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Variability in the physical, chemical and magnetic properties of reservoir sediments; implications for sediment source tracing

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Abstract Analysis of lake and reservoir sediment cores has provided information on sediment yields and sources and on environmental and contamination histories. Although high density coring is often used to minimize the error in estimating sediment mass and calculating sediment yield, recent research on environmental reconstruction and sediment source tracing has often used a single or small number of sediment cores. The variability associated with sediment sorting by the water body and the control of sorting processes on geochemical and magnetic characteristics are, therefore, largely ignored. Analysis of existing data sets for four lowland England reservoirs has been undertaken in order to compare downcore variability in sediment properties with spatial variations in the same properties at time synchronous levels within the sediment column. Results of this analysis suggests that the spatial variability is often higher than downcore variability. The implications of such variability for sediment source tracing and environmental reconstruction are discussed.

INTRODUCTION

Reservoir sediments have been used to provide quantitative estimates of sediment yield which have been shown to correlate reasonably well with monitored basin data (Foster *et al.*, 1985, 1986, 1990a, 1993). The major limitations on the accuracy of sediment yield estimation are those imposed by sedimentation rates and sediment focusing and the reliability and sensitivity of radiometric dating (Dearing, 1986; Dearing & Foster, 1986, 1993). In addition to the estimation of sediment yield, physical, chemical, radiometric and magnetic properties of the sediments have been used in order to separate the autochthonous and allochthonous contributions to the sediment column, identify dominant sediment sources and reconstruct environmental and contamination histories. Yield estimation is usually undertaken using high density coring in order to account for variations in sedimentation rate over the reservoir bed. Source tracing and geochemical analysis, however, frequently concentrate on a single core or on a small number of sediment cores retrieved from the reservoir (Heathwaite & O'Sullivan, 1991; Dearing, 1992). Despite an acknowledgment of variability in the same properties in basin sources (cf. Dearing, 1992; Foster & Walling, 1994) spatial variability in reservoir sediment properties is largely ignored.

This paper examines pre-existing data on reservoir sediments at four sites in lowland England. These data have been used in order to calculate sediment yields and to model sediment sources in a number of lakes draining forested, agricultural and urbanized

catchments. Specifically, analysis of these data has been undertaken in order to:
(a) compare downcore variations in lake sediment properties with spatial variations in the same properties at the mud-water interface;
(b) analyse the variability in the geochemical and magnetic properties of time-synchronous layers within the sediment column of two reservoirs;
(c) examine the impact of calculated variability on the interpretation of the physical, geochemical and magnetic sedimentary record.

STUDY SITES

Site details and basin descriptions of the lowland reservoirs discussed in this paper have been given elsewhere. The sites include Merevale Lake (forested basin) and Seeswood Pool (mixed arable and grassland basin), located in the rural English Midlands (Foster *et al.*, 1985, 1986, 1990a); Swanswell Pool (inner city lake basin with no river input) and Wyken Slough (urban fringe with 40% urban basin), located in the industrialized English Midlands (Foster *et al.*, 1991; Charlesworth & Foster, 1993). The catchments feeding the reservoirs are less than 5 km^2 in area and the reservoirs are less than 7 ha in area.

Bottom-sediment samples were recovered using a "Mackereth" type corer and were subsampled for analysis at 1 cm intervals. Surface sediments were taken from the upper 1 cm slice of sediment cores. Properties investigated in this paper include two physical characteristics; dry bulk density (DBD) and the particle size distribution (PSD). Particle size was determined by laser granulometry and a measure of sorting (SPAN) and the particle size (in μm) of the 10th percentile in the cumulative frequency distribution (D_{10}) were used for further analysis. Magnetic properties included two measures of susceptibility at Low (X_{LF}) and High Frequency (X_{HF}) from which Frequency Dependent Susceptibility (X_{FD}) was calculated. Two remanent properties were measured after subjecting samples to a forward and reverse magnetic field ($IRM_{0.8T}$, $IRM_{-0.1T}$) from which the S-Ratio and HIRM were calculated (cf. Thompson & Oldfield, 1986). Chemical characteristics include concentrations (in $\mu g\ g^{-1}$ dry sediment) of selected heavy metals, Fe and Mn and were analysed using techniques described by Foster *et al.* (1987).

