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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

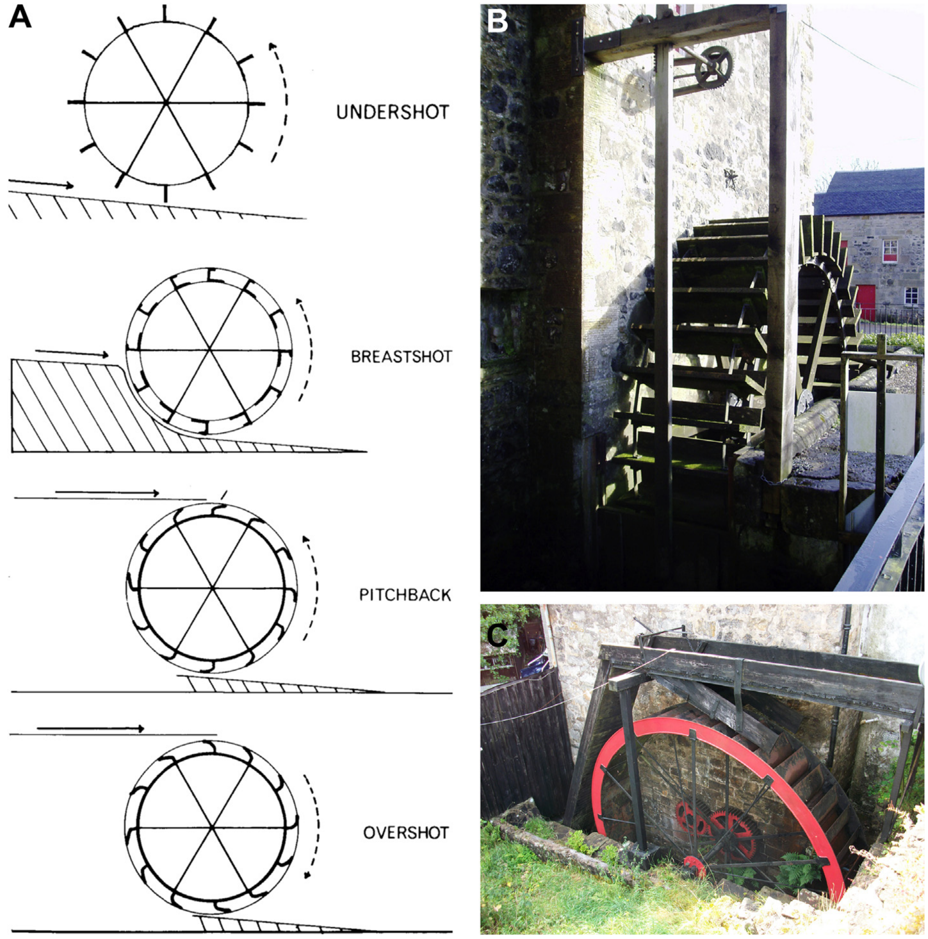

Fig. 1. A. Types of vertical water wheel, modified from Shaw's (1984) Fig. 5. The undershot wheel is shown with open-sided radial blades or vanes against which the water flow turns the wheel. B. Dalgarven mill, Scotland, showing the open-sided blades of the undershot mill wheel. The blades may also be called floats, floatboards or paddles (Reynolds, 1983). C. Pitchback mill wheel at Baldernock Mill, Scotland, showing the launder (the wooden trough, upper right, that delivers the water from the lade), and the mill wheel buckets with their enclosed sides to hold water and thereby to use the water's weight to drive the wheel. The water flows right to left along the launder, and then back to the right through an opening in the floor of the launder so as to drive the wheel in a clockwise direction (i.e., pitchback). This mill was originally a grain mill and was converted in the late 19th century to a saw mill (dark timber building, lower left) (Bishop et al., 2010). The size of the opening in the floor of the launder, and hence the rate at which water flows from the launder onto the mill wheel and thus the speed of the mill wheel, is controlled by a cable connected to a control lever where the operator stands at the saw blade in the saw mill.

wheel, and enclosing the two sides of the vanes so as to form 'buckets' that hold the water, mean that the water's weight, rather than its flow velocity, is used to turn the wheel, with a resultant efficiency of 50–70% (Reynolds, 1983). Such mill wheels are breastshot when the water is delivered part-way up the mill wheel, and overshot or pitchback when the water is delivered to the top of the mill wheel and depending on which way the water is directed to the wheel, and the wheel's direction of turn (Fig. 1).

Overshot, pitchback and breastshot water wheels require infrastructure to deliver the water to the top of, or at least part-way up, the wheel. Depending on where the mill wheel is located, such infrastructure can include a channel that delivers water to the vicinity of the mill, and a trough (a 'launder') to carry the water to the wheel (Fig. 1C); the channel is known by many names, including lade, leat, mill race, head race, and power race. The undershot wheel is generally easier and cheaper to build, not requiring such infrastructure but only a means of directing the river flow at sufficient velocity past the bottom of the water wheel. Whether an undershot, breastshot, overshot or pitchback wheel was built depended in part on the finances available – if efficiency was not a major concern, then the cheaper undershot wheel might have sufficed – but also on the nature of the channel on which the mill was being built. Overshot, pitchback and breastshot wheels require that the elevation of the river channel not too far upstream be at least at the height of the upper part of the wheel, and at the top of the wheel for the overshot or pitchback setups (Fig. 2). Thus, the more efficient breastshot, overshot or pitchback designs require the water surface to be elevated in some way.

