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Temporal variability in streambank response to individual flow events: the River Arrow, Warwickshire, UK

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Abstract Response variability is just as important as response magnitude in deciphering the operation of hydrological and geomorphological systems. This paper discusses the application of the new Photo-Electronic Erosion Pin (PEEP) system to the quasi-continuous monitoring of river bank erosion and deposition events and their temporal variability. The PEEP system quantifies the erosional and depositional work of each, individual, flow and meteorological event, and defines a more complete picture of variability than is normally available with conventional methodologies. At least 60 erosion/deposition events were detected over the 16-month study period (33 erosion; 27 deposition), revealing a hitherto unsuspected level of dynamism for a river bank site. Five types of variability were also identified: complex response, nonlinearities in the flow-erosion relationship, hysteresis in the stage *vs.* bank-change relationship (hitherto unobserved), oscillatory effects, and flow-independent behaviour. The type, magnitude, direction and variability of bank response was related to both flow magnitude and bank preconditioning processes. The effective role of combinations of weathering processes and subsequent fluvial removal is stressed. A simple sediment balance for the lower bank suggests it is in quasi-equilibrium.

INTRODUCTION

In explanations of physical processes, system response *variability* can be just as illuminating as response *magnitude*, and can reveal the presence of secondary and tertiary controls which condition the precise level of system reaction. Although a number of workers have identified substantial scatter in plots of flow magnitude against bank erosion rates (e.g. Knighton, 1973) three important problems remain. First, the full scope of this bank response variability has been masked, because field observations have necessarily been *temporally lumped*, i.e. although continuous flow data may be available, only temporally coarse erosional response information is collected. Secondly, types and explanations of variability remain elusive. Thirdly, most models of bank behaviour simply predict erosion rates as a function of some index of hydrodynamic force, such as discharge or near-bank velocity perturbations (e.g. Hasegawa, 1989; Pizzuto & Meckelnburg, 1989). This approach does not admit the possibility of a *range* of bank responses to a given stress level, related to antecedent characteristics, stochastic tendencies or the conditions under which that stress is applied. Thus, river bank retreat processes are at present relatively weakly represented in many models of fluvial system behaviour.

This paper, therefore, attempts to define and unravel the nature of bank erosion variability through time at a site on the lowland River Arrow in central England. Specifically, the aims are:

(a) to demonstrate that full variability in erosion and deposition response can be detected in the field with new automated techniques, which offer greatly improved temporal resolution;
(b) to show that this variability to specific (flow) events is much more substantial and complex than has hitherto been recognized;
(c) to deconstruct temporal variability by identifying different *types* of bank response present;
(d) to define the complete erosional and depositional event structure and hence the sediment balance over the 16-month study period for the lower bank zone.

THE "TRUE" TEMPORAL DISTRIBUTION OF EROSION AND DEPOSITION EVENTS

The research problem

One of the problems in (fluvial) geomorphology is that we have little knowledge of the real *dynamics* of erosion and deposition *events* at a time resolution comparable to that available for flow and sediment transport rates (Lawler, 1992a). Such information is required to allow detailed process-response coupling to be effected and modelled. Conventional, *manual*, field monitoring methods such as erosion pin or cross-section resurveys (Lawler, 1993a) merely reveal net change in the position of a bank surface since the previous measurement: they do not quantify the temporal distribution of change *between* site visits. This means that the precise bank response to each *individual* flow or meteorological event is generally unknown. Clearly, with a multiplicity of weakening and removal processes at work, process explanations and model building and testing will be more securely-based when (a) the full episodicity of change is detected, and (b) these specific erosion and deposition events are related to continuous information on the temporal fluctuations in the suspected driving forces.

Towards a solution: the Photo-Electronic Erosion Pin (PEEP) system

To help address these and other problems, the Photo-Electronic Erosion Pin (PEEP) system has recently been developed (Lawler, 1991a; 1992a,b, 1993b). The system comprises inexpensive single or multiple PEEP sensors connected to a datalogger. The PEEP sensor is simply a row of photovoltaic cells connected in series and enclosed within a waterproofed, transparent, acrylic tube of 12 mm I.D. (Lawler, 1992a). The cells generate an analogue voltage proportional to incident radiation, and hence to the total amount of photosensitive material that is exposed to light. A reference cell allows output signals to be normalized at the analysis stage for varying light intensity. The PEEP sensor is inserted into the bank much like the traditional erosion pin: subsequent retreat of the bank face exposes more cells to light which increases their voltage output. Deposition reduces voltage outputs. Subsequent scrutiny of the sharp changes in the logged PEEP signal thus reveals the magnitude, frequency and timing of erosion and deposition events much more precisely than has hitherto been possible (Lawler, 1992b). Although nocturnal events are not detected until the following morning, the achievable resolution is still far in excess that of traditional methods (Lawler, 1992a).