SPATIAL AND DOWNCORE VARIABILITY IN RESERVOIR SEDIMENT PROPERTIES

In a recent review of sediment sampling strategies in small lakes and reservoirs (Foster *et al.*, 1990b) it was identified that widely different coring densities have been used, ranging from as high as 1 core per 0.0035 ha to as low as 1 core per 12 ha of reservoir area. To date, no attempt has been made in the literature to identify the optimum coring density in order to take account of the spatial variability in sediment properties and analyse the differences between spatial variability and downcore variability in the same property. Where spatial variability exceeds downcore variability, it seems likely that the property of interest is dominated by the characteristics of the reservoir. In relation to physical properties, particularly particle size and density, this will reflect the sorting and redistribution of the incoming sediments both from autochthonous and allochthonous sources. For many chemical properties, for example Fe and Mn concentrations, spatial differences may relate to varying lake water conditions at the reservoir bed, particularly in redox potential which will drive chemical exchanges at the mud-water interface (cf. Håkanson & Jansson, 1983).

Table 1 gives the coefficient of variation (CV) at 2 standard deviations (95%) for surface properties in four reservoirs and the same measure of variability as recorded in a single deep-water sediment core from each site. It is apparent from these data that the relationship between spatial variability and downcore variability is unique to each reservoir, although some generalizations may be made from these data. The spatial variability in physical properties is similar to, or greater than, the downcore variability. In contrast, the spatial variability in magnetic properties is similar to or less than the downcore variability, although the CV exceeds 100% for all but the S-Ratio in all cases. For heavy metal concentrations, downcore variability is significantly higher than spatial variability suggesting that trends identified in a single core in the two urban sites might be expected to provide a good representation of historical trends in contaminant loading to the lakes.

The important question is whether the grid size used to collect the sediment cores has a significant impact on the calculated spatial variability. In order to address this

Table 1 Coefficient of variation at 2 standard deviations (95%) for surface sediments and a deep water sediment core in four reservoirs.

Site property	Merevale Lake		Seeswood Pool		Wyken Slough		Swanswell Pool	
	Surface $n = 56$	Core $n = 21$	Surface $n = 27$	Core $n = 21$	Surface $n = 16$	Core $n = 58$	Surface $n = 12$	Core $n = 72$
Physical properties								
DBD	69.8	82.6	122.3	75.6	47.1	55.3	120.0	71.1
SPAN	28.5	32.4	21.6	7.7	-	-	-	-
D_{10}	35.4	38.0	16.5	24.2	-	-	-	-
Mineral magnetic properties								
χ_{LF}	45.7	81.6	52.6	84.9	129.5	130.9	75.4	150.4
$IRM_{0.8}$	-	-	-	-	140.9	170.8	100.3	121.0
$IRM_{-0.1}$	-	-	-	-	135.0	178.6	129.7	170.7
S-Ratio	-	-	-	-	10.5	24.3	24.7	200.0
HIRM	-	-	-	-	134.8	187.1	100.0	396.2
Sediment chemistry (total digestion)								
Pb	-	-	-	-	99.1	175.0	44.6	112.2
Cu	-	-	-	-	110.7	292.3	72.1	135.2
Ni	-	-	-	-	26.8	40.0	55.5	111.6
Zn	-	-	-	-	36.9	181.3	66.1	206.8
Fe	-	-	-	-	128.5	43.9	41.9	125.1
Mn	-	-	-	-	22.4	139.5	131.2	83.5

