reservoir had a pH of 5.0 prior to drainage (Appendix 1).

The sediments are now extensively colonised by terrestrial vegetation, but where they are exposed the sediments exhibit typical polygonal cracking associated with desiccation. There were also fine smooth silt-clay deposits suggesting localised reworking following inundation and puddle formation.

A number of cores were taken in April 1986 using a 50 cm Russian corer at various sites within the basin. Maximum recovery was c. 1 m. The low recovery suggests that the peaty sediments have undergone substantial compaction following exposure. Because of the distorted nature of the sediments no lithological analyses were made.

Because of the period of exposure and the possibility of colonisation of the surface sediments by aerophilous diatoms and the development of temporary communities associated with puddles, the immediate sub-surface of the core was sub-sampled together with a number of lower levels.

Diatom preservation in the top sample (1-2 cm) was quite good and a reasonable assemblage was present dominated by *Surirella* species (*S. linearis* and *S. delicatissima*), *E. pectinalis* (including var. *ventralis*) and *E. exigua*. In samples from deeper sediments the diatom content is minimal and suggests that the diatom assemblages of the surface sediments represents either *in situ* colonisation (and therefore not diatom communities growing in the littoral zone of the reservoir when it was full), or changes in preservation. Both conditions limit the usefulness of the site for further palaeoecological investigation.

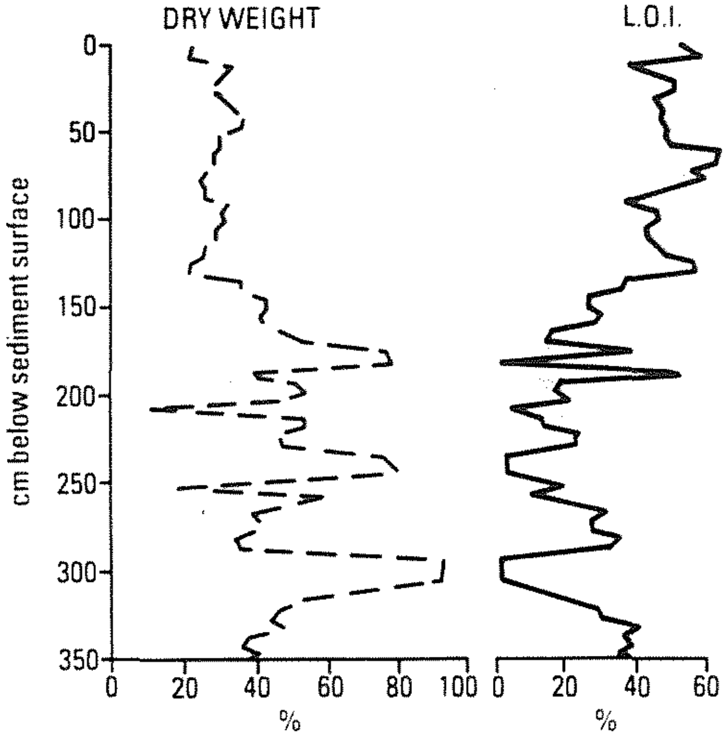


Figure 5. Dry weight and LOI profiles for Chelburn Lower sediment core

6.3 Acid head water reservoirs

Three reservoirs - Chew, Swineshaw Higher and Wessenden Head, were considered together because of their location close to areas of extensively eroding blanket peat. At each site a 1 m Mackereth core was taken during April and May 1986.

6.3.1 Chew

Built in 1907 at an altitude of 480 m, Chew (Fig. 1) has experienced very high rates of sediment infilling following extensive erosion of the blanket peat in the catchment. Consequently a major drawdown of the reservoir was planned to permit excavation of sediments in front of the embankment wall. The reservoir was cored prior to any disturbance to the sediments caused by the drawdown and drainage. Mean surface water pH is 5.25 (Appendix 1).

Two 1 m Mackereth cores were taken in May 1986. The lithological characteristics of these cores are presented in Figures 6a and 6b. Dry weight profiles are similar for both cores, with a decrease at c. 40 cm, reflecting the increase in LOI values above this depth. the LOI values are very high (>60%) indicating the peaty nature of the sediments. Although taken close together (<20 m apart) LOI profiles exhibit some variation, perhaps reflecting the localised and heterogeneous nature of sediment accumulation in the reservoir. There is a pronounced surface peak in core 1, while core 2 has a number of marked peaks between the surface and 40 cm depth.

6.3.2 Swineshaw Higher

This reservoir, constructed in 1864, lies 2 km to the north of Glossop (Fig. 1) at an altitude of 220 m. The reservoir drains an upland catchment within which extensive peat erosion is occurring. The mean pH of the reservoir water is 4.7 (Appendix 1).

A 1 m mackereth core was taken in 14 m of water in April 1986. The presence of eroding blanket peats in the catchment is clearly indicated by the high LOI profile (Fig. 7), which is consistent at or above c. 50% throughout the core. There is no clear profile trend except that values are stable at c. 45% above 30 cm and shows more variation below this depth. Maximum values (c. 75%) occur as a peak between 35-40 cm. The dry weight profile (Fig. 7) is relatively constant at c. 25%.

6.3.3 Wessenden Head

Wessenden Head lies at 350 m in moorland some 10 km to the south-west of Huddersfield (Fig. 1). It was built in 1881 and covers an area of 6 ha (Appendix 1). It is the uppermost of a chain of four reservoirs which feed into the Colne Valley system.

A 1 m Mackereth core was taken in c. 12 m of water in April 1986. LOI values (Fig. 8) are low compared to those recorded at Chew and Swineshaw Higher (Figs 6a, 6b, 7), varying between 25% and

35%. There is a decrease in values to c. 20% between 40 and 70 cm depth corresponding to an increase in dry weight values to c. 40% (Fig. 8).

Sediment distribution in this reservoir was heterogeneous. A number of cores were taken which had extensive minerogenic horizons and were consequently discarded. This variability may relate to either peat erosion and channel erosion within the catchment, or sediment disturbance and re-deposition within the reservoir itself.

6.3.4 Diatoms in Chew, Swineshaw Higher and Wessenden Head

All three reservoirs have similar diatom assemblages that are remarkable for their lack of diversity. The assemblages are dominated by small Eunotias (E. exigua - E. tenella complex). These small Eunotias appear to be reasonably robust and preserve well. Many other diatom valves can be partially dissolved or pitted in the case of more heavily silicified species (eg. Pinnularia). As well as water level fluctuations causing dissolution problems, abrasion of the valves caused by the minerogenic fraction in the sediments during re-working, may also be important.

At Chew the small Eunotias are virtually the only diatoms present in the sediments. At both Swineshaw Higher and Chew the low concentrations are largely the result of the high sediment accumulation rates causing dilution of the microfossils. At Wessenden Head E. exigua and E. tenella are complemented by the Pinnularias (P. microstauron, P. subcapitata, P. appendiculata) and at Swineshaw Higher E. exigua is dominant with occasional Pinnularias, Gomphonema parvulum, Tabellaria flocculosa, Achnanthes minutissima and very occasionally partly dissolved Frustulia rhomboides v. saxonica was observed.

6.4 Diatoms in other reservoir deposits

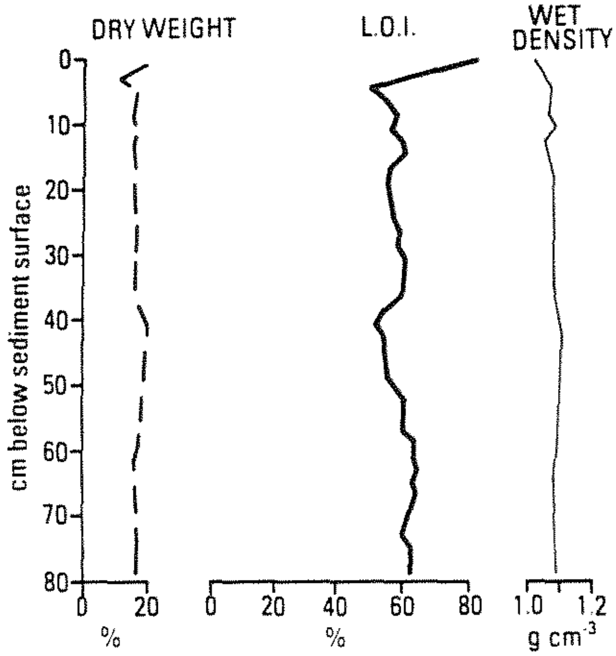
Core samples from Norman Hill (Prethorne Valley, Saddleworth, built in 1866) and material from a sediment trap placed in Trentabank Reservoir, two of the higher pH reservoirs in the North West Water Authority district, were obtained from Dr A.W. Stott and were prepared for diatom analysis.

Compared to the acid sites discussed above there is a more diverse and varied diatom assemblage. A number of circumneutral taxa, not observed at the acid sites reflect the higher pH of these reservoirs. However, even in comparison with acidified lakes the diatom record is still extremely poor.

The presence of Cyclotella comta in the 1-2 cm sample of Norman Hill suggests that the reservoir may have a diatom plankton albeit of low numbers, something not observed at the very acid sites. The other important diatoms at Norman Hill are A. minutissima and to a lesser extent Brachysira vitrea, which can be compared to the E. exigua-tenella complex which dominates the acid sites. the Eunotias were present but in lower numbers together with P. microstauron, A. marginulata, Surirella delicatissima, Synedra minuscula and Gomphonema parvulum. The lower core samples only contained A. minutissima and S. linearis and as Norman Hill undergoes almost annual drawdown (Stott 1984),this may suggest differential dissolution down the core rather than an assemblage change.

The Trentabank sediment trap sample contained Asterionella formosa and Tabellaria fenestrata which again indicates the development of a diatom plankton. It also contained a number of species not regularly encountered at the acid sites, for example Brachysira vitrea, Synedra ulna, Gomphonema angustatum, Gomphonema parvulum and Cymbella minuta together with a number of Nitzschia (palea, gracilis, frustulum, acuta) and Navicula (lanceolata, gregaria, rhyncocephala, cryptocephala) species. Although many of these species are very tolerant and are found over a wide range of pH, they do reflect an obvious difference in water quality, suggesting that the development of a calibration data set may be feasible in the future. Because the material was from a sediment trap the diatoms were reasonably well preserved despite the presence of large amounts of minerogenic material.

Figure 6a. Dry weight, LOI and wet density profiles for Chew 1 sediment core



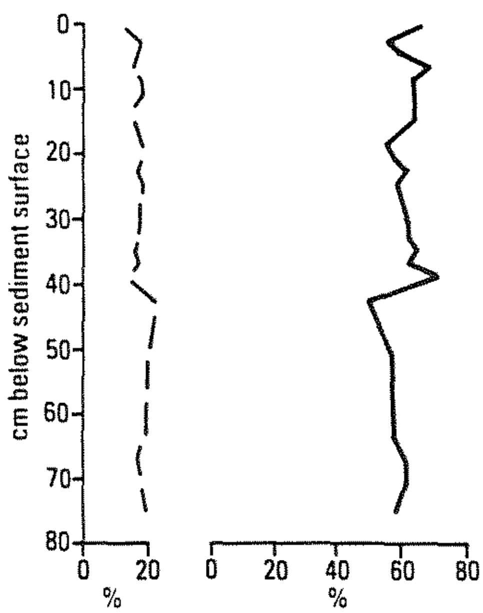


Figure 6b. Dry weight and, LOI profiles for Chew 2 sediment core

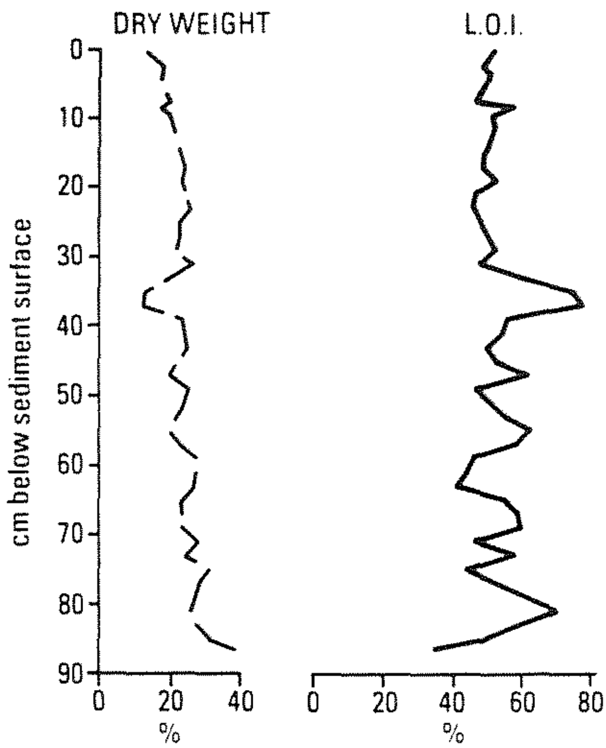


Figure 7. Dry weight and LOI proflies for Swineshaw Higher sediment core

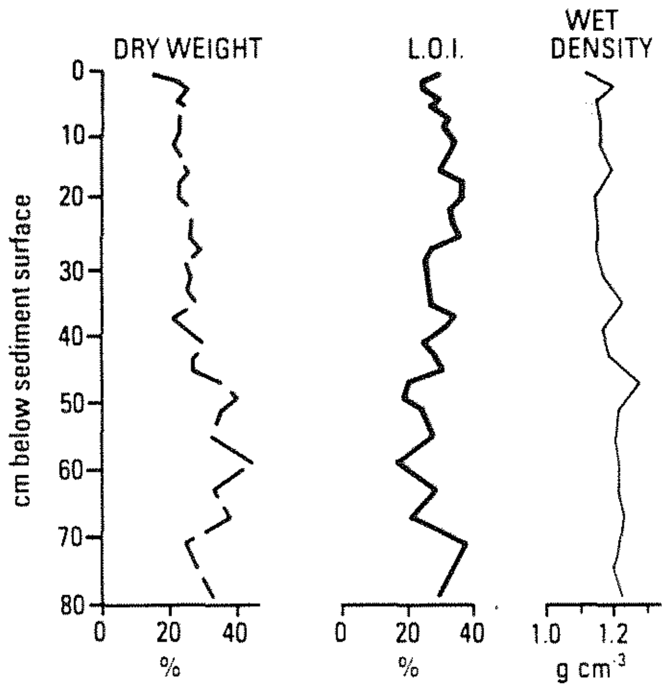


Figure 8. Dry weight, LOI and wet density profiles for Wessenden Head sediment core

7.0 Watersheddles: a case study

Following the results of the initial survey of other selected reservoirs (above) and the examination of a preliminary core taken at Watersheddles in April 1986 which indicated acceptable diatom preservation, a more detailed multi-coring strategy was adopted for the site in May 1986. Experience of the problems of obtaining suitable sediment cores from a lake with complex sediment distribution and hiatuses (cf. Anderson et al. 1986) and the problems encountered at other reservoir sites, determined that a detailed multi-core approach was considered necessary to fully evaluate sediment distribution at Watersheddles.

7.1 Site details

Watersheddles (Fig. 9) lies on the western border of the Yorkshire Water Authority area (Fig. 1) at an altitude of 335 m. It is a head water reservoir with an area of 15.9 ha and a maximum depth of c. 15 m. The bathymetry is presented in Figure 10. The reservoir was completed in 1877 as part of a scheme to supply water to the town of Keighley. It is therefore not a site at which an assessment can be made of the effects of atmospheric deposition in the early-mid 19th century. However, it was considered that the possibility of obtaining a continuous sediment record, without extensive hiatuses and problems of alluvial deposition (cf. Chelburn Lower - see Section 6.2.1, and Stott 1984), offset this negative aspect of the site.

