The potential impact of green agendas on historic river landscapes: Numerical modelling of multiple weir removal in the Derwent Valley Mills World Heritage Site, UK

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ABSTRACT

The exploitation of river systems for power and navigation has commonly been achieved through the installation of a variety of in-channel obstacles of which weirs in Britain are amongst the most common. In the UK, the historic value of many of these features is recognised by planning designations and protection more commonly associated with historic buildings and other major monuments. Their construction, particularly in the north and west of Britain, has often been associated with industries such as textiles, chemicals, and mining, which have polluted waterways with heavy metals and other contaminants. The construction of weirs altered local channel gradients resulting in sedimentation upstream with the potential as well for elevated levels of contamination in sediments deposited there. For centuries these weirs have remained largely undisturbed, but as a result of the growth in hydropower and the drive to improve water quality under the European Union's Water Framework Directive, these structures are under increasing pressure to be modified or removed altogether. At present, weir modifications appear to be considered largely on an individual basis, with little focus on the wider impacts this might have on valley floor environments.

Using a numerical modelling approach, this paper simulates the removal of major weirs along a 24-km stretch of the river Derwent, Derbyshire, UK, designated as a UNESCO World Heritage Site. The results suggest that although removal would not result in significant changes to the valley morphology, localised erosion would occur upstream of structures as the river readjusts its base level to new boundary conditions. Modelling indicates that sediment would also be evacuated away from the study area. In the context of the Derwent valley, this raises the potential for the remobilisation of contaminants (legacy sediments) within the wider floodplain system, which could have detrimental, long-term health and environmental implications for the river system. Worldwide, rivers have a common association with industry – being the focus of settlement and development since the earliest civilisations with channel engineering a common practice. Therefore, the conceptual issues raised by this study have global resonance and are particularly important where heritage protection is less robust and structures can be removed with little consideration of the environmental consequences.

Keywords: numerical modelling; contamination; river restoration; heritage

1. Introduction

On a global scale, many of the world's great civilisations have developed around river systems with growth and prosperity dependent on working with and managing their associated hydrological regimes (Macklin and Lewin, 2015; Vianello, 2015). In the UK, the exploitation of river systems for navigation and power, particularly since medieval times (Lewin, 2010, 2013), has been carried out through channel modifications, including locks, weirs, leets, and races. Weirs, in particular, are one of the most widespread forms of historical channel modification – regulating channel flows, usually to provide a head of water for power generation or to aid navigation via lock systems. The historical importance of many of these structures has led to numerous examples gaining conservation designations more normally associated with major buildings of national importance. In many ways, weirs and other riverine structures have been transformed from water management features to culturally important and protected features of the contemporary riparian corridor (Firth, 2014, 2015). As a point of clarification early on in this paper, we should note that in North American literature, the term 'weir' as used here is replaced by 'dam' and size does not appear to be used to differentiate these structures from larger features that impede flow and lead to the retention of a large body of water (reservoir) as might be practiced in the UK (for example, see the use of the term 'dam' by Magilligan et al., 2016).

Many weirs within river corridors remain relatively unaltered and fossilised within the landscape, providing glimpses of an industrial past and former trade networks. Many are still maintained and conserved, being now seen as part of the contemporary riparian environment. However, during the last decade these structures have come under increasing pressure to be modified or removed from drainage networks as a result of two major initiatives. The first of these comprises river restoration projects associated with the legal obligation on the UK government to improve water quality, habitats, and fish passage in response to the (currently enforced) European Water Framework Directive (WFD; European Commission, 2000). Weirs can provide longitudinal physical barriers to the migration of fish as well as the downstream movement of sediment affecting river 'quality'.

Nationally, the Catchment Restoration Fund (CRF), established in 2012 by the UK government and administered by the Department for Environment, Food & Rural Affairs (Defra), aimed to have spent up to £28 million between 2012 and 2015 on projects related to WFD objectives. In the financial year 2013-2014, work under the CRF comprised installation of three technical fish passes, the removal of 29 weirs or other barriers to fish movement, completion of 17 large-scale and 21 small-scale fish easements, and installation of 24 eel passes (Defra, 2014). These figures demonstrate that the number of national interventions remains significant, although we acknowledge here that not all are based around weir structures. Locally, proposed changes to weirs can be considerable; for example, Turnbull (2012) undertook a detailed investigation of eight historic weirs on the River Loxley in South Yorkshire as part of Ancient Monument planning consent in advance of structural modifications to provide fish passes. Whilst we acknowledge that the WFD is a major piece of European legislation, and as such restoration projects and their associated challenges are not just restricted to the UK (e.g., Lespez et al., 2015), the cultural value of such in-channel fluvial features in the UK is particularly high. This reflects, in part, the influence of the Industrial Revolution, but also the robust statutory framework of heritage protection in the UK.

The second initiative is the potential to modify these structures under schemes designed to generate hydropower, and so contribute toward UK government sustainable energy targets (https://www.gov.uk/harnessing-hydroelectric-power). Entec Ltd (2010) estimated that there are 25,935 barriers across rivers in England and Wales that have the potential to produce varying outputs of hydropower. Although the Entec Ltd (2010) report does not identify how many of these sites are associated with historic weirs, a significant number may be predicted in view of the estimated total number of water barriers and the historic use of many weirs for industrial power generation.

Planning law in the UK requires that any modifications to historic weirs include an assessment of their heritage value as part of the overall design process (e.g., Passmore and Pink, 2011; English Heritage, 2014). However, by their very nature engineering solutions have tended to focus on individual sites and structures (e.g., Ghimire and Jones, 2014) rather than the wider valley floor context or reach-scale geomorphology and system dynamics. Certainly from the perspective of hydropower, design engineering considerations of the sensitivity of any proposed changes appear to be restricted to species and habitat considerations related to Special Areas of Conservation (Entec Ltd, 2010). More recently, their heritage value has been highlighted by Historic England (English Heritage, 2014). However, an important point that appears to have been ignored in literature associated with these structures, even by archaeologists (Firth, 2014, 2015), is that many weirs on river systems, particularly in northern and western Britain, were associated originally with heavy industries such as mining, textile manufacturing and a wide range of chemical manufacturing processes. These, in turn, have left a legacy of pollution trapped within the surrounding floodplain sediments and soils, posing threats to long-term environmental stability, particularly under scenarios of future climate change (e.g., Foulds et al., 2014; Buchty-Lemke et al., 2016). Within certain valley floor reaches therefore, disturbance to floodplain sediments around weirs or erosion and sedimentation resulting from the readjustment of local base levels following weir modification and/or removal may have significant environmental consequences for the wider river catchment. Whilst such issues are familiar to engineers, geomorphologists, and catchment managers (Rickard et al., 2003), many of whom have highlighted similar potential problems as a consequence of river restoration projects focused on large-scale dam removal (Bednarek, 2001; Grant, 2001; Evans and Gottgens, 2007; Gartner et al., 2015), the transfer of knowledge and practice to smaller scale weir (and dam) systems does not seem to have been widely made in the peer-reviewed literature, though a recent paper by Magilligan et al. (2106) highlights the importance of such research.

As part of a study investigating the potential impacts of future climate change on the UNESCO Derwent Valley Mills World Heritage Site (DVMWHS), Derbyshire, UK (Howard and Knight, 2015; Howard et al., 2015), numerical modelling was undertaken to predict valley floor geomorphic responses to enhanced discharge associated with changing precipitation conditions. Major historic weirs form an integral part of the World Heritage Site designation, but as fixed obstacles they also significantly influence contemporary hydrology and so were an important consideration during the design of the fluvial modelling work package. As in other UK valley floors, they are also important obstacles to consider with respect to meeting water quality and habitat objectives of the WFD. Given this context, as part of the empirical study to elucidate the impact of future climate change on the Derwent Valley, numerical models were run to explore how the river system might respond to future environmental change with the weirs *in situ* and with the weirs removed.

We must stress at the outset that the international historical value of these weirs as WHS assets is such that it is inconceivable that they will face calls for their widespread removal as a consequence of WFD policy, although minor modifications to facilitate the passage of fish or permit the development of hydropower may be anticipated (e.g, Darley Abbey: Flintoft, 2014, 2015). In contrast, many historic weirs elsewhere in the UK are under pressure to be substantially remodelled or removed altogether. Impact assessments appear to be undertaken principally at the site-specific level with the focus firmly upon the weir structure rather than the wider riparian environment. Furthermore, we note little investment in the development of frameworks for post-modification monitoring and assessment of river response or of floodplain adjustment to new boundary conditions - a common criticism often aimed at dam removal projects in the United States (Magilligan et al., 2016).

Therefore, with these challenges in mind, the aims of this paper are to (i) consider the riparian corridor of the River Derwent WHS and to use numerical modelling to forecast how weir removal might affect the geomorphology and floodplain dynamics of what is, in essence, a typical UK valley floor; (ii) consider whether these results can help inform a more generic policy focused around weir removal; and (iii) consider whether the challenges of preserving historic weirs and associated structures are incompatible with the appetite of governments globally for green environmental agendas and policies.

