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River bank erosion events on the Upper Severn detected by the Photo-Electronic Erosion Pin (PEEP) system

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ABSTRACT The absence of an appropriate automatic system for bank erosion monitoring has inhibited the collection of reliable field data on the precise timing, frequency and magnitude of erosional and depositional activity. Traditional, manual, techniques simply reveal net change to a bank face since the previous measurement, and not the temporal distribution of that change within any given measurement interval, in response to a variety of potential driving mechanisms. We describe here the application of the Photo-Electronic Erosion Pin (PEEP) system, recently developed at the University of Birmingham, to a pilot bank erosion project on the Upper River Severn, mid-Wales, UK. This inexpensive system allows, for the first time, quasi-continuous time series of erosion and deposition data to be collected automatically - a capability which is especially valuable in highly episodic systems and for remote sites which cannot be visited frequently. Example bank erosion sequences show how the system can quantify the impact of individual, rather than aggregated, forcing events, reveal the full complexity of geomorphological change on river banks, and enhance explanatory power. The PEEP system should permit the future testing of erosion models of high temporal resolution, and facilitate a more rigourous coupling of 'real-time' channel-side sediment supply to catchment sediment output.

INTRODUCTION

A basic requirement in any observational science is an ability to quantify the temporally-varying properties of the system, relative to fluctuations in the driving forces, with sufficient resolution to facilitate strong process-inference. A minimum requirement of rainfall-runoff modelling, for example, has long been the availability of continuous or quasicontinuous time series of precipitation input and river discharge data derived from appropriate instruments. Similarly, the study of suspended sediment dynamics has been revolutionized by the arrival over the last forty years of turbidity meters which, when connected to chart recorders or dataloggers, provide the crucial detail on the temporal variations in fluxes. However, these technical developments in the <u>hydrological</u> sciences have not been matched by a capability to obtain automatic and continuous data on <u>geomorphological</u> change - a point made by Gregory (1977). This is surprising, given that a central aim of geomorphology is to document and explain temporal change and adjustment of landforms, increasingly with respect to contemporary timescales.

This deficiency affects most of process geomorphology. It is especially noticeable, however, in explanatory studies of the dynamics of river suspended sediment transport, because hitherto there has been no method to collect automatically quasicontinuous data on sediment removal and storage at sites within catchments. Existing, manual, methods (e.g. Lawler, in press; Thorne, 1981) simply reveal the net change to sites occurring between field visits. Explanations are hampered, then, by an inability to compare observed fluctuations in suspended sediment transport with information on the precise magnitude, frequency, duration and timing of erosion and deposition within river basins. A device to overcome some of these problems in studies of nearshore sediment movement was presented by Erlingsson (1990, 1991). This instrument, the Sedimeter, has considerable potential but cannot be used on exposed basin surfaces which ambient infra-red radiation can reach, and has to operate in water of at least a few metres deep.

In response to these methodological difficulties, a Photo-Electronic Erosion Pin (PEEP) sensor has been designed which, for the first time, can be used to measure erosion and deposition automatically on hillslopes, river banks, gully sides etc. (Lawler, 1989a). Subsequent field trials at a bank site on the relatively quiescent, low-power, lowland River Arrow, Warwickshire, UK (Lawler, 1991, 1992a, 1992b) demonstrated the feasibility of the general approach and the ability of the PEEP system to define the true temporal distribution of river bank change, quantify the erosional impact of individual flow and desiccation events, and discriminate between competing hypotheses of process-control in erosional contexts.

This paper discusses the application of the method to a much more dynamic upland headwater site on the Upper River Severn in mid-Wales, UK, as part of a series of tests in a variety of erosional and depositional situations. The project complements recent work on erosion and sediment transport processes in the region (e.g. Leeks, 1992; Leeks and Newson, 1989; Newson and Leeks, 1987). Following a brief description of the PEEP system itself, a few example bank erosion events are presented to illustrate the potential and some of the problems of the PEEP system.