The pilot PEEP used here was 0.40 m long, although various sensor lengths and designs are possible to suit the application (e.g. gully, hillslope, streambank, channel bar, coastal cliff, desert dune or beach sites). Prior laboratory calibration is achieved using an iterative procedure of recording sensor outputs as progressively increasing amounts of bank retreat are simulated. These calibrations are encouragingly strong (see Lawler, 1992a), and are checked for drift and nonlinearities against manual field measurements of exposed PEEP length at the time of each field visit (Lawler, 1993b).

METHODS

Erosion measurements took place on an outside bend of the meandering, lowland, River Arrow, near Studley, west Warwickshire, UK (National Grid Reference SP 082635). The river here drains an area of 98 km^2, and the banks are composed of silty cohesive materials. Two PEEP sensors were installed within a traditional erosion pin network for the period January 1989 to May 1991. One sensor (PEEP 2) was installed around 20 cm above normal winter river level, with PEEP 3 approximately 40 cm higher, and a little upstream of PEEP 2 (Lawler, 1992b). Space permits discussion here only of results for the second part of the study period (January 1990-May 1991) from PEEP 2 alone, which is representative of the lower bank zone. The logger scanned at 30-minute intervals, and was also connected to sensors for the automatic monitoring of on-site stage – as an index of flow energy and bank area submerged during flow events – and air and bank surface temperatures. The magnitude, date and time of each erosion, deposition and flow event was then carefully abstracted from the datalogger records. In the case of uncertainties with, for example, some multiple flow events or low-light conditions, further clarification could usually be obtained from field notes, site photographs and concurrent meteorological data. Although in some cases subjective decisions were unavoidable, the results are considered to be internally consistent and reasonably representative.

RESULTS

There were 33 erosion and 27 deposition events identifiable between 20 January 1990 and 5 May 1991. The high total (60) reflects the ability of the PEEP system to detect most geomorphological work achieved by the succession of passing hydro-meteorological events. It represents a much more dynamic picture of change than has hitherto been suspected for river banks. Considerable temporal variability in bank responses was also observed. Again, the PEEP sensors prove advantageous in that, for the first time at a bank site, the *full* scale and structure of variability at the seasonal, subseasonal and event scale can be defined. This is useful for process identification, and prediction of sediment injections into the flow. Several inter-related types of variability are discussed below.

Complex response

Because of temporal changes in bank erodibility, different reactions to a given flow are observed. This is a temporal analogue of the spatially-referenced "complex response" concept of Schumm (1981, p. 309) who recognized that "the system to which stress is applied is itself changing through time". Note, for example, how the moderate flow of 26 October 1990 produces significant retreat of 11 mm (Fig. 1), while the net result of the much larger event on 8 February 1990 was 4 mm of deposition (Fig. 2). Field observations confirmed that in October 1990 the lower bank had been covered with loose aggregates which are relatively easily removed, while in February no such accumulations existed. Clearly, this example shows that factors other than hydrodynamics are at work (Carson *et al.*, 1973).

Nonlinearities in the flow-erosion relationship

When all such erosion and deposition events are plotted against the respective preceding peak stage achieved, there is a tendency for the larger erosion events to be associated with flow rises of intermediate magnitude, which reach just a few centimetres above the height of the PEEP sensor itself (Fig. 3). Because this pattern is partly mirrored by the deposition events, where the positive connection between accretion rates and stage is