This elevation of the water level is achieved in many settings by a reservoir upstream of the mill with a wall that elevates the water surface to the required height (Gauldie, 1981; Reynolds, 1983; Tann, 1965) (Fig. 2). The mill and its wheel can be immediately downstream of the reservoir, in some cases even being built into the wall of the reservoir (Reynolds, 1983; Tann, 1965). The water can also be brought to the mill wheel along a lade from the dam (Reynolds, 1983; Tann, 1965). In other cases, the mill is located a little downstream of a knickpoint, which is a step (abrupt drop) in the river long profile or even simply a steeper reach in the profile (Tann, 1965). If the amount of water that can be abstracted from a steep river is sufficient to drive the mill wheel without requiring a dam or reservoir to store water for dry periods, then the mill can operate on the 'run of the river' flow (a 'burn mill' in Scottish terminology – Shaw, 1984). The mill exploits the knickpoint to take water directly from the river and bring it along the lade to the upper part of the wheel. Such an arrangement is relatively cheap on several counts: only a low weir is required in the river to divert water into the lade;

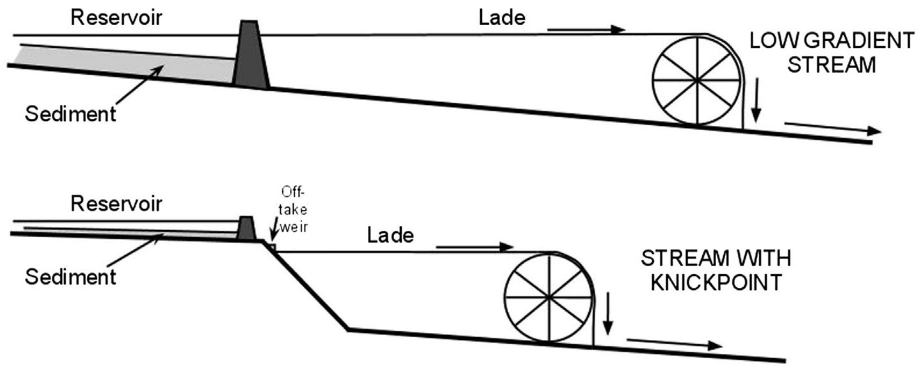

Fig. 2. Schematic diagram of stream long profile, mill dam, lade and wheel for two long profile types, highlighting how the lower gradient long profile (top) requires a higher (and hence larger) dam and may require a longer lade for the water to be brought to the top of the mill wheel, depending on the long profile gradient.

the lade can be comparatively short, because the relative steepness of the river means that, a short distance upstream, the river bed is at a sufficient elevation for water off-take for breastshot, backshot or overshot operation; and there is no need of a high dam wall. Even if a reservoir is required in that setting to guarantee the water supply, exploiting a step in the long profile means that the dam wall does not necessarily have to be high enough to elevate the water up the mill wheel, but simply high enough to store sufficient water for dry spells. Higher rainfalls mean, of course, that dams can be relatively smaller.

Mill dams are costly to build and maintain, the more so the higher they are. And the higher they are (and the larger they are in terms of storage capacity), the greater their trap efficiency, which is a measure of how effectively a dam traps the sediment carried into it by inflowing streams (Brune, 1953). Trap efficiency is a function of the capacity of the reservoir relative to the annual inflow (the 'capacity-inflow ratio'), the plan-view geometry (shape) of the dam's water-body, and the calibre of the sediment brought in by the inflowing streams (Brune, 1953; Heinemann, 1981, 1984). Trapping of sediment and loss of storage capacity are major issues in dam design and a low trap efficiency is desirable for maintaining a sediment-free dam for longer. Nonetheless, dams do trap sediment and eventually they fill in. Mills may continue to function in that situation if run-of-the-river operation is possible, which it will not be in dry periods when there is no back-up from a sediment-filled reservoir.

Undesirable flooding of land by mill dam impoundments further enhances the attractiveness of steep reaches for siting a water mill. Mill dams flood land along the dammed river, removing that land from agricultural production, although that issue was probably of limited importance in pre-Industrial Revolution times because many valley-bottoms prior to the major human disturbances of agricultural improvement and/or European colonisation were swampy and poorly drained anyway (e.g., for the US: Walter & Merritts, 2008; for Scotland: Gauldie, 1981; for England: Brown, 1997; for Australia: Eyles, 1977). Indeed, Gauldie (1981) has noted that drainage of valley-bottom swamp-lands in Scotland interfered with water flows to mills downstream. A greater problem associated with mill dams is the fact that the impounded stretch of water cannot be used for mills (Reynolds, 1983). This impact is particularly marked for a large reservoir, the head of which may be a considerable distance upstream of the wall, especially in a low gradient river. Such back-water impacts are serious where there is high demand for water-side locations for mills (Reynolds, 1983). Tann (1965) noted many historical examples of litigation associated with such mill dam back-water effects, which were exacerbated when a mill dam wall was raised in height to raise the level of the water at the mill wheel when a larger wheel was fitted or there was a change from under- or breastshot operations to over- or backshot. Reynolds (1983) has also noted that the latter issue can be exacerbated by millwrights' preference for low gradient mill lades to bring the water to the mill wheel (remembering that the velocity of the water plays little or no part in driving overshot or backshot mill wheels, which are powered by the weight of the water). Low gradient lades mean that water off-takes and reservoirs may have to be located considerable distances upstream in low gradient rivers, further complicating the locating of mills on heavily used reaches.

In summary, steeper channels are preferable for locating water mills. Steep reaches simplify the delivery of water to the top of the mill wheel, thereby avoiding the need for high mill dams which trap sediment more efficiently than do smaller dams, and have long and wide reservoir water bodies and long lades, both of which complicate the siting and lay-out of mills and lades. Thus, a key issue for assessing the potential for mill dams to constitute an ongoing management issue (Downward & Skinner, 2005; Pizzuto & O'Neal, 2009) is the arrangement for water abstraction and delivery to the mill wheel. Those abstraction and delivery issues reflect (i) the type of mill wheel being used, (ii) the geomorphology of the stream, and (iii) the hydrology of the area, especially in terms of the size of the reservoir needed to ensure continuity of flow. The latter two issues fundamentally concern the geomorphology of mill location, to which we now turn in relation to Britain.