THE PHOTO-ELECTRONIC EROSION PIN (PEEP) MEASUREMENT SYSTEM

The PEEP sensor

The Photo-Electronic Erosion Pin (PEEP) sensor is a simple and inexpensive optoelectronic device consisting of an array of photovoltaic cells connected in series, and enclosed within a waterproofed, transparent, acrylic tube of 12 mm internal diameter (Fig. 1). The cell series generates a small analogue voltage proportional to the amount of light falling on the cells. A reference cell at the front end of the device allows output signals to be normalized for changing ambient illumination. The version used here is 0.40 m long, with an 'active length' of 0.11 m (i.e., ten cells only to keep costs down (Fig. 1)), although much longer total and 'active' lengths are possible. No power supply is needed in the field, because the cells are photovoltaic, and transform directly incident light energy into electrical outputs. See Lawler (1992b) for further details.

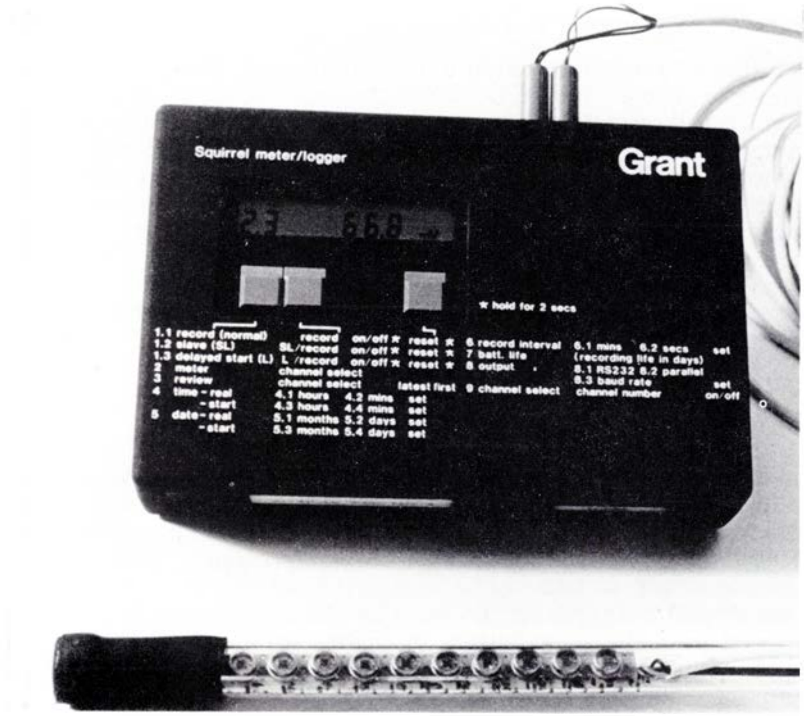

FIG. 1 A prototype PEEP sensor connected to a datalogger. Full tube length is 40 cm although only half is shown here.

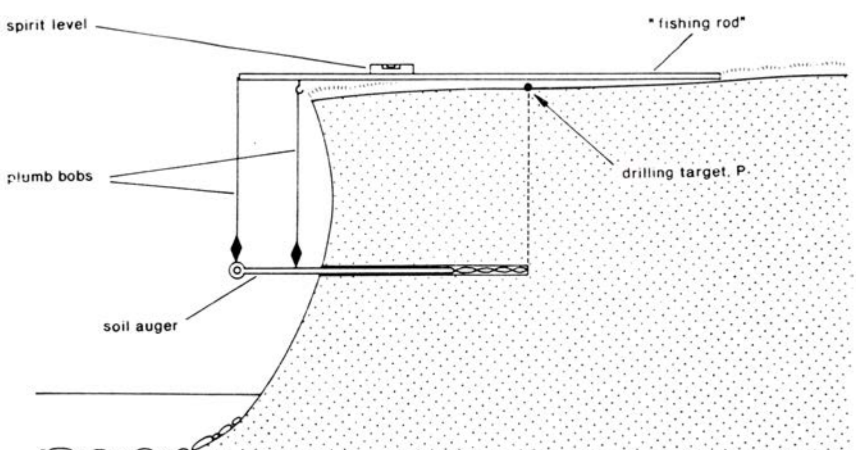

FIG. 2 Use of the simple 'fishing-rod' levelling device to determine drilling target ('P') for cable-access shaft.