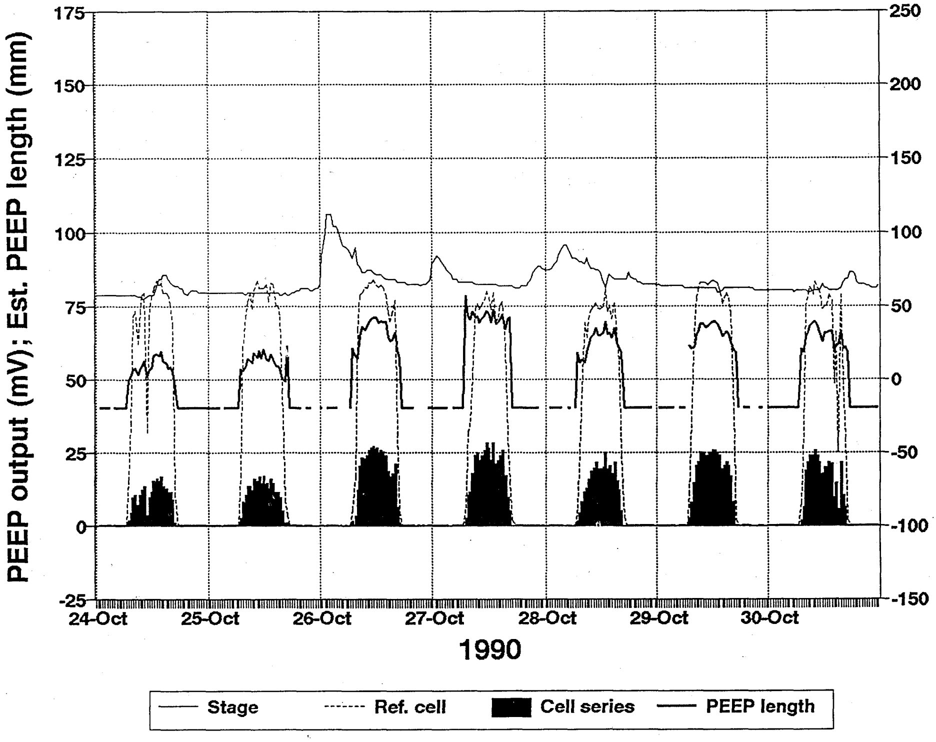

Fig. 1 A moderate flow event on 26 October 1990 producing 11 mm of bank retreat, as detected by the sudden increase in the diurnal trends in PEEP 2 cell series outputs and derived estimated PEEP lengths.

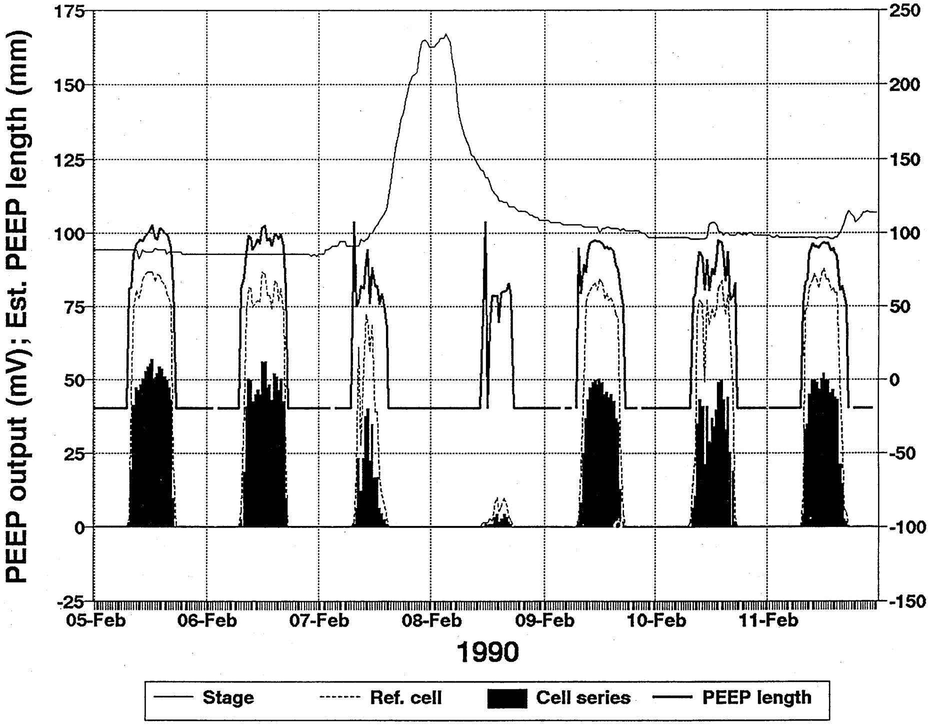

Fig. 2 A very large flow event on 8 February 1990 producing 4 mm of deposition, as detected by the small declines in the diurnal trends in PEEP 2 cell series outputs and derived estimated PEEP lengths (cf. Fig. 1).

