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Sediment accumulation in the Broads

A report to the Broads Authority

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A report to the Broads Authority

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Cover Photograph: Upton Great Broad (Ewan Shilland)

Executive summary

Sediment accumulation rate data are described for 15 cores from 11 sites in the Norfolk and Suffolk Broads. Sediment dating was determined using a combination of radiometric (^{210}Pb, ^{137}Cs) and spheroidal carbonaceous particle techniques. These approaches were combined to produce a ‘best available chronology’ for each site. However, at some sites results were still poor and the resulting data must be treated with caution.

Five cores, from different sites, showed an increase in sediment accumulation rate over the period covered by the available chronologies. Of these, accumulation rate increases varied by between 2 and 7-fold over basal rates.

Six cores showed no real change in sediment accumulation rate although for four of these reliable chronologies were only available back to the 1940s, or later. Two cores showed highly variable rates of sediment accumulation through time, precluding an assessment of change, and no cores showed a decrease in accumulation rate.

The data presented in this report, and that of some other previously published studies, would suggest that an accumulation rate in the range 0.01 – 0.04 g cm^{-2} yr^{-1} may be a reasonable estimate for an unimpacted site of this type. However, data are few and other published data suggest basal accumulation rates considerably lower than this.

Further work should include:

- A more detailed assessment of basal sediment accumulation rates from as early a period as possible in order to both confirm this rate and determine the full extent of accumulation rate increases at as many sites as possible.
- A better assessment of the scale of within-site variability to determine how representative accumulation rates from a single core are to a basin as a whole.
- A synthesis of available palaeolimnological data to identify evidence for the causes of sediment accumulation rate increases, in particular internal or external causes, and to identify gaps in knowledge.
- An assessment of the biological consequences of sediment accumulation rate increases and in particular the implications of lake shallowing on macrophyte loss and establishment.

Contents

Introduction

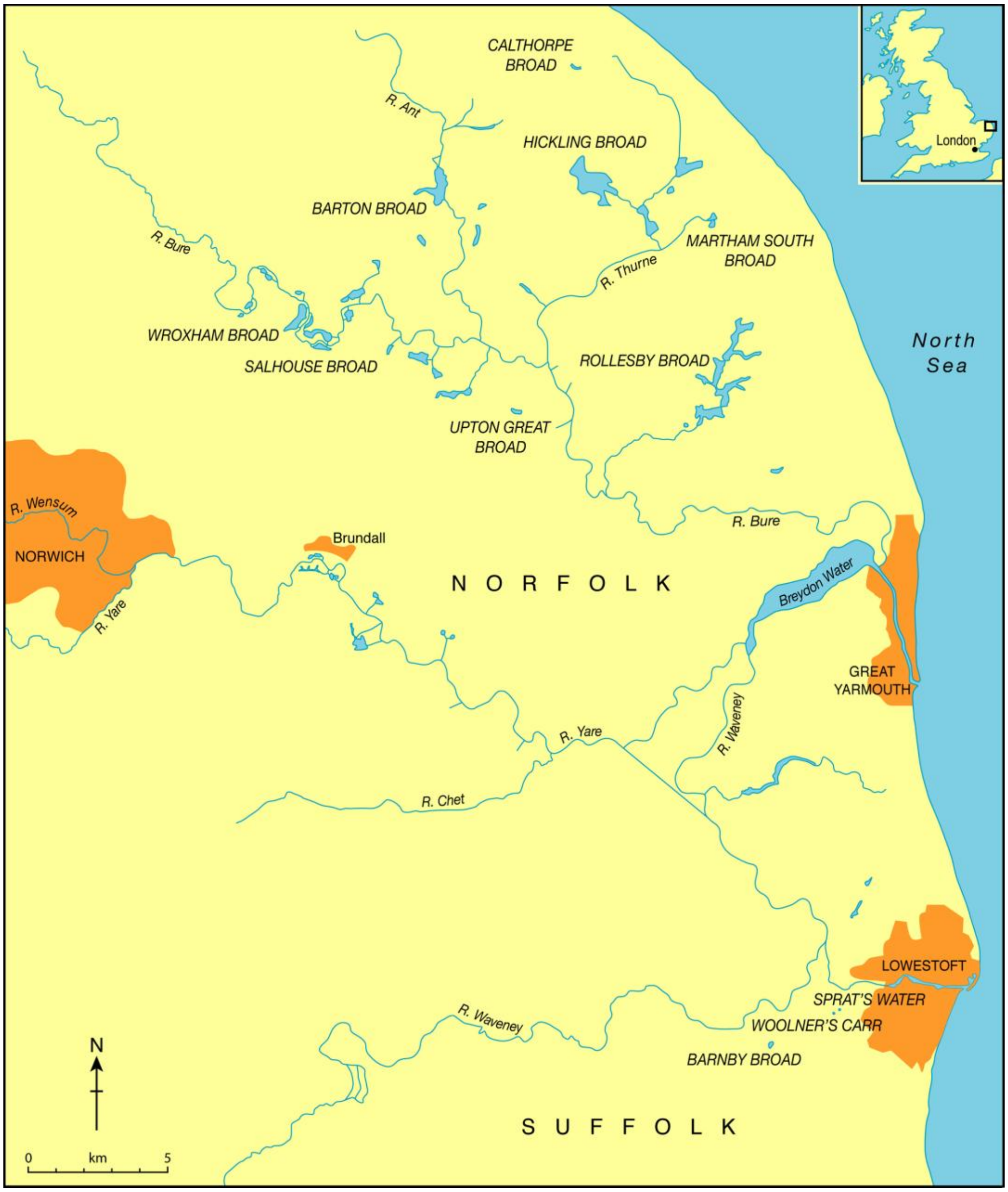
This report summarises the sediment accumulation rate data produced as result of a number of research projects undertaken by the Environmental Change Research Centre (ECRC), University College London, in the Norfolk and Suffolk Broads between 1995 and 2004.

Data are presented on 11 sites: Barnby Broad, Barton Broad, Calthorpe Broad, Hickling Broad, Martham Broad, Rollesby Broad, Salhouse Broad, Sprat's Water, Upton Great Broad, Woolner's Carr and Wroxham Broad. Locations of these are given in Figure 1. As this report represents an amalgamation of data generated as a result of a variety of research projects, the distribution of sites and data included here is totally serendipitous.

Sediment core chronologies are mainly based on radiometric measurements undertaken at the Environmental Radioactivity Research Centre, University of Liverpool by Prof. Peter Appleby, supplemented by spheroidal carbonaceous particle (SCP) analyses undertaken by Neil Rose at the ECRC. Data for each site are presented in two formats, as a rate of accumulation of sediment depth (i.e. cm yr^{-1}) and as a flux of dry material to the accumulating sediment basin from which the core was taken (g cm^{-2} yr^{-1}). Data for some of the cores included in this report have previously been published elsewhere e.g. BART1, ROLL1, WROX1 and UPTO1 (Bennion 1996; Bennion et al., 2001; 2003); HICK1 and BART9 (Hoare et al., 2004). No attempt has been made to extrapolate accumulation rates or chronologies beyond those justified by the data and therefore some of the chronologies are quite restricted and extend back only as far as the 1940s or even later. However, given the considerable variation in sediment accumulation rates observed through some of the cores, it was considered preferable only to attempt to interpret data which were known to be reasonably reliable.

Whilst the data included in this report is a summary of that compiled by the ECRC since 1995, earlier studies on sediment accumulation in the Broads have been undertaken. Osborne & Moss (1977) and Moss (1980) provided sediment accumulation rate estimates for Barton Broad, Moss (1979) shows data for Strumpshaw Broad and Moss et al. (1979), data for Alderfen Broad and Upton Broad. Whilst these studies provide some useful comparisons for the data presented in this report they also estimate rates back over hundreds of years to the origin of the Broads. However, at best, such an approach can only provide the broadest indication of mean sediment accumulation rates over these long periods and no information can be gained about variability in sedimentation rates. These data are considered further under the relevant sites and in the discussion sections.

Figure 1. Map of sites considered in this report.



Methods

Coring and sample treatment

All cores, except that from Salhouse Broad, were taken using a wide-diameter Livingstone corer. The core from Salhouse Broad was taken using a 14 cm diameter 'Goldsmith' piston corer. Both are operated from a raft supported by two inflatable boats. Table 1 shows the collection date for the sediment cores discussed in this report along with the most accurate estimate of sampling location.

Data are available for three cores from Barton Broad (1995, 1999 and 2001) whilst two cores have been taken from both Upton Great Broad (1995 and 2004) and Wroxham Broad (1995 and 2000). Most cores were taken from central areas of the Broads basins except the latter Upton Broad core (UPTO 3) and the two latter Barton Broad cores (BART 5 and BART 9) which were taken at 'near-shore' locations.

Most of the cores were taken prior to any dredging or mud-pumping activities at the sites. The exception to this was Barnby Broad where the south-western half of the Broad was mud-pumped in 1990. However, the cores discussed in this report were taken at locations as far away from dredged areas as possible in the northern end of the lake. The disturbance generated by such activities would preclude any meaningful data being generated from the sediment cores, but there is no evidence for such disturbance in the Barnby Broad data.

All cores were extruded vertically in 0.5cm or 1 cm interval slices and stored in plastic bags prior to lithostratigraphic (water and organic content, wet density) and all subsequent measurements.

Sediment chronologies from radiometric measurements

Radiometric dates were obtained for the sediment cores by measuring ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by gamma spectrometry using well-type, coaxial, low background, intrinsic germanium detectors fitted with NaI(Tl) escape suppression shields (Appleby et al. 1986). ^{210}Pb is a naturally occurring radionuclide of half-life 22.26 years. Measurements of the down-core decline in ^{210}Pb activity in excess of the supporting ^{226}Ra are used to determine a chronology for the past 100-150 years. ^{137}Cs and ^{241}Am are artificial radionuclides first

Table 1. Dates and locations for the sediment cores discussed in this report. (Note: 5-figure grid references represent GPS-derived locations). All cores are from 'central' areas of the basin except where stated.

Site	Core code	Core date	Core location
Barnby Broad	BARB 4	2003	TM 47999 90652
Barton Broad	BART 1	1995	TG 363 215
	BART 5 (near-shore)	1999	TG 356 214
	BART 9 (near-shore)	2001	TG 356 214
Calthorpe Broad	CALT 1	2003	TG 410 258
Hickling Broad	HICK 1	2002	TG 418 210
Martham South Broad	MART 1	1995	TG 458 201
Rollesby Broad	ROLL1	1995	TG 461 146
Salhouse Broad	SALG 1	2003	TG 317 157
Sprat's Water	SPRA 1	2003	TM 50575 91782
Upton Great Broad	UPTO 1	1995	TG 389 133
	UPTO 3 (near-shore)	2004	TG 389 133
Woolner's Carr	WOOC 1	2003	TM 50330 91566
Wroxham Broad	WROX 1	1995	TG 309 165
	WROX 2	2000	TG 307 164

introduced into the environment on a global scale in 1954 by the atmospheric testing of thermo-nuclear weapons. Fallout of ^{137}Cs from this source reached a maximum value in 1963 and then declined sharply following the treaty in that year banning further atmospheric tests. Sediment records of this maximum can be used to identify the 1963 level in the core. The nuclear accident at Chernobyl in 1986 released substantial quantities of both ^{137}Cs and ^{134}Cs into the atmosphere and resulted in further wide-scale fallout. Post-1986 cores frequently contain a second ^{137}Cs peak that can be used to identify the 1986 level. Where there is doubt about the provenance of a ^{137}Cs peak, the 1963 peak may be identified by an associated ^{241}Am peak (Appleby et al. 1990; Appleby et al. 1991).

