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Dynamics of bank erosion on the River Dane, England

JANET HOOKE

School of Environmental Sciences, University of Liverpool, Liverpool L69 7ZT, UK
janet.hooke@liv.ac.uk

Abstract Evidence for the temporal and spatial variability in bank erosion rates is provided from air photo evidence for three periods and annual ground mapping evidence since 1981. Data on rate and distances of bank erosion are analysed in relation to parameters of peak discharge. Based on the period 1984–1996, a scaling relationship and calibration equation for calculating mean amount of erosion in each year is produced and tested against actual amounts in the period 1997–2001 and 2001–2007. The variability of the bank erosion has important implications for sediment supply and downstream impacts.

Key words river channel; bank erosion rate; flood impacts; river meanders; channel morphology; sediment; England

INTRODUCTION

Bank erosion is a major component of lateral movement of river channels and can cause practical problems at the location and also downstream effects from supply of sediment. It is important to understand the dynamics of the processes. Ideally, for both geomorphological purposes and for channel management a predictive model of erosion and movement of the bank line is needed. Various approaches may be taken including whole meander modelling (incorporating bank erosion processes), modelling of bank erosion alone, and extrapolation of prior rates.

Much research has been undertaken into the mechanisms and controls of bank erosion both using field measurements and experimentation (Lawler *et al.*, 1998). Simulations based on theoretical formulations of flow conditions in meanders have also been used and it is widely accepted and applied within modelling that bank erosion is primarily controlled by the excess near-bank velocity. Empirical analyses have shown that magnitude of erosion on highly active banks is related to discharge events to a large degree (Pizzuto, 2009), Research into key discharge conditions, testing various flow properties, has revealed that the amount of hydraulic erosion of cohesive riverbanks is dictated by flow peak intensities (Julian & Torres, 2006). Several studies have also shown the importance of soil moisture and pore water conditions (e.g. Hooke, 1979; Simon & Curini, 1998) and detailed measurements have indicated how these affect the mechanism, depending on the type of material and height of banks (e.g. Luppi *et al.*, 2009). Both empirical and theoretical work has demonstrated that rate of erosion or channel movement is closely related to bend curvature (Hickin & Nanson, 1975). Recent research has refined the measures of curvature and experimented with length of channel that influences meander changes (Guneralp & Rhoads, 2009). Experiments have also investigated the influence of different shape bends (e.g. Abad & Garcia, 2009). Field and remote sensing evidence of meander morphology over time indicate that active meanders tend to evolve in morphology (Brice, 1973) and rate varies with the phase of evolution, which is related to curvature (Hickin & Nanson, 1975; Hooke, 1987). Recent research has confirmed the acceleration of rate with development of bends until the phase of compound development, when rates decrease slightly again (Hooke & Yorke, 2011). However, in much modelling and formulation of bank erosion this autogenic development of bends and inherent variation in rate over time, irrespective of flow and hydrological conditions is often not taken into account. The influence of bars and the extent to which bankline movement is erosion- or deposition-driven is still debated.

On active meandering rivers, rate of bank erosion over time is therefore related to peak flow discharges, soil moisture at time of events, form and curvature of bends, and resistance of banks influenced by materials and vegetation. Variations in channel slope and in resistance, as well as bend form and sequence of bends, will influence spatial patterns. Long spatial sequences and extended time periods are needed to understand patterns of variation. This paper uses a unique data set of a reach of about 100 loops over a period from 1981 to present. The specific objectives are:

(i) to analyse the spatial and temporal variability in rate over a 26-year period and up to 100 loops; (ii) to examine the relationship between erosion rate and peak discharge parameters; and (iii) to develop and test a predictive formulation incorporating evolution and type of bend.