Representative chemistry for the raw reservoir water is available for the period November 1979 - November 1986. The reservoir water is acid (mean pH 4.065). A summary of pH and other water chemistry parameters is presented in Table 2

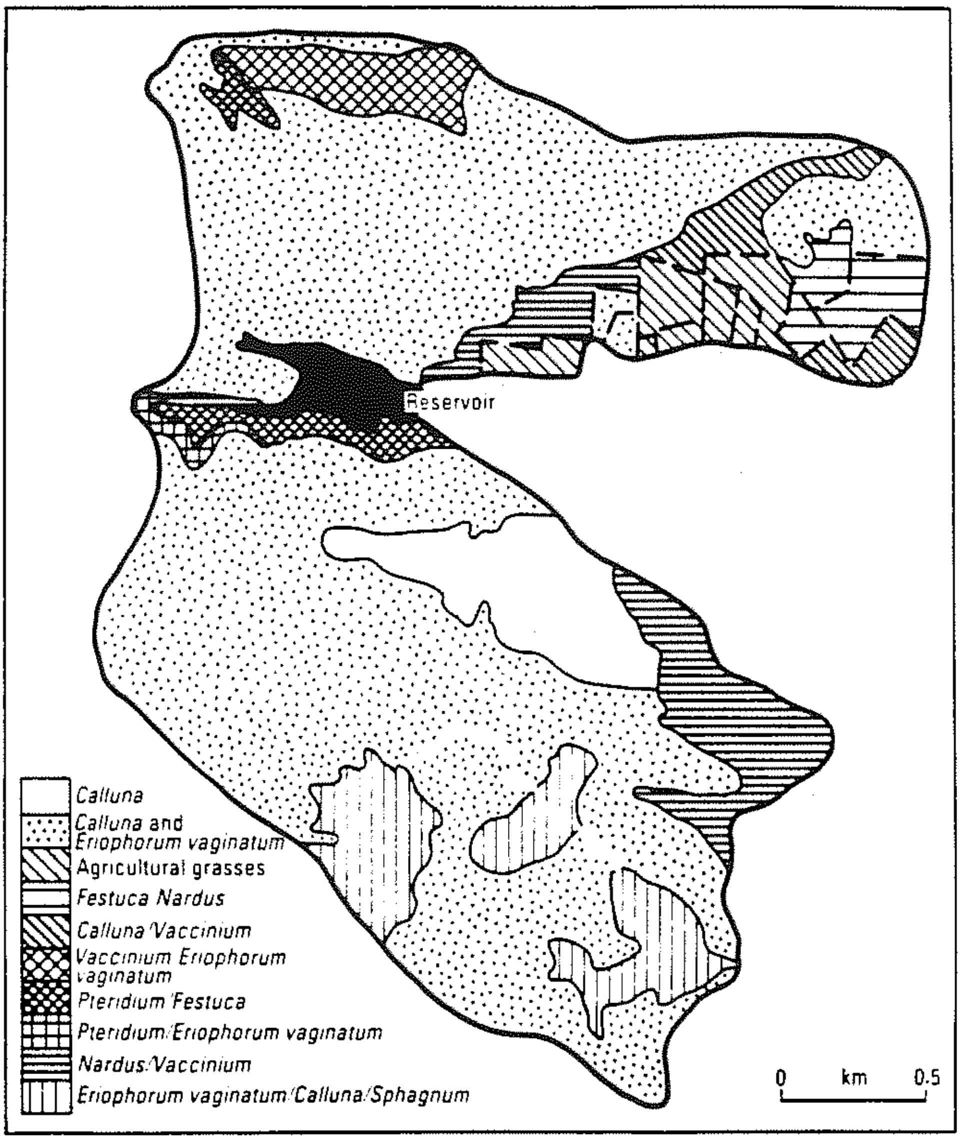


Figure 9. Site map of Watersheddles reservoir showing major vegetation zones

Table 2 Watersheddles raw water chemistry November 1979 - November 1986:

Yorkshire Water Authority data: summary

	Observations	Mean	Max.	Min.	St Dev.
pH	310	4.065	6.5	3.6	0.39
Conductivity uS cm^{-1}	261	106.4	155	70	13.48
Turbidity FTU	309	4.747	29	1.66	2.42
Hardness $CaCO_3$ mg l^{-1}	60	19.55	88	9	11.25
Total Alkalinity mg l^{-1}	109	1.36	8	<0.1	1.04
Sulphate mg l^{-1}	67	18.49	32.9	11	3.69
Ammoniacal Nitrogen mg l^{-1}	68	0.143	0.41	0.04	0.084
Orthophosphate mg l^{-1}	62	0.022	0.1	<0.01	0.024
Total aluminium mg l^{-1}	267	0.488	4.5	0.03	0.268
Total iron mg l^{-1}	303	0.971	13	0.22	0.777
Total manganese mg l^{-1}	303	0.102	0.25	0.01	0.024

The maximum capacity of the reservoir is some 870,000 m^3. However, the volume of water in the reservoir at any time depends on the amount drawn off by the Water Authority. Daily water level and volumetric data are extant from 1945. In normal circumstances water level has varied by up to 2 m throughout the year. Only under exceptional conditions usually associated with periods of low rainfall has the water drawdown been extensive. Since 1945 the two most extreme drawdowns were a maximum fall of 7 m in October 1949 (reducing water volume by 601,000 m^3 to 31% of capacity) and 10 m in October 1959 (reducing water volume by 757,000 m^3 to 23% of capacity). During such events extensive areas of reservoir sediment would be temporarily exposed.

The 'natural' catchment of the reservoir is some 225 ha, but this was considerably extended by the construction of two catchwater drains to the north-east and south-east. The total reservoir catchment is thus some 500 ha. Approximately 65% of water flow in the catchwater area is channelled to the reservoir, the remainder flows downstream to the River Worth. With the exception of a small area of improved land to the north-east the catchment comprises unimproved, unafforested Calluna dominated moorland (Fig. 9), which is utilised for sheep grazing and grouse shooting.

The location of the Mackereth and modified Livingstone cores are shown in Figure 10. Eight of the Mackereth cores were retained for extrusion in the laboratory. Cores were extruded at 1 cm and 2 cm intervals depending on location and the depth of sediment recovery at a site.

7.2 Lithostratigraphic results

7.2.1 Mackereth cores (Figs. 11a - 11h)

The depth of sediment recovery, dry weight and LOI profiles are all variable, with little repeatability between core sites. Recovery varied between c. 40-80 cm. A number of cores (eg. M3, M10) penetrated the peat deposits underlying the reservoir sediments (indicated in the LOI profiles by the rapid increase in percentage LOI at the base of the cores), while M2, M4 and M6 have minerogenic deposits (high basal dry weigh values), perhaps related to pre-damming soil development. Many of the cores have LOI values for the reservoir deposits of 20-30% which contrast to the c. 60% obtained at Chew and Swineshaw Higher (Figs 6a, 6b, 7). M9 has higher oscillating values (maximum > 70%) between 10-50 cm depth, with a corresponding variable dry weight profile (Fig. 11g).

7.2.2 Livingstone cores (Figs. 12a - 12b)

To assess whether the 1 m Mackereth cores were obtaining full sediment recovery, modified Livingstone 2 m cores were taken at four locations, but because of recoveries at two sites that were similar to those obtained with the Mackereth only two were retained (L1 and L4). Even with the longer cores maximum recovery was still only c. 80 cm, L1 penetrating basal peats, while L4 has higher a minerogenic content at its base. Apart from these latter differences and a LOI peak at 70 cm in L1 (Fig. 12a) and one at 40-50 cm in L4 (Fig. 12b), the LOI profiles are reasonably similar, with an up-core increase from c. 20% near the base of the cores to a zone of maximum values in the surface 20-25 cm. Further analyses for dating, diatoms, magnetics, sediment chemistry and carbonaceous particles were performed on sediment from core L4.

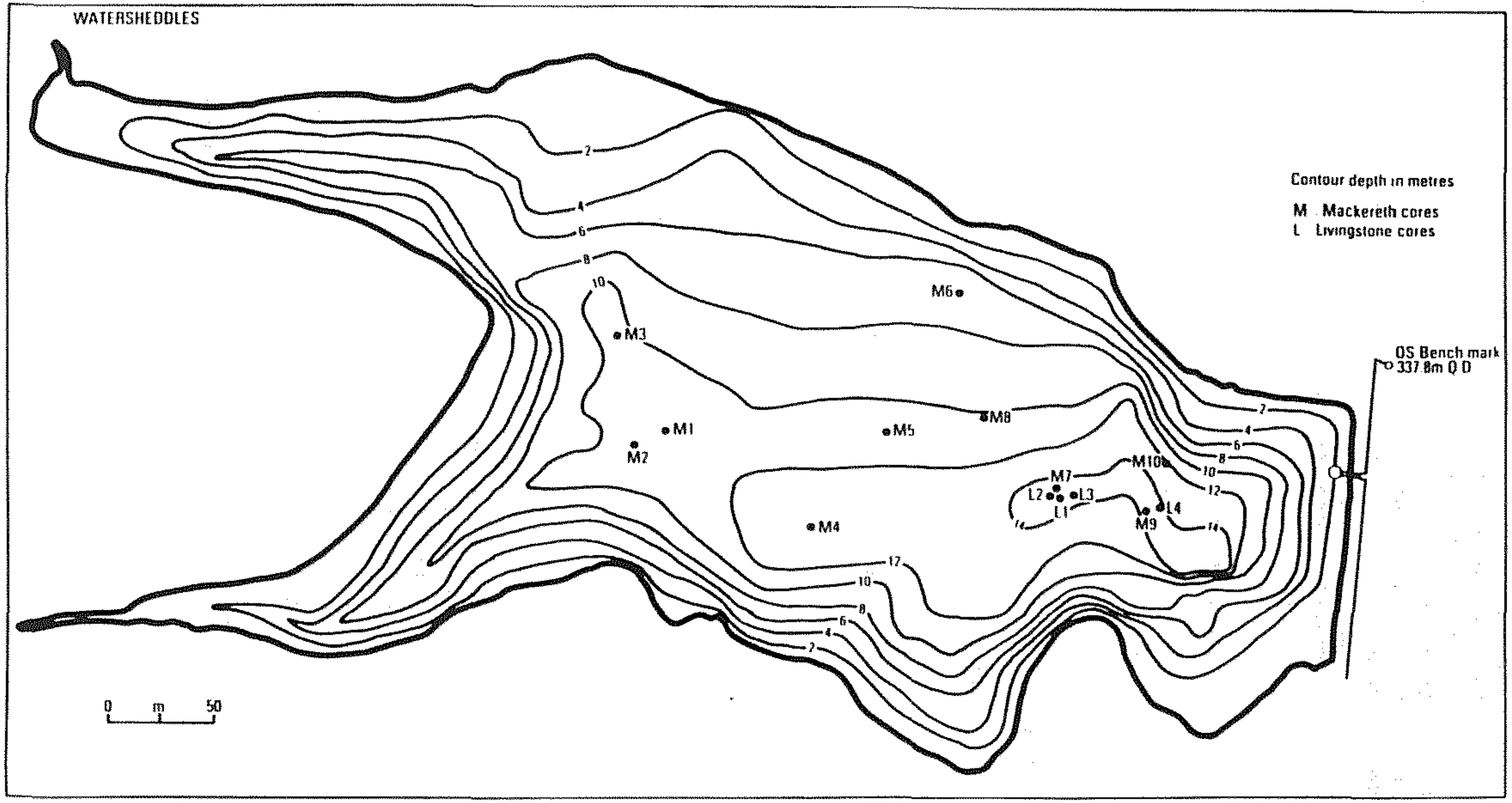


Figure 10 Watersheddles Reservoir: bathymetry and coring locations

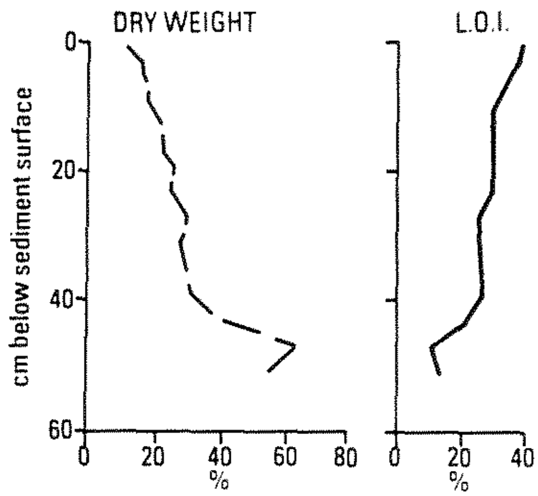


Figure 11a. Dry weight and LOI profiles for Watersheddles M2 sediment core

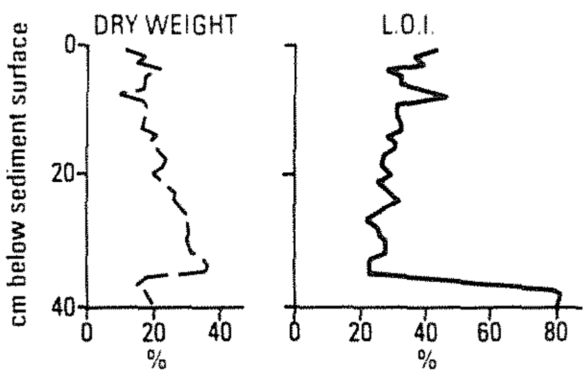


Figure 11b. Dry weight and LOI profiles for Watersheddles M3 sediment core

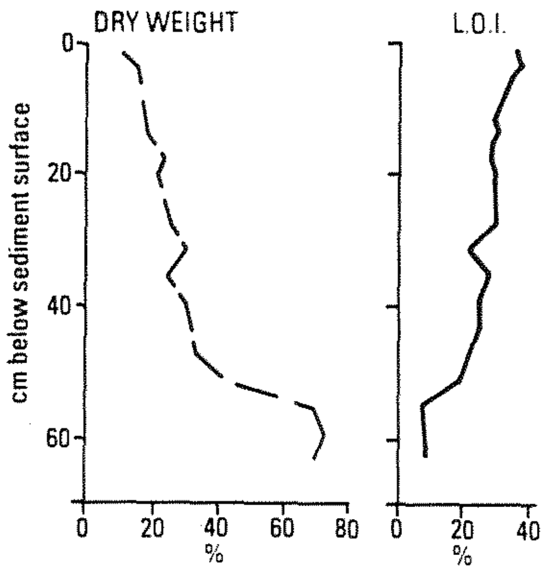


Figure 11c. Dry weight and LOI profiles for Watersheddles M4 sediment core

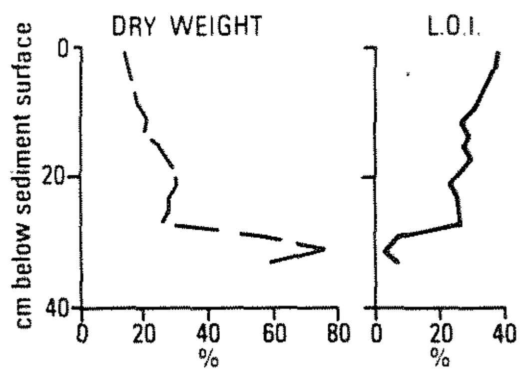


Figure 11d. Dry weight and LOI profiles for Watersheddles M6 sediment core

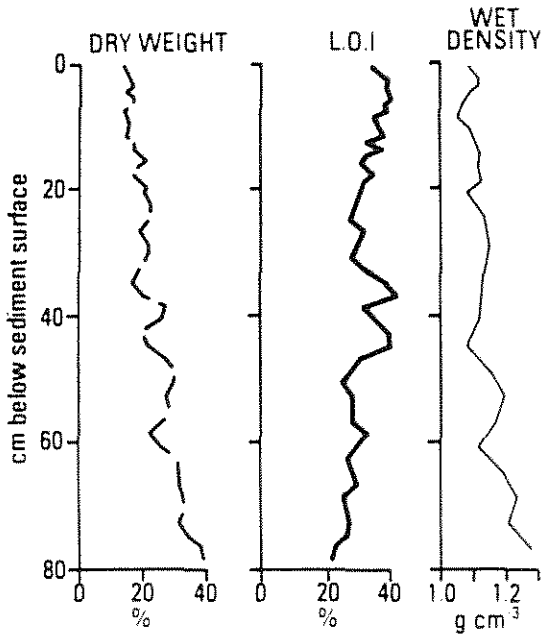


Figure 11e. Dry weight, LOI and wet density profiles for Watersheddles M7 sediment core

