

River bank erosion and the influence of frost: a statistical examination

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Revised MS received 28 December, 1985

ABSTRACT

River bank retreat around two meander bends in South Wales was monitored over a two-year period with dense grid-networks of erosion pins. Results show that strong seasonality in river bank erosion occurs, with almost all retreat taking place in the winter months of December, January and February. Catchment instrumentation and field observations allowed this seasonal pattern to be interpreted with respect to a range of geomorphological, hydrological and meteorological processes or indices. Frost action emerges as the strongest control of average and maximum bank erosion at the upstream sites. Intense cryergic disturbance of the bank surface often takes place in winter and prepares a layer of material for ready removal during subsequent stage rises. Minimal fluvial erosion occurs on unprepared banks. Detailed regression analyses provide the first statistical demonstration in a bank erosion study of the dominance of frost-related variables over other factors. Moreover, multiple regression equations developed for the first half of the study period successfully predicted bank erosion rates in the second half, and vice-versa. Although fluvial or hydrological factors seem to control the area of bank eroded, the indication here that the amount or *intensity* of erosion is largely determined by previous cryergic activity suggests that these processes may warrant closer scrutiny in future investigations.

KEY WORDS: River bank erosion, Frost action, Meanders, Multiple regression, Split-data test, Wales

INTRODUCTION

River bank erosion has recently attracted considerable attention from geomorphologists, hydrologists and engineers for a number of reasons. The meandering tendency of rivers has yet to be fully explained, but selective bank erosion is clearly a fundamental component process. Over longer time-scales, lateral stream migration can significantly influence flood-plain development (Lewin, 1978; Schumm and Lichty, 1963; Wolman and Leopold, 1957) and, if impingement on the valley side occurs, lateral erosion can cause slope instability. Moreover, a significant (and often the dominant) source of sediment output from a catchment may be produced by erosion of stream banks and bluffs. Bank retreat may also cause environmental problems by undermining roads and buildings, destroying valuable agricultural land and, if rivers marking local or national boundaries shift their course, legal or diplomatic disputes may result.

Previous work has tended to adopt one of three approaches. First, long-term channel movement has been studied by superimposing early maps and aerial photographs taken at different dates, usually over the last 150 years (e.g. Lewin and Hughes, 1976).

This type of investigation has added usefully to an understanding of river behaviour over the recent historical period, but it has often proved difficult to explain the channel movements that are observed. Second, engineering stability analyses of sections of river bank subject to periodic failure have been attempted (e.g. Thomson, 1970; Thorne and Tovey, 1981). These have tended to focus on larger river systems and have thrown light on failure mechanisms, although actual *rates* of erosion (and seasonal variations) are rarely reported. The third approach to emerge recently has been the monitoring over time of rates, patterns and, to a lesser extent, processes of river bank erosion in the field. If a spatial perspective is adopted (e.g. Dickinson and Scott, 1979), then bank retreat is monitored (often over a single measurement interval) at a number of sites: controlling processes are then inferred by attempting to relate differences in amounts of erosion to specific characteristics of the sites. It is seldom easy, however, to pin-point the significant features of a site which are apparently promoting or retarding bank erosion.

Hitherto, few studies have been based upon results from a short-term investigation designed to show how changing bank erosion rates monitored over

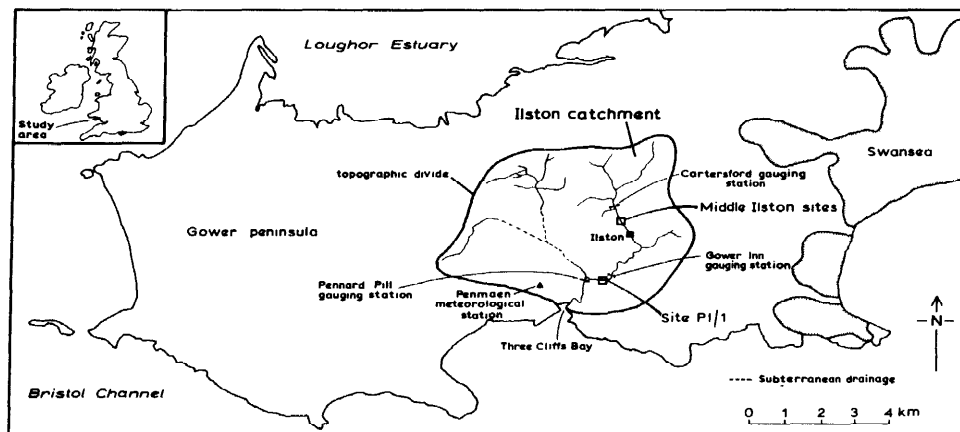


FIGURE 1. Location of the Ilston catchment and sites in Gower mentioned in the text

short time periods can be quantitatively related to influencing variables. Notable examples, though, are the regression analyses of erosional time-trends by Hooke (1979), and Kesel and Baumann (1981). Consequently this study as a whole was designed to couple detailed observation of bank erosion processes with measurement of the temporal fluctuations in the rate of bank erosion for a small stream in South Wales; these variations could then be examined statistically with respect to changes in a number of potentially important hydrological and meteorological variables. This paper concentrates on the results of the statistical analyses.

STUDY AREA AND INSTRUMENTATION

Catchment and site descriptions

The study catchment (the Ilston basin, Gower) drains a total area of 30 km² (Fig. 1). It is underlain by rocks of the Avonian series comprising the south crop of the South Wales coalfield: Millstone Grit, Namurian Shales, Coal Measures and Carboniferous Limestone (Owen, 1971). The Ilston is a gravel-bed river and two meander loops were chosen for study: Middle Ilston (MI) meander at SS 554909, where five erosion sites (named MI1, MI2A, MI2B, MI2C and MI3) were established and Parkmill Ilston (PI) meander at SS 548891, further downstream, where site PI/1 was established (Fig. 1). At the MI meander, the river drains an area of 6.75 km², bank height

averages 1.1 m and channel slope is 0.015. Drainage basin area at site PI/1 is 13.18 km², bank height rises to 1.5 m and channel slope is 0.005. Full particle-size information is available but is not presented here: all banks are composed of fine-grained, cohesive material (21 per cent—83 per cent silt-clay content) which overlies a thin band of coarse basal gravels.