2. The weirs and riparian environment of the UNESCO Derwent Valley Mills World Heritage Site

The River Derwent with a catchment area of around 1200 km^2, originates some 9 km east of Glossop at an elevation of 590 m Ordnance Datum (OD) and flows largely southward for a distance of 80 km to its confluence with the River Trent (100 m OD). The river enters the World Heritage Site buffer zone immediately upstream of Cromford and leaves it in the city centre of Derby (Fig. 1). The designation of the Derwent Valley Mills as a World Heritage Site in 2001 is based upon a series of eighteenth and nineteenth century cotton mills associated with the birth of the modern factory system. The construction of weirs and associated infrastructure provided not only the power to drive the machinery within these mills but also the energy for associated products: for example, mills to grind corn to feed the workforce and mills to manufacture and print paper (Derwent Valley Mills Partnership, 2011).

Within the World Heritage Site, six major historic weir complexes are present (Table 1), five associated with the main river Derwent and one with a tributary valley (the Cromford Mill basin weir). The most important of these weir structures have grades II or II* listed building status and range in height from around 1.2 to 3 m (Fig. 2). Earlier water-powered mills and associated water management features have been recorded at various sites along the river, notably around Duffield (Derbyshire Historic Environment Record Sites 19419, 19424, 19425) and Darley Abbey (Flintoft, 2014, 2015), but these features do not form extant barriers or restrict the flow of the contemporary channel.

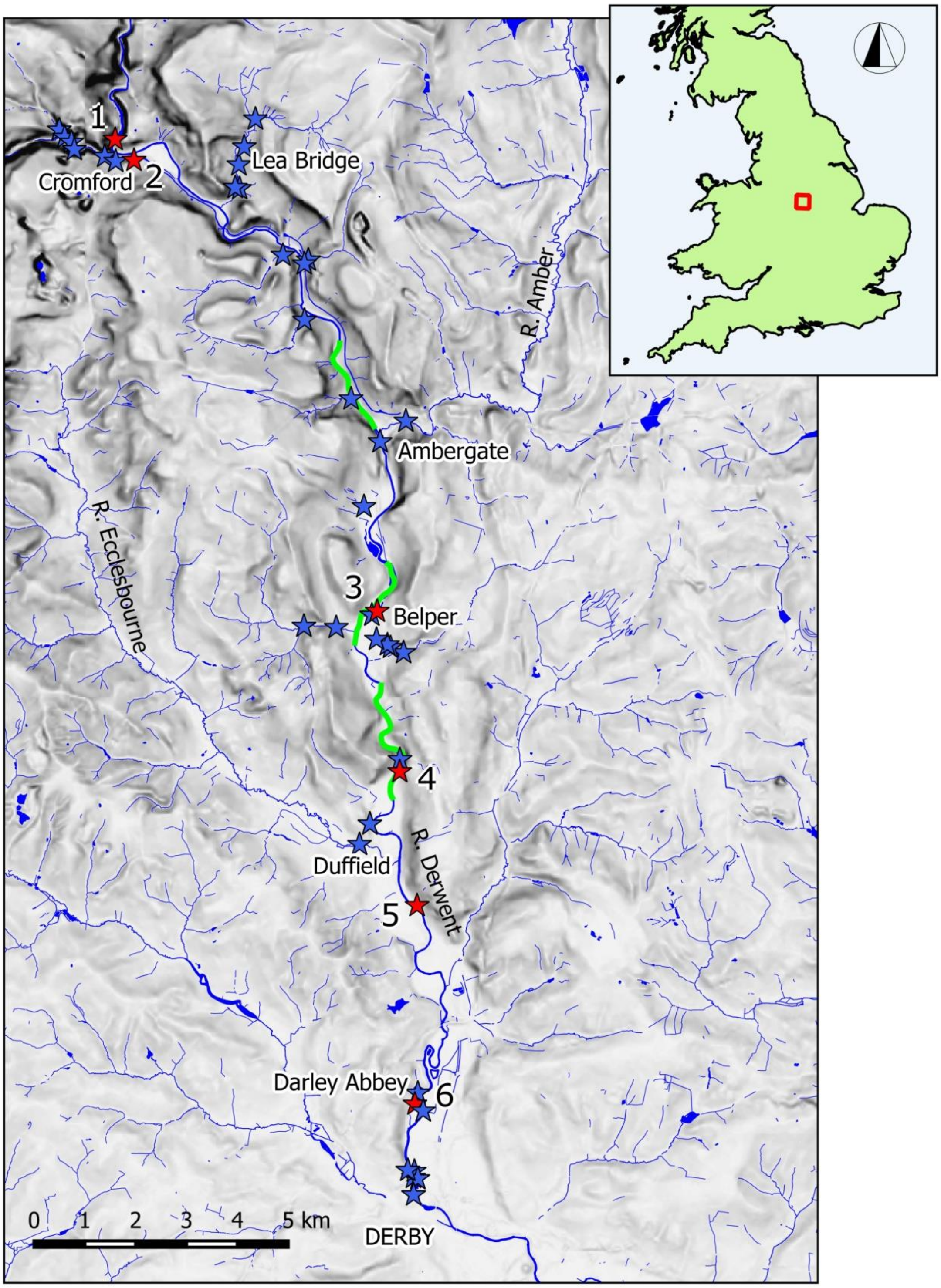


Fig. 1. The Derwent Valley Mills World Heritage Site. Mill complexes are denoted by blue stars. The listed weirs are denoted by red stars referred to in Table 1. Modelled stretches of river compared in Figs. 9-11 are shown by thick green lines (see Fig. 3 also).

Table 1

Historic weirs extant within the World Heritage Site[1].

Location	Description
Masson Mill Weir, No 1, Fig. 1	**LISTED GRADE II*.** Weir has convex shape. It is suggested to have been built in this form because of the underlying rock structure at this point in the river. Whilst undated, it was probably an early addition to the Masson site, if not contemporary with the textile mill itself.
Cromford Mill Basin Weir and Culverts, No 2	**LISTED GRADE I.** The basin weir was constructed around 1777, in the middle of the mill yard at Cromford. Note that this weir, although part of the site designation, is away from the River Derwent on a tributary stream.
Belper West Mill Horseshoe Weir, No 3	**LISTED GRADE II***. Convex shape as name suggests. Built 1797 by Jedediah Strutt but modified and increased in height in 1819 and 1843. This structure replaced Jedediah Strutt's first weir further north that powered the South and North Mills.
Hopping Mill Weir, Milford, No 4	**LISTED GRADE II**. The current weir dates from 1799-1801, but occupies the site of an earlier structure. Substantially altered by the Strutt family when they built their first cotton mill in Milford, it has a stone paved sloping surface and a concave curve upstream. The weir served three sites: on its north side, a corn mill and a fulling mill; on its south side, via a goyt, Strutt's printing mill and bleach works; farther downstream, south of the bridge across the Derwent, the main cotton mill site.
Makeney Road, Weir, No 5	**LISTED GRADE II**. The upstream weir of the two was constructed between 1787 and 1792, most probably by the Strutt family. The lower weir was added some time before 1840 and has a stone fish ladder in its centre.
Boar's Head Mill Weir, Darley Abbey, No 6	**LISTED GRADE II**. This Grade I mill complex includes the Long Mill (1782-89) and West and East Mills (1819-21). These mills were located on the east bank of the Derwent, which was traversed by a large weir (Grade II), constructed diagonally across the Derwent in *c*. 1782 and surveyed by Benjamin Outram in 1792.

[1] Source of data is the Derwent Valley Mills Nomination File (2001). Republished with several revisions in 2011 (DVMP, 2011), and a survey of Boar's Head Mills, Darley Abbey by Adam Menuge (2006). Grade II* buildings are particularly important buildings of more than special interest and constitute 5.5% of listed buildings; Grade II buildings are of 'special interest' (https://historicengland.org.uk/listing/what-is-designation/listed-buildings/).