METHODS

Study reach

This research is based on the River Dane in northwest England (Fig. 1), with a catchment area of 150 km^2 in the 10-km study reach, which is an active meandering channel. The river flows in a floodplain of gravel and sandy alluvium bordered by sandy terraces, and marl bedrock in valley walls and higher terraces. Historical evidence of old maps indicates continuous evolution of the meandering course over the past 150 years (Hooke & Harvey, 1983). The study reach comprises about 100 loops, most of which have high rates of lateral movement in their apices. The mean annual daily discharge is 2.39 m^3 s^{-1} and the mean annual flood is 30 m^3 s^{-1}, which is approximately bankfull flow. The regime is flashy, influenced by rainfall on the western flank of the nearby Pennine Hills. The present river has an average bankfull width of 15 m and a floodplain height of 1.5 m. The reach is designated as a fluvial geomorphology Site of Special Scientific Interest and therefore management and activities affecting the channel are mostly not permitted.

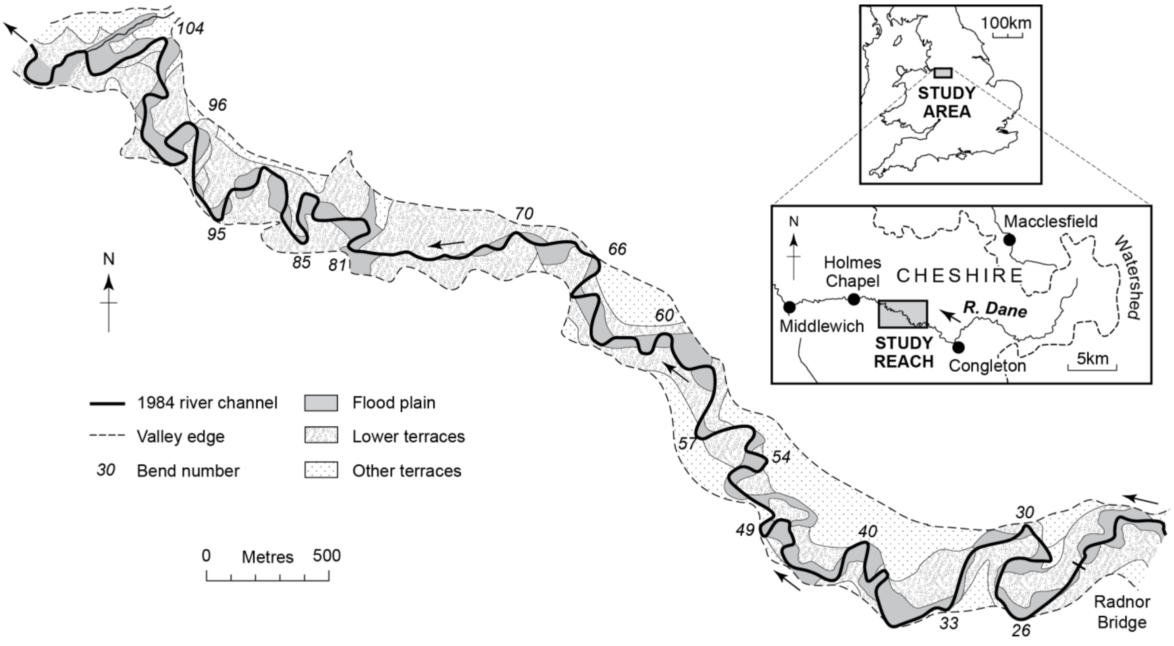

Fig. 1 Location and characteristics of the River Dane study reach.

Bank erosion data

Erosion rates are analysed for the period 1981–2007. Two main sources of data have been used, aerial photographs and ground mapping, from which various measures of erosion rate and channel movement have been derived.

Aerial photography was commissioned in 1984, 1996, 2001 and 2007, from Cambridge University Aerial Photography Unit, and the photographs have been used to map the channel position, characteristics and channel bars at those dates. The air photos are at scales from 1/5000 to 1/7000. All photographs were taken in April/early May of the year, at low flow. Mapping of the bank lines on the 1984, 1996 and 2001 air photos was by direct plotting using a stereo digital photogrammetric plotter and input to ArcGIS. The 2007 photographs were scanned on a high quality air photo scanner at resolution of 21.2 μm and the courses digitised in ArcGIS from mosaicked, georectified (using ground control points) images. The bank lines are assessed to be accurate to ±1 m and mostly to ±0.3 m.

