THE IMPACT OF WEATHER PATTERNS ON HISTORIC AND CONTEMPORARY CATCHMENT SEDIMENT YIELDS

R. L. WILBY,* H. Y. DALGLEISH[1] and I. D. L. FOSTER[2]

[1]*Department of Geography, University of Derby, Kedleston Road, Derby, DE22 1GB, U.K.*
[2] *Centre for Environmental Research and Consultancy, Division of Geography, Coventry University, Priory Street, Coventry, CV1 5FB, U.K.*

Received 25 June 1995; Revised 23 February 1996; Accepted 8 March 1996

ABSTRACT

Lake sediment-based estimates of sediment yield have frequently been used to reconstruct changing patterns of sediment supply arising from environmental change. Such analyses have often emphasized the importance of anthropogenic factors and, in particular, changing land use of management practices over timescales beyond the scope of direct process monitoring. This paper examines several U.K. sediment yield chronologies within the context of mesoscale atmospheric circulation patterns. Changes in the frequency of the winter cyclonic Lamb weather type since 1861 were found to account for a significant proportion of the variation in sediment yields. The results also have implications for future sediment accumulation rates given the potential geomorphological consequences of global climate change. © 1997 by John Wiley & Sons, Ltd.

Earth surf. processes landf., **22,** 353–363 (1997)
No. of figures: 2 No. of tables: 7 No. of refs: 44
KEY WORDS sediment yields; climate change; Lamb weather types; lake sediments

INTRODUCTION

Integrated lake catchment–hillslope studies provide a useful framework within which to investigate contemporary and historical sediment dynamics (Oldfield, 1977). Such analyses generally attempt to relate changes in erosional processes to temporally coincident trends in climatic, ecological or catchment land use and management variables (e.g. Heathwaite and Burt, 1992). However, despite an increasing understanding of the dynamics of soil erosion on hillslopes, such palaeolimnological reconstructions are complicated by the storage and remobilization of eroded material at intermediate sites over a range of timescales (Owens, 1990; Higgitt, 1991; Trimble, 1983). Sediment ‘fingerprinting’ techniques, such as the use of mineral magnetism, geochemical characteristics and radionuclides, have subsequently evolved as a means of disaggretating gross sediment yields to reservoirs and lakes (e.g. Walling and Woodward, 1992; Foster and Walling, 1994).

Whilst acknowledging that there may be a temporal discontinuity between long-term changes in catchment properties, soil erosion and sediment delivery to the lacustrine environment, lake sediments have been widely used to examine the significance of land use change to sediment yields (cf. Boardman *et al*., 1990). Other studies have examined the potential or actual effect of land use change through detailed field surveys (Evans, 1990), process-based studies (Carling *et al*., 1993) or mathematical modelling of soil erosion and sediment delivery (Gurnell and Midgley, 1993).

The majority of contemporary (e.g. Pimentel, 1993) and long-term studies have tended to emphasize the significance of land management techniques and modified vegetation cover to soil loss. This is because these two factors govern the arable landscape’s annual cycle of changing sensitivity to erosion (Boardman, 1993). Most erosion in present-day western Europe occurs predominantly under winter cereals in early autumn and is produced by low intensity rainfalls giving rise to rill erosion (Evans, 1990; Govers, 1991; Auzet *et al*., 1993). Such erosion is not the result of rainfall energy but of runoff energy, and for this reason rainfall amount rather than intensity provides the better indication of rainfall erosion in these environments (D. T. Favis-Mortlock, pers. comm.).

* Correspondence to: R. L. Wilby

CCC 0197-9337/97/040353–11 $17.50

Table I. Summary of lake catchment study sites and data sources

Site name and location	Years and no. of time zones	Site details and current land use	Reference
Seeswood Pool, Midlands, England. OS grid ref. SP327905	1765–1982 11 zones	Catchment area 221 ha (2 subcatchments) Permanent pasture, grass ley and arable Stagnogleys and argillic brown earths Annual rainfall 670 mm Maximum altitude 160 m Lake area 6·7 ha Maximum depth 1·5 m	Foster *et al.* (1986)
Merevale, Midlands, England. OS grid ref. SP3000970	1838–1982 9 zones	Catchment area 195 ha Delicious and coniferous woodland, permanent pasture Stagnogleys and argillic brown earths Annual rainfall 670 mm Maximum altitude 175 m Lake area 6·5 ha Maximum depth 4 m	Foster *et al*, (1985)
Old Mill, South Devon, England.	1942–1991 4 zones	Catchment area 158 ha Improved pasture, rough grazing, arable. Deciduous and coniferous woodland Denbigh Association Annual rainfall 1228 mm Maximum altitude 194 m Lake area 1·9 ha Maximum depth 9 m	Foster and Walling (1994)
Llyn Geirionydd, North Wales. OS grid ref. SH605763	1882–1985 10 zones	Catchment area 324 ha Coniferous woodland, rough pasture and improved pasture Spoil tips from mining Peaty, gleyed, stagnogley Annual rainfall 1500 mm Maximum altitude 414 m Lake area 25 ha Maximum depth 14·6 m	Dearing (1992)

