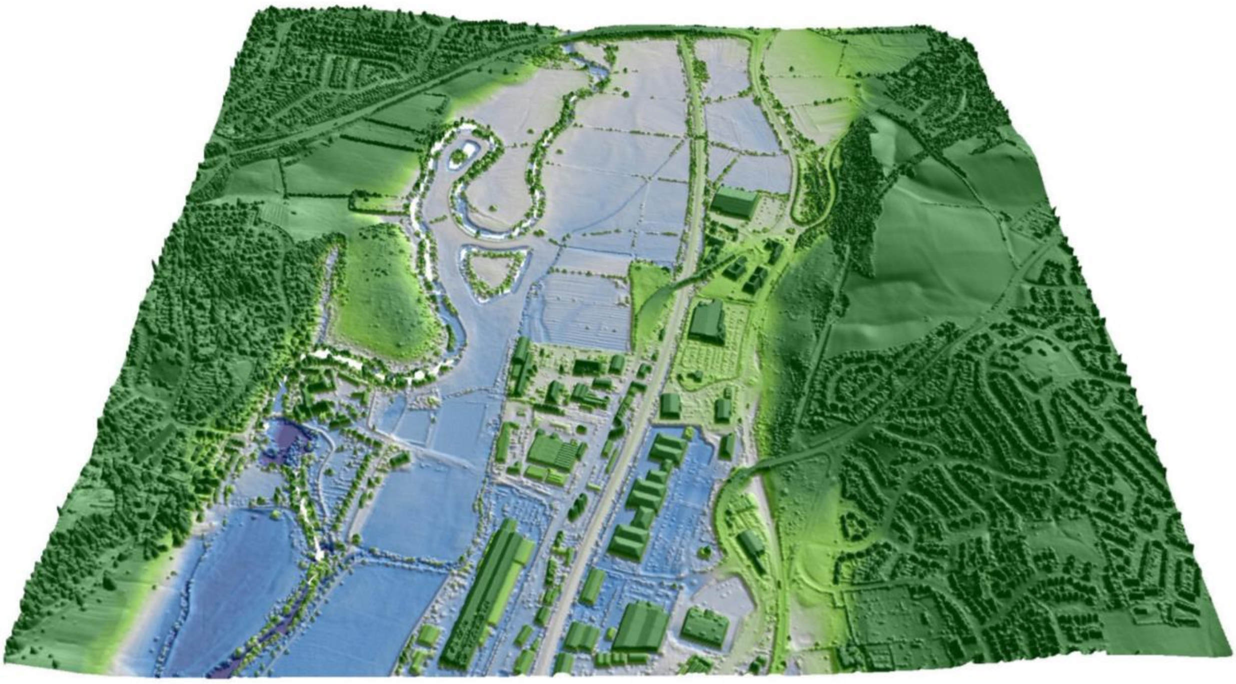
FUTURE CLIMATE AND ENVIRONMENTAL CHANGE WITHIN THE DERWENT VALLEY MILLS WORLD HERITAGE SITE

Report for English Heritage

Andy J. Howard (Landscape Research & Management) and
David Knight (Trent & Peak Archaeology, York Archaeological Trust)

With contributions by Steve Malone, Samantha Stein and Tiago Queiroz (Trent & Peak Archaeology), Tom Coulthard (University of Hull), Karen Hudson-Edwards and David Kossoff (Birkbeck, University of London)



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LIST OF CONTRIBUTORS

Project Executive: Dr David Knight, Trent & Peak Archaeology

Project Manager: Dr Andy J. Howard, Landscape Research & Management

GIS Manager: Dr Steve Malone, Trent & Peak Archaeology

GIS Research Assistants: Tiago Queiroz and Dr Samantha Stein, Trent & Peak Archaeology

External Specialist, CAESAR modelling: Professor Tom Coulthard, Department of Geography, Environment & Earth Sciences, University of Hull

External Specialists, geochemical analysis: Dr David Kossoff and Professor Karen Hudson-Edwards, Department of Earth & Planetary Sciences, Birkbeck, University of London

Core Management Team: Tim Allen, Dr David Barrett, Dr Andy J. Howard, Dr David Knight and Mark Suggitt

EXECUTIVE SUMMARY

Current news reports are demonstrating the severe impact that extreme climatic events are beginning to have on infrastructure, communities and the wider environment, including historic assets. Both empirical evidence and computer simulation modelling suggest that these problems will be exacerbated under future UK climate scenarios. In addition to the direct impacts of climate change, empirical evidence, particularly from elsewhere in the upland and piedmont regions of the UK, suggests that the legacy of environmental pollution associated with past base-metal mining, which is itself an historic artefact, may well exacerbate the impacts.

In the light of potential future climatic change, exacerbated by the environmental impacts of industrial activities, this project has sought to examine the nature of possible environmental and geomorphological landscape transformations along an approximately 24km stretch of the River Derwent, Derbyshire and the potential impact on the globally important historic assets of the Derwent Valley Mills World Heritage Site (DVMWHS) and its designated Buffer Zone (Derwent Valley Mills Partnership 2011, 4).

The project has drawn together a range of historical, geomorphological and environmental datasets to assess past landscape change within the valley floor during the last millennium: a timescale encompassing the last two episodes of well-documented major climatic instability (namely the Medieval Warm Period [MWP; *c*.900-1300] and the Little Ice Age [LIA]; *c*.1450-1850).

This empirical data has been supplemented by numerical modelling of valley floor evolution to identify areas potentially vulnerable to future climate change, with results from both empirical and modelling studies being compared to existing knowledge of historic environment assets amassed in the Derbyshire Historic Environment Record (HER).