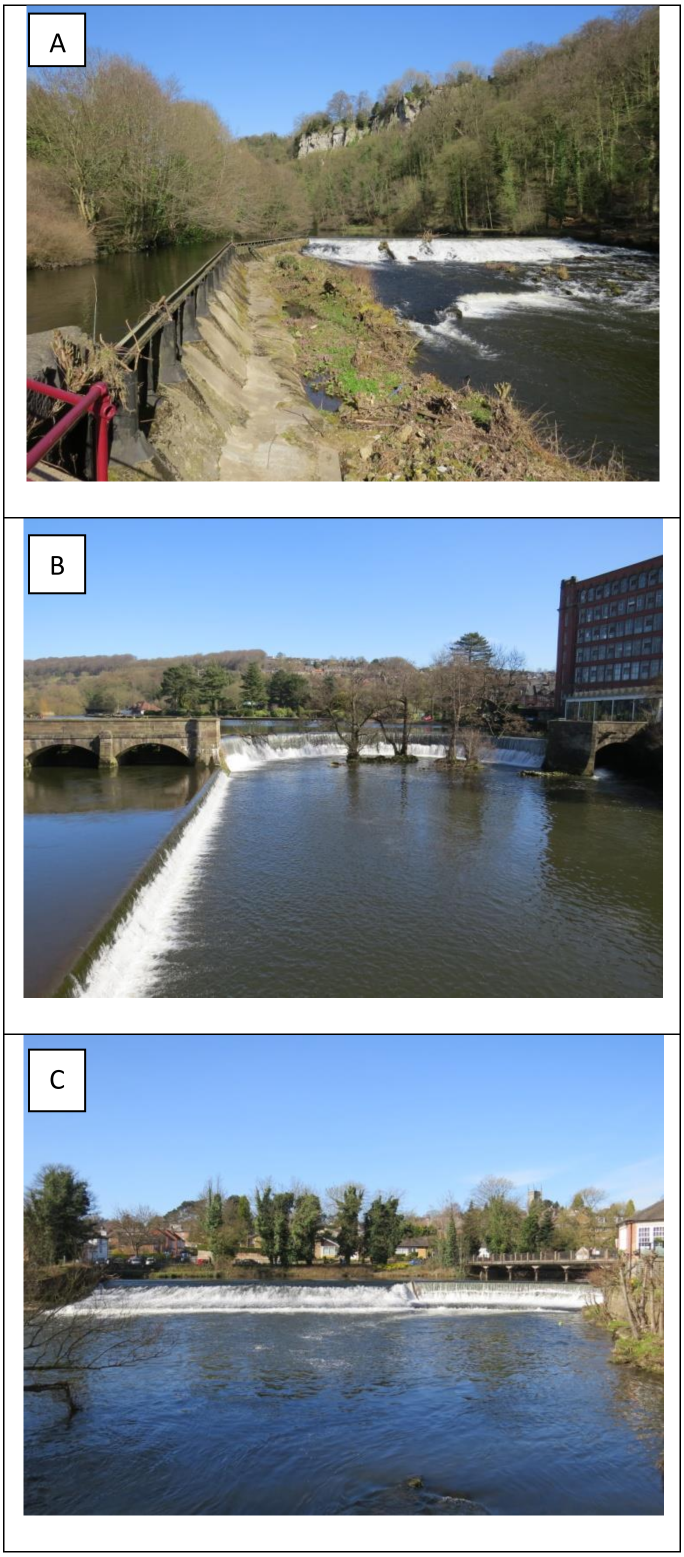


Fig. 2. Examples of listed weir structures along the Derwent listed in Table 1: (A) is Masson Mill weir; (B) is Belper West Mill Horse Shoe weir; (C) is Boar’s Head Mill weir.

Although the weirs of the WHS are unlikely to face calls for their complete removal, some modifications have already been undertaken within the WHS river reach. At Darley Abbey weir, a fish pass has been installed as part of WFD objectives and led to the discovery of major archaeological remains, possibly associated with an earlier mill site (Flintoft, 2014). At Upper Milford, a weir has been modified as part of a hydropower scheme (Defra, 2014).

In addition to its importance to the textile industry, the River Derwent drains Carboniferous limestone bedrock that has played host to a rich base-metal mining industry, principally lead and zinc in the Derwent catchment, with peak production taking place in the eighteenth and early nineteenth centuries. An indirect consequence of this mining activity has been the release of metal-contaminated sediments into the environment. These have been deposited across the valley floor and are stored within the floodplain alluvium at levels often exceeding health guidelines (Bradley and Cox, 1990; Kossoff et al., 2016). By causing water to back up behind them, weirs reduce the energy of flow upstream, generating conditions that aid the deposition of sediment – especially fine-grained suspended sediment with which metal contaminants are associated. In effect, therefore, weirs can act as local sediment traps within the valley floor and, given that the weirs are inset within the floodplain, any disturbance to such structures has the potential to release further metal-contaminated sediments into the wider river system. We emphasize that the construction of weir systems as a means of capturing power and aiding navigation more generally has a longer history than the significant expansion of activities associated with the industrial revolution (Lewin, 2013) and therefore by the eighteenth and nineteenth centuries, river systems were already primed to trap contaminants.

3. Modelling methodology

In order to simulate long-term river development within the DVMWHS and the impact on the riparian corridor with the weirs *in situ* and removed, a hydromorphic model (CAESAR-Lisflood) was used to simulate erosion, deposition, and the passage of floods through the Derwent River corridor. CAESAR-Lisflood is a two-dimensional hydraulic model that simulates the erosion and deposition of sediment (bedload and suspended load) over a range of grain sizes. It has previously been applied to over 50 river reaches and catchments across the globe and allows comparatively large tracts of river to be simulated over decadal or greater timescales (Coulthard et al., 2012). Important inputs to CAESAR-Lisflood include the topography represented by a Digital Elevation Model (DEM) and river flow data and the workflow for the model is reported elsewhere (Van De Wiel et al., 2007). Here, the DEM was constructed from airborne laser altimetry data (LiDAR) supplied by the Environment Agency with 2 m ground posting. Undertaking modelling at this 2 m scale along the entire 24 km length of the WHS riparian corridor would have resulted in a DEM of several million cells, thereby creating considerable numerical complexity and making the model run slowly. Therefore, to simplify processing and analysis speeds, the 2 m resolution DEM was re-sampled to 20 m grid cells (Fig. 3). Whilst this change of scale may have resulted in some reduction of detail, the resolution still provided a good representation of the valley floor, floodplain and channel environment including channel, channel boundaries, floodplain morphology, and the weir structures. Mean grain size information to drive the model was gathered from a field survey–however, to include the heterogeneity of grain size that develops in channels and floodplains, the model uses a ‘spin up’ period widely used in CAESAR-Lisflood applications (see Coulthard and Skinner, 2016). This involves starting the model with the same grain size distributions throughout the reach, then running the model for a period (here 10 years) allowing spatial and vertical grain size distributions to develop (e.g. fine material behind weirs, and coarsened after).

Fig. 3. LiDAR-derived DEM of the DVMWHS modelled. Reaches where long profiles were compared in Figs. 8, 9, and 10 are indicated by the black lines.

To drive erosion and deposition within the model, river flows and floods within the Derwent catchment were simulated and calibrated using flow data obtained from the National Rivers Archive. A complete set of data for three rivers associated with the catchment downstream of Matlock Bath (the Derwent at Derby and the Ecclesbourne and Amber rivers) provided information for a 23-year period from 1971 to 2004 (Fig. 4).

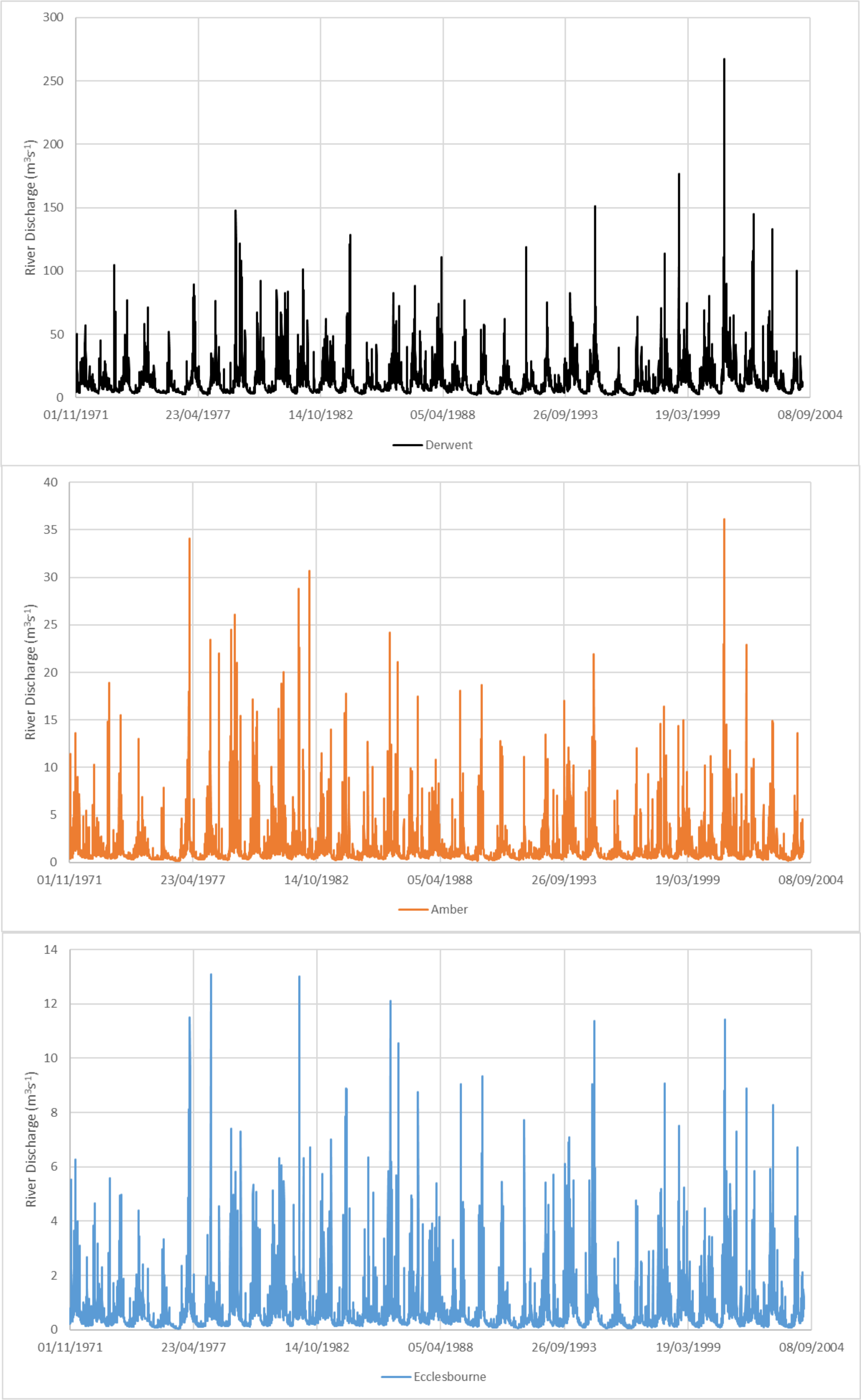


Fig. 4. Flow data for the Derwent at Derby and the Ecclesbourne and Amber rivers from 1971-2004. Note different scales for discharge (*y*) axis.

