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Tectonics, geomorphology and water mill location in Scotland, and the potential impacts of mill dam failure

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A B S T R A C T

In this paper we assess the ways in which the topography of glaciated northern Britain has affected the siting and operations of water mills, and compare those factors and mill locations for mills in unglaciated southern Britain. We then explore the impacts of these findings on the potential downstream impacts of mill dam failure.

We used a GIS to plot the locations of all 1712 localities in Britain's Ordnance Survey Gazetteer that include "mill", "milton" ('milltown') and "miln" in their name. We then examined the geomorphology of mill locations in two study areas, one in northeast Scotland (glaciated; 421 localities) and one in southern England (unglaciated; 438 localities), assessing (i) mill location within the drainage net, and (ii) the steepness of an adjacent stream within a radius of 500 m of the mill locality. The large majority of mills are located within the first 10 km of the drainage net in both study areas, presumably on relatively stable bedrock channels. The data for most of the mills in both study areas indicate that catchment areas of less than 200 km^2 are sufficient to supply the water necessary for operation of a mill, but the higher rainfalls and runoff in Scotland (almost twice the values in the England study area) mean that mill dams in S England must have been higher and of higher capacity than those in NE Scotland. That finding is consistent with the results related to channel steepness, which show that mills in Scotland are associated with steeper channels than is the case in England. The generally greater channel steepness in Scotland (and the greater downstream extent of those steeper channels, as also confirmed by the data) reflect both the many glacially steepened bedrock channel reaches in Scotland and the steepening of Scotland's coastal bedrock channels as a result of glacio-isostatic rebound.

The technical requirements of water mill operation favour situations where water can be delivered to the top of, or at least part-way up, the mill wheel. Scotland's steeper rivers and its higher rainfalls mean that Scotland's mills require smaller mill dams, if they are needed at all. It would therefore be expected that catastrophic or managed failure of mill dam walls in northern Britain would release lower volumes of trapped sediment to the downstream fluvial system. These lower volumes would in turn result in lower geomorphological impacts downstream of the dam, both in terms of changing channel patterns and burial of the bed. Such dam failure is a key current issue in geomorphology and one case study of a small failed mill dam in western Scotland confirms the minimal downstream impacts of that failure.

Introduction

The influence of tectonics on Earth surface processes is obvious (e.g., Bishop, 2007), and such influences are also clear for human land-use, as earthquakes and volcanic eruptions continue to demonstrate (e.g., Iran in 2012; Christchurch in 2010). A range of more subtle influences of tectonics can also be demonstrated, and one such influence – the impacts of glacio-isostatic rebound (glacio-isostatic adjustment, GIA) on the location of water mills – is the subject of this paper. GIA is a form of tectonics – vertical or lateral movement of the Earth's crust – and leaves a prominent signature in the topography of glacially rebounding areas, which may in turn influence the location of industrial activities that depend in some way on topography or river flow.

Water mills are mills that are powered by water, largely diverted from rivers. These mills have been used in a large number of industrial activities, ranging from the well known ones of the milling

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of cereal grains and the weaving of cloth, to the less well known uses of water mills for the boring of cannons, the grinding of the ingredients for gunpowder, and the powering of bellows for blast furnaces (Reynolds, 1983). The locations of such mills are intimately bound up with geomorphology, and recent work has also drawn attention to the landscape and geomorphological legacies of such water mills (e.g., Bishop & Jansen, 2005; Downward & Skinner, 2005; Pizzuto & O'Neal, 2009; Walter & Merritts, 2008). Downward and Skinner (2005) examined the riverine impacts of mills and mill dams, including 'clear-water' erosion below intact and operational mill dams, and main channel abandonment due to semi-permanent diversion of the river's flow into and through the mill structure. They also examined channel stability and flood-management issues elsewhere along the channel related to mill abandonment and decay (see also Bishop & Jansen, 2005).

Pizzuto and O'Neal (2009) examined the issue of channel changes upstream of failed mill dams, in the context of the amounts of sediment trapped in eastern USA's "tens of thousands of 17th- to 19th-century mill dams" (Walter & Merritts, 2008: 299). Walter and Merritts (2008) had identified many such colonial mill dams in the Atlantic drainage systems and argued that the ubiquity of these mill dams and the sediment trapped within them mean that mill dam sediment forms the substrate for many Atlantic drainage systems. They then argued that much of the quantitative interpretation of fluvial geomorphological relationships developed in the second half of the 20th century from those Atlantic drainage systems – and summarised, for example, in the classic text of Leopold, Wolman, and Miller (1964) – is not based on 'natural' streams but on streams that are flowing over the 'artificial' substrates of mill dam infill sediment. Walter and Merritts (2008) went so far as to suggest "that widespread mid- to late medieval alluviation and burial of pre-Roman organic-rich soils observed in 'all lowland and piedmont river valleys in Britain and much of Northern Europe' [Brown, 1997] might [also] have been the result of mill damming" (303–304). A major implication of that conclusion is that the quantitative fluvial relationships that have been the basis for alluvial geomorphology for more than 50 years may not in fact be characteristic of 'natural' humid temperate rivers (Walter & Merritts, 2008). As interesting as that contention is, however, we do not address it here but follow Downward and Skinner (2005) and Pizzuto and O'Neal (2009) in asking whether the failure of such mill dams constitute major management issues. We do this by assessing the tectonic and geomorphological settings of water mills in the contrasting terrains of northern and southern Britain. Northern Britain is experiencing ongoing GIA, whereas the south was not glaciated in the Quaternary and may in fact be experiencing ongoing flexural downwarping.