There are two principal methods for determining the initial ^{210}Pb activity of a sediment layer necessary for the calculation of its ^{210}Pb date. These are the CRS (constant rate of unsupported ^{210}Pb supply) model (Appleby and Oldfield 1978) and the CIC (constant initial ^{210}Pb concentration) model. Factors governing model choice are discussed in Appleby and Oldfield (1983; 1992). The CRS model is perhaps the most widely accepted and is based on the hypothesis that the ^{210}Pb supply to the sediments is dominated by a constant atmospheric fallout. This model is not valid where there are interruptions or changes to the ^{210}Pb supply, for example with a sediment hiatus. Where there are uncertainties about the ^{210}Pb chronology, the independently derived 1963 and 1986 fallout dates may be used to help discriminate between the two principal models. Where neither of these models are valid, best available chronologies can be determined following an assessment of all the data, using the procedures described in Appleby (2001). In some instances, the sediment record of ^{210}Pb is not always sufficiently good to provide reliable dates. In these cases a best available chronology can be constructed from, for example, the extrapolation of ^{137}Cs data or by means of an alternative dating technique such as spheroidal carbonaceous particles (SCPs).

Sediment chronologies from SCP measurements

SCP analyses followed Rose (1994) whereby sequential attack by mineral acids removes unwanted fractions of the sediment. Nitric, hydrofluoric and hydrochloric acids are used to remove organic matter, siliceous material and carbonates respectively, leaving a suspension of mainly carbonaceous material in water. A known proportion of this suspension is evaporated onto a coverslip, mounted onto a microscope slide and the SCPs counted at 400x magnification under a light microscope. SCP concentrations are produced as number of particles per gram dry mass of sediment (gDM^{-1}). Detection limits for the technique can vary from core to core (defined as the concentration resulting from counting a single SCP on the coverslip) but are typically 50 – 150 gDM^{-1}.

The SCP record in European lake sediments has been found to be consistent and reliable (there are no problems of re-mobilisation or dissolution etc.) such that one of the main uses of the SCP record has been for dating purposes (e.g. Rose *et al*., 1995). In a given region, once a reliable SCP chronology has been established (using independent dating such as varve counting or ^{210}Pb dating etc.) then the SCP profile can be used with confidence to ascribe dates to the last 150 years of the sediment record of undated sites. Traditionally, dates are attributed to the start of the SCP record, the rapid increase in SCP concentration and the SCP concentration peak. Although there are regional variations, in the UK the date of the start of the SCP record is usually given as the mid-nineteenth century as a result of developments in the Industrial Revolution whilst the start of the rapid increase in SCP concentration is usually ascribed to c.1950 due to the boom in electricity generation after the Second World War. Usually the most replicable and identifiable feature within a region is the peak in SCP concentration. It is also the feature which is most likely to vary between one region and another as the recent "post-peak" decrease is due to many factors such as implementation of air quality legislation, introduction of particle arresting equipment and trends in industrial output, fuel use and economic development. In addition to these factors, the situation may be further complicated by the trans-boundary nature of the depositing particles. For example, most lakes receive deposition from the emissions of more than one country and the combination of national air quality legislation may result in a unique depositional regime for the region. However, in the UK the situation is simpler as most deposition is from the UK and the peak in the area of the country of interest in this report is ascribed the date 1970 ± 5 years.

More recently, the technique of dating sediment cores using SCPs has been developed (Rose & Appleby, submitted) such that dates are ascribed on the basis of cumulative percentage inventories calibrated using a number of independently dated profiles from across a number of defined regions in the UK. South and central England forms one of these regions and the inventory dates are based on 15 independently dated sediment cores including several from East Anglia. Being based on inventory data these profiles are not susceptible to many of the processes which may affect SCP concentrations (e.g. in-wash events) and hence the technique is more robust than 'traditional' SCP dating which uses concentration data only. The inventory technique uses the SCP peak depth as 100% and all other percentiles are calculated relative to it. The advantage of this approach is that dates can be allocated to each 10-percentile resulting in 11 dates for each core rather than the previous three. The disadvantage is that only dates between 1850 and the peak date (here, 1970) can be allocated to a core. Errors in SCP dates ascribed in this manner are based on the variability between the 15 independently dated sediment cores from the region, and the errors from the original radiometric dating against which the SCP records were calibrated.

Results

Barnby Broad

BARB 4

Equilibrium between total ^{210}Pb activity and the supporting ^{226}Ra is still not reached at the depth of the deepest sample analysed (33 cm). Unsupported ^{210}Pb activity declines more or less exponentially with depth, though there are non-monotonic features at ~8-9 cm and ~20-21 cm suggesting episodes of accelerated sedimentation. ^{137}Cs activity has a relatively well resolved subsurface peak between 20 and 25 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Due to the incomplete determination of the ^{210}Pb record, dates calculated using the CRS model alone are unlikely to be reliable, and corrected ^{210}Pb dates were calculated using the 1963 ^{137}Cs date as reference point. The results are plotted in Figure 2, together with dates determined from the SCP record. Where they overlap, these two independent chronologies are in relatively good agreement. The SCP dates suggest a mean sedimentation rate for the pre-1960 period of 0.037 g cm^{-2} y^{-1} (0.29 cm y^{-1}), significantly less than the mean post-1960 value of 0.054 g cm^{-2} y^{-1} (0.56 cm y^{-1}), and contemporary value of ~0.074 g cm^{-2} y^{-1} (0.77 cm y^{-1}), determined from the radiometric record. A corrected chronology, also shown in Figure 2 and given in detail in Table 2, has been constructed using the radiometric dates for the post-1960 period, and the SCP determined mean sedimentation rate for the earlier period.

Barton Broad

BART 1: 1995

Low ^{210}Pb activities were recorded in BART1, and although unsupported ^{210}Pb was detectable down to c.30 cm values were scarcely above the limits of detection. There was a significant increase in ^{226}Ra values in the top 20 cm, presumably indicating a shift in recent decades to a more minerogenic sediment. BART1 does not have a well resolved peak in ^{137}Cs activity, but a steep increase in activity between 20-30 cm would appear to distinguish pre-1950 sediments from those post-dating the period of maximum fallout in the early 1960s. Traces of ^{137}Cs below 40 cm depth (pre-dating the 1954 onset of weapons test fallout) can be attributed to post-depositional transport either by mixing or diffusion through the pore waters.

Calculation of tentative ^{210}Pb dates using the CRS model was possible in spite of the very low activities. Although the dates of specific levels have very high standard errors, the mean sedimentation rate calculated for the past 40 years of 0.15 ± 0.03 g cm^{-2} y^{-1} is in relatively good agreement with the post-1963 sedimentation rate of 0.19 ± 0.03 g cm^{-2} y^{-1} (0.78 cm y^{-1}) determined from the ^{137}Cs date (Figure 3). Table 3 gives a chronology

Figure 2. Chronology of Barnby Broad core BARB4, showing the radiometric dates, SCP dates, and corrected dates based on both methods.

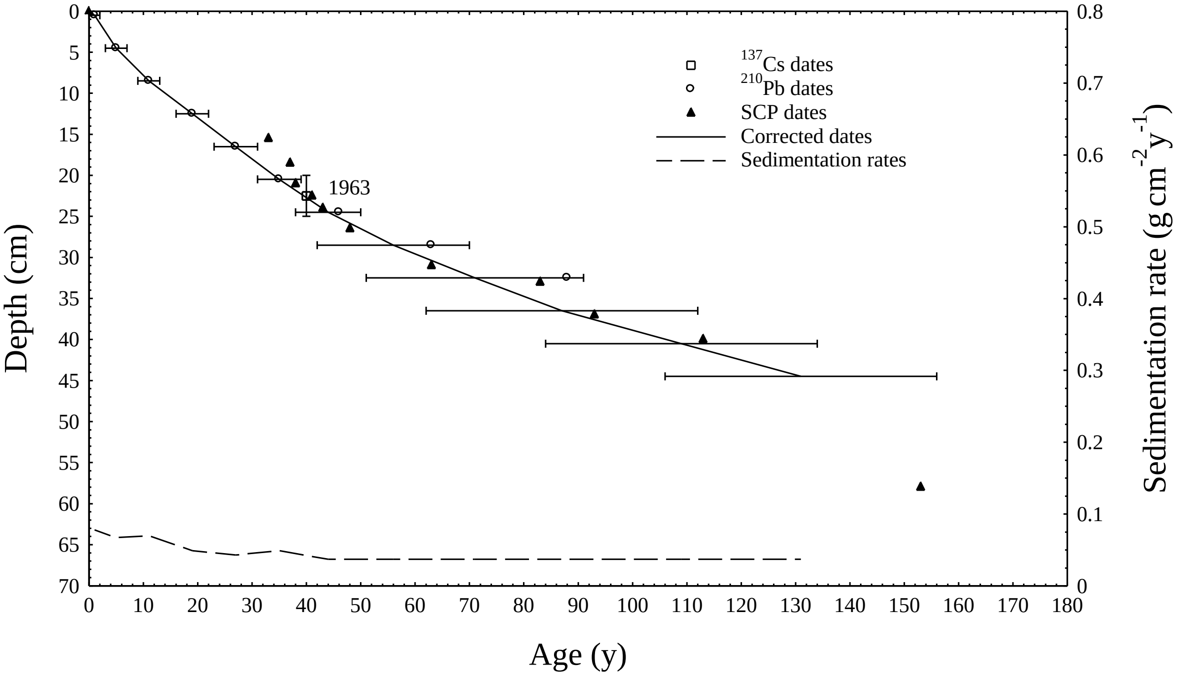


Table 2. Combined (radiometric and SCP) chronology of Barnby Broad core BARB4

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			0.0
0.5	0.04	2002	1	1	0.078	0.90	29.8
4.5	0.37	1998	5	2	0.067	0.80	24.8
8.5	0.81	1992	11	2	0.070	0.57	34.9
12.5	1.25	1984	19	3	0.049	0.50	25.9
16.5	1.63	1976	27	4	0.043	0.50	34.0
20.5	2.00	1968	35	4	0.049	0.47	42.3
24.5	2.39	1959	44	6	0.037	0.38	
28.5	2.82	1947	56	14	0.037	0.30	
32.5	3.38	1932	71	20	0.037	0.25	
36.5	3.99	1916	87	25	0.037	0.21	
40.5	4.79	1894	109	25	0.037	0.18	
44.5	5.60	1872	131	25	0.037	0.19	

for the core based on the average value from these two methods of 0.17± 0.03 g cm^{-2} y^{-1}, though in view of the very poor quality of the radionuclide records the dates must be viewed with a good deal of caution. From the relatively uniform radionuclide activities in the top 20 cm it is quite conceivable that the sediments are highly mixed and that real sedimentation rates are substantially lower than those given in Table 3.

BART 5: 1999

^{210}Pb concentrations in excess of the supporting ^{226}Ra were above limits of detection only above a depth of c.20 cm and because of the high standard errors, little significance can be attached to the unsupported ^{210}Pb concentration versus depth profile. The low mean unsupported ^{210}Pb implies a limit on the ^{210}Pb dating of not more than c.30 years. The ^{137}Cs activity has a relatively well-resolved peak at a depth of 25.5 ± 3.5 cm that can be assumed to record the maximum fallout of the radionuclide in 1963 from the atmospheric testing of nuclear weapons. Dating this core by ^{210}Pb was not possible because of the very poor record of ^{210}Pb fallout. The ^{137}Cs record implies a mean post-1963 sedimentation rate of 0.13 ± 0.04 g cm^{-2} y^{-1} (0.71 cm y^{-1}). Sediment dates calculated by applying this value to the whole core are given in Table 4, but since there is no evidence that sedimentation rates have remained constant throughout this time, dates prior to 1963 should be regarded with caution.

BART 9: 2001.