There is growing concern that global climate change could modify existing precipitation, temperature and runoff regimes and hence rates of soil erosion, channel change, mass movements and sediment transport processes (e.g. Favis-Mortlock *et al*., 1991; Newson and Lewin, 1991; Rumsby and Macklin, 1994; Dalgleish *et al*., 1995). Such studies are typically of a more speculative nature, modelling the impact of climate change scenarios on the erosion rates associated with given land use or farming practices. For example, Boardman and Favis-Mortlock (1993) used the EPIC (Erosion–Productivity Impact Calculator) model to demonstrate that rainfall increases of up to 15 per cent in winter would increase erosion form cereal fields on the South Downs, U.K. by up to 27 per cent by 2050. Increases in summer storm frequency, the area of irrigated land, and the introduction of new erosion-susceptible crops such as maize are also anticipated to increase erosion rates. However, the rainfall–erosion relationship is likely to be non-linear because of changes in the timing and extent of plant growth rates and crop cover relative to the timing of the heaviest rainfall (Favis-Mortlock and Boardman, 1995). Accelerated soil loss may also arise from the indirect effects of future changes in climate on land management and crop type (Hulme *et al*., 1993).

It is evident that historic sediment yields have responded to both anthropogenic and climatic controls, yet the former have received far greater emphasis in the literature (e.g. Foster, 1995). However, there is a realization that greenhouse gas-induced global warming could significantly affect the spatial extent, frequency and magnitude of future soil erosion, both directly and indirectly. Accordingly, this paper examines the influence of mesoscale weather patterns on contemporary and historic sediment yields with a view to forecasting future trends in sediment flux. This is accomplished by an analysis of continually monitored suspended sediment

Table II. Summary of land use histories in each catchment

Catchment	Significant land use changes	Time period
Seeswood Pool	Lake construction	1765
	Underdrainage, tile drainage	1765 to present
	Mole drainage, new technology	1934 to present
	Removal of hedgerows	1854 to present
	Increased intensity of grazing	1926 to present
Merevale	Lake construction	1837
	Headwater afforestation	1837–1839
	Open cast mining (small area)	1949–1952
	Conifer plantation	1949–1952
Old Mill	Lake construction	1942
	Woodland and coniferous planting	1960s
	Increased grazing intensity	1950s to 1970s
	Hedgerow removal	1970s to present
	Increased plough depth	1970s to present
Lyn Geirionydd	Lake construction natural	Unknown
	Conifer plantations (3 phases)	from 1929 (early 1930s; early to mid-1950s; early to mid-1980s)
	Ore extraction, lead and zinc	From 17th century to 1940s Peaks: 1873–1888 and 1903–1912

concentrations and the published sediment accumulation rates of several lake catchment studies in England and Wales.

STUDY SITES

The sites which are considered in this study have all been previously described, and the full methodology and sediment yield analysis given by the authors is cited in Table I. The sediment chronologies which are reviewed are from the following lake catchment basins: Seeswood Pool (Foster *et al*., 1986) and Merevale Lake (Foster *et al*., 1985) in the English Midlands; Old Mill Reservoir (Foster and Walling, 1994), in Devon, England, and Llyn Geirionydd (Dearing, 1992) in North Wales. These are all small (<350 ha) agricultural and wooded catchments whose present and historic land use descriptions are given in Tables I and II respectively.

The authors estimated the historic sediment yields to the four lakes by sampling at intervals across their surfaces using a Mackereth type corer to extract undisturbed sediment cores of <2 m length (Foster *et al*., 1985, 1986; Foster and Walling, 1994; Dearing, 1992). In each case the cores were divided into 1 to 1·5 cm depth intervals and oven dried. Radionuclide concentrations down-core were then obtained for the selected cores, providing sediment dating. The cores from Seeswood Pool, Merevale Lake and Old Mill Reservoir were dated using ^{137}Cs to provide dating points for 1954 and 1963, when ^{137}Cs first appears in the profile and when the peak associated with nuclear weapons testing is observed. Cores from Seeswood Pool, Merevale and Llyn Geirionydd were also dated using ^{210}Pb, to confirm the ^{137}C dates and extend the dated time period to about 1850 using constant rate of supply and constant initial concentration dating models (Apleby and Oldfield, 1978). There was little disagreement between the dates produced by ^{210}Pb and ^{137}Cs. For example, the 1963 ^{137}Cs fallout maximum at Llyn Geirionydd was dated by the constant rate of supply ^{210}Pb model to 1961–1973 (Dearing, 1992). Core correlations were obtained for each lake using mineral magnetism, chemical analysis, particle size and sediment bulk density. This was achieved by matching sediment characteristics of cores across each lake with the characteristics of dated sediments. This provided a chronology for each core, from which lake sediment accumulation rates were calculated on the basis of dry mass loadings to the lakes.

Sedimentation rates to the lakes were translated by the original authors into an estimate of catchment sediment yield (in t km^{-2} a^{-1}). Since each lake received sediments from both allochthonous and autochthonous sources, corrections were made to the estimates of sedimentation rates by allowing for autochthonous and atmospheric inputs (see Foster *et al*., 1990a). The corrected values given by each author were then used in the present study. These were correlated with the mean annual frequency of dominant weather patterns in order to investigate the climatic component of the historic sediment yields.

