The Structure, Function and Management Implications of Fluvial Sedimentary Systems (Proceedings of an international symposium held at Alice Springs, Australia, September 2002). IAHS Publ. no. 276, 2002.

Reconstructing historic floods using sediments from embanked flood plains: a case study of the River Tay in Scotland

JANIS L. PAINE, JOHN S. ROWAN & ALAN WERRITTY
Environmental Systems Research Group, Department of Geography, University of Dundee, Dundee DD1 4HN, UK
e-mail: j.l.paine@dundee.ac.uk

Abstract Sedimentary evidence of past floods can be preserved in flood plain sediment sinks during overbank flood events. The potential for using such flood plain sediments to reconstruct long-term flooding histories was explored in the lower reaches of the River Tay in Scotland. Granulometric analysis and radionuclide dating undertaken on cores from an embanked palaeochannel has shown that the sedimentary record appears insensitive to relatively frequent overbank spills, but low-frequency, high-magnitude floods which breach the embankments are preserved. A discharge threshold for such events has been identified through analysis of the embankment breaches associated with specific flood discharges in the instrumental record. Where hydroclimatic records are limited, the method can be used to extend flood histories for the largest flood events, enabling recent changes in flooding regimes to be assessed in a longer historical context.

Key words flood plains; historic floods; overbank deposition; embankment breaches; radionuclide dating; River Tay; Scotland

INTRODUCTION

Analysis of past flood events in their correct historical context is essential for realistic and cost-effective strategic planning of flood alleviation policies, particularly under current climate change scenarios. Fluvial response to quite subtle shifts in climate can result in major changes to flood magnitudes and frequencies (Knox, 2000). Extreme flooding on a number of Scottish rivers since 1988 has highlighted the lack of long-term instrumental records of precipitation, runoff or river discharge (Werritty, 2002). Few Scottish hydroclimatic records cover more than 50 years and many remote, upland catchments remain ungauged (Black, 1996). In the absence of quality long-term instrumented records a proxy flood history can be preserved in flood plain sediments, particularly in palaeochannels, where flood events can be represented as discrete and recognizable flood layers (Nicholas & Walling, 1997).

This paper reports preliminary findings from work exploring the extent to which palaeochannels in the River Tay accumulate and preserve flood sequences, and how far these deposits can be related to flood events identified in the instrumental record over the last 50 years. Matching identifiable flood units in the stratigraphy to specific flood events with known magnitudes and return periods is a vital precursor to the reconstruction of long-term patterns of flood frequency and magnitude. Flood embankments complicate patterns of overbank sediment deposition (cf. Asselman & Middelkoop, 1995), but work on such sites is particularly important as embanked flood plains are most significant in population and economic terms. Given the brevity of instrumental flow records in many countries, further development of this method for reconstructing historic floods will enable recent changes in flood frequency to be placed within a longer historical context.