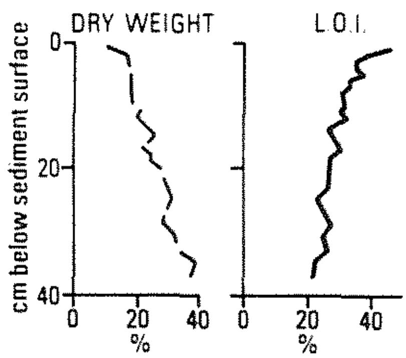


Figure 11f. Dry weight and LOI profiles for Watersheddles M8 sediment core

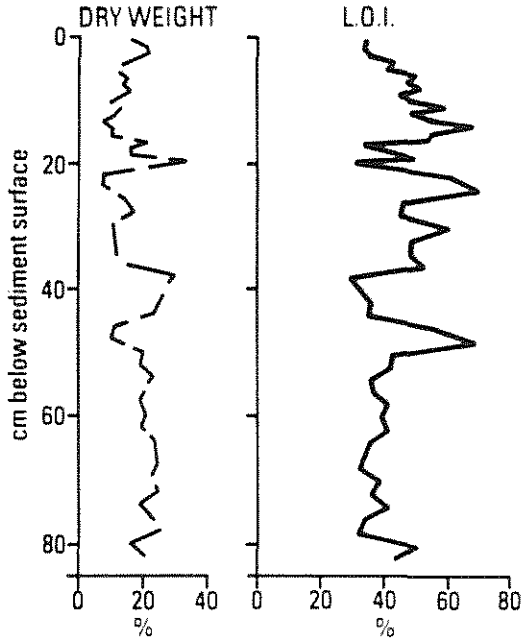


Figure 11g. Dry weight and LOI profiles for Watersheddles M9 sediment core

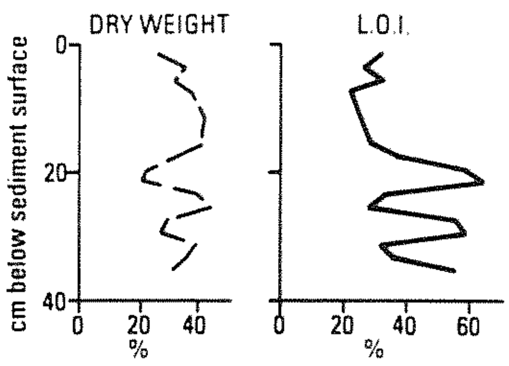


Figure 11h. Dry weight and LOI profiles for Watersheddles M10 sediment core

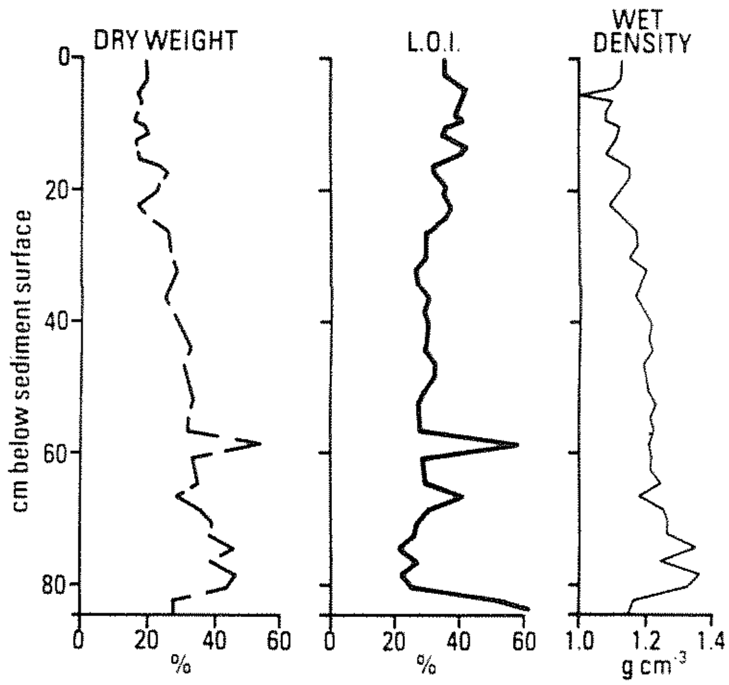


Figure 12a. Dry weight, LOI and wet density profiles for Watersheddles L1 sediment core

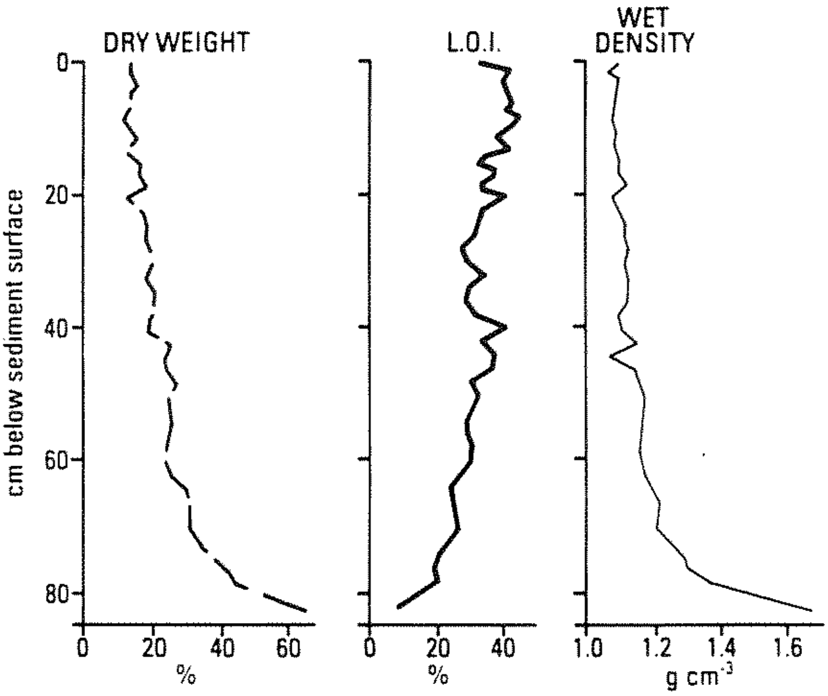


Figure 12b. Dry weight, LOI and wet density profiles for Watersheddles L4 sediment core

7.3 ^{210}Pb dating

Sediment samples from core L4 were analysed for ^{210}Pb, 226Ra, 137Cs and 241Am by gamma spectrometry using a well-type coaxial low background intrinsic germanium detector fitted with a NaI(TL) escape suppression shield (Appleby et al. 1986). The ^{210}Pb and ^{226}Ra results are given in Table 3. The ^{137}Cs and ^{241}Am results are given in Table 4. Table 5 gives values of a range of other radioisotopes determined by the gamma spectra.

The unsupported ^{210}Pb inventory of the core was calculated to be 8.43 $pCicm^{-2}$ which represents a constant ^{210}Pb flux of 0.26 $pCicm^{-2}\ y^{-1}$. The nearest comparable sites from which data were available, Ringinglow Bog and Rostherne Mere, had ^{210}Pb flux values of 0.21 $pCicm^{-2}\ y^{-1}$ and 0.20 $pCicm^{-2}\ y^{-1}$ respectively. The similarity of this parameter for all three sites suggests that the principal source of ^{210}Pb in the Watersheddles core is direct atmospheric fallout. In contrast to this, the ^{137}Cs inventory of the Watersheddles core of 45.2 $pCicm^{-2}$ is well in excess of the expected value and suggests a significant input of this isotope from the catchment. The increase in ^{137}Cs activity in the top 1 cm of the core appears to derive from Chernobyl fallout but does not make a significant contribution to the ^{137}Cs inventory.

^{210}Pb chronologies have been calculated using both the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978) and the results are given in Figure 13. For the most recent sediments the ^{210}Pb dates are in reasonable agreement with the ^{137}Cs and ^{241}Am results. Table 4 shows that the latter two isotopes both have clearly defined peaks at 14.5 cm and this level should accordingly be dated 1963. The CRS model puts 1963 at 11.5 cm. The CIC model dates are rather scattered owing to the irregular nature of the profile, but when subjected to a smoothing routine put 1963 at 16.5 cm. In the chronology given in Table 6, post-1963 dates have been calculated using the mean accumulation rate of 0.101 g $cm^{-2}\ y^{-1}$ given by the ^{137}Cs date.

The ^{210}Pb profile (Table 3) reveals the presence of an anomalous layer at a depth of 17.5 cm, the very low unsupported ^{210}Pb activity of which may be an indication of old sediment arising from a drawing down of the reservoir. This layer is dated to c. 1950 by the CRS model and to 1957 by an extrapolation of the ^{137}Cs chronology. It may perhaps represent the 77% reduction in water volume experienced in October 1959 (see Section 7.1). Below this level there is a significant divergence between the ^{210}Pb chronologies. During the period 1900-1950 the CIC model indicates a mean accumulation rate of 0.089 g $cm^{-2}\ y^{-1}$, compared to a value of 0.055 g $cm^{-2}\ y^{-1}$ for the CRS model. Since it is unlikely that accumulation rates following the construction of the reservoir in 1877 were significantly below recent values, the value given by the CIC model appears more reasonable and forms the basis for calculating the pre-1950 dates shown in Table 6. Taking the rise in bulk density at c. 70 cm to mark the pre-1870 land surface, accumulation rates during the late 19th century may indeed have been significantly higher than at later times. In these circumstances of high sedimentation rates and low ^{210}Pb flux, dilution of the unsupported ^{210}Pb will generally cause CRS model dates for older sediments to be less reliable.

Table 3 Watersheddles ^{210}Pb and ^{226}Ra data

Depth	Dry mass	^{210}Pb conc. Total		Unsupported		^{226}Ra conc.	
cm	g cm^{-2}	pCi g^{-1}	+/-	pCi g^{-1}	+/-	pCi g^{-1}	+/-
0.5	0.0799	2.53	0.23	1.39	0.25	1.14	0.10
1.5	0.2411	3.99	0.44	3.07	0.47	0.92	0.17
2.5	0.4059	3.66	0.28	2.50	0.30	1.16	0.10
6.5	1.0734	3.42	0.26	2.66	0.27	0.76	0.08
9.5	1.5062	2.42	0.26	1.73	0.27	0.69	0.08
12.5	2.0062	2.87	0.32	1.73	0.34	1.14	0.11
14.5	2.3282	2.83	0.33	1.97	0.35	0.86	0.11
17.5	2.9093	1.49	0.23	0.24	0.25	1.25	0.09
20.5	3.4789	2.26	0.17	1.13	0.18	1.13	0.06
25.5	4.4567	1.87	0.21	0.79	0.22	1.08	0.07
30.5	5.5953	1.57	0.16	0.32	0.17	1.25	0.06
35.5	6.7415	1.45	0.14	0.40	0.15	1.05	0.05
40.5	7.9119	0.92	0.16	-0.14	0.17	1.06	0.06
44.5	8.9962	0.89	0.15	-0.19	0.16	1.08	0.06

Unsupported ^{210}Pb inventory: 8.43 +/- 0.54 pCi cm^{-2}

Table 4 Watersheddles ^{137}Cs and ^{241}Am data

Depth	Dry mass	^{137}Cs conc.		^{241}Am conc.	
cm	g cm^{-2}	pCi g^{-1}	+/-	pCi g^{-1}	+/-
0.5	0.0799	13.91	0.15	0.00	0.00
1.5	0.2411	9.76	0.22	0.00	0.00
2.5	0.4059	11.93	0.20	0.00	0.00
6.5	1.0734	10.09	0.18	0.00	0.00
9.5	1.5062	11.12	0.18	0.00	0.00
12.5	2.0062	14.73	0.24	0.06	0.02
14.5	2.3282	16.26	0.28	0.08	0.02
17.5	2.9093	7.61	0.16	0.00	0.00
20.5	3.4789	7.79	0.11	0.00	0.00
25.5	4.4567	1.32	0.07	0.00	0.00
30.5	5.5953	0.60	0.05	0.00	0.00
35.5	6.7415	0.51	0.04	0.00	0.00
40.5	7.9119	0.48	0.05	0.00	0.00
44.5	8.9962	0.07	0.03	0.00	0.00

Inventories: 45.2 +/- 0.8 pCi cm^{-2} 0.06 +/- 0.01 pCi cm^{-2}

Table 5 Watersheddles miscellaneous radioisotopes

Depth cm	^{226}Ra	^{238}U	^{235}U	^{228}Ac	^{228}Th	^{40}K
			pCi g^{-1}			
0.5	1.14	0.95	0.18	0.86	1.09	16.12
1.5	0.92	0.00	0.07	0.81	1.20	14.32
2.5	1.16	0.90	0.03	1.04	0.86	17.73
6.5	0.76	0.00	0.10	0.81	0.74	11.23
9.5	0.69	0.13	0.10	0.53	1.21	10.22
12.5	1.14	0.80	0.13	1.32	1.20	14.85
14.5	0.86	2.47	0.10	0.73	1.79	19.56
17.5	1.25	0.04	0.14	0.67	1.31	15.46
20.5	1.13	0.72	0.11	1.16	1.69	15.69
25.5	1.08	0.89	0.14	1.08	1.95	20.33
30.5	1.25	0.71	0.11	1.29	1.89	19.34
35.5	1.05	0.71	0.15	1.09	1.85	17.45
40.5	1.06	0.56	0.17	0.95	1.37	15.40
44.5	1.08	0.44	0.10	0.78	1.41	15.31