Estimates of contemporary daily sediment yields for Seeswood Pool were obtained from measurements of suspended sediment concentration and streamflow collected at 2 h intervals from the outlets of two subcatchments between October 1986 and September 1987 (Grew, 1990). Based on this limited data set, Foster *et al*. (1990b) calculated sediment yields in the river flows draining a pasture and an arable subcatchment as 68·9 and 8·7 t km^{-2} a^{-1}, respectively. These data suggest an area-averaged sediment yield from the catchment to the Seeswood Pool of 51·5 t km^{-2} in 1986/87.

WEATHER PATTERNS AND SEDIMENT YIELDS

The Lamb (1972) catalogue of daily weather types (LWT) has been used extensively in studies of the British climate (El-Kadi and Smithson, 1992). This classification system provides a daily record of surface pressure patterns across the British Isles since 1861, of which the cyclonic anticyclonic, westerly, northerly, southerly, northwesterly and easterly LWTs are the most common. In addition to the seven main LWTs there are also 20 hybrid types and one unclassifiable group. The LWT scheme has a bearing on U.K. soil erosion as a consequence of the distinctive temperature (Sowden and Parker, 1981) and precipitation (Sweeney and O'Hare, 1992) characteristics of each of the main classes. Although the LWTs are subjectively defined, the complete catalogue is internally consistent and represents a composite of meteorological variables such as rainfall intensity, duration, wet-day persistence and frequencies. This record of weather patterns allows a link to be made between controlling factors, such as rainfall–runoff energy, temperature and potential evaporation, and the resultant hillslope erosion and sediment transport. It also provides the potential for stochastic rainfall simulation and for reconstruction of rainfall patterns (Wilby, 1994, 1995a). Such procedures facilitate the downscaling of mesoscale surface pressure patterns generated by general circulation model simulations of future climate into subgrid scale or point representations of key variables such as rainfall or evaporation (see Wilby, 1995b). Daily weather patterns therefore provide a valuable surrogate for a suite of hydrological processes relevant to the analysis of past, present and future sediment yields.

Table III. Mean annual sediment yields (t km^{-2}a^{-1}) estimated from lake sediment cores*

Seeswood Pool		Merevale		Old Mill		Lyn Geirionydd	
Years	Sed. yield	Years	Sed. yield	Years	Sed. yield	Years	Sed. yield
1978–1982	36·2	1965–1982	10·5	1977–1992	90	1979–1985	11·7
1973–1977	18·3	1954–1964	5·5	1964–1976	48	1968–1978	8·9
1965–1972	13·9	1944–1953	6·5	1954–1963	41	1955–1967	7·2
1948–1964	12·0	1937–1943	14·0	1942–1953	21	1947–1954	8·5
1934–1947	12·7	1923–1936	10·5			1939–1946	10·3
1926–1933	16·1	1915–1922	14·0			1931–1938	12·2
1920–1925	21·6	1906–1914	13·5			1921–1930	8·2
1903–1919	9·6	1879–1905	4·5			1911–1920	6·6
1881–1902	8·1	1861–1878	6·0			1896–1910	5·4
1854–1880	12·2					1882–1895	3·8
1765–1853	7·0						

* Data from references given in Table I for each site.

Historic mean annual and seasonal (winter/summer) LWT frequencies were correlated with the reconstructed sediment yields derived from each lake sediment series shown in Table III. By employing mean LWT frequencies, differences in sediment yields between catchments and/or non-synchronous time periods were normalized. For comparative purposes other climate data, such as long-term station rainfall and temperature, were also correlated with the mean sediment yields at each site. Daily sediment loads monitored at the Seeswood Pool catchment for the hydrological year 1986/87 were cross-tabulated with the prevailing LWT

Table IV. Results of the correlation analysis

Variable	Seeswood	Merevale	Old Mill	L. Geirionydd
Rainfall				
Annual	0·109	0·128	0·769	–0·327
Winter	0·308	0·586	0·802	–0·042
Summer	–0·118	–0·202	0·225	–·578*
Temperature				
Mean annual	–0·149	0·159	0·240	0·298
Winter	0·143	–0·128	–0·281	0·458
Summer	0·054	–0·017	0·534	0·778***
Cyclonic				
Annual	0·697**	0·502*	0·984**	0·609*
Winter	0·828***	0·474	0·983**	0·622**
Summer	0·051	0·051	0·894	0·464
Anticyclonic				
Annual	–0·171	0·026	0·377	0·162
Winter	–0·142	0·487	0·151	0·105
Summer	–0·072	–0·555	0·343	0·353
n	11	9	4	10

Significance levels: * $p = 0{\cdot}10$; ** $p = 0{\cdot}05$; *** $p = 0{\cdot}01$
Meteorological data: Seeswood and Merevale; Hatton Grange; Old Mill, Exeter and Plymouth; L. Geirionydd, Llandudno

on each of the 12 days when the most significant sediment transport occurred. This provided a means of assessing the relative significance of each LWT to the suspended sediment concentrations and yields originating from arable and pasture land use types.

