Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). IAHS Publ. no. 174, 1988.

Lake-catchments: an evaluation of their contribution to studies of sediment yield and delivery processes

IAN D. L. FOSTER, JOHN A. DEARING & ROBERT GREW

Department of Geography, Coventry Polytechnic, Priory Street, Coventry CV1 5FB, UK

Abstract Hydrologists and fluvial geomorphologists are frequently concerned with the perceived instability of catchment systems responding to land use change. Such instability is reflected in changing sediment yields, often as a result of changes to the sediment delivery process. Many hydrological studies have been instigated in forested and urban basins, for example, to quantify the magnitude and direction of change. It is argued that there is a fundamental problem in matching methodological and conceptual frameworks in order to examine change in fluvial systems and that most models of change can only partially be tested through contemporary process studies. It is suggested that the most significant problem lies with selecting the appropriate time scale of system response and recovery and providing data at that timescale. With reference to a number of case studies, the relevance of a combined lake-catchment approach is argued to be one of the most powerful methodological frameworks available for testing conceptual models and evaluating complex response:recovery relationships at the most appropriate timescale.

Bassins hydrographiques lacustres: une évaluation de leur contribution aux études de la production de sédiments et des processus d'apport

Résumé Des hydrologues et des géomorphologues fluviaux s'intéressent fréquemment à l'instabilité des systèmes de bassins en réponse aux changements de l'utilisation des sols. Une telle instabilité est reflétée dans le changement du taux de production de sédiments qui résulte souvent d'une modification dans les processus d'érosion. On a entrepris bien des études hydrologiques sur des bassins boisés et urbains; par exemple, pour évaluer quantitativement l'ampleur et la direction du changement. On soutient que la confrontation des cadres méthodologique et conceptuel pour examiner le changement dans les systèmes fluviaux pose un problème fondamental: la plupart des exemples du changement ne peuvent être que partiellement vérifiés au moyen des études contemporaines des processus. On avance que le problème le plus significatif se trouve dans la sélection de l'échelle de temps appropriée pour la réponse du système et pour sa récupération ainsi que dans la fourniture de données pour ce pas de temps. En ce qui concerne un nombre d'études de cas, on soutient que la pertinence d'une approche combinée lac-bassin fournit un des cadres méthodologiques les plus puissants pour mettre à l'essai des modèles conceptuels, pour évaluer des réponses complexes: relations de récupération dans l'échelle de temps la plus appropriée.

INTRODUCTION

Soil erosion, and subsequent sediment transport, pose a number of problems for watershed management. In forested basins, high sediment yields may arise from a variety of management strategies, especially from deforestation practices, as well as from a diversity of sediment generating processes in the undisturbed forest such as gullying and shallow landsliding. In the cultivated environment, increased sediment yields result from a variety of processes relating to the planting and harvesting strategy adopted. Increased overland flow and associated rill and interrill erosional processes are common whilst in extreme cases, gullying may ensue.

Information and data requirements depend upon the specific problem at hand, but the following list, highlighted by Dunne (1984) for forested basins, probably represents the most significant areas of interest in forested and non-forested basins at the present time:

(i) background regional rates,
(ii) long term sediment yields,
(iii) sediment supply processes,
(iv) identifying "sensitive" catchment areas,
(v) intra-basin sediment budgeting.

The perspective adopted for studying sediment transport may derive from a desire to interpret the geomorphological implications of such processes when (i) and (ii) above may be used to predict long term landscape response. Alternatively, (iii), (iv) and (v) may be more directly relevant to applied aspects of watershed management yet have important geomorphological implications in understanding long term landform development. This paper examines some of the implications of the above approaches for studying sediment yields and budgets based upon the lake-catchment approach.

The lake-catchment ecosystem model described and discussed by Oldfield (1977) and by O'Sullivan (1979) forms a logical extension to the unitary nature of the drainage basin (Chorley, 1969) and the watershed ecosystem model expounded by Bormann & Likens (1979). As indicated in Fig. 1, the natural watershed ecosystem is linked by fluxes of sediment, solutes and water directly to the lake or reservoir. Any forcing variable, climatic or human in origin, will be reflected in the response of the lake through an influx of greater quantities of sediment or through a change in water quality. However, the response of the lake sediments assumes that the change in yield is not absorbed by a response in the sediment delivery ratio. These forcing variables can also affect the lake directly through changes in the water balance or through atmospheric pollution (Fig. 1).

