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The sedimentary data base: an appraisal of lake and reservoir sediment based studies of sediment yield

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Abstract Direct monitoring provides a highly resolved data base with which to study short term process response systems, whilst sedimentary information, based for example on stratigraphic and palaeoecological studies of river terraces and valley deposits, provide palaeohydrological information covering much of the Holocene period. Medium term changes, over decades and centuries, are much less well represented in the hydrological literature for two major reasons. First, monitoring programmes have not been established for a sufficient period of time to detail changes over these timescales and secondly, sedimentary features in river valleys are rarely deposited continuously over these timescales. These sediments do not preserve material of use for highly resolved dating and the relationships between sediment yield and deposition in such situations is complex. One solution to this problem is to analyse the accumulating sediments in natural lakes and reservoirs in order to estimate sediment yield changes through time. This paper reviews the application of the lake-watershed ecosystem framework over the last decade, in studies reconstructing sediment yield histories in a wide variety of geographical environments from northwest Europe, Scandinavia, North America, North Africa and Asia. An attempt is made to identify some of the technical problems in sampling lake sediments, in methods of dating and core correlation and in the interpretation of the sediment yield information, once collected, in order to account for non-catchment contributions to the sedimentary record. The evidence obtained to date shows that lakes in most environments preserve a record sufficiently well for the reconstruction of quantitative sediment yields. Geomorphological implications of the development of lake catchment studies are highlighted.

INTRODUCTION

In a recent UNESCO report for the International Hydrological Programme, Hadley (1985) has considered the monitoring requirements for the investigation of natural and manmade changes to the hydrological regime and related ecological environments. Within this brief report, six major objectives are identified for monitoring networks. These objectives are summarized below:

(a) to aid in the understanding of natural processes and how process rates are influenced by human activity and climate;
(b) to detect trends and periodicities in hydrologic time series;
(c) to formulate hypotheses for possible causes of change in the system;
(d) to measure process rates under natural and altered conditions;
(e) to describe qualitatively and measure quantitatively the effects of human activity on the environment; and
(f) to aid prediction in the management of land and water resources in the future.

Undoubtedly, process monitoring is essential for the collection of highly resolved data, the detailed examination of process dynamics and the construction of dynamic models of soil erosion and sediment transport in the fluvial environment. Direct process monitoring alone may, however, be inappropriate for the aims encompassed in points (b), (c), (e) and (f) above, because of the relatively short time scales concerned (less than a decade). The most obvious limitations here relate to the inherent variability in natural hydrological systems and the need to identify the time scales over which adjustments to human and natural changes occur. Streamflow and sediment and solute transport rates are inherently variable in contemporary systems. For example, Walling & Webb (1981) report the annual sediment yields for a 7 year continuously monitored record from the River Creedy, Devon UK. This record has an annual coefficient of variation of 57.9%. The record of sediment yields entering the Aswan High Dam for a 15 year period after completion have a coefficient of variation of 32.9% (based on data in Shalash, 1982). Furthermore, Foster (1980) has highlighted the importance of extreme events in runoff and solute load data for an East Devon catchment, where the annual coefficient of variation for a 3 year record including the 1976 UK drought was 63.9% for runoff and 58.1% for chemical denudation. Inherent variability in short term records gives rise to two major difficulties: first, in obtaining representative rates of process operation for a given environment in order to examine regional and climatic controls and second, in obtaining realistic magnitude and frequency data. Further complications inevitably arise in selecting the most suitable method for sediment yield estimation (cf. Walling, 1978; Ferguson, 1986, 1987).

In addition to the problem of obtaining data at the relevant timescale, contemporary reviews of erosion and sediment yield research highlight the need to link the fluvial environment to the hillslope and valley floor (cf. Hadley *et al.*, 1985). This linkage is likely to prove difficult from studies of fluvial processes alone yet it has been stressed by Dunne (1984) that attempts should be made to identify sediment sources and sinks within studies of fluvial sediment transport.

LAKE AND RESERVOIR SEDIMENTATION

Reservoir resurvey methods have been used for many years to estimate the expected life of the reservoir and catchment sediment yields (cf. Brown, 1944). A comprehensive range of survey and resurvey techniques have been developed to calculate the sediment volumes deposited (Bruk, 1985; Pemberton & Blanton, 1980; Rausch & Heinemann, 1984; Vanoni, 1975). Many studies based on resurvey and/or remote sensing methods report average yields for the entire life of the reservoir (e.g. McManus & Duck, 1985) but developments in the ^{137}Cs dating of reservoir sediments reported by Ritchie *et al.* (1973) have enabled some estimate to be made of variations in deposition rate through time (cf. Batten & Hindall, 1980).

Despite these and other technical developments, and the strengthening of conceptual links between lakes and their contributing catchments (Oldfield, 1977), a number of important practical difficulties still remain in utilizing the bottom sediments of lakes and reservoirs for reconstructing sediment yield histories. These include the identification and/or quantification of sediment source, trap efficiency, resuspension processes, sediment density changes, autochthonous and allochthonous contributions to the sediment and the significance of authigenic and mixing processes. Furthermore, refinements in sediment retrieval techniques and the methods employed to derive an absolute chronology must be seen as essential to the accurate quantification of sediment yield histories. These problems are briefly outlined below.

Sources of sediment

Hakanson & Jansson (1983) identify four major factors which control sedimentation in lakes. First, a depositional factor which expresses the capacity of a lake to act as a sediment trap (all other things being equal, larger lakes tend to be more efficient sediment traps). Secondly, the lake or reservoir will have its own internal productivity which will contribute towards the accumulation of sediment at the lake bed. Thirdly, pretrapping of sediment in upstream lakes and reservoirs will limit sediment supply. Fourthly, the natural load factor derived from allochthonous inputs (direct drainage basin derived inputs or atmospheric contributions to the lake surface). Any attempt to utilize the lake sediment record must be capable of distinguishing the respective contribution of autochthonous and allochthonous material and the relative contribution derived from the drainage basin and the atmosphere.

Trap efficiency

Sediment trap efficiency has attracted considerable attention from hydrologists. Graf (1983), for example, has shown that the general pattern of sedimentation is a function of changing hydraulic conditions, with the relatively high velocity turbulent inflow being transferred to slow flowing water within the lake or reservoir. Coarser particles, including the bedload, are usually deposited as a delta whilst the lighter particles, especially fine silts and clays, are distributed further into the water body. The exact distribution of the sediment will depend on factors such as the relative densities of the inflowing river and lake waters and the position of the thermocline (or pycnocline) if one exists (Fig. 1(a)). Furthermore, the chemical properties of the water in which settling takes place may enhance or inhibit settling through the impact of the sodium adsorption ratio on flocculation (e.g. Trujillo, 1982).