Study areas

Scotland and England are the northern and southern portions, respectively, of the island of Great Britain. The British Ice Sheet covered northern Britain during the Quaternary (Bradwell et al., 2008; Clark et al., 2004; Evans, Clark & Mitchell, 2005; Hubbard et al., 2009). The ice limit mapped by Clark et al. (2004) and Evans et al. (2005) on mainland Britain extends (very approximately – the precise detail is not critical here) north-north-east from Bristol in the southwest through Leeds to Bridlington on the east coast and south to the vicinity of Hull. The ice mass depressed the Earth's crust, with the depression being accommodated by outward flow of the mantle (e.g., Lambeck, 1995). After deglaciation, the crust responded to the unloading consequent on the ice sheet melting by floating upwards isostatically, generating, in effect, falling relative sea-levels in northern Britain since deglaciation (e.g., Lambeck, 1995; Shennan, Bradley et al., 2006; Shennan, Hamilton et al., 2006). Conversely, the crust of southern Britain, which was not ice-covered, has been broadly flexed downwards since deglaciation, partly as a result of a 'lever-arm' effect of the flexural rigidity of the Earth's crust (i.e., northern Britain 'up', southern Britain 'down') and perhaps partly reflecting the movement of mantle back under northern Britain. The amounts of the consequent rock uplift in the north and subsidence in the south are clear in relative sea-level curves (see, for example, Shennan, Bradley et al.'s (2006) Fig. 7) as well as in recent high precision continuous GPS measurements (Bradley, Milne, Teferle, Bingley, & Orliac, 2009). The geological and modern data both confirm 'north up, south down'. The glacioisostatic rebound of Scotland since late Pleistocene deglaciation has been exploited in assessments of the controls on the retreat of knickpoints generated by the glacioisostatically driven base-level fall (e.g., Bishop, Hoey, Jansen, & Artza, 2005; Castillo, Bishop, & Jansen, 2013; Jansen et al., 2011), whereas those glacioisostatically derived knickpoints are absent in the England study area.

The GIS-based method outlined below was applied to a >20,000 km^2 area in formerly glaciated northeast Scotland and an ~18,000 km^2 in unglaciated southern England (Fig. 3). Both areas have many mills because both areas were foci of grain crop production in the era of small to medium-sized water mills (Gauldie, 1981; Shaw, 1984).

Runoff and its uniformity of annual distribution are also critical to water mill operation, being the key determinants of the amount of water available to drive the wheel throughout the year, and, conversely, of the need to store water for drier periods (Tann, 1965). Average annual rainfall and runoff are substantially higher in NE Scotland than in S England, even though the former is in a rain shadow area (Fig. 4).

Methods

For each mill location, the GIS-based method, summarised in Fig. 5, extracts the following data for the river reach closest to the mill: (1) the distance to the head of the river; (2) the drainage area; and (3) the maximum channel slope. These values are selected because distance to the head of a river provides a strong indication as to whether the river is behaving as a bedrock or alluvial channel. Shorter distances to the head of a river mean that the reach is closer

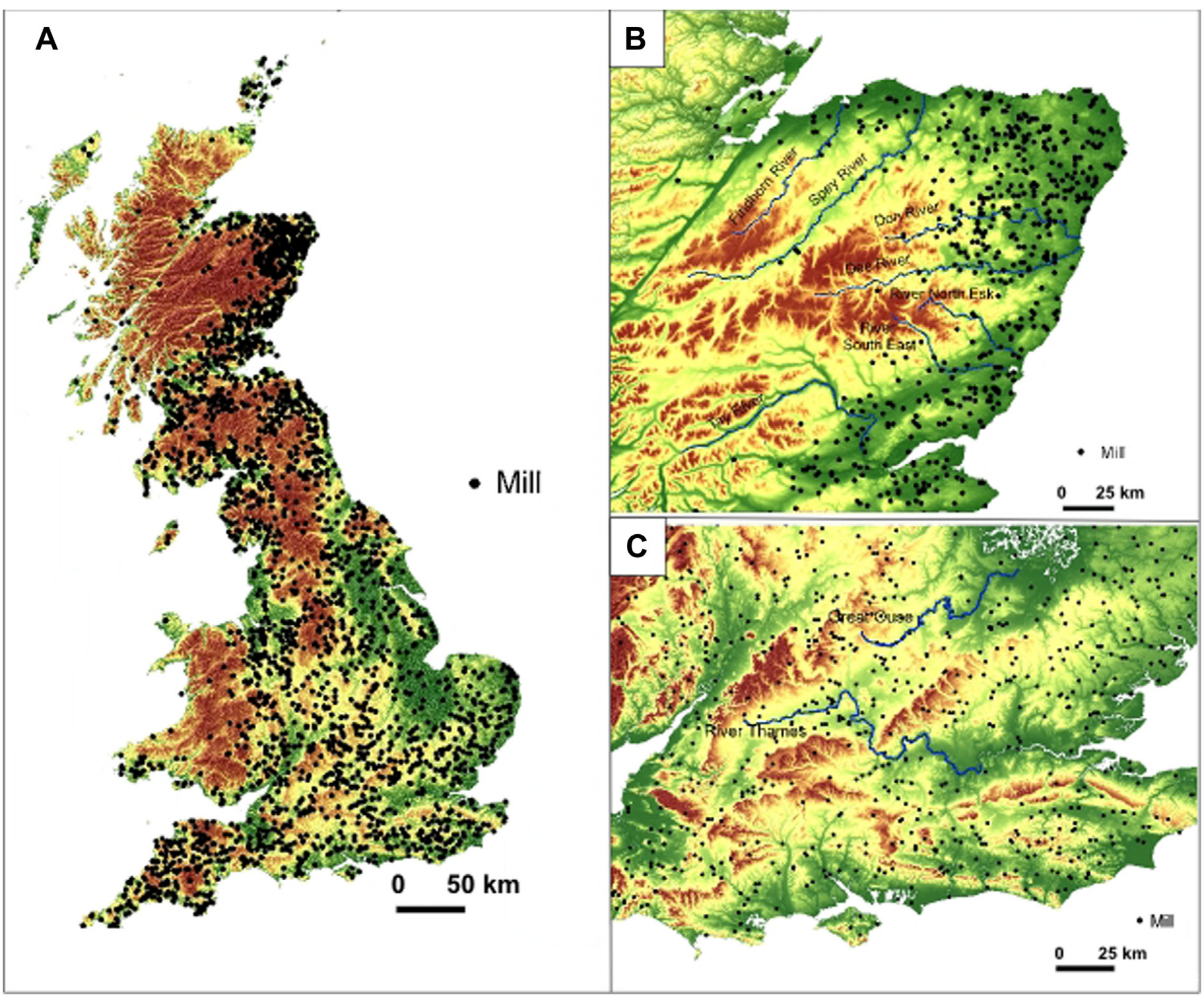

Fig. 3. A. All localities in the ordnance survey gazetteer that include "mill", "milton" or "miln" in their name. Note the general absence of such localities from high altitudes, presumably reflecting the lack of grain cultivation at high altitudes (and water mill-based manufacturing in later times). In Scotland for the period 1550–1870, Shaw (1984, p. 24) has recorded "something like 4000 mills … in active use. … [T]he only areas they were largely absent from were those above 750 feet [~250 m], presumably the upper limit of cultivation." Shaw (1984, p. 8) noted that the term "mhuilinn" (the Gaelic language word for mill) "appears widely as a topographical term on the first ordnance survey maps" but the OZ gazetteer used here contains only two "mhuilinn" localities. Shaw's map of "mhuilinn" place names in Scotland on the ordnance survey first edition maps (1:10,250 scale) shows 62 localities (Shaw, 1984, Fig. 4) but these are very largely in the west and north of Scotland, the areas that spoke predominantly Gaelic in the mid-nineteenth century when the OS first edition maps were being compiled. None of those "mhuilinn" localities is in our northeast Scotland study area. B and C. OS gazetteer mill localities in northeast Scotland and southeast England.