This real flow data was then used to calibrate separate hydrological models running at a coarser spatial resolution for the catchment above the WHS and for two major lower tributaries: the Ecclesbourne and Amber rivers. This calibration allowed the generation and modelling of realistic flood sizes when using future predictions of rainfall for the catchments feeding the river Derwent.

For the hydrological calibration, the upstream models were then run for 30-year periods (starting with the present-day shape and position of the channels) using synthetic rainfall modelled upon baseline criteria (computer-generated rainfall based on present-day rainfall patterns) from the UKCP09 weather generator (Prudhomme, 2012). As synthetic rainfall is generated according to probabilities of existing rainfall patterns, there is a random component in this process, and so this process was repeated 100 times (as recommended by Coulthard et al., 2012). From these 100 simulations, daily river flow averages were taken and used to generate a frequency distribution of daily flow amounts. To calibrate the model, this process was repeated six times, each time varying a key parameter (m) in the hydrological model, which alters the size and length of floods. Figure 5 shows the mean frequency of the daily flows for all six of these 100 sets of simulations and those from the actual flow data in the Derwent at Derby. Notably, single large events (e.g. above 175 $m^3 s^{-1}$) will be disproportionately overrepresented compared to the mean simulated data with values below 1. From these data, a visual calibration was made to set m at 0.025.

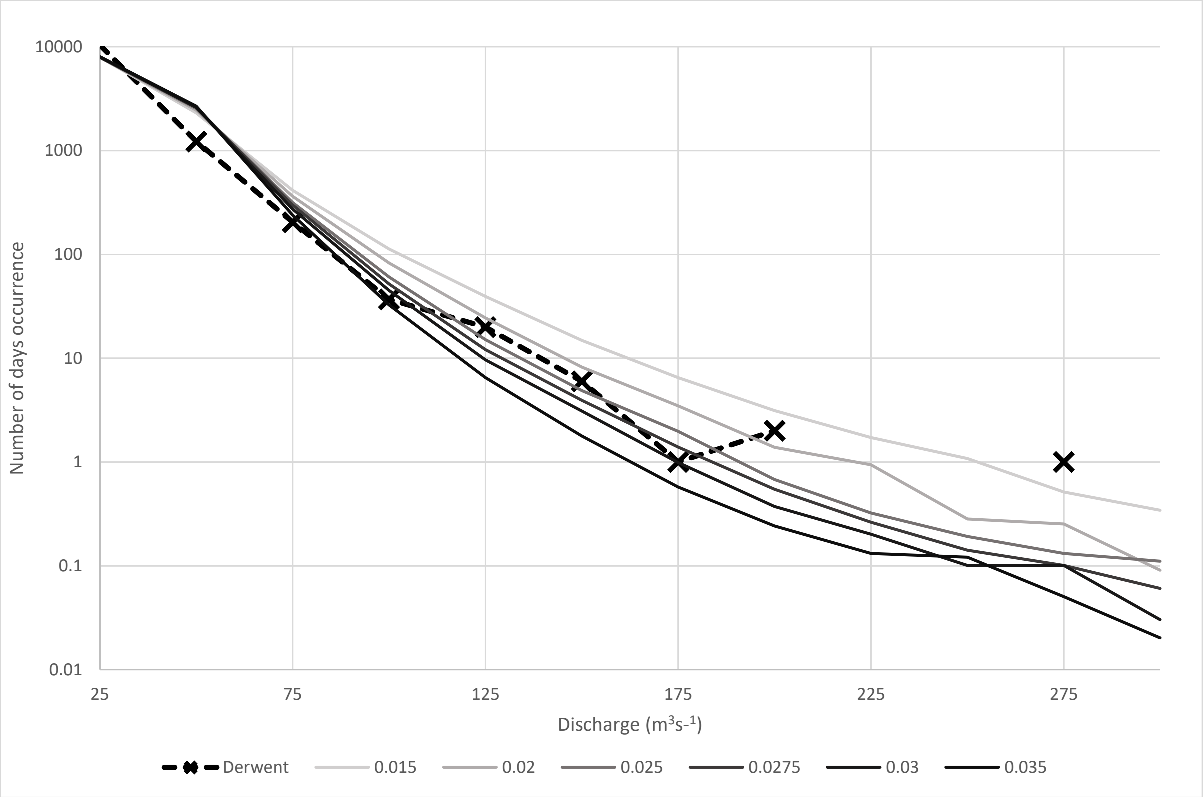


Fig. 5. Frequency distribution of daily flow magnitudes for the Derwent and baseline simulations with a range of values (0.015 to 0.035 m).

To model the impact of future climate change on the riparian corridor, with and without weirs, rainfall predictions were needed to generate future flood events. These were simulated using the UKCP09 Weather Generator and, specifically, the high emissions scenario for the time period 2020-2049. The weather generator produced 100 30-year hourly rainfall simulations for the catchment above the Derwent. From these 100 simulations, 20 were randomly selected and used to generate 30-year periods of flows and future erosion and deposition patterns within the DVMWHS reach.

As the rainfall (and thus flood) input to each simulation is slightly different, 20 patterns of erosion and deposition were generated for each scenario. All modelling simulations started with the same topography, were driven by the same rainfall, and experienced the same floods, differing only with respect to the lowering of elevation in model cells where weir structures had been removed. To smooth the data, volumes of erosion and deposition were combined; and Figs. 6 and 7 illustrate mean erosion and deposition for the upper and lower halves of the reach modelled (Fig. 3).

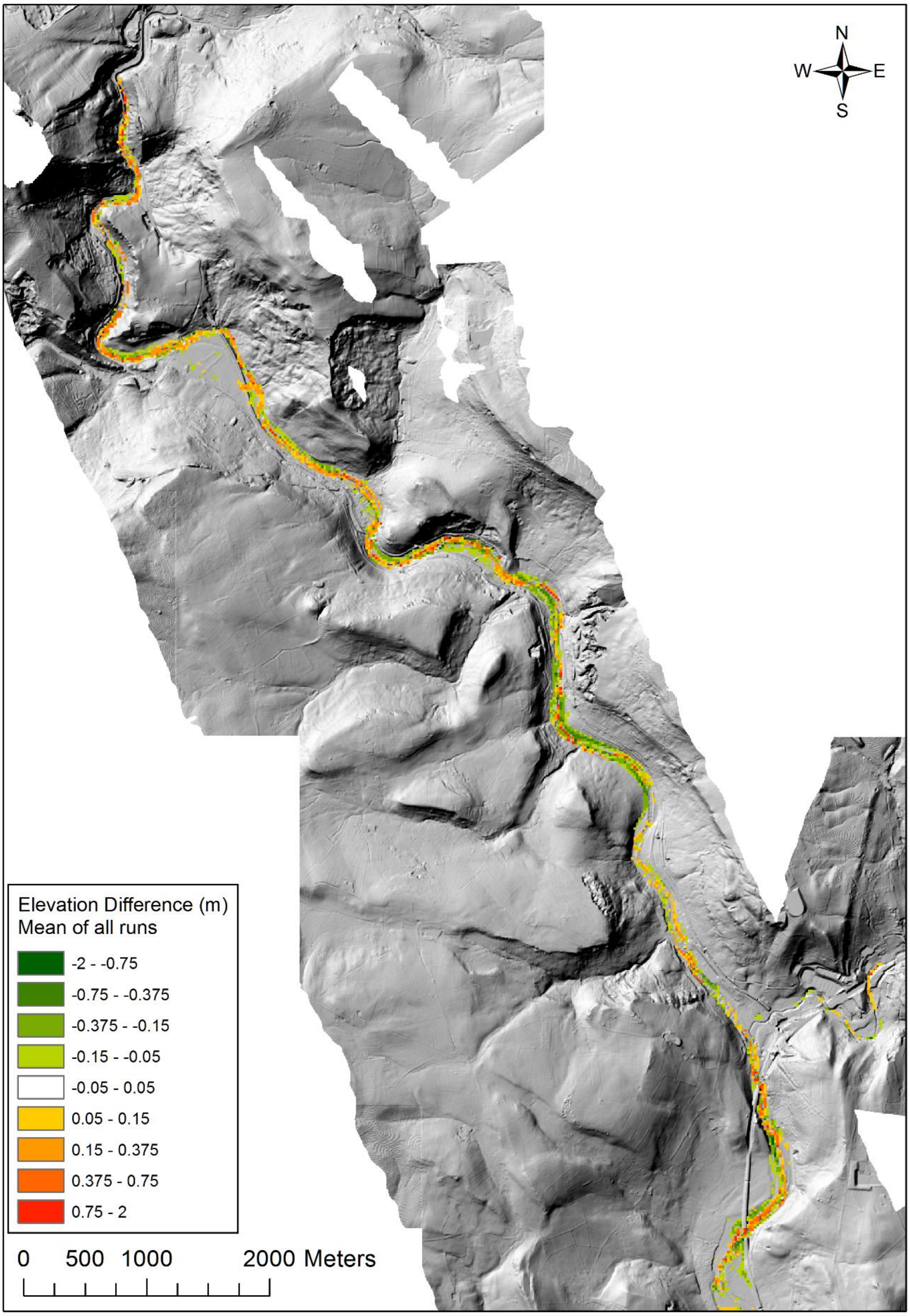


Fig. 6. Patterns of mean erosion and deposition for the upper half of the reach.

