Assessing riverine threats to heritage assets posed by future climate change: a methodological approach based on understanding geomorphological inheritance and predictive modelling, tested within the Derwent Valley Mills WHS, UK

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Key Words: Climate Change; Heritage Management; Environmental Modelling; Derwent Valley Mills

ABSTRACT: Future climate change is likely to pose significant challenges for heritage management, especially in landscape settings such as river valleys as the magnitude, intensity and nature of geomorphological processes alter in response to changing threshold conditions. Industrial landscapes afford particular challenges for the heritage community, not only because the location of these historic remains is often intimately linked to the physical environment, but also because these landscapes can be heavily polluted by former (industrial) processes and, if released, the legacy of contaminants trapped in floodplain soils and sediments can exacerbate erosion and denudation. Responding to these challenges requires the development of methodologies that consider landscape change beyond individual sites and monuments and this paper reports the development of such an approach based on investigation of the Derwent Valley Mills World Heritage Site, Derbyshire, UK. Information on geomorphological evolution of the Derwent Valley over the last 1000 years, a time period encompassing the last two periods of major climatic deterioration, the Medieval Warm Period and Little Ice Age, has been dovetailed with archaeological and geochemical records to assess how the landscape has evolved to past landscape change. However, in addition to assessing past evolution, this methodology uses national climate change scenarios to predict future river change using the CAESAR-Lisflood model. Comparison of the results of this model to the spatial distribution of World Heritage Site assets highlights zones on the valley floor where pro-active mitigation might be required. The geomorphological and environmental science communities have long used predictive computer modelling to help understand and manage landscapes and this paper highlights an approach and area of research cross-over that would be beneficial for future heritage management.

1. Introduction

It is now widely acknowledged by the global scientific community that greenhouse gas emissions are causing irrevocable changes to our climate system. Whilst the precise impact of these emissions upon climate remains uncertain, it seems likely that both the frequency and intensity of severe weather events will increase, with extremes of both temperature and rainfall commonplace. These predictions of the nature of change, based upon a combination of empirical data analysis and computer simulation, appear to be confirmed by major news reports from around the globe.

In the UK, the focus of this paper, climate change scenarios [1] provide an insightful backdrop to the major river flood events recorded at Boscastle (Devon) in summer 2004 [2], nationwide in summer 2007 [3], at Cockermouth (Cumbria) in autumn of 2009 [4] and nationwide in the autumn and winter of 2013-2014 [5-8]. Of course, weather conditions alone cannot be held responsible for the severity of these events, with physiography, antecedent conditions, landscape and current flood mitigation measures, all affecting response to individual storms. These exacerbating factors have been termed 'risk multipliers' [9].

Economically, the cost of floods in the UK is substantial; for example, the summer floods of 2007 resulted in a bill of around £3 billion (http://www.floodfreehomes.org.uk). However, the social, environmental and political impact of flooding is equally as significant [10]. Within our communities, the Historic Environment plays a unique role in economic generation (e.g. sustainable tourism), social/cultural cohesion and well-being, and over the last decade there has been a growing awareness of the potential impact of climate change upon these assets, both in the UK [11-17] and globally [18-23].

Within the Northern and Western parts of the UK, some of the landscapes and heritage assets most vulnerable to climate change are those associated with the 'Industrial Revolution' (considered for the purposes of this paper, the 18th and 19th centuries). During this period of rapid industrial and economic growth, industry exploited natural resources, including coal, limestone and metal ores and used water for power; however, paradoxically, many of these advantageous physiographic and geological characteristics essential to industrial development are also environments where geomorphological processes are most sensitive to climatic change. Furthermore, many of these regions, particularly those specifically associated with historic metal mining, have a legacy of pollution now trapped in floodplain soils and sediments [24-27]. Empirical evidence has shown that the release of large volumes of fine-grained sediment and toxic contaminants during periods of increased flood frequency and magnitude caused a significant number of rivers in the Northern Pennines (North Yorkshire, County Durham and Northumberland) to transform from single to multi-channelled braided systems during the Little Ice Age [28], the last period of major climatic deterioration.

Given the scenario developed above, there is clearly a need to mitigate against the impacts of future climate change over large areas of industrialized historic landscape, but a major challenge is the development of strategies and methodological approaches that look beyond (single) heritage sites and provide an integrated approach to land management.

This paper focuses on the development of such a methodology evaluated within the Derwent Valley Mills World Heritage Site (hereafter, DVMWHS), situated along a 24km stretch of the River Derwent, Derbyshire, UK. This novel, interdisciplinary approach utilises information on past landscape history reconstructed using a variety of archaeological, geochemical and geomorphological records, coupled with computer modelling of future river development. These results are compared against the spatial distribution of assets of the World Heritage Site and used to flag key factors of concern for heritage and environmental managers.

2. The Character of the Derwent Valley Mills World Heritage Site

The River Derwent has a catchment area of around 1200km^2. It originates some 9km east of Glossop at an elevation of 590m OD on the high moorland of the Peak District National Park and flows south, encountering the northern boundary of the DVMHWS at the downstream limit of the dramatic incised gorge at Matlock Bath (Fig. 1). The DVMWHS was inscribed in 2001 and encompasses a series of 18th and 19th century cotton mills recording the birth of the modern factory system, together with its associated infrastructure including workers housing, schools, churches and model farms [29].