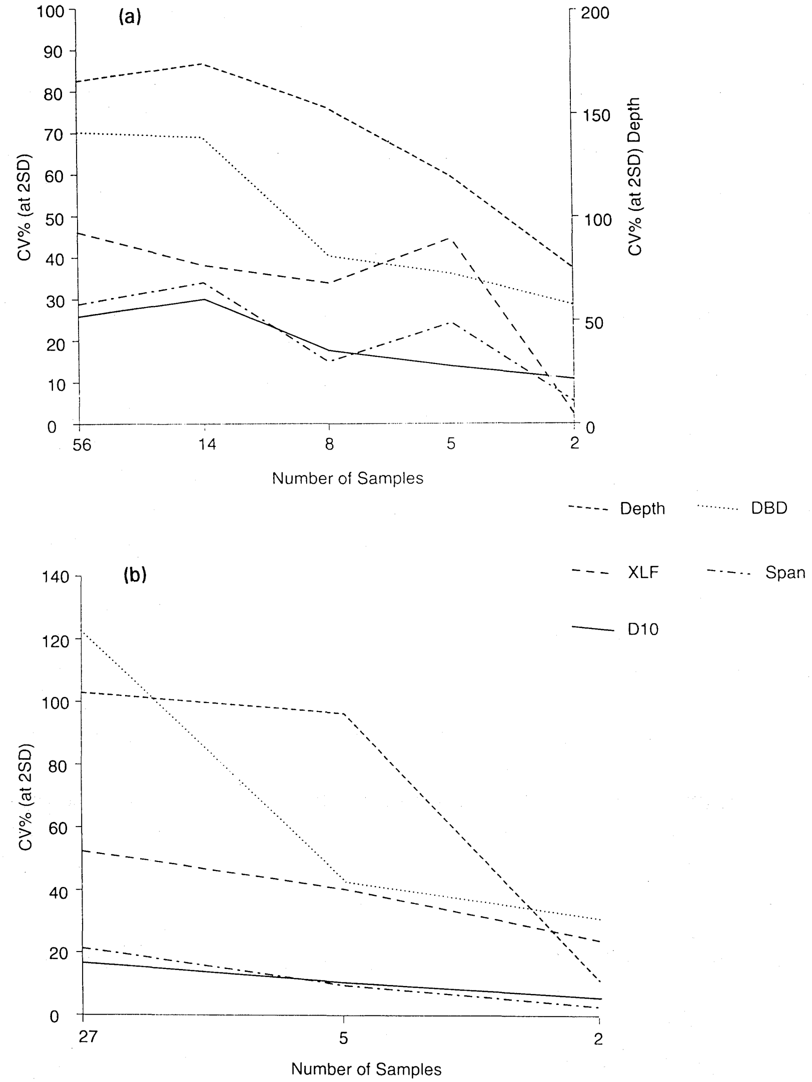

Fig. 1 The impact of coring grid density on the variability in surface sediment properties and average sediment thickness in Merevale Lake (a) and Seeswood Pool (b).

issue, the surface sediment samples for Merevale Lake and Seeswood Pool have been analysed because the initial coring densities were high (at the intersection of a 25 × 25 m grid at Merevale giving 56 cores; and a 50 × 50 m grid at Seeswood giving 27 cores). Figure 1 shows the effect of coring density on the calculated CV (95%) of selected physical and magnetic properties. Density and core depth show greatest variability at both sites and the particle size characteristics are least variable. The variability in X_{LF} lies between these two groups of physical properties. Trends in variability in both lakes are reasonably consistent and show an increase with higher coring densities. The data also show no increase in variability between the 14 and 56 core samples in Merevale Lake.

DOWNCORE VARIABILITY AND THE RECONSTRUCTION OF TRENDS

It has been suggested that the relative significance of a reservoir in controlling sediment properties might be evaluated through a comparison of spatial and downcore variability statistics and that the most useful indices for environmental reconstruction and interpretation of basin dynamics are those where downcore variability significantly exceeds spatial variability. As suggested in the introduction, however, studies using a single core from a reservoir in order to reconstruct the environmental and contaminant loading history fail to take account of the inherent variability associated with sampling position. Furthermore, as shown by Dearing (1986), the point of average sediment accumulation at the reservoir bed may vary with time, which suggests that a single coring location may not be representative of the reservoir as a whole.

In reconstructing the trends in heavy metal loading and sediment geochemistry for Merevale Lake and Seeswood Pool, seven and four sediment cores were analysed for each site respectively. The sediment mass had already been divided into synchronous dated levels (nine time zones for Merevale and 11 time zones for Seeswood) on the basis of radiometric dating and mineral magnetic core correlation (Foster *et al.*, 1985, 1986). Sediment samples were bulked and subsampled for each time zone in all of the cores analysed. The CV (95%) for sediment geochemical properties in both lakes lies between 20 and 100%. As an example, Fig. 2(a) shows the mean and 95% confidence levels on the estimate of the mean Zn concentrations. Although there is a clear trend in metal concentrations upcore in both lakes, the high CV increases the difficulty in comparing site histories, quantifying trends and identifying significant differences between the early and recent history of individual sites.