^{210}Pb concentrations in excess of the supporting ^{226}Ra were above limits of detection down to a depth of between 25-35 cm. Unsupported ^{210}Pb concentrations were however very low and the mean ^{210}Pb supply rate was only around 50% of the estimated atmospheric flux. However, the ^{137}Cs activity has a relatively well-resolved peak at a depth of 30.5 ± 4.5 cm indicating the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Figure 4 compares ^{210}Pb dates calculated using the CRS model with the 1963 date determined from the ^{137}Cs record. Use of the CIC model was precluded by the non-monotonic variation in unsupported ^{210}Pb activity. The initial ^{210}Pb results place 1963 at a depth of 20.5 cm, significantly above the depth of the ^{137}Cs peak. The discrepancy is almost certainly due to errors in the ^{210}Pb inventory arising from the very low

Figure 3. Radiometric chronology of Barton Broad core BART1 showing CRS model ^{210}Pb dates together with the 1963 date determined from the ^{137}Cs stratigraphy.

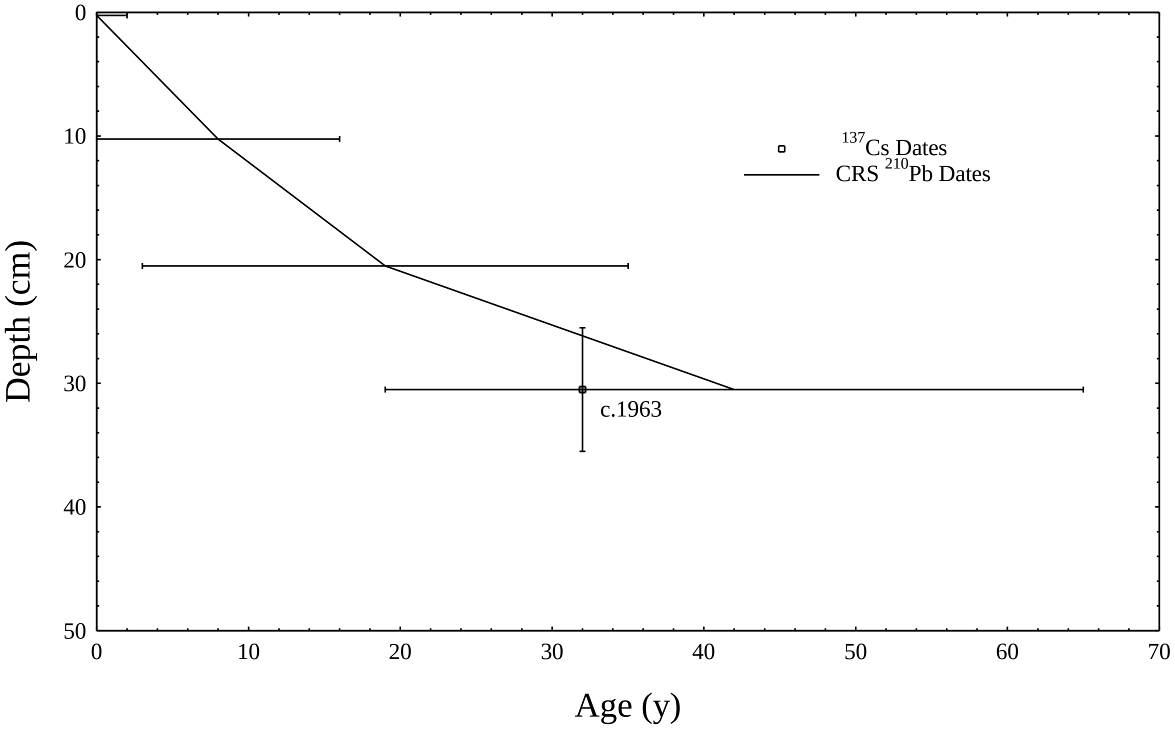


Table 3. Radiometric chronology of Barton Broad core BART 1.

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.0	1995	0				
5.0	0.8	1990	5	1	0.17	0.78	18%
10.0	1.7	1985	10	2	0.17	0.78	18%
15.0	2.8	1979	16	3	0.17	0.78	18%
20.0	3.9	1972	23	4	0.17	0.78	18%
25.0	4.9	1966	29	5	0.17	0.78	18%
30.0	6.0	1960	35	6	0.17	0.78	18%
35.0	7.3	1952	43	8	0.17	0.78	18%
40.0	8.6	1944	51	9	0.17	0.78	18%

Table 4. Radiometric chronology of Barton Broad core BART5

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	1999	0	0	0.13		27%
5.5	0.69	1994	5	1	0.13	0.93	27%
10.5	1.49	1988	11	3	0.13	0.76	27%
15.5	2.43	1981	18	5	0.13	0.65	27%
20.5	3.53	1972	27	7	0.13	0.57	27%
25.5	4.75	1963	36	10	0.13	0.54	27%
30.5	5.97	1954	45	12	0.13	0.56	27%
35.5	7.10	1945	54	15	0.13	0.60	27%
40.5	8.17	1937	62	17	0.13	0.69	27%
45.5	9.02	1931	68	19	0.13	0.76	27%
50.5	9.91	1924	75	21	0.13	0.72	27%
55.5	10.86	1917	82	23	0.13	0.70	27%
60.5	11.79	1910	89	25	0.13	0.65	27%
65.5	12.89	1901	98	27	0.13	0.63	27%
70.5	13.90	1894	105	29	0.13	0.71	27%
74.5	14.57	1889	110	30	0.13	0.71	27%

concentrations. Revised ^{210}Pb dates were calculated using the ^{137}Cs date as a reference point (Appleby 2001). The corrected results, also shown in Figure 4 and given in detail in Table 5, suggest significant fluctuations in the net rate of accumulation of sediment during the past 50 years, ranging from ~0.5 cm y^{-1} in the late 1950s and late 1970s to more the 1.3 cm y^{-1} in the late 1960s and late 1990s. However, since the validity of the CRS model is questionable, this chronology should be treated with caution.

Calthorpe Broad

CALT 1

Total ^{210}Pb activity reaches equilibrium with the supporting ^{226}Ra at a depth of about 24 cm. Unusually, unsupported ^{210}Pb activity is very low in the uppermost sample analysed (1-2 cm). This could be due to a very recent inwash event, or deposition of reworked older sediments from the margins of the lake. In the deeper sections, unsupported ^{210}Pb activity declines more or less exponentially with depth from a maximum value in the 6-7 cm section, suggesting relatively uniform sedimentation rates over most of the period of time spanned by the core. ^{137}Cs activity shows a relatively well-resolved peak between 11-17 cm that presumably records the 1963 fallout maximum.

Figure 4. Radiometric chronology of Barton Broad core BART9 showing the CRS model ^{210}Pb dates and the 1963 depth determined from the ^{137}Cs stratigraphy. Also shown are corrected CRS model dates calculated using the ^{137}Cs date as a reference point, and the sedimentation rate versus time.

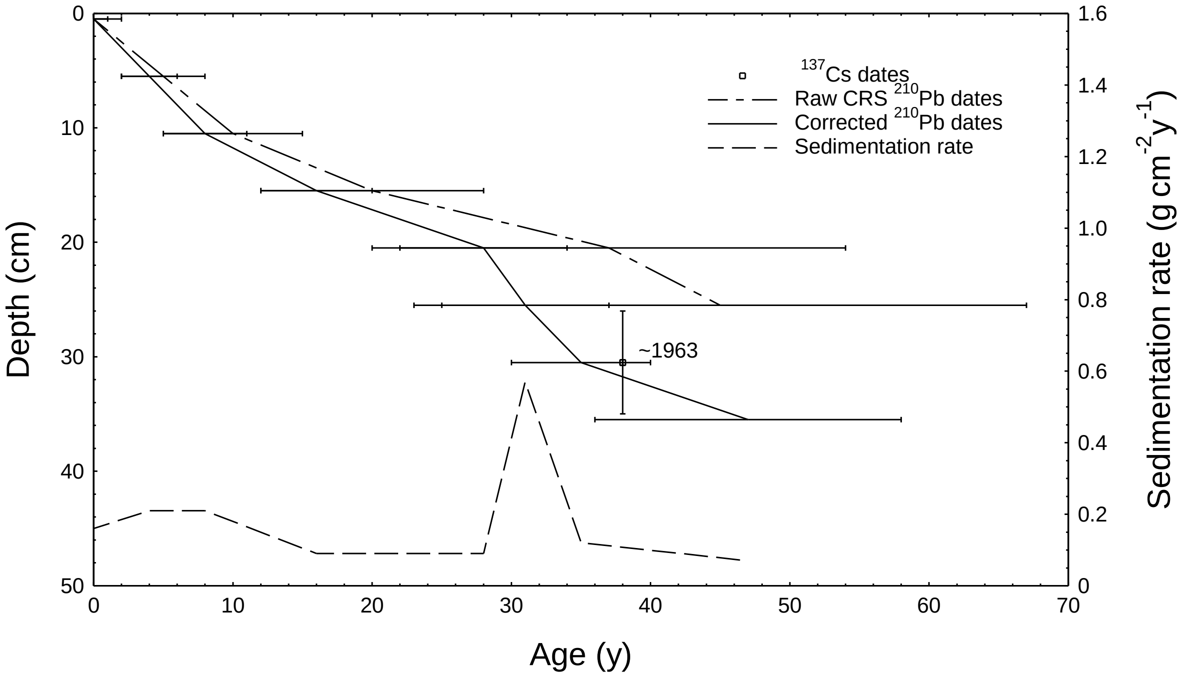


Table 5. Radiometric chronology of Barton Broad core BART9

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.0	2001	0	0			
0.5	0.0	2001	0	1	0.16	1.38	46.3
5.5	0.8	1997	4	2	0.21	1.25	62.8
10.5	1.6	1993	8	3	0.21	0.83	61.5
15.5	2.6	1985	16	4	0.09	0.50	30.7
20.5	3.6	1973	28	6	0.09	0.66	48.0
25.5	4.7	1970	31	6	0.57	1.48	28.3
30.5	5.9	1966	35	5	0.12	0.62	16.8
35.5	7.1	1954	47	11	0.07	0.40	16.8

^{210}Pb dates and sedimentation rates calculated using the CRS dating model are shown in Figure 5, together with the depth of the 1963 section determined from the ^{137}Cs stratigraphy. The dates determined by these two independent methods are in good agreement. The resulting chronology, given in detail in Table 6, suggests a relatively uniform sedimentation rates from 1931 through to 1996, with a mean value during this period of 0.017 ± 0.003 g cm^{-2} y^{-1} (0.21 cm y^{-1}). At some point since 1996 there appears to have been a brief episode of very rapid accumulation, resulting in a mean sedimentation rate over the most recent seven years of ~0.057 g cm^{-2} y^{-1} (0.93 cm y^{-1}).

Hickling Broad

HICK 1

Total ^{210}Pb activity reaches equilibrium with the supporting ^{226}Ra at a depth of around 23 cm. Unsupported ^{210}Pb activities decline relatively slowly in the top 10 cm of the core at which point there is a relatively abrupt change with a much steeper rate of decline in the deeper sediments. Within this deeper section the profile more or less follows an exponential relationship, apart from a possible non-monotonic feature near the base of the ^{210}Pb record. ^{137}Cs activity has relatively well resolved peak between 13-16 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons. This interpretation is supported by the detection of traces of ^{241}Am in the 14.5-15.5 cm sample.

Figure 6 shows ^{210}Pb dates calculated using the CRS and CIC dating models together with the 1963 depth determined from the ^{137}Cs stratigraphy. The CRS model places 1963 at a depth of 11.75 cm, significantly above the depth suggested by the ^{137}Cs record. The CIC model gives a better agreement, placing 1963 at a depth of 14 cm, though dates calculated by this model are generally more irregular. Better results, also shown in Figure 6 and given in detail in Table 7, are obtained by the CRS model using the 1963 ^{137}Cs date as a reference point (Appleby 2001). These calculations suggest that since 1950 sedimentation rates have fluctuated between 0.031 and 0.055 g cm^{-2} y^{-1}, with a mean value of 0.041 ± 0.009 g cm^{-2} y^{-1} (0.31 cm y^{-1}). They also suggest that sedimentation rates were significantly lower during the period 1920-50, though because of the low ^{210}Pb concentrations below 15 cm values from this period have large uncertainties.