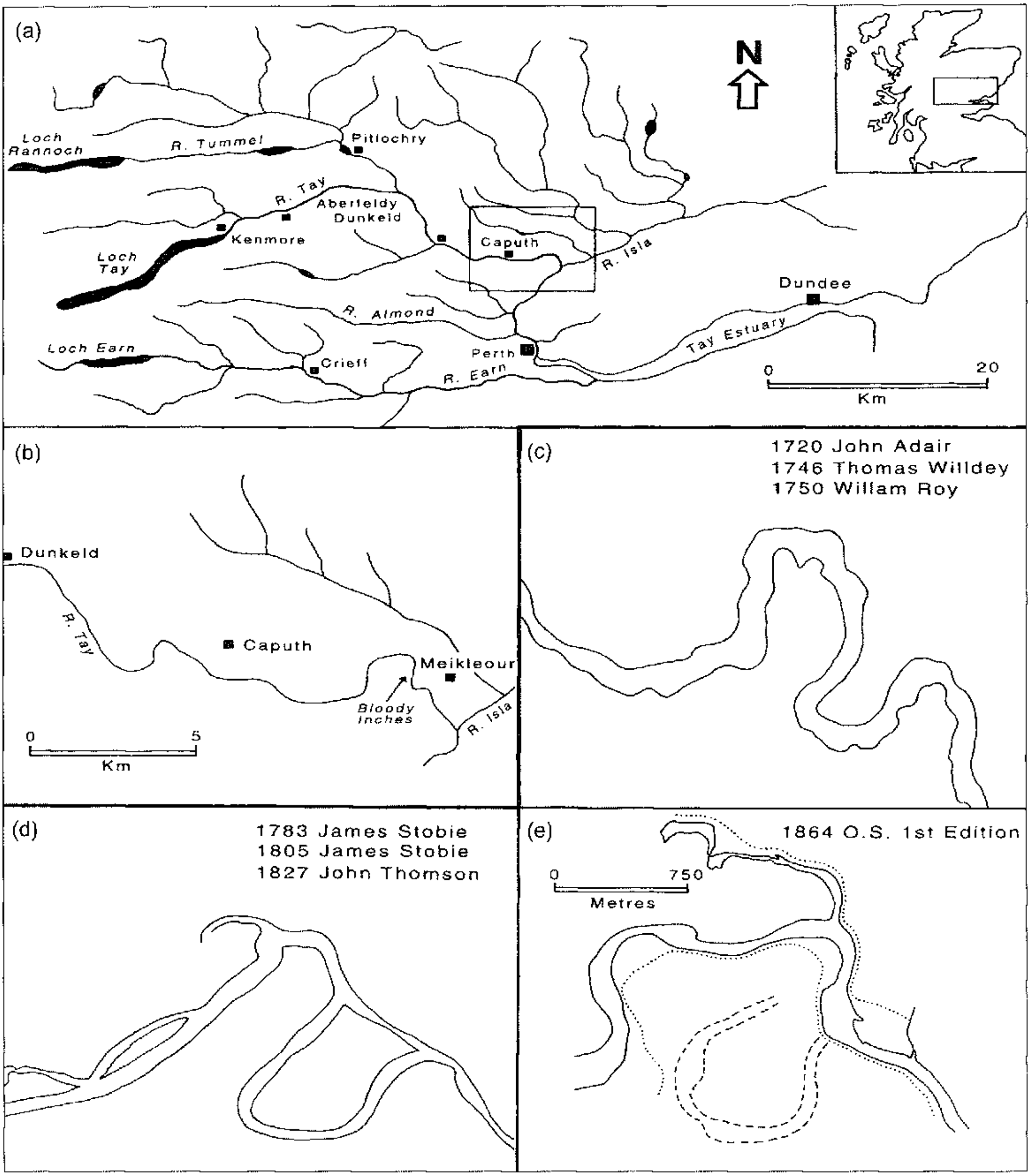

Fig. 1 (a) Geographical location and the River Tay drainage basin; (b) the study area; (c)–(e) historical development of the Bloody Inches oxbow.

THE STUDY AREA

The River Tay system in Scotland (Fig. 1(a)) has a mean annual discharge of 160 $m^3\ s^{-1}$, the largest in the UK, with a drainage basin area of 4690 km^2. The average annual precipitation is 1255 mm for the whole basin, but ranges from 2500 mm in the west to 1500 mm in the east.

Most of the upper catchment lies on impermeable quartz–mica–schist, grit, slate and phyllite metamorphics of the Upper Dalradian (late Precambrian and Cambrian), with thin soils (till and morainic drift) in the southern Grampian Mountains. In the middle and lower reaches, sedimentary Lower Old Red Sandstones of the Palaeozoic are overlain with glacial sands and gravels, and some alluvium. Low evapotranspiration, thin soils and impermeable basin geologies contribute to the high runoff rates (Gilvear & Winterbottom, 1992). The river is gauged at a number of locations, and the Caputh station 5 km upstream from the field site has a continuous record from 1952. Land use in the basin is primarily moorland but the flood plain area has been drained, embanked and intensively farmed over the last 200 years. Much of the system (62%) is controlled by major hydroelectric power schemes developed in the upper reaches from the 1930s to 1957. The present paper focuses on a flood plain field site (Fig. 1(b)), known locally as the "Bloody Inches".