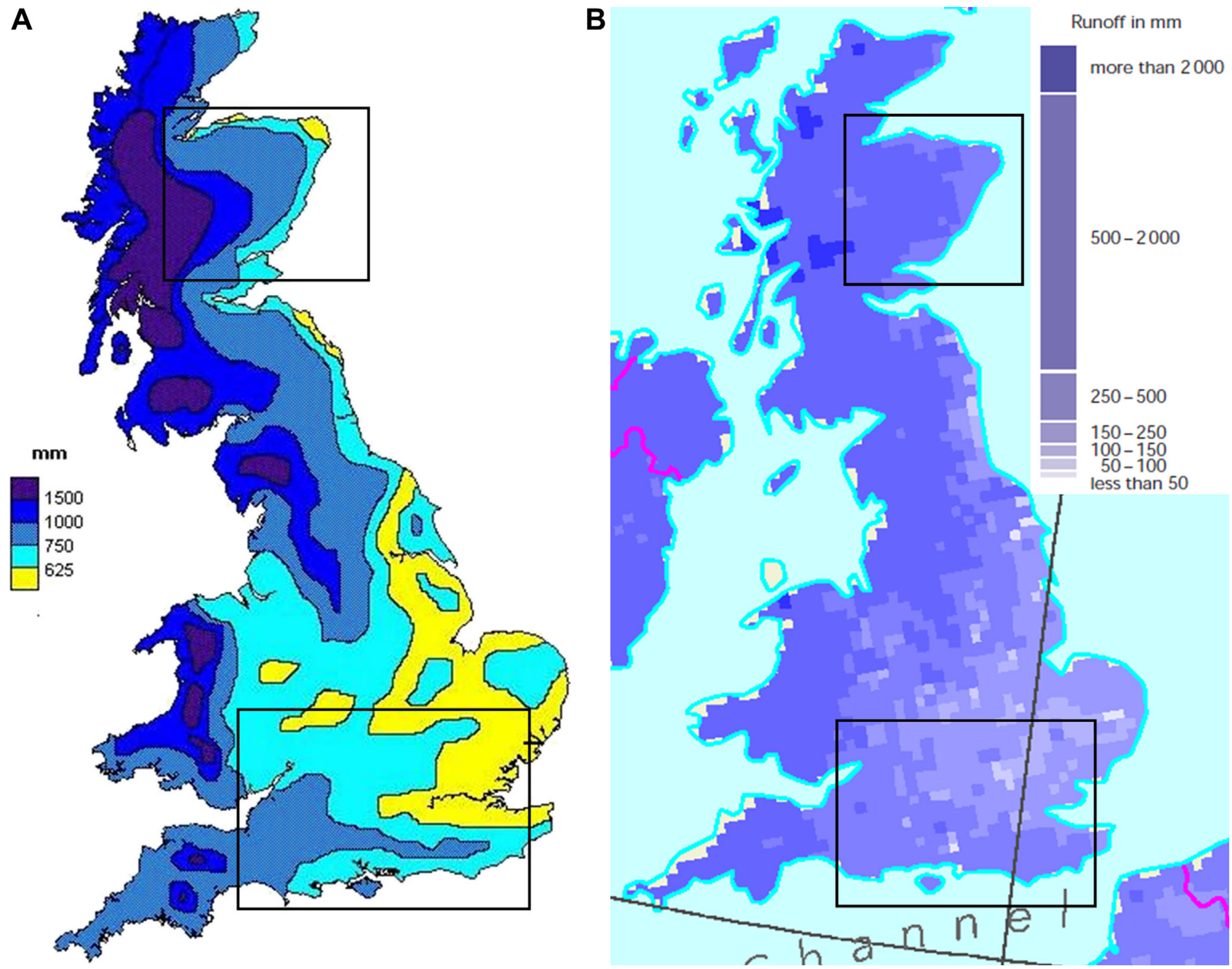

Fig. 4. Maps of Britain with boxes giving the locations of Fig. 3B and C A. Mean annual precipitation (from http://www.british-towns.net/weather/annual_precipitation.asp#Footnotes). B. Mean annual runoff (from Rees, Croker, Reynard, & Gustard, 1997). Boxes show the two study areas.

to the headwaters where rivers are steeper and flow on bedrock (e.g., Whipple & Tucker, 1999). Drainage area is a long-standing surrogate for discharge (e.g., Hack, 1957, pp. 45–97), and the maximum slope is used here as a proxy for identifying river knickpoints, which are steps in the channel long profile that may be preferred locations for mill dams to reduce the height of the dam walls, as explained above.

The GIS-based method was used to obtain information from the Ordnance Survey (OS) Gazetteer on mill locations in the two study areas and required the setting up of two initial layers, the first containing the terrain digital elevation model (DEM) and the second the mill locations around Britain (Fig. 3). Several GIS steps were then followed using Arc View 3.2 and Arc GIS 9.x, as follows. The DEM was obtained from the online digital archive of Ordnance Survey/EDINA after downloading the OSland-form PANORAMA raster layers of 1:50,000 scale and 50 m pixel size. This pixel size was used for the rest of the raster layers created during the application of the GIS-based method. The mill locations were obtained from the OS Gazetteer, also provided by the Ordnance Survey/EDINA. The geographical coordinates were extracted for all OS Gazetteer localities containing the words “mill”, “milton” (‘milltown’) and “miln” (Fig. 3). Using these geographical coordinates, a point vector layer was created in ArcView in which each point represents the location of a mill. As a check that this gazetteer-based method for identifying mills and their locations was appropriate, we confirmed that randomly selected mill locations correspond to localities where there are mills (or were known to be historically from, for example, Ordnance Survey mapping).

