Automated monitoring of bank erosion dynamics: new developments in the Photo-Electronic Erosion Pin (PEEP) system

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INTRODUCTION

Bank erosion processes are still not well understood or specified in river dynamics and sediment flux models. The field is particularly complicated by the operation of both fluvial and non-fluvial erosion processes in channel systems, the change in bank material erodibility over different timescales which induces complex bank responses to similarly-sized flow events and - the specific focus here - the lack of bank erosion data *at the event timescale*. The main aims here are to: (1) describe recent developments in the Photo-Electronic Erosion Pin (PEEP) automatic erosion monitoring system; (2) demonstrate its potential to establish more clearly the timing of individual bank erosion events, including the concept of *thermal consonance timing* (TCT); and (3) outline the general importance of automatic erosion and deposition monitoring within the fluvial sciences and geomorphology more generally; (4) call for further research to address the outstanding process monitoring challenges.

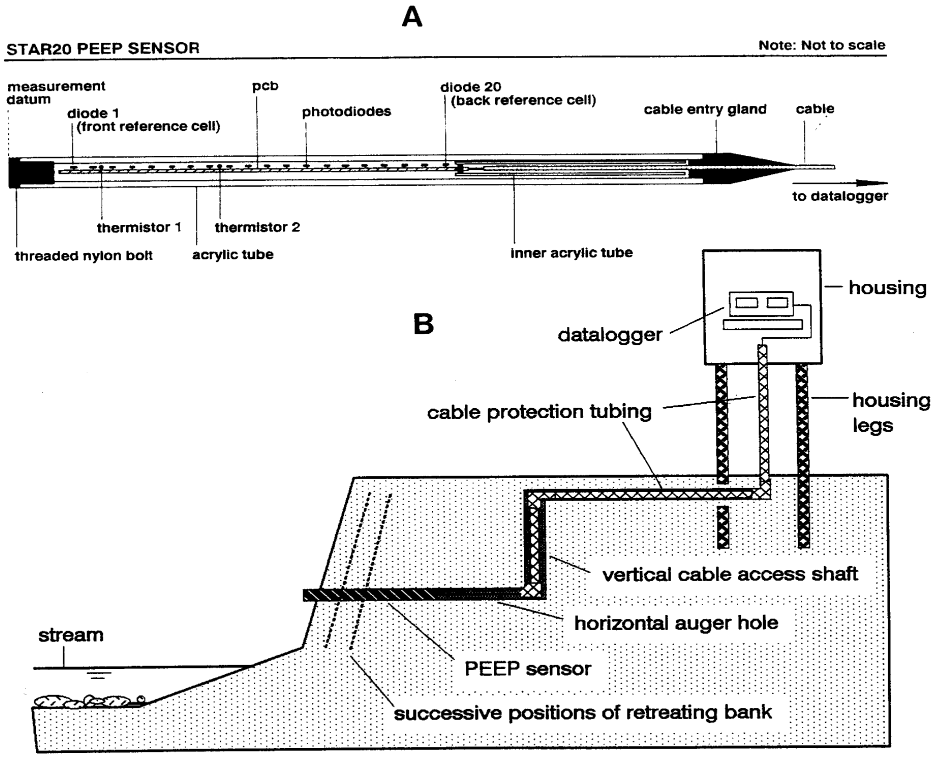
RATIONALE

For the interpretation of contemporary erosional patterns and processes, hydrologists commonly rely on continuous, automatically-monitored data on stage, discharge, precipitation intensity and turbidity, recorded with pressure transducers, automatic raingauges and turbidity meters. However, the erosion and deposition time series themselves are likely to form the weakest part of the investigation. This is because conventional, *manual*, field monitoring methods, typically erosion pins, cross-section resurveys or terrestrial photogrammetry (Lawler, 1993), merely reveal *net* change in the position of a bank or gully surface since the previous measurement. They do not quantify the precise *temporal distribution* of that change. This means that erosion event *timing*, and the precise bank response to *individual* flow or meteorological events, is generally uncertain. Because of the limitations of existing measurement methods, little knowledge has yet emerged of the *dynamics* of bank erosion and deposition *events* at a time resolution comparable to that available for flow and sediment transport rates (Lawler, 1992; 1994). Clearly, bank erosion process explanations and model development and testing will be more securely based when (a) the full episodicity of bank change is detected, including event *timings* and (b) magnitude/timing information for specific erosion and deposition events can be related to continuous information on the temporal fluctuations in the suspected driving forces.