The course was previously divided into bends by points of inflexion and each loop numbered (Fig. 1). The bank lines of each date have been compared in ArcGIS and the areas of difference for erosion and deposition for each epoch calculated using ArcToolBox. Areas of change for every polygon along the course for each of the three epochs of change: 1984–1996, 1996–2001 and 2001–2007, were then totalled for individual bend sections. Areas from each epoch have been converted to annual areal rates of erosion or deposition for each polygon and each bend. The areas are also converted into equivalent linear distance of erosion or deposition or movement of the bankline by dividing by the path length between the stable point divisions. This gives an average rate of erosion per bend section. In addition, distances of movement of the bankline, specifically maximum, minimum and apex movement, have been measured directly in each bend using ArcGIS. Curvature at each date has been measured by digitisation of the centreline of each course and calculation of the curvature (radians) every 10 m along that line.

Changes and processes along the study reach have been monitored since 1981 by annual ground field mapping and ground photography of the whole length. Field mapping included the location, bank length and severity of bank erosion. The lengths of bank have been digitised in GIS and an index of erosion for each year to April calculated by summing the classified erosion intensity for all bends (Hooke, 2008). The values of erosion in each bend are classified from 1 (no erosion) to 4 (intense erosion).

Some analysis is based on the full reach, bends 22–105, but most analysis concentrates on bends 27–63 to standardise the set and remove the effects of missing data (due to access). The bend morphology has been classified based on Brice (1974) into straight, simple symmetric, simple asymmetric, compound symmetric and compound asymmetric. Types of movement are classified based on the types identified by Hooke (Hooke & Harvey, 1983; Hooke, 1995) into stable, migration, growth, compound development (including lobing and double-heading) and cut off. Particle size analysis of the different types of material in the eroding bank zones, classified into floodplain, low terrace, and bedrock-based terrace or valley wall, produced average values of % silt-clay of the alluvial material ranging from 37% to 56%. However, previous analysis using simple division of bends into bedrock and alluvial showed surprisingly little difference in rate (Hooke & Yorke, 2011).

Discharge data

Discharge data are provided from the Environment Agency river gauge downstream at Rudheath. Continuous records since 1949 are available. Peak over threshold (POT) is defined as peaks exceeding 50 $m^3 s^{-1}$. Various parameters of discharge have been abstracted and relationships of erosion tested. These include peak discharge, peak winter discharge and number of peaks over threshold, all for year-to-April to match the time of mapping and aerial photography. The peak winter discharge is tested because much research has shown that wetness of the banks is a key factor, and because observations of the few summer floods indicate much less impact than comparable-sized flows in winter.

RESULTS

Variability in amounts and rates of erosion

Using the accurate measurements from the three air photo epochs, 1984–1996, 1996–2001 and 2001–2007, the averages and ranges for a standard set of bends using various parameters of rate of movement are given (Table 1). The averages vary, with the period 1996–2001 being highest for all erosion parameters. In all periods stable sections occur within the reach so obviously the range is up to the maximum. These show that average annual distances per bend range between 0.4 m $year^{-1}$ and 0.64 m $year^{-1}$ for the three epochs, and between 1.28 m and 2.33 m for annual maximum distance.

The variability in unit average erosion rate in individual bends sections ranges up to 0.98 m year^{-1}, 1.41 m year^{-1} and 1.13 m year^{-1} in the three epochs, respectively. Not all bends vary consistently and proportionately in the three periods. Most increase, then decrease in rate over the three periods, but several depart from these trends.

Table 1 Mean rates of bank erosion and discharge parameters for three epochs.

