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Timescales of denudation: the lake-drainage basin approach

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ABSTRACT This paper examines two methods of estimating rates of denudation in small basins in an attempt to compare timescales of 10^0-10^1 years based on stream monitoring with those obtained from lake sediment based studies covering timescales of 10^1-10^2 years. An attempt is made briefly to evaluate the problems associated with each technique and preliminary results from a drainage basin in Midland England are considered.

INTRODUCTION

Rates of erosion and denudation may be assessed in a variety of ways. For example, many studies attempt to isolate the significance of processes in the same environment on the basis of hillslope studies (e.g. Young, 1969) or by means of river water quality data collected at regular intervals for periods of months or years (e.g. Foster, 1980). Other methods include estimates of the dissection of original landforms (e.g. Mills, 1976) or the calculation of volumes of accumulated sediment in reservoirs or natural lakes (e.g. Dearing *et al.*, 1981). Such techniques provide information over various timescales and at different levels of resolution, yet few attempts have been made to use more than one technique in the same environment either to lengthen the temporal reference scale or to improve the resolution of calculated process rates.

It is the aim of the current investigation to calculate rates of denudation from first, a small drainage basin experiment which provides detailed solute and sediment budgets for a short time period, and secondly, an analysis of sediments from a lake below the monitored stream in order to establish erosion rates over the past 140 years and to relate them to environmental change. Furthermore, a comparative study of this kind may provide valuable information on the validity of both techniques.

DRAINAGE BASIN STUDIES

The water quality of rivers and streams is a function of precipitation chemistry plus a complex series of reactions and interactions between this input and the vegetation, soil and rock of the drainage basin. Two major components dominate water quality studies, namely sediment and solutes, which are usually treated in isolation, although recent research has revealed interactions between them (e.g. Ongley *et al.*, 1977; Walling & Peart, 1980).

Several themes relating to water quality investigations have emerged from recent research. One of the major trends has been to analyse quality dynamics in the context of catchment ecosystems (Bormann & Likens, 1969) linking studies of the hydrological cascade with nutrient cycling and geochemical inventories. Detailed experiments over a period of a number of years, with the exception of the Hubbard Brook Experimental Forest (cf. Likens *et al.*, 1977) are rare, although various components of the system have received considerable attention (e.g. Bryan, 1974; Cryer, 1976; Cole & Johnson, 1977; Walling & Webb, 1978). Such frameworks have also been used to identify the impact of land use and land use change on water quality (e.g. Walling & Gregory, 1970; Anderson *et al.*, 1976). Considerable emphasis in geomorphological experiments has been placed upon evaluation of denudation rates for a range of environments (e.g. Pulina, 1972; Douglas, 1973) and the quantification of specific weathering reactions (e.g. Verstraten, 1977; Waylen, 1979). Of major interest in the present investigation is the calculation of denudation and erosion rates and concern has been expressed in recent studies relating to the accuracy of solute and sediment load determinations from instrumented catchments (e.g. Walling, 1978; Foster, 1980).

Notwithstanding potential sources of error in calculating rates of erosion and denudation, the major problem with all current experiments is the short temporal scale, usually 10^0 to 10^1 years. Many drainage basin studies attempt to extrapolate current process rates by making assumptions regarding bulk density of sediment and produce figures in rates of lowering per unit time (e.g. Bubnoff units = $m^3 km^{-2} year^{-1}$ or ground lowering in mm $year^{-1} \times 10^3$). These estimates are totally misleading and imply a constancy of geomorphic process rates over long periods of time, usually failing to identify the significant variability in hydrological regimes over the monitoring period. It is also implied that the present day climatic conditions are "normal", yet Lamb (1977) has suggested that climatic data for the first half of the twentieth century are far from normal.

In order to extrapolate over longer periods of time with some confidence, an alternative source of information, namely lake sediments are being used to calculate erosion rates in the recent past and will be compared with rates derived from current process monitoring.