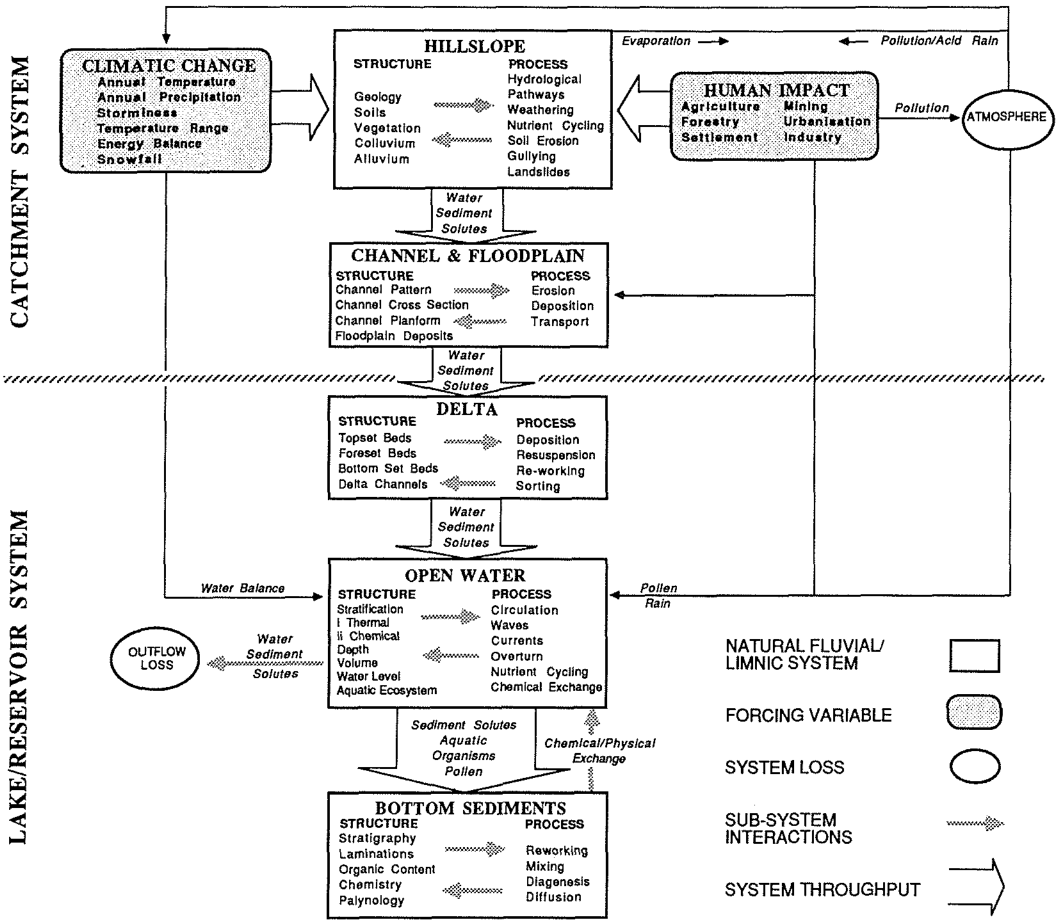

Fig. 1 A sediment yield and budget model within the lake-catchment framework.

Many practical problems exist in the recovery and analysis of lake and reservoir sediments. These issues are not the concern of the present paper, and have been discussed in a number of recent hydrological and limnological publications (e.g. Rodda, 1985; Rausch & Heinemann, 1984; Bruk, 1985; Petts & Foster, 1985; Berglund, 1986; Foster *et al.,* in press). However, it is important to recognize from these studies that present methods of core correlation and sediment dating will provide a sediment yield estimate averaged at best over 5 to 10 years in the present century which may increase to a resolution of at best hundreds of years at the start of the Holocene period.

The remainder of this paper is devoted to an assessment of the usefulness of reconstructed sediment yields and sediment sources for erosion and sediment transport studies.

SEDIMENT YIELDS

Since the publication of Davis' (1975) work on sediment yield changes at Frains Lake, Michigan and the study of environmental changes at Mirror Lake, New Hampshire (Likens & Davis, 1975), a number of researchers have attempted to reconstruct sediment yields from lake sedimentation rates. Where direct rates of erosion have not been calculated, trends in sediment accumulation may be used to isolate periods of higher or lower than average catchment erosion. However, these data must be treated with some caution, since sedimentation rate is only in part a function of minerogenic influx and is also related to the morphometry of the lake basin through sediment focussing.

Erosion and sedimentation rates have been used to infer hydrological and geomorphological changes over medium ($10-10^2$ years) to long ($10-10^4$ years) time scales. The sediment yield approach has greater practical and theoretical relevance than studies of sediment accumulation rates but is more complicated in that in addition to sediment dating, some means of core correlation is necessary in order to link a master chronology to sedimentation rates in various parts of the lake and to calculate total sediment influx (cf. Dearing, 1986).