Annual average erosion rates				Discharge	
Epoch	Area (m^2)	Mean distance (m)	Max distance (m)	Peak flow (m^3 s^{-1})	No. peaks over threshold
1984–1996	76.70	0.40	1.28	74.55	1.75
1996–2001	124.51	0.64	2.33	102.68	4.60
2001–2007	108.73	0.57	1.70	76.78	2.17

The spatial variability in average bend erosion rate along the whole reach is high, although it experiences the same flow conditions throughout (Fig. 2). This demonstrates the scale of variation to be expected over decadal timescales and the variability for any particular bend. The largest range in rates between the three epochs is in bend 40, with an annual average ranging from 1.86 to 5.98 m for maximum distance, and in bend 46, from 0.59 to 1.41 m year^{-1} bend average.

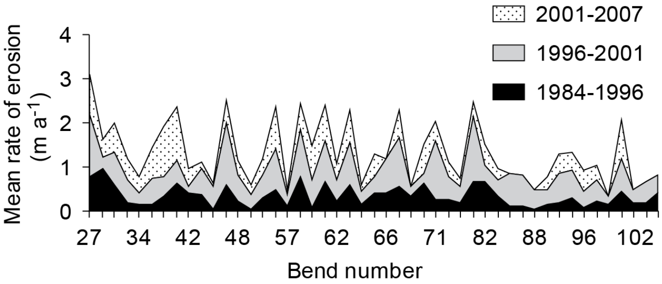

Fig. 2 Average mean maximum rate of erosion in bends for three periods. (Bends are not all consecutive numbers because of cut-offs and amalgamation for reach division).

The rates of erosion for different types of bend can be differentiated according to: (1) morphology of the bend, (2) type and phase of development of bend, and (3) material and erodibility, i.e. alluvial or bedrock (Hooke & Yorke, 2011). Averages for each of these for each period are given (Table 2). Differences are found particularly in relation to morphology of the bend, and also to phase or type of movement.

The total erosion index derived from annual mapping and classification (1–4) of erosion has been analysed for a standardised set of bends in the reach. The average index ranges from 94 to 133.
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Table 2 Average maximum distances (m year^{-1}) for different types of bend (bends 27–63).

Classification	Bend type	Period		
		1984–1996	1996–2001	2001–2007
Morphology	Straight	0.56	1.13	1.61
	Simple symm	1.31	2.18	1.61
	Simple asymm	2.04	2.28	1.68
	Compound	0.72	2.30	1.05
Confinement	Bedrock	1.38	2.25	1.63
	Alluvial	1.37	2.19	1.38
Movement	Stable	0.18	0.93	1.06
	Migration	1.25	2.12	1.56
	Growth	1.01	2.57	2.15
	Compound	2.42	1.03	1.18

The corresponding total length of eroding bank digitised from field maps varies from 963 m to 2333 m in the 26-year period.

Relationship to discharge

The rate of erosion is expected to vary with some measure of peak discharge, number of peaks or high flow duration (Julian & Torres, 2006). Means of discharge parameters for the three epochs have been compared (Table 1). The differences between the three periods are not sufficient to give a rating curve of erosion in relation to peak discharge, but mean rate of erosion shows a correspondence through the three epochs with mean annual peak flow characteristics (Fig. 3).

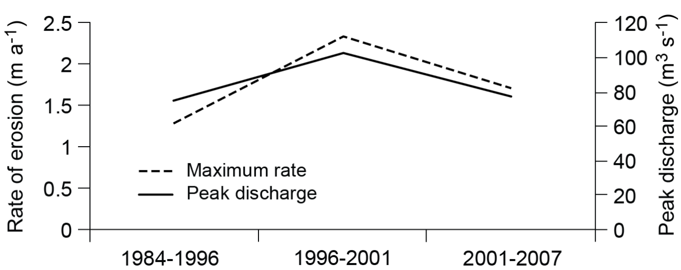

Fig. 3 Mean maximum erosion rate and mean annual peak discharge in each epoch.

