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Can reservoir bottom sediments be used in the estimation of long-term catchment sediment budgets?

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Abstract In the last 30 years, major progress has been made in the development of methods for establishing catchment sediment budgets. Reservoir bottom sediments are important because they provide valuable medium- to long-term archives of catchment sediment yield. Dating techniques, such as ^{137}Cs and ^{210}Pb further provide the opportunity to subdivide this stratigraphic record into shorter time periods. Recently, sediment-fingerprinting approaches have been applied to dated sediment cores to gain insight into changing patterns of sediment supply. In this study, a land-use-based sediment fingerprinting study was undertaken in the 4.9 km^2 Crombie Reservoir catchment in northeast Scotland to infer historical changes in sediment supply over the past 135 years. The unmixing model employed, features a novel enrichment-inclusive subroutine. Fingerprinting results show a rise in agricultural sediment production from effectively zero in 1890 to >80% in 1980, with patterns broadly correlating to known land-use changes with a climatic overprint.

Key words Crombie Reservoir, Scotland; enrichment; land-use reconstruction; sediment budget; sediment fingerprinting

INTRODUCTION

Sediment budgets are useful and powerful conceptual frameworks for examining the relationships between sediment sources, sinks, catchment yields, residence times, land-use, and climate variability. Over the last 30 years, major progress has been made in the development of methods and techniques available for establishing and predicting long-term catchment sediment budgets. One example is the study of reservoir bottom sediments, which provide important archives of historical sediment supply, since they are typically sequential and undisturbed over medium to long timescales and offer the potential to elucidate longer-term (10s–100s years) regional trends (Duck & McManus, 1995). Important limitations should be considered when using reservoir sediments for long-term sediment yield estimations, including proper identification of the true catchment area (including catchwater systems), adequate characterization of sediment trapping efficiency, and representative measurements of sediment bulk density (Dearing & Foster, 1993).

When considering the body of sediment stored within reservoirs from the time of impoundment, dating techniques (e.g. ^{137}Cs, ^{210}Pb) provide the opportunity to subdivide the stratigraphic record into shorter time periods and, where comparable data exist for several sites, provide a basis for estimating regional sediment yields. More recently, sediment-fingerprinting approaches have been applied to dated sediment cores to gain insight into changing patterns of sediment supply. Fingerprinting uses certain diagnostic properties of cored sediment samples to quantify the relative importance of representative catchment sediment sources (e.g. erosion of topsoils *vs* channel banks). A significant problem associated with such reservoir sediment-based reconstructions of sediment yields is whether a change in yield represents: (a) an increase in erosion rate from the same source; (b) a change in sediment source; (c) a change in sediment delivery ratio; or a combination of all three factors (Walling, 1990).

This study reports the use of a range of radionuclide, mineral magnetic, and geochemical properties of reservoir sediments compared with the same properties of catchment source sediments to identify changes in eroded sediments over time (cf. Krause *et al.*, 2003), and tests whether known land-use changes can be reproduced using a fingerprinting unmixing model (FR2K), inclusive of a novel enrichment routine. The latter was validated using test admixtures and is shown to produce reliable results.

STUDY AREA CHARACTERISTICS AND SAMPLING METHODS

The 16-ha Crombie Reservoir (British National Grid Reference NO 515527) is situated within the northeastern sector of the Midland Valley, Scotland, UK. The mean annual precipitation in the area is 860 mm year^{-1}, and the rolling topography of the 4.9 km^2 catchment is characterized by a limited relative relief ranging from 160 to 210 m. Straightening and resectioning associated with both agricultural drainage operations, and the construction of a railway embankment which bisects the catchment, have modified the channel network extensively. Present land-use is a mixture of woodland, rough and improved pasture, and arable land (Small *et al.*, 2003).