The outputs of the project have directly informed the developing Research Framework for the Derwent Valley Mills World Heritage Site[1] and in particular Theme 10 (Landscape and Environment). It has also built upon points raised in Section 13 (*Environmental and Climate Change Issues*) of the recently developed Management Plan for the DVMWHS (Derbyshire County Council, 2013).

The research outputs of this project provide wider generic lessons for the management of historic assets in the light of future climate change, not only associated with World Heritage Sites but also the historic environment more widely.

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[1] www.derwentvalleymills.org

1. INTRODUCTION

1.1. Background

This project design was developed in response to a call by English Heritage for proposals focused upon '*better disaster planning and building in resilience for heritage*' (National Heritage Protection Plan Activity 2C1: Major Environmental Threats) in the light of future climate change (IPCC, 2007, 2013).

As well as addressing the key theme of inland water inundation that was identified in the Atkins Assessment of Heritage at Risk from Environmental Threats Key Messages Report (Croft, 2013) and considered under NHPP 2C1.3, this study also builds upon a much wider body of literature and pure and applied policy research recognising the threats of climate change to the historic environment. This work not only focuses upon studies of World Heritage Sites by UNESCO (2008) and others (Colette 2007; Perry, 2011; Howard, 2013), but also includes a broader consideration of the wider heritage record (English Heritage, 2003; Cassar, 2005; English Heritage, 2006a; Howard *et al*., 2008; Kincey *et al*., 2008; Murphy *et al*., 2009; English Heritage, 2010).

The research also addresses directly the UNESCO strategy requesting that World Heritage Sites integrate climate change issues in updates of their Management Plans (UNESCO 2007, 2008; see Phillips 2014). English Heritage has begun to implement this policy with the consideration of climate change issues in the revised plan for Stonehenge and Avebury (English Heritage, in press). However, a recent paper by Phillips (2014), based on the results of a questionnaire survey of UK heritage professionals engaged in the management of World Heritage Sites, has suggested that site managers are facing a number of key challenges in their attempts to implement strategies focused around climate change adaptation; these concerns are focused around: (1) the integrity and reliability of data that informs decision-making; (2) resource constraints and; (3) the need for more specialist skills and guidance.

Furthermore, the implementation of the *Water Framework Directive* (WFD) by the Environment Agency, together with the changing responsibilities of local authorities under the *Climate Change Act 2008* and the *Flood and Water Management Act 2010* (such as the development of Surface Water Management Plans and Sustainable Urban Drainage approval provision), have the potential to impact significantly on the historic environment if consideration of these assets and the effects of climate change are not considered during the implementation of mitigation strategies.

Current news reports are demonstrating the severe impact that extreme storm events are beginning to have on infrastructure and the wider environment. Both empirical evidence and computer simulation modelling suggest that these problems will be exacerbated under future UK climate scenarios (Jenkins *et al.,* 2009). By combining the collection and analysis of multi-disciplinary empirical datasets from archaeology, geology and geomorphology with future modelling of valley floor development, this project has provided an opportunity to develop a new approach to the analysis of historic assets in the light of future climate and environmental change. Furthermore, analysis of the industrialised landscape of the DVMWHS provides an interesting contrasting case study to that already undertaken on the prehistoric rural landscape of Stonehenge and Avebury (English Heritage, in press).

1.2 Research Aims and Objectives

Historically, the location of industrial heritage is often intimately linked to physiography and the natural resources that provided the power for the factory-based textile and other industries that kindled the 'Industrial Revolution' (Naylor, 2008). Paradoxically, however, many of these locations also correspond to environments where geomorphological and geological processes are most sensitive to climate change.

In the Derwent Valley, in addition to the historic remains of the World Heritage Site, the region has a rich base-metal mining heritage, principally associated with lead, silver, fluorspar and related waste, and the floodplain and valley-side sediments of the region contain a legacy of contamination (Bradley and Cox, 1990). This is important, as empirical geomorphological studies elsewhere in the UK have demonstrated that during the most recently documented period of significant climatic change (the Little Ice Age, *c*. 1450-1850 AD), remobilisation of comparably polluted sediments in response to changing flood frequency and magnitude and increased slope channel coupling transformed valley floors from single channels into actively braiding river systems (Macklin, 1997).

The potential for transformation of the valley floor of the River Derwent in response to climate change, exacerbated by the release of toxic contaminants, has profound implications for both the preservation and future sustainable management of the WHS. Within this contextual framework, the aims of this study were to:

> (**1**) provide a baseline assessment of past landscape change and variations in the intensity of geomorphological processes within the valley floor and upon the surrounding slopes during the last millennium: a timescale which encompasses the last two episodes of well documented major climatic instability (the Medieval Warm Period [MWP] and the Little Ice Age [LIA]).
>
> **(2)** apply advanced computer simulation techniques to model potential landscape changes, including river erosion, sedimentation across the valley floor and surrounding slopes.

(3) use this information to inform the developing local management strategy for the DVMWHS and to augment understanding of the potential impact of future climate change on the cultural resource.

(4) use this information to establish a guidance framework for the management of the cultural heritage of the Derwent Valley within the context of wider catchment management strategies led by multiple stakeholders, and to identify generic principles that can be applied within national and international contexts.

To achieve these aims, the following key objectives were identified, which were focused upon the DVMWHS and its designated Buffer Zone (Figure 1):

A) construction of a GIS incorporating datasets pertaining to the natural environment (physiography, geology, geochemistry etc.) and Historic Environment Records (HERs) relating to the archaeological and built environment resource of the WHS.

B) mapping and analysis of the landform assemblages of the valley floor and the wider Buffer Zone (e.g. palaeochannels, terraces, alluvial fans and landslips) from historic maps, lidar and other sources.

