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Of ice and water: Quaternary fluvial response to glacial forcing

Stéphane Cordier [a,*], Kathryn Adamson [b], Magali Delmas [c], Marc Calvet [c], Dominique Harmand [d]

[a] Département de Géographie-UMR 8591 CNRS-Université Paris 1-Université Paris Est Créteil, 61 avenue du General de Gaulle, 94010 Créteil cedex, France
[b] School of Science and the Environment, Manchester Metropolitan University, M1 5GD Manchester, UK
[c] Université de Perpignan-Via Domitia, UMR 7194 HNHP, 66860 Perpignan Cedex, France
[d] Laboratoire LOTERR, Université de Lorraine, site Libération, BP 13387, 54015 Nancy, France

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ABSTRACT

Much research, especially within the framework of the Fluvial Archives Group, has focused on river response to climate change in mid-latitude non-glaciated areas, but research into the relationships between Quaternary glacial and fluvial dynamics remains sparse. Understanding glacial–fluvial interactions is important because glaciers are able to influence river behaviour significantly, especially during glacial and deglacial periods: (1) when they are located downstream of a pre-existing fluvial system and disrupt its activity, leading to hydrographical, hydrosedimentary and isostatic adjustments, and (2) when they are located upstream, which is a common scenario in mid-latitude mountains that were glaciated during Pleistocene cold periods. In these instances, glaciers are major water and sediment sources. Their role is particularly significant during deglaciation, when meltwater transfer towards the fluvial system is greatly increased while downstream sediment evacuation is influenced by changes to glacial–fluvial connectivity and basin-wide sediment storage. This means that discharge and sediment flux do not always respond simultaneously, which can lead to complex fluvial behaviour involving proglacial erosion and sedimentation and longer-term paraglacial reworking. These processes may vary spatially and temporally according to the position relative to the ice margin (ice-proximal versus ice-distal). With a focus on the catchments of Europe, this paper aims to review our understanding of glacial impacts on riversystem behaviour. We examine the methods used to unravel fluvial response to 'glacial forcing', and propose a synthesis of the behaviour of glacially-fed rivers, opening perspectives for further research.

1. Introduction

River systems are highly sensitive to environmental changes, including the effects of tectonic, climatic, glacial, and anthropogenic forcing. Fluvial morpho-sedimentary records, and the natural (e.g. palaeontological) and human (archaeological) archives preserved within them, can provide valuable palaeoenvironmental information. They allow us to reconstruct environmental evolution at local to regional scales, and over modern to Pleistocene timescales. Reconstructing Quaternary river dynamics is fundamental to our understanding of present-day fluvial systems because long-term Quaternary incision has shaped modern valley landscapes (Bridgland and Westaway, 2008). At the same time, the study of present-day river systems makes it possible to better understand the significance of the older, Pleistocene, fluvial archives, and the relationship between catchment evolution and fluvial dynamics.

The impacts of Quaternary glacial–interglacial cycles on mid-latitude river systems have long been emphasised (e.g. Vandenberghe, 1995, 2003, 2008, 2014; Bridgland and Westaway, 2008). These climatic influences have been both direct and indirect: temperature and rainfall directly control river discharge and, in many cases, erosion and sediment production. Climatic controls on the presence/absence of permafrost and the type/quantity of vegetation cover exert an indirect control on river-system behaviour. Both of these parameters influence catchment-scale water and sediment transfer, from the hillslopes to the valley floor and channel(s) (Vandenberghe, 1995, 2001). The complexity of fluvial response to Pleistocene climate change has been investigated for

* Corresponding author.
E-mail addresses: stephane.cordier@u-pec.fr (S. Cordier), k.adamson@mmu.ac.uk (K. Adamson), magali.delmas@univ-perp.fr (M. Delmas), calvet@univ-perp.fr (M. Calvet), dominique.harmand@univ-lorraine.fr (D. Harmand).

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many decades (e.g. Sörgel, 1939; Büdel, 1977; Vandenberghe, 1995, 2003; Bridgland, 2010). Research has mainly focused on fluvial systems from Northwest Europe, which were characterized by periglacial conditions during Pleistocene cold periods. The Thames, Meuse, Somme, Rhine, and Vistula catchments have been investigated in detail, and have become established as reference areas for the reconstruction of Quaternary climatic forcing on fluvial systems (e.g. Bridgland, 1994; Starkel, 1994; Van den Berg, 1996; Antoine et al., 2000, 2007; Busschers et al., 2007; van Balen et al., 2010). They have provided a better understanding of hillslope–river coupling at the 100 ka timescale. However, many studies focusing on climatic forcing either were performed on non-glaciated catchments/sections of valleys, or have paid little attention to the presence of glaciers in the upstream part of the catchment, as is the case for the Rhine (e.g. Boenigk and Frechen, 2006; van Balen et al., 2010). In fact, despite the evidence that glaciers covered up to 30% of the global land surface during some Pleistocene cold periods, and the fact that fluvial terraces have been identified downstream of glaciated areas for more than a century (Carney, 1907; Penck and Brückner, 1909), the relationships between glacial and fluvial dynamics have not been examined in detail except for some areas such as the United-Kingdom (Bridgland and Westaway, 2014). Such relationships are important because (1) the course of a river can be transformed by the damming of valleys by ice or moraines, (2) glaciers play a major role in shaping landscapes through erosion, (3) this erosion produces vast amounts of sediment that is transported downstream by rivers and (4) glaciers are major water reservoirs that can strongly influence catchment hydrological regime.