Due to the relatively homogeneous underlying geology, potential sediment source groups were defined on the basis of land-use classes. Twenty samples were collected from sites representative of each of the four land-uses, with a further 30 samples collected from channel bank sources; the sampling scheme was limited by accessibility and permission aspects. Additionally, a core capturing a profile of undisturbed reservoir sediments was collected (representing target sediment) and analysed at 0.5–1 cm intervals. Each of the 110 bulk source samples and 75 target samples were subjected to particle size analysis (Coulter LS230 laser granulometer) to generate the specific surface area (SSA) values the fingerprinting unmixing model employed. Although many tracers have great potential (see Foster & Lees, 2000), time, financial, and analytical resources have constrained the present study to the following sediment property measurements:

(a) χ_{lf} – low frequency (0.47 kHz) magnetic susceptibility (μm^3 kg^{-1}).
(b) χ_{hf} – high frequency (4.7 kHz) magnetic susceptibility (μm^3 kg^{-1}).
(c) X-ray fluorescence spectrometry (XRF) to determine:

(i) Major oxides: Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO and Fe_2O_3 (% concentration).

(ii) Trace elements: V, Cr, Co, Ni, Cu, Zn, Pb, Rb, Sr, Y and Zr (mg kg^{-1}).

A fractionation procedure (cf. Walden & Slattery, 1993) was undertaken on two representative samples from each of the five source groups ($n = 10$). This involved the settling out of sediment particles, according to Stokes' Law, into four sub fractions (<2 μm, 2–16 μm, 16–63 μm and 63–1000 μm). Subsequently, the fractionated samples were subjected to the same particle size (to determine SSA), magnetic susceptibility, and geochemical analysis programmes as the original bulk samples.

FR2K SEDIMENT FINGERPRINTING MODEL

The sediment fingerprinting model (FR2000) was first developed by Franks & Rowan (2000) for assessing uncertainty issues in such models. The model assigns mean source group contributions to target sediment (i.e. a reservoir sediment profile) and calculates confidence intervals (e.g. 95%). FR2000 achieves this through Monte Carlo sampling of the derived probability distributions for each sediment source and sink; subsequently, these are fed into an optimization scheme. The modelling routine has been validated using synthetic and controlled laboratory data and has been shown to produce reliable results (Small *et al*., 2004).

A new version of FR2000 (now FR2K) has been developed to include a specific surface area (SSA) based grain-size enrichment function. SSA dependency is determined from the analysis of size-separated sediment subsamples from the source and target areas, producing functional relationships between the tracer concentrations and corresponding SSA values. Functions are made dimensionless by dividing the size-separated tracer concentrations and SSA values by the corresponding bulk values.

Tracer selection procedure

To minimize modelling uncertainty, it is necessary to apply a general tracer selection procedure. The first stage is to evaluate their grain-size dependency, as expressed by SSA values. Tracers showing a high degree of scatter and/or unexplainable grain-size dependency, are removed from further analysis. The second stage is to subject the remaining tracers to Multiple Discriminant Analysis (MDA) to establish a composite suite of tracer properties capable of discriminating between the identified source groups. Final appraisal of the selected tracers is undertaken to ensure their reliability and also tracers vulnerable to diagenetic processes (e.g. certain magnetic parameters, oxides in lake cores) must be avoided (cf. Foster & Lees, 2000).

Validation of updated FR2K enrichment routine

The tracer selection process was applied to controlled soil mixture data as a validation exercise for the FR2K enrichment routine. A series of artificial mixtures of known source group contributions, and various degrees of enrichment, were created and analysed to produce a test batch of mixtures. Four tracers were identified from MDA analysis; the resultant plots suggested that they should produce reliable results. Tracer variability expressed as a coefficient of variation was held at 10%, based on previous measurements and by comparison with peer-reviewed datasets (cf. Collins & Walling, 2002).

Figure 2(a) and (b) illustrates the results of a two-source, group modelling exercise. The original bulk source group tracer and SSA values (corrupted values; Fig. 1(a)) and the corrected tracer and SSA values (Fig. 1(b)) were independently applied to the enrichment scheme, with the associated functional relationships. It is evident from an examination of the corrupted results that the model fails to apportion the source group contributions with any degree of accuracy. The modelled mean and controlled source group contributions show a 4–47% deviation, with large uncertainty envelopes ranging from 40 to 90%. The results of the corrected values illustrate that the differences between the modelled mean contributions and the controlled source group contributions were small (0–3% deviation).