For most of the length of the World Heritage Site, the River Derwent cuts through complexly folded and faulted mudstones, shales, siltstones and sandstones of Carboniferous age, although at its southern end, it cuts through mudstones, siltstones and sandstones of Permo-Triassic age. Despite being a sizeable river, it is constrained within a relatively narrow valley floor (maximum width of 500m), which has prevented the preservation of laterally extensive river terraces along its valley sides; instead, fragmentary remnants have been preserved.

The mills themselves required water for power and are therefore situated on the contemporary floodplain, immediately adjacent to the channel and associated with elaborate systems of weirs and sluices, which maintained a head of water (Fig. 2). In contrast, the infrastructure associated with milling (e.g. housing, schools) were situated on the higher terrace fragments, enlarging hamlets and villages to create small towns such as Belper. As well as activity directly associated with milling, much of the surrounding landscape was owned by the industrialists and became the focus of agricultural innovation, particularly through the development of ‘Model Farms’ [30-31], creating an even richer supplementary legacy of post-medieval archaeological remains.

Whilst the World Heritage Site designation is associated with the textile industry, the limestone bedrock that crops out in the far north of the study area is host to a rich base-metal mining industry, principally lead and zinc in the Derwent catchment, with peak production in the 18th and early 19th centuries. An indirect consequence of mining has been the release of metal-contaminated sediments into the environment, which have been deposited across the valley floor and is stored within the alluvium [32]. The release of contaminants initially commenced during mining, but importantly, is on-going through the erosion of spoil heaps and former processing areas; these deposits are akin to the agro-industrial alluvium reported in the northern Pennines [33].

3. Methodology

To provide a tight research focus, the project area was restricted to the established boundaries of the DVMWHS core zone (1,229 hectares) and buffer zone (4363 hectares), as defined in the site designation and inscription (http://whc.unesco.org/en/list/1030) (see Fig. 1). Inclusion of the buffer zone was deemed crucial to methodological development since much of this area includes abandoned mine workings and areas of slope instability, which may be influential in supplying contaminated sediments to the valley floor.

Geoarchaeological evolution of the valley floor over the last 1000 years was selected as the timescale of study, since this period includes the major climatic anomalies of the Medieval Warm Period and Little Ice Age. To elucidate geomorphological development of the valley floor, landform assemblages (river terraces, palaeochannels, ridge and swale topography) were identified and mapped from aerial photographs and lidar with additional information provided by historic maps and published literature. Information on the geochemical and contamination history of the region was collated from mine records, published literature, unpublished doctoral theses and the holdings of the British Geological Survey. Historic Environment Records (HER) for the medieval, post-medieval and modern periods provided information on the location and interpretation of heritage assets, although the analysis of lidar mapping identified a number of additional archaeological features unrecorded by the HER. Further information on each data source is provided in Table 1 as well as in the full project report [34]. The capture of all of these data within the project GIS (QGIS version 2.6 Brighton) allowed landscape evolution to be compared with the location of heritage assets to assess the hazards posed to these remains based on historic natural processes.

However, as well as understanding the past and contemporary landscape, a key aim of the methodological approach was to assess how the River Derwent might respond to future climate change and how these changes might impact on historic assets of the World Heritage Site. In geomorphology, the application of computer modelling to elucidate landscape evolution and system response has a long history of development [35-37], but this approach has rarely been used for heritage management; Clevis *et al.* (2006) provide one of the few examples, although it is tangential, providing a hypothetical simulation of deposition within a meandering river to consider issues of archaeological preservation [38]. This project aimed to simulate river erosion and deposition within the World Heritage Site using CAESAR-Lisflood [39], a model that divides the landscape into a series of cells representing the landscape over which the flow of water and the subsequent erosion and deposition of sediment is simulated. This allows the evolving morphology of river catchments and reaches to be simulated over time periods from events to hundreds of years. It is beyond the scope of this paper or the nature of this journal audience to describe this model in detail, or to justify its choice; suffice to say that it has been developed and evaluated over a 17 year period and been used to simulate morphological changes in variably sized river systems in many parts of the world [40-44].

4. Results

4.1. Landscape evolution during the last millennium and the archaeological record

Table 2 provides a summary of the geological characteristics of the DVMWHS and an assessment, based on empirical evidence, of how the landscape has evolved over the last millennium and the potential implications for its heritage assets. It is clear that upstream of Milford, channel mobility has been limited, but downstream of this point, palaeochannels with dimensions akin to the contemporary channel indicate that the river has moved across its floodplain, though Ordnance Survey historic mapping suggests that this was before AD 1820-1830. Ridge and Swale topography suggests that at least some of this movement was through lateral migration. Whilst flooding has been historically important, particularly during the climatic deterioration of the Little Ice Age, the regulation of the Derwent, which was completed by 1943, has lessened the impact of such high magnitude events on the contemporary catchment. Notably, there are a series of reservoirs constructed in the main headwater tributaries for water supply that also reduce peak flows. However, the increasing intensity of storms under scenarios of climate change may require the controlled release of more water from reservoirs during such events, while not resulting in catastrophic floods, may well lead to some erosion of the floodplain. A review of the geochemical data has demonstrated that the floodplain alluvium is heavily contaminated with metals reworked from mine sites and any disturbance of these sediments may result in complex change of the floodplain, depending on the character of contaminant redistribution [45] as well as mobilising material which may impact on the fabric of built assets [46]. Furthermore, the blanket peats in the upland headwaters of the catchment contain a significant legacy of metal pollutants deposited historically through atmospheric fallout from industrial sources in the surrounding conurbations [47]; again, these have the potential to be remobilised through the riparian system, augmenting the supply of contaminants already in the fluvial system.