The variability of the erosion index from year to year and also number of active bends and percentage of bends with active banks are shown in relation to peak discharge and peak winter discharge in Fig. 4. The erosion index generally follows the peak discharge but does not show the rise expected in the wet period of 1998–2002 and after that is rather lower than in the previous period, though comparable with the early part of the measurement period. The relationship between index and peak discharge has a low correlation ($r^2 = 0.12$). The number of bends exhibiting moderate or severe erosion matches more closely, but % active bends departs from peak winter discharge after 2001.

The length of actively eroding bank for selected years shows a better relation to peak discharge (Fig. 5(a)). Peak discharge therefore provides a general scaling. It is hypothesised that the effects of a year with particularly high or very low peak discharge could produce a "memory" effect so that responses in the succeeding period are lagged and affected by the previous conditions and state of bank. Thus the trajectories in phase space have been examined and indicate the variability to be expected (Fig. 5(b)).

The seasonality and month of occurrence of the peak flow have also been investigated because of the importance shown in previous research of the soil moisture and pore water pressures. In the period 1984–1996 there was much more distinction between the winter and summer seasons, with virtually no peak flows in summer; in 1996–2001 there was an extremely large number of high flows in the autumn months of 2000; and in the period 2001–2007 there were many more high flows in August and September than in the previous periods. Taking the month of peak flow in each year, more of the peaks are in October in the very wet period 1999–2001 and it is possible that, although flows were so high, the impact was not as great or was not as obvious by April as with later season peak flows.

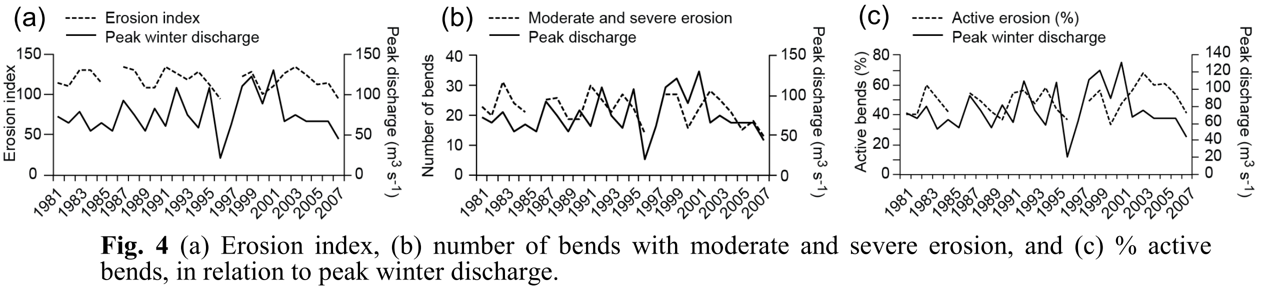

Fig. 4 (a) Erosion index, (b) number of bends with moderate and severe erosion, and (c) % active bends, in relation to peak winter discharge.