Data collection techniques

The bulk of the bank erosion data was provided by dense networks of erosion pins which, despite the problems associated with the technique (Haigh, 1977; Lawler, 1978), proved to be reasonably successful. In total, 230 erosion pins were installed between March 1977 and January 1978, and read at roughly monthly intervals until June 1979. The pins were set in grid networks composed of vertical lines (mostly at a 1 m longstream spacing), each with 4–8 pins. Pin density exceeded that of all similar studies (Lawler, 1984, pp. 43–5) and more than 3800 individual pin measurements were made during the study period. Readings were taken on 22 occasions at Middle Ilston site 1 (MI/1)—the first to be instrumented—with 15 recordings at the remaining five sites.

Three gauging stations were established in the catchment to provide continuous flow data at points near to the erosion sites (Fig. 1). Comparison between stations, and cross-checks with stage boards at the erosion sites themselves, revealed such strong similarity in flow regime that only data from Cartersford

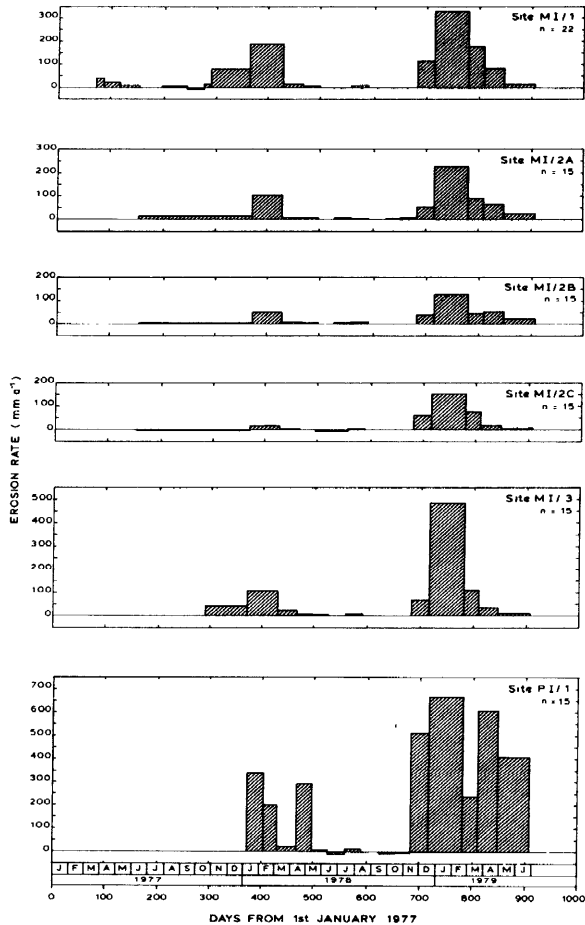


FIGURE 2. Trend of average bank erosion rate through time for each Ilston site (n = number of measurement periods)

gauging station (Fig. 1) have been used in the statistical analysis reported here. It was thought that susceptibility of bank material to erosion might vary over time in response to temperature-related factors such as desiccation, frost activity and soil moisture status. Thus, a Stevenson screen, containing a Casella thermo-hydrograph, mercury-in-glass thermometers and a Grants autographic temperature recorder (with sensors in the bank material itself), was installed adjacent to the MI sites. However, all temperature-based variables used in the analysis here are derived from the unbroken records at Penmaen meteorological station, a few km from the erosion sites (Fig. 1).

Again, cross-correlation checks revealed a very strong similarity in thermal regime. Data for rainfall and soil-moisture variables were also obtained from Penmaen.

RESULTS

Strong seasonality in bank erosion was noted at all sites, with most material removal taking place in the winter months of December, January and February (Fig. 2). This is typical of humid temperate environments (see, for example, Hill, 1973; Hooke, 1979; Wolman, 1959). Field observations suggested that

the amount of erosion was dependent not only on streamflow characteristics but also on the degree of preparation of bank material prior to a rise in stage (Lawler, 1984). A given flow effected much less material removal in summer than in winter, and this variability in response is reflected in the scatter diagrams to be presented later. Further observations, briefly summarized below, suggested that bank erodibility increased in the winter months due mainly to frost or cryergic activity. In periods of cold weather, after nocturnal air temperatures had dropped to at least -1°C or -2°C , intense frost disruption of the bank material at most sites was observed. Although a vertical zonation in the nature of cryergic processes was evident, the most important type of activity appeared to be development of needle ice along the lower half of the river bank. This is a form of segregated ice which grows externally to the ground surface as a collection of ice filaments orientated at right angles to the slope. Controls of needle ice growth including, in particular, the critical role of unfrozen moisture supply, are reviewed by Outcalt (1971). As growth proceeds, large amounts of sediment may become incorporated within the ice needles: analysis of Ilston samples revealed weights of extruded material to be more than 4 kg m^{-2} for needles 50 mm long. During melting, some of this displaced sediment was transported downslope in a variety of ways, but most appeared to remain as a skin of friable, cohesionless material. This layer of prepared material was easily removed by a subsequent rise in river stage. If the stream level failed to rise above the limit of prepared material, an erosional notch was created which marked the maximum stage attained. If, however, river level rose above the vertical extent of previous needle ice growth, then a notch tended to be created at the upper limit of the ice-needle zone and not at the level of peak stage achieved. These further observations suggested that significant bank erosion and morphological change was accomplished by fluid forces only when the bank material had first been conditioned by cryergic activity.

STATISTICAL PROCEDURES

Due to the apparently complex nature of bank erosion in the river system, with oscillation between periods of quiescence, material preparation and fluvial entrainment, stepwise multiple regression was used in an attempt to identify the more important

influences (Hauser, 1974). The utility of the technique for river bank erosion problems has already been demonstrated by Hooke (1979) and Kesel and Baumann (1981), although regression analysis as a tool for process inference in geomorphology has its limitations. Nevertheless, it is thought reasonable here to use the technique in an exploratory, descriptive way to provide simple models which may be tested by future research. Because of the difficulties of continuously measuring, say, boundary layer shear stress (Bathurst, 1979) or surface temperatures (Harrell and Richardson, 1960), most geomorphologists, whilst acknowledging the attendant drawbacks, use surrogate variables to represent the real controlling forces involved. This practice is followed here although, to a certain extent, the problems are reduced on two counts. First, the selection of variables was greatly assisted by prior field observation and measurement and, second, surrogate data were drawn from stations relatively close to the erosion sites (distances $< 3.5\text{ km}$, Fig. 1), following a series of calibration cross-checks. A list of potentially important 'explanatory' variables was constructed (using, as a basis, the previous fieldwork, other studies and relevant theory) and is discussed in the following section. The SPSS version of stepwise multiple regression (Nie *et al.*, 1975) was then used to search through this list to build up a regression equation, one variable at a time, each introduced on the criterion of accounting for maximum unexplained variance in the erosion (dependent) variable. The technique assumes that the data conform to the requirements of the general linear model: although these vary slightly between authors (see the useful discussion in Ferguson (1977) and Poole and O'Farrell (1971)), the central issues of linearity, homoscedasticity, multi-collinearity and normality will be addressed where appropriate.