Table 6 Watersheddles radiometric chronology

Depth	Dry mass	Date	Age		Sedimentation rate	
cm	g cm^{-2}	AD	Yr	+/-	g cm^{-2} y^{-1}	cm y^{-1}
0.00	0.0000	1986	0			
2.00	0.3235	1983	3	2		
4.00	0.6562	1979	6	2		
6.00	0.9900	1976	10	3		
8.00	1.2898	1973	13	4	0.101	0.63 +/- 17%
10.00	1.5895	1970	16	4		
12.00	1.9229	1967	19	5		
14.00	2.2477	1964	22	6		
16.00	2.6187	1960	26	6		
18.00	3.0041	1956	30	7		
20.00	3.3832	1952	34	7		
22.00	3.7716	1947	39	7		
24.00	4.1631	1943	43	8		
26.00	4.5706	1938	48	9	0.089	0.42 +/- c.30%
28.00	5.0260	1933	53	10		
30.00	5.4814	1928	58	10		
32.00	5.9392	1923	63	10		
34.00	6.3976	1918	68	10		

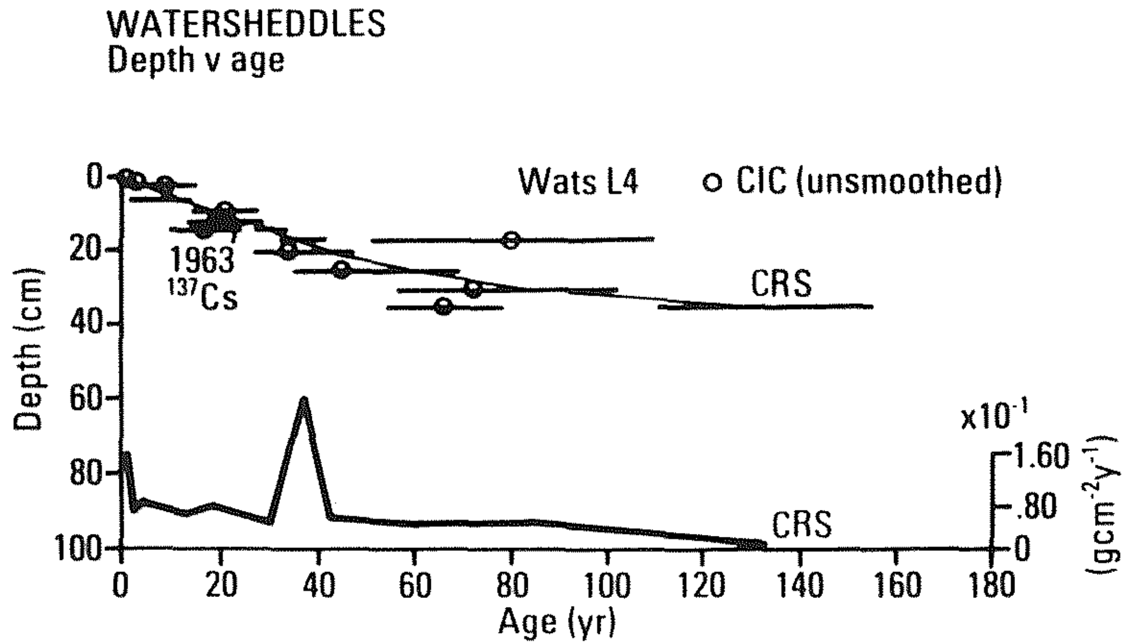


Figure 13. ^{210}Pb age/depth chronology for Watersheddles L4 sediment core

7.4 Magnetics

Sediments from core L4 were packed into previously screened styrene sample pots and subjected to the sequence of magnetic measurements outlined in Stevenson et al. 1987a.

All remanences were measured on a Minispin slow-speed spinner fluxgate magnetometer. Susceptibility was not measured as the combination of small sample size and relatively weak magnetisation made the samples unsuitable.

Figure 14 plots the results of all but the reverse field ratio measurements which proved unreliable. The generally higher SIRM and ARM values above 40 cm are associated with relatively low SIRM/ARM quotients suggesting a catchment as well as an atmospheric input. This interpretation is further supported by the higher total volume of magnetic minerals than would be expected from atmospheric deposition alone.

7.5 Sediment chemistry

Trace metal concentration - depth profiles are used to determine if the reservoir has been contaminated by material deposited from the atmosphere. It is almost certain that there are no trace metal-bearing effluents entering the reservoir, therefore any contaminants must come from an industrially polluted atmosphere.

The catchments of many lakes have been disturbed and this alters the basic sediment composition. Changes in the basic sediment composition can also alter the trace metal concentration of sediments even in the absence of contamination. Such changes can be detected by examining the dry weight, LOI and major cation profiles.

7.5.1 Major cations

Below 70 cm the sediment is coarse (high dry weight) and inorganic (low LOI) (Fig. 12b). This lower part of the core represents the land surface which was flooded in the 1870s to make the reservoir. Above 70 cm the dry weight gradually drops and the organic content slowly increases towards the sediment surface.

The calcium, magnesium, potassium and to a lesser extent sodium concentrations are all low in the sub-70 cm layer (Fig. 15, Appendix 2). Above 70 cm the major cation concentrations decrease gradually towards the sediment surface, but this decrease is removed (or almost so with calcium), when the concentrations are expressed per gramme minerals (Fig. 16). This way of expressing the results removes the effect of changing organic content.

The major cation results indicate that there has been little change in the erosion of material from the catchment since the construction of the reservoir. This is supported by the fairly constant fluxes of major cations to the sediment (Fig. 17). Although the flux-depth behaviour shows some fine detail, the results confirm the low level of catchment disturbance around the reservoir.

7.5.2 Trace metals

As the major cation results indicate that there has been little change in catchment inputs that might alter the trace metal concentrations, the trace metal profiles should reflect changes in the strength of any contamination source.

The concentration of trace metals is low in the sub-70 cm layer (Fig. 18, Appendix 2). Above 70 cm, there is little copper and nickel contamination, while the lead and zinc concentrations are high, particularly in the 5-30 cm layer. When the concentrations are expressed per gramme minerals there is evidence for a small amount of copper and nickel contamination (Fig. 19). As the concentrations of the four trace metals drop above 8 cm, the degree of contamination may be decreasing. The trace metal flux results confirm this (Fig. 20). There is fine detail in all the trace metal profiles, but the 'anomalous' layer at 17.5 cm, which may represent draw-down of the reservoir, is not recorded in these profiles (or in the major cations).

The fairly high sediment accumulation rate in the reservoir permits the calculation of flux values over a larger sediment interval than usual. This provides finer detail of changes over time. Figures 18 - 20 show that there was trace metal contamination of the sediments right from the building of the reservoir. This contamination increased around 1950 and has dropped since the mid-1970s. The fluxes of copper and nickel in the early 20th century are high and do not represent background values.

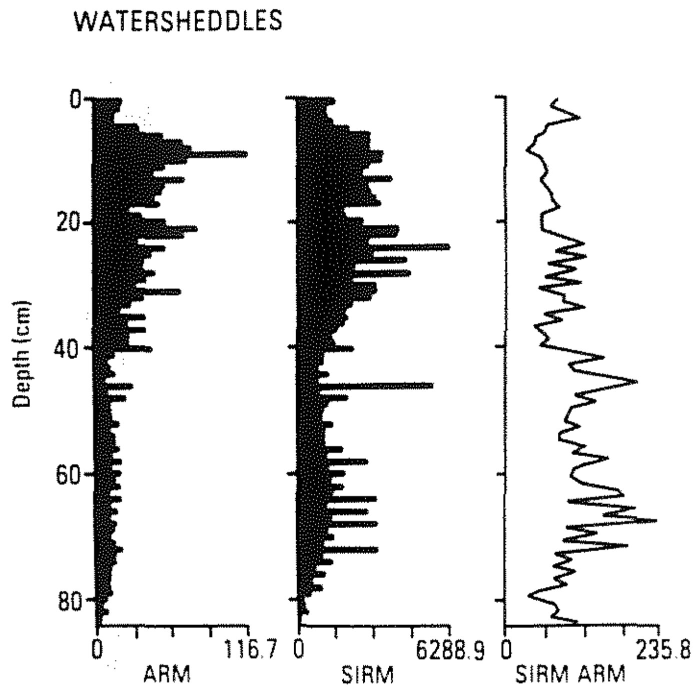


Figure 14. Magnetic profiles for Watersheddles L4 sediment core

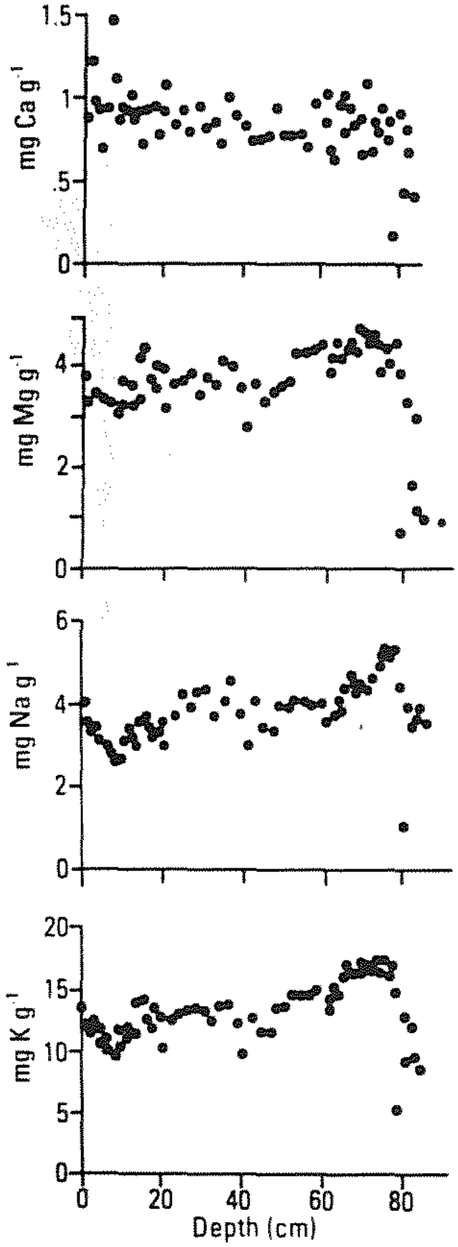


Figure 15. Variation of calcium, magnesium, sodium and potassium in the sediments of Watersheddles Reservoir

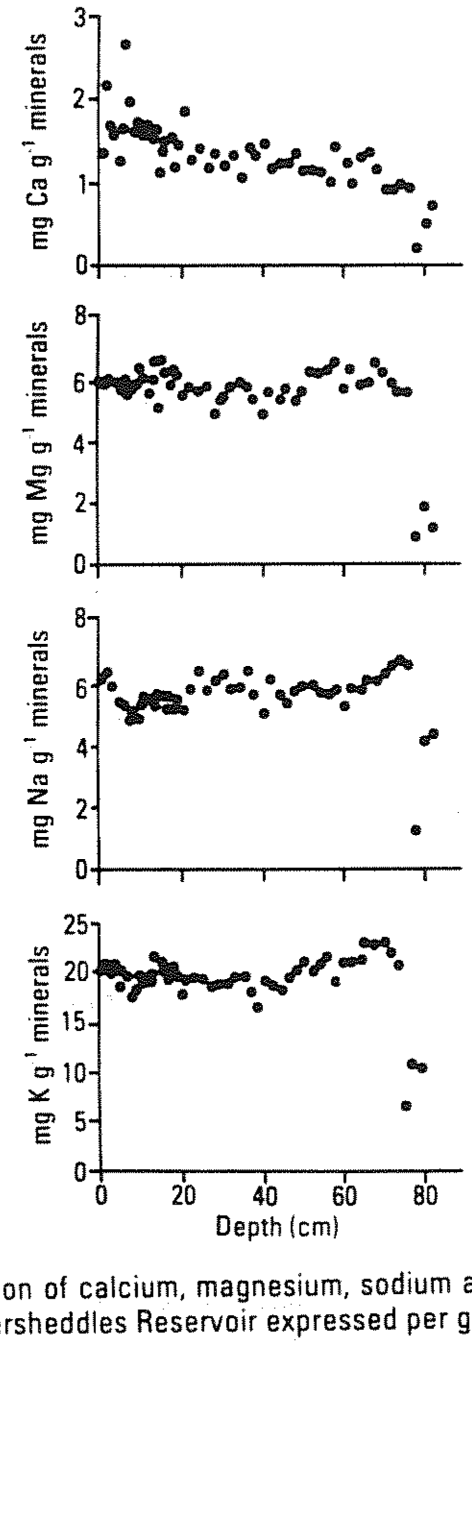


Figure 16. Variation of calcium, magnesium, sodium and potassium in the sediment of Watersheddles Reservoir expressed per gramme minerals

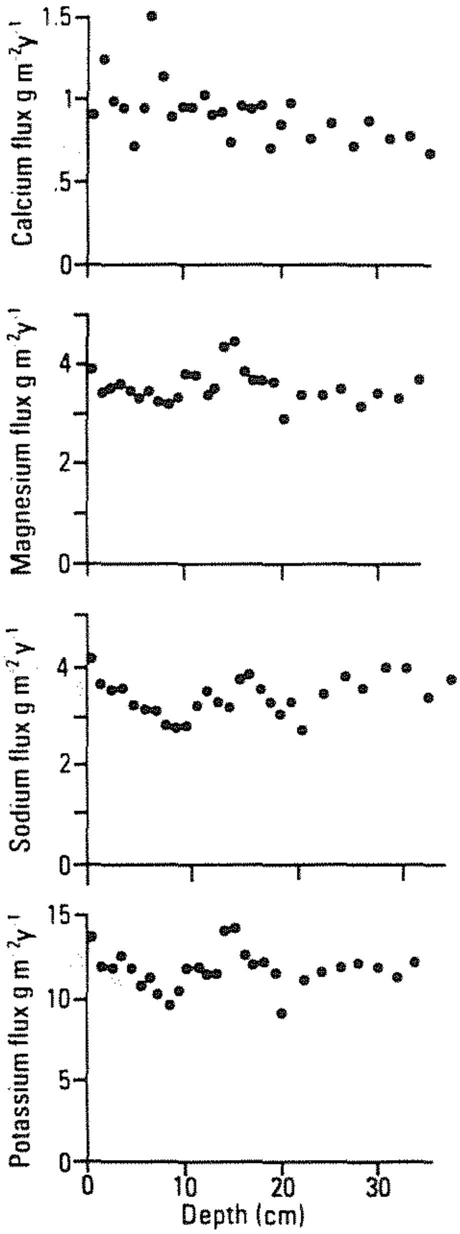


Figure 17. Variation of calcium, magnesium, sodium and potassium fluxes in the sediments of Watersheddles Reservoir

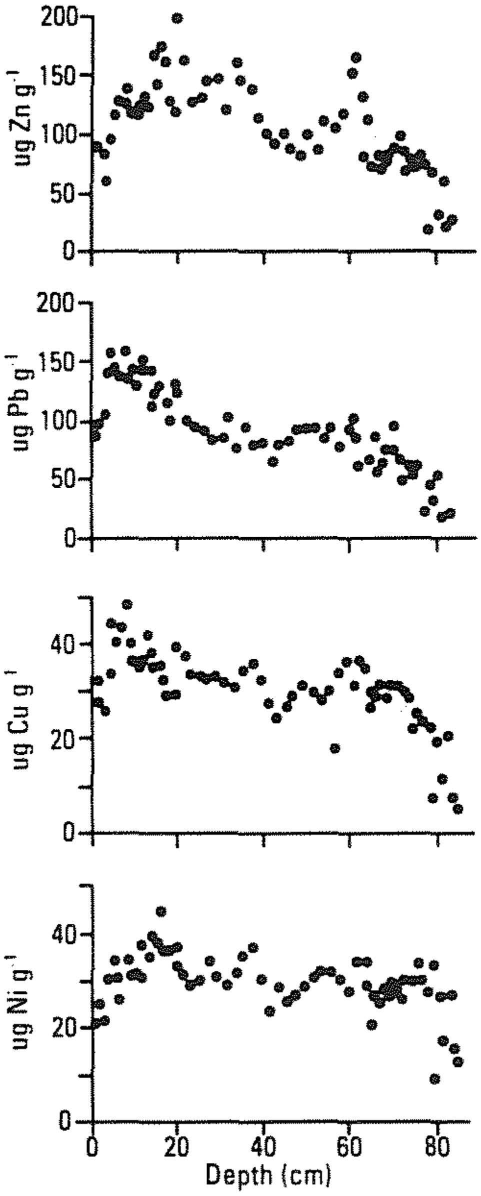


Figure 18. Variation of zinc, lead, copper and nickel in the sediments of Watersheddles Reservoir