A similar problem is encountered in relation to mineral magnetic properties which are often used to model sediment sources. Figure 2(b) shows the mean and 95% confidence levels on the mean from the seven and four cores analysed for Merevale Lake and Seeswood Pool. Here, the CV approaches 50% in individual time zones in Merevale Lake and 90% in Seeswood Pool sediments. Such variability has significant implications for the use of X_{LF} in modelling sediment sources. Furthermore, X_{LF} in the sediments of both lakes is significantly correlated at the 95% level with the total heavy metal concentration and with particle size characteristics (SPAN and D_{10}). These latter relationships suggest that at least part of the magnetic signal is a function of sorting within the reservoirs.

A further example of the effect of coring location on the variability in sediment properties and environmental interpretation derives from an analysis of four cores on a transect along the long axis of the Wyken Slough from inflow to outflow. In general, the greatest downcore variability in physical, magnetic and geochemical properties is associated with the two sediment cores collected near the inflow. These sediments are characterized by poor sorting and are coarser than those at the outflow end of the lake where sorting improves and the sediments are generally finer. Of 17 physical, chemical and magnetic properties analysed, only total Ni and P concentrations and the magnetic parameter $IRM_{-0.1T}$ have a higher CV (95%) in one of the two cores near the outflow than in either of the two cores near the inflow. The physical, magnetic and chemical characteristics of the sediments in each of the four cores have been compared independently with the same properties of potential sediment sources (catchment soils and fine fluvial bed-sediments) other basin sinks (local wetland surface sediments and