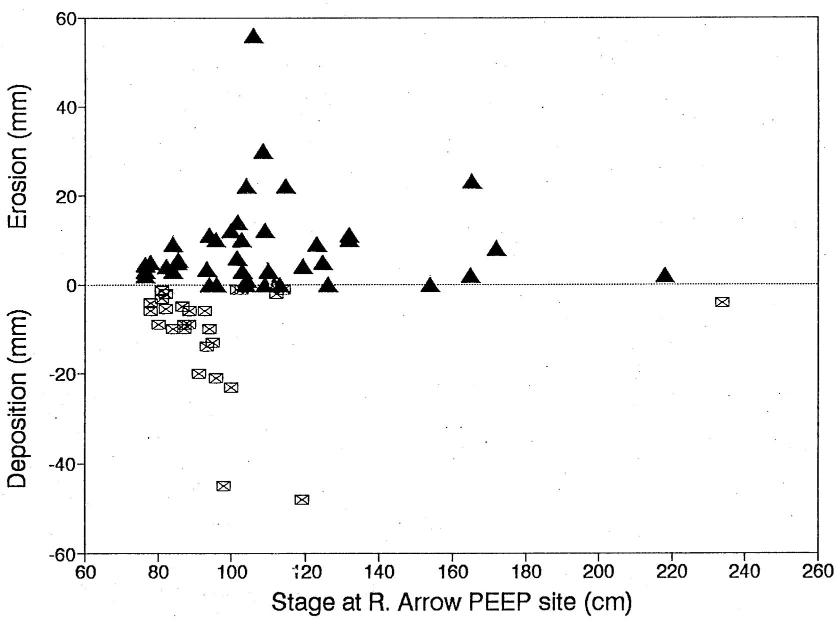

Fig. 3 Relation of peak stage of specific flow rises to the magnitude of associated erosion and deposition events (n = 70) on the River Arrow, as recorded by PEEP 2 between January 1990 and May 1991.

surprisingly strong, the resultant distribution is kite-shaped or cruciform (Fig. 3). The larger sample size created by the PEEP system record is clearly very useful: in this example, the 70 events – all < 60 mm – plotted in Fig. 3 (which includes 10 instances of zero erosion) represent around three times the number that would normally have been obtained with conventional methodologies. Traditional analyses also force a matching up of *net* change to a single, lumped, value for flow intensity in the whole measurement *interval* (e.g. Hooke, 1980; Lawler, 1986), and therefore ignore important response features and nonlinearities (e.g. Figs 1-3).

Hysteresis in the relationship between stage and bank changes

Furthermore, much of the scatter of Fig. 3 is the product of nested clockwise and anticlockwise hysteresis at various timescales in the relationship between peak flow and erosion/deposition magnitudes. This is the first time that such effects have been explicitly identified for a bank erosion system, and parallel the hysteretic trends observed in plots of discharge against suspended sediment concentration for many river systems (e.g. Bogen, 1980; Walling & Webb, 1981; Lawler, 1991b), and may suggest similar causes, at least in some instances. One clear example, affecting the biggest flood in the study period, is the clockwise hysteretic loop defined by sequential events 1 to 8 (24 January-3 April 1990), in which generally increasing flow peaks are associated with declining erosion (Fig. 4). This is entirely consistent with a declining supply of readily available loose sediment on the bank face as successive flows reduce the erodible stores. These stores can be built up, for example, by the spalling of aggregates from the upper bank by desiccation and frost processes (Harrison, 1970; Lawler, 1992b; 1993c). The

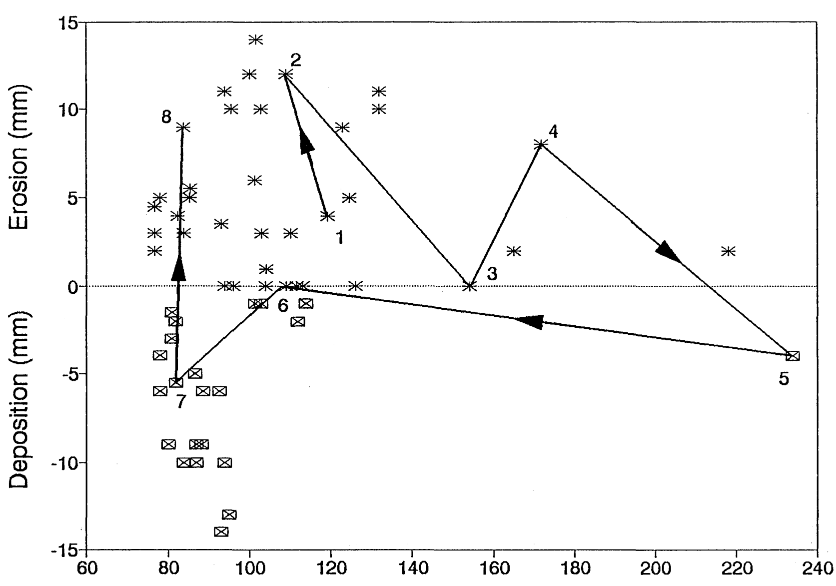

Fig. 4 Clockwise hysteresis in the relationship between peak stage and erosion/deposition events for the lower bank on the River Arrow (event 1 is 24 January 1990; event 4 is 31 January; event 5 is 8 February; event 8 is 3 April 1990).