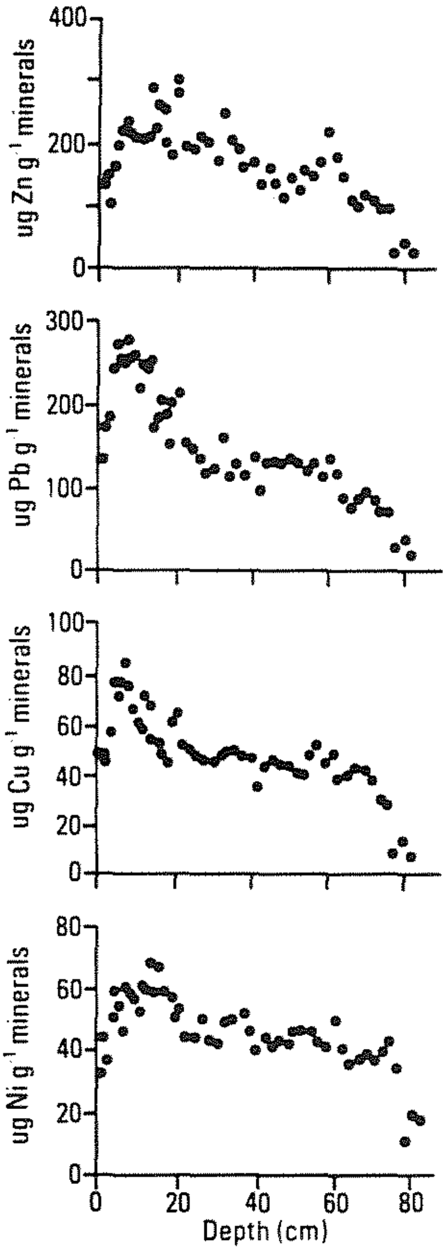


Figure 19. Variation of zinc, lead, copper and nickel in the sediments of Watersheddles Reservoir expressed per gramme minerals

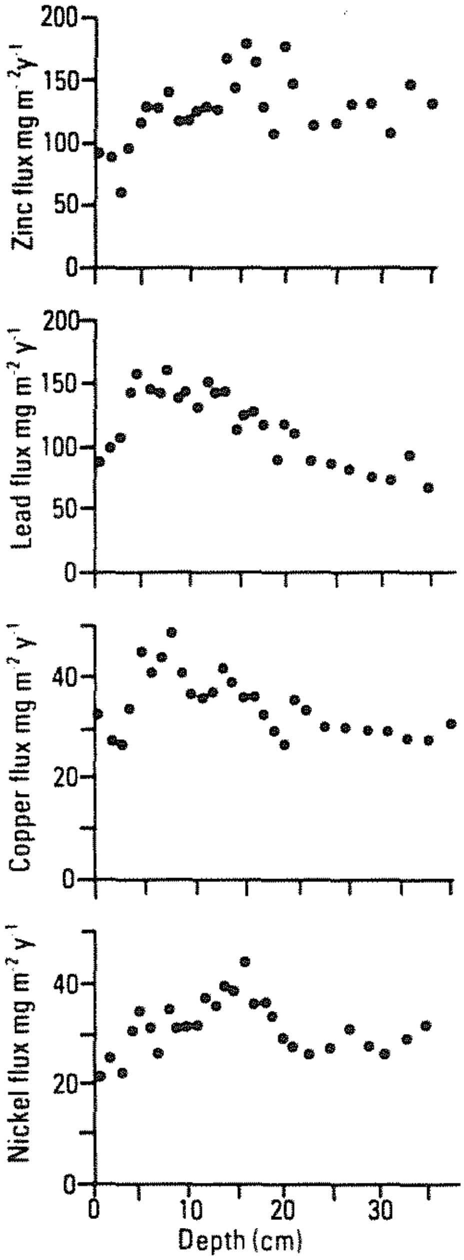


Figure 20. Variation of zinc, lead, copper and nickel fluxes in the sediments of Watersheddles Reservoir

7.6 Spherical carbonaceous particle ('soot') analysis

Sediment samples from core L4 were analysed for concentration of spherical carbonaceous particles (SCPs) (Stevenson et al. 1987). Forty sub-samples were taken down to 80 cm depth. The results are given in Table 6 and shown graphically in Figures 21a and 21b. The particles were observed in all the sediment sub-samples analysed.

Figure 21a indicates that concentrations of SCPs are observed in small numbers in the lower depth of the core. There is a trend showing a slight increase in concentration upwards to a depth of 38 cm. Above this level which represents the early 20th century they rise significantly and show a rapid increase towards the surface. Peaks can be identified at 25-20 cm (c. 1940-1952), at 17 cm (c. 1958) and at 5 cm (c. 1977).

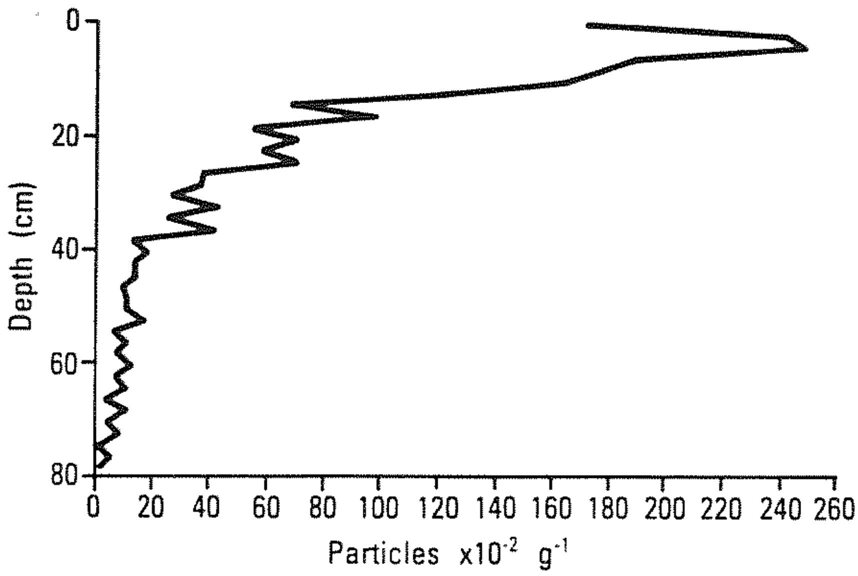
The concentrations expressed in terms of the organic content of the dry sediment (determined by LOI) (Fig. 21b), give a pattern of distribution similar to that described in Figure 21a except the peaks observed at 17 cm and 25-20 cm are not so marked and the concentration of SCPs remain particularly stable between 38-68 cm depth.

A significant decrease in particle concentration in the top 4 cm (c. 1979-1986) is observed in Figures 21a and 21b. This corresponds with the drop in trace metal contamination from the mid-1970s (Section 7.5.2).

Many particles were observed in all the sub-samples that are reminiscent of charcoal and other particulate products of burning. Particles up to 2 mm in length were observed.

Shiny and very hard black spherical particles were observed in many of the sub-samples, especially below 40 cm depth. These were distinguished from the SCPs only by the sheen of the surface and their resistance to applied pressure.

Figure 21a. Carbonaceous particle profile (g^{-1} dry weight sediment) for Watersheddles L4 sediment core



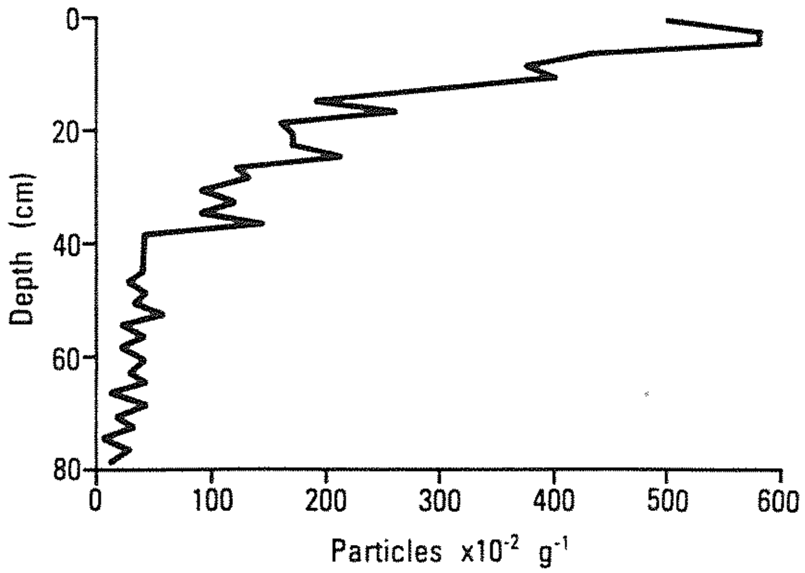


Figure 21b. Carbonaceous particle profile (g^{-1} organic content of dry sediment) for Watersheddles L4 sediment core

Table 7 SCP analysis for Watersheddles core L4

	Number of SCPs	
Depth cm	g dry sed.* 10^{-2}	g organic content sed. * 10^{-2}
0-1	172.4	498
2-3	242.4	580
4-5	248.6	584
6-7	188.5	432
8-9	176.6	382
10-11	162.7	398
12-13	122.3	295
14-15	68.9	194
16-17	97.7	255
18-19	56.1	159
20-21	70.1	168
22-23	59.4	169
24-25	69.5	210
26-27	37.8	118
28-29	37.3	132
30-31	27.4	90
32-33	42.1	120
34-35	26.2	87
36-37	41.8	145
38-39	13.0	40
40-41	17.9	43
42-43	13.9	41
44-45	13.9	37
46-47	9.0	24
48-49	11.0	36
50-51	10.5	32
52-53	17.1	55
54-55	6.2	21
56-57	10.9	37
58-59	6.6	21
60-61	11.6	38
62-63	6.8	25
64-65	9.6	40
66-67	2.6	10
68-69	10.4	40
70-71	4.0	15
72-73	7.5	31
74-75	0.9	4
76-77	4.7	25
78-79	2.1	11

7.7 Diatoms

Although diatom concentrations were low and preservation variable, it was possible to construct a full diatom diagram (Appendix 3). Compared to diatom assemblages in natural lakes (Battarbee 1986) and particularly other acid lakes (eg. Fritz et al. 1986), the Watersheddles results are of low floristic diversity. The profiles of three taxa dominate the diagram - E. exigua, E. tenella, P. microstauron. Few taxa have clear profile trends and given the lack of autecological information for diatoms in acid reservoirs, none are readily interpretable in palaeoecological terms. A. minutissima percentages decrease from c. 35 cm, while E. tenella values peak at 45 cm and then decline to a constant 10%, while E. exigua percentages vary between 25% and 60% throughout the core.

At the base of the core diatom preservation is poor probably as a result of increased abrasion associated with the higher minerogenic content of the sediments.

The methods used to reconstruct pH at other sites (eg. Flower 1986, Stevenson et al. 1987a) are inapplicable because of the uncertainty concerning diatom ecology in these very acid, stressed environments.

7.7.1 Diatom sources in Watersheddles and its inflows

Because of the low diatom content of reservoir sediments and the presumed low primary productivity of the system, external diatom inputs/sources might be important both numerically and floristically in reservoirs, which is not usually the case in natural lakes (Battarbee 1986). In April and May 1986 a number of samples of living diatom material were taken within the reservoir and its inflows, in an attempt to assess possible diatom sources within the system.

Rock scrapes and sand samples from within the reservoir itself were dominated by E. exigua with very occasional occurrences of P. microstauron. Diatoms were more numerous on rocks, presumably because it is a more stable substrate than sand, particularly during brief exposures during drawdown and disturbance caused by wind driven turbulence.

Given its dominance at all the acid head water reservoirs and its presence at other, higher pH, sites, it appears that E. exigua is both extremely tolerant of very acid water (and in the Pennine area, water with high humic and dissolved aluminium levels) and regular desiccation caused by exposure during drawdown. This success may be the result of an ability to form a resting stage) or its ability to rapidly re-establish itself as the water level rises, as well as its physiological adaptation to acid and trace metal stress.

Inflow stream and inflow leat Jungermannia and rock scrapes possessed abundant diatoms, but again they were floristically simple, with E. exigua dominant in all samples. Also present were E. rhomboidea, E. cf. curvata and its varient var. subarcuata (which was commonly deformed), T. flocculosa, F. rhomboides v. saxonica and P. subcapitata-hilseana.

A number of circumneutral species were found in the sediments, albeit infrequently. No indication of their possible source was found in living material. This may reflect reworking of old diatoms or an acidification of the inflows or the reservoir itself in the recent past.

Although a very limited study, these samples do not identify the possible sources of, for example, Caloneis bacillum which occurs in the sediments, but also suggest that F. rhomboides v. saxonica and T. flocculosa are predominantly derived from the inflow stream. To some extent this is supported by the corroded nature of the Frustulia valves that occur in the sediments. Further work is required, particularly on seasonal changes, before firm conclusions can be made.

7.8 Catchment land use and management history

Standard documentary sources (Patrick 1987, Stevenson and Patrick 1987a) indicate that the pattern of land use in the catchment today has pertained from at least the 1840s. Most of the catchment (Fig. 9) comprises unimproved moorland which is utilised for sheep grazing and grouse shooting. An upper limit on sheep density is set by the Water Authority, but in practice this is not met and sheep numbers have not varied greatly in recent years.

The only active management of the moorland is the regular burning of Calluna and the coarse grasses in strips, primarily for the benefit of the grouse population. There is no evidence that lime has ever been applied to this acid moorland nor that any attempt has been made to drain it.

The small area (c. 20 ha) of enclosed, improved land in the north-eastern sector of the catchment (Fig. 9) is sown to agricultural grasses and has been utilised in this way in living memory. However, relict cultivation ridges suggest that this land may have been cultivated for arable or root crops in the more distant past. The contemporary grasses are maintained by liming and a grazing regime which involves cattle and sheep.

7.9 Watersheddles: summary

LOI and dry weight profiles indicate variability of sediment deposition and distribution, even in this small, relatively undisturbed reservoir and catchment.

^{210}Pb dating of the core is good given the potential for sediment disturbance in reservoir sediments. Above 17.5 cm the correspondence of ^{210}Pb dates with dated ^{137}Cs and ^{241}Am peaks is indicative of a reliable chronology. An anomalous layer in the 210Pb profile at 17.5 cm may relate to a major drawdown in water level and extensive sediment exposure in 1959. Below this level data derived from the CIC model are considered to provide the more accurate chronology.

Trace metal analysis of the sediment core indicates that the reservoir has been contaminated by trace metals deposited from an industrially polluted atmosphere from its first flooding in 1877. the contamination increased around 1950 and has dropped in the last ten or so years.

