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# River entrenchment and terrace formation in the UK Holocene

M.G. Macklin [a,*], J. Lewin [a], A.F. Jones [b]

[a] Centre for Catchment and Coastal Research and River Basin Dynamics and Hydrology Research Group, Institute of Geography and Earth Sciences, Aberystwyth University, Ceredigion SY23 3DB, UK
[b] School of Geography, Planning and Environmental Policy, University College Dublin, E001 Newman Building, Belfield, Dublin 4, Ireland

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A B S T R A C T

A meta-analysis of a large database of $^{14}$C dated fluvial units is used to assess the chronology and controls of episodic Holocene river entrenchment and terrace formation in the UK. Most Holocene terraces are of a ‘fill-cut’ type developed in Pleistocene sediments, in places now reaching down to pre-Holocene bedrock. Holocene terraces are widespread in higher-relief areas of the UK and peripheral higher-energy rivers, and include up to 7 levels in some valley floor reaches. Using $^{14}$C constrained data subsets for incision episodes, the onset, vertical ranges, formation times, and rates of entrenchment are examined, together with geographical distributions. The height range of terrace separation is relatively small (0.5–3.5 m) with a long-term averaged incision rate over the late and mid-Holocene of 0.43, 0.5, 0.67, 0.7 and 0.81 m/ka in the Tweed, Rheidol, Severn, Ouse and Ribble catchments, and a regional similarity in the scale of incision events. The periods 4200–3700, 3100–2900, 2100–1900, 1800–1500 cal. BP and most notably the last 1000 years (with prominent peaks at 900–800 and 700–600 cal. BP) were times of accelerated incision. It appears likely that extreme flood events triggered the formation of incision ‘slots’, rather than entrenchment being a direct response to glacio-tectonic uplift, or the result of incremental valley-floor lowering by combined incision and lateral reworking. River entrenchment has also been rapid in recent centuries, reflecting the coupling of extreme-events with anthropogenic effects on catchment hydrology. Incision results in changes of river channel flood power and overbank flood extent, and improved data on the long-term and large-scale vertical tendency of UK rivers are needed for flood risk management purposes.



## 1. Introduction

Meta-analysis of the UK Holocene fluvial archive that began more than 20 years ago has demonstrated the episodic nature of river alluviation (Macklin and Lewin, 1993, 2003). It has also shown that fluvial units which mark changes in the style of sedimentation cluster into time periods and coincide with phases of environmental change (Macklin et al., 2005, 2010, 2012a; Johnstone et al., 2006) controlled by climatic fluctuations and human activities. This approach has been successfully adopted in mainland Europe, (Macklin et al., 2006; Starkel et al., 2006; Thorndycraft and Benito, 2006; Hoffman et al., 2008), North Africa (Zielhofer and Faust, 2007), the Indian subcontinent (Kale, 2007), the American Southwest (Harden et al., 2010) and most recently in New Zealand (Macklin et al., 2012b; Richardson et al., 2013), and is transforming our understanding of Holocene river dynamics and its controls. Underlying this new methodology is the long-held (e.g. Macklin et al., 1992a,b; Macklin, 1999) realisation that single-reach studies usually contain only a partial picture of Holocene alluviation, both because the quality of geochronologies depends on, and partly reflects, the sedimentary environments available within a single site (Lewin et al., 2005) and the degree to which these have been preserved from later erosion and removal (Lewin and Macklin, 2003). However, what has not been systematically evaluated either at a multi-reach and particularly at a multi-catchment scale is the nature and timing of Holocene river entrenchment, and the factors that control long-term and large-scale incision in alluvial rivers. In this paper meta-analysis of a large database (826) of $^{14}$C-dated Holocene fluvial units from the UK is used for the first time to address this meso-form development problem, and to try to better understand river terrace development more widely. It has two primary objectives: 1. to establish the number, magnitude, duration and timing of Holocene fluvial incision episodes in UK rivers; and 2. to evaluate the short and long-term controls of Holocene river incision, including changing flooding regimes (resulting from climatic fluctuations and human modifications of catchments),

* Corresponding author. Tel.: +44 (0) 1970 622656; fax: +44 (0) 1970 622659.
*E-mail address:* mvm@aber.ac.uk (M.G. Macklin).

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anthropogenic activity, and land uplift as a consequence of glacio-isostatic effects of Late Devensian glaciation within the Holocene period.

## 2. A typology of UK Holocene river terraces

Valleys in western and northern Britain have been characterized by progressive incision over the Holocene, which has cumulatively resulted in modern river channels being located c. 5–10 m below the surfaces of Pleistocene age river terraces. Episodic incision has produced between one and seven reported terrace levels (Table S1, and references therein); in some cases Holocene incision has proceeded down to and into bedrock (Macklin et al., 1992a,b). Generally terraces have been mapped and classified by surface elevation above present river level and dated, where possible, using $^{14}C$ dating of organic materials – for the most part in palaeochannel fills from where more than 60% of $^{14}C$ ages have been obtained (Macklin et al., 2010). Near-surface coring and mechanical excavation have additionally provided information on the nature of sedimentation otherwise only visible in cut-bank sections. It has not usually proved possible to examine the erosional bedrock base of alluvial units, and the nature and number of aggradation phases that comprise terrace units, as well as the vertical extent of the punctuating incision episodes, are generally not well documented.