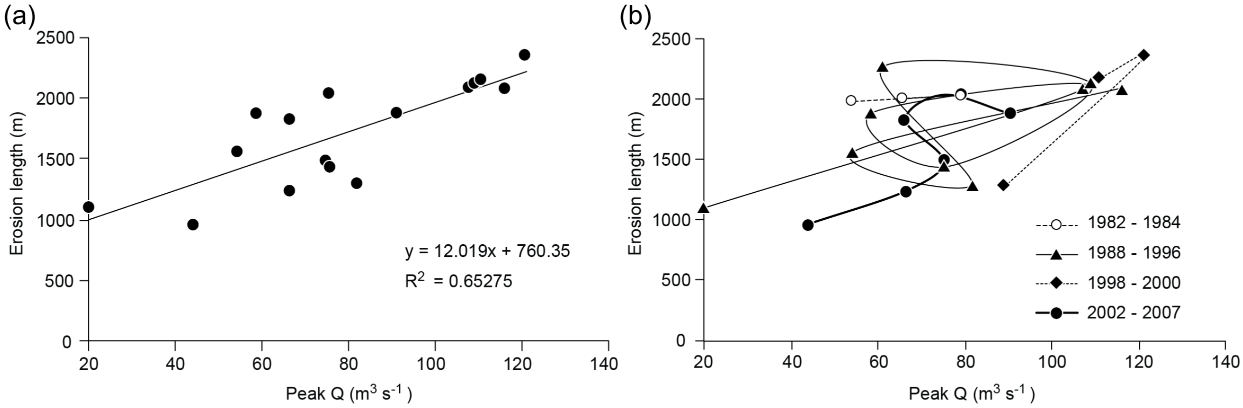

Fig. 5 (a) Relationship of total length of active bank erosion to peak discharge for selected years, and (b) time sequences of length of eroding bank in relation to peak discharge ($m^3\ s^{-1}$).

Modelling and testing of predictive equations

It has been shown that the amount of erosion is generally scaled to peak discharge or peak winter discharge. Accurate amounts of erosion are only available for the air photo epochs, but to derive a relationship the total amount of erosion (as area, average distance per step length or maximum distance) in the period 1984–1996 has been distributed between the years in that period by applying the ratio of each year's maximum discharge to the average maximum peak discharge for the period in order to calculate a proportionate amount of erosion each year. This has been plotted (Fig. 6) and can then be used as a calibration equation.

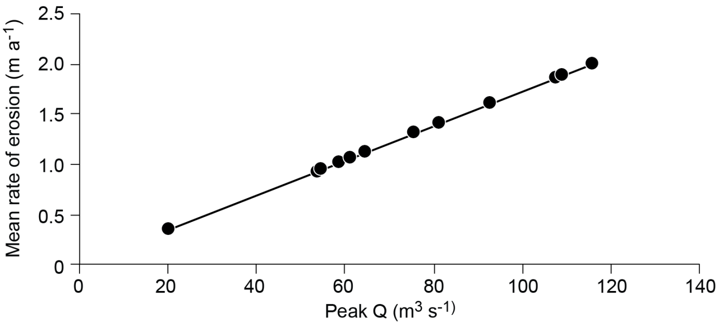

Fig. 6 Average maximum erosion per year calculated as proportionate relation to peak discharge, 1984–1996.

The equation for average maximum erosion for the reach is:

$$E_{max} = 0.0172Q_{max} \tag{1}$$

and for unit path length rate it is:

$$E_{mean} = 0.0054Q_{max} \tag{2}$$

These equations have then been used to calculate the expected amount of erosion for the peak discharge of each of the years 1997–2007 and tested against the actual total amounts for the periods 1996–2001 and 2001–2007 (Table 3) measured from the air photos in the GIS. This has been applied for both maximum distance for the standard set of bends (27–63) and average rate per unit path length. The outcomes show that for path length the estimate is 87% of the actual in 1996–2001 and 80% 2001–2007, and for maximum distance it is 76% and 84% for the two periods, respectively.

It is recognised that in most years it is not one single high flow alone which produces erosion so testing of a weighting for number of peaks over threshold was applied. The ratio for number of peaks in a year was calculated as ratio of each year to mean in 1984–1996, then this weighting was applied to the previous calculation of expected erosion rate. Weighting with various coefficients was tested and a weighting of 0.1 ratio of number of peaks gave a reasonable estimate. In the case of maximum erosion it produced estimates that were 98% and 96% of the actual values for the two periods, 1996–2001 and 2001–2007, respectively. For path length it overestimates by 69% and 14% respectively, 1996–2001 being a period with an exceptionally high number of extreme flows.