Measurement principle

The PEEP tube is inserted into an eroding (river bank) face and connected to a datalogger housed on the floodplain nearby. As the eroding bank, cliff, hillslope or gully wall retreats, more photovoltaic cells in the PEEP sensor are exposed to light, which increases the millivolt output from the device. Accretion causes photovoltaic outputs to drop. Peaks, ramps and troughs in the logged signal thus reveal the magnitude, frequency and timing of erosion and deposition events much more precisely than has hitherto been possible. The simple electronics in the device (Lawler, 1992b) is designed such that 1 mV of 'extra' cell series output equates to around 1 mm of bank retreat. Being based on natural daylight, the system will not, of course, reveal nocturnal erosional events until the sensors are re-activated the following morning.

Calibration

Laboratory calibration of PEEP sensors is first achieved under natural illumination by simulating, with a movable light-tight sleeve, known amounts of bank retreat. Strong, linear, relationships are obtained between the length of PEEP tube exposed and sensor outputs (Lawler, 1992b). Coefficients of explanation are around 99.7% for a sample of 250 scans, with standard errors for estimated tube length as low as 1.26 mm. Standard errors could be further reduced by using data loggers of higher resolution than those used in these experiments and by averaging a number of instantaneous scans over a given sampling period. In-situ field calibrations (based on 'ground-truth' measurements) are also recommended as a check on satisfactory operation. These are accomplished by measuring manually at periodic intervals the actual amount of protruding PEEP tube with vernier callipers, as with traditional erosion pins, and regressing the results against sensor outputs.

STUDY AREA

A site for PEEP monitoring on the Upper Severn in the Institute of Hydrology (IH) research catchments at Plynlimon was chosen because (a) it afforded the opportunity of evaluating the performance of the PEEP system in a hostile upland fluvial environment; (b) the existing intensive IH instrumentation provides detailed data on the likely influential variables (e.g. river stage, discharge, rainfall intensity, soil and air temperatures, radiation loading); (c) as a 'manned' experimental basin, on-site field assistance with 'ground-truth' and traditional erosion pin measurements and routine downloading of dataloggers is available; and (d) the availability of high-resolution suspended-sediment data for the catchment since 1979 (Leeks, 1992) would allow the implications of bank erosion for sediment fluxes to be explored in a future phase of the project.

The Upper Severn basin is located in upland mid-Wales at Plynlimon, and receives up to around 2400 mm of precipitation each year. The catchment is characterised by a flashy hydrological regime, and experiences about 162 days of ground frost per annum. The reach selected is a right-bank site of the Hafren (the main Severn headwater tributary) immediately below its confluence with the Tanllwyth (UK National Grid Reference SN 8433 8755). Drainage basin area at the Hafren flume from where flow data are drawn, a few hundred metres upstream of the erosion site, is 3.67 km^2. Total drainage area at the site itself, which includes the Tanllwyth catchment, is 4.6 km^2. Bankfull width here is around 6-8 m, with a bankfull depth of about 1.2 m. At an altitude of 350 m

O.D., this erosion-monitoring site is one of the highest in the UK. The bank here is composed of fine-grained cohesive materials with very high organic matter contents, interspersed with occasional coarse sand/fine gravel lenses. The meteorological data quoted in this paper derive from the nearby Moel Cynnedd station.

SITE INSTRUMENTATION

Four PEEP sensors (reference numbers 901, 902, 903, 904) were installed at the site on 12 October 1990 at 9.8, 28.5, 14.0 and 39.2 cm above current water level respectively. These were surrounded by traditional erosion pins to cover a 5 m-length of instrumented bank face. PEEP sensors were inserted into pre-drilled horizontal auger holes which were made long enough to accommodate anticipated future resetting. The cables are taken out of the back of the sensors through the bank interior (to avoid fouling the delicate bank surface) and thence to the datalogger. This required a vertical access tube to be drilled on the floodplain surface to intersect with the horizontal hole for the sensor. Determining where the vertical shaft needed to be sunk (point P on Fig. 2) was solved with the use of a simple yet remarkably successful 'fishing-rod' levelling device (Fig. 2). Two or more PEEPs may use a common vertical cable-access shaft as in Fig. 3 (see also Lawler, 1992b). To minimize disturbance effects, only the tip of the PEEP device protrudes from the bank, with just the reference cell and the first cell in the series wholly visible (Fig. 4). For this study we used a Campbell Scientific CR10 datalogger scanning at 15-minute intervals to record PEEP outputs, although almost any commercially-available logger will suffice (e.g. the Grant Instruments Squirrel/1200 logger (Fig. 1)(Lawler, 1991, 1992a)).