C) collation of documentary records to identify major flood events and flood histories (e.g. Chronology of British Hydrological Events Database[2]) to characterise floodplain evolution and key transformative events during the last millennium.

D) assessment of knowledge regarding the metal-mining history of the catchment from inspection of published sources (e.g. mine inventory records) and collation of data derived from geochemical analyses of valley floor sediments (e.g. British Geological Survey records, University studies and information held by the Environment Agency and Natural England) to determine the scale of contamination and hence the ability of the natural system to repair itself following degradation.

E) modelling of the geomorphological evolution of the valley floor and other landforms of the study area by means of the CAESAR (**C**ellular **A**utomaton **E**volutionary **S**lope **A**nd **R**iver) - Lisflood model. This model has been successfully developed to elucidate the impacts of

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[2] http://www.hydrology.org.uk/Chronology_of_British_Hydrological_Events.php

environmental change, metal contamination, changing sediment supply and vegetation degradation on landscape evolution (e.g. Coulthard and Van De Wiel, 2012).

F) comparison of the geomorphological history with the distribution of archaeological remains relating to the last millennium within the DVMWHS and its Buffer Zone to allow the identification of areas of stability and instability and areas under threat of landscape transformation.

G) input of knowledge into the developing Management Framework of the DVMWHS and identify generic principles that can be transferred to other areas of the historic environment, especially industrial landscapes.

H) input of knowledge and transfer of generic principles into the wider sphere of catchment management undertaken by multiple stakeholders, especially in the light of the developing strategies implemented under the *Water Framework Directive* (WFD), the *Climate Change Act 2008* and the *Flood and Water Management Act 2010*.

1.3. The Study Area and Project Scope

To provide a tight research focus, this project was restricted to the established boundaries of the DVMWHS Core Zone (1,229 hectares) and Buffer Zone (4363 hectares), as defined by the UNESCO site designation and inscription[3]. This designated area (Figure 1) includes the contemporary valley floor, river terraces and adjacent slopes of the Derwent Valley. Inclusion of the WHS Buffer Zone was deemed crucial since much of this area includes abandoned mine workings and areas of slope instability, which may be influential in determining future (contaminated) sediment supply to the valley floor.

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[3] http://whc.unesco.org/en/list/1030

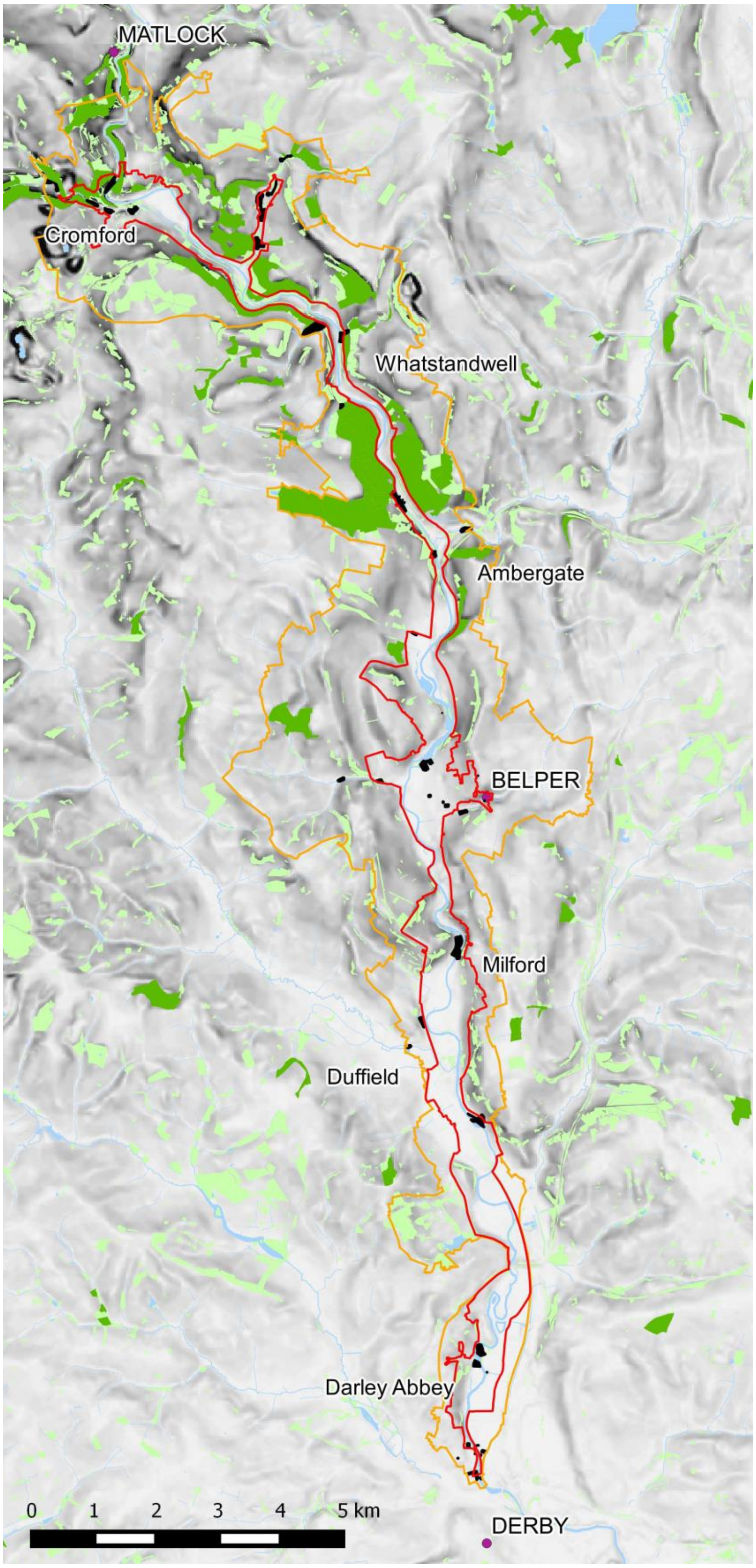

Figure 1: Location of the study area, and of the main sites within the study area (red) and buffer zone (yellow)