Downward and Skinner (2005) noted that mill dam failure will trigger a knickpoint in the sediment impounded in the dam, and that that knickpoint will migrate upstream through the sediment, generating sediment that moves downstream. In situations where the mill dam is completely filled with sediment, the dammed river will be flowing across the impounded sediment, and it might not even be apparent that a mill dam is responsible for the sediment that forms the river's substrate, as Walter and Merritts (2008) have shown. Dam failure and knickpoint propagation will then trigger channel adjustment upstream of the failed dam, in a stream that might be understood to be essentially 'natural'. Pizzuto and O'Neal (2009) data from mill dam failure along the South River in Virginia confirm that mill dam breaching results in increased river bank erosion in meandering streams upstream of the breaches. Downward and Skinner (2005) likewise reported channel adjustments upstream of failed mill dams, with undesirable impacts of riparian activities along those streams.

Many positive downstream effects are generated when a river is undammed, especially for in-stream ecology (e.g., Bednarek, 2001), and such positive effects are leading to major campaigns to remove dams, especially in the US. However, the sediment produced by post-failure erosion of mill dam sediment may have negative downstream impacts on stream morphology and habitat, particularly when the impounded mill dam sediments are contaminated with heavy metals and/or other pollutants (e.g., Juracek & Ziegler, 2006; Shotbolt, Thomas, & Hutchinson, 2005; Tylmann, Gołębiewski, Woźniak, & Czarnecka, 2007). Even if the sediment is not contaminated, the mobilised sediment may blanket the bed, filling pools and covering riffles, thereby changing in-stream habitats. The sediment may also increase flood risks by elevating the bed and decreasing channel capacity (e.g., Lane, Reid, Tayefi, Yu, & Hardy, 2008). Increased sediment fluxes may also trigger changes in channel pattern, as recognised in Schumm's qualitative syntheses (Shen et al., 1981). In short, failure of a mill dam may have major impacts, both upstream and downstream of the dam.

In this paper, we contrast the potential for geomorphological impacts of mill dam failure in two different geomorphological and tectonic settings, namely Scotland – formerly glaciated by a major ice sheet and now glacioisostatically rebounding – and southern England, which was unglaciated and has not been subject to glacioisostatic rebound. We first outline the geomorphological requirements of different technologies for water mill wheels, concluding that steeper river reaches generally provide better locations for water mills. We then compare the long profile characteristics of streams that support water mills in formerly glaciated Scotland and in southern England. We do this by implementing a GIS-based method designed for rapid acquisition of regional geomorphological river data that would otherwise require major investment of field time.

Water wheel technology and mill dams

Water-driven mills use either the force of flowing water or the weight of water to turn water wheels that drive machinery to power an extensive range of industrial activities and food processing (e.g., Reynolds, 1983; Shaw, 1984). This wide range of applications means that water mills were a major feature of waterways prior to, during and after the Industrial Revolution. The Domesday Survey documented 5624 water mills in England by the 11th century (Downward & Skinner, 2005; Shaw, 1984). Intensity of use increased dramatically over time and it became common for tens of mills to be crowded along heavily-used stretches of water. One river in early 17th century England had 24 mills on just 15 km of river (Downward & Skinner, 2005), and Reynolds (1983) reported three water mills per kilometre of stream in the Sheffield area at the end of the 18th century. Late 17th century France had more than 95,000 water mills (Reynolds, 1983) and Walter and Merritts (2008) reported the even more astonishing figure of more than 65,000 water mills in 20 states of the eastern US by 1840.

Water mills extract power from water on the mill wheel in several ways. In early water mills, flowing water drove a horizontal water wheel, but we are not concerned with that technology here; see Gauldie (1981), Reynolds (1983) and Shaw (1984) for more detail. For the vertical water wheel, our focus here, water may be directed to flow past radial blades or vanes of the mill wheel at the bottom of the mill wheel (Fig. 1). Such undershot wheels operate most efficiently with higher velocity water flow (say, >1.5 m s^{-1}), converting 15–30% of the energy of the running water to mechanical power at the water wheel shaft (Reynolds, 1983). This relatively low efficiency of energy conversion reflects the loss in efficiency that arises when a jet of water strikes the flat vanes of the undershot wheel (Shaw, 1984), and John Smeaton showed in the eighteenth century that delivering water to the upper part of the