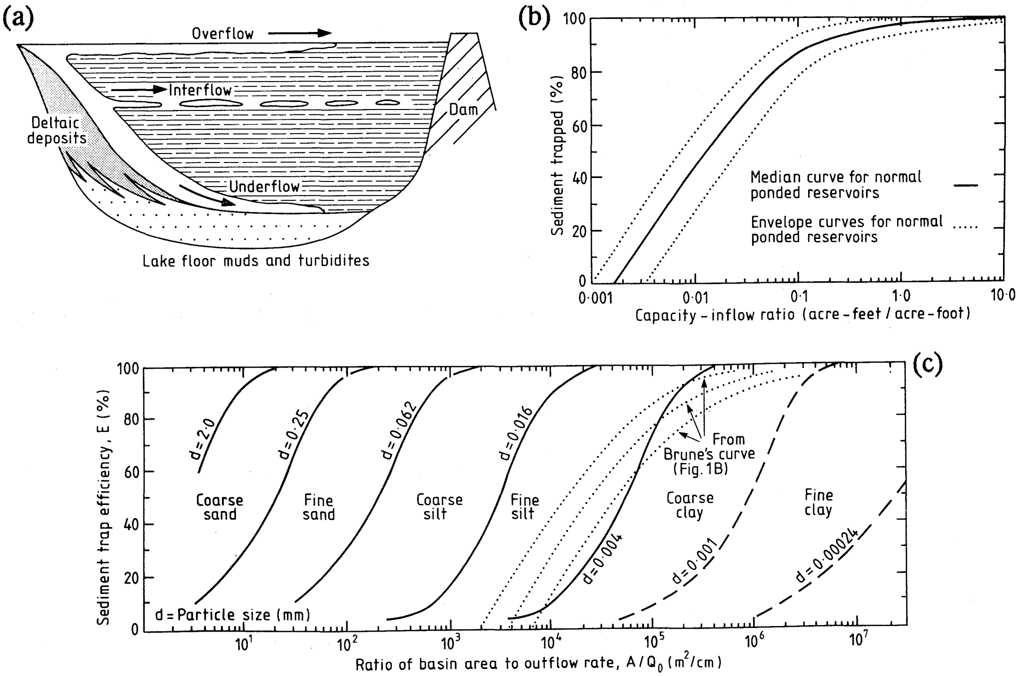

Fig. 1 Lake and reservoir trap efficiency: (a) mechanics of sediment delivery and distribution; overflow, interflow and underflow rates depend on the relative density of inflowing water and the presence of a thermocline; (b) trap efficiency as related to the capacity-inflow ratio (based on Brune, 1953); (c) trap efficiency as related to particle size and the ratio of basin area to outflow rate (based on Chen, 1975). The Brune curve is included for comparative purposes.

The efficiency with which reservoirs trap sediment can be predicted in a number of ways. Brown (1944) suggests that trap efficiency (*Te*) can be determined from:

$$Te(\%) = 100 \times 1 - \frac{1}{1 + 0.1C/DA}$$

where C = reservoir capacity; and
DA = basin area.

The drainage area parameter, however, seems to be a relatively poor substitute for inflow volume, and Brune (1953) developed the use of the capacity inflow ratio in preference to the capacity drainage area ratio (Fig. 1(b)). In his survey of 44 reservoirs, Brune found a range of trap efficiencies. Reservoirs with low capacity inflow ratios may fill and scour depending on the pervading streamflow conditions, whereas high retention capacities are to be found in reservoirs with high capacity inflow ratios, where continuous sedimentation is experienced and clear water is released downstream. In small basins, the trap efficiency curve developed by Heinemann (1981) may be more appropriate or, where a particle size differentiation is seen to be important, the capacity inflow/particle size relationship may be relevant (see Fig. 1(c); Chen, 1975; Heinemann, 1984; and Rausch & Heinemann, 1984). Trap efficiency, although a vital component for quantitatively estimating sediment yield, may vary in the same lake or reservoir depending on inflow conditions. For example, the trap efficiency of the Aswan high dam for a 15 year period between 1964 and 1979 varied from 84.8% to 99.9% (based on data in Shalash, 1982). For the purposes of sediment yield estimation, lakes and reservoirs with trap efficiencies approaching 100% will provide optimum sites for sediment yield studies.

Resuspension

Despite the relatively efficient trapping of sediments in some lakes and reservoirs, the resuspension, redeposition and sediment focussing process has a significant bearing on the methods which may be employed to estimate sediment yield. These problems have been investigated in recent limnological research, for example by Davis (1974) and Davis & Ford (1982) in Mirror Lake, New Hampshire and in Esthwaite Water in the UK (Hilton, *et al.*, 1986). Resuspension appears to be most relevant to the use of seston traps for estimating sediment accumulation rates in lakes and reservoirs (cf. Bloesch & Burns, 1980; Blomqvist & Hakanson, 1981), although it may also have implications for the preservation of the radioisotope record as discussed below. In a more general review of the problem, Hilton (1986) suggests that four processes dominate the resuspension and potential focussing of lake sediments. These include peripheral wave attack, random redistribution, intermittent complete mixing and slumping and sliding on slopes. Indeed, Davis *et al.* (1984) have argued that little information is as yet available on the understanding of the hydrodynamic and sedimentological processes which control sediment deposition in small lakes, although some attempts to model the process have been made on the basis of lake morphology (e.g. Lehman, 1975). An inability to predict the process of sediment focussing has implications for the design of sediment survey techniques, since basic morphometric properties cannot be used to predict the points of maximum minimum and, more importantly, average sedimentation for a lake basin. A Dearing (1983) has shown in a small Scanian lake, the point of avera sediment accumulation at the lake bed may vary over time depending changes in exposure conditions or in response to local depositio processes.

Sediment density

In many cases, reservoir resurvey techniques have been used to estimate the volumetric accumulation of sediment for economic as well as geomorphological reasons (e.g. Stromquist, 1981; Bruk, 1985; McManus & Duck, 1985). Although the resurvey technique may be of value in assessing reservoir life, it is suboptimal for assessing sediment yield for a number of reasons. Firstly, sediment density may not be measured directly and may be assumed or estimated from one of the available empirically-derived formulae. Secondly, without sediment cores for analysis, the relative proportions of the autochthonous/allochthonous components cannot be estimated. Thirdly, the sediment yield estimate may span the entire life of the reservoir covering several periods of human impact or change. Fourthly, initial surveys following construction may be inadequate to provide a baseline against which to adequately assess subsequent deposition, since early adjustments might involve a greater proportion of bank derived sediments.

Of particular importance in sediment yield estimation is the change in density which can occur either during deposition or in post-depositional diagenesis. The density of sediment can be estimated from one of two major approaches. Reservoir engineers, for example, frequently consider the compaction of sediment in terms of the removal of pore water through time, assuming that the increase in compaction is time and/or particle size dependent. The methods most commonly used, according to Vanoni (1975), include that of Lane & Koelzer (1953) where the sediment density (p) after t years is given as:

$$p = p_1 + k \log t$$

here: p_1 is the sediment density after 1 year, k is a constant and t is time
ce deposition in years.
The detailed considerations given by Bolton (1986) to the above and
equations are too lengthy to be presented in detail here, but after
ing a range of models based on inadequately formulated hydraulic
es, Bolton suggests that a mathematical formulation of the density
such as:

$${}_{f} - a\ e^{by}$$

sediment density, a and b are constants which can be obtained
ting techniques, p_f is a hypothetical maximum density value and
be more appropriate.
ions of this approach are seen in hydraulic terms to relate to
pressure dissipation during consolidation, although the
manifest itself in slowly sedimenting basins where this
brate through time. However, the assumption that the
ards a finite maximum is invalidated by the observations
ontinuous sedimentary sequence in Lake Biwa, Japan
re density increases with depth through over 200 m of

sediment. Such records may form an important basis for the evaluation of a variety of models of sediment density.

An alternative approach to the density problem is presented by Hakanson & Jansson (1983). They assume that water content is the key component which they define as:

$$W = \frac{gws - gds}{gws}$$

where gws and gds are wet and oven dry masses respectively from a known sample volume.

Water content will decline with depth in the form of a negative exponential. More importantly, water content is also related to wet bulk density (pw), organic content and the density of organic material. Although humus may have a density close to water (1.3 to 1.5 g cm^{-3}), the density of minerogenic sediments may exceed 5.0 g cm^{-3}. Clearly, the mixture of sediments of various types affect the final density, not simply because of pore pressure and particle size differences, but also as a result of differential organic:inorganic loadings. Analyses of the organic matter content of lake sediments have shown that values may range from a few percent to over 30% by weight (Engstrom & Wright, 1984) and may reflect the organic productivity in the epilimnion of stratified lakes receiving high nutrient loadings. A recent investigation by Foster & Dearing (1987) has shown that in two morphologically and geologically similar reservoir basins in the Midlands of England, the average organic matter content of the sediments in the two basins ranged from 8 to 15% of dry sediment mass.