Geologically, the project area of the DVMWHS is largely composed of Carboniferous age strata. Immediately upstream of Cromford, the WHS and its Buffer Zone is underlain largely by limestones well exposed in the dramatic cliffs of Matlock Gorge (e.g. Monsal Dale Limestone Formation; Eyam Limestone Formation), although beds of basaltic lava also occur locally. Below Cromford, the solid geology comprises complexly folded and faulted mudstones, shales, siltstones and sandstones (e.g. Bowland Shale Formation, Marsden Formation, Millstone Grit Group), which crop out until the northern outskirts of Derby, where they are replaced by mudstones, siltstones and sandstones of Permo-Triassic age (e.g. Mercia Mudstone Group, Nottingham Castle Sandstone Formation).

Despite being a sizeable river, the Derwent valley floor is relatively narrow, certainly as far downstream as Milford. This feature of the physiography has prevented the preservation of laterally extensive Pleistocene river terraces along the valley sides. Instead, isolated patches, split stratigraphically into two terrace units by the British Geological Survey, have been mapped, notably around Ambergate, Belper and Duffield. The contemporary valley is blanketed by a thin veneer of post-glacial (Holocene) alluvium. Other superficial sediments comprise isolated, heavily dissected patches of glacial till of mid-Pleistocene age on the interfluves across the region as well as occasional aprons of late Pleistocene/early Holocene head deposits on the valley sides and margins (e.g. around Makeney, Belper and Ambergate).

Although an early focus of the Industrial Revolution, a distinctive feature of the World Heritage Site is its preservation of extensive blocks of rural landscape away from the industrial towns and villages that developed around the mill sites. In addition to the historic built remains, therefore, the WHS Core and Buffer Zones preserve a rich fauna and flora, the quality of which is recognised by designation of several Local Nature Reserves (LNRs), Sites of Special Scientific Interest (SSSIs) and areas of Ancient Woodland. These occur usually on the valley sides, and are particularly densely distributed upstream of Ambergate (Figure 1)

Assessment of the potential impacts of climate change on cultural heritage assets was focused upon those remains associated with the industrial heritage of the WHS and its Buffer Zone (as defined in the inscription volume *The Derwent Valley Mills and its Communities*) and held within the HER of Derbyshire County Council. However, consideration of these remains was not simply restricted to the major monuments such as the mills and their immediate infrastructure, but was extended also to the wider industrial heritage record associated with the economic and social fabric of the key industrial communities (notably Cromford, Belper, Milford and Darley Abbey), related infrastructure (canals, railways etc.) and the agrarian landscape within which they were located (with particular emphasis upon the area's rich record of ridge and furrow). In their entirety, these remains are associated with a timescale spanning the last millennium.

2. METHODOLOGY

This project has drawn upon a variety of published and unpublished geomorphological, geochemical and geoarchaeological literature sources and datasets, which have been placed within a palaeoenvironmental context. The capture of this information within the project GIS (using QGIS software), together with HER, environmental and lidar data (Table 1) has allowed landscape models to be constructed that elucidate the evolution of the valley floor over the past 1000 years and provide snapshots of the archaeo-environmental resource. Computer simulation of future valley floor evolution has provided an additional dimension to the project, allowing assessment of how the river might respond to future climate change, providing results which can be compared against the HER Resource within the DVMWHS and its Buffer Zone.

This section provides method statements as described in the original project design (Howard and Knight, 2014). Additional methodological information concerning the CEASAR Modelling and Geochemical Review of valley floor contamination can be found in the respective full reports, archived in Annexes 1and 2.

The project was divided into five stages, with each stage comprising a number of discrete tasks:

Stage 1: Data collation.

Stage 2: Construction of GIS and CAESAR model

Stage 3: Analysis of data and dovetailing of environmental and cultural heritage results.

Stage 4: Presentation of data to wider audience, analysis of feedback and revision of models.

Stage 5: Final reporting and dissemination of results.

2.1. Data collation

Stage 1 of the project involved the mining of data from a number of established open-sources as well as those provided in-kind by project partners (including HER data from Derbyshire County Council, lidar data from the Environment Agency and geological Information on land instability from the British Geological Survey). For the sake of brevity in this report, information on the key data sources is summarised below.

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
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 1: Data types collected by the DVMWHS Climate Change project

2.2 Construction of GIS and CEASAR Model

Stage 2 of the project comprised the construction of the Geographic Information System (GIS), which provided a repository for collected data and provided a platform for data analysis and interpretation; the GIS software utilised was Quantum GIS. Given the novelty of applying computational predictive modelling of valley floor (landscape) evolution as an aid to assessing the impact of future geomorphological processes on the sustainable preservation of heritage assets, a summary is provided below of the modelling approach.

The CAESAR-Lisflood modelling (CL from here forward) aimed to simulate erosion and deposition by running water over a digital representation of the Derwent valley floor created from lidar data. Since the lidar data were acquired at a 2m scale, modelling at this resolution over the entire 24km length of the WHS would create several million computer cells, adding significant numerical complexity and causing the model to run very slowly. Therefore, this 2m resolution Digital Elevation Model DEM was re-sampled to 10m and 20m grid cells to allow the model to run faster (i.e. individual 2m cells were amalgamated). Whilst this change of scale may result in some reduction of detail (i.e. identification of subtle and complex features/landforms on the floodplain), the 20m resolution chosen still provides a satisfactory representation of the valley floor, floodplain and the channel and is capable of providing information of interest at an archaeological scale.