Fig. 1 gives three alternative scenarios for Holocene terrace development in the UK by which identical surface forms can be produced by different histories of incision and aggradation. Fig. 1a represents a set of 'fill-cut' terraces (using the terminology of Bull, 1991) developed in prior Pleistocene sediments, (b) shows a 'cut-and-fill' sequence, and (c) strath terraces developed during punctuated incision into bedrock. Holocene river development in the UK uplands generally has been one of episodic incision into prior alluvial and glacigenic sediments, in some cases with about half of Late Pleistocene fills having been removed from upland and piedmont river valleys during the Holocene (Passmore and Macklin, 2001). The Holocene valley history of coastal streams undergoing isostatic recovery such as those in western Scotland (Bishop, 2007) with thin Quaternary sedimentary covers has been characterised by rock incision and knick point recession. Elsewhere there is a longer sequence of incision activity (e.g. Tyne catchment – Macklin, 1999; Moores et al., 1999; Passmore and Macklin, 2001) and these show (especially in the later Holocene associated with the influx of anthropogenic alluvial material) that major components of some terraces are aggradational (e.g. Jones et al., 2010), rather than simply representing episodic incision by streams leaving only a 'working depth' of sediment as they incise and laterally migrate through Pleistocene fills. Thus type (a) in Fig. 1 appears to be the dominant Holocene river terrace style in the UK, but with elements of (b) especially in the later Holocene because of contributing thicker fine members related to anthropogenic activity (Macklin et al., 2000), and elements of (c) in areas of glacio-isostatic recovery (Robertson-Rintoul, 1986; Foster et al., 2008).

Studies of even the last few centuries show continuing and quite complex histories of channel movement, aggradation and incision in response to short-term climate controlled changes in flood frequency and magnitude (Macklin and Lewin, 1989; Macklin et al., 1992a,b; Passmore et al., 1993; Rumsby and Macklin, 1994; Brewer and Lewin, 1998; Passmore and Macklin, 2001), in conjunction with mining and agriculture-related fluctuations in sediment delivery to drainage networks (Foulds et al., 2013). This has left small-scale landforms, including 'micro-terraces' and these are present both on the historical floodplain and on higher terrace surfaces where they have not been eliminated by agricultural activity.

After the Lateglacial, it is presently not clear as to which major incision episodes result from a common set of 'allogenic' changes (climatic episodes or ones relating to human activity phases; the latter likely being regionally time-transgressive) and which are randomly-preserved stages in an on-going 'autogenic' down cutting process. A distinction has long been made between 'paired' and 'unpaired' terraces; the former produced by catchment and large-scale environmental change or resulting from progressive but time-transgressive up-valley headward recession, and the latter resulting from successive sweeps of laterally migrating and vertically eroding rivers. The last are of no great significance for establishing spatially and altitudinally consistent terrace levels that can be related in a meaningful way to environmental change. Adjacent catchments can produce contrasted terrace sequences, especially given variable preservation factors (Taylor and Lewin, 1997). Last, sediment-system modelling has demonstrated that in response to simulated episodes of rapid Holocene climate change, slow depositional phases could be punctuated by brief but intense periods of sediment removal, and that these periods were not consistent in time or space either within or between the valley systems modelled (Coulthard et al., 2005). These model results mirror the concepts of complex (Schumm, 1977) and non-synchronous response (Germanoski and Harvey, 1993). In this context, our analysis of a wider set of field data than hitherto has been used may be useful to investigate the timing and controls of river entrenchment in the UK Holocene.

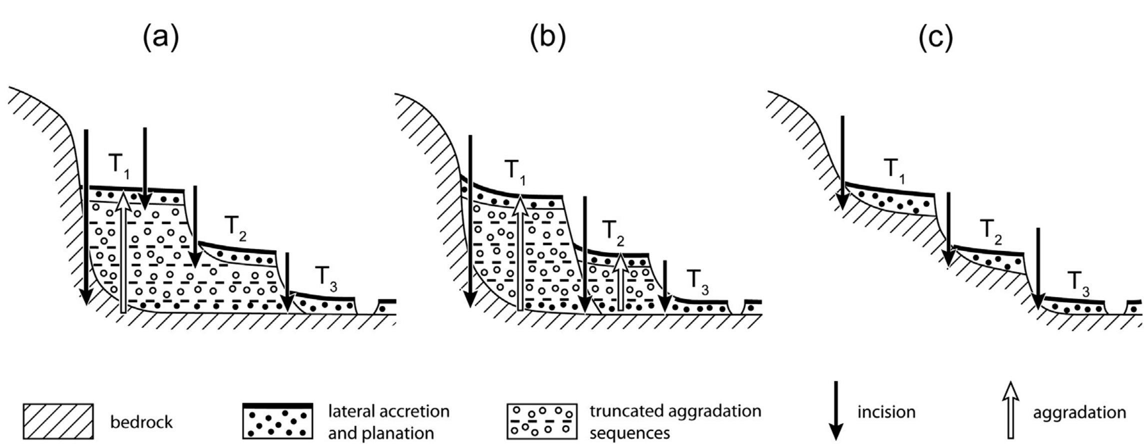


**Fig. 1.** Holocene terrace formation sequences which produce similar surface forms: (a) by progressive incision into a prior valley fill ('fill-cut' in Bull's (1991) terminology); (b) by repeated episodes of cutting and filling ('cut-and-fill'); and (c) by repeated incision into bedrock (with a shallow 'working depth' of sediment) to produce strath terraces.