The accuracy of sediment yield estimates for whole lake basins may be inadequate, not only because of errors in estimating the vertical variations in density but also because spatial variations in density over the lake or reservoir bed will relate to inflow and secondary sorting processes as well as to local variations in erosion and deposition. For example, Smith *et al.* (1960) have shown that dry densities of surficial sediments in Lake Mead ranged from 0.53 to 0.91 t m^{-3} (excluding deltaic deposits). Such a range of densities would produce a significant variation in the estimated sediment mass and any consequent calculation of sediment yield.

The assumptions behind many of the hydraulic models reviewed by Bolton (1986) are also invalidated for a number of reasons, as illustrated by the variable nature of short core densities in a range of environments (Fig. 2). All of these profiles (except Lake Bussjo which was sampled with a "Russian Corer") were obtained from samples extruded from a Mackereth corer (Mackereth, 1969). Despite some of the problems in coring techniques outlined below, a number of important conclusions can be drawn with regard to these cores. For example, Fig. 2(a) is derived from a reservoir in Midland England and exhibits a relatively uniform increase in density with depth which appears to conform best to hydraulic models of compaction. The dramatic increase at 1 on the graph represents the corer penetrating the clay liner to the reservoir. Figure 2(b) refers to an upland lake in north Wales showing evidence of density increases (1 and 2) as a result of the inwash of mining

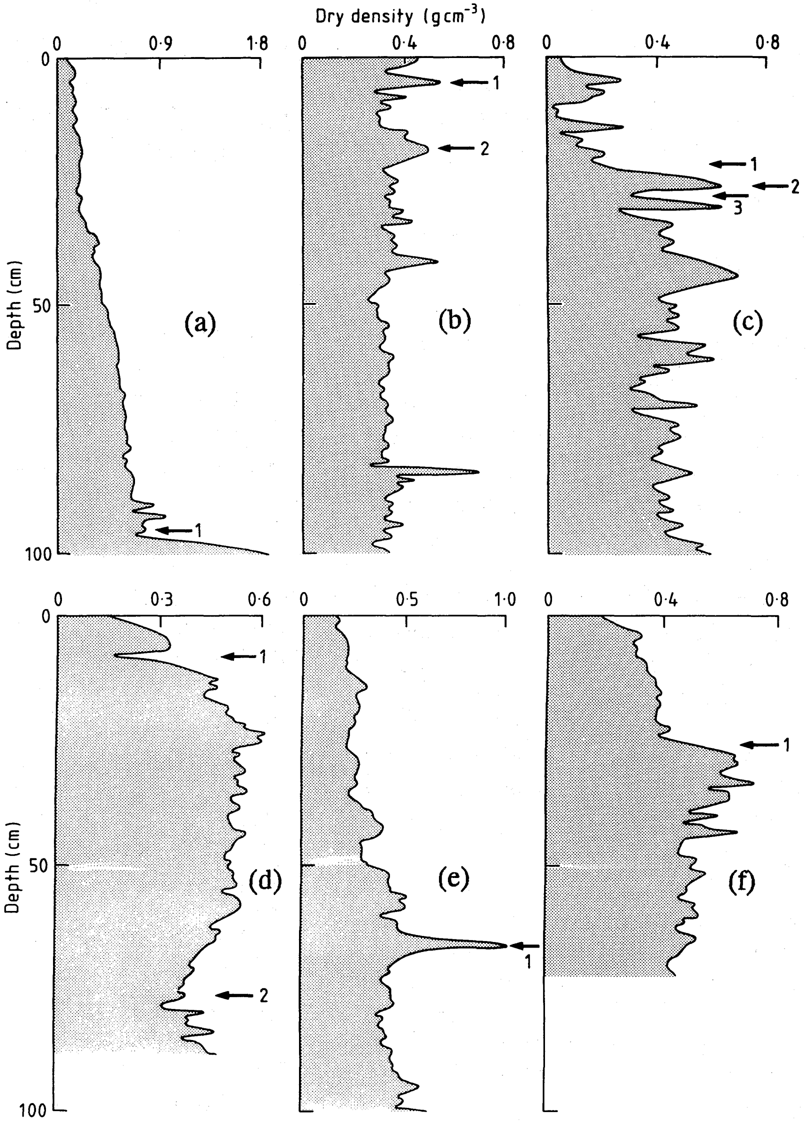

Fig. 2 Variations in sediment density in short cores. (a) Seeswood Pool, Midland England; (b) Llyn Geirionydd, N. Wales; (c) Lake Bussjo, Scania, S. Sweden; (d) Dayat er Roumi, Lowland Plain, Morocco; (e) Dayat Affougah, Middle Atlas, Morocco, (f) Coombe Pool, Midland England.

waste from adjacent streams during the region's recent history. Figure 2(c) is the density profile for a small kettle-hole lake in Scania, south Sweden, typified by alternating biogenic (3) and minerogenic (2) deposition producing a rhythmic density profile. The dramatic decrease in density at 1 on Fig. 2(c) is thought to represent a period of drainage during the 1950s and a reduction in effective sediment contributing area. Figure 2(d) illustrates the impact of a change of sediment source in a lake-catchment in Morocco, where the increase in density at around 70 cm depth is associated with the initiation of gully development (see Flower *et al.*, 1984; Flower *et al.*, 1989; Foster *et al.*, 1986a). Figures 2(e) and 2(f) reflect water level lowerings. Figure 2(e), which refers to a small lake in the Middle Atlas of North Africa, shows a peak (1) reflecting the presence of a high density shell layer thought to represent a period of lower water levels whilst Fig. 2(f) relates to a small reservoir in Midland England where an increase in density at *c.* 20 cm depth has been caused by drawdown for an extended period of around 4 years in the 1940s. Clearly, the range of factors responsible for controlling sediment density, which will also include particle size considerations, precludes the prediction of density with any degree of certainty. At the present time, there appears to be little substitute to the application of coring methods to quantify accurately spatial and post-depositional variations in sediment density. (These methods are discussed below).

Autochthonous and allochthonous sources

Lake sediments will comprise material derived from erosional processes within the upstream drainage basin, lake marginal erosion processes, atmospheric sources and biotic processes within the circulating water body which may selectively assimilate elements delivered to the lake in solution. Some attempt to distinguish these sources must be made where they are likely to contribute significantly to the accumulating sediment. Little has yet been done on the possible significance of lake marginal erosion processes, where imperceptible backwearing may make significant contributions to the accumulating sediment. This problem has been investigated theoretically by Dearing & Foster (1986) who produced the nomogram shown in Fig. 3 in an attempt to quantify the maximum acceptable bank erosion rate in a range of recent lake sedimentbased estimates of sediment yield. The factors controlling bank erosion rates will include wave height, height of erodible shoreline, fetch, local water level lowerings and the magnitude of currents capable of transporting eroded sediments to the central part of the lake or reservoir. Water level lowering is more problematic in reservoirs, and many studies have evidenced the secondary erosion/depositional sequences associated with the reworking of deltaic or other sediments (cf. Bruk, 1985; Szechowycz, 1973). Particularly problematic is the deliberate use of scour valves to remove reservoir bottom sediments. Such disturbances are likely to invalidate the lake sediment based method of sediment yield estimation. It is recommended that some attempt be made to monitor contemporary rates of bank retreat in order to quantify the magnitude of this problem in a variety of locations. Erosion pin studies are currently being carried out by the authors on a reservoir site in Midland England in order to quantify this problem.