Figure 5. Radiometric chronology of Calthorpe Broad core CALT1 showing the CRS model ^{210}Pb dates and sedimentation rates, together with the 1963 depth determined from the ^{137}Cs record.

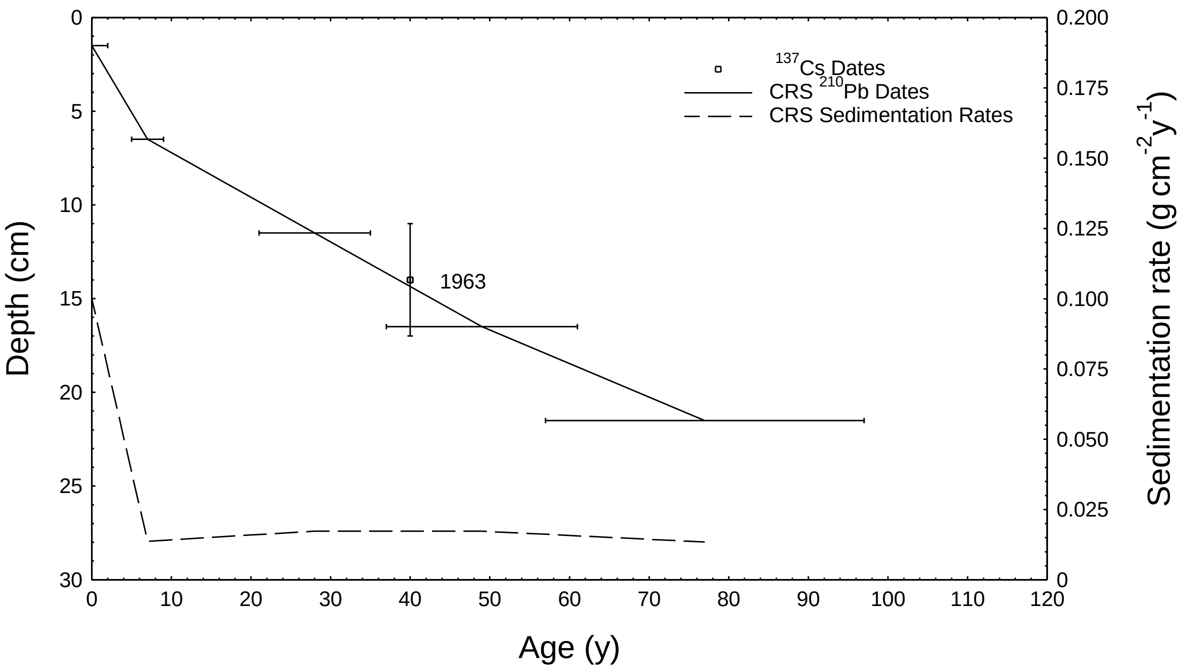


Table 6. ^{210}Pb chronology of Calthorpe Broad core CALT1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
1.5	0.1	2003	0	2	0.100	0.93	
6.5	0.4	1996	7	2	0.014	0.36	24.6
11.5	0.7	1975	28	7	0.017	0.24	24.6
16.5	1.1	1954	49	12	0.017	0.19	24.6
21.5	1.6	1921	82	20	0.014	0.15	24.6

Figure 6. Radiometric chronology of Hickling Broad (HICK1) showing the CRS and CIC model ^{210}Pb dates and the 1963 depth determined from the ^{137}Cs stratigraphy. Also shown are the corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs date as a reference level.

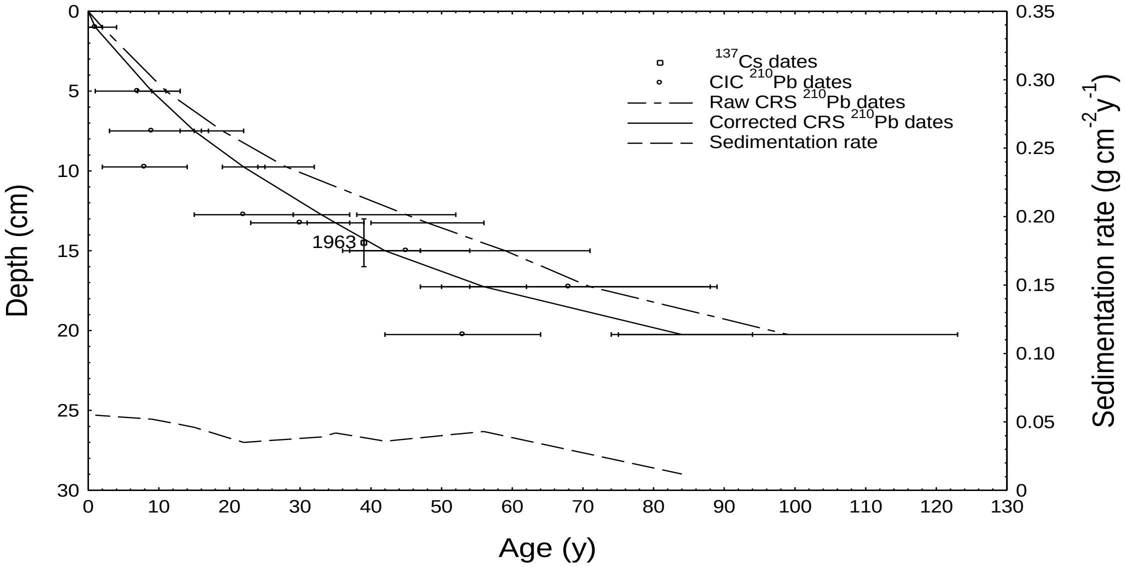


Table 7. ^{210}Pb chronology of Hickling Broad core HICK1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2002	0				
1.0	0.07	2001	1	1	0.055	0.67	11.9
2.0	0.18	1999	3	2	0.054	0.57	12.7
3.0	0.29	1997	5	2	0.053	0.50	13.4
4.0	0.40	1995	7	2	0.053	0.44	14.2
5.0	0.50	1993	9	2	0.052	0.44	14.9
6.0	0.62	1990	12	2	0.050	0.40	16.2
7.0	0.74	1988	14	2	0.047	0.36	17.4
8.0	0.86	1985	17	2	0.043	0.36	18.1
9.0	0.99	1982	20	2	0.039	0.31	18.3
10.0	1.11	1979	23	3	0.035	0.29	18.9
11.0	1.25	1975	27	3	0.037	0.29	20.5
12.0	1.38	1971	31	4	0.038	0.27	22.1
13.0	1.52	1968	34	4	0.043	0.26	23.6
14.0	1.69	1964	38	5	0.046	0.27	26.8
15.0	1.87	1960	42	9	0.037	0.21	30.8
16.0	2.06	1956	46	10	0.031	0.16	46.8
17.0	2.24	1949	54	11	0.042	0.14	62.7
18.0	2.45	1940	63	13	0.035	0.12	60.9
19.0	2.66	1931	72	15	0.025	0.11	53.3
20.0	2.88	1922	81	16	0.014	0.11	45.6

Martham South Broad

MART1

Very low unsupported ^{210}Pb activities throughout the upper 30 cm of core MART1 do not permit dating by the ^{210}Pb method. The ^{210}Pb inventory in the top 30 cm was less than 30% of the fallout record. However, the ^{137}Cs profile has a well defined maximum at 10.25 cm, which almost certainly records the 1963 weapons fallout peak. This suggests an accumulation rate of c.0.3 cm y^{-1}, which would put 1930 at c.20 cm, and 1900 at c.28 cm.

Rollesby Broad

ROLL 1

ROLL 1 appears to have a reasonably complete record of fallout ^{210}Pb. Total ^{210}Pb activity in this core declines more or less steadily with depth from a maximum value in the topmost sample, and reaches equilibrium with the supporting ^{226}Ra at c.50 cm. There is a significant increase in ^{226}Ra values in the top 20 cm, possibly indicating a shift in recent decades to a more minerogenic sediment. The core does not have a well resolved peak in ^{137}Cs activity but there is a steep increase in activity between 20-30 cm that would appear to distinguish pre-1950 sediments from those post-dating the period of maximum fallout in the early 1960s. Traces of ^{137}Cs below 40 cm depth (pre-dating the 1954 onset of weapons test fallout) can be attributed to post-depositional transport either by mixing or diffusion through the pore waters.

Although significant irregularities in the unsupported ^{210}Pb activity profile give rise to substantial discrepancies in dates obtained from the CRS and CIC models (Figure 7), the two methods give similar values for the mean sedimentation rate. Figure 7 also shows that the ^{210}Pb dates are in quite good agreement with the 1963 ^{137}Cs date. A combination of the three methods provides a mean sedimentation rate of 0.042 ± 0.008 g $cm^{-2}\,y^{-1}$ (0.51 cm y^{-1}), and this value has been used to calculate the chronology given in Table 8.

Figure 7. Radiometric chronology of Rollesby Broad core ROLL1 showing CRS model ^{210}Pb dates together with the 1963 date determined from the ^{137}Cs stratigraphy.

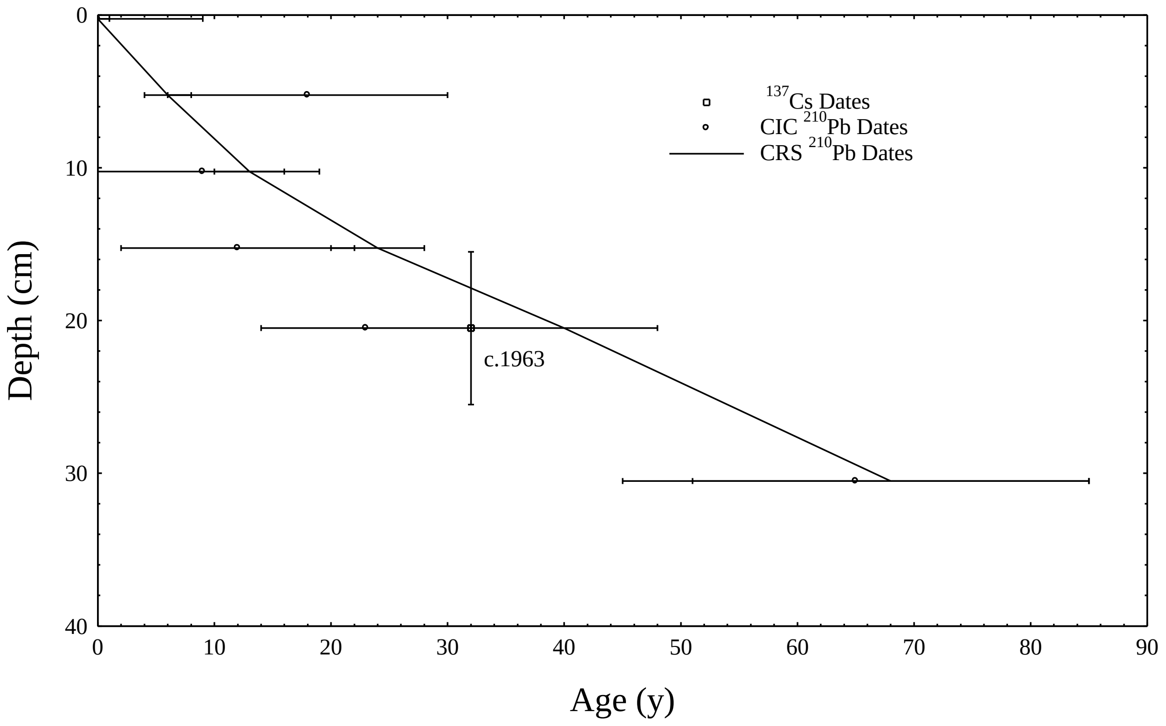


Table 8. Radiometric chronology of Rollesby Broad core (ROLL 1)

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.0	1995	0				
5.0	0.3	1987	8	1	0.042	0.51	18%
10.0	0.7	1979	16	3	0.042	0.51	18%
15.0	1.1	1970	25	5	0.042	0.51	18%
20.0	1.5	1960	35	6	0.042	0.51	18%
25.0	2.0	1949	46	8	0.042	0.51	18%
30.0	2.4	1938	57	10	0.042	0.51	18%
35.0	2.9	1927	68	12	0.042	0.51	18%
40.0	3.3	1916	79	14	0.042	0.51	18%

Salhouse Broad

SALG1

Total ^{210}Pb activity was only significantly in excess of that of the supporting ^{226}Ra in the uppermost sample. In all deeper samples, unsupported ^{210}Pb activity was either close to, or below, the limit of detection. The ^{137}Cs activity profile is a little irregular, though it does have a relatively well defined peak between 32.5 and 40.5 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Because of the poor ^{210}Pb record it was not possible to date this core by this means. The ^{137}Cs record does however show that the top 40 cm of the core only spans around 40 years. From the depth of the ^{137}Cs peak, the mean sedimentation rate during this period is calculated to be 0.28 ± 0.03 g cm^{-2} y^{-1} (0.91 cm y^{-1}) and Table 8 and Figure 9 show the radiometric chronology calculated on this basis. The surficial unsupported ^{210}Pb flux is close to that of the estimated atmospheric flux and it appears that the poor ^{210}Pb record is simply due to dilution of the atmospheric flux by very rapid sedimentation.