restriction of erosion to the first event, only, of a double-peaked hydrograph event here in October 1989 illustrates precisely this effect (Lawler, 1992b). Once supplies of erodible materials are re-established through weathering processes, then high rates of removal become possible once again (e.g. event 8, Fig. 4) (see Carson *et al.*, 1973).

Oscillatory structures in bank response data

It follows that, should replacement of exhausted lower-bank sediment drapings be especially vigorous, then short-period oscillations in deposition and erosion of the lower bank zones become possible. Indeed, distinct sequences of alternating accumulation and removal events were detected (e.g. between 16 February and 4 March 1991 (events 54-60) in Fig. 5). This oscillation embraces the largest erosion and deposition events of the whole study period. Clearly, identification of these patterns helps further to rationalize the scatter in the flow-erosion relationship (Fig. 3).

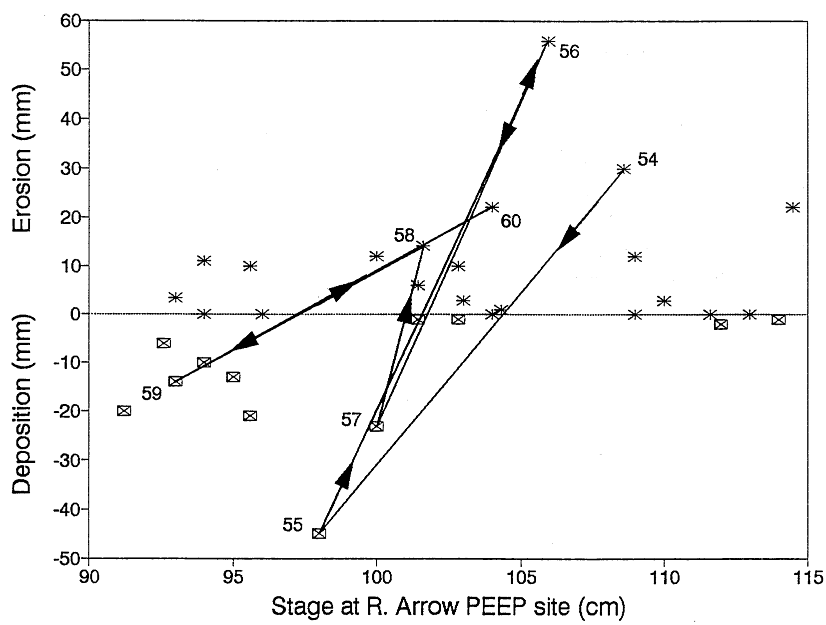

Fig. 5 Oscillatory behaviour in bank response to rapid flow changes (event 54 is 16 February 1991; event 57 is 23 February 1991; event 60 is 4 March 1991).

Flow-independent behaviour

A number of incidences of bank retreat – but especially advance – took place during periods of low river levels. Fieldwork confirmed that deposition episodes, in particular (see Fig. 3), were not related to the accretion of fluvially-transported sediments, but by the widespread accumulation near the bank toe of crumbs of bank material. These had been spalled from further up the profile by frost processes in winter (e.g. Harrison, 1970; Lawler, 1993c) and desiccational activity in summer (Lawler, 1992b). They are thus most prominent during periods of subzero or very high temperatures (Lawler, 1992b), and are much more common than might be assumed (Fig. 3). Therefore, deposition on the lower slopes largely reflects erosion of the upper slopes. Loose superficial material may also be eroded by rainwash and deflation processes in between flow rises.