An indication of how the lower reaches of the DVMWHS below Milford have responded to past climatic deterioration is provided by a number of areas of ridge and furrow of varying dimensions and morphology identified from lidar (Fig. 3). An unknown proportion of these earthwork remains might be a product of the steam ploughing that accompanied the industrialisation of agriculture in the wake of the Industrial Revolution, but many of the ridges compare in terms of their profile, dimensions and plan-form with the wide, reversed-S shape ridges that are diagnostic of the strip fields associated with the medieval Open Field System. The origins of this system may be traced in the Midlands to the period before the Norman Conquest, while it persisted in some parts of that region well beyond the medieval period [48], but with this proviso it seems likely that much of the extant ridge and furrow in the Derwent Valley relates to medieval arable farming. A significant number of sites have been identified where river channels truncate these features that in terms of their morphology and layout most probably date from the High Medieval period. This may signify a phase of medieval agricultural expansion across the floodplain, followed by abandonment and subsequent fluvial erosion. Changing floodplain hydrological conditions are ultimately driven by climate, although land-use is important for priming landscapes for change, and it is tempting, therefore, to suggest that the expansion of arable farming to the floodplain might be associated with the ameliorating climate of the Medieval Warm Period, but to interpret the climatic downturn of the Little Ice Age as a driver for enhanced fluvial activity and the truncation of blocks of floodplain ridge and furrow.

4.2. Modelling future landscape change and its impact on historic assets

Evidence from landform assemblages demonstrates that the River Derwent has been mobile within the valley floor during the last millennium, though this mobility precedes the earliest Ordnance Survey maps of 1820-1830, which demonstrate that the channel has been stable for around 180 years. Furthermore, computer simulations of contemporary hydrological conditions suggest that the flow regime poses little threat to the historic remains of the DVMWHS, and it seems likely that surface water flooding poses a more immediate risk.

However, a key part of the developed methodology was to use the CAESAR-Lisflood model to predict future channel change and flood events under predicted rainfall patterns under climate change scenarios. Future rainfall was simulated using the UKCP09 Weather Generator, with 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 DVMWHSB reach. From these 100 simulations, 20 were randomly selected and used to generate 30-year periods of flows to drive future erosion and deposition patterns within the DVMWHS reach itself. The results of this modelling suggest that there should be minimal problems with sedimentation or erosion in response to changing flood patterns up to 2050, assuming that current valley floor and channel characteristics are not altered significantly, for example, by the implementation of new flood protection measures and associated engineering. In general, the results of the future climate change scenarios suggest that the present channel pattern will remain relatively stable, with generally low levels of lateral erosion, and that metal contaminants bound within the alluvium of the wider floodplain will not be remobilised significantly. Given that there is little likelihood of significant changes in the overall channel shape of the channel or shifts in its position, there will be little change in the areas affected by flood events of the same size as are recorded today, but the larger flood events that may be suggested on the basis of current climate change models may well inundate areas that are at present rarely if at all flooded.

However, localised stretches of the river may be subject to intensified erosion and deposition, but comparing the location of these processes alongside the spatial distribution of World Heritage Site assets can help manage and mitigate the impacts of any change. For example, some of the mill complexes, such as those at Masson (Fig 4A) and Milford (Fig. 4b), appear little affected by increased erosion, but others, particularly at Belper (Fig. 4b) and Darley Abbey (Fig. 4C), are more vulnerable to intensified erosion and hence will require tighter monitoring and management. Beyond the mill complexes, Figures 4a-c provide valuable tools for assessing the vulnerability to climate change of other archaeological or built environment assets, and can make a significant contribution to management of the entire historic environment resource: for example in the vicinity of Whatstandwell, where modelling predicts intense fluvial erosion (Fig. 4A), or immediately downstream of Milford, where assessment of changes in the levels of erosion and deposition can assist management of the agricultural landscape and built heritage assets associated with Strutt's Moscow Farm of 1812-15 (Fig. 4B, Fig. 5). These examples indicate how such predictive modelling can be used to inform future management practices with the DWHWHS or in other areas where applied.

5. Conclusions

Recent papers have highlighted the challenges faced by heritage assets in the light of future climate change and the need for site managers and historic environment custodians to have access to robust datasets and specialist information to guide decision making and the implementation of adaptation strategies [49-50]. Within the discreet context of World Heritage Sites, UNESCO now requires all individual designations to prepare and implement assessment plans for climate change. However, preparation of such strategies and informed decision making requires a baseline assessment and understanding of the threats to the resource, and one which looks beyond the immediate historic asset and considers it within a wider landscape context. This paper provides a methodological template for investigating past natural landscape development using a variety of geomorphological, palaeoenvironmental, geochemical and cultural archaeological datasets in order to provide a contextual framework for mitigating the impacts of future climate change. However, the methodology goes further by exploring future landscape development, in this example within a river valley floor, by using computer modelling to simulate channel change and demonstrates the application of an approach, yet to be used widely within the field of heritage management, despite being regularly used by fluvial geomorphologists and river engineers for over two decade.

It is envisaged that the approach outlined in this paper, dovetailing empirical and modelled data, could be applied to other river valleys in a variety of climatic settings beyond the temperate zone, providing that proxy environmental records and landform assemblages are preserved, which will allow reconstruction and assessment of landscape evolution. Furthermore, if past geomorphological processes can be identified, information gleaned from these sources allows for the modelling of future conditions and calibration of results. Whilst this example has been focused on historic assets assigned World Heritage status, the approach could be applied across the stratum of heritage remains.