Sprat's Water

SPRA1

Total ^{210}Pb activity apparently reaches equilibrium with the supporting ^{226}Ra at a depth of about 25 cm, though since the maximum unsupported ^{210}Pb concentration is very low this is unlikely to span much more than around 60 years. Unsupported ^{210}Pb activity declines irregularly with depth, with a significant non-monotonic feature at around 12-13 cm. ^{137}Cs concentrations in the core are very low, though there is a relatively well defined peak at 16-17 cm that probably dates from the period of maximum fallout. Since the events diluting the ^{210}Pb activity at 12-13 cm may have also diluted the ^{137}Cs activity, the maximum value of the ^{137}Cs/^{210}Pb ratio may be a better guide to the 1963 depth. Since this occurs in the 12-13 cm sample, the best estimate of the 1963 depth is that it occurs between 12-17 cm.

Figure 9 plots ^{210}Pb dates calculated using the CRS model, together with the 1963 depth indicated by the ^{137}Cs record. The ^{210}Pb dates place 1963 at a depth of around 18 cm, a little deeper than the depth determined from the ^{137}Cs record. Figure 9 also compares the radiometric dates with those determined from the SCP record. The SCP dates

Figure 8. Radiometric chronology of Salhouse Broad core SALG1 showing the 1963 depth determined from the ^{137}Cs stratigraphy and the sediment depths versus age assuming a constant dry mass sedimentation rate

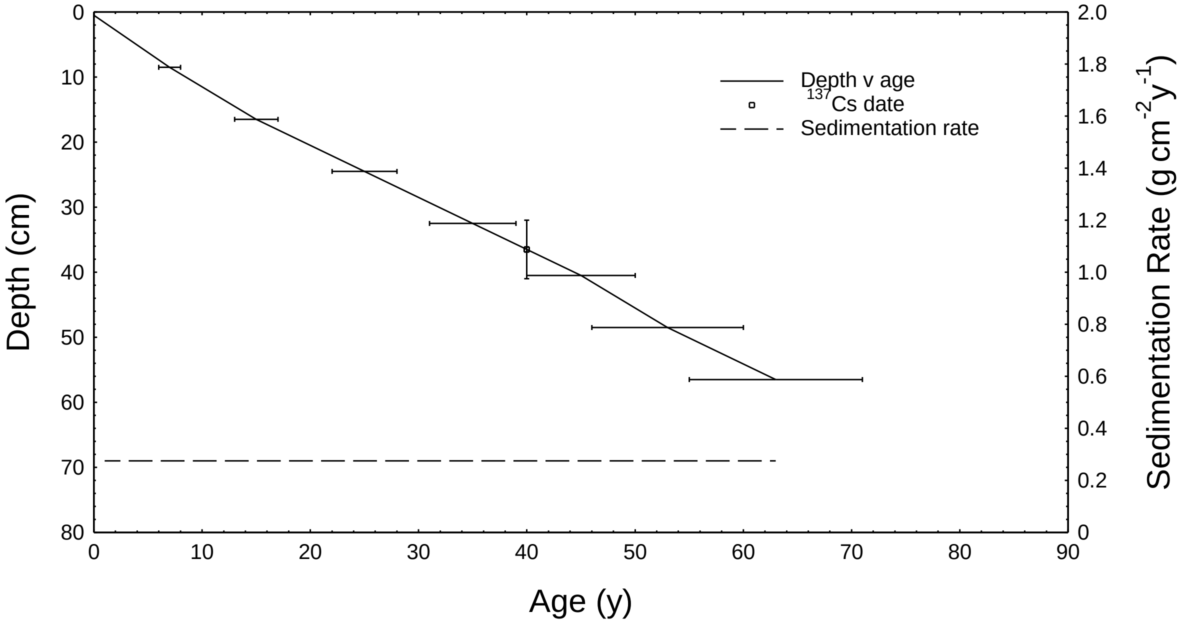


Table 9. Radiometric chronology of Salhouse Broad core SALG1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003					
0.5	0.1	2003	0	0	0.28	1.48	12.3
4.5	0.8	2000	3	0	0.28	1.26	12.3
8.5	1.8	1996	7	1	0.28	1.02	12.3
12.5	3.0	1992	11	1	0.28	0.93	12.3
16.5	4.2	1988	15	2	0.28	0.87	12.3
20.5	5.5	1983	20	2	0.28	0.79	12.3
24.5	7.0	1978	25	3	0.28	0.77	12.3
28.5	8.4	1973	30	4	0.28	0.80	12.3
32.5	9.7	1968	35	4	0.28	0.83	12.3
36.5	11.0	1963	40	5	0.28	0.86	12.3
40.5	12.3	1958	45	5	0.28	0.90	12.3
44.5	13.5	1954	49	6	0.28	0.91	12.3
48.5	14.7	1950	53	7	0.28	0.87	12.3
52.5	16.0	1945	58	7	0.28	0.82	12.3
56.5	17.4	1940	63	8	0.28	0.80	12.3

c.1963 are in quite good agreement with the radiometric dates for this period, though they do suggest a much stronger episode of accelerated sedimentation in the early 1960s. Prior to this event the SCP dates suggest a mean sedimentation rate of 0.040 g cm^{-2} y^{-1} (0.17 cm y^{-1}), significantly higher than that suggested by the ^{210}Pb results. A corrected chronology, shown in Figure 9 and given in detail in Table 10, has been constructed using the radiometric dates for the post-1970 period and the SCP results for the earlier period.

Upton Great Broad

UPTO1: 1995

This core appears to have a relatively simple ^{210}Pb profile. Sediment accumulation appears to be quite rapid, and equilibrium with the supporting ^{226}Ra is reached at a depth of more than 50 cm. Calculations using the CRS and CIC ^{210}Pb dating models both indicate a more or less uniform sedimentation rate since c.1960 of 0.060±0.010 g $cm^{-2}y^{-1}$ (0.64 cm y^{-1}), though there is some divergence in the deeper sections, possibly due to lower accumulation rates during the first few decades of this century.

There is however a significant contradiction between the ^{210}Pb and ^{137}Cs results. The ^{137}Cs measurements place the 1963 fallout peak at 10 ± 2.5 cm (Figure 10). This suggests a mean post-1963 sedimentation rate of ~0.03 g $cm^{-2}y^{-1}$, just half the ^{210}Pb value. Since there is no evidence of mixing, the most likely cause of the discrepancy is post-depositional loss from the record. The inventories of both radionuclides are significantly below values expected from direct fallout, though the losses are much greater for ^{137}Cs (~90%) than ^{210}Pb (~50%). In view of this, and the coarse resolution of ^{137}Cs peak, the ^{210}Pb dates are probably more reliable. Table 11 gives the CRS model ^{210}Pb dates which, in the light of the above discussion, should be regarded with caution. However, SCP data are in general agreement with this chronology with a start of the SCP record at c. 55cm. By extrapolation of the chronology in Table 11, this gives a date to the start of the SCP record of 1850 – 1860 which is that generally accepted for the UK (Rose et al. 1995).

Figure 9. Chronology of Sprat's Water core SPRA1, showing the radiometric dates, SCP dates, and corrected dates based on both methods.

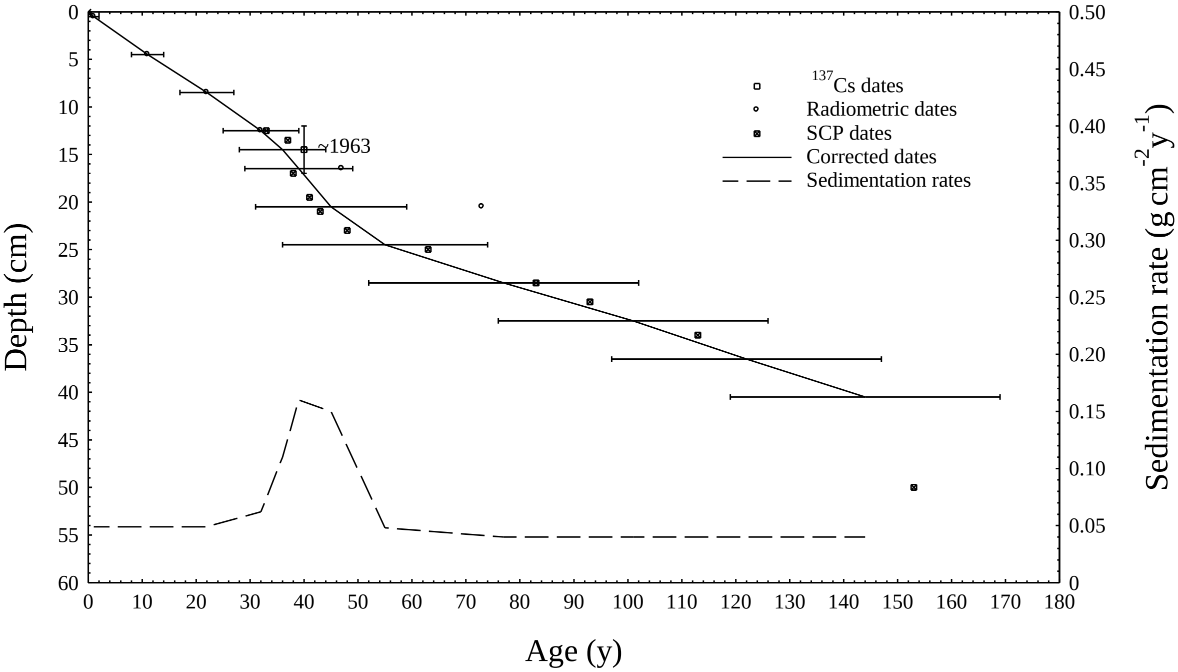


Table 10. Combined chronology of Sprat's Water core SPRA1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
0.5	0.05	2002	1	1	0.049	0.42	17.9
4.5	0.52	1992	11	3	0.049	0.39	17.9
8.5	1.06	1981	22	5	0.049	0.37	17.9
12.5	1.64	1971	32	7	0.062	0.41	17.9
14.5	1.98	1967	36	8	0.11	0.59	19.2
16.5	2.36	1964	39	10	0.16	0.71	19.2
20.5	3.22	1958	45	14	0.15	0.51	
24.5	4.20	1948	55	19	0.048	0.25	
28.5	5.16	1926	77	25	0.040	0.17	
32.5	6.12	1902	101	25	0.040	0.18	
36.5	6.96	1881	122	25	0.040	0.19	
40.5	7.84	1859	144	25	0.040	0.18	

Figure 10. Radiometric chronology of Upton Broad core UPTO1 showing CRS and CIC model ^{210}Pb dates together with the 1963 date determined from the ^{137}Cs stratigraphy. Also shown are sedimentation rates calculated using the CRS model.