THE PHOTO-ELECTRONIC EROSION PIN (PEEP) SYSTEM

To help address these measurement problems, the Photo-Electronic Erosion Pin (PEEP) system was developed in the early 1990s (e.g. Lawler, 1991, 1994). The PEEP sensor is a simple optoelectronic device containing a row of overlapping photovoltaic cells connected in series, and enclosed within a waterproofed, transparent, acrylic tube of 12 mm I.D. and 16 mm O.D. (Fig. 1A). The sensor generates an analogue voltage proportional to the total length of PEEP tube exposed to light. A reference cell adjusts outputs for variations in light intensity (Fig. 1A). Small networks of PEEP sensors are normally inserted into carefully pre-augered holes in the bank face, and connected to a nearby datalogger set to record PEEP mV outputs at 15-min intervals, though any frequency is possible (Fig. 1B). Most dataloggers are compatible. Subsequent retreat of the bank face exposes more cells to light, which increases sensor voltage output (Fig. 1B). Deposition reduces voltage outputs. Data recovered from the logger thus reveal the magnitude, frequency and timing of individual erosion and deposition *events* much more clearly than has been possible before (Lawler, 1992, 1994).

Figure 1: The Photo-Electronic Erosion Pin (PEEP) erosion monitoring system: (A) The PEEP sensor, which is now extended to 660mm length (200mm active) and includes two reference cells and two thermistors; (B) typical installation of a PEEP sensor and datalogger at a river bank site



Various PEEP designs are possible to suit the application (e.g. bank, gully wall, channel bar, hillslope, cliff, dune, beach).

Laboratory calibration establishes relationships between PEEP outputs and exposed tube lengths. These relationships are encouragingly strong: the position of the sediment surface is generally known with 95% confidence to within ± 2-4 mm (Lawler, 1992), although low light levels can reduce confidence. Further details of PEEP system measurement principle, design, calibration, installation and applications can be found in Lawler (1991; 1992; 1994; 2001), Lawler et al. (1997a), Prosser et al. (2000) and Stott (1999). Advantages and potential of the PEEP system are listed in Table 1.

Table 1. Advantages and potential of the Photo-Electronic Erosion Pin (PEEP) sensor

Advantages	Potential
* No power needed; PEEP based on solar cells	* Temporal distribution of erosion established more clearly
* Reference cells normalise for light level changes	* Process inference and model testing stronger
* Easy to connect to dataloggers	* Threshold identification more definitive
* Simple and reasonably robust	* Magnitude-frequency analysis more comprehensive
* Temperature and light monitoring capability	* Relation of erosion to sediment dynamics possible
* Sufficiently inexpensive for networks (e.g. 4-8)	* Erosion-warning capability via telemetry systems viable
* Applicable to many erosion/deposition contexts	* Real-time monitoring for research or management

Research is proceeding, however, to address certain limitations of PEEP systems. For example, being a visible-light system, nocturnal events are not detected until the following morning, although temporal resolution is still much better than with traditional manual methods. Data gaps at night can be plugged with programmed bursts of artificial light. Also, as with traditional erosion pins, PEEPs are invasive (although their small size minimises this), and they may be less suitable for gravel materials or for large mass-failure situations. The addition of data transmitters to PEEP sensors will obviate the need for cabling and backfilled access holes (e.g. Fig. 1B). Some PEEP data are occasionally degraded in low-light conditions, or when the bank is covered by snow, snagged vegetation or highly turbid water.

PEEP DESIGN DEVELOPMENTS

The early generation of PEEP sensors were 0.40m long, and were equipped with an array of 10 photovoltaic cells to provide an active length of ~90mm. The PEEP sensors were redesigned in 1996 and 2001 as follows (Fig. 1): (a) sensors were lengthened to 200mm active length and 660mm total length to allow for higher bank retreat rates; (b) a second reference cell was added to permit inverted installation, and to confirm minimum erosion magnitudes for large events; and (c) two thermistors were incorporated to generate bank temperature data at the sediment surface and at 68 mm depth, to help evaluate bank freeze-thaw, desiccation and biological (e.g. vegetation growth) processes. For example, two freeze-thaw events are detected in the bank temperature time series of Fig. 2. Thermistors also allow erosion events to be better timed through the use of *thermal consonance timing* (TCT), as discussed below.