BANK EROSION EVENTS

The monitoring programme is ongoing and the full dataset has yet to be analyzed, but a few sample events from the many recorded in the winter of 1990/91 will serve to demonstrate the utility of the technique and highlight a few limitations. Detailed examination of the dynamics of erosional activity is reserved for future studies.

The first example, of a moderate flow event on 20 December 1990 followed by an extended recession, is shown in Fig. 5. PEEP sensor 902 shows a moderate erosion event of 5 mm on 23 December (Fig. 5), as revealed by a rise in the diurnal cycles of cell series outputs to ~24 mV on that day, from previous daily maxima of ~18 mV (1 mV $\simeq$ 1 mm bank retreat here). The fact that this is a delayed erosional event - at least two days after the flow peak (Fig. 5) - does not point to the importance of fluid entrainment processes here. Such falling-stage erosion is common in the case of 'drawdown' failures when lateral support on bank faces provided by the flood waters themselves is withdrawn, leaving the saturated material to collapse en masse. However, this 5-mm retreat event is more suggestive of micro-ped or aggregate removal than block failure, and it may, therefore, be a small-scale example of 'pop-out' failure caused by progressively increasing pore water pressures in the bank material (see Bradford and Piest, 1977). Figure 5 illustrates, too, the ambiguous nature of some of the output signals when the PEEP sensor is submerged under turbid water, as on 20 December. Near-maximum reference-cell outputs throughout the recessional limb, however, demonstrate that the delay of the erosion event is real, and not simply an artifact of the sensor re-emerging from turbid water.

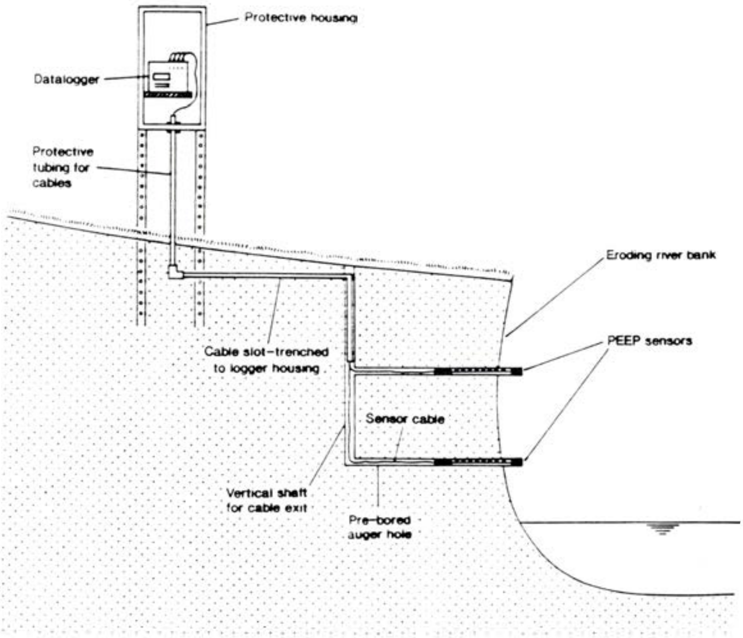

FIG. 3 Schematic installation of two PEEP sensors at a river bank site, connected to a datalogger in an environmental housing.

A runoff event of similar magnitude (but different shape) followed on 1 January 1991 (Fig. 6) and illustrates the complexity and nonlinearity of bank erosion dynamics. Much more intense and widespread erosion was associated