Selection of variables

Efforts were made to be as comprehensive as possible in variable selection, and a number of indices were chosen which aimed to measure different aspects of the same control. Thus, the 37 independent variables used in the initial multiple regression analysis may be grouped into five hydro-meteorological categories: air frost/air minimum temperature; ground frost/grass minimum temperature; precipitation; soil moisture and antecedent wetness; streamflow. Table I gives the reduced list of those variables mentioned in this paper (others being found to be duplicative and/or

TABLE I. Variables used in multiple regression analysis, with abbreviation and definition of each. The flow indices are based on Cartersford gauging station; all other variables are derived from Penmaen meteorological station data

Abbreviation	Independent variable
<i>Air temperature indices:</i>	
AIRFR%	Number of days of air frost (as % of period length). Air frost = minimum temperature $\leq 0.0^{\circ}\text{C}$
AIRFRO	Number of days of air frost in erosion period
FRODU%	Total duration of air temperatures $\leq 0.0^{\circ}\text{C}$ (as % of period length)
FTCYC%	Number of air 'freeze-thaw' cycles (as % of period length)
LMIN1	Number of days with minimum temperature $\leq -1.0^{\circ}\text{C}$
MEANMIN	Mean daily minimum temperature ($^{\circ}\text{C}$)
<i>Grass minimum temperature indices:</i>	
GFMEAN	Mean ground-frost intensity ($^{\circ}\text{C}$)
GFRO%	Number of days of ground frost (as % of period length). Ground frost = grass minimum temperature $\leq 0.0^{\circ}\text{C}$
<i>Rainfall indices:</i>	
GT5MM%	Number of days with > 5.0 mm precipitation (as % of period length)
MAXDP	Maximum daily precipitation in erosion period (mm)
MDP	Mean daily precipitation in erosion period (mm)
<i>Antecedent ground moisture indices:</i>	
API94	Antecedent Precipitation Index (API) with decay constant (K) = 0.94 (see Gregory and Walling, 1973, p. 187). Mean API for period obtained
SMD	Soil Moisture Deficit as calculated by Meteorological Office. Mean deficit for period obtained
<i>Streamflow indices:</i>	
AMAXST	Absolute maximum stage recorded in the erosion period (m)
MDDIS	Mean daily discharge in erosion period (m^3s^{-1})
MDSTAGE	Mean daily stage in erosion period (m). Each daily stage value is obtained by averaging 48 x $\frac{1}{2}$ -hourly readings
MMAXST	Mean daily maximum stage in erosion period (m). The daily maximum is the highest of 48 x $\frac{1}{2}$ -hourly readings

unimportant). The apparent influence of cryergic processes on bank erosion led naturally to the inclusion of several indices of air and ground frost representing aspects of intensity, frequency and duration of

freezing and thawing conditions (Table I). The daily rainfall record at Penmaen yielded some measures of average and peak precipitation inputs to be used as crude substitutes for direct raindrop erosion or bank moisture. Perhaps a better estimate of bank moisture status is the Antecedent Precipitation Index often used as a guide to initial catchment wetness in simple runoff models: the version used here is based on daily precipitation totals, calculated using the formula given in Gregory and Walling, (1973, p. 187) (Table I). Soil Moisture Deficit values were also used to help characterize the wetness of each measurement interval (Table I). Finally, a range of streamflow indices, summarizing average discharge and velocity, and average and peak stages were calculated from the autographic record at Cartersford gauging station (Fig. 1, Table I). The weaknesses of these indices are discussed elsewhere (Lawler, 1984, pp. 290–338).

For the dependent variables, three measures of bank erosion were selected (Hooke, 1979): (a) mean erosion per pin per epoch, expressed as a rate in millimetres per annum (mm a^{-1}), (b) maximum erosion (mm) and (c) percentage of pins showing some erosion. It is stressed that these measures cannot summarize or represent all aspects of the distribution of erosion, but are chosen because they yield simple information on the intensity and areal extent of erosion.

STATISTICAL ANALYSIS

Although bivariate and multivariate analyses were conducted for all six sites (Lawler, 1984, pp. 339–418), only the results for site MI/1, which are largely representative of the Middle Ilston meander, are presented in detail here: results for other sites are summarized. Site MI/1 has the longest run of erosion data ($2\frac{1}{4}$ years) with 22 readings of the erosion pin network and was subjected to the most detailed process observation of all sites studied.

Erosion rate (ERRATE)

Bivariate aspects. It is clear from the matrix in Table II that erosion rate correlates most strongly with indices of air frost. Streamflow and ground-frost variables also emerge very strongly, but even the majority of variables in the weakest groups (rainfall and antecedent wetness) correlate significantly with erosion rate at the 5 per cent level. The index

TABLE II. Correlation coefficients between each erosion variable at site MI/1 and 17 independent variables acting as indices of air frost, ground frost, precipitation, antecedent wetness and streamflow ($n = 22$)

	Dependent variable		
Independent variable	Erosion rate (ERRATE)	Maximum erosion (ERMAX)	Percentage of pins showing erosion (ERODE%)
Air temperature indices:			
AIRFR%	0.971	0.942	0.753
AIRFRO	0.924	0.944	0.681
FRODU%	0.924	0.915	0.687
FTCYC%	0.954	0.894	0.842
LMINI	0.873	0.900	0.659
MEANMIN	−0.773	−0.667	−0.828
Grass minimum temperature indices:			
GFMEAN	0.593	0.568	0.807
GFRO%	0.848	0.745	0.832
Rainfall indices:			
GT5MM%	0.596	0.536	0.786
MAXDP	0.272	0.459	0.365
MDP	0.535	0.518	0.760
Antecedent ground moisture indices:			
API94	0.659	0.667	0.812
SMD	−0.551	−0.472	−0.757
Streamflow indices:			
AMAXST	0.833	0.902	0.863
MDDIS	0.893	0.851	0.851
MDSTAGE	0.778	0.663	0.857
MMAXST	0.794	0.694	0.902