METHODS

Study Area

The bank erosion results reported here derive from the UK Land-Ocean Interaction Study (LOIS) study, 1994 - 2001. The aims of LOIS were to understand the fluxes and dynamics of sediments, contaminants and nutrients from the land surface to the ocean (North Sea) (e.g. Leeks et al., 1997). We focused bank monitoring on the fluvial and estuarine part of the Swale-Ouse-Wharfe river system in northern England from January 1996 - April 1998. This paper concentrates mainly on the R. Wharfe PEEP site at Easedike in Yorkshire, for which flow and suspended sediment concentration data are available from Tadcaster, 2 km downstream. At Tadcaster, the Wharfe drains an area of 818 km^2 (Webb et al., 1997), and it is a largely rural, cool, humid temperate basin (Jarvie et al., 1997). Average annual precipitation (1961-1990) is 1139mm, rising to over 1500mm in the headwater areas. Banks here are high (>2.5 m), very steep and are formed from fine-grained sediments.

Monitoring techniques

A total of 26 representative fine-grained eroding bank sites (16 fluvial; 10 estuarine) were established for bank monitoring. Grid networks of ~30->100 erosion pins were installed and re-read at ~20-day intervals for between 1 and 2.25 years. Repeat survey was used to quantify major changes in bank position. For a clearer picture of erosion events, we deployed the Photo-Electronic Erosion Pin (PEEP**)** *automatic* erosion-monitoring system at up to six strategic points at eight key bank sites near LOIS Core Monitoring stations (5 fluvial; 3 estuarine). All sensors, including PEEPs, were connected to Campbell-Scientific CR10X dataloggers programmed to scan at 1-minute intervals and store data as 15-minute means. An Automatic Water Sampler was used within the LOIS Core monitoring programme to assess temporal changes in suspended sediment concentration (SSC) and for turbidity meter calibrations (Leeks et al., 1997). Flow and meteorological data were obtained from nearby UK Environment Agency stations. All timings are in GMT (Greenwich Mean Time).

EXAMPLE BANK EROSION EVENT SEQUENCES

Erosion dynamics

This is believed to be one of the most detailed river bank erosion investigations ever undertaken, in terms of the holistic basin approach adopted, the number of sites and points monitored, and the temporal resolution of measurement achieved. Around 15,000 manual erosion pin measurements were made over the 2.25-year monitoring period, plus 15-min PEEP readings. Some early data are published in Lawler et al. (1999, 2001) and Mitchell et al. (1999).

Much bank erosion took place in discrete, episodic events, rather than as a slower, continuous process. Moreover, in most cases, these bank erosion events were virtually instantaneous, and generally took less than 15 minutes to be completed (i.e. the logger scan interval). This underlines the need to adopt an automatic (quasi-) continuous approach to the monitoring of erosion in fluvial and other systems. Focus here is on bank erosion event sequences at Easedike to illustrate the how the PEEP system can clarify bank erosion event timings with respect to the hydrograph.

November 1996 Event

Fig. 2 illustrates a typical PEEP diurnal data sequence. The sudden increase in PEEP series outputs, with respect to a largely constant reference cell signal, clearly reveals that a large (>150 mm) erosion event occurred during a flow rise in early November 1996. Maximum readings for the PEEP back reference cell also confirm that the complete active length of the sensor has been exposed by bank retreat. In addition, the pattern of PEEP outputs indicates that the erosion event took place within an 18-hour 'window' between 14.15 h on November 6 and 08.15 h on November 7 (Fig. 2), i.e. around the time of the flow and suspended sediment concentration peaks.

THE CONCEPT OF THERMAL CONSONANCE TIMING (TCT)

Although defining the 'erosion event window' as above is very useful, and a significant improvement over conventional methodologies, the moment of material removal can be further fine-tuned through what I have called *thermal consonance timing* (TCT). PEEP sensors now include two thermistors, one at the bank surface and one at 68 mm depth (Fig. 1B). Under normal conditions, micrometeorological theory and empirical data suggest that thermal regimes at the soil surface (which acts as a radiation exchange surface) are much more extreme than at depth.