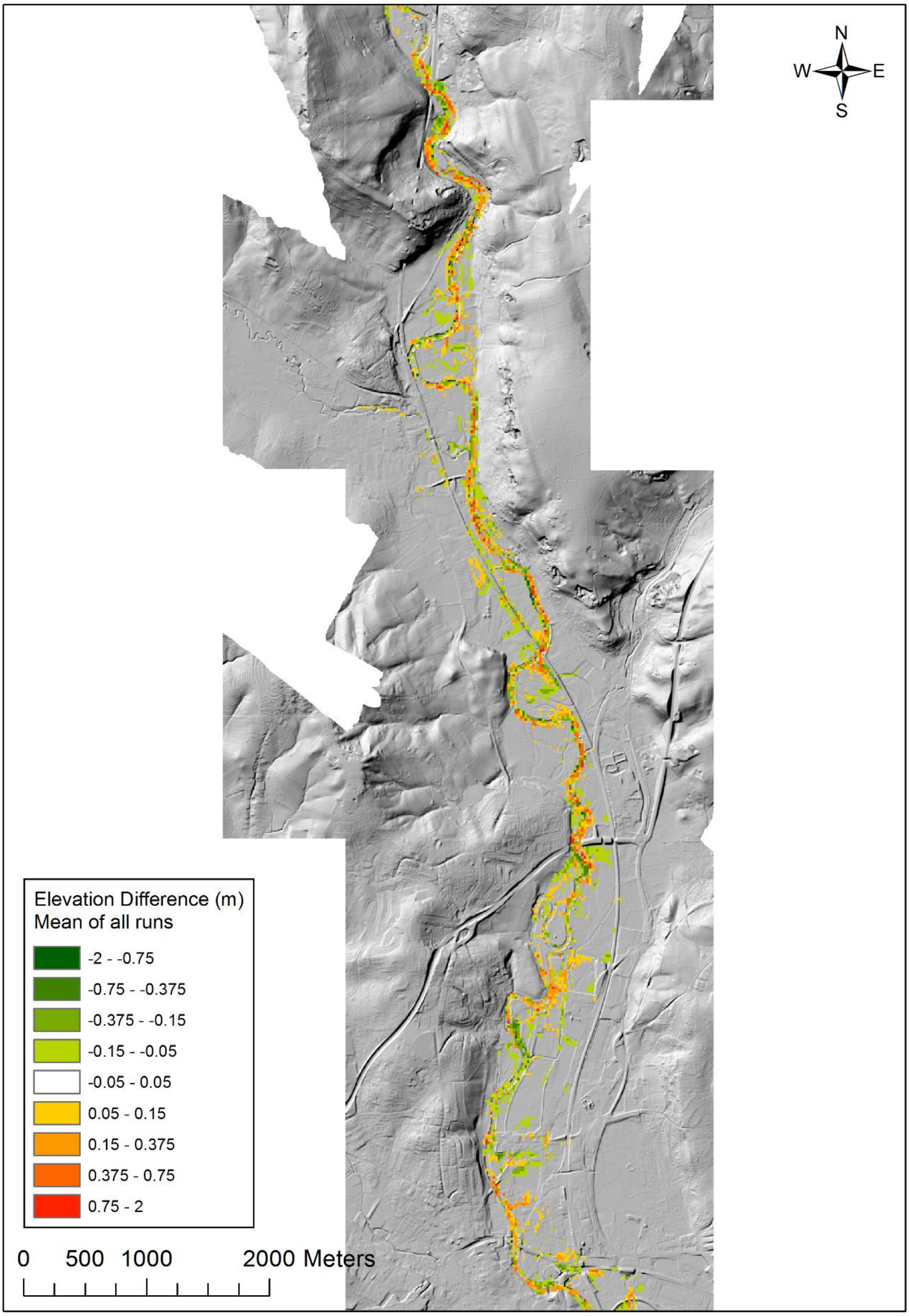
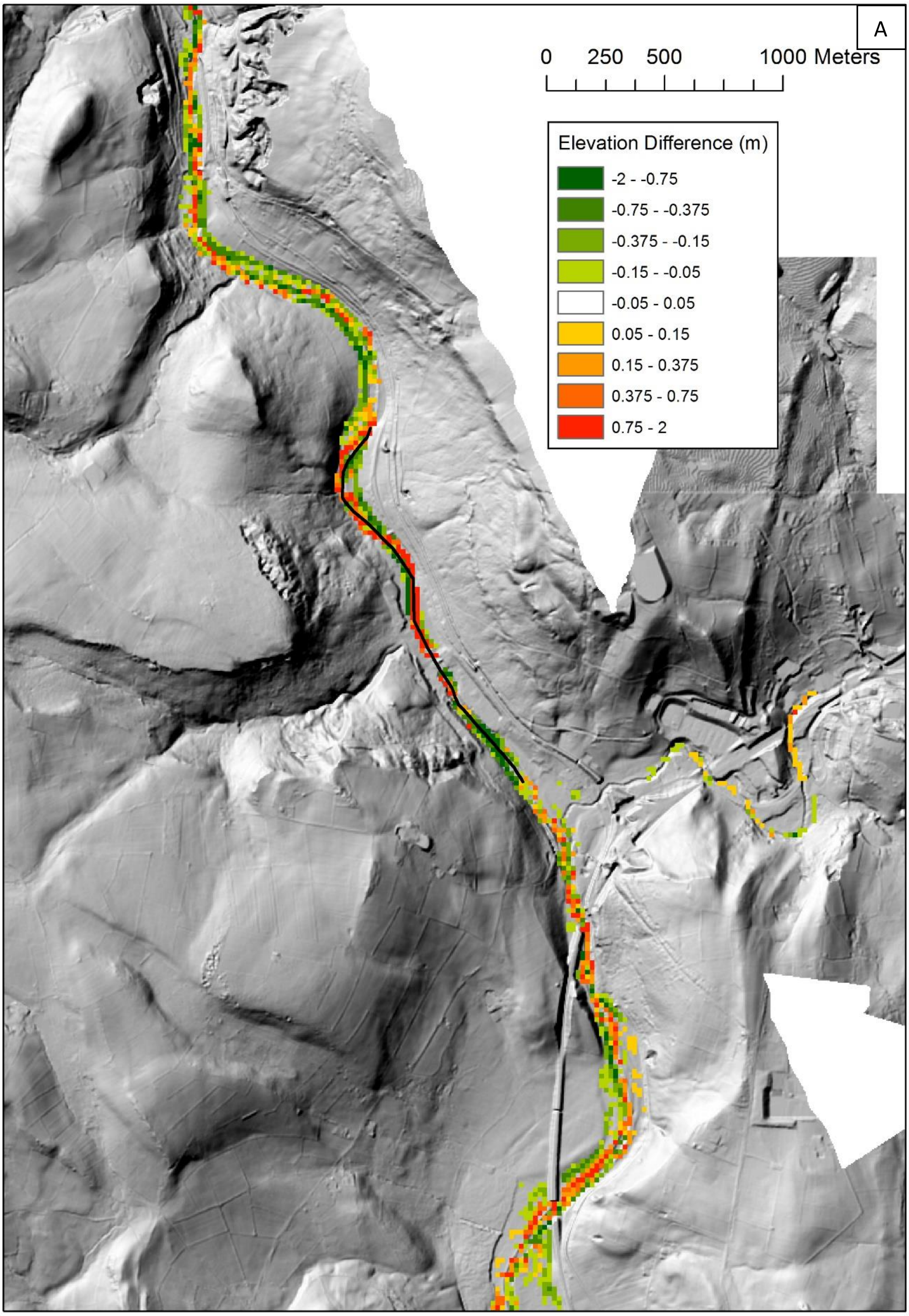


Fig. 7. Mean erosion and deposition for the lower half of the reach.

4. Modelling the fluvial corridor with weirs in situ and weirs removed

Modelling with weirs *in situ* demonstrates that whilst erosion and deposition occur throughout the WHS reach during the 30-year simulations, overall, from a geomorphological perspective, changes in erosion and deposition are not great (Figs. 6 and 7). Only in very few places is mean erosion or deposition >1 m vertically. In most locations where we noted a change, it is in the order of a few centimetres. We recorded no predicted dramatic shifts in the location of the channel or areas of high erosion and deposition, and the low river dynamics indicate a comparatively stable river system. This suggests that as well as forming structures of significant contemporary aesthetic value and historically playing a key role in ensuring power to the textile mills, the historic weirs along the valley continue to play an important role in regulating geomorphic changes within the riparian corridor. Analyses of historic Ordnance Survey maps demonstrate that the river has remained relatively fixed within its valley floor since at least the 1880s, around 30 years before the first of three major reservoirs was constructed within the upper Derwent Valley (Petts, 1987). In contrast, analysis of LiDAR imagery from the valley floor, notably around Duffield, indicates truncation by multiple river courses of ridge and furrow earthworks typical of medieval arable agriculture – suggesting, therefore, that the river has been highly mobile across its valley floor since the High Middle Ages and prior to the 1880s (Howard et al., 2015). This may possibly be associated with the enhanced flow conditions of the Little Ice Age (ca. 1450-1850), as observed in other rivers across Britain and northwest Europe (Rumsby and Macklin, 1996), and suggests that the Derwent, described by Daniel Defoe (1724-1727) as a 'frightful creature when the hills load it with water' (http://www.visionofbritain.org.uk/travellors/Dafoe/30), may have been characterised during that period by significant lateral channel mobility. It may also imply that the weirs of the Derwent have played an important role in reducing channel dynamics and increasing channel stability.