Correlations greater than 0.63 are statistically significant at $p = 0.001$; correlations greater than 0.41 are statistically significant at $p = 0.05$

AIRFR% (percentage of days with air frost) correlates more strongly with erosion rate than any other variable ($r = +0.971$, Table II) and represents a roughly linear relationship (Fig. 3A), as does FTCYC%, the number of 'frost shifts' (Fig. 3B). Slightly less convincing relationships emerge when duration of freezing (Fig. 3C) and mean minimum air temperature (Fig. 3D) are considered, where evidence of non-linearity can be seen.

The associations between indices of streamflow and bank erosion rate tend to have greater scatter

and lower correlations than the frost-erosion relationships (Figs 3 and 4), although both groups suffer from a lack of values at the higher ranges. Figure 4 shows reasonably linear relationships between erosion rate and both mean daily discharge (MDDIS, Fig. 4A) and absolute maximum stage (AMAXST, Fig. 4D), while curvilinearity can be seen in the association between erosion and mean daily stage (MDSTAGE, Fig. 4B) and mean daily maximum stage (MMAXST, Fig. 4C), implying that small changes in river-level at moderate to high stages

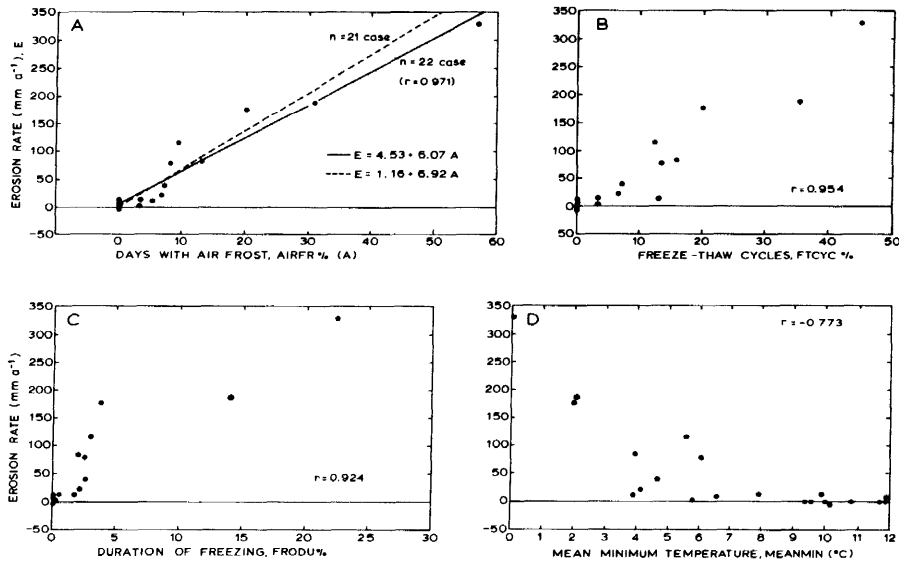


FIGURE 3. Relationship of bank erosion rate at site MI/1 to frost indices

have greater influence on erosion at this site. Linear relationships between erosion rate and climatic variables weaken still further when rainfall frequency and antecedent wetness are analyzed. The two

examples given in Figure 5 illustrate considerable scatter, although the apparent threshold in the relation between bank erosion rate and antecedent precipitation index (Fig. 5B)—with almost no