Historical perspective of the Bloody Inches

The selected field site is a large oxbow separated from the main channel of the lower River Tay before 1864. The evolution of the channel plan form has been reconstructed from analysis of historical maps (Fig. 1(c)–(e)). While the planimetric accuracy of the earlier maps is poor, the channel patterns are considered reliable and show two active channels between 1783 and 1827. Commencement of the cut-off most likely occurred between 1746 and 1783, possibly associated with major flood events in 1761, 1767/68, 1773/74 and 1780/81 (Macdonald, personal communication). Isolation of the Bloody Inches from the main channel was completed between 1827 and 1864. The precise mechanism of isolation is not clear, but it is likely that flood embankments already in place at the site were extended across the old, but periodically active, channel to complete its separation from the main channel. The sediment stack overlying the gravel channel lag has thus been constrained following its complete isolation from the main channel.

Nevertheless, sediment-laden floods still access the abandoned channel during large flows (Gilvear *et al.*, 1994). The flow required for embankment failure or over-topping at the Bloody Inches site has been calculated at 850 $m^3\ s^{-1}$ (Gilvear & Black, 1999). Based on this threshold, the discharge record for Caputh illustrates that a total of 25 floods will have over-topped the local embankments and inundated the Bloody Inches palaeochannel during the previous 50 years. Of particular note are the largest floods in 1990, 1993 and 1950 with estimated return periods of 65, 45 and 20 years respectively.

FIELD AND LABORATORY METHODS

The stratigraphy at the site was characterized using sediment cores collected at the apex of the meander in the Bloody Inches oxbow. A Vibro-corer, a 50-cm Russian auger and an 18-cm Dutch auger were all employed. The typical depth of channel fill above the former channel bed was 1.4 m. Cores were graphically logged and sectioned in the laboratory at a range of increment depths, but always separated at sedimentological boundaries. After oven drying at 40°C and gentle disaggregation, organic material was removed from the samples by the addition of 40% hydrogen peroxide. A solution of 0.4% sodium hexametaphosphate was added prior to ultrasonic dispersion and analysis in a Coulter LS230 laser granulometer.

Radiometric dating offers the means to independently and absolutely date sediment profiles. Radiometric dating (^{137}Cs) of the cores was undertaken by gamma spectrometry using an Ortec Lo-Ax high purity germanium detector housed in a copper lined lead shield. Count times were typically 86 000 s and produced values of radionuclide activity with a precision of ±5% at the 2 σ confidence level. Caesium-137 offers scope to date accretion rates since the early 1950s (He & Walling, 1996).

RESULTS AND INTERPRETATION

A typical ^{137}Cs profile of cores retrieved from the Bloody Inches is shown in Fig. 2, and the ^{137}Cs limit of activity is 24.5 cm depth. This is taken to represent 1954 when

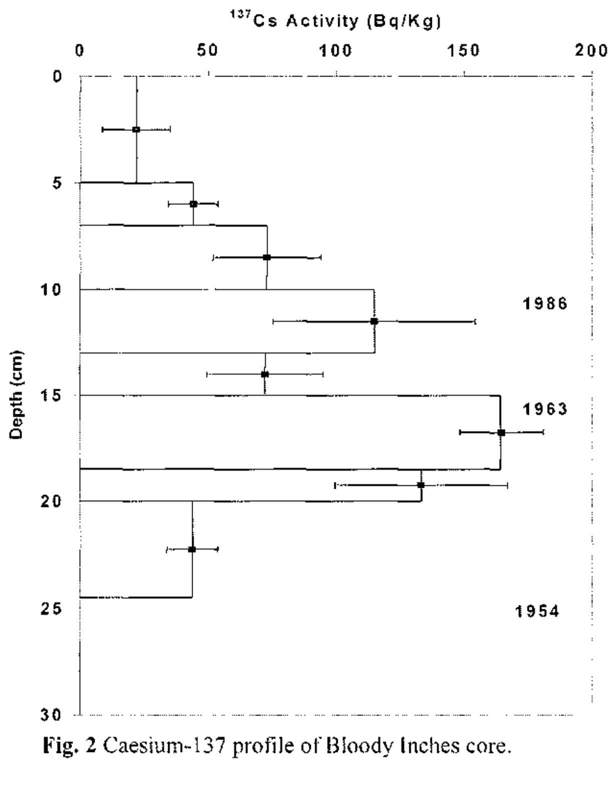

Fig. 2 Caesium-137 profile of Bloody Inches core.

weapons testing fallout first appeared in sedimentary environments. Both the 1963 peak from atomic testing and the 1986 Chernobyl peak are clearly recognized in the profiles (cf. Rowan *et al.*, 1993), and constrains the sediment chronology within the period of hydrological records.