As CL carries out erosion and deposition calculations on this DEM, it was necessary to add areas that can or will not change such as weirs, bridges, solid riverbank revetments and defences (i.e. any structures that interfere with the natural hydraulics of the river). These anthropogenic features were identified and mapped during field survey and by reference to structures observed on Google earth and then added to the CL model.

To drive erosion and deposition within the model, river flows and floods within the Derwent had first to be simulated and calibrated. In order to do this, flow data were obtained from the National Rivers Archive, where a complete set of data for all three rivers (Amber, Ecclesbourne and Derwent) associated with the catchment was provided for a 23 year period from 1971 to 2004. This real flow data was then used to calibrate separate hydrological models running at a coarser spatial resolution for the catchment above Matlock Bath (i.e. upstream of 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 Derwent.

For the hydrological calibration, the upstream models were then run for 30 year periods (starting with the present day channel shape and position) using synthetic rainfall that was modelled using baseline criteria (computer generated rainfall based on present-day rainfall patterns) from the UKCP09 weather generator. As synthetic rainfall is generated according to probabilities of existing rainfall patterns, there is a random component, and so this process was repeated 100 times. From these 100 simulations, daily river flow averages were taken and used to generate a frequency distribution of daily rainfall totals. To calibrate the model, this process was repeated 6 times, each time varying a key parameter in the hydrological model, which alters the size and length of floods (this parameter is denoted in equations by the letter ‘m’).

To model the impact of future climate change on the DVMWHS, future rainfall predictions were needed in order to generate future flood events. These were 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 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.

The weirs which were constructed to provide power for the mills of the Industrial Revolution form an important part of the WHS infrastructure and have had a profound impact upon the hydrology of the valley floor. However, new legislation such as the European Water Framework Directive and new initiatives such as the development of hydropower schemes along the Derwent mean that many of these features are under pressure to be modified. Furthermore, the antiquity of many of the weirs and the on-going cost of maintenance have implications for their future sustainability. With these issues in mind, one of these future rainfall scenarios was used in the WHS reach to model the system with the weirs removed to assess how the Derwent might respond to such measures.

Figure 2: The Horseshoe Weir, built by Jedediah Strutt to power the West Mill at Belper. Construction commenced in the last decade of the 18th century. The weir was heightened and modified in 1819 and 1843 but remains substantialy unaltered. Photograph: D. Knight

2.3. Analysis of Data and Dovetailing of Environmental and Cultural Heritage Datasets

Using the information gathered during Stages 1 and 2, we aimed to provide during Stage 3 a synthesis of the landscape history of the Derwent Valley study area during the last millennium. For ease of interpretation, the characterisation was divided into three time periods (AD 1066-1539; 1540-1900; 1900-present day), which align with time divisions used by the Derbyshire County Council HER, thereby allowing maximum compatibility.

Once landscape evolution was characterised, this information was used to study the impact of natural environmental change on the valley through time, with particular emphasis upon landscape-climate relationships before and after industrialisation (i.e. pre- and post-contamination impacts on the landscape). Zones of landscape stability and instability identified through empirical data analysis and CAESAR modelling have been compared to the record of archaeological remains associated with the WHS to assess areas that might be vulnerable to landscape change during periods of climatic downturn. The analysis also sought to identify geochemical hotspots, which might exacerbate future problems.

The model of landscape development has been used as the foundations for a risk assessment of the WHS and its Buffer Zone and builds upon a study undertaken by English Heritage within the boundaries of the prehistoric landscape of the Stonehenge and Avebury World Heritage Site (English Heritage, in press) and provides a useful additional critique of approaches to risk management and mitigation. The risk management strategy has undergone rapid field evaluation.

2.4. Presentation of Data to Wider Audience, Analysis of Feedback and Revision of Models

Throughout the life cycle of the project, results and other information have been reviewed by the Core Management Team and Steering Group, each of which has met three times during the course of the study. All meetings have taken the form of workshop style sessions with a presentation leading to discussion and feedback. With Stages 1-3 completed, Stage 4 culminated with a final Steering Group meeting (held within the 3D Visualisation Suite at the British Geological Survey in Keyworth), where the findings of the project were described in full, providing an opportunity for feedback and further discussion. Following this meeting, models and results were reviewed as appropriate and the final results are presented in this report.

2.5. Final Reporting and Dissemination of Results

The results of this project are summarised in this report, which includes as annexes full reports on the geochemical analysis and CAESAR_Lisflood modelling. This report provides the basis of a methodological paper focusing upon the approach applied in this study to assessment of the potential impact of climate change upon the historic Environment of the DVMWHS. This will be submitted to an appropriate international heritage publication such as the *Journal of Cultural Heritage.* Papers focusing on the geomorphological and geochemical aspects of the project are also in the process of preparation. Together with a short popular article published in the 2015 issue of *Archaeology and Conservation in Derbyshire* (Howard, Knight and Malone, 2015), these form value-added contributions not conceived at the beginning of this project.

A session proposal focused around ‘Climate Change and Heritage’ has been accepted by the organisers of the European Association of Archaeologists annual conference in Glasgow (September 2015) and will be convened by the Principal Investigators (Howard and Knight), together with colleagues from Universities in Germany, Ireland and The Netherlands. Finally, a paper on this project will also be delivered at the Chartered Institute of Archaeologists annual conference in Cardiff in April 2015.

Digital datasets generated by this project have been archived in an appropriate format and transferred to the Derbyshire County Council HER (which also serves the DVMWHS). Copies of the final project report have also been uploaded to the Archaeology Data Service (ADS) via OASIS (**O**nline **A**ccess to the **I**ndex of Archaeological **S**ites[4]).