Sediment yields covering a range of time scales have been reported in the literature, from as little as 30–40 years in northern England (Stott, 1987) and North Africa (Flower *et al.*, in press) to as much as 10 000 years in Lake Trummen, Sweden (Digerfeldt, 1972), Mirror Lake, New Hampshire (Likens & Davis, 1975) and Gallie Pond, British Columbia (Souch & Slaymaker, 1986). As shown in Fig. 2A, these Holocene records generally indicate that sediment yields have varied in the same environment by at least an order of magnitude. The highest accumulation rates in these long term records seem to correlate with either immediate post glacial erosional episodes (Digerfeldt, 1972) or with local inputs of volcanic ash (Souch & Slaymaker, 1986). The results from Mirror Lake and Lake Trummen, for example, suggest that sediment yields in the immediate post glacial period were particularly high, declining to stable levels at around 8000 to 9000 years BP. Some caution must be exercised in the interpretation of these trends, however, since the effects of sediment focussing at different time scales on rates of deposition have not been taken into account.

Intermediate timescales of sediment yield are illustrated by the reconstruction in Figs 2B and 2C. Despite the fact that the data are derived from contrasting cool temperate lowland and tropical upland environments, the impact of increases in cultivation intensity are well established in the record. In the case of Lake Havgardssjon, the most dramatic increase occurred between 950 and 1300 AD. In contrast, the rapid rise of sediment

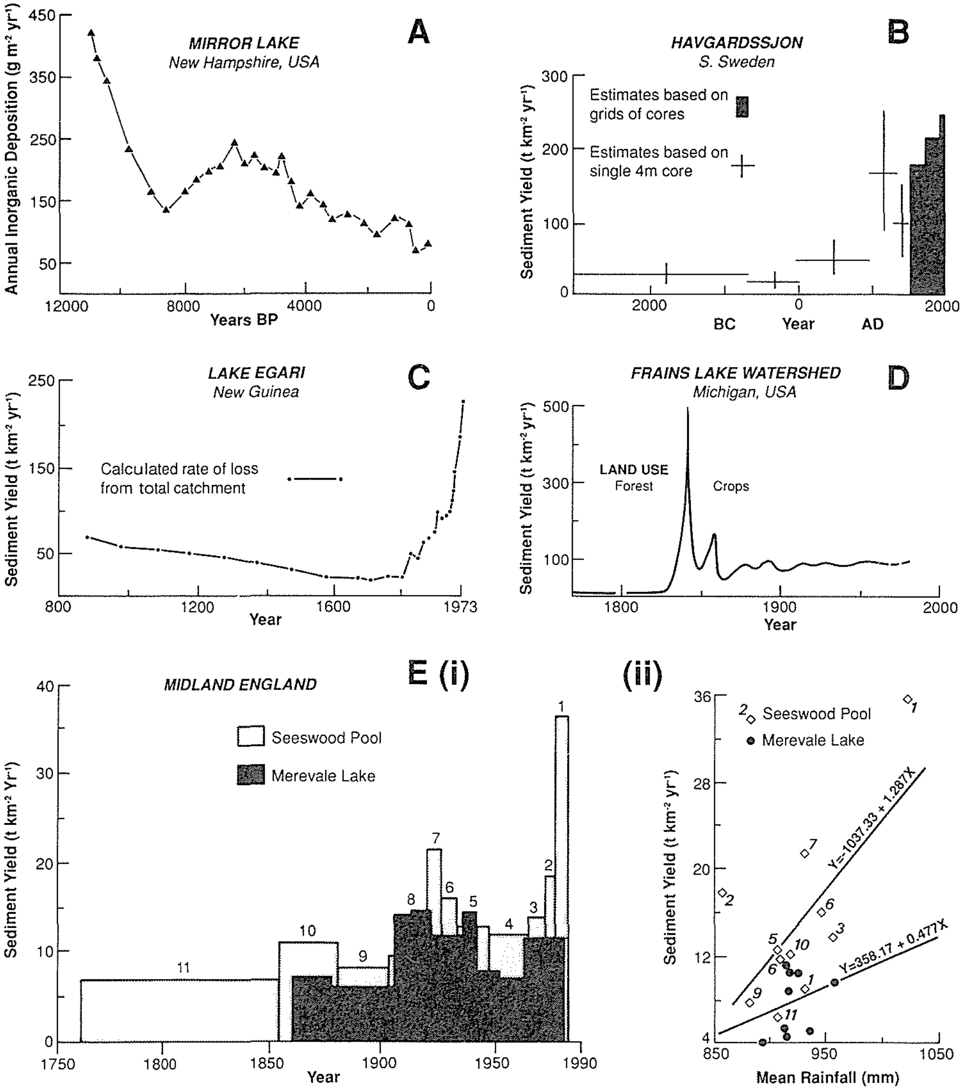

Fig. 2 Reconstructions of sediment yield. A, Mirror Lake (Likens & Davis 1975); B, Havgardssjon (Dearing et al., 1987); C; Lake Egari (Oldfield et al., 1985); D, Frains Lake (Davis, 1975); E, Merevale Lake and Seeswood Pool sediment yields (i) and relationships between yield and rainfall (ii) (Foster et al., 1985, 1986; Dearing & Foster, 1986).

yield in the New Guinea Highlands (Fig. 2C) dates from *c.* 1800 AD.