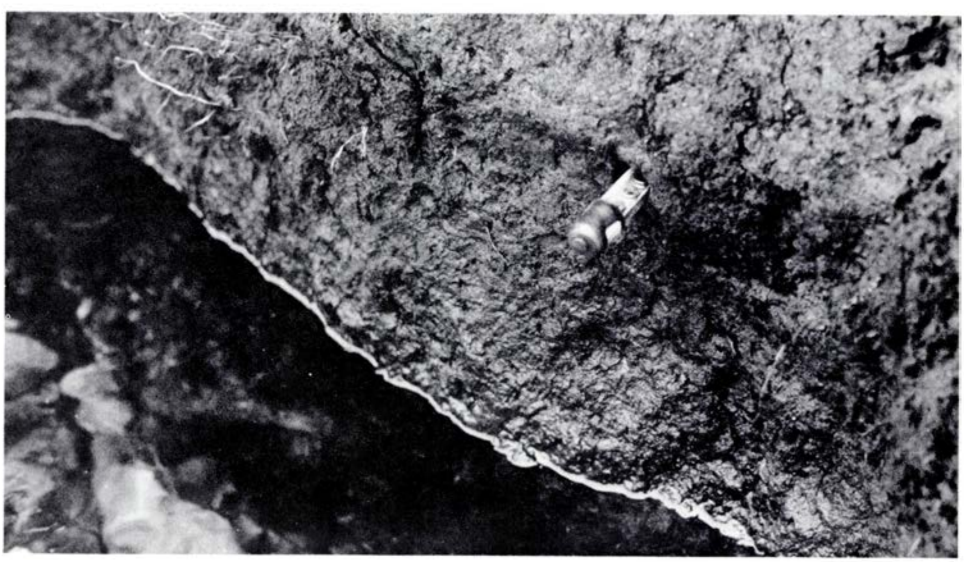

FIG. 4 A PEEP sensor emerging from the bank face at the Upper Severn site. The reference cell and two cells in series can be seen (photo: A. James).

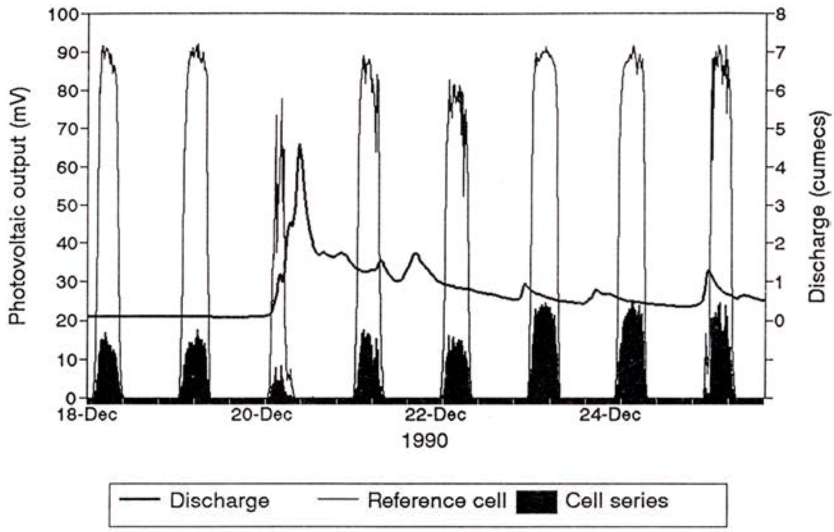

FIG. 5 A small-scale erosion event on 23 December 1990 as shown by an increase in the diurnal maxima of cell series outputs of PEEP sensor 902.

with this event. Note how the cell series outputs of PEEP 902 jump to their maximum possible values on 2 January 1991 immediately after the passage of the flood (Fig. 6), representing bank retreat of over 70 mm. This is a minimum figure, because the whole 'active' part of the PEEP sensor had been exposed by