3. SYNTHESIS OF RESULTS

3.1 Geochemical Analysis (David Kossoff and Karen Hudson-Edwards)

The rich metal-mining heritage of the Peak District has introduced significant contaminants into the natural environment. In the UK, land is considered contaminated if levels of lead are greater than 450mg/kg for residential land and 750 mg/kg for industrial land (Defra, 2002); for cadmium, these levels are 10mg/kg and 230mg/kg respectively. Table 1.1 in Annex 2 illustrates how the levels set for the UK compare with those globally.

3.1.1. Geological Context of Metal Mining

The southern section of the Pennines is formed by an anticlinal dome of Carboniferous limestone [$CaCO_3$]. The limestone is over 1,000 m thick and is interbedded with igneous basaltic lavas, tuffs and dolerites collectively locally known as toadstone. To the east, west and north, the limestone is flanked by Carboniferous shales and sandstones (Millstone Grit). A variety of mineralisation (characterized geologically as Mississippi Valley Type) known as the fluoritic sub-type formed during the Permo-Triassic, when hydrothermally-driven veins invaded the limestone along bedding planes, faults, joints and between adjacent bedded strata. The introduced minerals were principally galena (PbS), sphalerite (ZnFe)S, fluorite [CaF_2], quartz [SiO_2], pyrite (FeS_2), chalcopyrite [$CuFeS_2$] and barite ($BaSO_4$). The mineralization comprises a large number of long (up to km scale) and narrow (m scale) ribbon-like masses of ore (oreshoots) of limited vertical extent. There are also a number of significant replacement ore-bodies and, when these were accessible, the miners described them as bonanzas; a good example is the Hubberdale Mine Pipe (Flagg, Derbyshire) find in the 1760s (Ford and Rieuwerts, 1970). Trace elements are associated with the major minerals. For example, sphalerite can contain around 0.1-0.2% Cd, while pyrite can host arsenic [As], antimony [Sb], cobalt [Co] and nickel [Ni].

3.1.2. Mining History

There are no currently operating dedicated base-metal mines in Derbyshire; hence, contamination issues are of historic rather than contemporary origin. Britain was a significant Pb producing region

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[4] www.oasis.ac.uk

for the Empire and, within Britain, Derbyshire was one of the most significant ore fields (Dearne, 1990). Recently the historical record of mining has been pushed back a further 1,500 years with discoveries dating to the Bronze Age being unearthed at the Ecton Hill copper mines and 7th century BC Pb mining artefacts at Mam Tor and Gaslow (Guilbert, 1996; Barnatt, 1999; Barnatt and Smith, 2004).

Medieval Pb working in Derbyshire was an important local and, by extension, national industry. It is noteworthy, for example, that accounts in the Doomsday Survey (*c*. AD 1086) list seven smelters and a number of mines at Bakewell, Ashford, Matlock, Crich and Wirksworth (White, 1991). Many of the great medieval cathedrals were roofed and plumbed with Derbyshire Pb both domestically and abroad (van Duivenvoorde *et al*., 2013). For example, there was a substantial and long-standing Pb export trade to the Low Countries, the Baltic and Scandinavia (Riden, 1987) and by the 17th century Pb was second only to wool in value as a British export (Slack, 2000; Willies and Parker, 1999).

Additionally there were a multitude of local laws and customs constraining the development of the industry. For example, along the mineralized veins, otherwise known as rakes, a new mine title was granted every 28-32 yards, often with each title having the right to sink an individual shaft (Palumbo-Roe and Colman, 2010). The large topographical footprint of the mines and the associated processing facilities, coupled with the small-scale of the individual enterprises, resulted in a multitude of small, potential contaminant point sources.

Later, during the 18th and 19th centuries as industrialisation proceeded, fewer mines produced greater outputs. Due to the permeable nature of the limestone, an important constraining factor was the ability to drain the mine. Hence the construction of drainage channels locally known as soughs, which began in the early 17th century, was necessary as the miners prospected ever deeper for ore deposits (Ford and Rieuwerts, 1970). Drainage was facilitated by the newly available pumping technology of the Industrial Revolution, which allowed previously inaccessible ore seams to be worked (Willies and Parker, 1999). These soughs largely remain *in situ* as landscape features and some have evolved to become an integral part of the present water supply infrastructure (James, 1997; Kirkham, 1968). A further boon to the profitability of the Derbyshire orefield was the introduction (in the early years of the 18th century) of the reverberatory furnace, or cupola, which allowed for the cheaper and more efficient smelting of Pb ores (Merry, 1988).

For the Derbyshire ore field as a whole, overall ore production has been estimated to be in the millions of tons, the bulk of this being sourced from within the Derwent catchment (Ford and Rieuwerts, 1970, especially p.16). Ford and Rieuwerts (1970) give a figure of 3-6 million tons of Pb ore and ¼- ½million tons of Zn ore, while Palumbo-Roe and Coleman (2010) give an estimate of 2.5 million tonnes of Pb.

Maximum Pb production is often reported as having occurred during the 18thcentury. For example, Willies (1986), after examining the historic records, estimated that 100,000 tons of ore were produced in the Winster Barmote through the course of the 18th century, with production falling to 44,500 tons for the 19th century.

While this generalisation likely holds good for much of the orefield, the Mill Close mine at Darley Bridge is an exception. This mine produced around 70 % of Derbyshire Pb, and almost all of the Zn, during the late 19th- and early 20th-century. Indeed, this mine was the last major mine close in 1939, following severe flooding (Brearley, 1977, cited in Zhang, 2008).