Medium timescales of erosion are represented by the data of Figs 2D and 2E. In the former, the record of response to and recovery from deforestation could represent a valid historical test of general models of system response and recovery. The latter diagram represents the testing of a range of multiple working hypotheses through application of a paired lake-catchment approach (see Foster & Dearing, 1987). These studies of sediment accumulation rates in Midland England reservoirs have revealed similarities between yield estimates derived from lake sediment accumulation rates and from contemporary catchment monitoring (Foster et al., 1985). They also show that the background variation in yields in two contrasting catchments in terms of contemporary and historical land use is broadly synchronous. The relationships between yield and average rainfall for the region for the appropriate time period in each lake is suggested to indicate the energy limited state of both environments (Dearing & Foster, 1986).

The results presented in Fig. 2 demonstrate a methodology which can extend erosional studies to timescales covering the Holocene period, provide rigorous tests of models of landscape response and recovery at the appropriate time scale and, through paired experiments, evaluate the most significant controls on sediment yields. Dearing *et al.* (1987) have also tried to examine the ecological value of long term sediment yield data, arguing for the existence of a fundamental link between vegetation, soil organic matter, soil stability and sediment yield. In the Havgardssjon catchment, devoid of significant channelled inflows, testing the impact of such relationships may be possible since the complicating channel, flood plain and delta subsystems of Fig. 1 are not represented in the basin and the reconstructed yields represent changes in hillslope erosional processes alone. Such an argument is also applicable to the basins studied in the New Guinea Highlands by Oldfield *et al.*, (1985). Interpretation of sediment yields in contemporary hydrological studies, however, demands an understanding of the sources of sediment and of the sediment delivery ratio in addition to the yield of sediment from the drainage basin.

SEDIMENT SOURCES AND BUDGETING

Catchment based studies of contemporary (Rapp, 1960) and historical (Trimble, 1976) sediment source area/yield relationships add a significant dimension to the understanding and prediction of sediment yields through the sediment budgeting approach. One such opportunity to identify sediment sources is based upon the properties of in-channel suspended sediments rather than physically mapping and quantifying relative contributions from the source areas themselves. The approach is often, although not exclusively, based upon the use of a range of mineral magnetic measurements employed to define the relative proportion of different materials which become mixed together in the suspended sediments. Studies of contemporary fluvial transport in rural basins, such as in the Jackmoor Brook, east Devon, UK, have demonstrated that the relative contribution of topsoil and subsoil sources to the suspended sediment may change from topsoil domination in the early part of a storm to channel erosion domination during the later part of the storm (Walling *et al.*, 1979). Furthermore, in urban basins, many of the mineral magnetic properties relate to the heavy metal content of the suspended sediment and provide an opportunity for identifying the changing sources of urban stormwater (e.g. Beckwith *et al.*, 1986; Thompson &