This is precisely what is recorded. Note how, before the November 6 flood, bank surface temperatures tend to be higher during the day and lower during the night than the bank interior (e.g. November 1-6, Fig. 2). However, once erosion 'exposes' both thermistors so that they experience very similar microclimates, minimal thermal differences and hence *thermal consonance*. The time when sustained thermal consonance is first established, therefore, reveals the moment of material removal. This is especially useful for those periods when PEEPs do not produce strong signals (e.g. when in nocturnal 'sleep' mode or if inundated by turbid water). The simple plot of the temperature difference time series in Fig. 2 reveals when *thermal consonance* has been established, i.e. when thermal differences become low (< 0.4 deg C) and constant.

For example, TCT in Fig. 2 suggests that the bank erosion event which exposed both thermistors occurred on November 6 at 15.00 GMT. This was 1.5 hours after inundation, 1 hour before the suspended sediment concentration peak, and 2 hours before the flow peak. In this case, therefore, at least 68 mm (the inter-thermistor distance) of the 150 mm bank erosion recorded was achieved as a *rising limb* event. Data on the timing of material removal with respect to the hydrograph can help to clarify the minimum stresses required for entrainment.

A further example is discussed of a triple-peaked hydrograph event in February 1997. Here, PEEP data themselves show that bank erosion was a *delayed retreat* incident, occurring *at least* 6 hours after the flow peak of 12.45 h on 18 February. TCT evidence suggests that the main bank retreat occurred towards the end of this window, within a 6-hour period between 02.15 h and 08.15 h on February 19.

Delayed retreat events, well after the discharge peak, suggest that direct *fluid entrainment* is not the main erosion process. Instead, such delays are usually taken as the signature of *a mass failure* or bank collapse process, and reflects either the removal during or following the hydrograph recession of transient lateral buttressing support to the bank provided by the flood waters themselves, or time-lags in the attainment of the critical pore-water pressure conditions necessary for geotechnical instability (e.g. Lawler et al., 1997b). Although there is some anecdotal evidence in the literature to suggest that delayed bank retreat events can occur, it is significant that the PEEP data are able to confirm that the phenomenon exists and also quantify the magnitude of delay. Thus, PEEP data on erosion *timing* can help to advance or eliminate certain controlling processes. Future parallel investigations of the variables driving such mechanisms should therefore provide a method of evaluating competing hypotheses, and testing erosion and sediment transport models.

DISCUSSION AND CONCLUSIONS

This application of the PEEP system has demonstrated that bank erosion event details can be determined much more clearly than was possible hitherto - especially the magnitude, frequency and timing of erosional and depositional activity in relation to fluctuations in river flow and hydrometeorological conditions (e.g. Fig. 2). The study has also yielded new information on the time-dependent behaviour of bank erosion. Erosion sequences presented show how the PEEP system can (a) quantify the impact of *individual*, rather than aggregated, forcing events, (b) reveal the full complexity of bank response to flow sequences, and (c) help to identify likely driving processes. The occurrence of *delayed* bank retreat events, up to 19 hours after the flow peak, indicating mass failure processes rather than fluid entrainment mechanisms, has been confirmed and quantified.

PEEP techniques have been used to improve the temporal resolution of erosion and deposition monitoring on other river systems (e.g. Lawler, 1991, 1994; Lawler and Leeks, 1992; Lawler et al., 1997a, 1997c). PEEP systems are now also being applied by other research teams to different contexts, including snow ablation and accumulation, beaches, tidal systems, drainage ditches and artificial channels (e.g. Mitchell et al., 1999; Prosser et al. 2000; Stott, 1999).

Such high-resolution information on the temporal distribution of bank erosion is vital to a sound process understanding of: the mechanics of bank instability, the fate of failed material, operation of basal clean-out cycles, and the delivery and storage of bank sediment to river systems, especially time-lags between hydrograph peaks, erosion events, and sediment injection to rivers. In particular, given the importance of data on the *timing* of inputs and outputs, coupling PEEP systems with concurrent flow and turbidity monitoring should help in future studies to evaluate the relations between erosion, sediment supply and sediment transport in fluvial systems and other geomorphological contexts.

There is an urgent need for further research, however, to refine *existing* techniques and to develop *new* methods for the continuous monitoring of erosion and deposition events in many geomorphological contexts. Such research could usefully exploit recent developments in micro-electronics, communications and data acquisition systems.

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Figure 3. PEEP series showing bank erosion event, flow, suspended sediment concentration (SSC) & bank temperature series: the R.Wharfe at Easedike, UK, October 31 - November 18 1996