Glebe Mines, Derbyshire, was the last significant Pb producer in the UK, with *c.*100 tons of concentrate being produced annually, although this was generated indirectly as a valuable bi-product of a fluorspar mining operation (Lusty, 2010). Two severe spills from a mine tailings dam occurred from the company's waste depository at Stoney Middleton in 2007; the company subsequently went into liquidation and its mines and processing plant were closed (Deloitte, 2012). However, these have since reopened under new ownership (British Fluorspar, 2014). Such spills can have significant long last environmental impacts (Kossoff *et al*., 2014).

Lead smelting remains a significant ongoing local industry, despite the absence of contemporary mining. The H. J. Enthoven and Sons secondary Pb smelter at Darley Dale (on the site of the Mill Close mine) is the largest capacity single site lead producer in Europe (Lageard *et al*., 2008), with a production of *c*. 80,000 tonnes of Pb per year (as well as 5,000 tonnes of propylene and 20,000 tonnes of gypsum products).

3.1.3. Environmental impacts of mining

It is of note that historic accounts of Pb poisoning, or to use the local term Belland, are comparatively rare from Derbyshire. They are, however, to be found in the historical record; for example, Dr. Thomas Percival, a local Bakewell practitioner, reported the following in the late 18th century (Meiklejohn, 1954):

> *"The men first complain of a weight, pain of the stomach and costiveness, which are generally relieved, if they apply early for advice, by a vomit, and pills of soap, rhubarb and aloes: or by any aperient medicines of the liquid kind, with oil added to them. But if these symptoms be neglected, the patients complain of their saliva becoming sweet, of clammy sweats, lassitude, feebleness of the legs, a total loss of appetite, obstinate costiveness, and a fixed pain in the abdomen, with severe retchings.''*.

Fortunately, there was considerable local awareness of the potentially dangerous nature of the industry and there are reports of affected men periodically changing work from the lead mines to, for example, the lime kilns, with the latter alleviating the symptoms brought on by the former.

In this context it should be noted that the principal Pb ore mineral was galena, which is more stable than other Pb ores such as cerrusite and anglesite (Porter *et al*., 2004). Consequently, galena-hosted Pb is not as bio-available and, it follows, not as toxic. When galena is exposed to the atmosphere (as on the surface of a floodplain) it oxidises and forms secondary minerals such as anglesite and cerrusite. Hence, the new secondary Pb mineral host(s) will have greater impact on ecosystems through the mechanism of increased bio-availability.

Under stable conditions, metals can be stored in floodplain deposits for centuries, perhaps even millennia. Their remobilization can occur as the result of the physical geomorphological processes (e.g. flooding causing bank erosion) and/or chemical processes. For example, a reduction in water tables can mobilise metals by exposing them to the higher potential for atmospherically-mediated oxidation. Changes in acidity can also affect metal mobility; for example, Zn's mobility generally increases as acidity rises, while that of As declines (Olías *et al*., 2004). Constraining the ongoing evolution of the chemical parameters of pH (acidity) and Eh (the potential for oxidation) can therefore be of predictive value in terms of likely metal mobility.

The Derbyshire Derwent's catchment is heavily contaminated by the potentially toxic metals lead, cadmium and zinc. However, the principal catchment rock within the mining area is limestone, which forestalls the development of acidity normally brought on by the weathering of mine waste materials (i.e. the calcium carbonate increases pH). Hence, the globally-widespread problem of acid mine drainage is not present in Derbyshire and therefore this is not an issue for the Derwent and its tributaries that drain through the heart of the DVMWHS.

3.1.3a The Upper Derwent Valley (upstream of the major reservoirs)

In the upper course, this heavy metal contamination is wind-borne and sourced from the neighbouring industrial conurbations, in particular Manchester, with Rothwell *et al*. (2005) recording Pb levels of 1050mg/kg in the upper 5cm of soils from the peat uplands. The upper course contamination is currently isolated from the lower reaches of the river system by the intervening reservoir complex. A significant amount of contaminated sediment is held in storage within these reservoirs. Under current management regimes (i.e. retention of the reservoir complex), it is unlikely that significant amounts of sediment will be released from the upper part of the system, even under scenarios of future climatic change. Furthermore, the implementation of changing management practices in the uplands (e.g.

reduction of peat erosion through the blockage of gripping systems) may further aid the stabilisation of the contaminated peatland sediments.

3.1.3b The Middle Derwent Valley (downstream of the reservoirs to Matlock Bath)

Below the reservoirs in the middle course of the Derwent Valley, the contamination mostly arises from historic mining, although there are high background concentrations of zinc and, particularly, cadmium in the shale bedrock. A soil geochemical atlas of England and Wales published by Rawlins *et al*. (2012), but building on the earlier work of McGrath and Loveland (1992), indicates that the middle reaches of the Derwent catchment have contamination hotspots with the highest concentration of 20.7-47.5 mg/kg for cadmium and 3,960-10,000 mg/kg for lead.

The principal contaminant transport mechanism in the middle course is fluvial, although wind-borne transport was significant, particularly around past (and present) smelter sites (e.g. in Darley Dale). Bradley and Cox (1990) quantified soil floodplain concentrations at Darley Dale immediately downstream of the Mill Close Mine site. Sixteen sediment cores were collected in transects across the floodplain, and each core was sectioned at 5cm increments on site (Table 5). Lead concentrations showed no clear trend either vertically with depth or horizontally with distance from the river channel. It can be concluded, therefore, at least from this site, that soil Pb concentrations reflect a long-standing contaminant input. Zinc and Cd concentrations, however, demonstrate an exponential increase from depth to the surface and maximum concentrations on an elevated terrace some 450m from the river. The vertical upward increase in concentrations likely reflects the latter years at Mill Close, where Zn extraction assumed increasing importance as the deeper levels were worked (Kirkham, 1968). It might be speculated that the terrace Cd and Zn hotspot reflects an exceptionally high flood, which mobilized a portion of these surface-rich sediments. These in turn remained isolated from the ongoing year to year fluvial mobilization downstream.