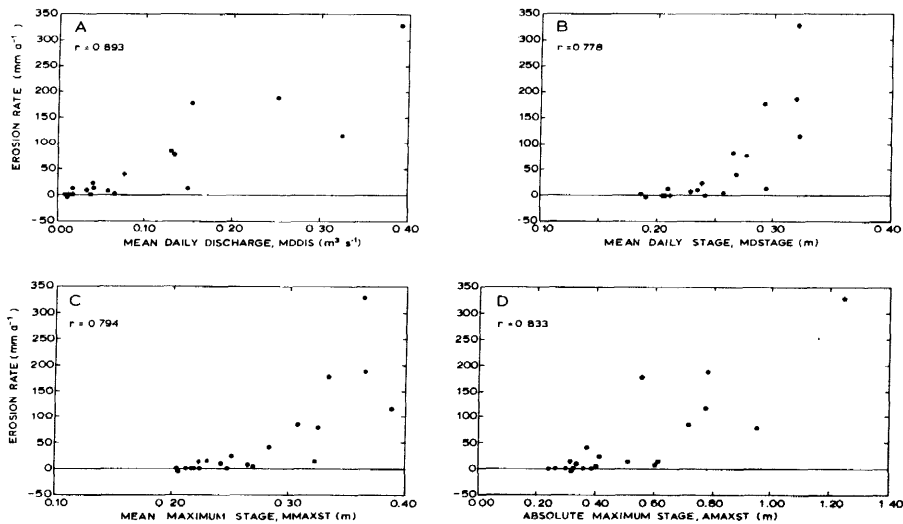


FIGURE 4. Relationship of bank erosion rate at site MI/1 to streamflow variables

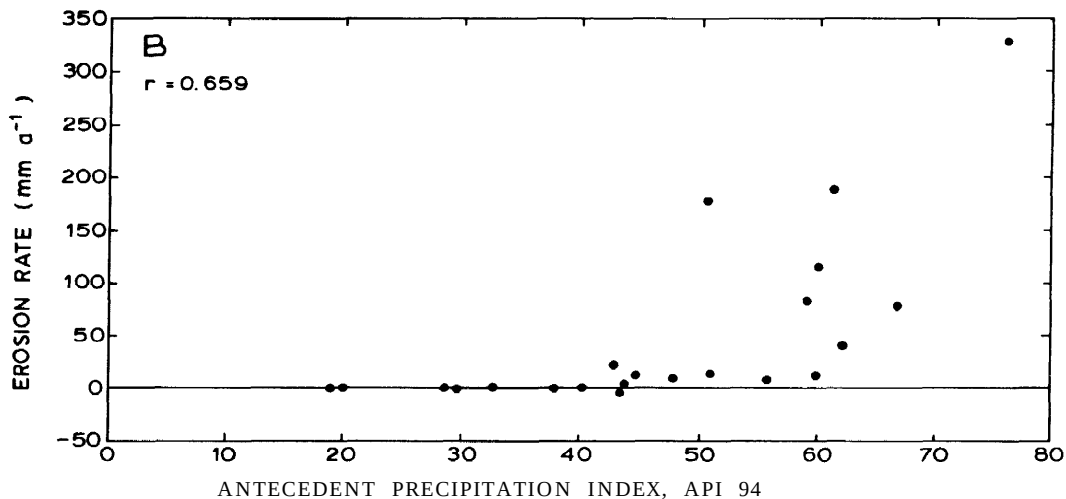
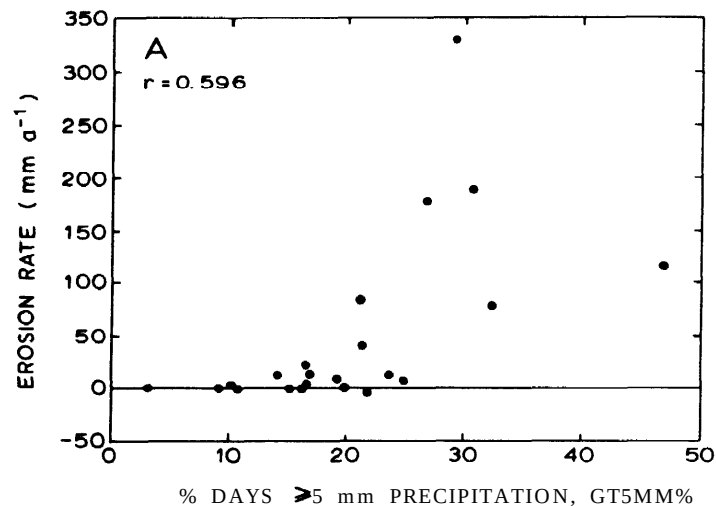


FIGURE 5. Relationship of bank erosion rate at site MI/1 to (A) rainfall frequency index; (B) antecedent precipitation index

erosion taking place when the mean API₉₄ value lies below 45—is very similar to that found by Hooke (1979, her Fig. 5 and Table VI). It is immediately clear from Figures 3–5 that many of the distributions are not ideally suited for the (parametric) Pearson

correlation technique. However, the use of the non-parametric measures of Kendall and Spearman made no difference to the general conclusion that frost-related variables appear to be the dominant control of bank erosion rate at site MI/1.

TABLE III. Summary of multiple regression results: site M1/1 bank erosion rate (ERRATE) with reduced set of independent variables b = partial regression coefficient; p = significance level based on F test). Standard error of the estimate = 16.38 mm a^{-1}

Step number	Independent variable	R^2	b	b standard error	F	p
1	AIRFR%	0.942	5.852	0.435	181.18	0.001
2	GT5MM%	0.963	2.291	0.608	14.18	0.01
3	API94	0.970	-0.818	0.448	3.32	0.10
4	MEANMIN (constant)	0.970	-0.174 -0.941	1.723	0.01	—

Multiple regression. With such a large number of independent variables, intercorrelation can cause computational difficulties in multiple regression analyses and, if extreme, the results may be difficult to interpret. There are, however, '... problems in knowing whether collinearity is sufficiently large to impede interpretation of the regression equation' (Johnston, 1978, p. 76). In the Ilston study, collinearity was generally assumed to be unacceptable if bivariate correlations between explanatory variables exceeded 0.8. This '... admittedly arbitrary rule of thumb (Farrar and Glauber, 1967, p. 98) was also recommended by Hauser (1974) and adopted by Hooke (1979) although it does have flaws. One or other of the collinear variables may then be excluded from the regression (Freund and Minton, 1979; Hauser, 1974, Poole and O'Farrell, 1971) although selecting which one remove can be a problem. For this study, a preliminary multiple regression analysis was run which identified the 'best' ten independent variables. This group was then shortened by working down the list in the order of inclusion and eliminating all variables which correlated excessively (pairwise $r > 0.8$) with other independent variables higher up the 'ranking'. In practice, although multi-collinearity was noticed in preliminary analyses, the 'short-listing' method seemed to present little hindrance to subsequent interpretation.

The summary results for the multiple regression analysis on the shortened list of variables (Table III) show that a very high value for R^2 was achieved. AIRFR% (air frost frequency), as the variable most strongly correlated with ERRATE (Table II), entered the equation first, explaining 94.2 per cent of the variation in bank erosion rate. The rainfall frequency index, GT5MM%, was included at step two, account-

ing for a further 2.1 per cent of the variance, but insignificant contributions were made by all other variables. It is interesting that GT5MM% was entered as the second variable in the equation: no rain-splash bank erosion was observed in the field and it is thought more likely that it is acting as a crude surrogate for either bank moisture (which may enhance material erodibility and the efficacy of cryergic processes) or streamflow characteristics.

Because this was thought to be the first time that frost variables had been demonstrated statistically to be of major importance in bank erosion, and because some of the relationships and distributions of Figures 3–5 might be considered less than ideal for the use of the general linear model (Lawler, 1984, pp. 354–61) it was considered prudent to perform checks on the results in the following three areas. First, the initial three erosion periods had made use of synthesized, retrodicted flow data (although these are considered to be reasonably reliable (Lawler, 1984, pp. 331–8), because gauging station records had not then been available. Little difference to the results emerged, though, when the multiple regression analysis was repeated without these first three periods. Second, the profusion of low or zero values in the frost-erosion relationships (Fig. 3) was suspected to have artificially inflated the respective correlation coefficients. Again, however, when the analyses were repeated using only those measurement periods which had experienced at least one frost (n reduces to 11), minimal differences were observed. Nor did the results change significantly when the largest observation was temporarily removed from the dataset (Fig. 3A). Finally, some power and logarithmic transformations were employed to tackle the varying degrees of non-linearity displayed in

TABLE IV. Comparison of bivariate correlations and regressions of bank erosion at site MI/1 (E) on air-frost frequency, AIRFR% (A), demonstrating the resilience of the relationship despite various forms of data exclusion. All correlation coefficients are statistically significant at $p = 0.001$