In contrast, simulations where the weirs were removed (Figs. 8-10) show that significant erosion would occur around the removed structures and that this erosion would move upstream in response to increased local water surface gradients, which drive velocity and hence erosion. This incision is shown to be widespread and to move in most circumstances ca. 1 km upstream as the river seeks to establish its preweir gradient.



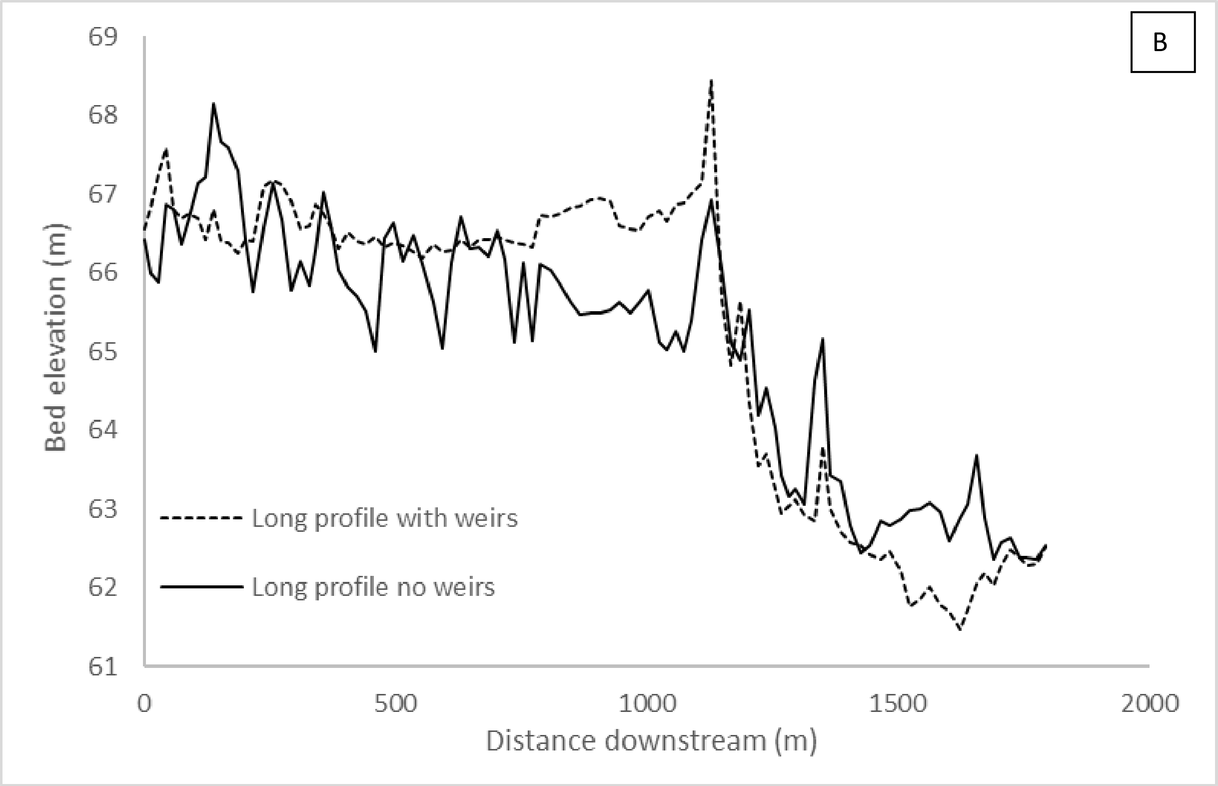
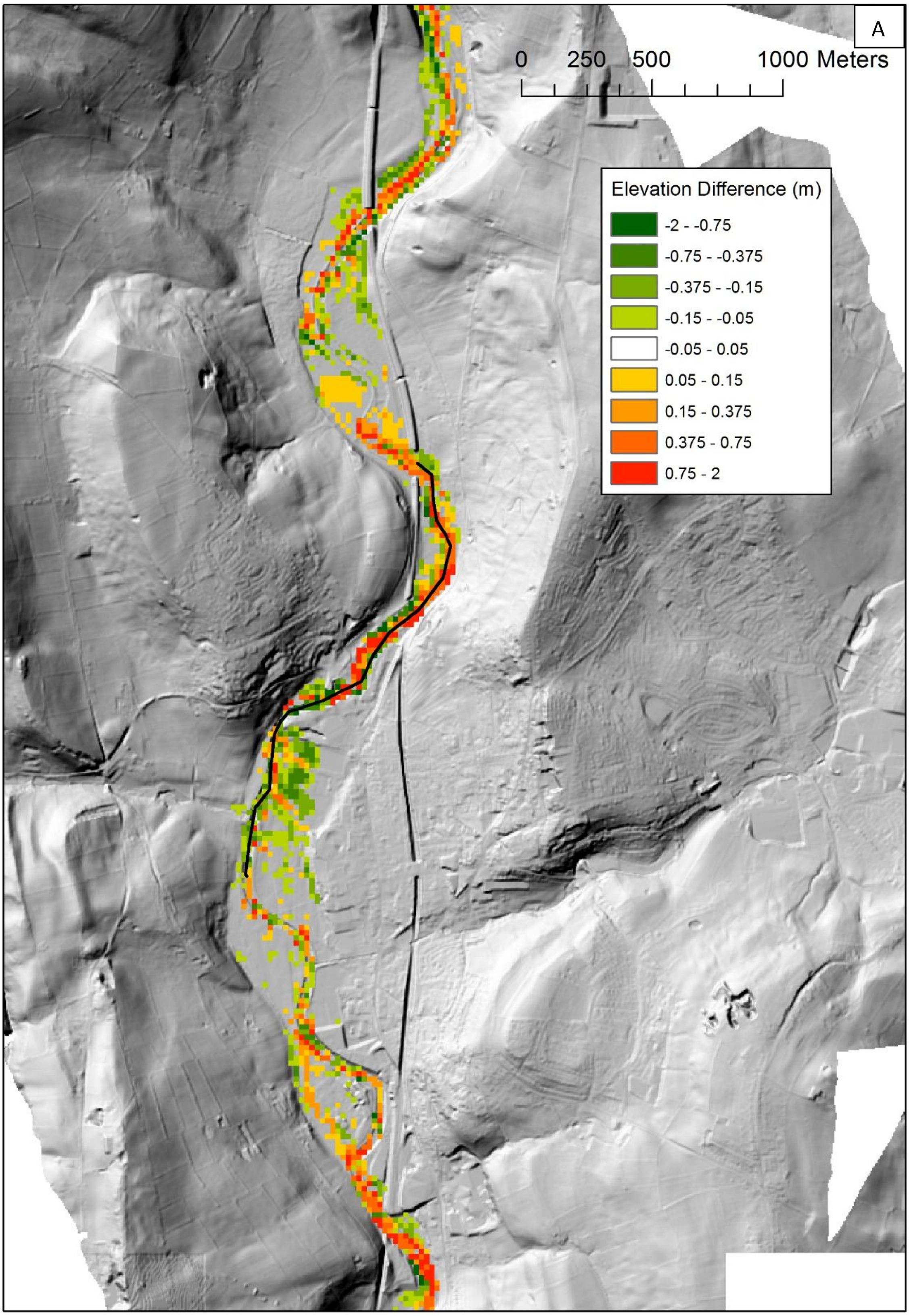