The contribution derived from atmospheric inputs is usually assumed to be negligible. Records from Midland England have, however, shown that localized dust fallout could exceed 30 t km^{-2} $year^{-1}$ in recent times. Undoubtedly, these fallout records are unlikely to represent regional rates of

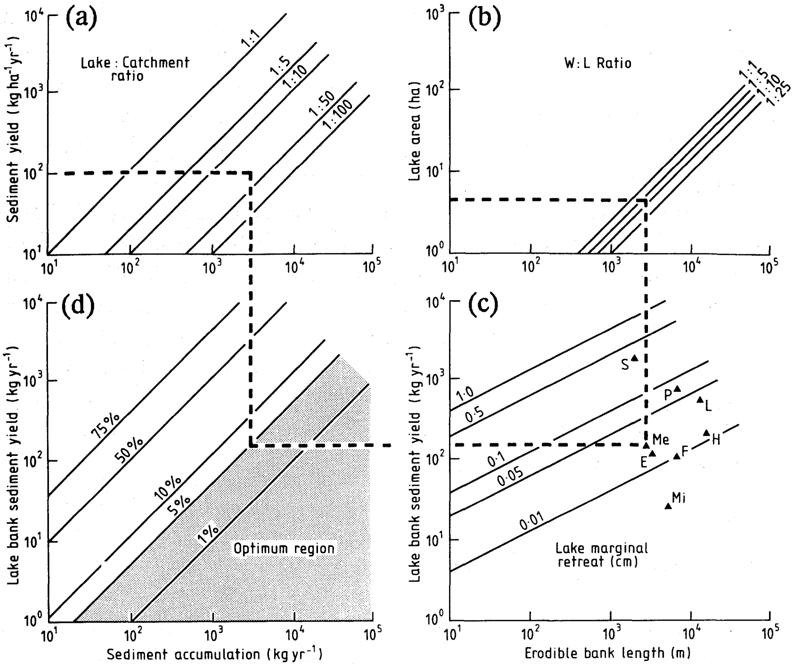

***Fig. 3** The impact of lake bank erosion on yield estimate: (a) relationship between lake:catchment area ratio and sediment yield to estimate dry sediment accumulation (kg yr^{-1}); (b) relationship between lake area and lake width to length (W:L) ratio to give estimate of erodible bank length; (c) relationship between erodible bank length, rate of retreat and sediment yield derived from bank erosion (assuming a bank height of 40 cm and a sediment density of 2.65 g cm^{-3}); (d) relationship between lake bank sediment yield, sediment accumulation and the % contribution to total yield by bank erosion.*

The nomogram requires two sets of input, a regional rate of sediment yield (Fig. 3(a)) and lake area and the W:L ratio (Fig. 3(b)). The example of its use, given for the dashed line of Merevale Lake, Warwickshire, shows a regional estimate of sediment yield of 100 kg ha^{-1} year^{-1}. In order for the lake marginal retreat to have less than a 5% contribution to sediment yield, a retreat of between 0.01 and 0.05 cm year^{-1} must be assumed. The following lakes are plotted: Merevale Lake (Me, Foster et al., 1985); Seeswood Pool (S, Foster et al., 1986b); Frains Lake (F, Davis, 1976); Loe Pool (L, O'Sullivan et al., 1982); Llyn Peris (P, Dearing et al., 1981); Havgardssjon (H, Oldfield et al., 1983); Mirror Lake (Mi, Likens & Davis, 1975); and Lake Egari (E, Oldfield et al., 1985) (based on a diagram in Dearing & Foster, 1986).

deposition, but attempts by Foster *et al.* (1985) to quantify this component in a slowly sedimenting Midland England reservoir suggests that the atmospheric input could contribute up to 9% of the gross sediment accumulation in recent years.

Estimation of the contribution made by internal productivity can be made by an analysis of the organic content of the accumulating sediment, which may be compared with the organic content of contemporary inflowing sediments. Hakanson & Jansson (1983) have empirically modelled the relationship between density and organic matter content, based on the weight loss recorded when sediments are ignited in a muffle furnace at low temperatures (540°C). Such analyses may only record a small component of the productivity controlled deposition, since diatom frustules composed of silica may constitute a large proportion of the sediment mass. Here, the contribution may be estimated by analysis of the accumulating sediments by an alkaline digestion procedure (cf. Engstrom & Wright, 1984 and Foster *et al.*, 1985, 1986b). Midland reservoirs in the UK may have as much as 30% of their sediment mass accounted for by organic matter and biogenic silica. Another particularly problematic area relates to the secondary precipitation of calcite in lake waters in lakes of high salinity or where soils are carbonate-rich. Extraction techniques seem unable to differentiate between autochthonous and allochthonous calcium carbonate and as far as is currently known, no lake sediment based estimate of sediment yield has yet attempted to deal directly with this problem. Several approaches may be adopted, such as to undertake comparative extractions in soils and lake sediments to assess the gross changes in calcium carbonate content, to undertake XRD analysis to quantitatively distinguish between calcite and dolomite in the sediments and sources, or to adjust for all $CaCO_3$ contents by expressing yields on a carbonate free basis. Other gypsiferous or sodium-rich deposits in arid and semiarid lakes may be more easily distinguished in the lake sediment record and their relative contribution adjusted accordingly. Other autochthonous components may be quantified by means of a variety of chemical methods discussed by Engstrom & Wright (1984) and Bengtsson & Enell (1986).

Authigenic and mixing processes

Of less significance for sediment accumulation studies, but of great relevance to the preservation of chemical and radiometric stratigraphies, is the variable nature of the combined effect of bioturbation and chemical diffusion. These processes are relevant here in that the separation of the sedimentary record into intervals approaching a decade in resolution is wholely dependent upon the mechanisms responsible for the delivery, adsorption and diagenesis of those isotopes which form the basis of radiometric chronologies. The two isotopes most commonly employed for short core studies are ^{137}Cs and ^{210}Pb. For timescales exceeding 100–200 years, varved, ^{14}C and/or palaeomagnetic chronologies may be more appropriate (see below). Few models as yet exist to quantify the significance of these components, but Fisher *et al.* (1980) in a series of laboratory experiments have shown how *Tubifex tubifex* incubated at different levels in the sediment could affect the movement and diffusion of ^{137}Cs in a laboratory tank experiment and Davis (1974) demonstrated that feeding depths of tubificids reached 15cm in the profundal sediments of Messalonskee Lake, Maine. More recently, Hakanson & Jansson (1983) have proposed a dynamic model of the process, which incorporates parameters such as sediment depth, rate of sedimentation, water content, bulk density, compaction, biotransport, substrate decomposition and bioturbation limit. Such a model may form the basis for assessing the importance of density variations as well as the bioturbation process on sediment yield estimation.

BOTTOM SEDIMENT SAMPLING

The selection of an appropriate sampling framework in order to provide accurate and precise estimates of sediment yields involves several problems. To date, most studies have performed multiple corings in order to account for the spatial variation in deposition rate. The coring densities associated with studies with which the authors have been involved range from 1 per 0.0035 ha in Llyn Goddionduon to 1 per 12.1 ha in Dayat er Roumi, Morocco. Some examples of coring densities are given in Table 1.