RESULTS

Table IV presents the results of the correlation analysis between the zone-averaged sediment yields and selected climatic parameters. The meteorological and weather pattern data were evaluated using annual, winter (November–April) and summer (May–October) rainfall and temperature statistics. Despite the contrasting land use histories and geographical locations, the winter frequency of cyclonic patterns emerged as the most significant variable correlating with the historic sediment yields. The fact that this variable consistently

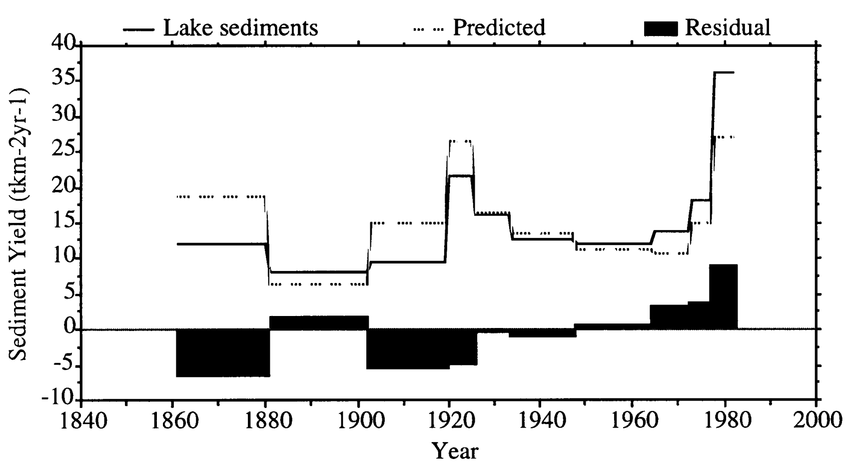
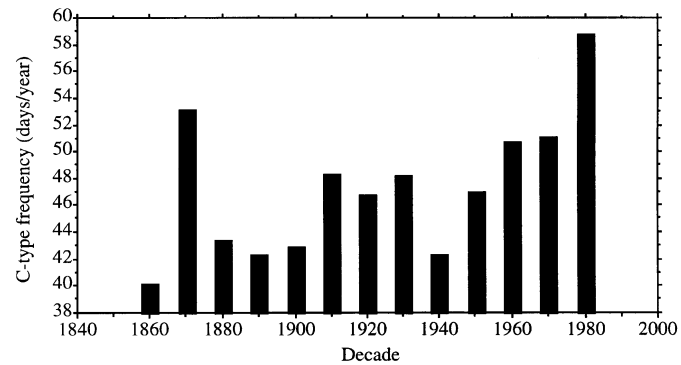


Figure 1. The reconstructed lake-sediment record at Seeswood Pool since 1861 (Foster *et al*., 1986), compared with the predicted and residual mean annual sediment yields derived using the weather pattern index of Wilby (1993)



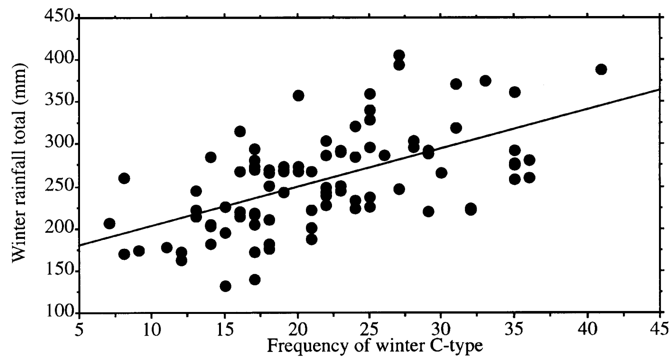


Figure 2. (a) The mean annual C-type frequency by decade 1861–1990. (b) The relationship between the winter frequency of the C-type and rainfall totals at Cambridge, U.K. 1898–1994. Sources: Lamb (1972) and P. D. Jones (pers. comm.)

produced stronger correlations than rainfall totals suggests that the C-type weather pattern frequencies capture additional relevant information such as the number of extreme events, storm interval times, antecedent soil moisture conditions, rainfall intensitities or storm durations.

In Figure 1 the reconstructed and predicted mean annual sediment yields at Seeswood Pool since 1861 are compared. The predicted values were obtained by regressing the historic sediment yields against a weather pattern index. This index has been described by Wilby (1993) and is derived from the ratio of C-type to A-type frequencies for any specified interval, in this case, the winter season. High values for the C/A index characterize periods of high rainfall runoff totals and wet-day frequencies; conversely, low values indicate below average rainfall runoff and persistent dry spells. As Figure 1 shows, this simple index can be used to explain a significant proportion of the variance in the reconstructed sediment yields (r^2_{adj} = 62 per cent SE = 5·0 t km^{-2} a^{-1}, p = 0·0044) without considering the documented land use changes since the 1920s and 1930s (Foster *et al.*, 1986). As Figure 2 indicates, periods of below average C-type frequencies (1880s to 1900s and 1940s) correspond with the lowest reconstructed sediment yields shown in Figure 1. Alternatively, periods of above average C-type frequencies (1870s and post-1960s) match phases of higher sediment yield.

Neither correlation nor temporal coincidence necessarily implies causation. Figure 1 and Table IV reveal a close relationship between long-term changes in the frequencey of the C-type and sediment accumulation rates at Seeswood Pool. At this particular site the sediment yield series appears to integrate changes in the magnitude, frequency and type of erosion and sediment transport processes to the lake. However, the residual between the reconstructed (observed) and predicted sediment yield series, also shown in Figure 1, reveals a systematic bias in the data. Since the 1900s there has been a progressive shift in the residual from a position of over-prediction to under-prediction of sediment yield. This trend may be indicative of pressures imposed by higher stocking densities, hedgerow removal and cereal cultivation (Foster, 1995), all of which increase sediment availability and are superimposed upon the climatic context.