Deposition of carbonaceous particles has occurred throughout the reservoir's history. A significant increase in their concentration is observed from the early 20th century, marked peaks occur in the 1940s, mid-1950s and mid-1970s. Within the last c. 5 years concentrations have decreased significantly.

With the exception of a small area of improved land, there is no evidence to suggest that land in the catchment has experienced other than low-intensity management for sheep and grouse since the construction of the reservoir.

Whereas the pollution history from SCP and metal analyses of Watersheddles sediments is generally good, diatoms do not provide a reliable indication of changing water quality.

The sediment diatom assemblage is floristically simple and typical of other acid headwater reservoirs, but few taxa have clear trends.

It is not possible to use the diatoms to reconstruct pH. The pH preference categories obtained for diatoms at other sites (eg. Flower 1986) are unlikely to be applicable in these extreme environments where diatoms may be responding to other factors as well as pH. Further work is required to identify diatom - water quality relationships in the Pennine reservoirs.

8.0 General conclusions

1. Reservoirs have complex and heterogeneous sediment accumulation patterns caused by frequent drawdown and the interaction of lacustrine and fluvial deposition. Sediments can be extensively eroded and re-worked, causing hiatuses and subsequent loss of stratigraphic conformity. In the Pennines this variability in the sediment record is compounded by the very high rates of sediment accumulation which results from erosion of peat deposits on the surrounding moors.

2. Although a number of reservoirs are sufficiently old to cover the increase in 19th century atmospheric pollution, the history of regular drawdown for both water supply and maintenance purposes, suggests that suitable stratigraphic records will seldom exist. The probability of sediment disturbances and the severity of such disturbance is likely to increase with the age of reservoirs. The identification of suitable sites, if they exist, would require very thorough and detailed coring or a large range of sites.

3. The identification of suitable sites has not been assisted by the loss of documentary records, particularly those relating to drawdown and maintenance operations.

4. Many of the assumptions that underpin the use of ^{210}Pb dating are invalidated as a result of sediment hiatuses, high accumulation rates and extensive re-working of fine organic fractions with which the ^{210}Pb is associated (McCall _et al._ 1984).

5. Even if suitable sites were found without extensive sediment disturbance, it appears that the diatom record could not provide a basis for inferring past changes in reservoir water pH as:

  a. Diatom preservation is at best variable and often there are no diatoms present in the sediment.

  b. The diatom assemblage is very limited and dominated by a few _Eunotia_ and _Pinnularia_ species (particularly at the acid upland head water sites). This may be a result of dissolution histories, but it also relates to the extreme nature of the reservoir environment for biota, which causes very low primary productivity and restricted floristic diversity in littoral habitats.

6. If further work is to be undertaken, a calibration set would be necessary to attempt to address the problem of pH reconstruction. There is some potential for this kind of work, since despite the problems outlined above, reservoirs with water of a higher pH (eg. Trentabank) do contain characteristic diatom floras.

7. A detailed history of pollution from atmospheric sources may be documented from an analysis of the chemistry and carbonaceous particle record in reservoir sediments. The major limitation to such reconstruction will be the availability of relatively undisturbed sediments.

8. Given the availability of reasonable water quality data for reservoir raw water since the mid-1970s a more favourable approach may be the analysis of short cores in conjunction with Water Authority pH records in an attempt to identify possible signs of pH increase.

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Appendix 1. Basic characteristics of Pennine reservoirs

NAME	GRID REF	DATE	Z(M)	AR(HA)	V(TCM)	TWL(M)	PH(RANGE)	PH(ME)	WA
AGDEN	43261923	1869	27.4	25	2541	196		0	YK
ARNFIELD	43013973	1850	15.9	0	975	164.8	4.3-6.0	5.2	NW
ASHWORTH MOOR	34830157	1908	13.1	0	1591	282.2	4.3-5.1	4.7	NW
BAITINGS	44010189	1958	47.2	26	3502	257.6	6.1-7.8	6.8	YK
BELMONT	34670170	1826	22.4	0	1887	260.1	5.2-6.9	0	NW
BLACKMOORFOOT	44099130	1876	12.5	41	3091	253.6	5.3-7.0	6.6	YK
BLAKELEY	44054096	1903	18.9	3	108	255.9		0	YK
BOLLINHURST	33973834	1872	16.5	0	384	222.7		0	NW
BOOTHWOOD	44030163	1971	46.5	22	3637	258.7		0	YK
BOSHAW WHAMS	44153057	1840	10.8	6	200	299.9		0	YK
BOTTOMS LODGE	43027969	1872	16.5	0	2300	150.3	4.2-9.0	7.1	NW
BROADSTONES	44195065		0	0	0	310	4.4-4.9	4.5	YK
BROOMHEAD	43269959	1934	27.7	50	4919	177.7		0	YK
BROWN HOUSE WHAM	34896163	1850	8.2	0	224	240.1	4.9-5.2	5.1	NW
BROWNHILL	44177064	1928	28.7	16	1185	219.8	5.7-7.3	6.5	YK
BRUSHES	33995991	1864	13.4	0	237	197.8		0	NW
BRUSHES CLOUGH	34956098	1859	13.7	0	182	281.7		0	NW
BUCKLEY WOOD	34902154	1839	9.9	0	109	171.5		0	NW
BUTTERLEY	44046105	1907	28.3	16	1773	234.5	4.4	4.4	YK
CALF HEY	34753225	1858	13.3	0	607	243.8		0	NW
CANT CLOUGH	34898309	1876	18.29	0	1373	281.6		5.5	NW
CASTLESHAW LOWER	34994096	1891	13.1	0	620	239.3		0	NW
CASTLESHAW UPPER	34998101	1891	19.7	0	1150	256.9	4.8-6.2	5.5	NW
CHELKER	44055515	1866	11.3	23	1036	219.6	9.2-7.6	8.1	YK
CHEW	44037019	1907	21.9	0	936	487.7	5.2-5.3	5.25	NW
CLAY LANE STORAGE	34860139	1865	8.8	0	309	187.7		0	NW
CLOUGH BOTTOM	34848269	1897	19.5	0	873	307.8	4.9	4.9	NW
CLOWBRIDGE	34827281	1866	11.6	0	1468	281.9		0	NW
COWM	34881187	1877	15.5	0	1084	248.7		0	NW
COWPE	34843201	1911	25.1	0	625	308.6	5.2-6.9	5.9	NW
CROOK GATE	34980115	1881	14.9	0	188	320.6		0	NW
DALE DYKE	43243917	1875	20.4	25	2118	212.1		0	YK
DAMFLASK	43284907	1896	25.9	47	5037	153.9		0	YK
DEAN HEAD	44038152	1840	17.3	7	436	302.3		0	YK
DEAN HEAD LOWER	44022305	1872	18.3	4	277	297.5		0	YK
DEAN HEAD UPPER	44022308	1872	16.6	4	258	310.3		0	YK
DEERHILL	44070117	1875	11	16	736	349	4.3-4.9	4.5	YK
DELPH	34700155	1921	23.8	0	2300	211.8		0	NW
DINGLE	34693147	1850	9.6	0	332	218.7		0	NW
DINGLEY	44110070	1953	41	18	3342	244.6		0	YK
DOE PARK	44078343	1862	15.8	8	486	244.9		0	YK
DOVE STONE	44016038	1960	31.4	0	5046	216.4	5.2-5.3	5.25	NW
DOWRY	34985112	1880	16.6	0	737	304.8		0	NW
EARNSDALE	34670221		0	0	0	220	7.9	7.9	NW
ELDWICK	44122413	1860	10.1	2	123	202.8		0	YK
ELSACK	34937482	1932	7.6	4	232	205.7	6.9-8.0	7.5	YK
GORPLE LOWER	34940314	1934	26.5	21	1253	298.7	4.3	4.3	YK
GORPLE UPPER	34920314	1934	24.4	22	1711	349	3.9	3.9	YK
GORPLEY	34910230	1905	23.2	6	598	257.7	4.7-6.5	5.5	YK
GREEN WITHENS	34990162	1924	20	21	1356	360.6		0	YK

Appendix 1 cont.

NAME	GRID REF	DATE	Z(M)	AR(HA)	V(TCM)	TWL(M)	PH(RANGE)	PH(ME)	WA
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GREENBOOTH	34885155	1956	33.5	0	3182	213.4		0	NW
GREENFIELD	44029054	1897	18.9	0	462	271.9	4.2	4.2	NW
GREENFOLDS	34822262	1860	15.24	0	300	295.1		0	NW
HANGING LEES	34969124	1866	9.14	0	95	269.5	5.5-6.6	6.1	NW
HARDEN	44153034	1899	18.4	5	348	366.1	7.1-7.9	7.6	YK
HEATON	34688097	1857	9.9	0	282	157.6		0	NW
HEWENDEN	44074356	1843	10.7	7	282	205.7		0	YK
HIGH LANSHAW	44132451	1850	1	1	3	348.5		0	YK
HIGH RID	34667103	1829	10.5	0	550	176.3		0	NW
HOLLINGWORTH	43008977	1850	15.9	0	331	169.1		0	NW
HOLMESTYES	44140906	1838	19.3	3	300	267.2	5.7-7.1	6.3	YK
HORCECOPPICE	33969837	1861	17.7	0	332	203.2		0	NW
HURST	43056938	1838	7.4	0	0.2	215.5	5.0-5.1	5.09	NW
HURSTWOOD	34889317	1925	29.9	0	1373	256.5	4.57	4.57	NW
INGBIRCHWORTH	44215060	1868	18	23	1332	253.9	6.5-7.9	7.1	YK
JUMBLES	34735140	1971	21.6	0	2050	132.3		0	NW
KEIGHLEY MOOR	34989394	1846	11	7	332	370.6	4.0-6.1	4.25	YK
KINDER	43055882	1912	29	0	2343	279.5	6.8-7.0	6.9	ST
KITCLIFFE	34960125	1866	8.23	0	238	230.9		0	NW
LANGSETT	44214002	1905	29	51	5901	246.9	4.0-4.6	4.2	YK
LEE GREEN	34880337	1866	7	0	100	203.6		0	NW
LEEMING	44038344	1877	17.4	8	550	255		0	YK
LEESHAW	44016353	1879	17.1	9	600	259.4		0	YK
LIGHT HAZZLES	34963198	1801	6.1	0	318	382.9		0	NW
LONGWOOD	44100173	1828	11.6	4	160	178.4	4.6-7.1	5.9	YK
LOW LANSHAW	44141449	1855	3.4	1	10	324.6		0	YK
LOWER LAITHE	44013368	1926	18.3	13	1318	266	5.9-7.3	6.6	YK
MARCH GHYLL	44122511	1906	16.8	7	395	213.4	4.8-8.2	6.6	YK
MARKLANES	34652121	1907	12.6	0	168	221.7		0	NW
MIDHOPE	43223994	1903	27.1	21	1632	243.8	4.3-5.2	4.7	YK
MILLOWNERS	43036963	1800	5.75	0	52	237.7		0	NW
MITCHELL'S HOUSE	34790275		0	0	0	300	6.7	6.7	NW
MIXENDEN	44060290	1873	9.1	9	478	266.7		0	YK
MOREHALL	43287958	1930	21.6	26	2027	146.3		0	YK
MOSSY LEA	43058946		4.3	0	32	213.1		0	NW
NADEN HIGHER	34852172	1846	16.8	0	364	261.8	4.5-4.9	4.7	NW
NADEN LOWER	34856162	1846	10.4	0	173	220.7		0	NW
NADEN MIDDLE	34854167	1863	19.8	0	691	243.2		0	NW
NEW YEARS BRIDGE	34984106	1881	16.7	415	288	0		0	NW
NORMAN HILL	34969132	1866	13.1	0	217	277.4		0	NW
OGDEN	34763225	1912	15.24	0	1.5	224.8		6.24	NW
OGDEN	44063309	1858	20.1	14	990	301.5		0	YK
OGDEN	34953125	1878	11.7	0	839	210.3		0	NW
PIETHORNE	34965128	1866	17.1	0	1564	287		0	NW
PONDEN	34995372	1877	15.5	12	964	233	5.8-7.2	6.4	YK
RAMSDEN CLOUGH	34917213	1882	21.4	0	473	295	3.7-5.1	4.4	NW
READYCON DEAN	34988124	1883	14.6	0	376.4	386.5	4.9-5.1	5	NW
REDMIRES LOWER	43268855	1849	8.8	12	566	325.5	4.7-7.4	6.3	YK
REDMIRES MIDDLE	43264855	1836	11	19	784	336.2	4.7-7.4	6.3	YK
REDMIRES UPPER	43259855	1854	13.1	23	1423	350.5	4.7-7.4	6.3	YK
REVA	44151426	1894	11.3	7	545	234.6	6.2-8.3	7.5	YK

Appendix 1 cont.