DISCUSSION: A BALANCE OF ACTIVITY

The net result of bank activity over the 16-month study period can be seen in Fig. 6, and it is clear that erosion and deposition events can occur at any time of the year (Fig. 6). However, the most interesting feature is the emergence of a clear seasonal signal in the bank sediment balance: both late-winter periods are characterized by net erosion, while depositional activity dominates the summer and autumn months. Indeed, for the 12-month period ending 20 January 1991 (day 385), the lower bank zone at this point is virtually in balance (4.5 mm net accumulation only) (Fig. 6). This is entirely consistent with other observations which suggest that initially high erosion rates (Lawler, 1992b) were subsequently reduced as the bank toe stabilized, perhaps in response to a series of dry summers and low flows which allowed vegetation colonization to take place on the lower slopes. This would reduce boundary shear stresses on the sediment surface (Thorne, 1990), and assist entrapment of aggregates being transported downbank. Nevertheless, by 3 May 1991 (day 488), the activity of the late winter and spring had pushed the bank strongly into deficit once more (net erosion of 41.5 mm; Fig. 6), with much more material apparently leaving the bank toe than was being replaced by spalling processes from higher up the profile.

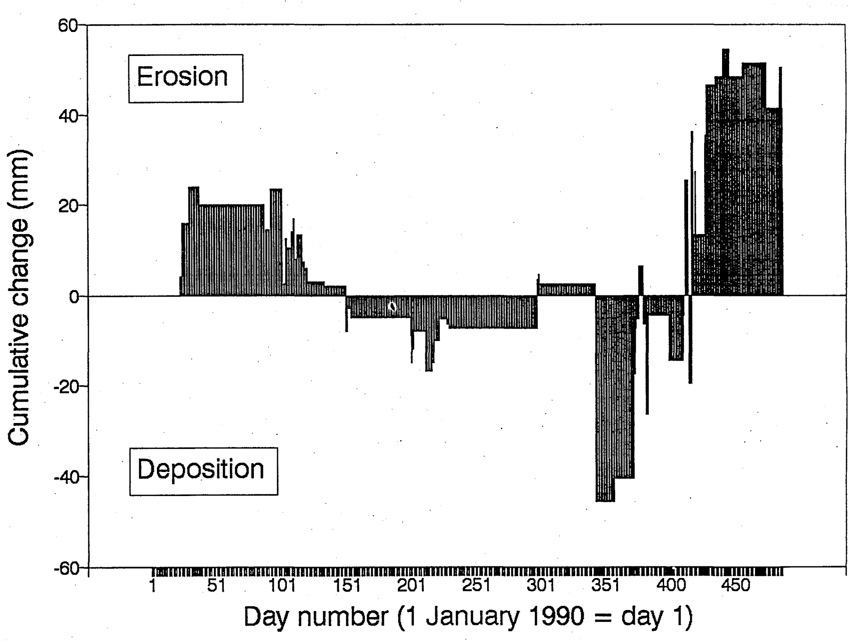

Fig. 6 The pattern of cumulative change at the River Arrow PEEP site 2. A clear seasonal cycle emerges, although erosion and deposition events can occur at any time of the year.

CONCLUSIONS

The following conclusions may be drawn from this study:

(a) The automatic PEEP monitoring system is capable of generating quasi-continuous erosion data which defines the timing and precise geomorphological impact of individual events, and hence, for the first time, the full range and variability of river bank dynamic response.

(b) The River Arrow site is very active, with 33 erosion and 27 deposition events identifiable from the 16-month PEEP record: this demonstrates that river banks can assume hitherto unsuspected levels of dynamic behaviour. The fact that so many events are self-cancelling reinforces the need for an automated technique to detect them.

(c) Bank response is highly variable, and five sources of variability were defined: complex response, nonlinearities in the flow-erosion relationship, hysteresis in the stage vs bank-change relationship, oscillatory effects, and flow-independent behaviour. Bank preconditioning processes were important controls of variability.

(d) A strong seasonal cycle in activity is observed, with net erosion emerging strongly in late winter, and depositional activity dominating summer and autumn. Over the calendar year, the site appears to have attained quasi-equilibrium; over the full 16-month study period, incorporating two winters, net retreat was 45 mm.

Existing models cannot express the possibility of many different, complex, bank erosional and depositional responses to similar flow rises occurring at different times of the year, in different sequences, combinations and juxtapositions, or under different conditions of bank material erodibility. The incorporation of such effects in a fresh generation of modelling efforts, at least for cohesive materials whose erodibility is subject to temporal change, is urgently needed to provide the platform for further progress. This should provide an additional dimension to conventional hydraulic engineering approaches based exclusively on hydrodynamics. Furthermore, the outputs even of existing models cannot be satisfactorily tested against field data of low temporal resolution collected with traditional methods. Although the PEEP system provides encouraging quasi-continuous data, further development would be beneficial, along with new methods to determine the precise magnitude, frequency, timing, duration and spatial coherence of erosional and depositional activity in a variety of landform contexts.

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