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List Figures

Fig 1. The Derwent Valley Mills World Heritage Site. The core site is shown in red, whilst the extent of the buffer zone is denoted by the brown line

Fig 2. East Mill, Belper and its associated horse shaped weir. An example of the historic assets of the World Heritage Site.

Fig. 3. Lidar derived image showing part of the Derwent valley floor below Milford illustrating the dynamic nature of past river activity and its impact on earthwork remains (ridge and furrow). Source data © Environment Agency.

Fig 4A. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the upper part of the study area (source data © Environment Agency).

Fig 4B. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the middle part of the study area (source data © Environment Agency)

Fig 4C. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the lower part of the study area (source data © Environment Agency).

Fig. 5. Processed lidar image showing palaeochannels, ridge and furrow and other earthworks on the valley floor where it widens immediately downstream of Milford. The historic assets of the Milford mill complex are shaded blue, palaeochannels are outlined in yellow and HER polygons are outlined in green. Source data © Environment Agency.

Table 1. Data collected by the project

Data Type	**Source**	**Use**	**Destination**
2m lidar	Environment Agency	Construction of natural landscape DSM and mapping of landforms	Within project GIS
Geological mapping of superficial deposits	British Geological Survey	Construction of geological context	Within project GIS
Geological mapping of selected hazards (landslips)	British Geological Survey	Construction of geological context	Within project GIS
Topographic mapping	Ordnance Survey	Construction of topographic landscape	Within project GIS
Vertical Aerial Photographs	Derbyshire County Council	Identification and mapping of landforms and archaeological features	Within project GIS
Historic mapping	Derbyshire County Council	Reconstruction of historic landscapes	Within project GIS
Historic flood data	Published/grey literature	Reconstruction of discrete flood events	Within this report
Geochemical data	Published/grey literature	Assessment of valley floor contamination associated with metal mining	Within this report
Flow data 1971-2004 (Derwent, Amber and Ecclesbourne rivers)	National Rivers Archive	Used in the construction of CAESAR-Lisflood Model	Within this report
Location of fixed obstacles within the Derwent	Field survey, published Environment Agency literature and Google earth images	Used in the construction of CAESAR-Lisflood Model	Within this report
HER	Derbyshire County Council	Reconstruction of the known archaeological and built environment record	Within project GIS

Table 2. Natural landscape characteristics of the DVMWHS and implications for heritage assets

Empirical Evidence	**Summary of Evidence in WHS**	**Implications for WHS Heritage Assets**
Bedrock geology mapping.	Carboniferous mudstones, siltstones and sandstones that crop out over the majority of the area are complexly folded and faulted and form alternating beds that are prone to slope failure. Carboniferous limestones that crop out in the north of the area are host rock metalliferous ores that have been extensively mined. Permo-Triassic mudstones and siltstones crop out in the southern part of the study area.	Slope failure of Carboniferous mudstones, siltstones and sandstones may introduce significant quantities of superficial sediments into the valley floor, some of which may be contaminated by heavy metals if close to mine sites. Subsidence associated with mass movement may impact on the stability of buildings. Mines shafts, adits and spoil heaps within the limestone area may include unconsolidated ore remnants and polluted waste materials capable of remobilisation
Quaternary geology mapping and landform assemblages	Narrow valley floor has prevented extensive river terrace development and where preserved, terraces are fragmentary. Periglacial slope deposits forms apron of sediment along the valley sides and are often closely associated with river terrace remnants. Some of the periglacial material may reflect post-glacial colluvial processes. Alluvium covers the contemporary floodplain. Upstream of Milford, palaeochannels are poorly developed in valley floor (<100m wide) and where preserved, they form simple, linear features close to the modern channel. South of Milford, the valley floor is wider (around 500m) and palaeochannels are well developed and divisible into two types: (1) major sinuous channels with wavelength amplitudes and dimensions similar to the modern channel; (2) minor distributaries irregularly scattered across the floodplain surface. Minor, curved features in parallel groups are indicative of ridge and swale topography.	Wider infrastructure associated with the mills concentrated on terrace features. Colluvium may have reworked archaeological material from the surrounding valley slopes and redeposited material on the floodplain or mask remains at the floodplain edge. Alluviation may burial archaeological remains on the floodplain. Palaeochannels upstream of Milford suggest limited past mobility of the river within the valley floor and where change has occurred it has been close to the contemporary channel. Downstream of Milford, the floodplain is wider and has allowed greater channel mobility demonstrating the ability of the river to migrate in this region. Ridge and furrow downstream of Milford demonstrate the potential of the river for lateral migration.