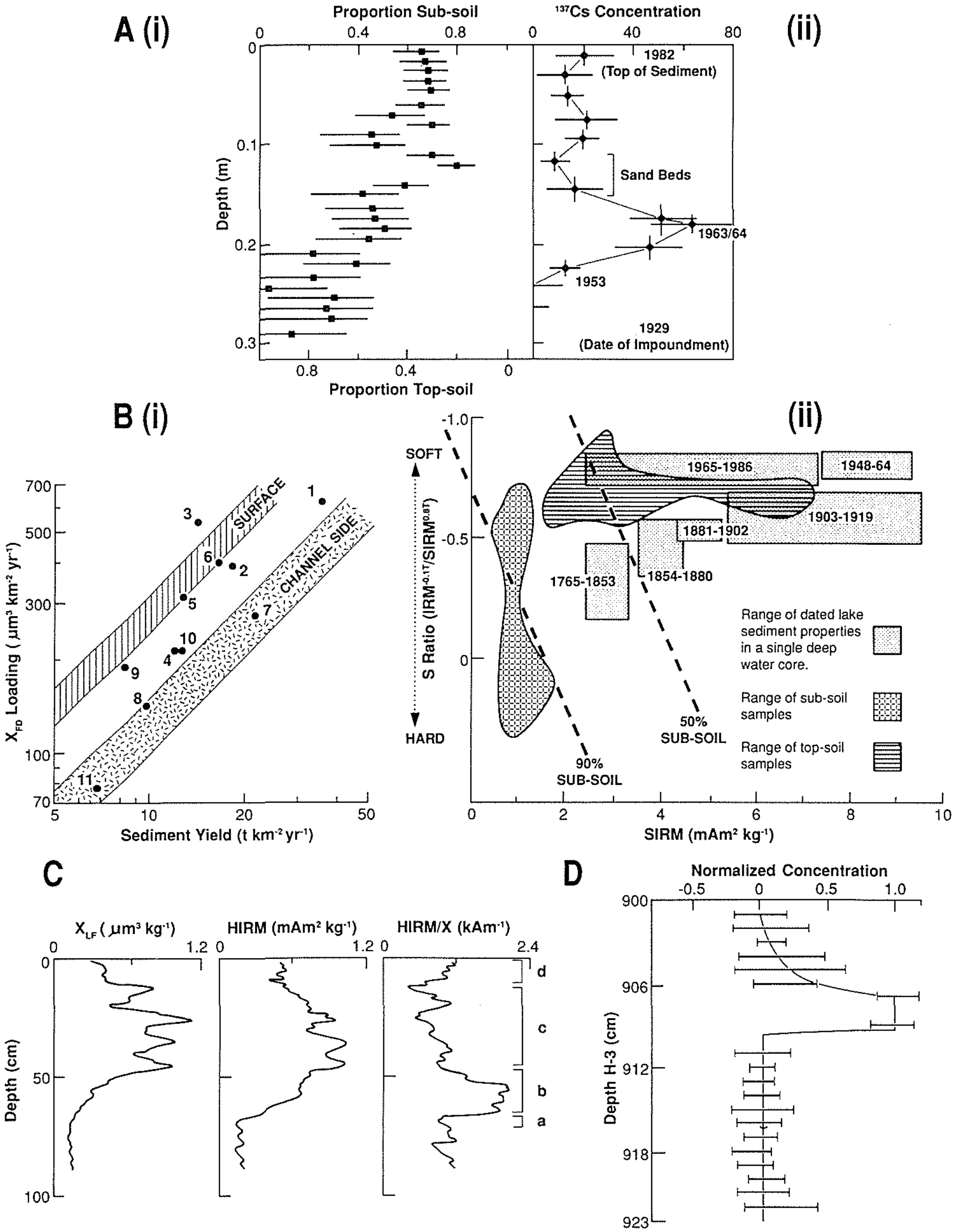

Fig. 3 *Sediment source tracing. A, A magnetic mixing model of sediment source (i) and sediment age (ii) for a northern England Reservoir (Stott, 1987). B, Mixing models for the Seeswood Pool catchment based on frequency dependent susceptibility (i) (Dearing & Foster, 1986) and the SIRM and S ratio of mixed soil samples (ii). C, Magnetic susceptibility, HIRM and the HIRM: susceptibility ratio in a sediment core from Dayat er Roumi (North Africa) showing gully initiation (a), downcutting (b), widening (c) and stabilization (d) (Foster et al., 1986). D, a chemical mixing model for the incorporation of volcanic ash into Icelandic lake sediments (simplified from Thompson et al., 1986) (Error bars represent precision of the range of laboratory counting on all 11 chemical elements analysed).*

Oldfield, 1986).

The suspended sediments transported in rivers systems are deposited in lakes and reservoirs and may also retain the magnetic signal reflecting sediment source. As a consequence it is possible to use magnetic and other properties of the deposited sediments in order to quantify changing sources through time.

A number of examples of the application of magnetic mixing models to a range of lake basin studies is given in Fig. 3. Figure 3A, for example, is taken from the work of Stott (1987). The relative proportion of topsoil to subsoil in the sediment accumulating in an embayment of a reservoir draining an afforested drainage basin shows that in the phase immediately following replanting in the pre 1953 period, topsoil contributed between 60 and 100% of the sediment. In 1963, a significant increase in the contribution from subsoil is observed which rose to as much as 65% in the upper 10 cm of the sediment core.

This relative contribution from various sources is based on the application of a magnetic mixing model. Stott (1987) suggests that the pattern of sediment sources can be used to provide a working hypothesis for the initiation of gullying and channel erosion during the 50 year post afforestation period. Figure 3B represents two attempts to produce a mixing model for the cultivated Seeswood Pool basin, Warwickshire, UK (see Foster *et al.*, 1986b; Dearing & Foster, 1986). The first example in Fig. 3B(i) is based upon the flux of frequency dependent magnetic susceptibility to the lake basin for the 11 erosional time zones indicated in Fig. 2. Zones 2, 3, 5, 6 and 9 are dominated by topsoil contributions, zones 1, 4 and 10 fall in an intermediate position whilst zones 7, 8 and 10 are dominated by channel erosional processes. Relatively poor discrimination of sources using this parameter has led one of the authors (RG) to investigate a range of magnetic mixing models for the same basin. Figure 3B(ii) shows the relationship between a demagnetization parameter (*S* ratio) and the SIRM of a range of natural soil samples and the same samples mixed together in different proportions. The characteristics of the lake sediment core in part reflects this mixture of sediments, especially in the nineteenth century. However, SIRM is particularly sensitive to the presence of heavy metals which dominate the magnetic signal in this catchment in the twentieth century as a result of high atmospheric influx. This preliminary model has yet to be fully modified in order to subtract the atmospheric contribution.