Number of periods, n	Highest correlating variable with erosion rate, ERRATE	ERRATE-AIRFR% regression equation	ERRATE-AIRFR% correlation coefficient	Standard error:	
				of the estimate (m m a^{-1})	of slope coefficient
22 (all periods)	AIRFR%	$E = 4.53 + 6.07 A$	+ 0.971	20.84	0.34
21 (minus period of highest erosion)	AIRFR%	$E = 1.16 + 6.92 A$	+ 0.945	19.59	0.55
19 (minus first 3 periods)	AIRFR%	$E = 5.86 + 6.07 A$	+ 0.972	21.78	0.35
11 (first 11 periods only)	LMIN1	$E = -0.62 + 6.08 A$	+ 0.966	15.33	0.54
11 (last 11 periods only)	FTCYC%	$E = 10.32 + 5.99 A$	+ 0.973	25.79	0.47
11 (periods with frost only)	AIRFR%	$E = 7.95 + 5.95 A$	+ 0.958	30.44	0.60

Figures 3-5 but these, too, failed to alter the general conclusion that bank erosion was most closely associated with frost frequency. Some of the results of these parallel 'with-and-without' analyses, showing the resilience of the frost-erosion relationship, can be summarized in Table IV: in the face of different types of selective data exclusion, an air-frost index emerges each time as the most strongly coefficient remains remarkably constant, and the stability and standard error of the slope coefficient suggests a certain robustness of the linear regression equation.

Split-data tests. Perhaps one of the most powerful tests of a model of the kind given in Table III is the 'split-data' or 'split-record test, often used by engineering hydrologists to gauge the efficiency of streamflow-synthesizing equations (e.g. Hamlin, 1971). With this technique, the behaviour of some variable in response to controlling factors is monitored over a period of time: only the first half of the record, though, is used to formulate a (regression) model, the predicted values of which are compared to the second half of the original data-sequence. The first half of the data (measurement intervals 1-11 inclusive), comprising the first 424 days of the 834-day study period, was chosen for the initial multiple regression analysis, using the independent variables that were free from excessive collinearity (see Table III). AIRFR% and GT5MM% were again

included at steps 1 and 2 respectively and together explained 94.6 per cent of the variation in bank erosion rate. The full equation, with five independent variables (including MDDIS), was then used to generate predicted bank erosion data for the whole 27-month period and may be compared to the observed sequence in Figure 6A. Naturally, departures of predicted from actual values increase in the second half of the period, but accordance is generally good. A tendency to underestimate low-points and slightly overestimate peaks is noticeable, although the period of peak erosion rate (December 1978-February 1979) is over-predicted by less than 34 mm a^{-1} (a mean bank retreat of 64.6 mm instead of the observed 58.6 mm)—an error of 10.2 per cent.

The reverse was then carried out by obtaining a multiple regression equation for measurement intervals 12-22 inclusive. AIRFR% and GT5MM% again entered at steps 1 and 2, together accounting for 97.4 per cent of erosion rate variance. Using the complete equation, predicted bank erosion values for the first half of the study period were generated and compared to the observed (Fig. 6B). Agreement is much stronger than the previous attempt (Fig. 6A), which probably reflects the greater range of erosion encountered in the latter half of the study. Generally, bank erosion was slightly over-predicted for the first period. Table IV gives the bivariate correlation and regression results for each half of the dataset analyzed.

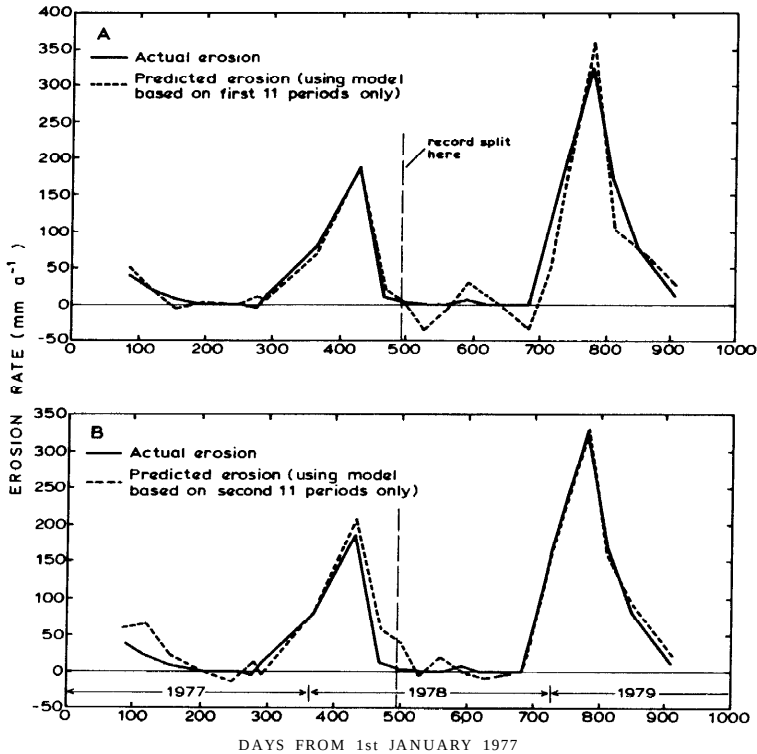


FIGURE 6. Split-data tests of multiple regression models of bank erosion rate at site MI/1:

- (a) equation developed for first half of study period used to predict erosion in second half (standard error of the estimate is 12.4 mm a⁻¹)
- (b) equation developed for second half of study period used to predict erosion in first half (standard error of the estimate is 16.1 mm a⁻¹)

In summary, the 'split-record exercise has appeared to confirm the general appropriateness and validity of the regression model and has suggested that the relationship between bank erosion rate and a small set of hydrological and meteorological variables was reasonably constant over the two years monitored. These and other parts of the analysis lend considerable statistical support to the field observations that cryergic processes acting on moistened banks are very important in lateral erosion of the River Ilston at site MI/1.