Historic mapping.	Early Ordnance Survey mapping (c. AD 1850) mapping suggests little variation in river pattern or channel position over the last *c*.150 years.	Mapping suggests the limited river movement during the last c. 150 years. This suggests that palaeochannels observed south of Milford predate *c*. AD 1850.
Documented floods.	AD 1066-1539 - 10 major floods recorded AD 1540-1900 – 31 major floods recorded AD 1901-1940 – 5 major floods recorded* * This final period is problematic since reservoirs were constructed and completed in the upper Derwent Valley in 1912 (Howden) and 1914 (Derwent), although it was not until the completion of Lady Bower Reservoir in 1943 that total flood regulation of the catchment was achieved	Documentary evidence suggests that severe floods have affected the Derwent valley during the last millennium, a finding that agrees with other national records (Macklin *et al*., 2005; 2010; 2012), but that regulation of the river through reservoir construction in the past century has reduced their severity. However, changing weather patterns may impact on regulation practices (e.g. more release of water from the reservoirs), which may not result in high magnitude flood events but may change the hydrological response through time.
Geochemical history.	Floodplain alluvium and soils are heavily contaminated by metal-pollutants reworked directly from mine tailings and processing areas on the valley sides and contain levels well above national guideline for contaminated land (Table 3). Contaminants may be particularly concentrated where sediment thicknesses are enhanced within the system, for example, immediately upstream of weir systems. Upland areas of blanket peat moorland contain high levels of metal pollutants deposited through (historic) atmospheric fallout from (historic) industrial sources.	Potential for remobilisation of contaminants within the valley floor resulting in degradation of the riparian environment (e.g. devegetation and increased channel bank erosion) and increased human exposure both directly and via the food chain. Potential for remobilisation of contaminants from areas of blanket peat, though under present management practices, any remobilised sediment is retained within the reservoir complex.

Figure 1

Fig 1. The Derwent Valley Mills World Heritage Site. The core site is shown in red, whilst the extent of the buffer zone is denoted by the brown line.

Figure 2

Fig. 2. East Mill, Belper and its associated horse shaped weir. An example of the historic assets of the WHS.

Figure 3

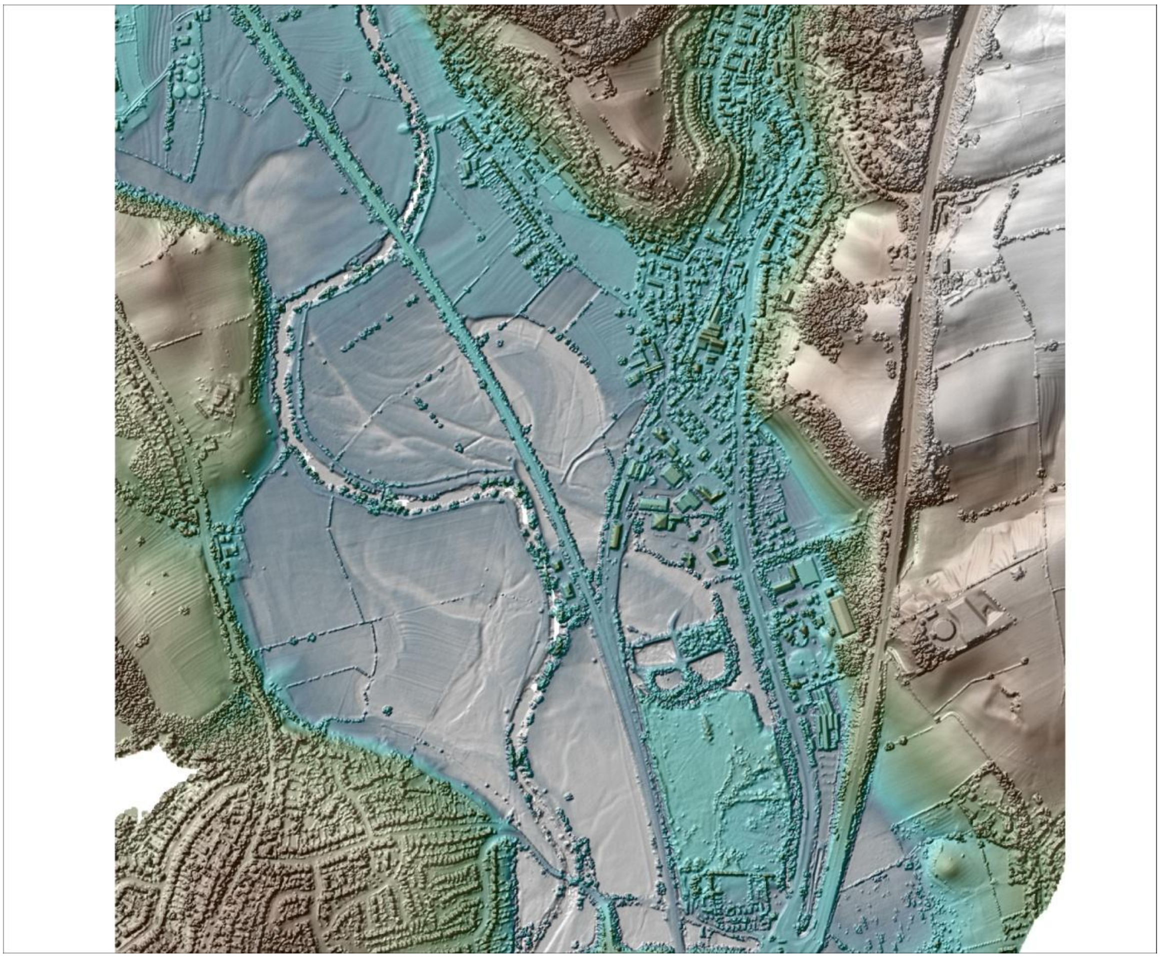

Fig. 3. Lidar derived image showing part of the Derwent valley floor below Milford illustrating the dynamic nature of past river activity and its impact on earthwork remains (ridge and furrow). Source data © Environment Agency.