LAKE SEDIMENT STUDIES

Many lakes trap a high proportion of inflowing particulates from the surrounding catchment thus providing opportunities to observe past rates of particulate flux over the timespan of a lake's existence (Oldfield, 1977). A common approach is to calculate sedimentation rates at the lake bed by dating sediment cores at various intervals (e.g. Edwards & Rowntree, 1980; Oldfield *et al.*, 1980). However, the possibility of complex sedimentation patterns in many lakes (cf. Dearing, in press) force such studies to treat the results as reflecting relative changes in previous levels of influx. Calculation of total sediment yield, as represented by the whole volume of deposited sediment, is problematical and necessitates high density core sampling. Several recent studies have attempted to estimate total sediment volumes for different time intervals by correlating synchronous levels in a large number of cores to a dated master core. Unless annual or dateable laminations are visible (cf. Simola *et al.*, 1981), core correlation is based on analytical techniques which give fluctuating and parallel downcore records in many cores. Methods for core correlation have included pollen analysis (Davis, 1976) and magnetic measurements (Bloemendal *et al.*, 1979; Dearing, in press; Dearing *et al.*, 1981), and so far have provided the basis for estimating erosion rates over timespans of 10^1-10^2 years. Such time intervals are usually represented in the uppermost metre of sediment, which is frequently the easiest sediment section to sample, but the availability of long corers (e.g. Mackereth, 1969) suggest that these could be extended in many lakes to cover periods of 10^3 years.

Chemical analysis of sediment cores has also played a significant role in palaeolimnological studies (cf. Mackereth, 1966), but analyses have frequently been of bulk chemistry (e.g. total K, total Fe). Such values reflect inputs to the sediments from a range of sources (allochthonous, autochthonous, authigenic) and cannot usually be directly compared with values of solute flux in the catchment. Observation of past solute flux through sediment analyses is unlikely to be at a finer resolution than as seen in the gross changes in nutrient loadings which accompany dramatic environmental change. Consequently, the use of lake sediments to extend the temporal scale of catchment based studies will primarily be in terms of particulate flux.

THE STUDY BASIN AND EXPERIMENTAL TECHNIQUES

The investigation is taking place in a second order drainage basin of 1.95 km^2 lying at an altitude of c. 130 m OD in North Warwickshire (Fig.1). The basin has a relative relief of 55 m and the river channels, with an average gradient of 0.046, are deeply incised and possess narrow flood plains.

Mature deciduous woodland, comprising *Quercus petraea* and *Alnus glutinosa* dominates the headwater and lake regions. A variety of conifer species, planted since the middle of the present century following a period of open cast coal mining, are to be found in the middle section of the basin.

The area is underlain by a variable thickness of boulder clay overlying a complex solid geology with strata ranging in age from the Cambrian Stockingford Shales surrounding the lake to the Keele Beds of the Upper Coal Measures (Carboniferous) in the headwater region (Fig.1(c)). Soils of the undisturbed area comprise the Bardsey Series (cambic stagnogleys) with gleyic brown earths of the Melbourne Series on the narrow sandstone bands (Whitfield, personal communication). Soils of the disturbed tract, with the exception of a variable thickness of pine litter, show no horizonation.

Some indication of land use history has been derived from map sources. The Stratford Estate map (1740-1741) and the County series map of 1817-1820 show little change in the distribution of woodland from the present day pattern, though no conifers were present. The Tithe map (1840-1850) indicates a period of clearance and