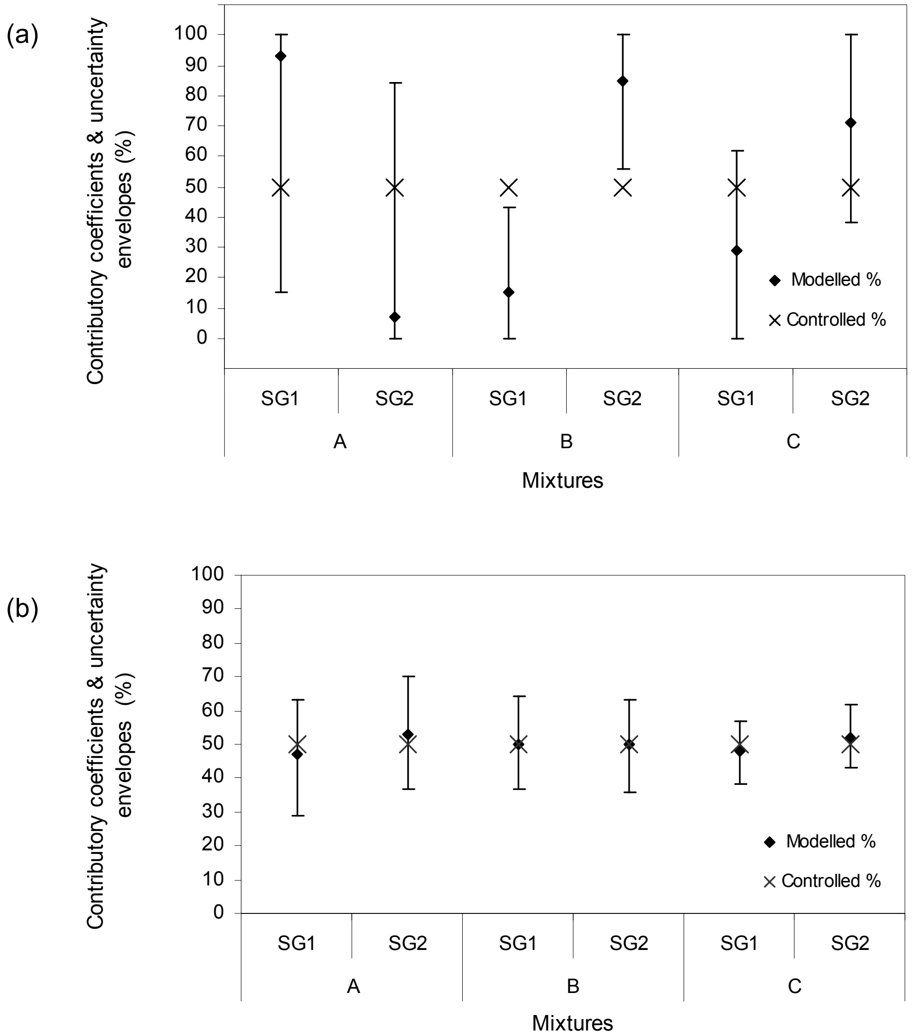

Fig. 1 Enrichment routine: (a) unmixing two SGs (corrupted values), and (b) unmixing two SGs (corrected values).