The sampling framework is usually arranged on a rectangular grid to

Table 1 *Coring densities in bottom sediment studies*

Site and Location	*Lake area (ha)*	*Coring density (ha per core)*
Goddionduon (1) *North Wales*	*6.2*	*0.0035 - 0.04*
Frains Lake (2) *Michigan*	*6.7*	*0.3*
Havgärdssjön (3) *Scania, Sweden*	*55*	*1.0*
Llyn Peris (4) *North Wales*	*20*	*1.3*
Merevale (5) *Midland England*	*6.5*	*0.08*
Seeswood (6) *Midland England*	*6.7*	*0.16*
Egari (7) *New Guinea*	*8.5*	*1.7*
Loe Pool (8) *Southwest England*	*44*	*1.0*
Geirionydd *North Wales*	*30*	*0.87*
Catherine *Northern Ireland*	*36*	*1.5*
Llangorse *Mid Wales*	*150*	*3.0*
Roumi(9) *Morocco*	*85*	*12.1*
Affougah (9) *Morocco*	*6*	*1.2*
Azigza (9) *Morocco*	*37*	*7.4*
Bussjo *Scania, Sweden*	*0.84*	*0.12*

1 = Bloemendal et al. 1979; 2 = Davis 1976; 3 = Dearing 1986; 4 = Dearing et al. 1981; 5 = Foster et al. 1985; 6 = Foster et al. 1986; 7 = Oldfield et al. 1985; 8 = O'Sullivan et al. 1982; 9 = Flower et al. (in prep).

improve the speed of sample point location and to ensure that a representative range of sedimentary environments is sampled. With small lakes and reservoirs, such as those listed in Table 1 (largest 150 ha) it is often appropriate to locate sampling stations within the lake either by stakes pushed into the bottom sediments or by buoys anchored at sampling points. Coring positions are identified at the intersection of marked shore stations located by back bearings from the boat to the shore. Where practicable, ropes can be stretched across small lakes and reservoirs between shore stations laid out by local ground survey. Exact coring positions may be located on each transect by measuring distance across the lake. Further refinements may be introduced with the use of automated techniques for sample site positioning, especially on large water bodies (e.g. Lambert, 1982; Battarbee *et al.*, 1983; Bruk, 1985). On lakes which are seasonally frozen, cores may be retrieved through the ice and traditional land survey techniques may be used to locate sampling positions.

Sediment retrieval

Numerous techniques have been developed in order to retrieve bottom sediments from lakes and reservoirs. The exact method selected will depend on the following criteria:

(a) depth of water;
(b) whether the water surface is frozen;
(c) stability of the coring platform;
(d) thickness of the sediment to be cored;
(e) cohesive properties of the sediment;
(f) whether an undisturbed surface is to be retrieved;
(g) whether undisturbed samples are to be subsampled in the field;
(h) mass of sediment required for subsequent analysis; and
(i) whether sediments are laminated.

Various sampling methods have been reviewed, for example, by Wright (1980) and Aaby & Digerfeldt (1986). Figure 4 illustrates some of the basic principles of corer operation. For example, Fig. 4(a), the "Russian" corer, is a chamber corer which samples undisturbed material. However, it can only be operated from a frozen surface or a stable raft or platform and, with deep water (>3–4 m), it requires guide tubes to avoid bending the rods. It is unsuitable for low density surface sediments, but in higher density materials it may retrieve a sufficiently undisturbed sample for density and palaeomagnetic determinations. In deeper water where rod operation is impractical, a line operated piston type sampler may be more appropriate (Fig. 4(b)). The fixed line holds a Kullenberg (1947) seal above the sediment surface and the piston is driven past the seal into the sediment with a line operated weight. The partial suction created by the seal prevents the sample falling out of the piston as it is raised to the surface. The "frozen finger" type sampler (Fig. 4(c)) is a gravity operated device which is filled with dry ice and alcohol. The sediment freezes to the outer surface of the corer which is retrieved with the hand line. Although the sampler may be unsuitable for density analysis, the

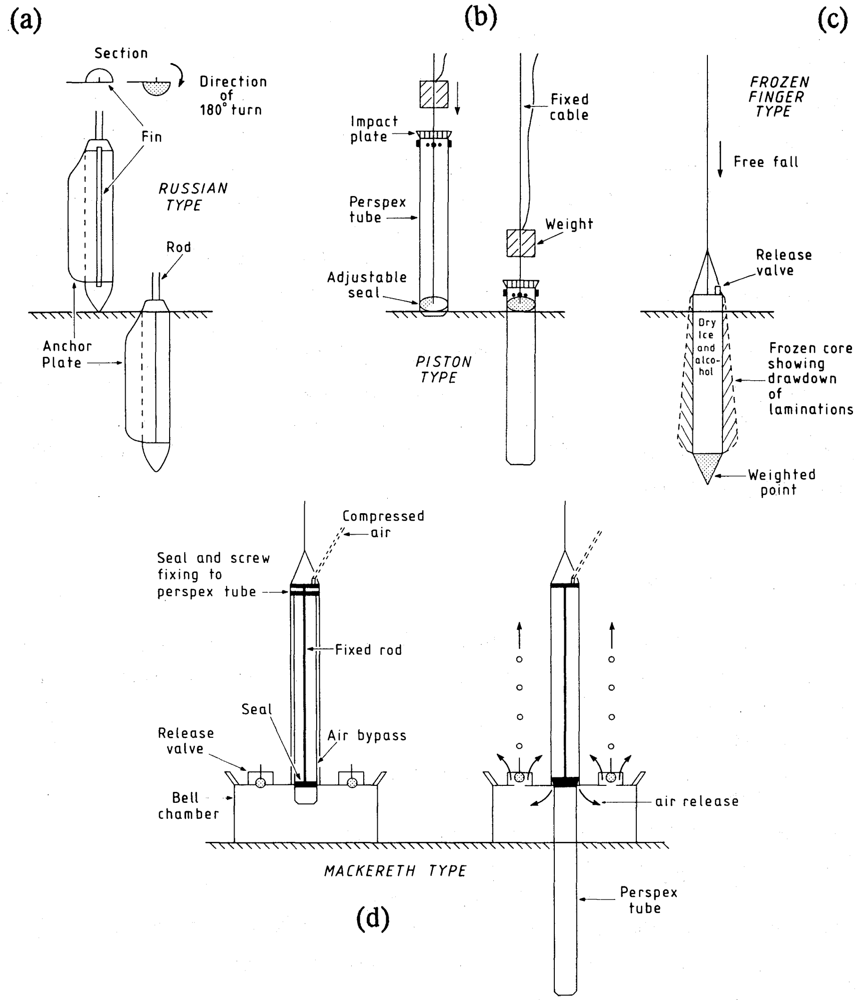

***Fig. 4** Coring devices for sediment retrieval: (a) the Russian type; (b) the piston type; (c) the frozen finger type; and (d) the Mackereth (pneumatic) type.*

technique is particularly suitable for the study of laminated sediments (cf. O'Sullivan *et al.*, 1982). One of the most important developments has been the availability of compressed air driven samplers (cf. Mackereth, 1969) which are capable of retrieving an undisturbed sediment surface as well as continuous cores of up to 6 m of undisturbed material from a variety of depths and, theoretically, in any depth of water exceeding the length of the corer. The principle of operation of the "mini corer" is shown in Fig. 4(d). A bell chamber provides a stable platform for the coring operation and the piston is pushed past a seal with compressed air pumped into the corer from the boat. The corer penetrates the sediment and air bubbles released through the release valves indicate completion of coring at the water surface. The corer is retrieved by hand. For 3 and 6 m versions of this sampler, the system is modified to "suck" the corer chamber into the sediment in order to improve stability and, once coring is complete, this chamber fills with compressed air to provide lift. Both corers can be operated from small boats. One of the greatest limitations of the piston samplers, including those driven by compressed air, is that they are unreliable in sediments with low cohesion and high water contents. Estimates of density are subject to error in the Mackereth and similar types of piston corer because some compaction, foreshortening and even sediment loss may occur during sampling (Blomqvist, 1985) and vertical extrusion of cores with a piston may also lead to some compaction.