Fig. 8. (A) Patterns of erosion and deposition in the upper section after the weirs have been removed. (B) Chart of the channel long profile (as indicated by black line in A showing changes in incision (upstream) and aggradation (downstream) following weir removal.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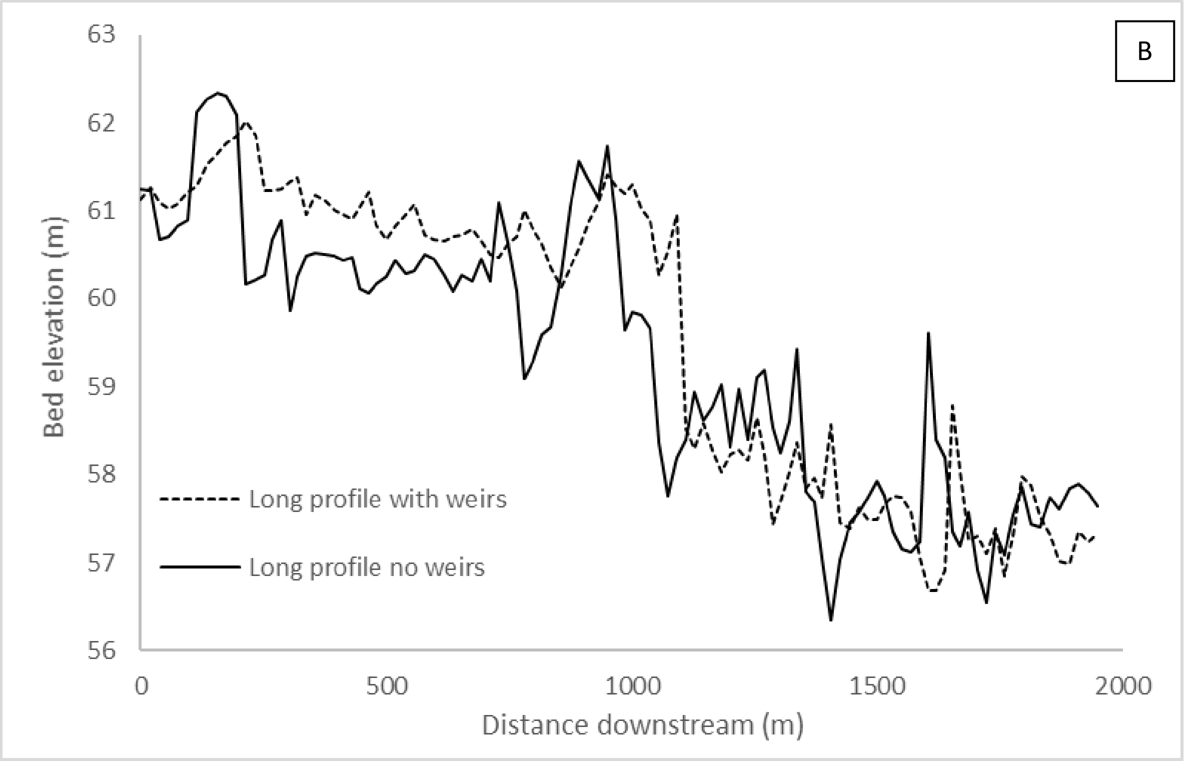
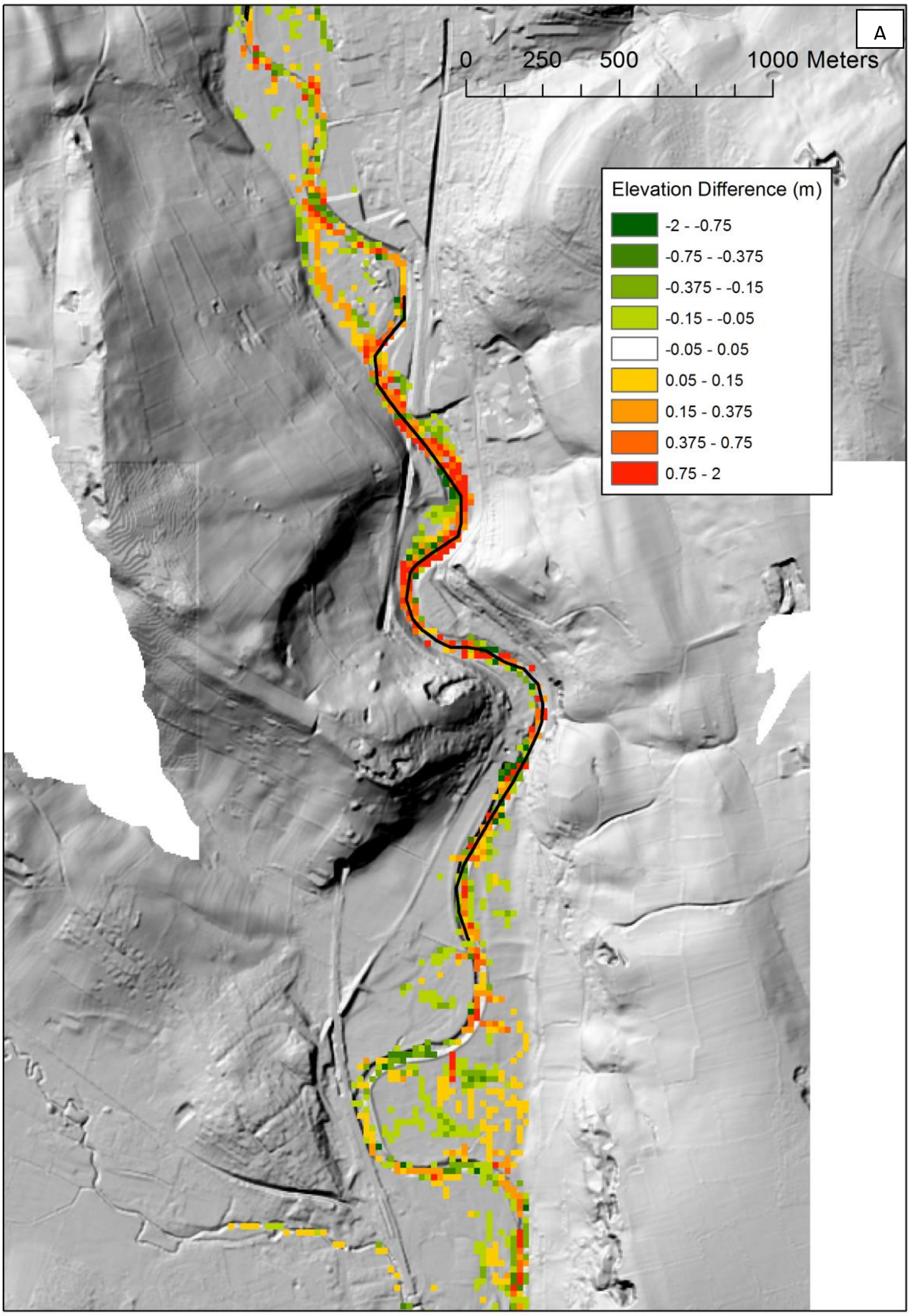


Fig. 9. (A) Patterns of erosion and deposition in the middle section with the weirs removed. (B) Chart of the channel long profile (as indicated by black line in A showing changes in incision (upstream) and aggradation (downstream) following weir removal.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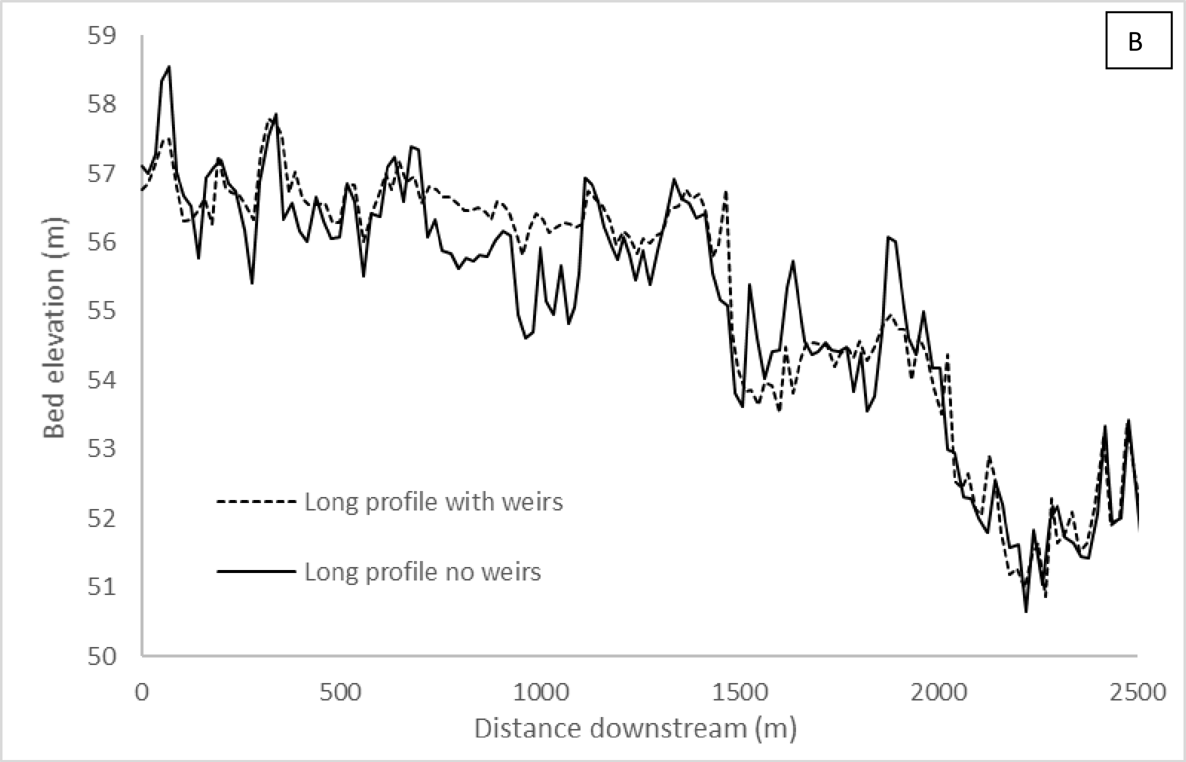

Fig. 10. (A) Patterns of erosion and deposition in the lower section with the weirs removed. (B) Chart of the channel long profile (as indicated by black line in A showing changes in incision (upstream) and aggradation (downstream) following weir removal.

Long profiles of the sections where weirs were removed are also plotted in Figs. 8-10. These are compared to the long profile of the mean erosion and deposition patterns from the 20 runs and generally show incision above the weirs and deposition below. The 'spikey' nature of the long profile reflects the sampling of the coarse DEM – picking up the odd cell where deposition has occurred in some simulations.

With increased erosion, a downstream increase in sediment deposition might be expected as the gradient of the riverbed rises to meet the decreasing upstream elevations. Certainly, cumulative sediment yields from the study area for the simulation with and without weirs demonstrate that, with the structures removed, there is a >100% increase in total sediment yield from the simulated reach (Fig. 11). We should note that simulated sediment yields of ca. 5100-11500 t y_{-1} are low compared to many UK basins (Foster and Leeds, 1999). We expected that differences in sediment yields would be greatest in the first 10 years of the simulations as under conditions of weir removal the channel bed adjusts to its newfound gradient. However, high rates of sediment removal are sustained long after weirs are removed, indicating that the reach is continuing to adjust to weir removal beyond the simulated 30-year periods. Given that the floodplain alluvium of the Derwent has elevated levels of metal contaminants (Kossoff et al., 2016), such a scenario of continued readjustment of the channel gradient over a prolonged timescale could have detrimental long-term health and environmental implications for the river system.