Figure 4A

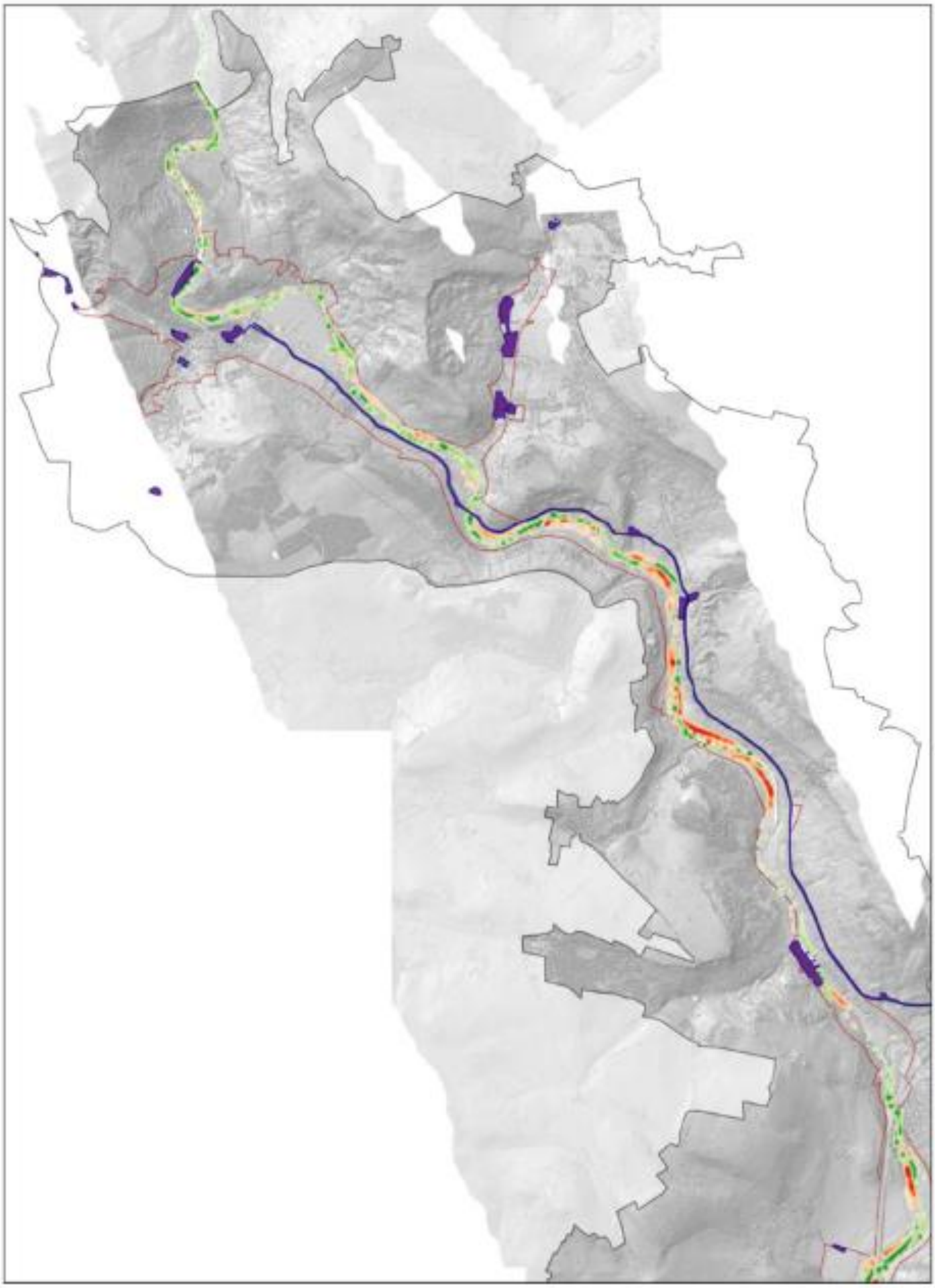

Fig 4A. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the upper part of the study area (source data © Environment Agency)