Mills are usually placed as close as possible to the river channel, to minimise the length of the lade, but far enough away from the river to avoid inundation during floods (Reynolds, 1983). It was judged that most water-mills would be located within a straight-line distance (radius) of 500 m of a channel and a 500 m buffer was therefore set up in the GIS method to assess channel characteristics at each mill location (Fig. 6). Mills located more than 500 m from a river were eliminated from the analysis, because it was possible that they were not water mills (Fig. 6B).

Using the DEM, three layers were obtained. The first layer contains in each pixel the distance between that pixel and the pixel identified as the highest one in elevation in the area identified after applying the Hydrology extension (Arc GIS Arc Hydro Tools extension commands Fill, Flow direction, Flow accumulation and Flow Length-upstream). The second layer was calculated applying Equation (1) in the ArcGIS Raster Calculator Tool:

$$\text{Discharge} = (\text{Accumulation}*2500)/1 \times 10^6 \quad (1)$$

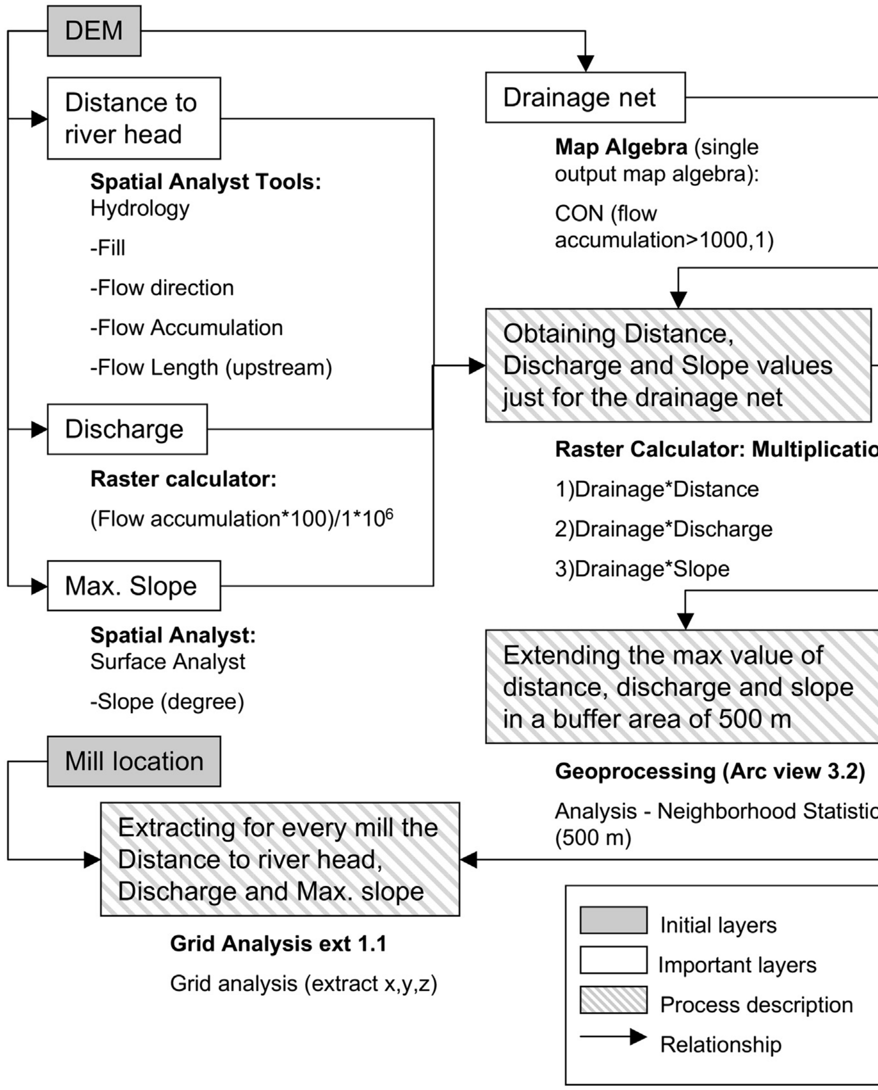

Fig. 5. The GIS-based method used to obtain for every mill location the values of distance to the head of the river, catchment area and maximum slope for the river reach closest to each mill.

where *Discharge* is the total surface area that contributes flow through the selected pixel, in km^2; *Accumulation* is a raster layer containing a value equal to the number of pixels draining that area; the value of 2500 is equal to the DEM pixel surface area in m^2; and the value of 1×10^6 is used to transform the final value from m^2 to km^2. The third layer contains the terrain slope in degrees in every pixel, obtained after applying the ArcGIS Spatial Analyst Tools command Slope.

The next step in the GIS-based method was to obtain a raster layer with the drainage net by applying the command: 'CON (Flow Accumulation > 1000,1)' in the ArcGIS Map Algebra Tool extension Single Output. In this way for all the pixels containing the drainage net the value of 1 was taken, and 0 for the remaining pixels. Using the ArcGIS Raster Calculator extension, the layers containing the distance to the headwater (source) of each river, the discharge and the slope values were multiplied, one by one, by the net drainage layer. The three resulting layers contain the values of the distance to the head of the river, and discharge and slope for those pixels that represent the drainage line (i.e., where the value of 1 was assigned in the net drainage layer). The maximum values of the distance to the head of the river, discharge and slope were used to fill up the pixels located in a river buffer of 500 m from the pixels of the net drainage using the ArcView Geoprocessing extension command Analysis Neighbourhood Statistics – Maximum Circle. By applying this command, a buffer of 500 m radius is created every 500 m along the river path and all the pixels inside a buffer are filled with the maximum value found inside the buffer. Using the resulting raster layers and the point vector layer containing the mill location, the ArcView Grid Analysis extension command Extract 'x,y,z' was used to extract the values of distance to the head of the river, discharge and slope in the table associated with the point vector layer containing the mill location. These values were used as results of distance to the head of the river, drainage and maximum slope associated with every mill location within a radius of <500 m to a channel.