Glacial controls on river behaviour cannot be considered as unequivocal without first establishing the spatial relationships between glacial and fluvial systems. Two main scenarios should be distinguished:

1) When glaciers occupy part of a pre-existing river basin, in its middle or lower reaches, and disrupt river behaviour (hereafter referred to as 'downstream control'). This can lead to the destruction of existing fluvial archives (Bridgland and Westaway, 2014). In some cases, river systems have been completely obliterated by glacial activity, including the Scandinavian fluvial systems, the proto-Soar/Bytham river in Great Britain (White et al., 2010, 2016; Gibbard et al., 2013), and the upper Ohio system in North America (Jacobson et al., 1988). The 'downstream control' scenario is typically found in the lowlands of northern Europe (such as the UK, Germany, Poland, Ukraine and Russia) and North America, where ice sheets covered large areas during Pleistocene cold periods. It is also observed locally, in montane areas, when valleys are dammed by glacial ice. Unlike lowland basins, the response of upland systems to downstream glacial activity is typically a transitional phenomenon occurring at the beginning or the end of a glacial period (see below 5.1), and secondly since it affects confined systems.
2) When glaciers develop in the headwaters of fluvial systems ('upstream' control). Such glacially-fed rivers are typical of montane areas, but can also be found in lowland areas where river systems drain major ice sheets, such as the Dnieper or the Don systems in Eastern Europe.

This paper examines the influence of Quaternary glacial activity on 'glacially-disrupted' and 'glacially-fed' river systems. The first section focuses on the methods used to recognize glacial forcing in the fluvial record, in particular at the Pleistocene timescale. The key role of geochronology (Rixhon et al., 2017) and modelling in conjunction with the indispensable field-based approach (morphological and sedimentological investigations) is underlined. The second section reviews the way that fluvial activity can be disrupted by the glaciers, especially when these are located downstream. The following sections focus more specifically on the glacial–fluvial interactions in glacially-fed rivers. This is because that scenario can produce a complex pattern of fluvial response, since glaciers located in the headwaters are able to influence both the water and sediment flows. We focus in particular on periods of ice retreat, because this transitional period is characterized by major shifts in meltwater and sediment dynamics that control the response of the fluvial systems downstream. We then develop a review of recent research applying these methods to examine Pleistocene glacial–fluvial interactions in catchments across Europe. This allows us to assess the nature of glacial forcing on fluvial behaviour, and unravel the importance of connectivity in glacial–fluvial systems. The subsequent discussion examines whether fluvial response to glacial dynamics (and in particular glacier retreat) in different basins is characterized by uniformity or diversity, and to open perspectives for further research.

2. Methods in the study of fluvial response to Pleistocene glacial changes: a multi proxy approach

Unravelling the influence of glacial activity on fluvial system behaviour requires a good understanding of glacial extent. In the case of glacially-fed rivers, the timing and characteristics of water flow and sediment flux, including the possibility of short-or long-term storage in morphological depocentres (Koppes and Montgomery, 2009), are also key parameters. Many studies have examined *either* glacial *or* fluvial system dynamics, but few have developed a coupled glacial-fluvial approach. As a consequence, there is an empirical 'grey area' in our understanding of the links between ice-proximal meltwater outwash dynamics, and the typical fluvial archives recognized kilometres or tens of kilometres downstream. Bridging this gap is a key research objective.

Several methods may be used to examine glacial–fluvial interactions, and these can be broadly categorized as: morphology/sedimentology, geochronology, and modelling.

2.1. Morphology and sedimentology

High-resolution geomorphological mapping of landform assemblages is key for distinguishing between glacial, transitional, and fluvial settings, and for exploring spatio-temporal relationships between glacial and fluvial processes both for 'downstream' and 'upstream' controls (Flageollet, 2002; Bridgland and Westaway, 2014; Stange et al., 2014; Delmas et al., 2015). This distinction can be challenging, especially for older parts of the Quaternary record; where glaciers no longer exist and spatial relationships between glacial and fluvial systems are unclear; and where landforms inherited from earlier Pleistocene cold periods have been reshaped or fragmented by subsequent fluvial or slope processes. We therefore rely on a combination of morphological (e.g. identification of moraines) and sedimentological evidence (e.g. sediment structure, bedding and grain characteristics), that can vary profoundly between glacial and fluvial settings. Detailed analysis of catchment topography allows us to examine pathways of meltwater and sediment flux and locate depocentres that may have disrupted downstream sediment transfer, and altered glacial–-fluvial connectivity. The value of field mapping cannot be overestimated, as demonstrated by the Fluvial Archives Group (Cordier et al., 2017). This approach can be enriched by the use of thematic maps, air photos, satellite remote sensing, and digital elevation models (DEMs), all of which have enabled landform recognition over large areas and/or where fieldwork is problematic (Wiederkehr et al., 2010; Stokes et al., 2012; Pazzaglia, 2013).