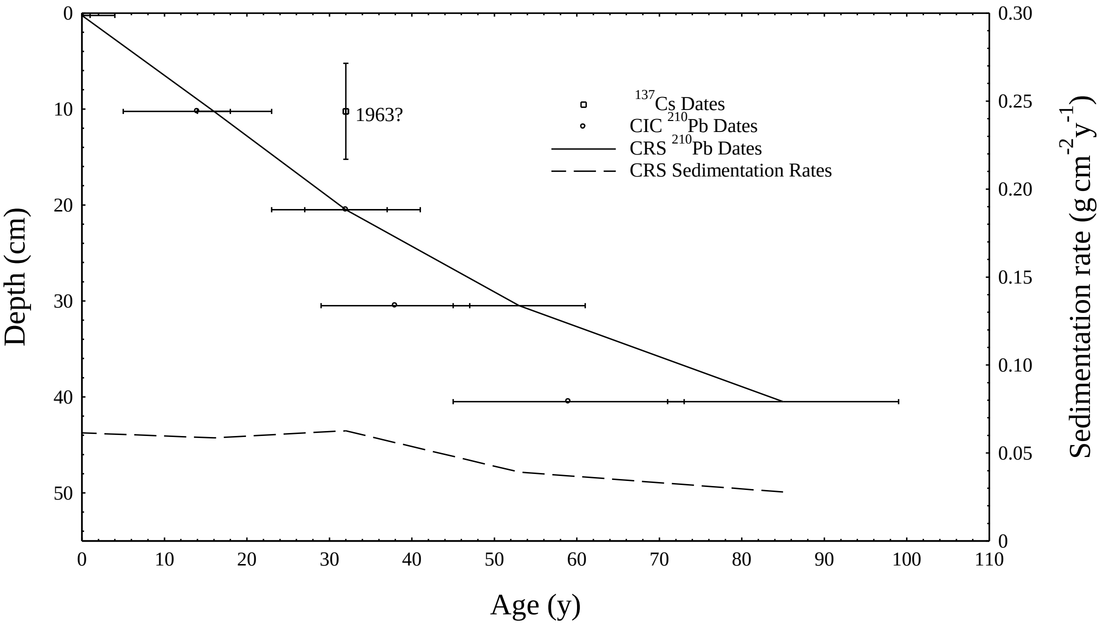


Table 11. Radiometric chronology of Upton Broad core UPTO 1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0	0.00	1995	0				
5	0.47	1987	8	3	0.060	0.64	19.1
10	0.94	1979	16	3	0.059	0.63	26.6
15	1.41	1972	23	4	0.061	0.63	27.8
20	1.87	1964	31	5	0.062	0.63	28.7
25	2.40	1954	41	6	0.052	0.51	30.9
30	2.93	1943	52	7	0.040	0.38	33.2
35	3.47	1928	67	10	0.034	0.31	36.7
40	4.00	1912	83	14	0.028	0.25	40.3

UPTO 3: 2004

In all of the samples analysed, total ^{210}Pb activity was significantly greater than that of the supporting ^{226}Ra. Since there is relatively little net decline down to a depth of 30 cm, and only a small net decline from this depth down to the base of the radiometric record at 43 cm, it appears that all analysed sediments are relatively modern. Similarly, the ^{137}Cs activity profile does not show a clear record of atmospheric fallout. Concentrations vary irregularly with depth, without a well-resolved peak to identify the 1963 fallout maximum. The relatively high concentrations suggest that the entire record post-dates the 1963 fallout peak.

In spite of the incomplete nature of the record, ^{210}Pb dates calculated using the CRS dating model place the early 1960s at around 35 cm, supporting the hypothesis that the core (down to around 40 cm) spans not more than a few decades. Use of the CIC model was precluded by the irregular nature of the ^{210}Pb record. Assuming that sediments from the 42-43 cm section date from the period 1964-72, ^{210}Pb dates were recalculated using this as a reference level. The resulting chronology, shown in Figure 11 and given in detail in Table 12, suggests a relatively uniform sedimentation rate over the past 30 years of 0.091 ± 0.02 g cm^{-2} y^{-1} (1.2 cm y^{-1}) apart from a brief episode of more rapid accumulation in the late 1960s or early 1970s.

Woolner's Carr

WOOC1

Equilibrium between total ^{210}Pb activity and the supporting ^{226}Ra is still not reached at the deepest sample analysed (45 cm) whilst the ^{137}Cs activity profile has a well-resolved peak at 40 - 41 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Due to the incomplete determination of the ^{210}Pb record, dates calculated using the CRS model alone are unlikely to be reliable, and corrected ^{210}Pb dates were calculated using the 1963 ^{137}Cs date as reference point. The results are plotted in Figure 12, together with dates determined from the SCP record. Where they overlap, these two independent chronologies are in relatively good agreement. A corrected chronology, also shown in Figure 12 and given in detail in Table 13, has been constructed using mainly the radiometric dates for the post-1960 period, and the SCP dates for the earlier

Figure 11. Radiometric chronology of Upton Great Broad core UPTO3 showing the raw CRS model ^{210}Pb dates, the late 1960s depth determined from the ^{137}Cs stratigraphy, and the corrected ^{210}Pb dates and sedimentation rates.

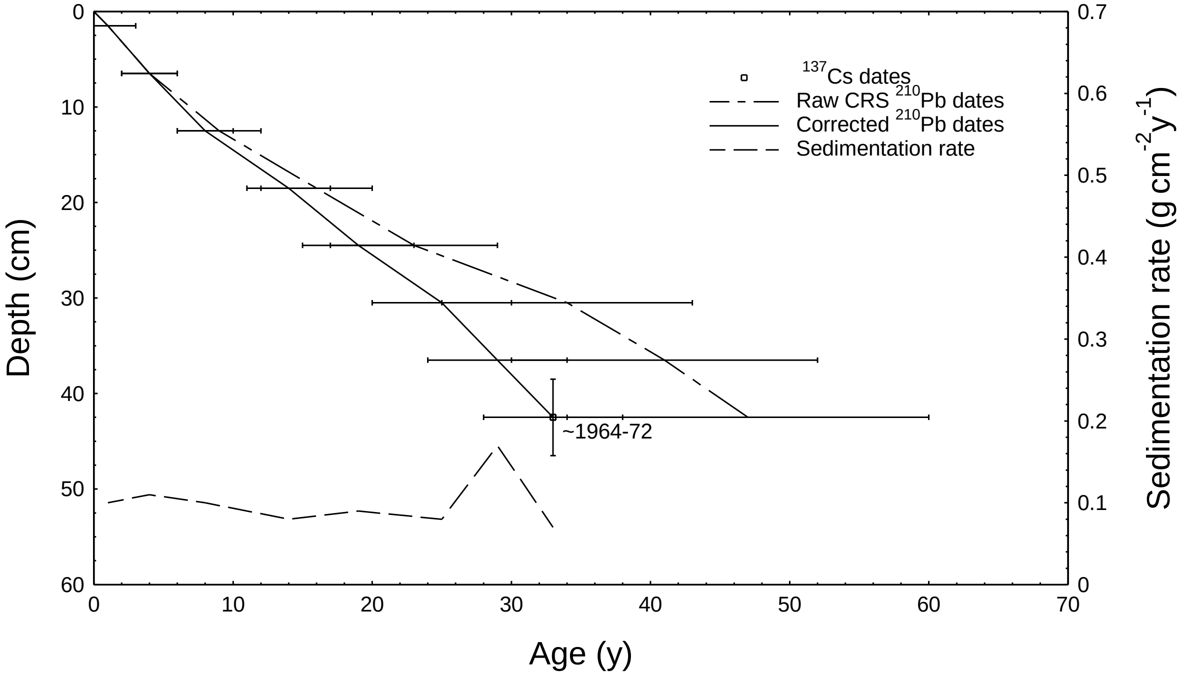


Table 12. ^{210}Pb chronology of Upton Great Broad core UPTO3

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2004	0	0			
1.5	0.08	2000	1	1	0.10	1.64	16.8
6.5	0.41	1997	4	2	0.11	1.46	16.8
12.5	0.86	1993	8	2	0.10	1.24	16.8
18.5	1.32	1987	14	3	0.08	1.13	16.8
24.5	1.76	1982	19	4	0.09	1.03	16.8
30.5	2.28	1976	25	5	0.08	1.16	25.4
36.5	2.77	1972	29	5	0.17	1.50	20.7
42.5	3.25	1968	33	5	0.07	1.49	16.8

Figure 12. Chronology of Woolner's Carr core WOOC1, showing the radiometric dates, SCP dates, and corrected dates based on both methods.

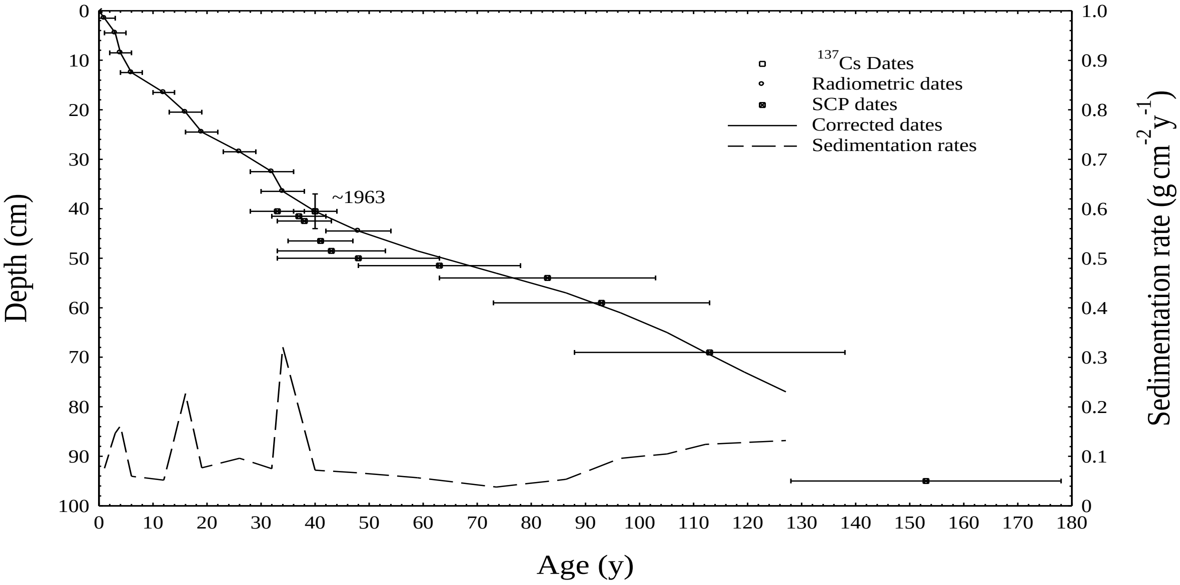


Table 13. Combined chronology of Woolner's Carr core WOOC1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
1.5	0.07	2002	1	2	0.076	1.50	26.1
4.5	0.24	2000	3	2	0.15	2.33	38.1
8.5	0.45	1999	4	2	0.16	2.67	53.0
12.5	0.74	1997	6	2	0.060	1.00	19.1
16.5	1.07	1991	12	2	0.052	0.80	19.7
20.5	1.47	1987	16	3	0.23	1.14	79.9
24.5	1.92	1984	19	3	0.077	0.80	30.3
28.5	2.45	1977	26	3	0.096	0.62	33.7
32.5	2.99	1971	32	4	0.075	1.00	37.6
36.5	3.53	1969	34	4	0.32	1.00	24.9
40.5	4.21	1963	40	4	0.072	0.57	44.2
44.5	4.80	1955	48	6	0.067	0.42	46.4
48.5	5.48	1944	59	10	0.057	0.33	
53.0	6.18	1930	73	17	0.038	0.31	
57.0	6.77	1917	86	20	0.054	0.35	
61.0	7.54	1906	97	20	0.096	0.43	
65.0	8.40	1898	105	22	0.11	0.51	
69.0	9.22	1891	112	25	0.12	0.56	
73.0	10.11	1884	119		0.13	0.54	
77.0	11.12	1876	127		0.13	0.53	
81.0	12.12	1869	134		0.14		

period. The results suggest a baseline sedimentation rate of ~0.065 g cm^{-2} y^{-1}, with brief episodes of rapid sedimentation c.2000, c.1987 and c.1969. The SCP results also suggest higher sedimentation rates in the late-19th century and early-20th century and possibly episodic in nature.