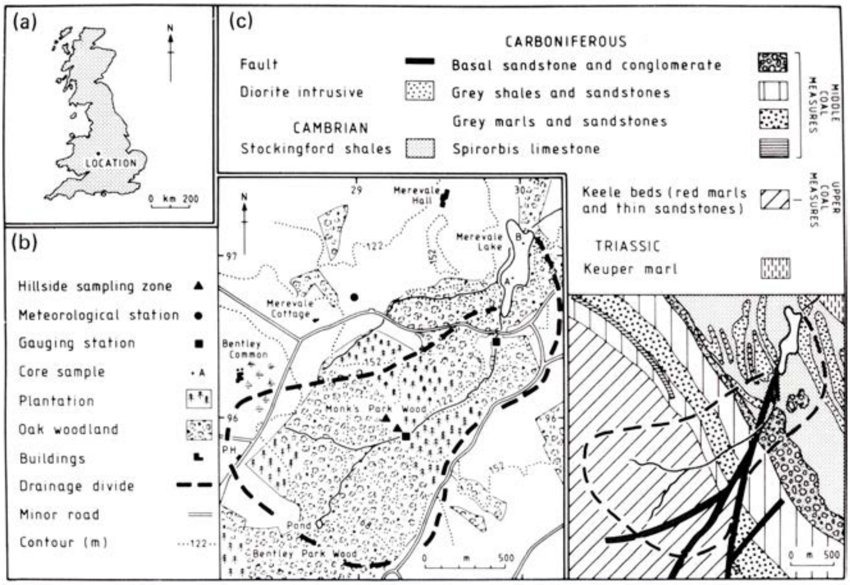

FIG.1 Merevale Lake and basin: (a) location, (b) basin characteristics and (c) solid geology.

cultivation (arable and pasture) which by 1870 (Ordnance Survey 1" map) had reverted to forest, again with a distribution similar to that of the present day. With the exception of a brief period of open cast mining (c. 1950-1954) in the central part of the basin, no other major land use changes have been identified.

Merevale Lake, an artificial impoundment, was constructed c. 1840-1845 and has a surface area of 0.065 km^2, giving a ratio of lake area to basin area of 1:30. It has a mean depth of c. 4 m, with a maximum depth of c. 8 m in the northeast section. An estimate of water residence time (c. 6 months) was derived from the calculated lake volume and one year's annual runoff data for the upper gauging station. It has yet to be established whether or not thermal stratification occurs in the summer months. An artificial drain at the present water level serves as the outflow.

Preliminary analysis of the water balance and the chemistry of inputs, throughputs and outputs has been undertaken for a single year in the undisturbed part of the basin. A second river monitoring station immediately upstream of the lake has recently been installed to monitor chemical and particulate losses from the entire basin contributing to the lake and to provide comparative data for the disturbed area. At present, a detailed inventory of chemical inputs and solutional and suspended load losses is only available for the upstream gauging station. This is based on weekly samples for precipitation and throughfall inputs and on rating curves derived from river water samples obtained at 8 h intervals using a vacuum water sampler and at weekly intervals from grab samples. A more detailed estimate based on the entire record was precluded by significant gaps in the pumping sampler data. However, comparison of rating curve estimates and continuously monitored data, where possible, suggests errors of the order of 5% for the annual figure.

TABLE 1 Water balance, chemical and particulate budgets 1979-1980

(a) WATER BALANCE

Precipitation input	Runoff	Precipitation - runoff
635.0 mm	198.4 mm	436.6 mm

(b) CHEMICAL BUDGETS (kg $ha^{-1} year^{-1}$)

Source	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	H^{+}
Bulk precipitation	9.43	2.40	17.66	6.49	11.80	0.18
Runoff	60.89	16.43	27.95	5.74	0.00	0.00
Balance	-51.46	-14.03	-10.29	+0.75	+11.80	+0.18

Source	NO_3^{-}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	DOM*
Bulk precipitation	21.61	39.67	44.40	22.17	-
Runoff	6.86	60.50	236.00	53.15	7.22
Balance	+14.75	-20.83	-191.60	-30.98	-

(c) RELATIVE LOADINGS (equiv. $ha^{-1} year^{-1} \times 10^3$)

Source	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	H^{+}
Bulk precipitation	0.47	0.20	0.77	0.17	0.44	0.18
Runoff	3.04	1.35	1.22	0.15	0.00	0.00
Balance	-2.57	-1.15	-0.45	+0.02	+0.44	+0.18

Source	NO_3^{-}	Cl^{-}	HCO_3^{-}	SO_4^{2-}
Bulk precipitation	0.35	1.12	0.73	0.46
Runoff	0.11	1.71	2.87	1.11
Balance	+0.24	-0.59	-3.05	-0.65

(d) ION BALANCE

	+	-
Input	2.23	2.66
Output	5.76	5.80

(e) SUSPENDED SEDIMENT (kg $ha^{-1} year^{-1}$)

Inorganic	15.53
Organic	2.35
Total	17.88

An attempt to identify the means for core correlation has been made on cores taken at two sites c. 100 m apart. Preliminary analyses are presented here and include the use of various magnetic and chemical analyses on 2 cm extruded levels.