A further application of mineral magnetic studies in identifying sediment source is illustrated for a lowland North African lake described by Flower et al. (1984). The magnetic stratigraphy of a single sediment core taken from this lake was interpreted by Foster *et al.* (1986a) to represent an initial phase of gully incision (phase a), followed by gully widening which produced a mixed magnetic mineralogy (phase b). The alternating peaks and troughs of phase c were suggested to represent rainfall triggered erosional pulses from the basin whilst phase d is associated with the stabilization of the gully sediments. Such a pattern is confirmed by more detailed work on these lake sediments (Flower *et al.*, in press). This more detailed work shows that although an absolute chronology for this site is difficult to determine, the combined ^{210}Pb and ^{137}Cs chronologies indicate a rapid rate of accumulation of greater than 2.2 cm $year^{-1}$ in the late 1950's and early 1960's. Subsequent aerial photographic evidence (Comati, personal communication) suggests that gully initiation followed the construction of an artificial cut made prior to 1945 in order to drain a small marsh and which was subsequently enlarged by accelerated erosion.

Many other studies have used magnetic properties to infer sediment source and catchment process. Down-core fluctuations in the magnetic susceptibility of lake sediments has been used to infer erosional intensity in a range of environments (e.g. Thompson *et al.*, 1975; Dearing & Flower, 1982). On many occasions, susceptibility is shown to relate to the particle size properties of the sediment, although the exact nature of the relationship will vary from site to site and will therefore have to be determined locally.

The final example of Fig. 3D illustrates the application of a chemical mixing model in order to determine sediment source and sediment delivery

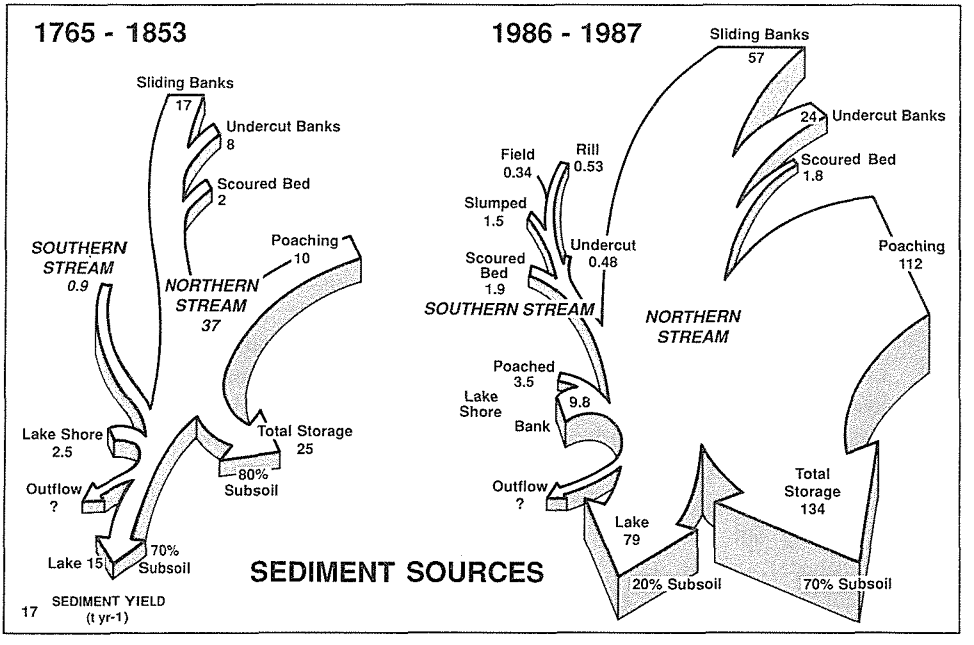

Fig. 4 Sediment budgets for the Seeswood Pool catchment 1765–1853 (A) and 1986–1987 (B). In both periods, sediment yields are estimated from lake sediment accumulation. A mineral magnetic mixing model (see Fig. 3B) has been used to estimate the relative contribution of topsoil and subsoil and other major sediment stores contributing to catchment erosion. Contemporary processes were field monitored during 1986–1987, while historical contributions are "best estimates" based on an extrapolation of present day sediment source linkage and available data relating to historical land use change.

ratios (Thompson *et al.*, 1986). It is included here to indicate that non-magnetic properties can also be used to interpret sediment sources and catchment erosional processes. The mixing model relates to the deposition and incorporation of tephra layers into the sediments of Lake Svinavatn, Iceland. Deviation of the lake model from observed patterns of tephra incorporation into ocean cores is suggested to result from post eruption erosion. The authors calculate from the mixing models that sediment delivery ratios for erosion of the ash deposited in the catchment in three eruptions (Hekla 4: 4500 BP, Hekla 3: 2900 BP and Hekla 1: 846 BP) are 4%, 2.5% and 3% respectively.