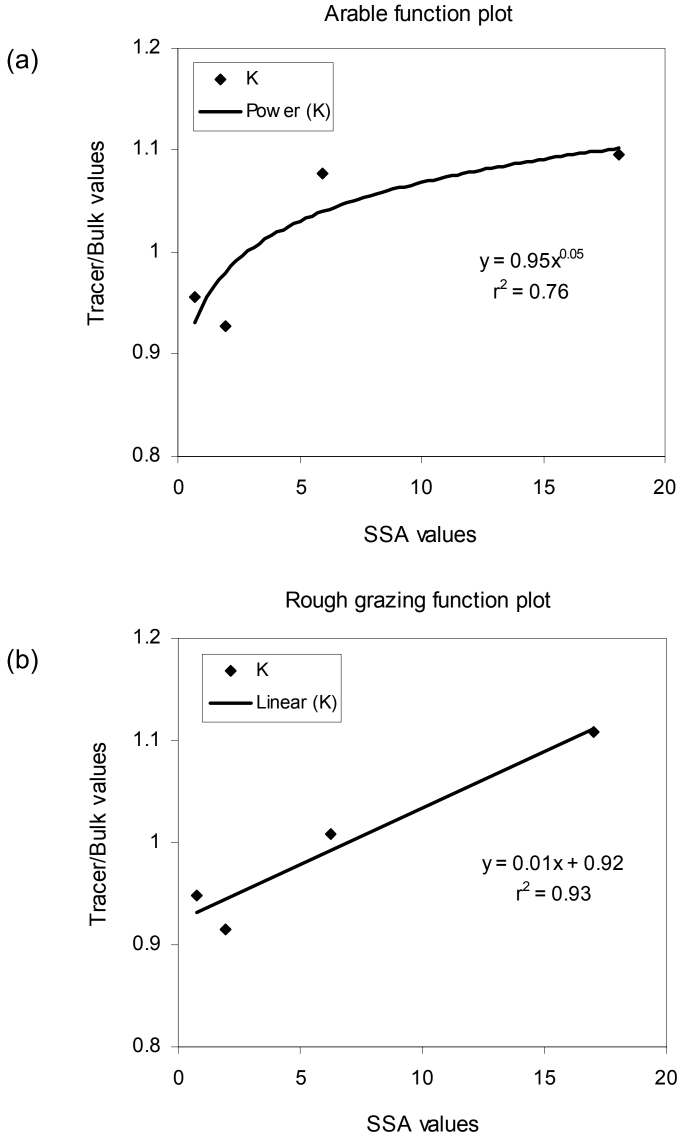

Fig. 2 Function plots (tracer K) for two catchment source samples.

These results illustrate that tighter levels of accuracy occur when applying the enrichment routine to enriched/depleted data (corrected values) compared with the original (corrupted) bulk data. It is evident that in any rigorous sediment fingerprinting study, the grain-size dependency of tracer properties has to be identified and, more importantly, has to be accounted for in the unmixing modelling routine.

Application to Crombie Reservoir: land-use reconstruction

The history of sediment deposition in Crombie Reservoir over the past 135 years was reconstructed using ^{137}Cs and mineral magnetic dating controls (Small *et al.*, 2003). Dated sediment cores provided the opportunity to test how effectively a stratigraphically-based fingerprinting approach can reconstruct the land-use history of the catchment.

Two representative samples from each of the five source groups were size-fractioned (<2 μm, 2–16 μm, 16–63 μm and 63–1000 μm), and the tracer selection was used to exclude erratic behaviours. The remaining tracers were subjected to MDA analysis that revealed six statistically significant tracers: χ_{hf}, CaO, Al_2O_3, MgO, K_2O, and P_2O_5, many of which showed a high grain-size dependency. The FR2K enrichment procedure was applied to infer source-group contributions as each tracer (e.g. K_2O; see Fig. 2) exhibited different enrichment functions in each of the source groups.

Sediment core samples were selected at 5-year intervals, with additional samples taken at periods of significant land-use changes (Fig. 3(a)). Data from a total of 30 target samples were subjected to the FR2K enrichment routine. The modelling routine was, however, unable to distinguish between arable and improved pasture source group contributions, as had previously occurred when analysing archival map material; therefore, in this study, these will be referred to as agricultural contributions. The modelled mean source group contributions and the associated uncertainty envelopes (95% confidence intervals) for the agricultural source group are illustrated in Fig. 3(b).