Core correlation and dating

Since sedimentation rates vary across the lake or reservoir bed, an important aspect of sediment yield reconstruction is the identification of time synchronous layers within the sediments, in order to calculate sediment volume. The solution to this problem demands some means of both core correlation and dating. Although dating methods may be applied to all cores, the prohibitive cost and time consuming nature of the analysis will frequently preclude more than one or two dated cores per lake. The techniques of core correlation have recently been reviewed by Dearing (1986) who suggested that correlation of synchronous levels between sediment cores demands that the property used for correlation should be areally continuous and synchronous. Various methods of core correlation have been used in lake and reservoir studies and these are summarized in Table 2. One of the more important developments in core correlation in recent years has been the measurement of the magnetic properties of lake sediments (see Thompson & Oldfield, 1986). These properties were shown to be particularly useful because of the speed of measurement in the first study of this type (Bloemendal *et al.*, 1979) and a range of magnetic properties have been used in many subsequent lake sediment based studies of sediment yield (e.g. Dearing *et al.*, 1981; Dearing, 1986; Foster *et al.*, 1985, 1986b). More recent investigations by Hilton & Lishman (1985) have, however, shown that some properties, such

Table 2 Some methods of core correlation

1 ***Visible Stratigraphy***	*e.g. annually laminated sediments (Simola et al., 1981);* *changes in texture and colour (e.g. Digerfeldt, 1976);* *tephra layers (Thompson et al., 1986).*
2 ***Palaeoecological Stratigraphy***	*e.g. Pollen horizons (Digerfeldt, 1974; Davis, 1976);* *diatom assemblages (e.g. O'Sullivan et al., 1973)*
3 ***Chemical Stratigraphies***	*e.g. loss on ignition (Tolonen et al., 1975; Davis, 1976).*
4 ***Radioisotope Record***	*e.g.* ^{137}Cs *record in surface sediments (Pennington et al., 1976).*
5 ***Magnetic Correlations***	***based on natural remanent and induced magnetic properties (see Thompson & Oldfield, 1986 and text for detail).***

as magnetic susceptibility may be controlled by a diagenetic process under differing redox conditions and may not be controlled by allogenic inputs to the lake basin. Some care should be exercised in selecting the most appropriate basis for magnetic or other core correlation methods, in order to adhere to the principles of areal continuity and areal synchroneity.

Provision of an accurate chronology is undoubtedly the most important aspect of sediment yield reconstruction and a variety of techniques have now been developed. These techniques may be based firstly, on the preservation of palaeomagnetic properties of inclination, declination and intensity, calibrated on a regional basis with radioisotope ages; secondly, on the production of natural isotopes in the environment which decay at a known rate relative to a stable form, such as ^{14}C and ^{210}Pb; thirdly, on the presence of an isotope such as ^{137}Cs which was introduced into the environment from atmospheric weapons testing; and, fourthly, on the existence of rhythmic or annual laminations or varves (cf. O'Sullivan, 1983). Space does not permit a full discussion of the technical problems involved and a number of recent reviews have dealt with palaeomagnetic methods (Thompson & Oldfield, 1986; Thompson, 1986) and radiometric dating including weapons testing isotopes (Cambray *et al.*, 1982; Lowe & Walker, 1984; Oldfield & Appleby, 1984; Olsson, 1986).

For reservoirs constructed over the last 200 years or less, a combination of ^{210}Pb and ^{137}Cs analyses seem to be most appropriate in providing resolution of a decade or less over the appropriate time period. Given the half life of ^{210}Pb of 22.26 ± 0.22 years, this radionuclide is particularly suited to this timescale and can potentially give accurate age determinations for up to 150 years. Recent investigations by Flower *et al.* (1989) in North Africa have, however, experienced some difficulty in obtaining a reliable chronology older than 30 years BP from this isotope in a lake basin which is accumulating at a particularly rapid rate.

One of the most important problems recently identified is the potential unreliability of the ^{137}Cs record and its apparent dependence not only on the bioturbation and mixing processes outlined above, but also on the potential downward molecular diffusion and adsorption of this ion. This problem was highlighted by Davis *et al.* (1984) in a number of Scandinavian and New England lake sediment cores which were dated by pollen marker horizons as well as by the ^{210}Pb method. The latter appears to be little affected by downward diffusion through the sediment column.

Some examples of the application of ^{137}Cs and ^{210}Pb for dating cores are given in Fig. 5 for two Midland England reservoirs. The degree of coincidence between the atmospheric and lake sediment records in Figs 5(a), 5(b) and 5(c) is variable and the correlation of these records with the ^{210}Pb record shown in Figs 5(d) and 5(e) depends on the model used to calculate the depth:age relationship in the sediment. At least two dated cores seem to be necessary to overcome the problems of sediment focussing discussed above and other independent means of core correlation between the two dated cores should be used in order to "fine tune" the depth:age curve in different parts of the basin (cf. Oldfield & Appleby, 1984; Fig. 5(e)).

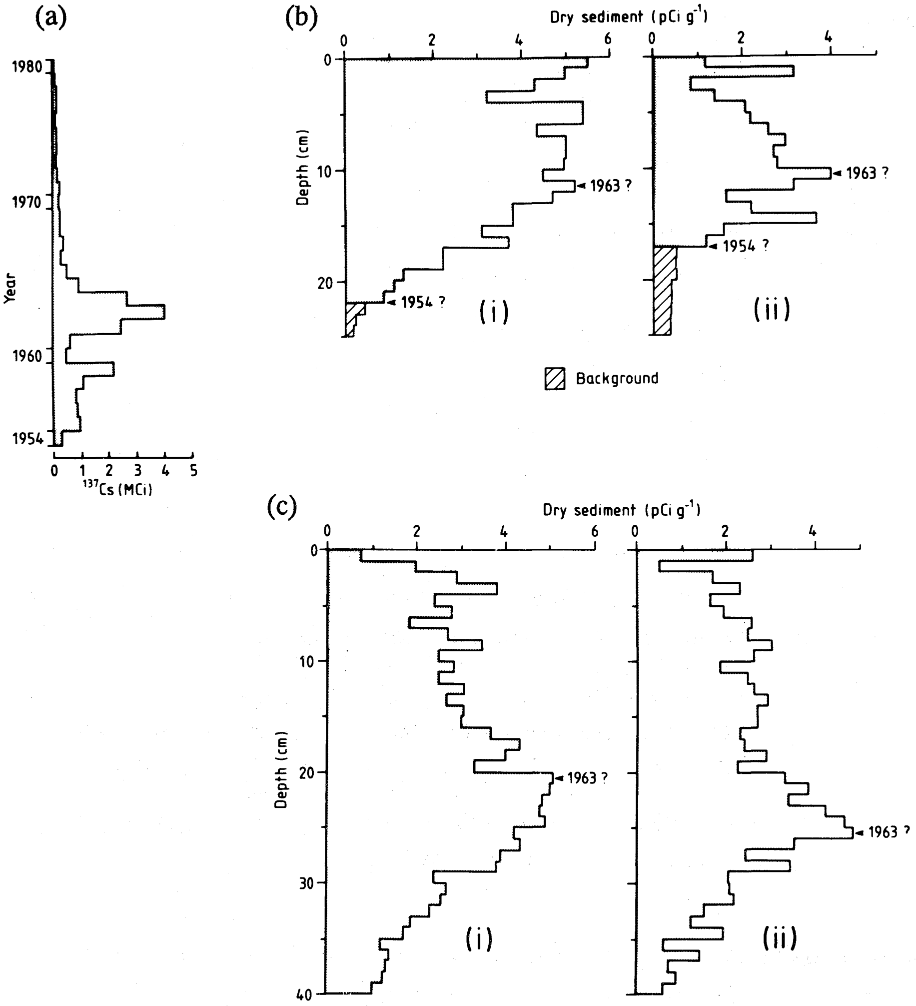

Fig 5 Radiometric dating of lake sediments: (a) the record of atmospheric fallout of ^{137}Cs in the northern hemisphere (based on data in Cambray et al., 1982); (b) ^{137}Cs record in Merevale Lake from cores A (i) and 11M (ii) (Foster et al., 1985) showing approximate position of 1954 and 1963 peaks; and (c) ^{137}Cs record in Seeswood Pool from cores C10 (i) and G2 (ii) (Foster et al., 1986b) showing approximate 1963 peaks. Sedimentation rates in Seeswood pool are approximately twice those of Merevale in the upper part of these cores.