Table V. (a) Maximum daily suspended sediment concentrations and (b) maximum daily suspended sediment loads, recorded at Seeswood 1986/87 in relation to the prevailing Lamb weather types (LWT)*

Rank	(a) Sediment concentration				(b) Sediment load			
	Arable		Pasture		Arable		Pasture	
	LWT	mg l^{-1}	LWT	mg l^{-1}	LWT	kg	LWT	kg
1	C	139	C	905	C	892	C	12 035
2	C	117	CE	861	CE	442	C	9542
3	CE	112	U	751	C	420	CE	8160
4	W	107	W	747	W	348	C	2815
5	C	100	W	732	C	271	E	2760
6	W	78	C	653	C	236	A	2470
7	C	76	W	602	A	203	W	2255
8	C	70	C	551	E	191	C	2162
9	CW	68	C	431	C	179	W	959
10	C	62	E	408	C	131	SW	916
11	U	62	A	346	W	129	C	804
12	W	60	A	255	C	103	C	743
			SW					

* Key: C, cyclonic; CE, cyclonic easterly; CW, cyclonic westerly; W, westerly; E, easterly; SW, southwesterly; A, anticyclonic; U, unclassifiable. Source of LWT classifications: P. D. Jones (*pers. comm.*)

Whilst accepting that only four time zones are available, the pattern of change at Old Mill Reservoir supports the suggestion of a strong link between the frequency of C-type and sediment accumulation rates. The largest residuals between predicted and reconstructed sediment yields were found to coincide with phases of plantation development in the early 1960s and increased cattle stocking in the late 1950s. However, these residuals were less than the standard error of the regression and therefore statistically insignificant.

The results obtained for Merevale and Llyn Geirionydd are less conclusive and are attributed to the impact of sediment storage within the catchments. At the former site, the installation of a sediment settling tank at the time of strip mining (*c*.1950) actually led to declining sediment accumulation rates until 1965. Similarly, the accumulation rates at Llyn Geirionydd are still dominated by sediment derived from unvegetated spoil heaps. Both of these sites underline the importance of considering the efficiency of sediment delivery to the lake system because sediment storage at locations intermediate to the hillslope and lake will distort the relationship between suspended sediment loads and lacustrine accumulation rates. An unexpected correlation is shown between the Llyn Geirionydd sediment yields and summer temperature and decreasing rainfalls. Dearing (1992) has shown an increase in sediment yields with mining activity and a temporal coincidence occurs between the main periods of mining activity and highest mean summer temperatures at this site. Therefore, it is believed that the observed correlation is not a result of the effects of temperature.

The analysis of monitored suspended sediment concentrations and loads at Seeswood Pool in relation to the prevailing LWTs (Table V) reveals a clear propensity for the cyclonic weather pattern to dominate both the sediment concentration and sediment yield for the top 12 days under both arable and pasture land use. As Table V(a) indicates, 8/12 days with the highest suspended sediment concentrations for the arable catchment had a cyclonic component compared with 5/12 days for the pasture. When these concentrations are combined with flow data to produce sediment loads, shown in Table V(b), a similar pattern emerged, with 8/12 cyclonic days for the arable and 7/12 days for the pasture. Note that these 12 days alone accounted for 60 per cent and 72 per cent respectively, of the total annual sediment yield in 1986/87, underlining the significance of the cyclonic and, to a lesser extent, the westerly and easterly types.

Table VI shows the extent to which the results in Table V are biased by differences in the relative frequency of each of the key LWTs. The A-type was found to have occurred on 19·2 per cent of days yet contributed only 9·9 per cent and 8·6 per cent of the gross sediment yield originating from the arable and pasture catchments, respectively. In contrast, the C-type occurred on 13·2 per cent of days and contributed 46·6 per cent of the gross yield from the arable catchment and 50·8 per cent from the pasture. With the exception of the C and E-types, all other LWTs generated disproportionately low sediment yields relative to their frequency. For example, for the

Table VI. The relative contribution to the annual suspended sediment load at Seeswood Pool (1986/87) of the key Lamb weather types (LWT)*

LWT	Percentage of days	Percentage of total suspended sediment load (kg)		Ratio	
		Arable	Pasture	Arable	Pasture
A	19·2	9·9	8·6	0·52	0·44
E	2·7	3·9	5·2	1·44	1·90
S	5·8	1·3	1·3	0·22	0·22
W	14·2	12·8	9·1	0·90	0·64
NW	2·5	0·3	0·5	0·12	0·20
N	5·5	1·8	1·1	0·33	0·20
C	13·2	46·6	50·8	3·53	3·85

* See Table V for key to LWTs

pasture catchment, the A-type produced 44 per cent of the expected sediment yield relative to its frequency. This compares with 385 per cent for the C-type and 190 per cent for the E-type.