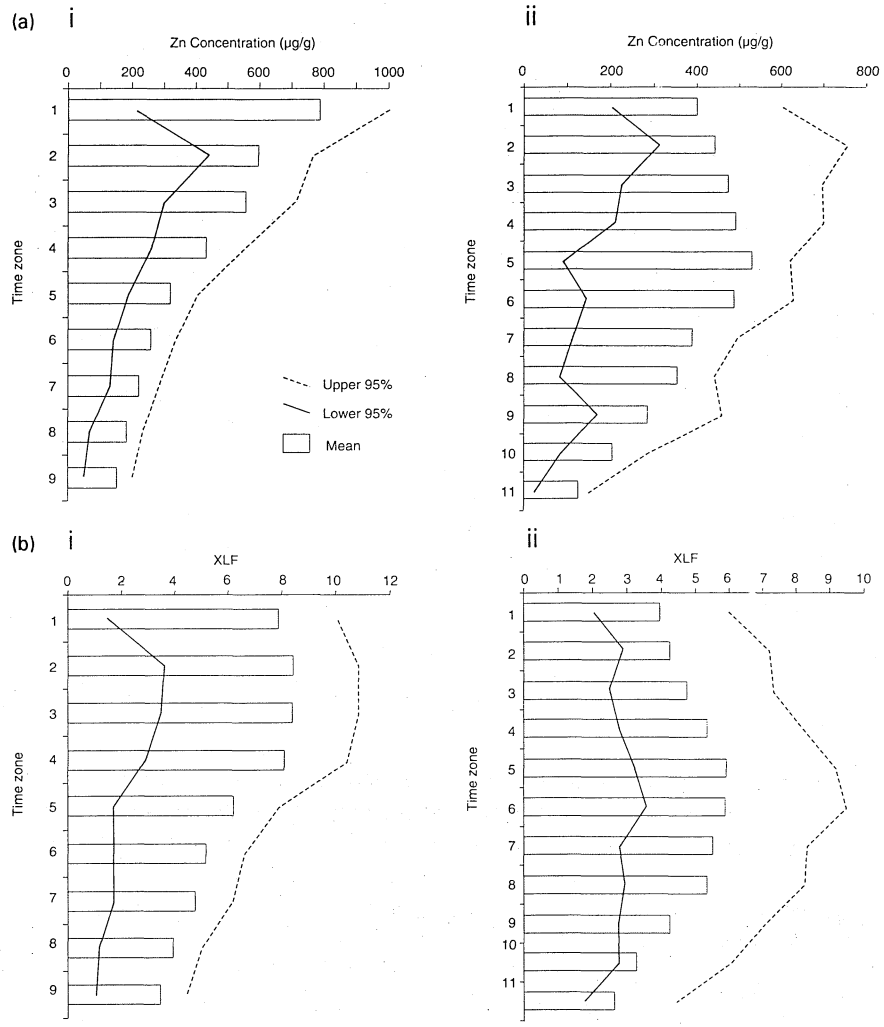

Fig. 2 The effect of multiple coring on the variability in (a). Total Zn concentration profiles in Merevale Lake (i) and Seeswood Pool (ii). (b) Low frequency magnetic susceptibility (X_{LF}) profiles in Merevale Lake (i) and Seeswood Pool (ii) (Mean concentrations are shown as a histogram. The upper and lower 95% confidence intervals (± 2 standard deviations) are shown as envelope curves).

wetland core samples) and surface reservoir sediments through a Principal Component Analysis in order to establish whether coring location would significantly influence environmental and source area interpretation. The location of envelope curves of major sources and sinks for the first two Principal Component plots (Fig. 3) would suggest that coring position has little impact upon the location of sediment core data in the Component Space and therefore has little effect on the interpretation.

DISCUSSION AND CONCLUSIONS

Attempts have been made to highlight the need for more information on variability in

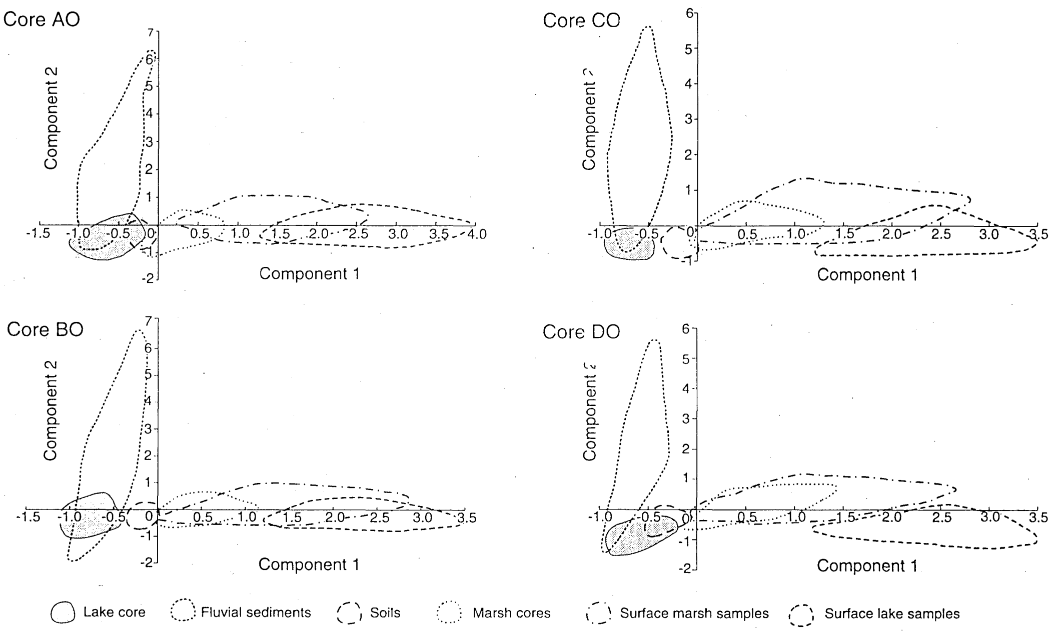

Fig. 3 Envelope curves for sediment sinks and sources in the Wyken Slough Basin based on a Principal Component Solution. Each of four sediment cores from Wyken Slough are identified individually in relation to other samples.

the physical, chemical and mineral magnetic properties of lake sediments which are frequently used for environmental reconstruction and sediment source tracing. This short communication has suggested that a comparison of spatial and downcore variability in sediment properties may assist in the identification of the most suitable variables for source area identification and the reconstruction of environmental and contamination history by maximizing downcore variability in relation to spatial variability. High spatial variability relative to downcore variability reflects controls within the reservoir and properties with high spatial variability may be generally unsuitable for source area modelling.

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