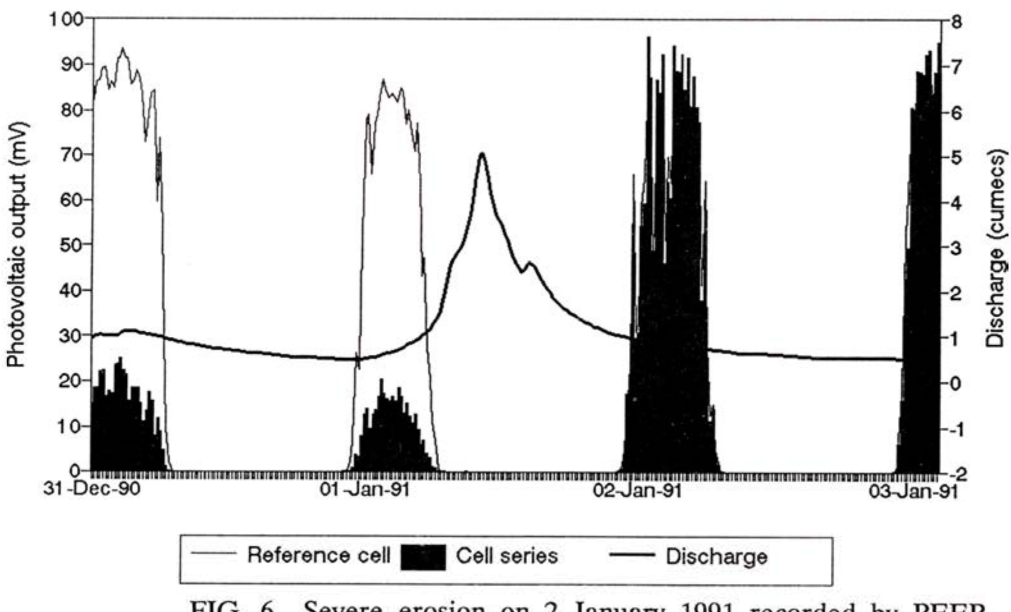

FIG. 6 Severe erosion on 2 January 1991 recorded by PEEP sensor 902. Bank retreat is so great as to disclose all cells in the series, causing outputs to peak.

erosion (Fig. 6). This illustrates the difficulties of predicting likely erosion rates for the purposes of instrument design!

It is tempting to explain this order-of-magnitude increase in erosional response over the 20 December event (compare Figs 5 and 6) in terms of fluvial pre-wetting concepts. The week before the storm leading to the 20 December event was cold and dry, with only moderately-heavy rain (57.9 mm) falling between 6 and 11 December. Under similar conditions of sub-zero air temperatures at the end of January 1991 extensive, but rather short and sediment-free, needle-ice was observed on the bank face, and it may have been present in this antecedent period too. The 2 January event on the other hand was the last of a sequence of significant flow rises over a 2-week period in which 260.1 mm of precipitation had fallen. Although freeze-thaw activity has been shown to be important at some sites (e.g. Curr, 1984; Hill, 1973; Gardiner, 1983; Lawler, 1986, 1987; Leopold, 1973; Stott et al., 1986) it can be tentatively suggested that pre-wetting is a more important erosional influence here. Wolman (1959, p.204) found that bank erosion on the Watts Branch in Maryland was also especially severe if flow events acted on banks which had first 'been thoroughly wetted'. Hooke (1979), too, pointed to the strong positive influence of soil moisture on bank erosion rates of some Devon rivers.

The final example shows how for daytime events the precise timing of an erosion event can be revealed. Note how, again as an apparent delayed response to the 20 December 1990 storm described above, PEEP 903 first registers erosion at 1330 h GMT on 22 December (Fig. 7): at sometime in the previous 15 minutes, therefore, over 80 mm of bank material had been removed. Again, this is a minimum figure.

Comparison of Figs 5 and 7 illustrates the order-of magnitude difference in erosional response to the same event between two points on the bank surface less than a metre apart and with a vertical separation of just 15 cm. Such spatial variability has often been recognized by bank erosion workers (e.g. Hooke, 1979; Lawler, 1989b). Variation across the bank in the timing of erosion is also