RESULTS

Drainage basin denudation and erosion rates

Summary data detailing the water balance, chemical and particulate budgets for the undisturbed area are presented in Table 1. These data reveal an excess evapotranspirational loss over runoff and a predominantly chemical denudation component, since suspended sediment only comprises some 2.9% of total output. With the exception of K^+, NH_4^+, H^+ and NO_3^-, all other ions are a net loss to the system.

The total rate of chemical denudation is 10.5 $m^3km^{-2}year^{-1}$ and is higher than rates for forested basins on non-carbonate rocks calculated by Likens *et al.* (1977) and Verstraten (1977) of 2.9 and 4.9 $m^3km^{-2}year^{-1}$ respectively. This difference probably reflects the presence of carbonate rich sediments in the Keele Beds and Coal Measures and the high proportion of Ca^{2+} and HCO_3^- in the denudational component.

Figures for bed load movement are currently unavailable and since the bed load is predominantly sand sizes, relative estimates based on published data are difficult to make. However, by assuming that the relative proportion of suspended to bed load sediment is similar to the Hubbard Brook study, a figure for total particulate denudation of c. 70 kg $ha^{-1}year^{-1}$, some 10% of total output, is proposed. More detailed estimates of particulate erosion will be available in the future from continuous monitoring of suspended sediment and the use of bed load traps.

Lake sedimentation

A preliminary survey of the lake sediments at six sites using Russian, Mackereth (1969) and simple piston corers revealed wet sediment thicknesses ranging between 20 and 80 cm with a mean figure of c. 50 cm. Cores taken in transparent tubes clearly show the interfaces between sediment and water, and between sediment and the underlying soil surface. The sediments are silty in texture and generally dark brown, becoming black in the most recent deposits. In an attempt to identify an analytical method for core correlation, duplicate Russian cores from two sites A and B (Fig.1) have been analysed for low-field magnetic susceptibility (χ), saturation isothermal remanence (SIRM), available and extractable Fe and loss-on-ignition (850°C). The results are shown in Fig.2. Comparison of the downcore fluctuations in records for A and B indicate that magnetic parameters, including the ratio SIRM/χ show greater between-core similarity than either the Fe analyses or results of loss-on-ignition determinations. Magnetic measurements are rapid, cheap and non-destructive and have provided the basis for core correlation in several studies (Bloemendal *et al.*, 1979; Dearing, in press; Dearing