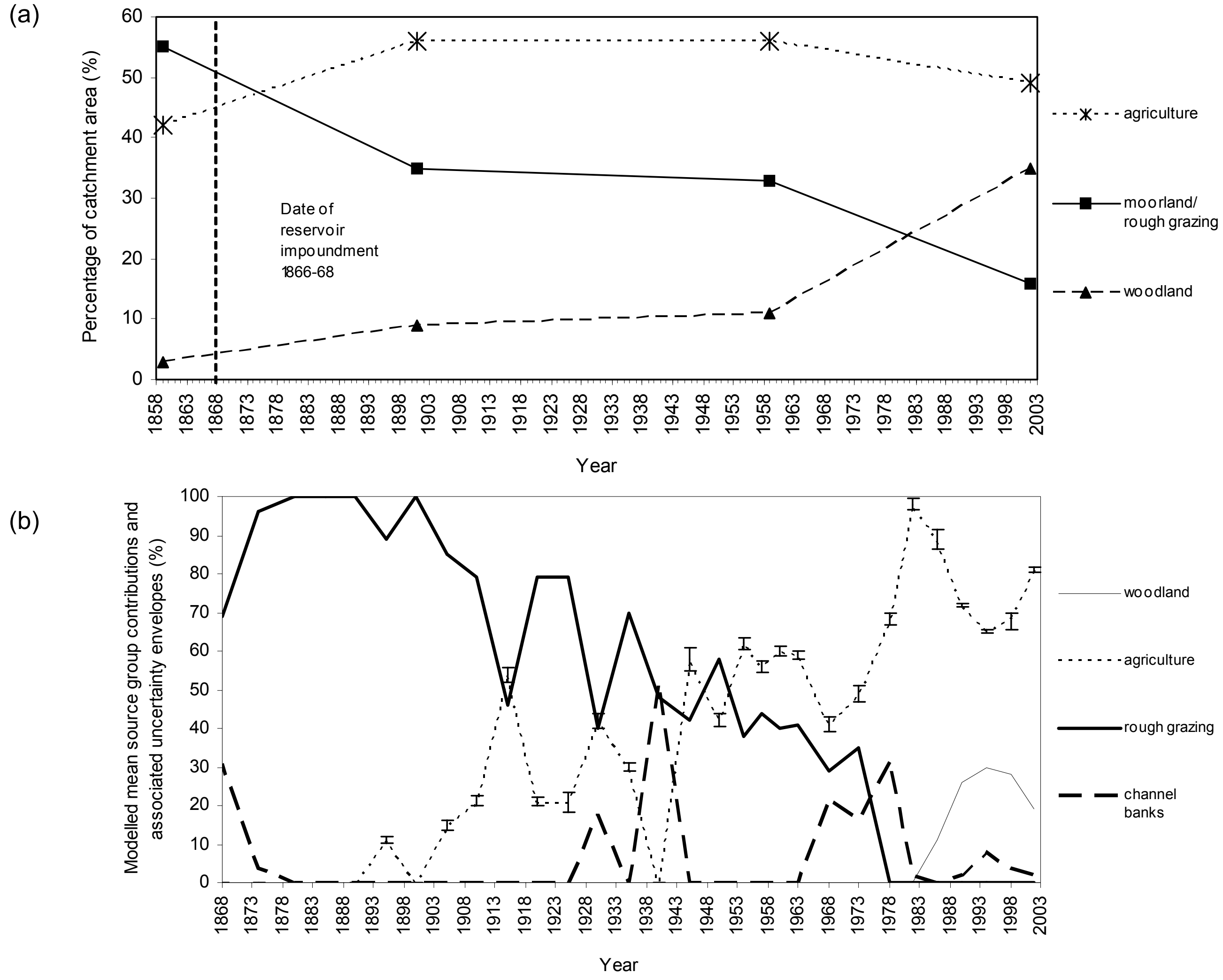

Fig. 3 (a) Observed land use changes in Crombie Reservoir catchment (1859–2002) and (b) modelled source group contributions of reservoir sediments (1868–2002).