Wroxham Broad

WROX1: 1995

^{210}Pb activities in the Wroxham Broad core WROX1 are low and this can be attributed to dilution resulting from higher dry mass accumulation rates. However, there is a well resolved ^{137}Cs peak at a depth of 40.5 cm that records the 1963 weapons test fallout maximum.

Because of the highly non-monotonic unsupported ^{210}Pb profile only the CRS ^{210}Pb dating model could be applied to this core. Even so, calculations using the ^{210}Pb data alone give dates that are clearly too old when compared with the ^{137}Cs date, presumably due to the low activities and consequent difficulty in assessing the full core inventory. From the well-defined 1963 ^{137}Cs date, the mean sediment accumulation rate for the past 30 years is calculated to be 0.37 ± 0.05 g cm^{-2} y^{-1} (1.3 cm y^{-1}). Since CRS model ^{210}Pb dates calculated using the ^{137}Cs date as a reference level (Figure 13) suggest a more or less uniform accumulation rate throughout this period, the above value has been used to calculate the core chronology given in Table 14.

WROX 2: 2000

^{210}Pb activity significantly in excess of the supporting ^{226}Ra was detected only in the surficial sample. Consequently, it was not possible to date this core by ^{210}Pb using conventional methods. The measured unsupported ^{210}Pb inventory was only 20% of the estimated atmospheric flux. The ^{137}Cs profile has a sub-surface peak between 20-30 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons and the best estimate of the 1963 depth is 27 ± 4 cm. From this ^{137}Cs date, the mean post-1963 sedimentation rate is calculated to be 0.26 ± 0.04 g cm^{-2} y^{-1} (0.73 cm y^{-1}), lower than the value of 0.37 ± 0.05 g cm^{-2} y^{-1} (1.3 cm y^{-1}) determined for the earlier WROX 1 core.

Figure 13. Radiometric chronology of Wroxham Broad core WROX1 showing CRS model ^{210}Pb dates together with the 1963 date determined from the ^{137}Cs stratigraphy.

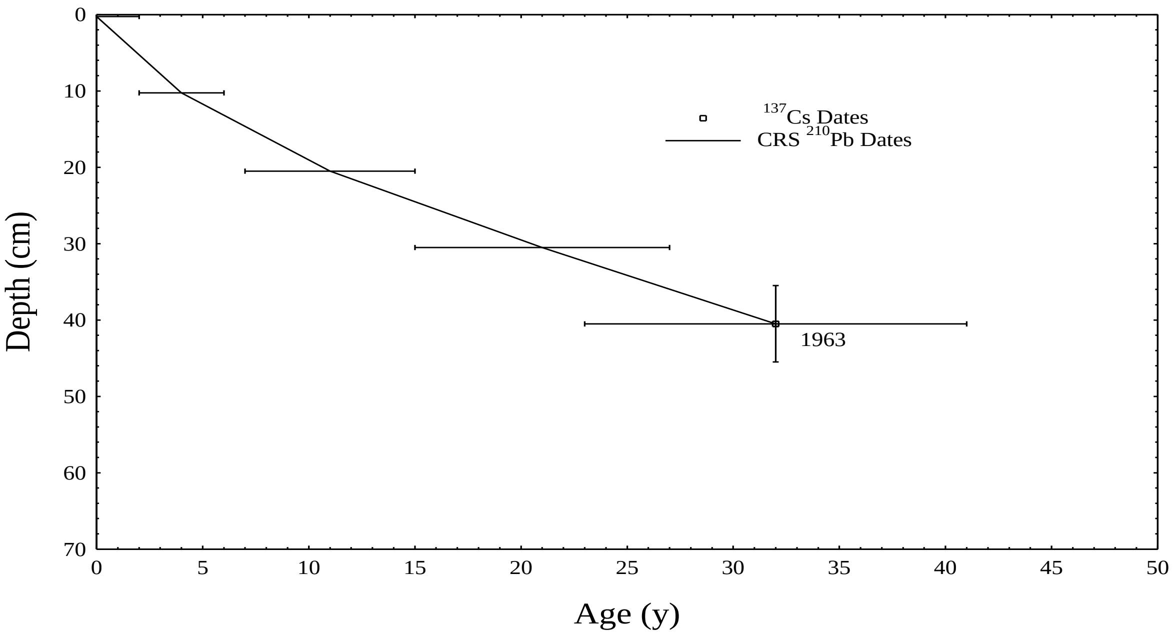


Table 14. Radiometric chronology of Wroxham Broad core (WROX1)

Depth		Chronology			Sedimentation Rate		
cm	$\mathrm{g\ cm^{-2}}$	Date AD	Age y	±	$\mathrm{g\ cm^{-2}\ y^{-1}}$	$\mathrm{cm\ y^{-1}}$	± (%)
0.0	0.0	1995	0				
5.0	1.2	1992	3	1	0.37	1.3	13%
10.0	2.5	1988	7	2	0.37	1.3	13%
15.0	4.1	1984	11	2	0.37	1.3	13%
20.0	5.8	1979	16	3	0.37	1.3	13%
25.0	7.4	1975	20	3	0.37	1.3	13%
30.0	9.0	1971	24	4	0.37	1.3	13%
35.0	10.4	1967	28	4	0.37	1.3	13%
40.0	11.7	1963	32	5	0.37	1.3	13%
45.0	13.0	1960	35	5	0.37	1.3	13%
50.0	14.4	1956	39	6	0.37	1.3	13%
55.0	15.8	1952	43	6	0.37	1.3	13%
60.0	17.3	1948	47	7	0.37	1.3	13%

Using the estimated atmospheric ^{210}Pb flux the surficial ^{210}Pb concentration can be used to estimate the contemporary sedimentation rate. This produces a value of 0.30 ± 0.07 g cm^{-2} y^{-1}, which is in good agreement with the value determined from the ^{137}Cs record. Therefore, it is reasonable to suppose that sedimentation rates at the core site have remained relatively constant throughout the past 40 years or so. Table 14 gives a chronology for this period based on this assumption.

Table 15. ^{210}Pb chronology of Wroxham Broad core WROX2

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.0	2000	0	0			
10.0	3.3	1987	13	3	0.26	0.8	15.4
15.0	5.2	1980	20	4	0.26	0.7	15.4
20.0	7.1	1973	27	5	0.26	0.7	15.4
25.0	9.0	1965	35	6	0.26	0.7	15.4
30.0	10.7	1959	41	7	0.26	0.8	15.4
35.0	12.2	1953	47	8	0.26	0.8	15.4
40.0	13.8	1947	53	9	0.26	0.8	15.4

Discussion

Limitations of the data

Where there are few or no problems with radiometric dating, the half-life of ^{210}Pb allows that a sediment chronology covering c.150 years can be reliably produced. This has led to wide-spread use of this technique for dating lake sediments as this time-span covers most of the post-Industrial period, a time when great changes have occurred both in the freshwater environment and in atmospheric deposition. Therefore it is interesting to note that of the 15 sediment cores described in this report, from 11 different Broads, only one has a chronology which reaches the mid-19th century (1859 – SPRA1). Indeed, only three reach the 19th century at all, whilst six have an earliest available date of 1940 or later. The chronologies from these sites are thus less than ideal, the time period covered is shorter than might be expected and the analysis of changes in sediment accumulation rates at the sites is similarly restricted.

Where the use of ^{210}Pb is precluded, for whatever reason, the use of the ^{137}Cs record often allows an indication of the depth at which 1963 occurred. However, whilst this is useful in determining an approximate duration covered by the core, any chronologies based upon it necessarily assume a constant sediment accumulation rate (e.g. MART 1; SALG 1, BART 5) and therefore cannot be used to assess changes in that rate. They are thus of limited use for this report but can provide a rough estimate of contemporary accumulation rates and hence have been retained.

As a result of these problems the chronologies in this report are the ‘best available’ and some have caveats associated with them that they should be ‘treated with caution’. However, whilst this is not ideal, this problem is not restricted to the Broads and many shallow, eutrophic lakes across the UK also have similar poor dating records. To help overcome this, the use of several independent dating approaches can allow additional confidence in final chronologies. Therefore, where possible, use of ^{210}Pb, ^{137}Cs and SCP techniques has been made and this combination of radiometric and SCP methods often allows a longer chronology to be constructed especially where the ^{210}Pb record is curtailed. Where this approach has been used in these Broads cores, the independent SCP and radiometric chronologies have proved to show reasonable agreement and hence the chronologies and sediment accumulation rate data produced are considered reasonably robust and reliable back to the mid-19th century. However, extrapolating chronologies back beyond dates justified by reliable data should be resisted as it is impossible to assess the variability of sediment accumulation rates prior to reliable measurements. Extrapolation of accumulation rates has been undertaken elsewhere in order to estimate mean rates over long periods (e.g. Osborne and Moss 1977; Moss 1979) but unless treated appropriately such estimates can lead to undue reliance being placed on essentially very doubtful chronologies.

General trends

Contemporary accumulation rates

Having compiled the best possible chronologies for these 15 cores, the sediment accumulation rate data can be compared. The cores cover the period 1995 (BART 1; ROLL 1; UPTO1; WROX 1) to 2004 (UPTO3) and therefore any comparison of ‘contemporary’ rates must take this into consideration. The range of sediment accumulation rates in these surface sediments is 0.042 (ROLL 1; 1995) to 0.37 (WROX 1; 1995) g cm^{-2} yr^{-1} or 0.3 (MART 1; 1995) to 1.64 (UPTO3; 2004) cm yr^{-1} and is thus highly variable across the sites.

Historical accumulation rates

The Water Framework Directive (WFD) aims to assess the structure and function of aquatic ecosystems in the absence of human-induced stress, relating various parameters to a 'reference condition' i.e. the ecological condition for that parameter at undisturbed or minimally disturbed sites for a range of lake types. Contemporary levels can then be assessed with respect to this reference condition with a view to their management and restoration back to that reference target. In the absence of undisturbed reference sites, palaeolimnological data can be used to determine these parameters, at the site-specific level, for a time when the lakes were either undisturbed or considerably less impacted than today. Hence palaeolimnological data are widely applicable to WFD aims. Whilst sediment accumulation rate is not one of the specified parameters in the WFD, it is fundamental to the functioning and development of lakes and an acceleration in accumulation rate could ultimately threaten the existence of shallow lakes as water bodies. In this context, it is therefore of interest to assess the evidence for a 'reference condition' for sediment accumulation rate in the Broads.