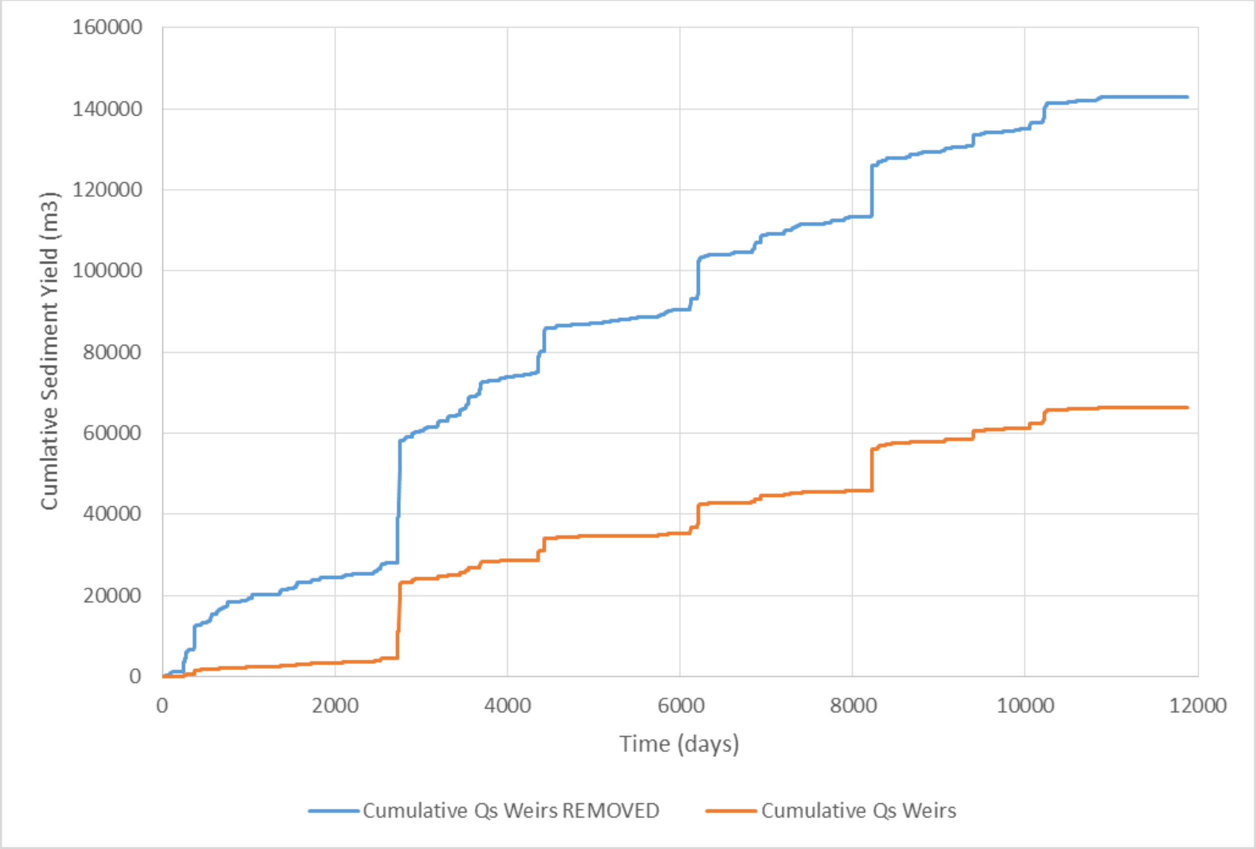

Fig. 11. Cumulative sediment yields from the simulated reach with and without weirs.

5. Discussion and conclusions

Weirs are responsible for reducing channel gradients upstream of individual features and creating zones of sediment storage within the floodplain; therefore, removal can have profound impacts on river behaviour: promoting erosion and deposition and leading to increases in channel instability (Downward and Skinner, 2005). This modelling study has demonstrated that the construction of weirs along the Derwent has moderated channel dynamics since at least A.D. 1880 - and well before the construction of major dams in the headwaters of the catchment during the early to mid-twentieth century.

The model results suggest that the removal of historic weirs from the World Heritage Site would lead to considerable but not catastrophic changes in the riverine and valley floor environments, creating hotspots of erosion immediately upstream of the structures, as the river adjusts to its newfound gradient. Whilst this erosion and channel adjustment might not be considered by engineers and hydrologists to cross significant geomorphological and environmental thresholds (e.g., Schumm, 1979), many catchments in northern and western Britain have multiple weir complexes that were constructed as part of an industrial history, which introduced a range of pollutants and contaminated sediments that now form elevated levels within these valley floors. In the case of the Derwent, these industrial contaminants are largely associated with historic metal mining and ore processing, much of this relating to industrial activity upstream of the World Heritage Site. At present, the contaminants are introduced primarily through sediment erosion at individual mining and ore processing sites (point sources of pollution). A limited contribution might also be made by the erosion of blanket peats in catchment headwaters enriched by heavy metals deposited by atmospheric fallout from the surrounding conurbations (Kossoff et al., 2016). However, these latter pollutants are upstream of the major dam complex of the upper Derwent, and it seems likely that the majority of eroded sediments remain stored within the reservoirs themselves or in other local sediment traps (Hutchinson, 1995): a hypothesis supported by the empirical analysis of analogous upland sites (Labadz et al., 1997; Yeloff et al., 2005). The simulations described in this paper have shown that removing weirs would focus erosion on contaminated alluvial sediments and result in their remobilisation within the fluvial system, with potentially significant environmental effects (Foulds et al., 2014).

This modelling has also demonstrated that the dispersal of eroded sediments during channel readjustment to local base levels is not straightforward. We expected that eroded particulate sediment would be deposited a short distance downchannel as hydraulic conditions changed, but the sediment appeared to be evacuated a considerable distance, beyond the downstream limits of the World Heritage Site as evidenced by the elevated post-removal catchment sediment yields (Fig. 11). Such enhanced sedimentation, particularly if contaminated, might therefore result in further management issues downstream.

Whilst this particular study has focused on fluvial change along a 24-km stretch of the River Derwent, it highlights issues regarding river structures that have generic resonance. As mentioned previously, many of the world's great civilisations have developed around major river systems (Vianello, 2015), and engineering solutions have commonly been implemented to manage hydrological regimes, particularly to exploit the potential for agriculture and trade (Csekö and Hayde, 2004; Fahlbusch et al., 2004). Therefore, any modification to weirs or other in-channel structures has the potential to raise similar issues and concerns. In areas where frameworks for heritage protection are not well developed, the consequences could be particularly damaging, especially if there is a pollution legacy.

The issues raised by this research demonstrate the need for engineers, hydrologists, and heritage professionals to work together to consider weirs as a group of assets within wider catchment frameworks, rather than considering modification or removal on a case-by-case basis. Some researchers might be argued that this study represents an extreme scenario, as it assumes removal of all weirs from a river reach; and we accept that fluvial dynamics might have produced different results if only individual structures had been removed or modified, as might be the case of a single larger dam structure. This would be a valid criticism, but we emphasise that the empirical evidence base is simply not available at present to assess either the initial impacts of change or the longer-term adjustments that might occur with fluvial systems. In the USA, we note that there is growing discussion of the impact of the construction and demise of milldams of the colonial age on sediment supply and fluvial dynamics, but the evidence is also far from clearcut (see Walter and Merritts, 2008; Pizzuto and O'Neal, 2009; Donovan et al., 2016). Also in the USA, a corpus of empirical data detailing the controls on and impact of large dam removal across a variety of watersheds is beginning to emerge (Sawaske and Freyberg, 2012; East et al., 2015; Gartner et al., 2015; Warrick et al., 2015); and whilst the scale of change is undeniably different, we suggest that there are common hydrological variables and hence methodological approaches that could be adopted in the consideration of weirs.

Furthermore, the project highlights that consideration of the historical importance of weirs must move beyond consideration of their construction and architectural importance, which are the key attributes often highlighted by heritage professionals who provide specialist input to engineering projects. Geoarchaeological investigations have the ability to inform other professions about the palaeoenvironmental context of industrialisation and its wider implications, particularly if these shed light upon issues of pollution. This knowledge would be invaluable as part of the wider decision-making frameworks that need to be developed for weir modification or removal, mirroring those suggested for dam removal in the USA (Pejchar and Warner, 2001; Hoenke et al., 2014).

In the UK, the heritage value of weirs is high, and whilst this may lead to a level of frustration and tension with those wishing to modify the riparian corridor, such constraints may result ultimately in a more measured approach to catchment management that in the longer term may be beneficial for all. However, in many countries across the globe where the evidence of river engineering is preserved but the level of heritage protection is less well developed, structures may be removed with ease, without consideration of the potential environmental consequences.

At a continental scale, the ‘green agenda’ associated with the Water Framework Directive and hydropower is beginning to have a profound influence on the character of historic anthropogenic structures in river valleys, especially weirs. Whilst it is important that the physical consequences of modification and/or removal are considered, the wider post-industrial legacy of this resource (i.e. its heritage value) should also be central to these discussions

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