Maximum erosion (ERMAX)

Less detailed correlation and regression analyses of this dependent variable have been carried out partly because ERMAX represents, of course, the reading

from just one erosion pin at each of the 22 recordings and hence is probably subject to greater variability than a figure for average erosion. Patterns of correlation between maximum erosion and the independent variables (Table II) are similar to those noted for erosion rate in that the highest r values are obtained for the air frost indices, followed by streamflow, ground frost, rainfall and antecedent moisture factors. Air-frost frequency (AIRFRO) is the dominant explanatory variable ($r = +0.944$). As with erosion rate, a preliminary multiple regression analysis was used as a basis for excluding collinear variables. The summary results for the repeated regression (Table V) show that AIRFRO and AMAXST dominate the model, together explaining 94.6 per cent of the variation in ERMAX. All other

TABLE V. Summary of multiple regression results: site MI/1 maximum erosion (ERMAX) with reduced set of independent variables (b = partial regression coefficient). Standard error of the estimate = 11.33 mm

Step number	Independent variable	R^2	b	b standard error	F	p
1	AIRFRO	0.891	3.365	0.515	42.721	0.001
2	AMAXST	0.946	73.650	16.985	18.802	0.001
3	MEANMIN (constant)	0.947	0.567 -22.662	0.973	0.339	—

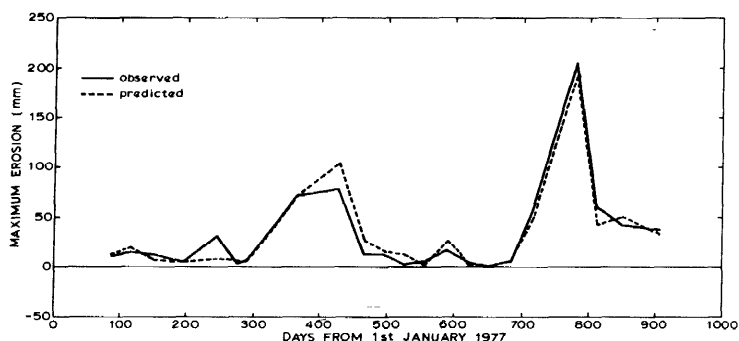


FIGURE 7. Predicted and observed maximum erosion at site MI/1 (standard error of the estimate is 11.1 mm)

variables increased R^2 by insignificant amounts. The predictive equation for maximum erosion at site MI/1 can therefore be seen just in terms of the 'best' two variables, neither of which need continuous autographic measurement:

$$\text{ERMAX} = -16.83 + 3.27 \text{ AIRFRO} + 70.91 \text{ AMAXST} \quad [1]$$

Equation [1] has been used to generate a predicted sequence of erosion maxima to compare with the observed values (Fig. 7). As with average erosion, maximum erosion shows clear late-winter seasonal peaks (with the 1979 winter about twice as erosive as the 1978 season), and also a small subsidiary peak in late summer. Despite these complexities, the predicted time series models the peaks and troughs of the seasonal trends quite well, with a standard error of the estimate of 11.13 mm (Fig. 7). It seems, then, that maximum erosion here is a function of both the efficacy of bank material preparation by frost action

and the processes of sediment removal by flow events, whereas average erosion appears to be determined largely by cryergic processes operating in the presence of moisture.

Percentage of pins recording erosion (ERODE%)

This index is intended to represent, however imperfectly, the spatial extent of erosion, as used by Hooke (1979, p. 47). The correlation matrix for ERODE% and each independent variable can be seen in Table II. Generally, the strongest relationships are between ERODE% and the flow variables, followed by the indices of frost, antecedent moisture and precipitation. The highest r value (+ 0.902) is for mean daily maximum stage (MMAXST). The multiple regression results, using independent variables free from excessive intercorrelation, are summarized in Table VI. Almost 87 per cent of the variation in ERODE% is accounted for by the two peak-flow variables, MMAXST and AMAXST (although both

TABLE VI. Summary of multiple regression results: site MI/1 ERODE% with a reduced set of independent variables (*b* = partial regression coefficient). Standard error of the estimate = 12.82%

Step number	Independent variable	<i>R</i> ²	<i>b</i>	<i>b</i> standard error	<i>F</i>	<i>p</i>
1	MMAST	0.813	276.71	92.00	9.046	0.01
2	AMAST	0.866	46.79	18.67	6.280	0.05
3	GFMEAN (constant)	0.890	5.91 -69.84	3.03	3.820	0.10

TABLE VII. Summary of most strongly correlating explanatory variables for each measure of bank erosion at each site

Site	Erosion rate (ERRATE)	Maximum erosion (ERMAX)	Percentage eroding (ERODE%)
MI/1	AIRFR%	AIRFRO	MMAST
MI/2A	AIRFR%	AIRFRO	AMAST
MI/2B	AIRFR%	AIRFR%	AMAST
MI/2C	AIRFR%	AIRFR%	GFRO%
MI/3	AIRFRO	AIRFRO	MMAST
PI/1	AMAST	SMD	AMAST

have high standard errors), with an extra 2.3 per cent provided by the ground frost intensity index, GFMEAN. It is not surprising that extent of inundation emerges as such a strong control of the area of bank eroded (although Hooke (1979, her Table III) found that antecedent precipitation index was the best predictor for percentage of pins eroding at four of her Devon sites, with discharge variables emerging most strongly for the other nine sites). Repeated runs of the correlation and regression analysis, using datasets from which had been removed, in turn, (a) the first three erosion periods with hindcast flow data (b) the most erosive period, and (c) the eleven periods in which no air frosts had been recorded, revealed negligible changes in results, with the dominant role of the peak-flow variables remaining.

DISCUSSION

Table VII summarizes the most influential factors that emerged in the analysis of three measures of bank erosion for all study sites. Indices of air-frost frequency emerge as overwhelmingly dominant in explaining average erosion rate and maximum

erosion at all the Middle Ilston sites. Measures of maximum flow, however, tend to correlate most strongly with the spatial extent of erosion (ERODE%). Site PI/1, further downstream, emerges quite differently from the others: erosion rate correlates most strongly with maximum stage, while peak erosion associates most strongly with soil moisture deficit. Needle ice growth at this site was observed, but it was stunted and contained little sediment. Particle-size analyses revealed that the bank material at site PI/1 is probably too finely-grained to allow moisture to migrate to the freezing front at a sufficient rate to support extensive ice segregation. Instead of the preparation-removal cycle observed at the Middle Ilston sites, most bank erosion at site PI/1 appeared to be achieved by fluvial undercutting followed by the collapse of overhanging peds or blocks. Such mass failure processes have been analyzed in detail by Thome and Tovey (1981).