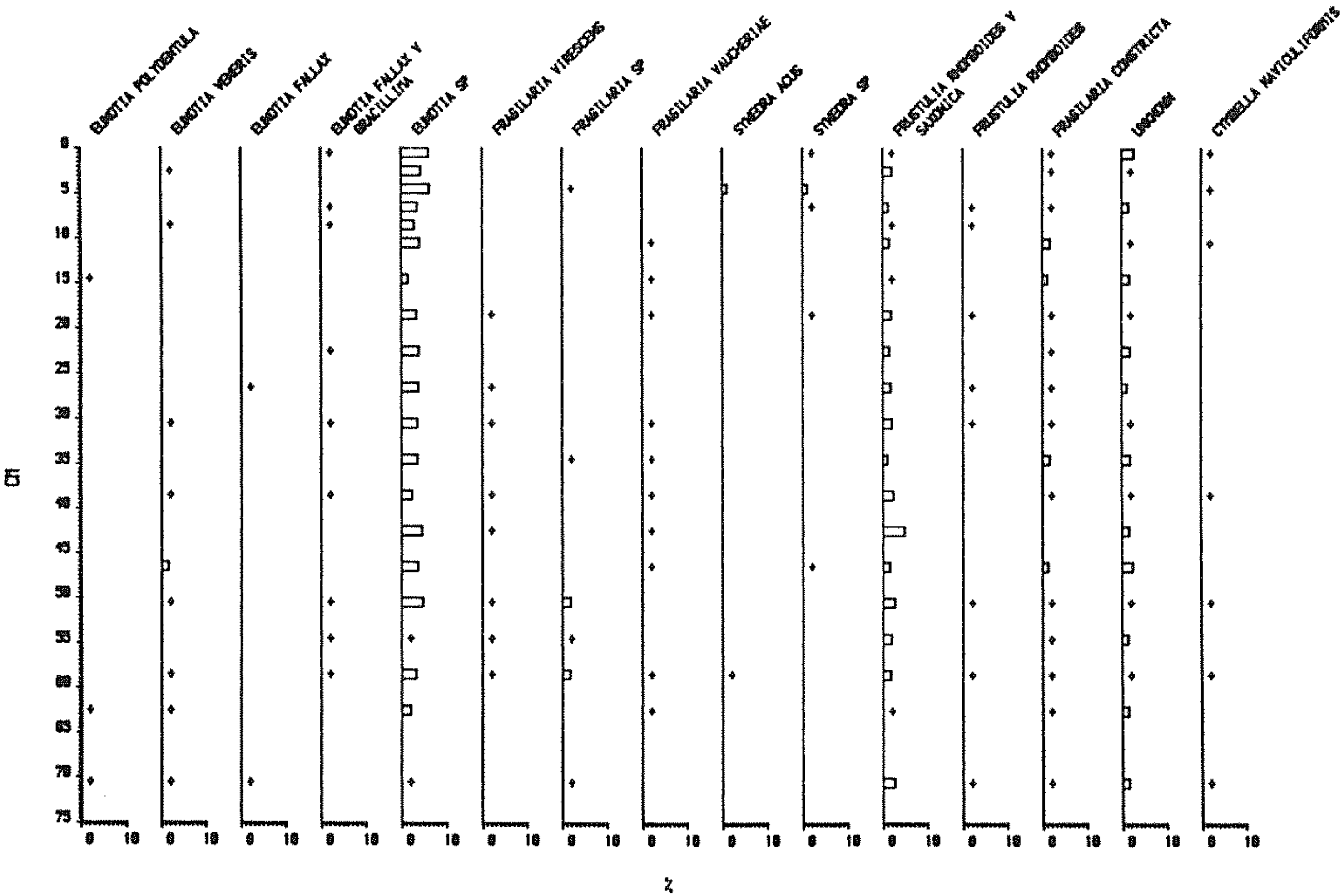
NAME	GRID REF	DATE	Z(M)	AR(HA)	V TCM	TWL M	PH RANGE	PH MD	WA
RHODESWOOD	43050993	1850	20.7	0	2270	175.1		0	NW
RINGSTONE	44051180	1883	13.9	18	1040	303.6		0	YK
RIVELIN LOWER	43277869	1848	15.1	12	525	204.8	4.5-7.4	5.7	YK
RIVELIN UPPER	43271868	1848	9.6	4	93	211.7	4.5-7.4	5.7	YK
RODDEN	34972118	1901	24.1	0	95	269.5		0	NW
ROYD MOOR	44222043	1934	19.2	15	812	257	3.6-5.4	4	YK
RUMWORTH	34678080	1849	8.7	0	432	110.7		0	NW
RYBURN	44024166	1933	29	11	949	192.9		0	YK
SCAMMONDEN	44053167	1970	51.8	42	7877	251		0	YK
SCOUT DIKE	44235047	1928	12.2	16	709	221.9		0	YK
SCOUT MOOR	34826196	1910	22.5	0	217	360.6		0	NW
SILSDEN	44045477	1862	22.8	11	650	275.4	6.9-7.9	7.2	YK
SNAILSDEN	44136040	1899	14.2	4	176	417.0	3.8-4.4	4	YK
SPRINGMILL	34876170	1887	14	0	604	305		0	NW
SPRINGS	34690147	1876	13.7	0	518	330.7		0	NW
STRINES	43222905	1869	30.4	22	2159	248.2	7.5	7.5	YK
STRINESDALE LOWER	34956165	1850	17.1	0	529	279.2		0	NW
STRINESDALE UPPER	34957068	1832	11.7	0	322	298.9		0	NW
STUBDEN	44106332	1868	16.8	2	450	323.9		0	YK
SWINDEN	34888334	1864	18.29	0	529	244.1		0	NW
SWINESHAW	43143958	1865	11	0	0	224.2		0	NW
SWINESHAW HIGHER	43105997	1864	16.1	0	768	291.7	4.3-5.1	4.7	NW
SWINESHAW LOWER	43004991	1864	13.6	0	282	265.8		0	NW
THORNTON MOOR	44052223	1885	8.7	18	785	378.2		7.5	YK
TORSIDE	43068984	1865	25.6		670	198.7		0	NW
TURTON & ENTWISTLE	34720175	1837	33.8	0	3323	230.4	6.2-7.3	6.8	NW
UNDERBANK	43253992	1907	16.2	42	2727	182.9		0	YK
VALE HOUSE	43097978	1869	12.2	0	1561	153.3		0	NW
WALKERWOOD	33987990	1864	18.6	0	912	179.2		0	NW
WALSHAW DEAN LOWER	34966332	1907	20.2	10	715	301.2		0	YK
WALSHAW DEAN MIDDLE	34966335	1907	21.2	15	1193	317.9	4.0-4.1	4.05	YK
WALSHAW DEAN UPPER	34968345	1907	27.4	10	911	335.2		0	YK
WARLAND	34958206	1801	12.8	0	1818	375.2	3.7-4.9	4.35	NW
WARLEY	44030217	1872	9.2	28	741	406		0	YK
WATERGROVE	34907176	1938	26.5	0	323	237.7		0	NW
WATERSHEDDLES	34969380	1878	12	15.9	867	335.5	3.8-4.5	4	YK
WAYOH	34735168	1876	24.9	0	5100	174.6		0	NW
WESSENDEN HEAD	44048076	1881	14.6	6	341	386		0	YK
WESSENDEN OLD	44058087	1839	15.2	7	391	300		0	YK
WHARNCLIFFE	43308978		6.1	3	65	251	5.0-6.2	5.6	YK
WHITEMOOR	34879433		0	0	0	229	7.0-9.2	7.9	NW
WIDDOP	34930330	1878	19.8	39	2880	320.6	4.0	4	YK
WINDLEDON LOWER	44158019	1872	16.8	5	357	320.1	4.2-4.7	4.45	YK
WINDLEDON UPPER	44153013	1890	17.1	8	606	350.7	4.1-4.9	4.46	YK
WINSCAR	44153026	1975	45	47	8296	343.8	4.1-7.3	4.7	YK
WITHENS CLOUGH	34985232	1894	18.7	25	1330	292.9	4.0-5.5	4.4	YK
WOODHEAD	43090996	1849	21.7	0	5769	278.4	4.2-6.3	5.3	NW
YARROW	34626155		0	0	0	152	4.7	4.7	NW
YEOMAN HEY	44021047	1876	19.8	0	575	274.1	5.2-5.3	5.25	NW

Key to Appendix 1

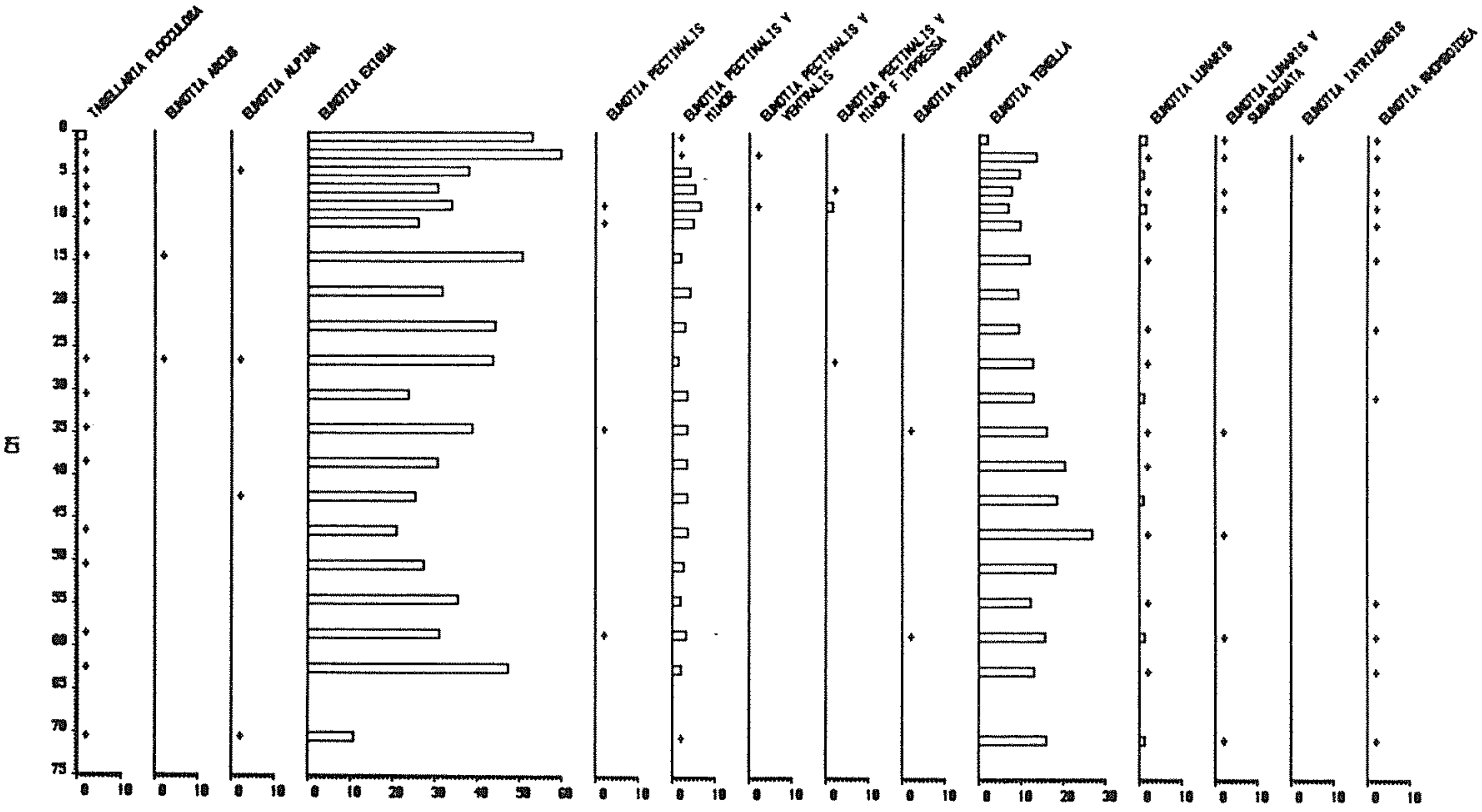
Date	Date of construction
Z (M)	Maximum depth (metres)
AR (HA)	Reservoir area (hectares)
V (TCM)	Volume ($m^3 * 10^3$)
TWL (M)	Top water level (metres above sea level)
pH (Me)	Mean pH
WA	Water authority - YK = Yorkshire NW = North west ST = Severn Trent

Appendix 2 Geochemical data for Watersheddles core L4 (all figures expressed as $\mu g\ g^{-1}$)

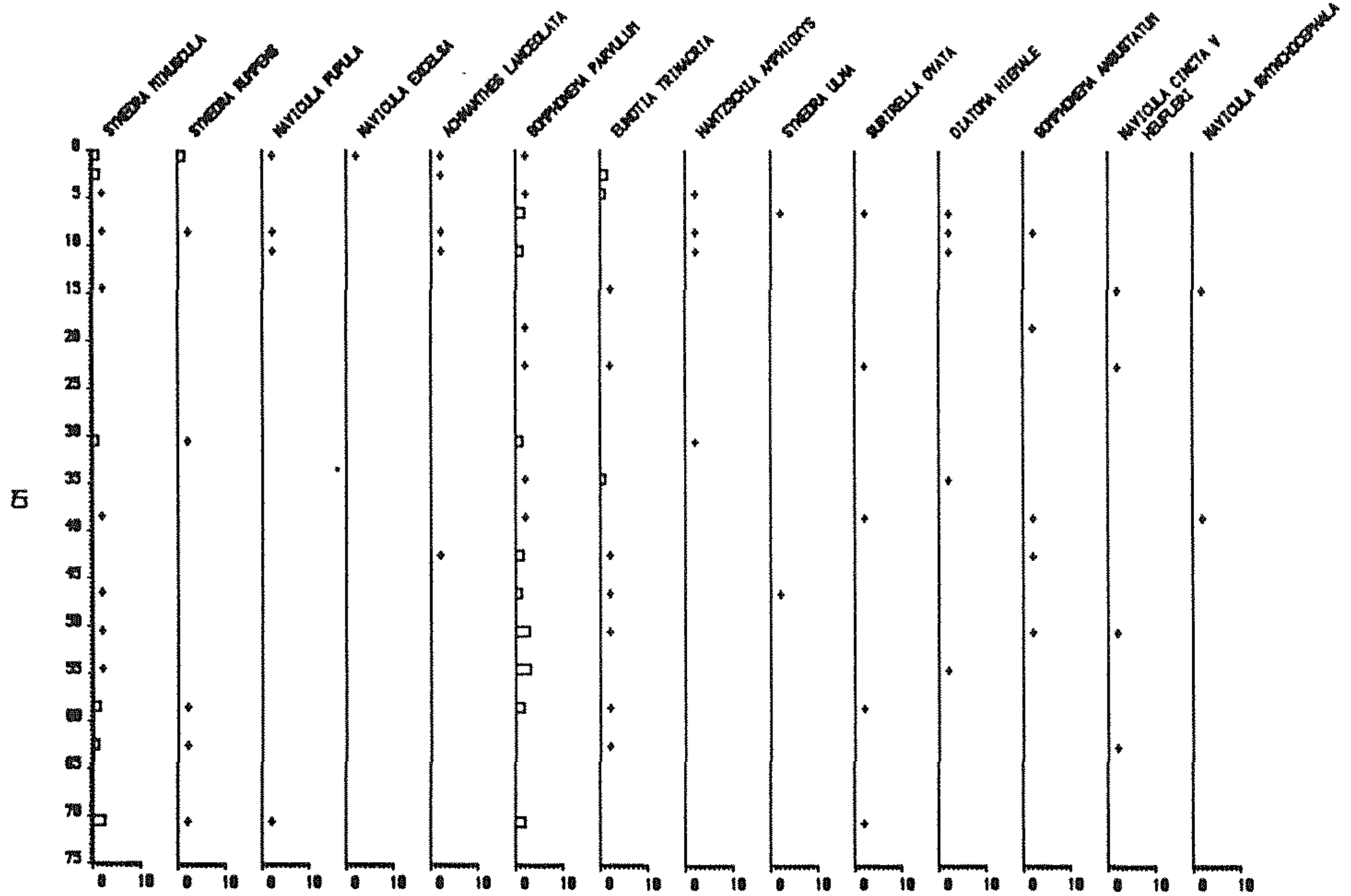
Depth	Zn	Pb	Cu	Ni	Ca	Mg	Na	K
0.5	91	87	32	21	0.89	3.87	4.02	13.57
1.5	86	97	27	25	1.23	3.37	3.56	12.00
2.0	61	105	26	22	0.98	3.43	3.39	11.78
3.5	95	141	33	30	0.94	3.52	3.44	12.43
4.5	115	155	44	34	0.71	3.40	3.14	11.82
5.5	127	143	40	31	0.94	3.28	3.05	10.74
6.5	125	139	43	26	1.48	3.38	2.98	11.23
7.5	138	158	48	34	1.13	3.22	2.73	10.32
8.5	118	136	40	31	0.88	3.11	2.65	9.71
9.5	118	141	36	31	0.95	3.28	2.68	10.39
10.5	123	127	35	31	0.93	3.75	3.07	11.75
11.5	128	148	36	37	1.02	3.68	3.36	11.84
12.5	124	140	41	35	0.89	3.30	3.17	11.38
13.5	166	141	38	39	0.92	3.39	3.00	11.42
14.5	144	111	35	38	0.73	4.25	3.60	14.00
15.5	177	120	35	44	0.94	4.39	3.70	14.15
16.5	163	125	32	36	0.94	3.82	3.42	12.57
17.5	127	113	29	36	0.95	3.63	3.17	12.03
18.5	121	98	29	37	0.78	4.06	3.31	13.49
19.5	199	128	39	33	0.94	4.03	3.54	12.89
20.5	165	123	37	31	1.08	3.21	2.97	10.44
22.5	128	97	33	29	0.84	3.73	3.72	12.56
24.5	130	93	33	30	0.94	3.78	4.17	13.01
26.5	146	89	32	34	0.80	3.92	3.90	13.26
28.5	147	82	32	31	0.96	3.50	4.32	13.49
30.5	121	82	31	29	0.83	3.79	4.30	13.24
32.5	162	101	30	32	0.86	3.74	3.71	12.51
34.5	146	76	34	35	0.73	4.11	4.06	13.80
36.5	138	90	35	37	1.01	4.07	4.50	13.93
38.5	115	75	32	31	0.90	3.66	2.97	9.81
40.5	102	78	27	24	0.85	2.87	2.97	9.81
42.5	93	63	24	29	0.75	3.69	3.98	12.82
44.5	101	78	26	26	0.76	3.34	3.44	11.71
46.5	87	81	28	27	0.78	3.54	3.35	11.54
48.5	82	88	30	29	0.94	3.64	3.93	13.58
50.5	100	89	29	31	0.77	3.76	3.89	13.69
52.5	91	89	28	32	0.78	4.30	4.06	14.64
54.5	113	83	29	32	0.78	4.34	3.99	14.52
56.5	108	88	33	30	0.71	4.42	3.96	14.80
58.5	120	77	35	28	0.97	4.50	3.94	15.01
60.5	153	90	31	34	0.86	3.99	3.60	13.42
61.5	165	97	35	34	1.03	4.22	3.71	14.34
62.5	133	82	34	29	0.69	4.55	4.09	15.27
63.5	82	60	26	21	0.63	4.24	3.82	14.73
64.5	114	64	29	27	0.97	4.45	4.33	16.10
65.5	75	62	28	26	0.79	4.53	4.71	16.92
66.5	82	54	30	28	1.02	4.42	4.50	16.09
67.5	72	83	28	27	0.93	4.36	4.32	16.35
68.5	78	61	30	29	0.84	4.80	4.48	17.16
69.5	85	71	30	28	0.87	4.73	4.33	16.69
70.5	88	70	30	27	0.67	4.58	4.63	16.91
71.5	99	92	29	30	1.09	4.66	4.61	16.49
72.5	85	62	28	30	0.69	4.48	4.88	17.38
73.5	72	48	21	30	0.86	3.97	5.07	16.63
74.5	79	57	24	34	0.79	4.41	5.31	17.51
75.5	76	51	22	30	0.93	4.12	5.12	16.35
76.5	81	57	22	28	0.74	4.50	5.27	16.91
77.5	78	57	21	33	0.87	3.94	4.37	14.82
78.5	22	20	6	9	0.17	0.76	1.01	5.21
79.5	69	42	18	27	0.91	3.36	3.93	12.94
80.5	35	30	10	17	0.44	1.67	3.48	9.23
81.5	62	49	19	27	0.82	2.99	3.61	12.03
82.5	24	17	6	16	0.67	1.14	3.91	9.61
83.5	27	18	4	13	0.42	0.97	3.52	8.56