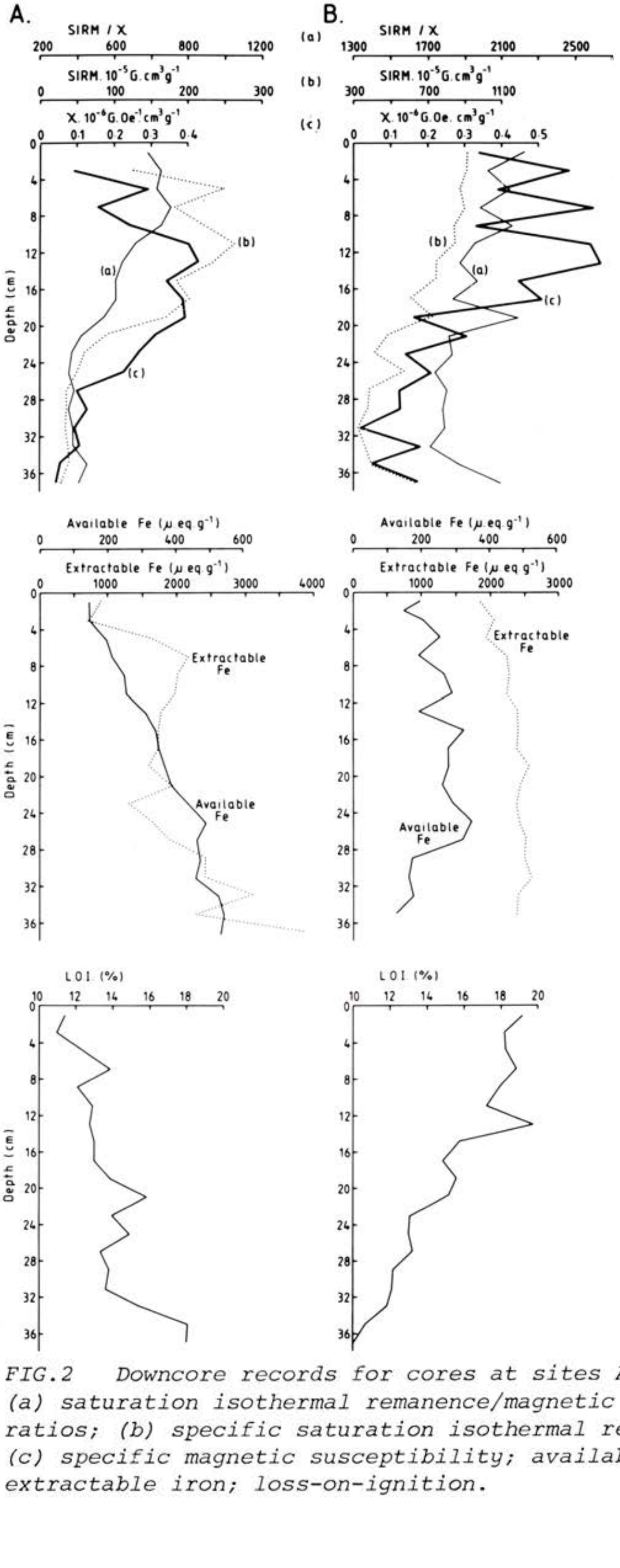

FIG.2 Downcore records for cores at sites A and B for (a) saturation isothermal remanence/magnetic susceptibility ratios; (b) specific saturation isothermal remanence; (c) specific magnetic susceptibility; available and extractable iron; loss-on-ignition.

et al., 1981) and have been found to be diagnostic of specific erosional processes in lake catchments (Dearing, 1979; Rummery *et al.*, 1979; Thompson *et al.*, 1980). The lack of correspondence between the Fe analyses and the magnetic records suggests that the magnetic minerals (e.g. magnetite) are allochthonous in origin and not due to the authigenic production of highly magnetic iron oxide or sulphide minerals at the sediment-water interface. It is planned to sample over 100 cores from the lake and to correlate synchronous levels to two dated cores (^{210}Pb, ^{137}Cs) using the combination of magnetic measurements shown here. Total sediment volumes will then be estimated for different periods over the past 140 years. At this stage it is only possible to produce a crude figure of total sediment deposition for the whole period based on an assumption of a mean sediment thickness of c. 50 cm. With a water content of c. 95% and loss-on-ignition values of c. 15%, the total mass of minerogenic sediment amounts to c. 2.8×10^6 kg, equivalent to an annual loss from the basin of c. 100 kg ha^{-1}.

DISCUSSION

The mean level of erosion as calculated from the lake sediments can be taken as a measure of inflowing minerogenic particulates of fine sand size and smaller. Comparison of this value with present day losses of suspended sediment (c. 17 kg $ha^{-1} year^{-1}$) suggests far higher levels of suspended sediment loss in the past. Errors in the former calculations, and contributions to profundal lake sediment by bed load material seem unlikely to account fully for the disparity. Whilst past land use, especially the open cast mining, may have been the cause of higher erosion levels, there remains the possibility that the results from the present monitoring scheme are inadequate for estimating losses from the whole basin. If open cast mining did cause high levels of erosion, then calculation of total sediment losses at finely resolved time intervals based on multiple core correlation will identify high levels of sedimentation for the period 1950-1954. The study is therefore set to examine rates of particulate denudation in forested, cultivated and mined environments, and to observe environmental stabilization following disturbance on a relatively long timescale which may well occur at rates not measurable by the present short term monitoring scheme.

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