Land-use changes reproduced from the enrichment modelling routine illustrate pronounced changes in source group contributions over the 135-year period. The predicted uncertainty envelopes associated with the source group contributory coefficients (Fig. 3(b)) are less than 7%, illustrating tight confidence intervals.

Prior to reservoir construction in 1868, the catchment area was mainly comprised of moorland (55%; Fig. 3(a)). The model results reflect this by suggesting rough grazing as the main contributor (69–100%) of reservoir sediment during this early period. The channel banks, as shown in Fig. 3(b), also are contributing up to 30% of the reservoir sediment during this initial 10-year period (1868–1878); it is suggested that this can be attributed to subsoil contributions from the diversion and enlargement of the Crombie Burn, and extensive water abstraction undertaken during the construction stage of the reservoir. By the late 19th and early 20th century, the model results illustrate two general trends: (1) an increase in agricultural contributions, and (2) a decrease in rough grazing contributions, with a crossover point at around 1914–1915 (the start of WWI). Agricultural contributions, predicted by the model, continue to rise to as high as 98 ± 2% (in 1983), with only a few fluctuations where contributions fall to below 40% (Fig. 3(b)). These results mirror known land-use changes (Fig. 3(a)), with agricultural land-use expanding significantly to become the largest single category in the catchment from 1901 to 2002. Area-specific sediment yields peaked during the 1930–1954 period (Small *et al.*, 2003), provisionally linked to increased agricultural production and land improvement, in the drive to increase domestic food production during World War II.

On the other hand, rough grazing contributions, identified by the model (Fig. 3(b)), decline until the late 1970s, after which no contributions are detectable. From this time forward, woodland source group contributions are identified and peak in 1993–1995 (30% of supply). The sediment contributions recorded in the core sediment profile show correspondence with historical land-use changes, e.g. afforestation schemes were commonplace in the catchment, from the 1960s onwards, and by 2002 this land-use comprised over 30% of the total catchment area (Fig. 3(a)). Channel bank contributions were inferred to peak between 1930–1945 and 1960–1980 (Fig. 3(b)). These periods correspond to episodes of agricultural intensification and afforestation, often linked to modifications in the channel network (cf. Small *et al.*, 2003).

Despite the correspondence between the known land-use history and the inferences of sediment sources provided by the FR2K modelling routine, the relationship between land-use change and sediment flux remains complex, as this will depend on other factors, such as system thresholds (Wasson *et al.*, 2002).

Changes in sediment yield are undoubtedly a complex phenomenon and entail both internal and external controls (i.e. storage effects and climate). Foster & Lees (1999) suggested that a significant proportion of the long-term variability in reservoir-based sediment yields could be accounted for by changing weather patterns (e.g. an increase in the frequency of Lamb's C-type weather patterns (Lamb, 1972) equating to the increased incidence of winter cyclones (see Wilby *et al.*, 1997)). The early 20th century (1900–1950), and the subsequent three decades (1960–1990), featured relatively high occurrences of C-type weather systems, which equate to relatively high mean annual sediment yields, within the same period from the Crombie catchment (58.1–91.7 t km^{-2} year^{-1}). The model results indicate that during these periods channel contributions were significant (e.g. 52% in 1940), whereas in the period 1950–1960, where a reduction in the frequency of winter cyclones occurred, no channel contributions were inferred (Fig. 3(b)).

CONCLUSIONS

The reservoir sediment profile of the Crombie Reservoir catchment appears to strongly reflect land-use change within the catchment as reproduced using an enrichment inclusive modelling routine. However, the comparability of the two independent data sources is questionable given the difference in temporal resolution and degree of confidence between the observed land-use changes and the modelled land-use reconstructions. However, this paper highlights the potential of reservoir sediments as archives of historical sediment supply, and further analysis will investigate a sediment budget in terms of land-use change, and specific yield estimates, based on the accretion rates determined in the reservoir.

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