Differences in the LWTs leading to 'peak episodes' under each land use type are attributed to variations in the eroding/transporting mechanisms. Hydrological pathways may be altered by decreases in infiltration rates under high animal stocking densities. Poaching by cattle also delivers sediment directly from the pasture to the stream and serves to break down the soil structure, making it more erodible. The sediment supply to the lake is therefore considered to be energy-limited. By contrast, the sediment yield in the arable subcatchment is believed to be sediment-supply-limited. Most of the sediment supplied to the stream from this area originates from soil detachment on the banks. Therefore, sediment derived from the arable area is more likely to reflect the influence of high magnitude runoff events (i.e. C-types) than the pasture area, which is subject to the random effects of cattle poaching in addition to the hydrological circumstances favouring sediment transport.

Table VII summarizes the precipitation characteristics of each of the key LWTs and provides a physical explanation for the results given in Tables V and VI. Between 1970 and 1990, the C-type was the second most commonly occurring weather type (14·7 per cent of days), yet relative to the other LWTs, cyclonic days have a higher frequency of wet-days (on average 78 per cent of days) as well as high mean wet-day precipitation amounts (5·1 mm d^{-1}). In contrast, the anticyclonic type occurred on 19·2 per cent of days and was characterized by relatively few precipitation events (15·6 per cent of days) of low magnitude (2·66 mm d^{-1}).

The final column in Table VII expresses the percentage of total rainfall contributed by each LWT in relation to the percentage of days on which each LWT occurred between 1970 and 1990. High (low) values are indicative of a weather pattern contributing disproportionately high (low) amounts of rainfall relative to its frequency. Thus, the A, NW and N-types were all relatively arid whereas the E, S and C-types were all disproportionately wet at this site. The latter group of LWTs, in particular the C-type is therefore likely to have greater 'geomorphic significance' in the long-term owing to sediment detachment, rilling and surface runoff. Hence, periods of high cyclonic frequency should provide the context for higher sediment yields, regardless of the land use at each site.

DISCUSSION

Climate change will almost certainly have implications for sediment yields in Britain but estimating the sources, scale and significance of the eroded material is highly problematic (Jones, 1993a,b). Uncertainties exist at a number of levels: the construction of realistic climate change scenarios at appropriate temporal and spatial resolutions; the translation of changing atmospheric, vegetation and hydrological variables into quantitative hillslope erosion and sediment transport processes; the quantification of human activities which may serve to either accentuate or retard such processes; and the absence of long-term data sets for model calibration and validation.

Unfortunately, the routine monitoring of suspended sediment concentrations has only occurred for a matter of decades and at relatively few sites. As a consequence, a number of long-term reconstructions of sediment

Table VII. Mean precipitation statistics associated with each of the key Lamb weather types (LWT)* for Coventry, Warwickshire, U.K. 1970–1991

LWT	Proportion of days	Proportion wet days†	Mean rain (mm) on wet days	% total rain/ % LWT days
A	0·192	0·156	2·66	0·219
E	0·036	0·464	4·94	1·211
S	0·044	0·660	4·03	1·405
W	0·142	0·630	3·24	1·079
NW	0·044	0·526	1·75	0·487
N	0·040	0·508	2·06	0·554
C	0·147	0·780	5·10	2·098

* See Table V for key to LWTs
† Wet days ≥0·1 mm d^{-1}

yields have been inferred from the accumulation rates of lake sediments. Such techniques introduce additional uncertainties, not least of which are the estimation of timescales of sediment delivery to lakes, when storage mechanisms are not fully understood. The effects of changing lake and/or catchment conditions, of errors introduced by sediment focusing, and sampling, dating and correlation methodologies all increase measurement uncertainty.

Despite these inherent uncertainties, however, the above results suggest that there is a strong link between contemporary weather patterns and daily mean suspended sediment concentrations originating from different land use types. The examination of reconstructed sediment yields in relation to mesoscale atmospheric variables therefore provides one means of elucidating the climatic component of past and present sediment dynamics. The Lamb weather types provide a useful means of disaggregating the climate and/or land use signal in sediment histories. This is because LWTs are indicative of general changes in atmospheric circulation across the British Isles and over time periods that exceed most hydrometeorological station data. Furthermore, finer spatial resolutions may be obtained by disaggregating LWTs into regional indices (Mayes, 1991).

In this analysis, the cyclonic LWT emerged as the most significant weather pattern in relation to historic and monitored sediment yields. The C-type represents an amalgam of hydrometeorological information beyond gross rainfall amounts that is of relevance to soil erosion studies. Other recent studies have also highlighted the significance of specific circulation patterns and rainfall regimes to episodic soil erosion (e.g. Goodess and Palutikof, 1994). Thus, long-term changes in the frequency of the C-type (Figure 2a) or the C/A index provide surrogate measures of the rainfall runoff energy environments in the U.K. on which land use change and management practices are superimposed. For example, Figure 2b shows, for a site in Cambridge, that the frequency of the C-type can be translated into winter rainfall with a high degree of confidence ($r^2 = 38$ per cent, $p = 0{\cdot}0001$).