Results

A total of 1050 locations containing the words "mill", "milton" and "miln" were found for Scotland and 662 locations for England. We used the GIS method to analyse the locational characteristics of the 421 and 438 such named places in the NE Scotland and S

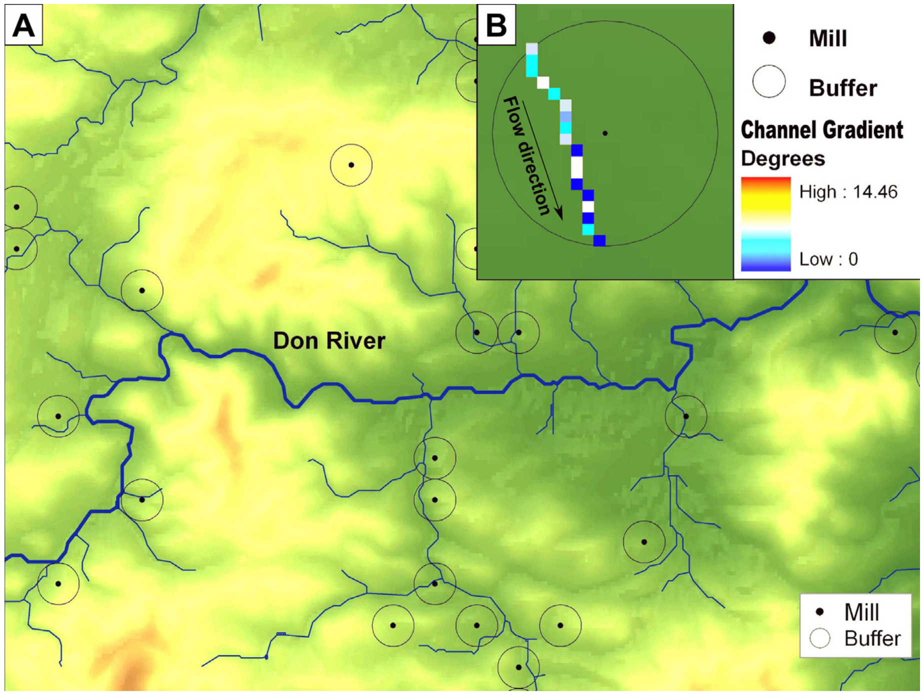

Fig. 6. A. Part of the Don river catchment in the NE Scotland study area showing “mill”, “milton” or “miln” localities in the OS gazetteer. The 500 m radius buffer at each locality is shown, illustrating some mills that are more than 500 m from a river and hence excluded from the analysis (see text). B. Illustration of how the channel gradient is extracted from the channel within the 500 m buffer for each mill that was analysed.

England study areas, respectively. The large majority of mills are located within the first 10 km of the drainage net in both study areas (Fig. 7). The fact that mills in both study areas are predominantly located close to the head of their drainage lines, where all channels are formed in bedrock, epitomises the fact that stable bedrock river channels provide better settings for water mills than do more dynamic alluvial rivers. This conclusion is confirmed by the late eighteenth century flood-related channel avulsion of an alluvial channel recounted in John Galt’s (1821) *Annals of the Parish* in lowland Ayrshire (Scotland):

> “… the river, in its fury, … burst through the sandy hills with a raging force, and a riving asunder of the solid ground… All in the parish was afoot and on the hills, some weeping and wringing their hands, not knowing what would happen, when they beheld the landmarks of the waters deserted, and the river breaking away through the country like the war-horse set loose in his pasture, and glorying in his might. By this change in the way and channel of the river, all the mills in our parish were left more than half a mile [~800 m] from dam or lade; and the farmers, through the whole winter, till the new mills were built, had to travel through a heavy road with their victual [i.e., the grain to be ground in the mill], which was a great grievance, and added not a little affliction to this unhappy year…” (126–127).

For most of the mills in both the Scottish and English study areas, catchment areas of less than 200 km^2 are evidently sufficient to supply the water necessary for operation of a mill (Fig. 7). UK Met Office data show that average rainfalls in the NE Scotland study area (mean annual rainfall 1521 mm for the period 1971–2000) are almost double those in the S England study area for the same period (mean annual precipitation = 782 mm), indicating that the mill dams in S England must have been higher and of higher capacity than those in NE Scotland.

The results for maximum values of channel slopes at each mill strongly contrast for the Scotland and England case studies (Fig. 8). Channel slopes within 500 m of mills in NE Scotland have a wider range of values than they do in S England, notably exhibiting higher (steeper) values in Scotland. The maximum values of channel gradient in Scotland range between 2° and 5°, these values being found between 0 and 30 km from the river source. In England the maximum slopes range between 0° and 2° and are mainly found within the first 10 km of the river (Fig. 8). Thus, mills in Scotland are associated with steeper channels than is the case in England.

Discussion and conclusion

Water mills in Britain are generally located close to the bedrock headwaters of rivers, where channels are more stable. Even at such low distances to the headwaters, and correspondingly relatively low catchment areas, discharges are sufficient to drive mills. In the case of Scotland, however, higher precipitation must provide higher discharges than in the case of England (Fig. 4). Moreover, Scotland had an annual mean value of 185 days of rainfall ≥1 mm for the period 1971–2000, whereas England had only 125 such days (UK Met Office data). As already noted, this difference can be translated into the need for larger mill dams in England than in Scotland, to store more water during dry periods. Moreover, the results show that mills in Scotland are associated with steeper channels than is the case in England. These higher bedrock channel slopes in Scotland are predominantly glacially sculpted ‘steps’ in the upper reaches of rivers, and headward propagating knickpoints in the lower reaches, the latter triggered by glacioisostatic rebound (Bishop et al., 2005; Jansen et al., 2011) and the former reflecting the glaciation of the higher topography of Scotland, inherited from earlier dynamic uplift (Persano, Barfod, Stuart, & Bishop, 2007). Such long profile steepening in Scotland means that water can be delivered to the more efficient overshot, backshot or breastshot water wheels by relatively short lades and without the need for high dam walls. Even the lower reaches of Scotland’s rivers may be relatively easily exploited for mills because, notwithstanding the