The upper 25 cm of a core on to which dates provided by ^{137}Cs analysis have been superimposed spans the entire post-1950 sedimentary history of the site. The Caputh discharge record indicates that 25 flood events overtopped the flood embankments during this period, but the stratigraphical evidence reveals only a small number of discrete sandy units. Caesium-137 data indicate a large sandy unit at 6.5–8.5 cm represents the 1990 and 1993 floods, which are known to have breached the embankments (Gilvear & Black, 1999). A second large sandy unit at 25–28 cm and below the ^{137}Cs limit records a significant incursion prior to 1954. The 1950 flood at Caputh had an estimated discharge > 1500 $m^3\ s^{-1}$ (Tay River Purification Board, personal communication). Based on stratigraphical evidence from the 1990–1993 floods, such a discharge will induce embankment breaches at this site.

Gilvear & Black (1999) illustrated that the frequency and length of embankment failures in this reach of the River Tay can be estimated using the following relationships:

$$n = 0.0041 * (Q - 850)^{1.348} \quad (1)$$

$$l = 0.0044 * (Q - 850)^{1.774} \quad (2)$$

where n is the total number of embankment failures and l is the total length (m) of embankment failures predicted for daily mean flows (Q) at the Caputh gauging station. Embankment breach characteristics are quadratically related to flood magnitude, and thus highlight a distinctive subset of breach-causing floods (Fig. 3) to be distinguished from those events involving over-topping flows only. This subset of events clearly maps to the sandy units identified within the dated channel fill sequences.

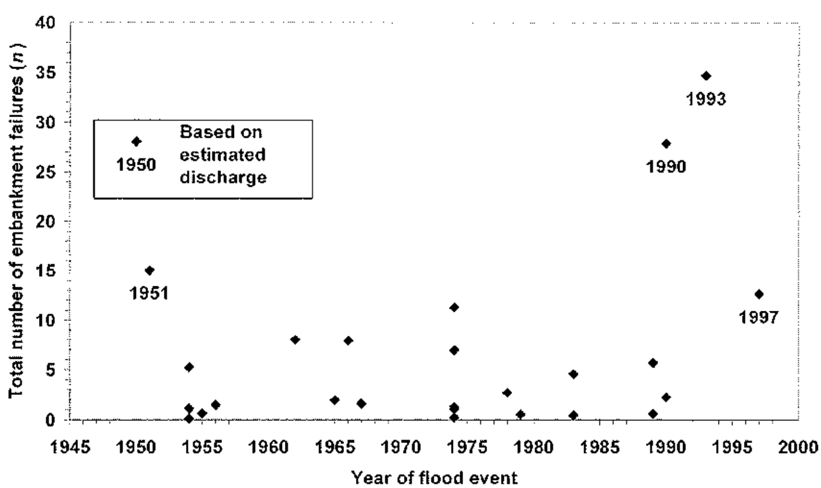

Fig. 3 Total number of embankment failures predicted to occur at specific discharges along the River Tay between Perth and Dunkeld, which includes the study site.

The next stage in the analysis was to identify specific flood units in the sediment stack pre-dating the instrumented period (Fig. 4). Granulometric anomalies defined by