SEDIMENT YIELD CALCULATION AND INTERPRETATION

The total influx of sediment to a lake or reservoir for each synchronous and dated horizon can be obtained by multiplying the associated mean wet sediment volume of each core by the percentage weight loss measured by

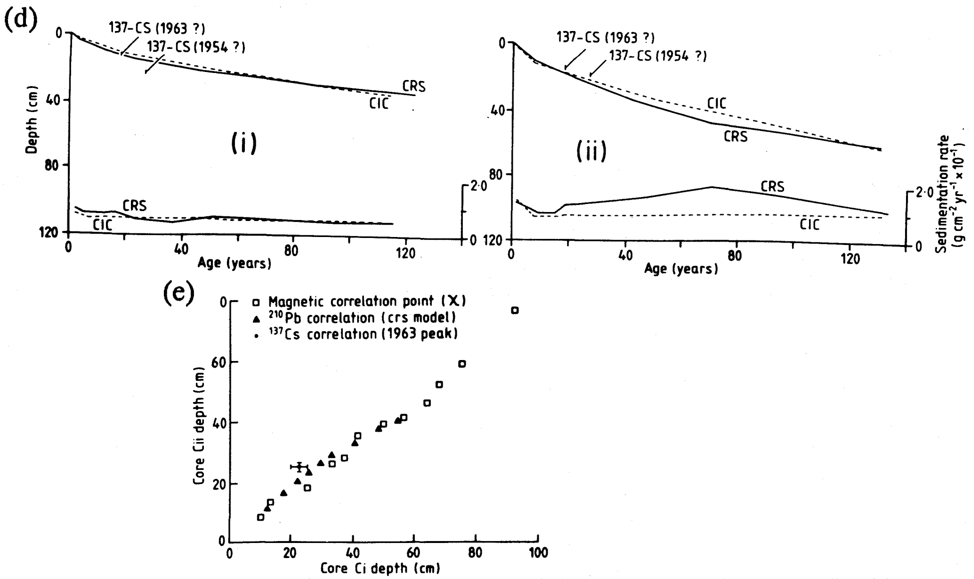

Fig. 5 Radiometric dating of lake sediments (continued): (d) comparison of the "Constant Rate of Supply" (CRS) and "Constant Initial Concentrations" (CIC) models for ^{210}Pb dating (see Oldfield & Appleby, 1984 for discussion); depth-age chronologies and sedimentation rates are for the two cores from Merevale lake shown in Fig. 5 (b)(i) and 5 (b)(ii), ^{137}Cs dates are also plotted for comparison; (e) comparison of radiometric chronologies (^{137}Cs and ^{210}Pb) for the Seeswood Pool cores (Fig. 5 (c)(i and ii)) as related to an independent magnetic correlation.

oven drying at 110°C, in order to obtain total dry sediment mass. A more accurate method is to use the dry sediment density data for all cores within each synchronous zone. A map of the dry sedimentation rate for each area of the basin can then be produced for each time zone, such as that shown in Fig. 6. The total mass of dry sediment over the lake bed is then calculated after measuring the area of lake bed receiving different amounts of dry sediment. This procedure not only accounts for the spatial variability in sedimentation rate across the lake bed but enables examination of how the patterns of sedimentation have changed through time. In the two examples shown in Fig. 6, early sedimentation in both reservoirs is restricted to the old river channels and valley floors. As time proceeds and these zones fill with sediment, the area receiving material expands towards the more marginal zones where later accumulation occurs.

As described above, the total mass of accumulating sediment is only partly a function of processes operating in the drainage basin and some attempt should be made to account for losses due to changing trap efficiency, and increases in mass caused by atmospheric input, lake marginal erosion and autochthonous and diagenetic contributions. These adjustments frequently demand chemical and other determinations on the retrieved sediment.

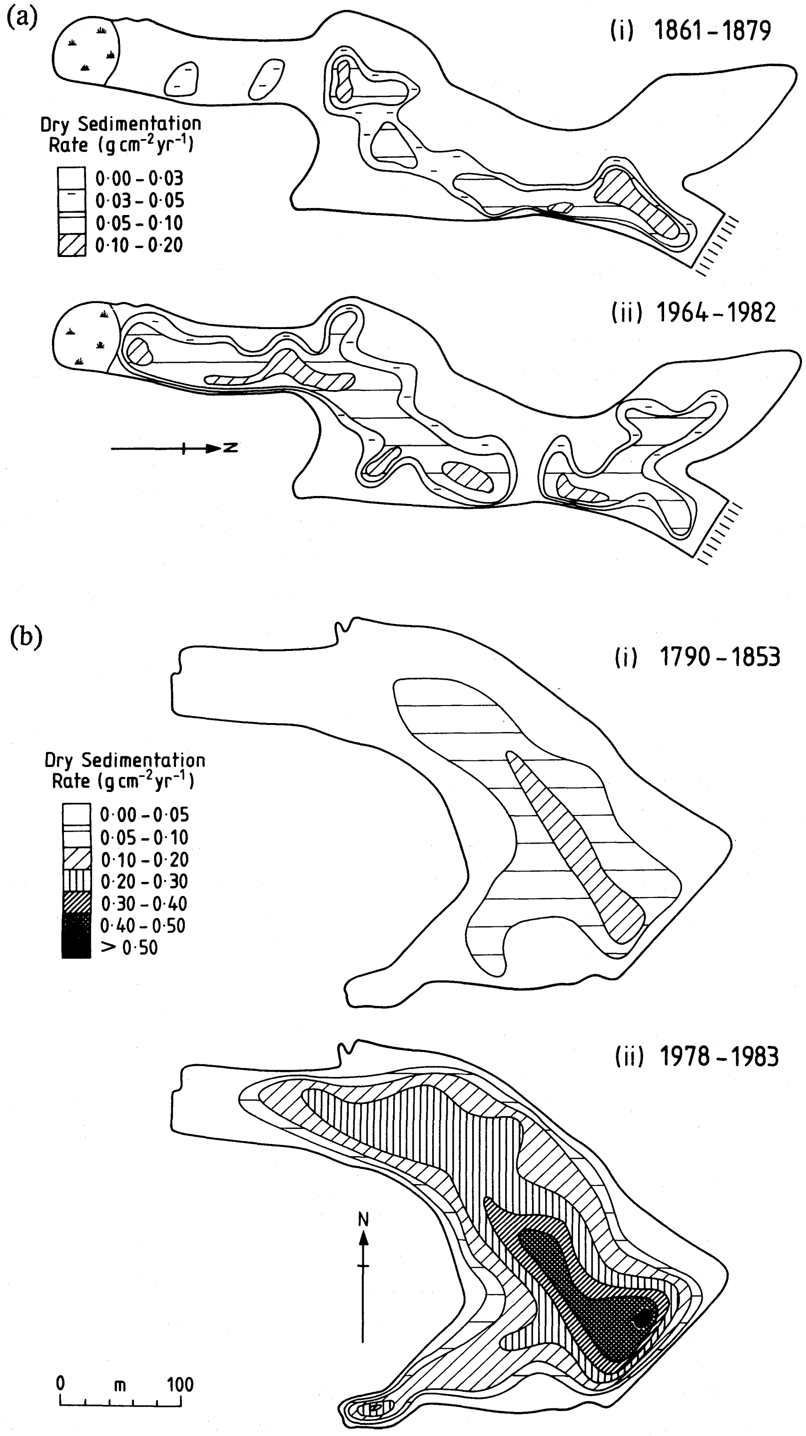

Fig. 6 Change in sedimentation patterns in reservoirs: (a) Merevale lake; (b) Seeswood Pool, showing the expansion of sedimenting area as the valley floor infills in both reservoirs.