Figure 4B

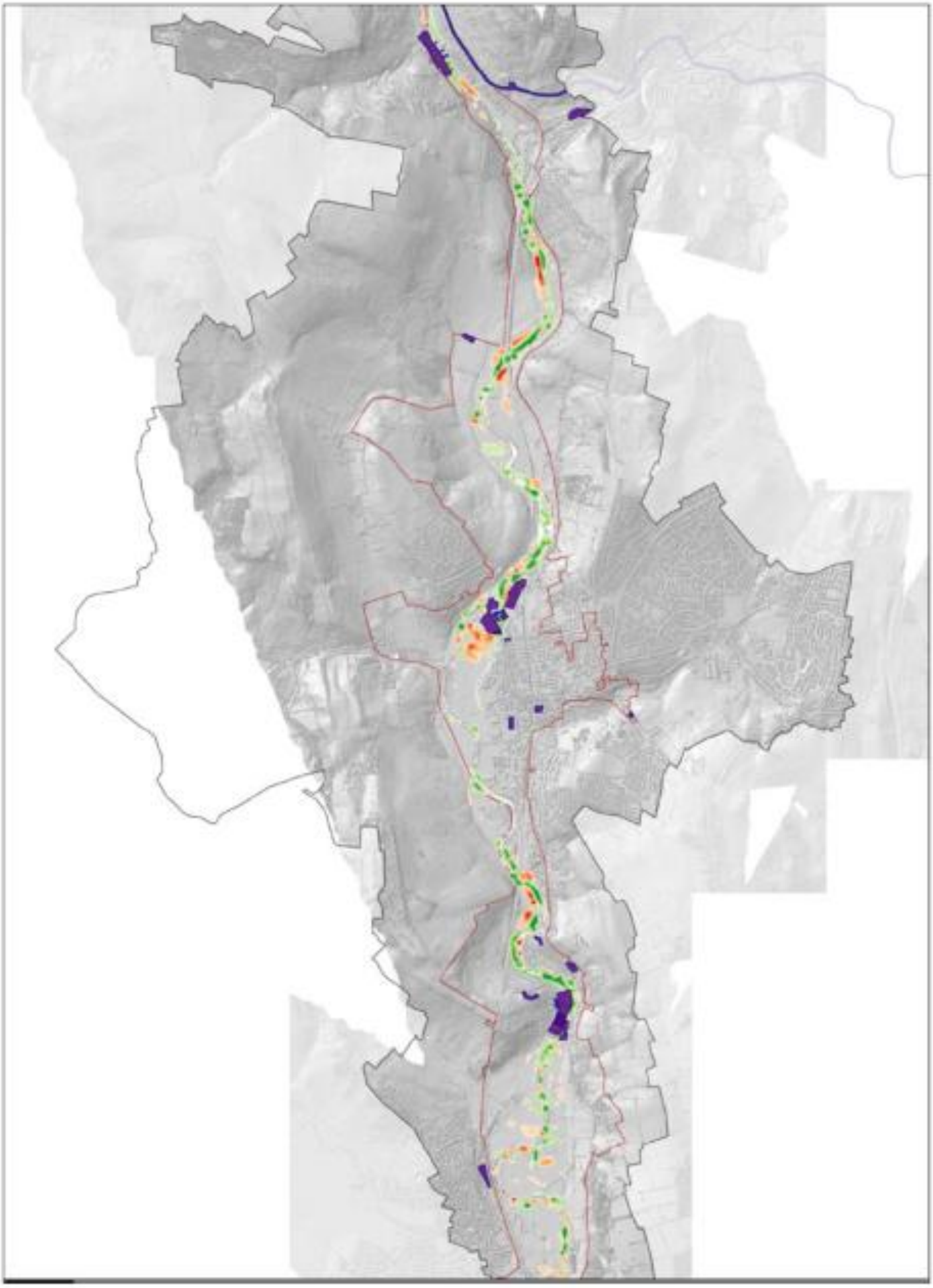

Fig 4b. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the middle part of the study area (source data © Environment Agency)