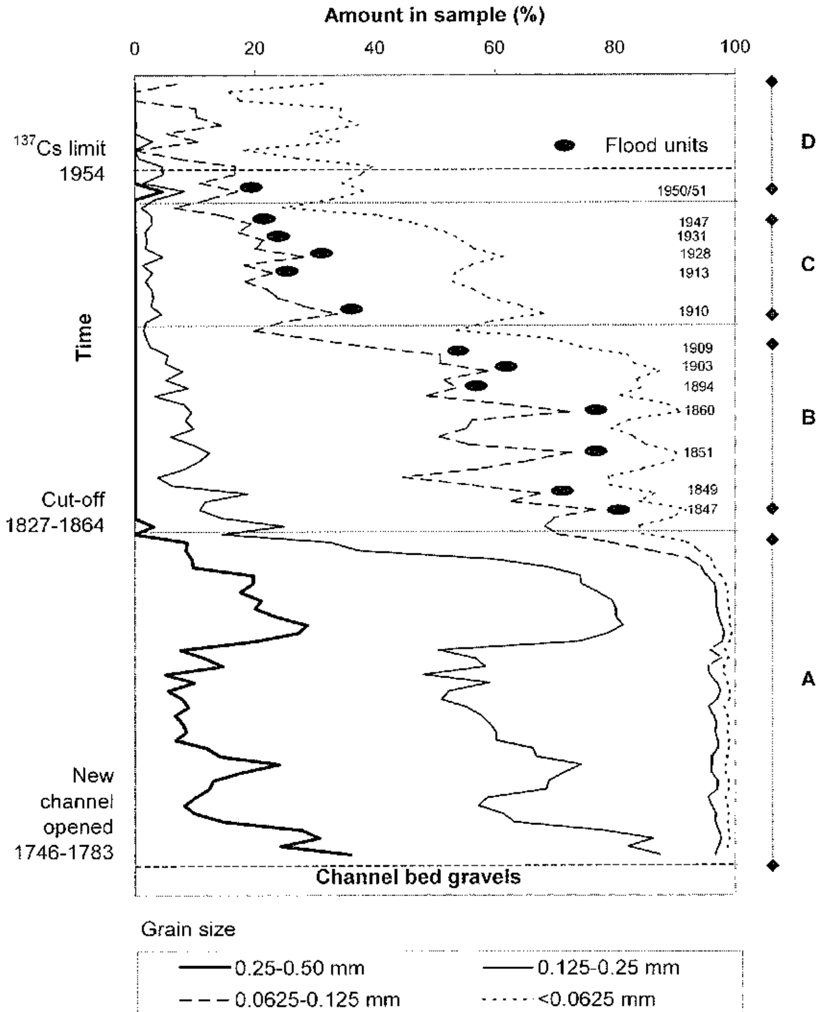

Fig. 4 Grain-size analysis of Bloody Inches core, spanning the period since the new channel was cut (1746–1783) to the present day.

the fine sand fraction (0.0625–0.125 mm) reveal 13 large flood events between the channel cut-off date (1827–1863) and the 1954 limit of ^{137}Cs. The grain-size analysis also reveals four distinctive sedimentological sub-units, defined in terms of both grain size, sorting and heterogeneity. These sub-units typically are distinguished by sharp contacts and can be interpreted to correspond to a series of local factors:

A channel abandonment when both channels were active;

B channel isolation and embankment raising;

C increased river regulation; and

D sediment starvation due to the introduction of HEP schemes (Gilvear & Winterbottom, 1992).

Dates are tentatively ascribed using radiometric controls, historical map analysis and historical flood records (McEwen, 1993).

DISCUSSION

Embankment breaches are of particular significance because inundation flows are competent to convey clastic sediment into palaeochannel environments in sufficient quantity to be preserved and recognizable within sediment stacks (cf. Marriott, 1992). In seeking to establish both local and regional flood frequency curves for the purposes of flood risk estimation, recognizing and establishing the number and scale of such events in the sedimentary record offers a proxy record of flood frequency.

Antecedent conditions, such as precipitation and the condition of embankments are also important in the preservation of stratigraphic flood units. The timing of embankment spillage is important for determining the flux of sediment onto the flood plain (cf. Asselman, 1999). It is well recognized that peak suspended sediment concentrations precede the discharge maximum, so flood plain sediment fluxes depend on the specific characteristics of the hydrograph. Equally important is the emplacement of the embankments; those overlying old channels are more susceptible to failure (Gilvear *et al.*, 1994).