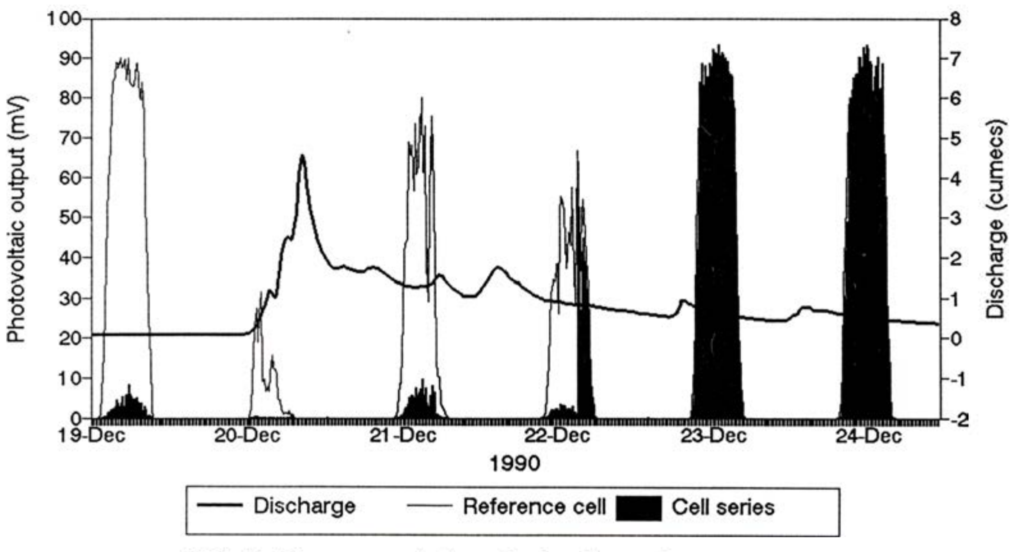

FIG. 7 The exact timing of a bank erosion event on 22 December 1990 revealed by the sudden rise in PEEP sensor 903 cell series outputs at 1330 GMT.

evident (Figs 5 and 7): note that the sensor closer to the water (PEEP 903) reacts ahead of the higher sensor (PEEP 902) by 3 - 18 h, which perhaps reflects an earlier exceedance of saturation thresholds, a longer period of applied excess shear stress, or simply more erodible bank material at the former site. This spatio-temporal variability reinforces the need to have a network of traditional erosion pins to detect spatial change, with a smaller network of PEEP sensors nested at strategic points to monitor temporal fluctuations. In this sense, the PEEP system is seen to be complementary to conventional techniques.

DISCUSSION AND CONCLUSIONS

Experience in using the PEEP system on the River Arrow (Lawler, 1991, 1992a) and Upper Severn has allowed a number of small problems to be identified. Like normal erosion pins, inserted sensors may disturb the bank surface, although the existing design (e.g. small size and cable-training through the bank interior) minimizes these effects. Similarly, gravel banks may be too difficult for the installation of PEEPs, and if erosion is by mass failure of large blocks of material PEEP sensors may be pulled out or have a reinforcing effect. Some data are inevitably lost due to temporary coverage of the device by snow, vegetation or sediment. The delayed detection of nocturnal erosion is a problem that can be solved by artificial lighting (automatically triggered by the logger for each scan) yet, even without this, the PEEP system still offers a much higher temporal resolution of erosional and depositional activity detection than has been available hitherto. The question of ambiguous underwater response noted above may be solved in the future with more sensitive photovoltaic cells or artificial lighting in some cases.

TABLE 1 Merits and potential of the PEEP system.

Merits:	Potential:
* No power needed in field	* True temporal distribution of erosion established
* Inexpensive	* Process inference and model testing stronger
* Simple to construct and install	* Threshold identification more definitive
* Simple interfacing with loggers	* Magnitude-frequency analysis more rigorous
* Reasonably robust	* Relation of erosion to sediment dynamics
	* Erosion-warning capability via telemetry

The advantages and potential of the PEEP system are summarized in Table 1. PEEP sensors are inexpensive, simple to construct and install in the field, easy to interface with dataloggers, reasonably robust and require no power for operation. Use of the system allows the true temporal distribution of erosional and distributional activity to be established more completely. Existing methods tend to underestimate activity rates, because only net change is revealed. PEEP systems therefore should provide a stronger basis for the inference of processes and the building and testing of models of erosional influences. Furthermore, the PEEP system should facilitate the definition of thresholds of change in relation to applied stress, and strengthen magnitude/frequency analyses, because the geomorphological impact of each event - and not simply the aggregate effect of a group of events in any given measurement interval - can be ascertained. Sediment dynamics work should be enhanced given that rigorous analysis of the covariation of high resolution turbidity and erosion rate (i.e. sediment supply) data can now be accomplished. Finally, as with any automatically-recording technique, a PEEP network could provide real-time data with the sensors or logger being interrogated remotely through telemetry systems, perhaps in an erosion-warning capacity at vulnerable sites.

Because of the complex responses observed in most erosional situations, techniques like the PEEP system are urgently needed to define the activity time series with much greater precision than has been possible before. Even in a moderately hostile upland environment, the PEEP network has succeeded in yielding promising results. Such methods are vital in unravelling process dynamics and, deployed at strategic points within traditional monitoring networks, can provide valuable insights, especially at remote sites which cannot be visited frequently.

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