Scaling and prediction of erosion rate was also tested on individual bends. The above equations were applied to each bend as a ratio of this mean rate for the two later periods to the 1984–1996 mean annual rate of erosion. This produces estimates with large errors compared with the actual rates for each period. This method assumes simple extrapolation and continuation of the same activity in a bend and it has been shown that most bends do not change in a consistent way over these kinds of timescales on this river. Simple weighting by bend type was also tested, given the variation seen above in relation to type of bend and movement (Table 2). It produces a better prediction for average unit erosion rate than maximum erosion rate, and better for movement than shape for maximum distance and shape than movement type for unit length rate. However, overall these give poor estimates for individual bends though average deviations are small.

DISCUSSION

Peak discharge explains 80–85% of the annual variation in bank erosion rate and this can be used as a predictor and for scaling. The level of explanation of peak discharge is similar to that found by Pizzuto (2009) and confirms that a high proportion of the bank erosion on active rivers, such as this, is due to direct fluvial erosion and not subaerial or other processes. This prediction is improved slightly by use of an index weighted for number of peak flows in a year, but it overestimated for the period with the extreme year of 2000–2001 when there were many very high flows close together. Maximum erosion is more sensitive to discharge than average unit erosion and this is important because it is highly influential in changing the shape of the bend as well as predicting extreme erosion activity.

The results have demonstrated the high variability of rates of bank erosion, both temporally and spatially, within a reach experiencing the same hydrological conditions. This emphasises how misleading measurements from only a very few selected or instrumented bends may be for assessing expected ranges of behaviour. Part of this variability is due to the differing morphologies and the known different rates for different stages of bend development. However, application and adjustment to allow for these did not improve prediction for individual bends. This may be because some of the bends changed behaviour within the period. It has been shown previously that bends can suddenly become active or slow down in activity, with no obvious spatial or temporal controls on this, such as sediment flux from upstream or extension into different materials (Hooke & Yorke, 2011). Some of the bend estimates are quite good, especially using bend shape rather than type of movement.

The length of eroding bank in a year, based on careful field mapping, has been shown to be a relatively rapid indicator of erosion amount in that year and sensitive to peak discharges. The erosion index calculated was also a general indicator, but proved not sufficiently sensitive in the very high flow years. An additional category of intense erosion might be needed, but this would be difficult to distinguish in the field.

A basic classification of a bend based on material as a measure of resistance has previously been shown not to be highly discriminating on this river. This is probably because the response is often not a simple slowing or acceleration of rate, but an alteration in the locus of maximum erosion into the more erodible part of the bend. The soft, marl bedrock here is also relatively erodible compared with most bedrock.

In an earlier analysis (Hooke, 2008) covering the period 1981–2002, it was suggested that perhaps the period of 1998–2002 was rather different and may be indicating a changed response of the river. However, the additional data now available plot in a similar relationship to that of the 1981–1989 period.

The results here have important implications for sediment supply. The variability of bank erosion not only affects the movement of the channel, but also the sediment supply to downstream. Further work is in progress to calculate the volumes eroded, to compare these with the deposition and to calculate sediment budgets. Bank erosion is the major sediment source and the data here indicate the scale of variability occurring.

CONCLUSIONS

Over 80% of the amount and intensity of erosion on river banks in this active meandering river is explained by peak winter discharge and this can be used as a general scaling relationship and predictor of rate of erosion in any year. The prediction is slightly improved by using a weighting for number of peaks over threshold in the year, but application of a weighting for morphology or phase of evolution of a bend does not improve individual bend predictions, in spite of overall variations in rate according to bend characteristics. This is mainly because behaviour may change within the period of evidence. Some of the variability in rate of erosion in relation to peak discharge is possibly explained by lag effects from the previous year and the effect on the state of the banks. The range of temporal and spatial rates of bank erosion identified gives an indicator of the scale of variability to be expected on such a river on decadal timescales and over reaches of tens of loops. This has important implications for supply of sediment and its likely variability. The strong relationship to peak discharge means that possible future climatic impacts can now be modelled.

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