A summary of multiple regression results for erosion rate at all six sites is given in Table VIII. The regression equations listed represent simple descriptive models (limited to two variables although more complex, and 'successful' models are available)

TABLE VIII. Summary of multiple regression analyses of erosion rate at all sites. All regressions are significant at the 0.1 per cent level

Site	Two-variable multiple regression equation (variables given in order of inclusion)	R ²	n	F	Standard error of the estimate (mm a ⁻¹)
M1/1	E = -2.235 + 5.56 A + 1.50 G	95.9	22	249.2	17.0
M1/2A	E = -4.24 + 3.71 A + 0.33 M	96.3	15	182.2	12.0
M1/2B	E = -4.18 + 1.99 A + 0.39 M	89.8	15	62.9	11.2
M1/2C	E = -11.63 + 2.15 A + 4.38 MD	68.6	15	16.3	24.8
M1/3	E = -11.79 + 11.86 AF + 0.23 S	87.6	15	50.4	43.5
PI/1	E = -26.56 + 568.41 AM - 2.49 S	70.5	15	17.7	132.3

The R² statistic in this table has been adjusted for the number of independent variables in the equation and the number of cases: 'it is a more conservative estimate of the percent of variance explained, especially when the sample size is small' (Kim and Kohout, 1975, p. 358). Abbreviations as follows:

E = ERRATE AF = AIRFRO G = GT5M M % MD = MDP
A = AIRFR% AM = AMAXST M = MAXDP S = SMD

which, with high R² and F values and relatively low standard errors, could be used satisfactorily to predict bank erosion rate at most sites. At site PI/1, the lower R² value and large standard error of the estimate may reflect the failure mechanism here: although considerable fluvial undercutting of the bank-foot may occur in one measurement interval, collapse of the upper cantilevers can take place in subsequent epochs. These 'carry-over' or time-lag effects might mean that erosion is only loosely related to the hydrological (and meteorological) characteristics of that particular measurement period. The greater uncertainty may also be reflective of the shorter monitoring period here (18 months): all other sites were investigated over at least two winters (Fig. 2). The inclusion of a rainfall-derived variable at step 2 in all six equations (Table VIII) is thought to represent not the direct impact of rain-drop erosion but the role of bank moisture in promoting the efficacy of cryergic processes and easing material entrainment. It may also be reflecting streamflow in a crude way (Kesel and Baumann, 1981, p. 68).

The general impression that cryergic activity can play a part in river bank erosion is not a novel observation in itself but, to the writer's knowledge, this is the first time that the extent of the influence of frost action has been quantified and its dominance over other variables demonstrated statistically. Some other workers have pointed in a qualitative (though valuable) way to the role of frost activity in river bank erosion in humid temperate environments. Wolman (1959) was perhaps the first to examine

these effects in any detail and showed for the Watts Branch, Maryland, USA, that while cryergic processes were not dominant, they enhanced the effectiveness of stage rises by increasing the susceptibility of bank material to fluid erosion. Leopold (1973) added a description of the effects of ice crystal growth for the same study area. Knighton (1973) noted that, while frost action was not a particularly active agent of bank erosion on the River Bollin-Dean, Cheshire, it did lead to the disaggregation of surface material and an increase in its erodibility. McGreal and Gardiner (1977) also observed that freezing processes can be important in the removal of material from river banks in Northern Ireland. Hill (1973) has demonstrated reasonably strong bivariate correlations between indices of frost and bank erosion on the Clady River, also in Northern Ireland.

In the light of these studies, and the results of the Ilston project, a case might be made for greater consideration of preparation processes in general, and cryergic activity in particular, in relation to future investigations of bank erosion in humid temperate environments. This argument is perhaps underlined by the fact that, whilst other rivers may (and do) behave differently, the Ilston study is considered reasonably representative on at least three counts. First, the study area is not unusually frost-prone: commensurate with its westerly, maritime position, Penmaen experiences only about 30 air frosts per annum. Second, comparison of study period climatic data with longer-term records suggested that the period of erosion monitoring was not climatologically extraordinary in any way. Third, analysis of

particle size distributions indicated that the Ilston bank materials were reasonably, but not excessively, frost-susceptible (Lawler, 1984, pp. 224–8).

CONCLUSIONS

A strongly seasonal pattern in bank erosion was observed with most material removal taking place in the winter months between December and March. In winter, river banks were subjected to vigorous cryergic disturbance, and streamflow events only seemed to become really effective when acting upon banks which had been preconditioned by frost activity. Indices of frost, in fact, emerged in correlation analysis as the strongest controls of average and maximum bank erosion at all Middle Ilston sites. Generally, however, correlation coefficients between measures of bank erosion and hydro-meteorological variables are much stonger than in comparable studies: this is thought to reflect perhaps the representativeness of the erosion data gathered from a very dense pin network, the limited distances between erosion sites and the points from which hydrological and meteorological information was collected, and the selection of a large range of reasonably meaningful surrogate independent variables based on detailed field observation. Rainfall-derived variables were shown to be additional influences on bank erosion at all sites: it is possible, however, that these variables were representing the increase in effectiveness of cryergic processes in the presence of moisture and/or streamflow levels. Multiple regression equations generally achieved high R^2 values and low standard errors, indicating their predictive capability for bank erosion at these sites (e.g. Fig. 6). The downstream site (PI/1) emerged differently to the others: although frost action was observed here, most bank retreat was accomplished through fluvial corrasion and the collapse of overhangs. Hence, statistically, erosion was most strongly associated with peak-flow indices. Stage variables also seemed to control the areal extent of erosion at most sites. With air-frost frequency, however, emerging as the dominant influence on average and maximum erosion at the MI sites, a more explicit consideration of cryergic activity in future research on bank erosion in humid temperature environments may be appropriate.

ACKNOWLEDGEMENTS

I am very grateful for the useful suggestions made on an earlier draft of this paper by Professor K. J.

Gregory, Dr R. Ferguson, Dr H. A. Brown and Dr A. J. Gerrard. Some of this research was carried out while the author was in receipt of a University of Wales Postgraduate Studentship. Climatological data from Penmaen Meteorological Station was kindly supplied by Mr J. Powell. I would also like to thank the two anonymous referees for their encouraging and helpful comments on the submitted manuscript.

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