Figure 4C

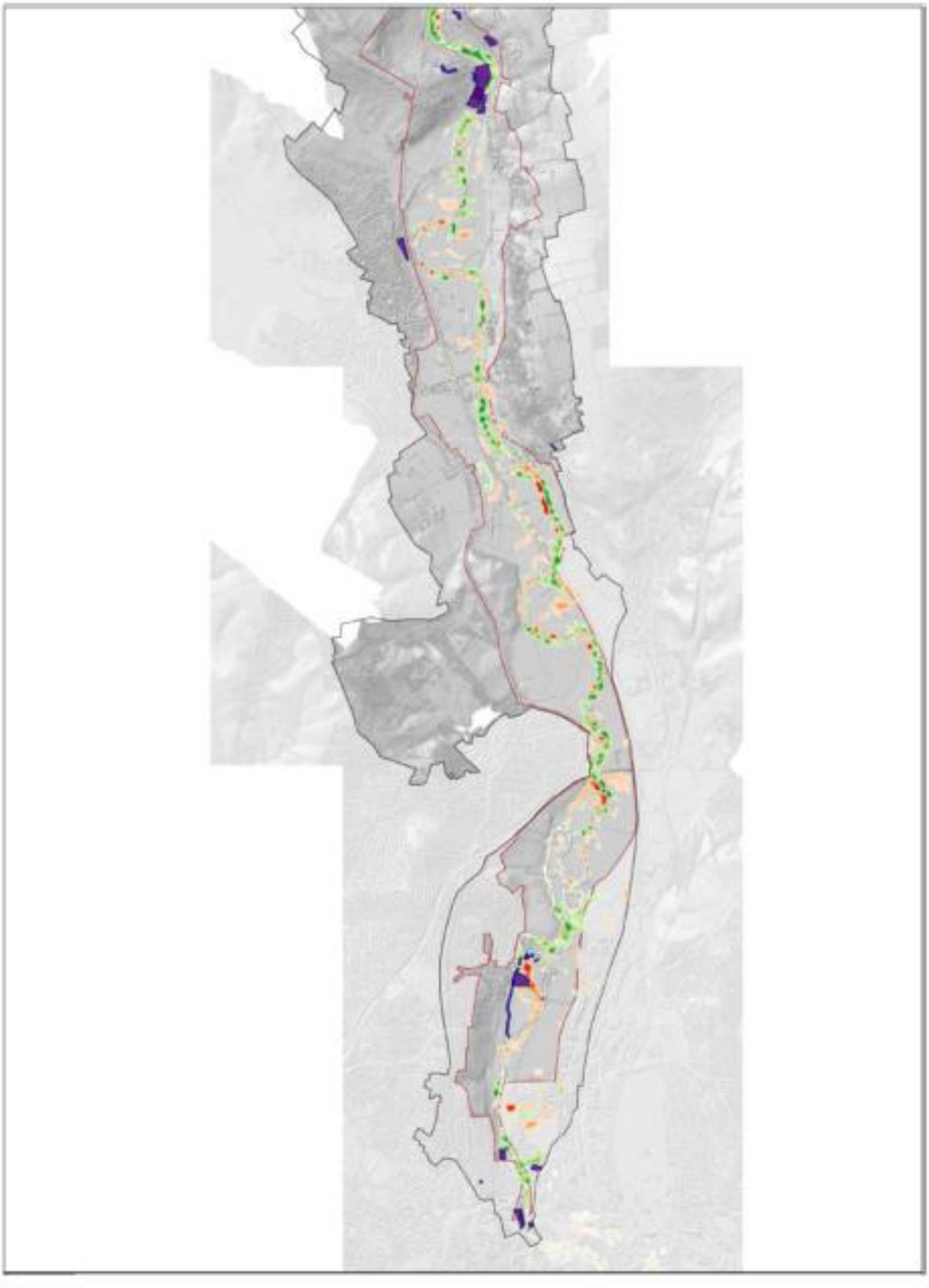

Fig 4c. Modelling of sediment erosion (red) and deposition (green) in relation to HER assets (blue) in the lower part of the study area (source data © Environment Agency)

Figure 5

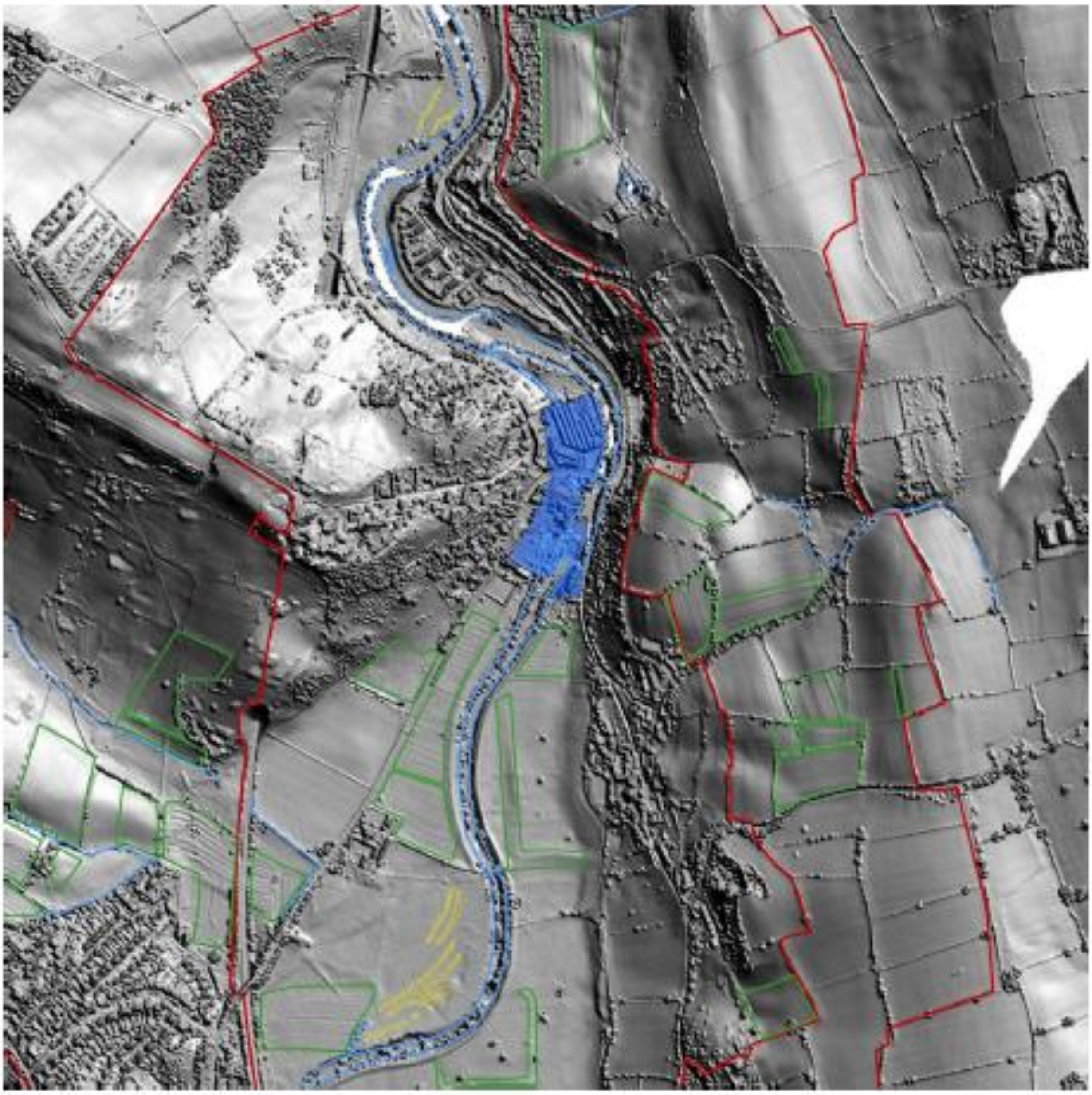

Fig. 5. Processed lidar image showing palaeochannels, ridge and furrow and other earthworks on the valley floor where it widens immediately downstream of Milford. The historic assets of the Milford mill complex are shaded blue, palaeochannels are outlined in yellow and HER polygons are outlined in green. Source data © Environment Agency.