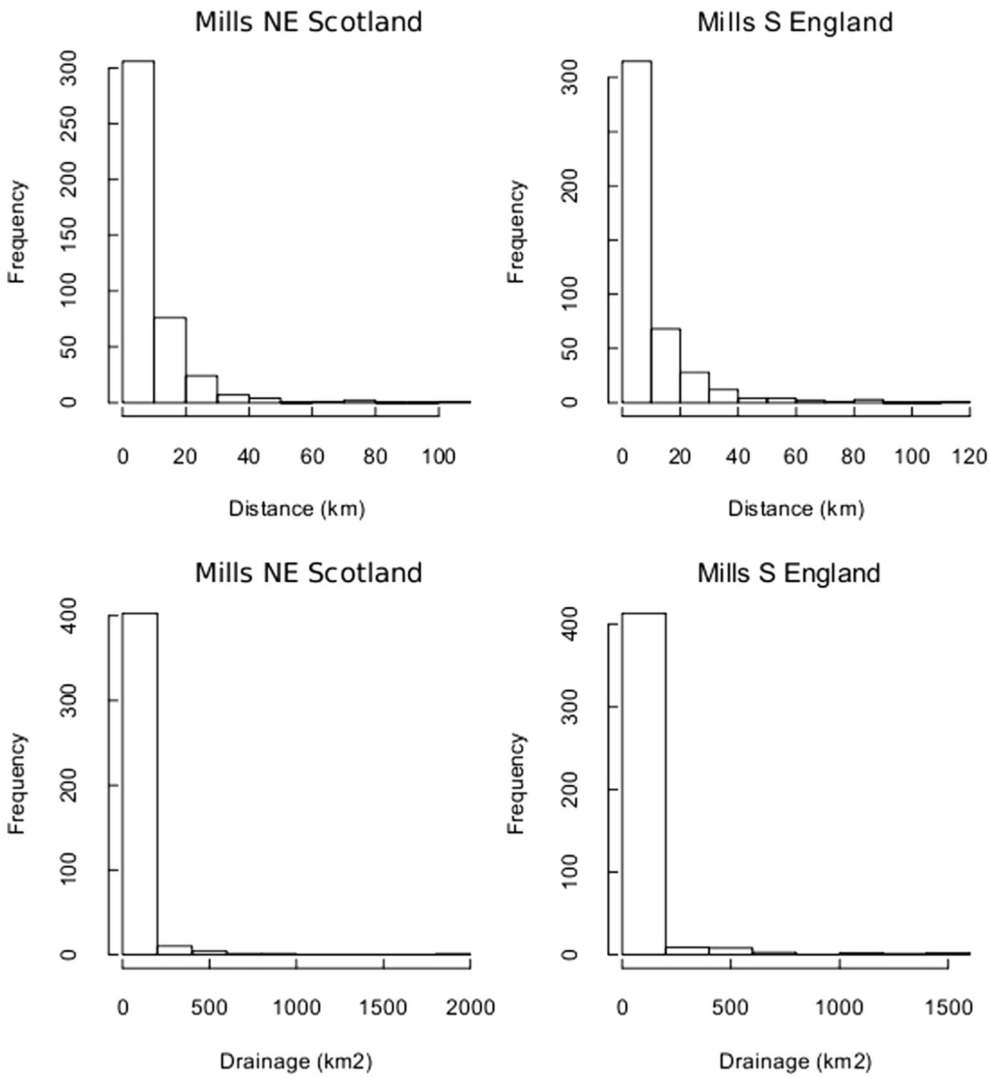

Fig. 7. Plots of the values of distance to the head of the river (upper) and drainage area (lower) for the mill locations in NE Scotland and S England. Most of the mills in both study areas are located within 10 km of the head of the river and have drainage areas of up to 200 km^2. The higher rainfalls in Scotland relative to those in England (Fig. 4) mean that river discharges for a given catchment area in England are lower. This likely results in larger mill dams for water storage in England than is the case for the Scottish mills.

example from *Annals of the Parish* quoted above, the lower reaches of many rivers in Scotland, especially coastal rivers registering glacioisostatic rebound, exhibit bedrock steepening that has been used to facilitate water diversion for powering mills. This use is especially appropriate in moderate sized streams with sufficient discharge to drive mills and sufficient glacioisostatic channel steepening to permit relatively easy diversion of that water.

The combination of Scotland's higher rainfalls and steeper channels means that mill dam walls in Scotland are lower, creating dams with smaller storage capacities and lower trap efficiencies. In many cases, the dam is simply a low weir to divert plentiful discharge to the mill. Proportionally lower volumes of sediment must be trapped in Scotland's mill dams, relative to English mill dams, meaning that when Scottish dams fail, less sediment is available to move downstream to trigger channel adjustment and metamorphosis. Likewise, the sediment trapped in Scottish mill dams is thinner, and so bank erosion in an alluvial channel flowing across that sediment after dam failure is likely to be less than in thicker sediment bodies because the river incises to an underlying bedrock substrate relatively quickly.

Such behaviours are illustrated by the Baldernock Mill dam about 15 km north of Glasgow. This small mill dam, which has a very low trap efficiency, sits at the top of a knickpoint and feeds a short lade to the Baldernock Mill (Fig. 1C). It was built in the early 19th century and failed in the early 20th century (Bishop, Muñoz-Salinas, MacKenzie, Pulford, & McKibbin, 2010). It is at least the second mill dam at this locality and comparison of the General Roy mid-18th century map with the mid-19th century 1st edition Ordnance Survey (OS) 1:10,560 and 1:2500 scale maps and all subsequent OS maps (to the present) confirms that there has been essentially no change in channel pattern downstream of the dam since the mid-18th century, and certainly not since the dam wall failed. Equally, the channel that has cut through the dam's impounded sediment since dam failure has a very low sinuosity that presumably reflects the steepness of the channel across the bedrock substrate of the mill dam. The steepness of the dam's bedrock substrate means that the post-failure channel has not meandered back-and-forth across the impounded sediment, as reported by Walter and Merritts (2008) and Pizzuto and O'Neal (2009) for the eastern USA. Once the post-failure channel in