Recent studies of contemporary erosional processes and the application of magnetic mixing models by the authors in the Seeswood Pool drainage basin in the English Midlands have produced a preliminary estimate of the relative erosional contributions made to the lake sediments for two time periods (Fig. 4). As well as indicating a change in sediment yield, the two drainage basins contributing to the lake have changed very differently through time. The southern basin which is heavily underdrained and currently dominated by cereal crops has shown a small change in sediment yield in the post 1960 phase of agricultural expansion and intensification in the UK. The northern basin which is dominated by improved pasture, appears to be the major source of sediment in the 1980s as a result of high cattle populations and the destabilisation of channel banks.

CONCLUSIONS

On the basis of the case studies and arguments presented above, it is suggested that the lake catchment framework provides an opportunity for:

(a) Reconstructing erosion rates for the Holocene period against which contemporary accelerated rates of erosion can be evaluated.

(b) Defining the magnitude and frequency of sediment transport over hydrologically and geomorphologically relevant timescales.

(c) Testing models of landscape response and recovery by choosing sites which permit hypothesis testing through historical enquiry.

(d) Extending the power of paired and multiple catchment experiments by providing an historical dimension to hydrological change and system response.

(e) Evaluating concepts of geomorphic effectiveness through an ability to reconstruct sediment source and delivery ratios through time.

(f) Identifying the components of system change in response to a variety of external forcing variables such as climatic change and human impacts on hydrological systems.

The major limitations of this approach have yet to be fully evaluated but are likely to be most severe in terms of obtaining highly resolved sediment yield data over periods of less than 10 years in the recent historical past and over less than hundreds of years for the Holocene period as a whole.

Acknowledgements The authors are indebted to a number of organizations and individuals for funding many aspects of this research. We would like to thank the Natural Environment Research Council, the National Advisory Body, The Royal Society, the Royal Geographical Society and Coventry Polytechnic for research funding. In addition, we wish to express our thanks to Gerry Comati of the US Army European Research Office, London, for providing aerial photographs of North Africa. Finally, our thanks go to Shirley Addleton for producing the usual high quality illustrations.

REFERENCES

Beckwith, P. R., Ellis, J. B., Revitt,. D. M. & Oldfield, F. (1986) Heavy metal and magnetic relationships for urban source sediments. *Phys. Earth Planet. Int.* **42**, 67-75.

Berglund, B. (ed.) (1986) *Handbook of Holocene Palaeocology and Palaeohydrology.* Wiley, Chichester, UK.

Bormann, F. H. & Likens, G. E. (1979) The watershed ecosystem concept and studies of nutrient cycles. In: *The Ecosystem Concept in Natural Resource Management* (ed. by Van Dyne).

Bruk, S. (Rapporteur) (1985) *Methods of Computing Sedimentation in Lakes and Reservoirs.* UNESCO, Paris.

Brunsden, D. & Thornes, J. B. (1979) Landscape sensitivity and change. *Inst. Brit. Geogr. Trans.* New Series **4**, 463-484.

Chorley, R. J. (1969) The drainage basin as the fundamental geomorphic unit. In: *Water Earth and Man* (ed. by R. J. Chorley). Methuen, London.

Davis, M. B. (1975) Erosion rates and land use conservation in Southern Michigan. *Environ. Conserv.* 3, 139-148.

Dearing, J. A. (1986) Core correlation and total sediment influx. In: Handbook of Holocene Palaeoecology and Palaeohydrology (e.d. by B. Berglund), 247-272. Wiley, Chichester, UK.

Dearing, J. A. & Flower, R. J. (1982) The magnetic susceptibility of sedimenting material trapped in Lough Neagh, Northern Ireland and its erosional significance. *Limnol. Oceanogr.* 27, 969-975.

Dearing, J. A. & Foster, I. D. L. (1986) Limnic sediments used to reconstruct sediment yields and sources in the English Midlands since 1765. In: *International Geomorphology 1986* (ed. by. V. Gardiner) Pt 1, 853-868. Wiley, London.

Dearing, J. A., Hakanson, H., Liedberg-Johnsson, B., Persson, A. Skansjo, S. S., Widholm, D. & El-Daoushy, F. (1987) Lake sediments used to quantify the erosional response to land use change in southern Sweden. *Oikos* **50**, 60-78.

Deevey, E. (1969) Coaxing history to conduct experiments. *Bioscience* 9, 40-43.

Digerfeldt, G. (1972) The post glacial development of lake Trummen. *Folia Limnol. Scand.* 16.

Dunne. T. (1984) The prediction of erosion in forests. In: *Symposium on the Effects of Forest Land Use on Erosion and Slope Stability* (ed. by C. L. O'Loughlin & A. J. Pearce). Environ. Policy Inst., University of Honolulu, Hawaii.