Ongoing analysis of the sedimentary stack is seeking to elucidate the links between specific flood units and their formative events in terms of inundation frequency and the importance of flood magnitude. The Bloody Inches field site highlights the importance of flood embankments in determining the temporal and spatial patterns of flood deposition at a site (cf. Middelkoop & Van der Perk, 1998). The development of sedimentological approaches to the extension of flood chronologies relies on the availability of good quality and reasonably lengthy instrumental records to confirm the identity of flood units in the stratigraphic record. Pristine reaches are generally preferred for field studies, but in Scotland such sites are usually ungauged, with few, if any, historical records of past flood events.

Large, lowland flood plain reaches tend to be heavily engineered and embanked, but this reflects their importance as centres of human and economic activity over long periods of time. The establishment of locally calibrated flood chronologies in such locations is thus of key important in establishing specific flood risk and instituting effective control along with related issues, such as conditioning insurance premiums. At sites where flood plain geomorphology offers suitable preservation conditions, the general applicability of this approach has the potential to elucidate flood histories and refine risk estimates in the absence of long term instrumented hydrological records.

Acknowledgements JLP acknowledges the award of a University of Dundee Postgraduate Scholarship, with assistance from the British Geomorphological Research Group, the British Hydrological Society, the Royal Scottish Geographical Society and the Whitehall Trust. The assistance of local landowners in access to the site is also gratefully acknowledged.

REFERENCES

Asselman, N. E. M. (1999) Grain-size trends used to assess the effective discharge for floodplain sedimentation, River Waal, The Netherlands. *J. Sediment. Res.* 69(1), 51–61.

Asselman, N. E. M. & Middelkoop, H. (1995) Floodplain sedimentation: quantities, patterns and processes. *Earth Surf. Processes and Landforms* **20**, 481–499.

Black, A. R. (1996) Major flooding and increased flood frequency in Scotland since 1988. *Phys. Chem. Earth* **20**(5–6), 463–468.

Gilvear, D. J. & Black, A. R. (1999) Flood-induced embankment failures on the River Tay: implications of climatically induced hydrological change in Scotland. *Hydrol. Sci. J.* **44**(2), 345–362.

Gilvear, D. J. & Winterbottom, S. J. (1992) Channel change and flood events since 1783 on the regulated River Tay, Scotland: implications for flood hazard management. *Regul. Rivers: Res. Manage.* **7**, 247–260.

Gilvear, D. J., Davies, J. R. & Winterbottom, S. J. (1994) Mechanisms of floodbank failure during large flood events on the rivers Tay and Earn, Scotland. *Quart. J. Engng Geol.* **27**, 1290–1303.

He, Q. & Walling, D. E. (1996) Rates of overbank sedimentation on the floodplains of British lowland rivers documented using fallout ^{137}Cs. *Geogr. Ann.* **78A**(4), 223–234.

Knox, J. C. (2000) Sensitivity of modern and Holocene floods to climate change. *Quatern. Sci. Rev.* **19**, 439–457.

Marriott, S. (1992) Textural analysis and modelling of a flood deposit: River Severn, UK. *Earth Surf. Processes and Landforms* **17**, 687–697.

McEwen, L. (1993) Issues in flood hazard management: a case study of the River Tay floods. In: *Scottish Geographical Studies* (ed. by A. H. Dawson, H. R. Jones, A. Small & J. A. Soulsby), 109–125. Departments of Geography Publication, Universities of Dundee and St Andrews, Scotland, UK.

Middelkoop, H. & Van der Perk, M. (1998) Modelling spatial patterns of overbank sedimentation on embanked floodplains. *Geogr. Ann.* **80A**(2), 95–109.

Nicholas, A. P. & Walling, D. E. (1997) Modelling flood hydraulics and overbank deposition on river floodplains. *Earth Surf. Processes and Landforms* **22**, 59–77.

Rowan, J. S., Higgitt, D. L. & Walling, D. E. (1993) Incorporation of Chernobyl-derived radiocaesium into reservoir sedimentary sequences. In: *Geomorphology and Sedimentology of Lakes and Reservoirs* (ed. by J. McManus & R. W. Duck.), 55–71. John Wiley, Chichester, UK.

Werritty, A. (2002) Living with uncertainty: climate change, river flows and water resource management in Scotland. *Sci. Total Environ.* **294**(1–3), 29–40.