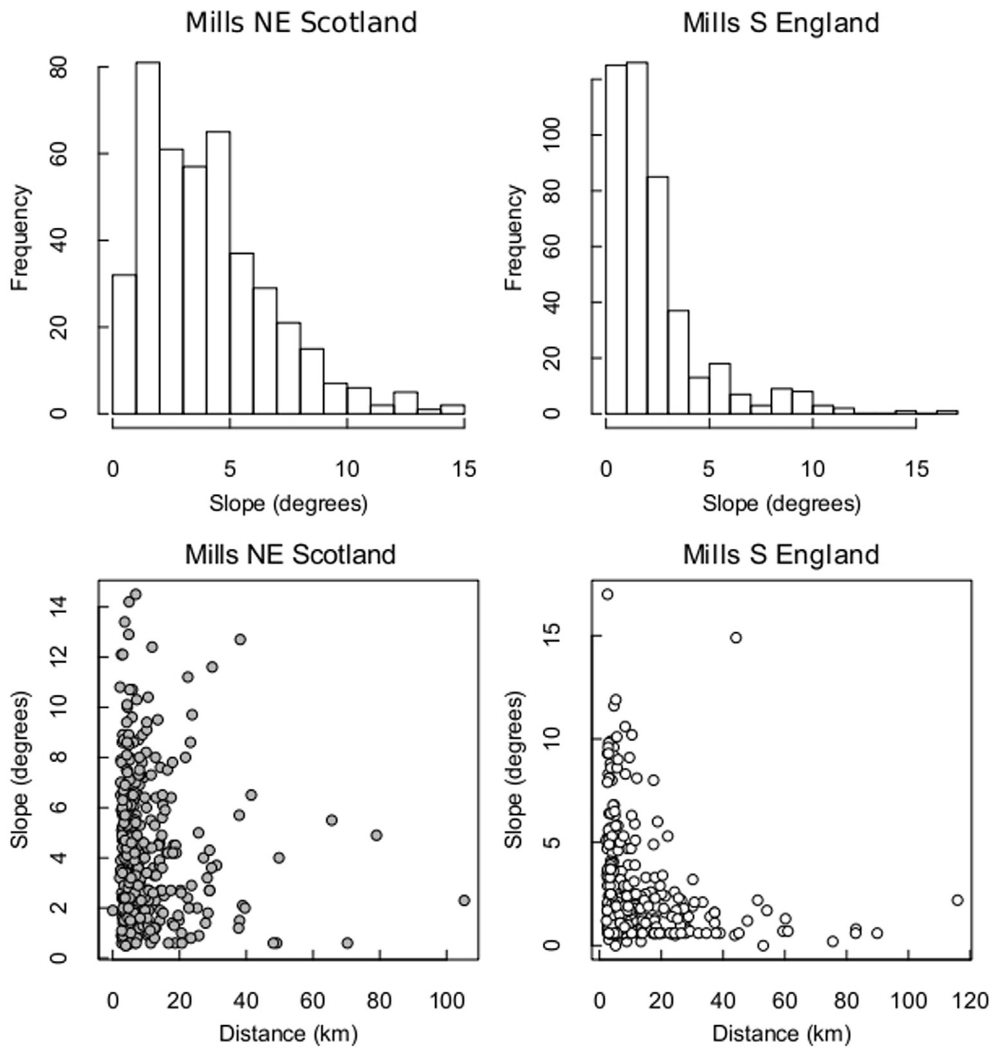

Fig. 8. Results of the GIS analyses of maximum channel gradient within 500 m of each mill locality (top) and combined plots of the distance and slope data (bottom) for all mill locations in the two study areas. Scottish mills are associated with channel gradients that are overall steeper than the channel gradients for English mills. Steeper channel gradients for the Scottish mills mean that lower mill dam walls are required for raising the water to the water wheels than is the case of England.

Baldernock had incised through the impounded sediment and established a large enough cross-sectional area to carry regular high flows, channel widening ceased, with the sediment produced by that incision into the impounded sediment now flushed through the steep channel downstream of the dam. This mill dam exhibits the key characteristics of Scotland's mill dams – a low wall and sited at the top of a bedrock step that means that water is delivered to the top of the mill's pitchback wheel (Bishop et al., 2010) – and its failure has resulted in virtually no channel change downstream of the dam wall and little upstream, beyond incision and enlargement of the channel to a stable cross-sectional area.

In general, Scotland's mill dam characteristics reflect the region's higher bedrock channel gradients and higher rainfalls, resulting in generally smaller mill dams which trap less sediment than do mill dams in England. The failure of Scottish mill dams thus constitutes much less of a management issue than does the failure of mill dams in England. The contrast between the two settings reflects their differing geomorphological histories, with the superimposition of Scotland's Quaternary glaciation onto steep upland bedrock rivers inherited from earlier (Cenozoic) uplift (Persano et al., 2007) leading to steep glacially-scoured bedrock channels, notably in the formerly glaciated upper catchments. Downstream reaches of Scottish coastal streams also exhibit steepening, driven by glacioisostasy, and many mills in Scotland are situated downstream of glacioisostatic and lithological knickpoints. The distances that these knickpoints propagate upstream scale with river size (catchment area as a surrogate for discharge – Bishop et al., 2005; Castillo et al., 2013; Jansen et al., 2011). Ongoing rebound throughout the Holocene means that the lower reaches of many coastal streams in Scotland have multiple knickpoints that are well suited to the construction of mills, with or without dams, depending on the reliability of river flow.

Thus, the potential for the failure of a mill dam to generate river management issues in the ways envisaged by Downward and Skinner (2005), Walter and Merritts (2008) and Pizzuto and O'Neal (2009) depends critically on the geomorphological setting and history of the dammed river. The failure of a dam on a steep bedrock river fed by reliable rainfall is unlikely to result in major management problems, either upstream or downstream, because only relatively low volumes of sediment will have been trapped in such a dam. Volumes are especially low where the rainfall and runoff are high and the dam's trap efficiency is low and most sediment passes over the dam wall (e.g., Bishop et al., 2010). Mill dams in Scotland exemplify the interactions of all these issues, whereas the mill dams of S England are more likely to be on lower gradient streams and hence to have higher dam walls, with higher trap efficiencies, in order for the water to be elevated to the upper parts of the mill wheel for more efficient mill operation. In short, the geomorphological and tectonic histories of a dam's location are central to managing the impacts associated with its failure, noting that any form of surface uplift – driven by passive isostatic rebound or active crustal thickening – that generates headward-propagating knickpoints is relevant here. This general point is well illustrated by mill dams in the different settings of NE Scotland and S England, but it applies to all dams and their possible failure.

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