The investigation of the significance of the climatic component in the sediment yields of the four U.K. lake catchment systems underlined the importance of sediment storage between the hillslope and the lake. C-type indices may provide a useful means of estimating background suspended sediment concentrations but not necessarily of sediment accumulation rates in the lacustrine environment. For catchments with relatively limited storage there may be a high degree of correspondence between sediment supply (inferred from weather pattern frequencies) and sediment accumulation rates. Conversely, differences between the two may be attributed to either the effects of land use change or variable sediment storage and delivery. It is also possible to envisage circumstances under which climate and land use change may operate in a compensatory way and thereby produce no detectable change in sediment yield. As the data from Seeswood Pool have indicated, the synoptic climatology may establish broad patterns of sediment yield, whilst land use governs the quantitative difference between sites (such as arable versus pasture).

There is an emerging consensus amongst the scientific community that the future climate and hydrology of the U.K. will be characterized by increased winter rainfall and flooding plus a greater likelihood of summer droughts and intensified storm activity. (Arnell *et al*., 1994; Beven, 1993; Wilby, 1995b). Historically, periods of above average precipitation have been associated with a higher frequency or intensity of cyclonic weather patterns. Observed trends in circulation patterns since 1861 are indeed suggestive of these conditions, lending support to the predicted rainfall scenarios (Wilby, 1993). In particular, the frequency of cyclones across the British Isles has been increasing steadily since the 1890s (Figure 2a). As Dalgleish *et al*. (1995) have shown, using a stochastic weather generator, should this trend persist into the next century then erosion rates and sediment yields will increase under many current agricultural land use scenarios. Daily weather patterns therefore provide a means of interpreting the significance of the climatic component in historic and contemporary sediment yields, and a source of data with which to extrapolate future rates of soil erosion.

ACKNOWLEDGEMENTS

The authors are grateful for the constructive comments made by two anonymous referees. Thanks are also extended to David Favis-Mortlock for his encouraging remarks and advice regarding the original manuscript.

REFERENCES

Apleby, P. G. and Oldfield, F. 1978. 'The calculation of lead-210 dates assuming a constant rate of supply or unsupported ^{210}Pb to the sediment', *Catena,* **5**, 1–8.

Arnell, N. W., Jenkins, A. and George, D. G. 1994. *The Implications of Climate Change for the National Rivers Authority,* National Rivers Authority R & D Report **12**, HMSO, London.

Auzet, A. V., Boiffin, J., Papy, F., Ludwig, B. and Maucorps, J. 1993. 'Rill erosion as a function of the characteristics of cultivated catchments in the north of France', *Catena,* **20**, 41–62.

Beven, K. 1993. 'Riverine flooding in a warmer Britain', *Geographical Journal,* **159**, 157–161.

Boardman, J. 1993. 'The sensitivity of Downland arable land to erosion by water', in Thomas, D. S. G. and Allison, R. J. (Eds), *Landscape Sensitivity,* Wiley, Chichester, 211–228.

Boardman, J. and Favis-Mortlock, D. 1993. 'Climate change and soil erosion in Britain', *Geographical Journal,* **159**, 179–183.

Boardman, J., Foster, I. D. L. and Dearing, J. A. (Eds). 1990. *Soil Erosion on Agricultural Land,* Wiley, Chichester.

Carling, P. A., Glaister, M. S. and Flintham, T. P. 1993. 'Soil erosion and conservation on land cultivated and drained for afforestation', *Hydrological Processes,* **7**, 317–334.

Dalgleish, H. Y., Wilby, R. L. and Foster, I. D. L. 1995. 'Modelling the impact of climate change on sediment yields under two land use scenarios', *British Hydrological Society Fifth National Symposium,* Edinburgh, September 1995.

Dearing, J. A. 1992. 'Sediment yields and sources in a Welsh upland lake-catchment during the past 800 years', *Earth Surface Processes and Landforms,* **17**, 1–22.

El-Kadi, A. K. A. and Smithson, P. A. 1992. 'Atmospheric classifications and synoptic climatology', *Progress in Physical Geography,* **16**, 432–455.

Evans, R. 1990. 'Water erosion in British farmers' fields – some causes, impacts, predictions', *Progress in Physical Geography,* **14**, 199–219.

Favis-Mortlock, D. T. and Boardman, J. 1995. 'Nonlinear responses of soil erosion to climate change: a modelling study on the UK South Downs', *Catena,* **25**, 365–388.

Favis-Mortlock, D. T., Evans, R., Boardman, J. and Harris, T. M. 1991. 'Climate change, winter wheat yield and soil erosion on the English South Downs', *Agricultural Systems,* **37**, 415–433.

Foster, I. D. L. 1995. 'Lake and reservoir bottom sediments as a source of soil erosion and sediment transport data in the UK', in Foster, I. D. L., Gurnell, A. M. and Webb, B. W. (Eds), *Sediment and Water Quality in River Catchments,* Wiley, Chichester, Ch. 15.

Foster, I. D. L. and Walling, D. E. 1994. 'Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of the Old Mill Reservoir, South Devon, over the past 50 years', *Hydrological Sciences Journal,* **39**, 347–368.

Foster, I. D. L., Dearing, J. A., Simpson, A. and Carter, A. D. 1985. 'Lake catchment based studies of erosion and denudation in the Merevale catchment, Warwickshire, U.K.', *Earth Surface Processes and Landforms,* **10**, 45–68.

Foster, I. D. L., Dearing, J. A. and Appleby, P. G. 1986. 'Historical trends in catchment sediment yields: a case study in reconstruction from lake-sediment records in Warwickshire, U.K.', *Hydrological Sciences Journal,* **31**, 427–443.