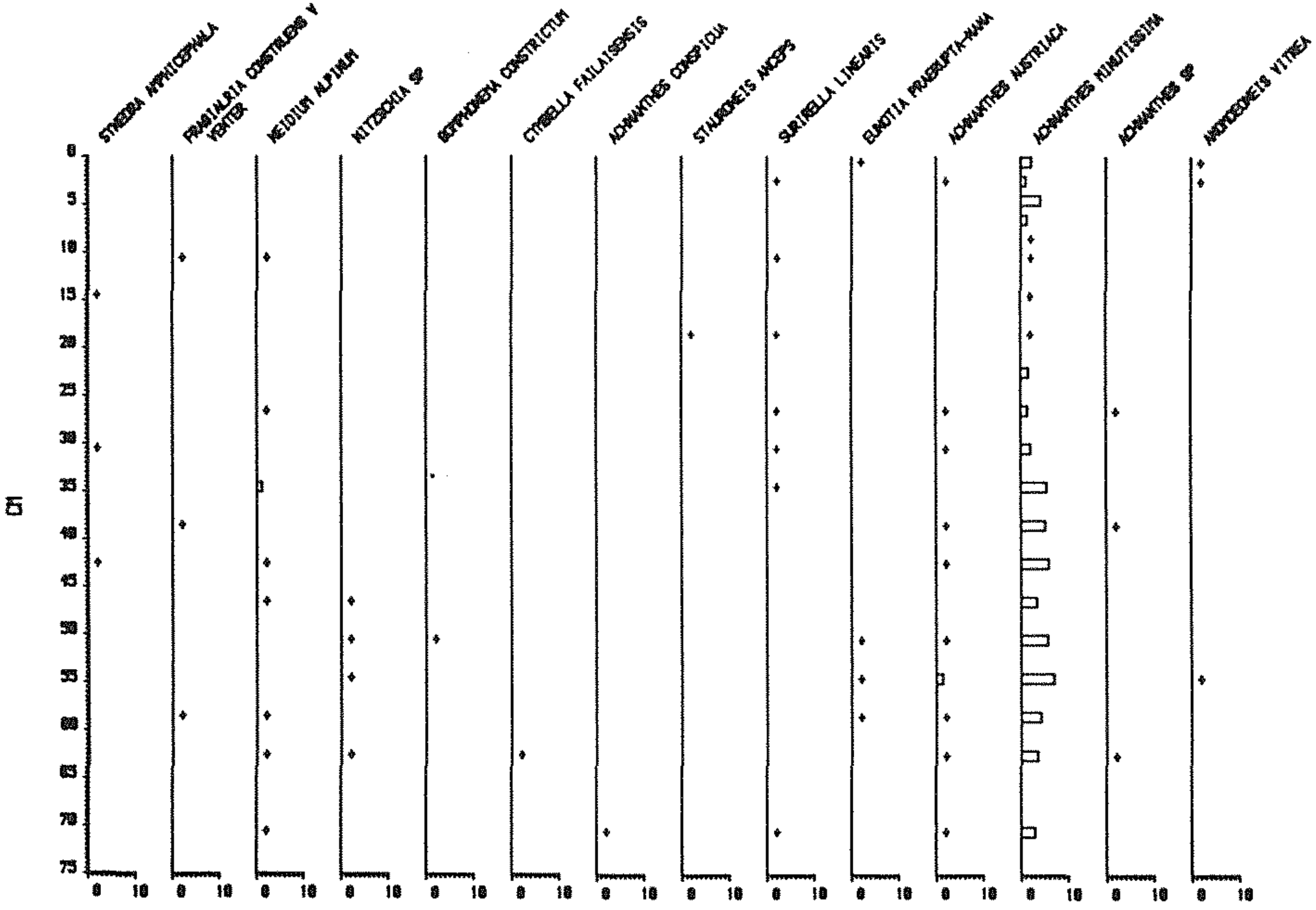
Appendix 3. Full diatom diagram for Watersheddles L4 sediment core



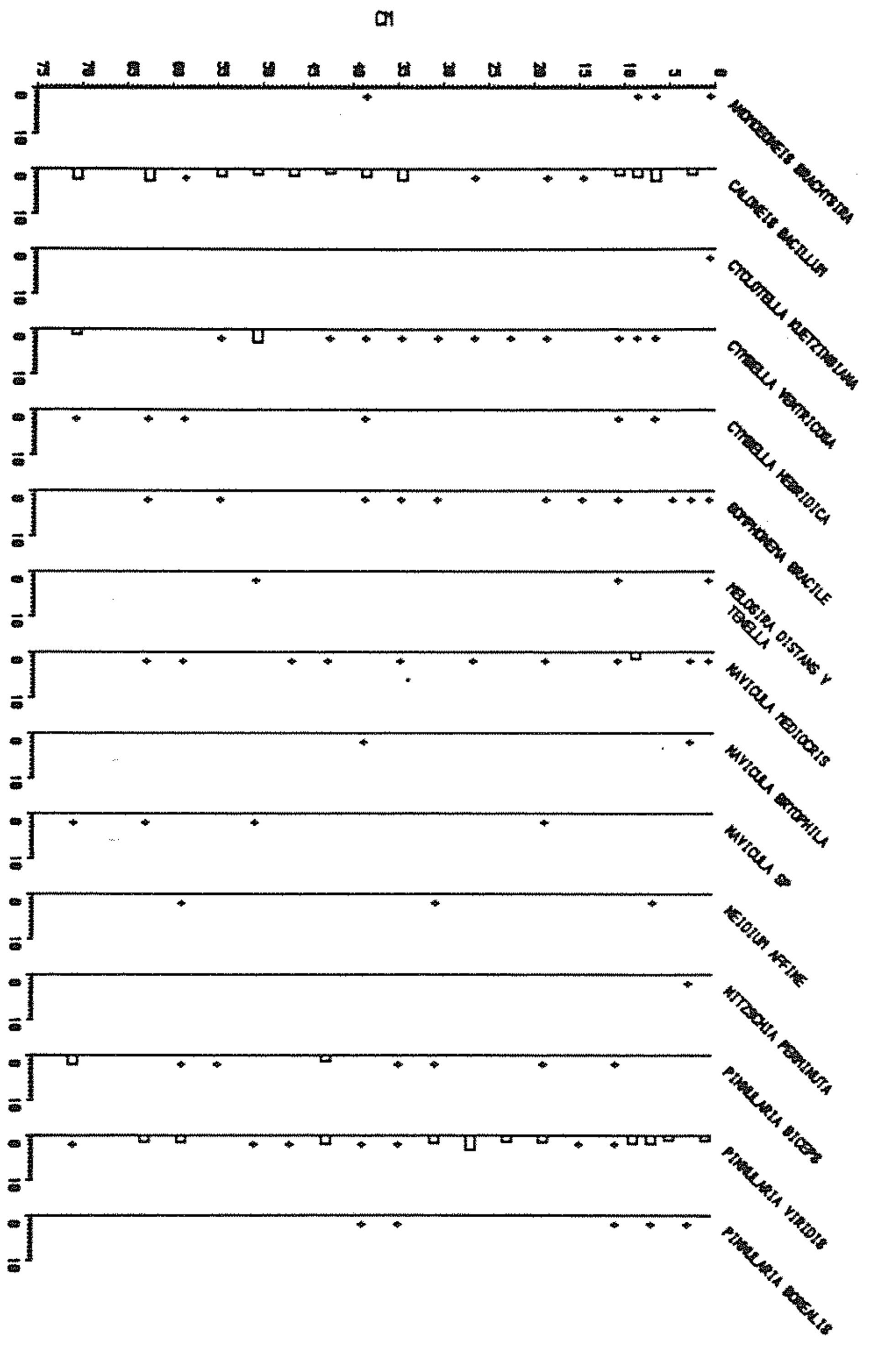
Appendix 3 cont.



Appendix 3 cont.



Appendix 3 cont.



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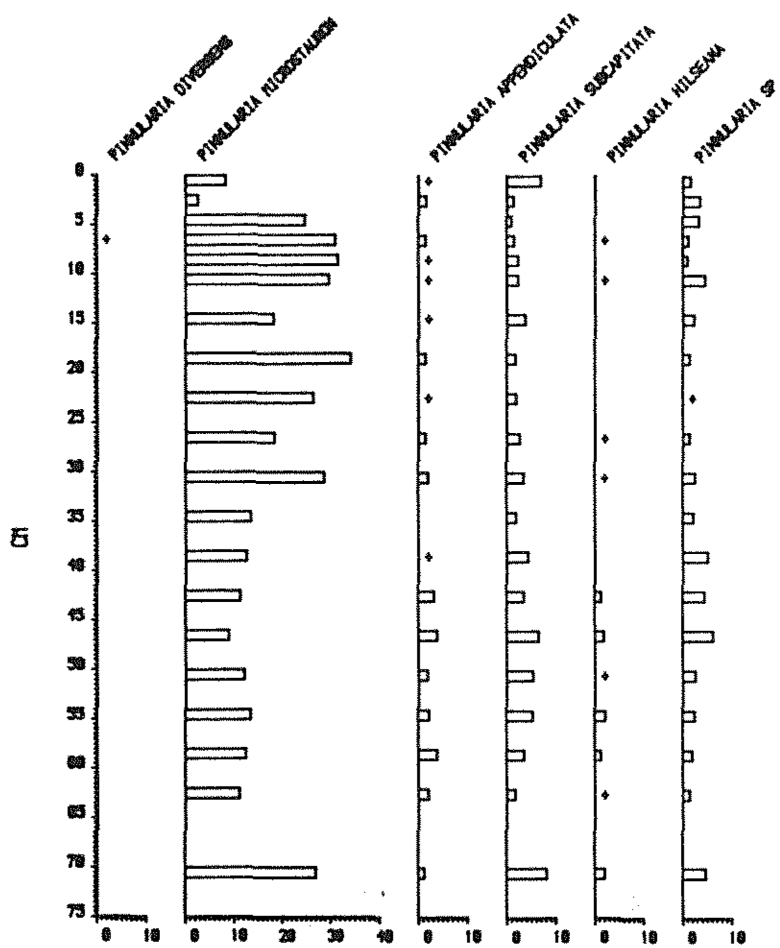

Appendix 3 cont.

Palaeoecology Research Unit: Research papers

No. 1 **Patrick, S.T. & Battarbee, R.W. 1981**
The influence of sanitary and other social changes on the eutrophication of Lough Erne since 1850: project introduction and a consideration of the potential role of metabolic wastes.

No. 2 **Battarbee, R.W. 1983**
Diatom analysis of River Thames foreshore deposits exposed during the excavation of a Roman waterfront site at Pudding Lane, London.

No. 3 **Patrick, S.T. & Battarbee, R.W. 1983**
Rural sanitation in the Lough Erne catchment: history and influence on phosphorus loadings.

No. 4 **Patrick, S.T. 1983**
The calculation of per capita phosphorus outputs from detergents in the Lough Erne catchments.

No. 5 **Patrick, S.T. 1983**
Phosphorus loss at sewage works in the Lough Erne region.

No. 6 **Flower, R.J. & Battarbee, R.W. 1983**
Acid lakes in the Galloway uplands, south west Scotland: catchments, water quality and sediment characteristics.

No. 7 **Patrick, S.T. 1984**
The influence of industry on phosphorus loadings in the Lough Erne region.

No. 8 **Battarbee, R.W. & Flower, R.J. 1985**
Palaeoecological evidence for the timing and causes of lake acidification in Galloway, south west Scotland.

No. 9 **Raven, P.J. 1985**
The use of aquatic macrophytes to assess water quality changes in some Galloway Lochs: an exploratory study.

No. 10 **Anderson, N.J. & Battarbee, R.W. 1985**
Loch Fleet: bathymetry and sediment distribution.

No. 11 **Battarbee, R.W. 1985**
Diatoms and acid lakes: proceedings of a workshop.

No. 12 **Battarbee, R.W. & Renberg, I. 1985**
Royal Society Surface Water Acidification Project (SWAP) palaeolimnology programme.

No. 13 **Raven, P.J. 1986**
Occurrence of *Sphagnum* moss in the sublittoral of several Galloway lochs, with particular reference to Loch Fleet.

No. 14 **Flower, R.J., Rippey, B. & Tervet, D. 1986**
34 Galloway lakes: bathymetries, water quality and diatoms.

No. 15 **Flower, R.J. & Nicholson, A. 1986**
Bathymetries, water quality and diatoms of lochs on the island of South Uist, the Outer Hebrides, Scotland.