Flower, R. J., Dearing, J. A. & Nawas, R. (1984) Sediment supply and accumulation in a small Moroccan Lake: an historical perspective. *Hydrobiologia* **112**, 81-92.

Flower, R. J., Stevenson, A. C., Dearing, J. A., Foster, I. D. L., Airey, A., Orend, K., Rippey, B. & Appleby, P. G. (In press) Palaeolimnological studies of three contrasted subhumid environments in Morocco. *J. Palaeolimnol.*

Foster, I. D. L. & Dearing, J. A. (1987) Paired lake catchment studies: a framework for investigating chemical fluxes in small drainage basins. *Appl. Geog.* 7, 115-133.

Foster, I. D. L., Dearing, J. A., Simpson, A. D., Carter, A. D. & Appleby, P. G. (1985) Lake catchment based studies of erosion and denudation in the Merevale Catchment, Warwickshire, UK. *Earth Surf. Proc. Landf.* **10**, 45-68.

Foster, I. D. L., Dearing, J. A., Airey, A., Flower, R. J. & Rippey, B. (1986a) Sediment sources in a Moroccan lake-catchment: a case study using magnetic measurements. *J. Wat. Resour.* **5**, 320-334.

Foster, I. D. L., Dearing, J. A. & Appleby, P. G. (1986b) Historical trends in catchment sediment yields: a case study in reconstruction from lake sediment records in Warwickshire, UK. *Hydrol. Sci. J.* **31**, 427-443.

Foster, I. D. L., Dearing, J. A. Grew, R. & Orend, K. (In Press) The sedimentary data base: an appraisal of lake and reservoir based studies of sediment yield. In: *Erosion,*

Transport and Deposition Processes (Proc. Jerusalem Workshop, April 1987) IAHS Publication.
Likens, G. E. & Davis, M. B. (1975) Post-glacial history of Mirror Lake and its watershed in New Hampshire, USA: an initial report. *Verh. Int. Ver. Limnol.* **19**, 982-993.
Oldfield, F. (1977) Lakes and their drainage basins as units of sediment-based ecological study. *Prog. Phys. Geogr.* **3**, 460-504.
Oldfield, F., Rummery, T. A., Thompson, R., & Walling, D. E. (1979) Identification of suspended sediment sources by magnetic measurements: some preliminary results. *Wat. Resour. Res.* **15**, 211-218.
Oldfield, F., Worsley, A. T. & Appleby, P. G. (1985) Evidence from lake sediments for recent erosion rates in the highlands of Papua New Guinea. In: *Environmental Change and Tropical Geomorphology* (ed. by I. Douglas & T. Spencer). Allen Unwin, London.
O'Sullivan, P. E. (1979) The ecosystem-watershed concept in the environmental sciences - a review. *J. Environ. Sci.* **13**, 273-281.
Petts, G. E. & Foster, I. D. L. (1985) *Rivers and Landscape.* Arnold, London.
Rapp, A. (1960) Recent development of mountain slopes in Karkevagge and surroundings, North Scandinavia. *Geogr. Ann.* **42**, 65-200.
Rausch, D. L. & Heinemann, H. G. (1984) Measurement of reservoir sedimentation. In: *Erosion and Sediment Yield: Some Methods of Measurement and Modelling* (ed. by R. F. Hadley & D. E. Walling). Geobooks, Norwich, UK.
Rodda, J. (ed) (1985) *Facets of Hydrology.* Wiley, London.
Souch, C. & Slaymaker, O. (1986) Temporal variability of sediement yield using accumulation in small ponds. *Phys. Geogr.* 7, 140-153.
Stott, A. P. (1987) Medium-term effects of afforestation on sediment dynamics in a water supply catchment: a mineral magnetic interpretation of reservoir deposits in the Macclesfield forest. *Earth. Surf. Proc. Landf.* **12**, 619-630.
Thompson, R., Battarbee, R. W., O'Sullivan, P. E. & Oldfield, F. (1975) Magnetic susceptibility of lake sediments. *Limnol. Oceanogr.* 20, 687-698.
Thompson, R. & Oldfield, F. (1986) *Environmental Magnetism* George Allen & Unwin, London.
Thompson, R., Bradshaw, R. H. W. & Whitley, J. E., (1986) The distribution of ash in Icelandic lake sediments and the relative importance of mixing and erosional processes. *J. Quat. Sci.* 1, 3-11.
Trimble, S. W. (1976) Sedimentation in Coon Creek Valley, Wisconsin. *Proc. 3rd Fed. Inter-Agency Sed. Conf.* US Water Resources Council, Washington DC, USA, 5-100-5-112.
Walling, D. E., Peart, M. R., Oldfield, F. & Thompson, R. (1979) Suspended sediment sources identified by magnetic measurements. *Nature* **281**, 110-113.