Foster, I. D. L., Dearing, J. A., Grew, R. and Orend, K. 1990a. 'The sedimentary data base: an appraisal of lake and reservoir sediment based studies of sediment yield', in Walling, D. E., Yair, A. and Benkowicz (Eds), *Erosion, Transport and Deposition Processes,* Proceedings of Jerusalem Workshop, March–April 1987, IAHS Publication No. **189**, 19–43.

Foster, I. D. L., Grew, R. and Dearing, J. A. 1990b. 'Magnitude and frequency of sediment transport in agricultural catchments: a paired lake-catchment study in Midland England', in Boardman, J., Foster, I. D. L. and Dearing, J. A. (Eds), *Soil Erosion on Agricultural Land,* Wiley, Chichester, 153–171.

Goodess, C. M. and Palutikof, J. P. 1994. *Regional Scenarios of Climatic Change: Changes in the Precipitation Regime of the Guadalentin Basin,* MEDALUS Working Paper 33, Climatic Research Unit, University of East Anglia.

Govers, G. 1991. 'Rill erosion on arable land in central Belgium: rates, controls and predictability', *Catena,* **18**, 133–155.

Grew, R. 1990. *Sediment Yields and Sources over Short and Medium Timescales in a Small Agricultural Catchment in N Warwickshire, UK,* unpublished PhD thesis, Coventry University.

Gurnell, A. and Midgley, P. 1993. 'A soil erosion and delivery model for the River Test catchment to estimate the effect of land-use change over fifty years', *British Hydrological Society Fourth National Symposium,* Cardiff, September 1993.

Heathwaite, L. and Burt, T. 1992. 'The evidence for past and present erosion in the Slapton catchment, southwest Devon', in Bell, M. and Boardman, J. *Past and Present Soil Erosion,* Oxbow Monograph **22**, Short Run Press, Exeter.

Higgitt, D. L. 1991. 'Soil erosion and soil problems', *Progress in Physical Geography,* **15**, 91–100.

Hulme, M., Hossell, J. E. and Parry, M. L. 1993. 'Future climatic change and land use in the United Kingdom', *Geographical Journal,* **159**, 131–147.
Jones, K. C. 1993a. 'Global warming and geomorphology', *Geographical Journal,* **159**, 124–130.
Jones, K. C. 1993b. 'Slope instability in a warmer Britain', *Geographical Journal,* **159**, 184–195.
Lamb, H. H. 1972. *British Isles Weather Types and a Register of the Daily Sequence of Circulation Patterns, 1861–1971,* Geophysical Memoir, **116**, HMSO, London.
Mayes, J. C. 1991. 'Regional airflow patterns in the British Isles', *Journal of Climatology,* **11**, 473–491.
Newson, M. and Lewin, J. 1991. 'Climatic change, river flow extremes and fluvial erosion – scenarios for England and Wales', *Progress in Physical Geography,* **15**, 1–17.
Oldfield, F. 1977. 'Lakes and their drainage basins as units of sediment-based ecological study', *Progress in Physical Geography,* **3**, 460–504.
Owens, P. N. 1990. 'Valley sedimentation at Slapton, South Devon, and its implications for the estimation of lake sediment-vased erosion rates', in Boardman, J., Foster, I. D. L. and Dearing, J. A. (Eds), *Soil Erosion on Agricultural Land,* Wiley, Chichester, 193–200.
Pimentel, D. 1993. *World Soil Erosion and Conservation,* Cambridge Studies in Applied Ecology and Resource Management, Cambridge University Press.
Rumsby, B. T. and Macklin, M. G. 1994. 'Channel and floodplain response to recent abrupt climate change: the Tyne Basin, Northern England', *Earth Surface Processes and Landforms,* **19**, 499–515.
Sowden, I. P. and Parker, D. E. 1981. 'A study of climatic variability of daily Central England Temperatures in relation to the Lamb synoptic types', *Journal of Climatology,* **1**, 3–10.
Sweeney, J. C. and O'Hare, G. P. 1992. 'Geographical variations in preciptiation yields and circulation types in Britain and Ireland', *Transactions of the Institute of British Geographers,* **17**, 448–463.
Trimble, S. W. 1983. 'A sediment budget for Coon Creek basin in the driftless area, Wisconsin, 1853–1977', *American Journal of Science,* **283**, 454–474.
Walling, D. E. and Woodward, J. C. 1992. 'Use of radiometric fingerprints to derive information on suspended sediment sources', in Bogen, J., Walling, D. E. and Day, T. (Eds), *Erosion and Sediment Transport Monitoring Programmes,* Proceedings of Oslo Workshop, September 1992, IAHS Publication No. **210**, 143–152.
Wilby, R. L. 1993. 'The influence of variable weather patterns on river quantity and quality regimes', *Journal of Climatology,* **13**, 447–459.
Wilby, R. L. 1994. 'Stochastic weather type simulation for regional climate change impact assessment', *Water Resources Research,* **30**, 3395–3403.
Wilby, R. L. 1995a, 'Simulation of precipitation by weather pattern and frontal analysis', *Journal of Hydrology*, **173**, 91–109.
Wilby, R. L. 1995b. 'Greenhouse hydrology', *Progress in Physical Geography,* **19**, 351–369.