Interpretation

Having subtracted the mass of sediment which is non-denudational, the remaining fraction should represent a value close to that calculated from river based sediment yields. Some attempt has been made to evaluate the correspondence between sediment yields calculated from river discharge and turbidity measurements and from reservoir sedimentation in Midland England (Foster *et al.*, 1985). This study has shown that within the likely variability in annual sediment yields demonstrated by the turbidity record, the adjusted lake sediment-based estimate of yield produces comparable results for the most recent time period. To date, however, insufficient emphasis has been placed on the comparison of lake sediment based estimates with estimates derived from river based studies.

To date, less than 10 continuous reconstructions of sediment yield, based on multiple coring of bottom sediments, have been published. These records cover a range of environments from Tropical lakes in highland Papua New Guinea (Oldfield *et al.*, 1985) to lowland lakes in seasonally cold environments of Southern Sweden (Dearing, 1986). Some of these records are reproduced in Fig. 7(a). Two types of lake are represented in this diagram. First, Frains Lake and Lakes Egari, Havgärdssjön and Bjäresjö are lakes receiving no channel inflow, where all inflowing sediments are presumably derived from surface erosional processes and/or lake marginal erosion. In contrast, the three lakes with lower sediment yields all have at least one and, in the case of Seeswood Pool, two major channel inflows. (The apparent decline in the sediment yield in Bjäresjö through the period of record appears to relate to a change in contributing catchment area).

In addition to the historical picture given by the published lake sediment based estimates of sediment yield, resurveys of reservoirs have provided average yield estimates over varying timescales. Some of these latter data have been used with the more detailed reconstructions to construct Fig. 2(b), which shows the relationship between the catchment to lake area ratio (CLR) and the estimated basin sediment yield. Two trends emerge from this relationship. First there is a general increase in yield with decreasing CLR. Secondly, two subsets appear in the data which distinguish forested basins with a lower yield than other basins for the same CLR. The upper relationship (Curve 1: Fig. 7(b)), which is statistically significant at the .001 level, includes a wide diversity of environments and land use types and the two patterns may be interpreted in a number of ways. First, the relationships suggest that the impact of deforestation on sediment yields is significantly affected by basin size, with smaller basins being more sensitive to change (the ratio between forested and non forested basins with a CLR approaching 1.0 is around a factor of 10 whereas in basins with a CLR of 100, the factor is less than 5). Secondly, not only can this relationship be demonstrated for different environments, but comparison of the trends shown by Frains Lake, and Lakes Egari and Bjäresjö demonstrates the same magnitude of change appropriate to their CLRs. Furthermore, comparison of Merevale Lake and Seeswood Pool, which are both in Midland England and have almost identical CLRs but contrasting land uses, indicates a ratio of forested to deforested basins in

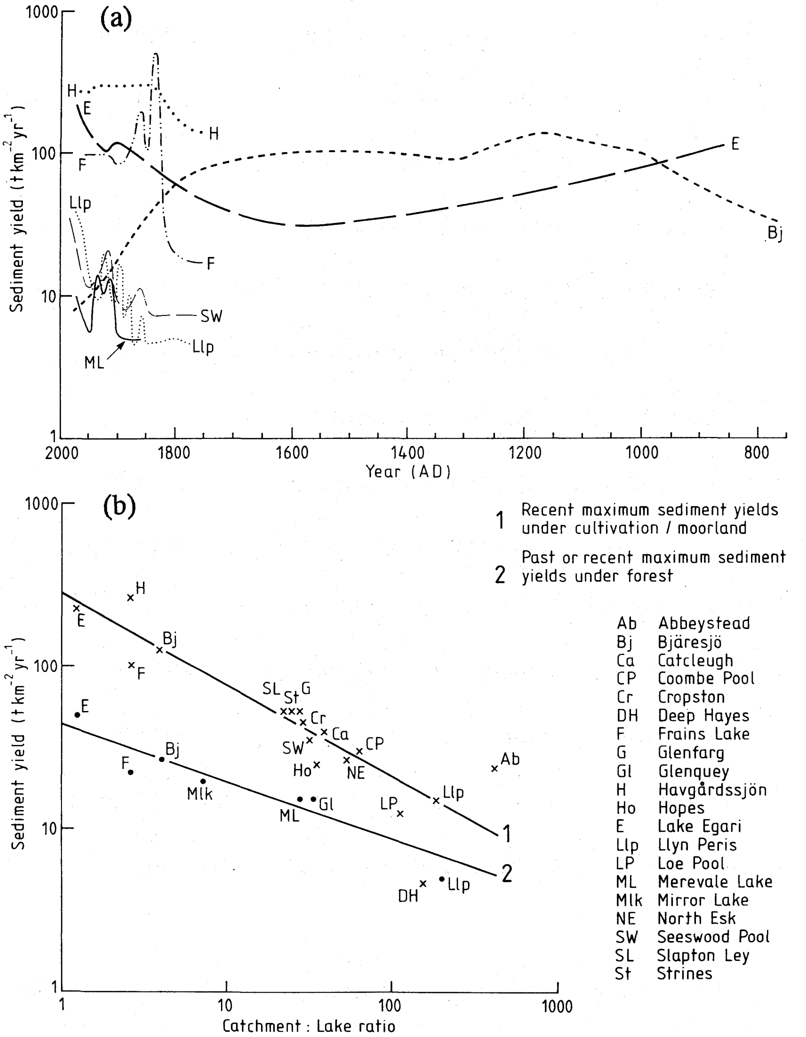

Fig. 7 Sediment yield estimates from lake and reservoir based studies: (a) some long term trends in sediment yield from lake sediment based studies; (b) sediment yields as related to the catchment to lake ratio (CLR). These include both lake sediment based and reservoir resurvey data, making allowance for water content and density.

Data from the following published sources: Crick (1985), Davis (1976), Dearing (1986), Dearing et al. (1981), Cummins & Potter (1972), Foster et al. (1985), Foster et al. (1986), Hall (1967), Ledger et al. (1974), Likens & Davis (1975), McManus & Duck (1985), Oldfield et al. (1985), O'Sullivan et al. (1982), Rodda et al. (1976) and Young (1958).

accordance with the general relationships obtained. The CLR parameter is dominated by the influence of catchment size and it is suggested that it may closely relate to the sediment delivery ratio in fluvial studies (cf. Walling, 1983).

An ability to reconstruct patterns of sediment yield for a single environment is valuable for a number of reasons. Firstly, it is possible to exert some experimental control on the influence of catchment size on the computed result. (A paired lake catchment based study should account for the changing sensitivity of the environment at different CLRs). Secondly, careful selection of the basin enables testing of various models of the fluvial environment and general models of landscape sensitivity to change by using historical data to conduct experiments on our behalf (cf. Deevey, 1969). The contemporary analogue model produced by Wolman (1967) is frequently reproduced in fluvial texts, yet the quantitative reconstruction of sediment yields following deforestation presented by Davis (1976) rarely appears in the hydrological literature. This latter study evaluates not only the equilibrium conditions under forest and clearance but also quantifies the response to and recovery from a period of change. Conceptually, the latter is to be preferred and one might argue that the Wolman model should be modified in the light of these data. More recently, the lake sediment based record of sediment yield has been used to evaluate the important controls on sediment production in contrasting environments through an analysis of the relationship between historical rainfall records and sediment yield for the last two centuries (Dearing & Foster, 1987) and in association with tephra layers, the technique has been used by Thompson *et al.*, (1986) to calculate changes in the sediment input to Icelandic lake sediments.

The lake sediment based record of sediment yield is undoubtedly suboptimal for a detailed evaluation of contemporary process dynamics, but it has already been shown to add a significant dimension to the interpretation of sediment yield and sediment source data at a timescale relevant to the testing of hydrological and fluvial models of landscape change.

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