The varying age of the oldest available data for the cores described in this report (1859 – 1968) makes comparison difficult. However, it is interesting to note that the two oldest data available (SPRA 1- 1859; BARB 4 - 1872) give similar rates of 0.04 and 0.037 g cm^{-2} yr^{-1} or 0.18 and 0.19 cm yr^{-1} respectively. Other basal data from 1910s and 1920s also provide rates of this order, for example, UPTO 1 (1912) 0.028 g cm^{-2} yr^{-1} or 0.25 cm yr^{-1}; CALT 1 (1921) 0.014 g cm^{-2} yr^{-1} or 0.15 cm yr^{-1}; HICK 1 (1922) 0.014 g cm^{-2} yr^{-1} or 0.11 cm yr^{-1} and these data therefore suggest that an accumulation rate in the range 0.01 – 0.04 g cm^{-2} yr^{-1} or 0.1 – 0.25 cm yr^{-1} (1 – 2.5 mm yr^{-1}) may be a typical rate for an unimpacted lake of this type. Such rates are of the same order as those estimated elsewhere for pre-1800 at Barton Broad (1.2 – 3.1 mm yr^{-1}; Osborne and Moss 1977) and Strumpshaw Broad (1.2 mm yr^{-1}; Moss 1979).

However, other estimates for pre-1800 values for Alderfen Broad (0.55 mm yr^{-1}; Moss et al. 1979), Upton Broad (0.7 mm yr^{-1}; Moss et al., 1979) and Barton Broad are considerably lower (0.001 – 0.24 g cm^{-2} yr^{-1} or 0.14 – 0.58 mm yr^{-1}; Moss 1980; Moss et al. 1996). Therefore, there remains uncertainty in these basal rate estimates and they should be treated with a suitable degree of caution. More data from older sediments at other sites are required to ascertain whether a ‘typical’ accumulation rate exists for this lake type under natural conditions, or whether this large range in accumulation rate both between and within sites is itself ‘typical’.

Accumulation rate changes

Compared with the older basal sediment accumulation rate data described above, sites where the oldest available dates are more modern, for example, BART 1 (1944), BART 9 (1954), SALG 1 (1940), WROX 1 (1948) and WROX 2 (1947), have higher rates of accumulation 0.07 – 0.37 g cm^{-2} yr^{-1} or 0.4 – 1.3 cm yr^{-1}. These data would seem to imply that sediment accumulation rates in the Broads are increasing and in general site specific data would seem to support this.

[Note: in these comparisons, cm yr^{-1} data are not used as they will decrease naturally with depth as a result of sediment compaction].

Barnby Broad: Sediment accumulation rates in BARB 4 increase from 0.037 g cm^{-2} yr^{-1} in 1872 to 0.078 g cm^{-2} yr^{-1} in 2003, a two-fold increase.

Barton Broad: Sediment accumulation rates in BART 1 appear to be constant between 1944 and 1995 (0.17 g cm^{-2} yr^{-1}) but BART 9 exhibits a two-fold increase from 0.07 g cm^{-2} yr^{-1} to 0.16 g cm^{-2} yr^{-1} between 1954 and 2001. The reliable post-1963 data for BART5 give an accumulation rate of 0.13 g cm^{-2} yr^{-1}. ‘Contemporary’ rates for these cores therefore seem to be reasonably consistent i.e. 0.13 to 0.17 g cm^{-2} yr^{-1} (although considerable variation exists within the BART 9 core itself). However, Moss (1980) and Moss et al. (1996) show much higher variability in 1970s accumulation rates across Barton Broad with values ranging from 0.057 to 0.27 g cm^{-2} yr^{-1}. These values are reported to represent an increase in accumulation of between 7 and 90 times over pre-1800 values (Moss 1980).

Calthorpe Broad: Sediment accumulation rates in CALT 1 increase 7-fold (0.014 g cm^{-2} yr^{-1} to 0.1 g cm^{-2} yr^{-1}) over the period 1921 to 2003, but this seems due to a recent rapid increase

Hickling Broad: Sediment accumulation rates in HICK 1 increase 4-fold (0.014 g cm^{-2} yr^{-1} to 0.055 g cm^{-2} yr^{-1}) over the period 1922 to 2002.

Rollesby Broad: Sediment accumulation rates in ROLL 1 appear to be reasonably constant between 1916 and 1995.

Salhouse Broad: Sediment accumulation rates in SALG 1 appear to be constant between 1940 and 2003, but this is due to the dating being based on the ^{137}Cs peak.

Sprats Water: Sediment accumulation rates at the surface (2003) of and base of the chronology (1859) for SPRA 1 are similar 0.049 and 0.04 g cm^{-2} yr^{-1} respectively but there is a period of rapid accumulation in the 1960s.

Upton Great Broad: Sediment accumulation rates in the central core UPTO 1 increase from 0.028 g cm^{-2} yr^{-1} in 1912 to 0.06 g cm^{-2} yr^{-1} in 1995, a two-fold increase, whilst the near-shore core UPTO3 (2004) has similar accumulation rates over the 30 years that are dateable. Moss et al. (1979) also report a near doubling of accumulation rate between 1935 and the 1970s in a centrally located core from Upton Broad.

Woolner's Carr: Sediment accumulation rates in the WOOC1 core are very irregular throughout the core.

Wroxham Broad: Both WROX 1 and WROX 2 cores have similar, rapid accumulation rates throughout the cores (0.37 and 0.26 g cm^{-2} yr^{-1} respectively).

In summary, five cores show an increase in accumulation rate by between 2 and 7-fold over the period covered by the available chronologies, 6 show no change (although in some cases this could be an artefact of the dating) and no cores show a decline in sediment accumulation rate. Two cores (SPRA 1 and SALG 1) are highly variable and no trend can be ascertained.

Multiple cores

An indication of within-site variability can be made where more than one core has been taken from the same site. Here, there are three sites for which we have multiple cores although there are no more than three cores from any one site and hence any interpretation is limited.

For Barton Broad cores were taken in 1995 (BART1), 1999 (BART 5) and 2001 (BART9). The earlier core appears to show little change in sedimentation rate over the 50 years covered by the chronology, whilst the latter core appears to show an approximate doubling in accumulation rate between 1954 and 2001. The ^{210}Pb record for BART 5 is poor and the chronology is based on ^{137}Cs data. As a consequence, only dates post-1963 have any reliability. Furthermore, neither of the chronologies for BART 1 or BART 9 are straightforward and, in particular, that of BART 9 should also be treated with caution. This later core also shows a period of rapid accumulation in the late-1960s and 1970s which is absent from the other cores. Therefore, whilst our data suggest ‘contemporary’ rates across Barton are reasonably consistent (0.13 – 0.17 g cm^{-2} yr^{-1}) there appears to be considerable variability within the cores at Barton. This within-site variability was also observed by Moss et al. (1996) where large differences were observed in the sediment accumulation rates of eight ^{210}Pb dated sediment cores taken across the site. However, this variability is reported to exist in both the pre-1800s and 1970s and highlights the caution that should be used when considering accumulation rate data from a single core to be representative of a site.

Cores were taken from Wroxham Broad in 1995 (WROX1) and 2000 (WROX2) and, in contrast to Barton Broad, there is better agreement between them. Both show approximately constant accumulation rates throughout the cores although again this may be an artefact of the dating resulting from poor ^{210}Pb. Chronologies from both cores extend back to the late-1940s and show rapid accumulation rates throughout (0.37 and 0.26 g cm^{-2} yr^{-1} or 1.3 and 0.8 cm yr^{-1}).

The two cores from Upton Broad (UPTO1 – 1995 and UPTO3 – 2004) differ in that the former is taken from a central area of the site whilst the latter is from a near-shore area. The central core appears to record a doubling in sediment accumulation rate between 1912 and 1995 whilst the near-shore core shows little change in rate between the upper and basal parts of the core, although there is a period of more rapid increase in the 1970s. Moss et al. (1979) also suggest an increase in sedimentation rate of about double from the 1930s to the 1970s from a centrally located core, in agreement with

UPTO 1. Whilst data are limited these results show considerable differences in accumulation rate changes across the site.

Conclusions

- Chronology and sediment accumulation rate data are described for 15 cores from 11 sites in the Norfolk and Suffolk Broads.

- Sediment dating was determined using a combination of radiometric (^{210}Pb, ^{137}Cs) and spheroidal carbonaceous particle (SCP) techniques. These independent approaches are combined to produce a ‘best available chronology’ for each site. However, in some instances, results are still poor and the resulting chronological and accumulation rate data must be treated with caution.

- Five cores, from different sites, showed an increase in sediment accumulation rate over the period covered by the available chronologies. Of these, accumulation rate increases varied by between 2 and 7-fold.

- Six cores showed no real change in sediment accumulation rate. However, for four of these reliable chronologies were only available back to the 1940s, or later, and hence any accumulation rate changes that may have occurred at these sites may not be apparent from these data.

- Two cores showed highly variable rates of sediment accumulation through time, whilst the nature of the dating results precluded a conclusion for two further cores. No cores showed a decrease in accumulation rate.

- Of the three sites for which there were replicate cores one showed reasonable agreement in sedimentation rate between cores (Wroxham Broad) whilst one showed considerable within-site variability (Barton Broad). For the other site, Upton Broad, data are available for a near-shore and a central core. The former shows little change in sedimentation rate whilst the central core shows an approximate doubling. This within-site variability of Barton and Upton Broad is in agreement with previous studies and suggests that caution must be used when sediment accumulation data from a single core are taken to represent a site.

- The data presented in this report, and that of some other previously published studies, would suggest that an accumulation rate in the range 0.01 – 0.04 g cm^{-2} yr^{-1} may be a reasonable estimate for an unimpacted site of this type. However, other published data suggest basal accumulation rates considerably lower than this range.

Further data availability and research requirements

The Environmental Change Research Centre continues to undertake sediment-based research in the Broads and this report represents a summary of the sediment accumulation data to the end of 2004. Further accumulation rate data will almost certainly be obtained over the coming years which can be used to test the hypotheses and conclusions described in this report. There are, however, three key areas which require further attention:

1. Basal sediment accumulation rates and within-site variability

The data presented in this report suggest that there is some consensus as to a sediment accumulation rate representative of a time when the sites were less impacted and there is some agreement with previously published work. However, these are based on only a few data points and therefore there is a need to determine more reliable accumulation rates from the 19th century, if possible, to ascertain:

a) whether typical 'reference' conditions exist for this lake-type (cf. WFD)
b) the true extent of accumulation rate changes over longer periods, and at more sites, than is currently possible, thus making between site comparisons more reliable.

Further, there is a need to explore the scale of within-site variation and thus how representative data from single cores are to the accumulating basin as a whole. Moss (1980) and Moss et al. (1996) suggest massive changes in rate from pre-1800 to the 1970s of between 7 and 90 times, and whilst our data do not show such changes either within a core or where we have multiple cores, the degree of within-site variability, and consequently the full scale of sediment accumulation changes, is currently unknown.

2. Causes of sediment accumulation rate increases

Having observed some significant increases in sediment accumulation rate it is crucial to determine the causes and, in particular whether these are internally (e.g. phytoplankton or macrophyte) derived or external from catchment sources (e.g. sediment loads from inflows or soil erosion). Palaeolimnological investigations provide these sorts of information and besides sediment accumulation rates, the ECRC has a wealth of biological and physical data on the cores described in this report. For example, there is a considerable archive of vegetation change data from which long-term vegetation dynamics of the Broads systems could be produced. Also, there is a wealth of palaeolimnological diatom data (assemblage changes, concentrations) which, whilst not being suitable for the reconstruction of phosphorus concentrations (owing to the dominance of *Fragilaria* taxa), might allow inferences on changes in productivity to be determined. These, when coupled with other proxies could allow an assessment of how lake structure and functioning has changed. Therefore, a detailed synthesis of these palaeolimnological data may provide indications as to the causes of accumulation rate changes, and furthermore, could highlight the areas where there is a lack of current information on sediment sources which could then be addressed by future studies.

3. Consequences of increases in sediment accumulation rate

It is important to determine the consequences of increasing sediment accumulation rate for lake biota and in particular the implications of lake shallowing on macrophyte loss and establishment. We suspect increases in sediment accumulation might impact upon macrophytes through creating less stable and more fluid surficial sediments. A PhD topic in this area has recently begun at the ECRC and data should become available over the next few years.

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