At the time of completion of the Bradley and Cox study, mining had ceased for around thirty years and, therefore, the authors were analyzing post-mining sediment concentrations; these provided an important assessment of the longevity of metal concentrations and hence contamination within the floodplain. For this period in particular, sediment accumulation is distinguishable by the presence of ^{137}Cs, which is a radioisotope released into the environment by atmospheric nuclear weapons testing. From analysis of these data, together with that of the rate of sedimentation, the authors calculated that the annual supply of metals to this study reach can be estimated as 360 kg of Pb, 100 kg of Zn, 10kg of Cu and 2 kg of Cd. Moreover, the authors went on to analyze how much of this loading would be bio-available and reported that, per square metre, this contaminant load was equivalent to an input of 266 mg of Pb, 36mg of Zn, 5.2mg of Cu and 0.1mg of Cd per annum. In summary, these authors found that contaminant mobility remained high on the floodplain despite the cessation of mining.

Further upstream, Zhang (2008), as part of a PhD thesis, reported on the concentrations of Cd, chromium [Cr], Cu, Mn, Ni, Pb and Zn in the Derwent and Manifold catchments though the latter results are not reported here. Four sites were chosen in the Derwent catchment: three in the highly contaminated Wye tributary catchment (sites 3, 4 and 5) and one on the Derwent, 2km downstream from the site of the former Mill Close Mine (site 6).

	n	**x**	**SD**	**Min**	**Max**
Pb	157	620	176	131.4	1179
Zn	157	194	198	9.3	1696.1
Cu*	157	17.2	8.2	2.9	64
Cd	157	2.5	2.1	0.08	12.5
* Cu is below shale rock background concentrations					

Table 2: Summary statistics (mg/kg) of total concentrations of lead, zinc, copper and cadmium in Derwent floodplain sediments (Zang, 2008).

(x) sample #	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Wye (24)	5.9 (1.4)	39.5 (5.1)	55.8 (13.6)	1 132.3 (438.6)	51.2 (6.3)	712.6 (195.0)	638.0 (115.6)
Derwent (18)	3.9 (1.3)	43.9 (5.7)	38.0 (5.8)	719.2 (54,2)	37.7 (4.2)	737.6 (69.3)	407.2 (99.3)
Background in Wye and Dewent[2]	1.0 (0.4)		32.2 (6.4)	806 (211)	53.3 (15.1)	350 (121)	170 (29.4)
National levels[3]	0.8 (0.9)	41.2 (28,2)	23.1 (37.0)	760.9 (979.3)	24.5 (17.4)	74 (267.0)	97.1 (109.3)

(1) Bradley and Cox, 1986 (2) Li, 1993 (3) McGrath and Loveland, 1992 (CV% was given instead of s. d.) (CV%, coefficient of variation =SD/Mean* 100, therefore, s. d. =CV% x mean/100)

Table 3: Total heavy metal concentrations (± s. d.) in Wye and Derwent floodplain soils (mg/kg) with relevant background and national average levels

Floodplain	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Site 3 (n=8)	4.9	42.4	52.5	916.5	53.8	637.6	561.9
Site 4(n=9)	5.2	37.3	61.2	1413.5	51.5	886.2	596.1
Site 5(n=7)	7.8	38.9	52.6	1017.5	47.8	575.3	778.8

Table 4: Heavy metal concentrations in the Wye floodplain soils (mg/kg)

Table 3 presents total soil metal concentrations in floodplain soils. It is apparent from these data that Cd, Pb and Zn concentrations in the Wye and Derwent floodplains are much higher than their respective local background and national average concentrations. Table 4 presents site-specific data for contamination of the Wye floodplain soils.

Table 5 summarizes data from floodplain traverses across the Wye and Derwent valleys and thereby gives a measure of the lateral distribution of contaminants. The distributions of Cd, Pb, Zn and Mn across the three sample localities of the Wye floodplain (sites 3, 4 and 5) exhibit a relatively constant pattern. For the Derwent (site 6), however, contaminant soil concentrations tend to increase away from the river channel. This is particularly so at 190m distance, where there is a marked rise in the Cd and, in particular, the Zn profiles (compare Bradley and Cox, 1990). This might possibly represent the course of a palaeochannel, but it is likely that the explanation lies in the deposition of contaminated fine-grained sediments by river flooding. It should be noted that distance downstream increases with sample number and, of the seven elemental concentrations reported, only Ni consistently falls. This is the consequence of additional point sources along the course of the Wye supplying fresh contaminant loads

Site 3							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	4.2	31.4	30.3	764.4	41.7	516.6	481.1
5	4.4	38.4	39.6	885.5	49.5	581.3	500.1
10	5	41.8	54	910.3	54.9	581	557.9
15	5.5	49.8	69.2	997.6	65.8	692.1	628.3
20	5.3	48.7	66.3	985.3	62.5	758.6	618.4
25	4.8	36.9	51.1	952.9	45.3	514.1	543.8
30	5.4	45.3	52.5	985.3	55.4	681.1	596.1
35	4.9	47.1	57.2	850.3	55.4	775.9	569.4

Site 4							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	3.9	27.3	32.4	733.9	37.7	570	469.6
5	4.8	40.3	52.1	1155.4	51.2	807.1	813.3
10	4	37.9	44.4	1042.3	48.3	774.9	512.4
15	6.2	40.3	57.6	2322.3	58.2	801.1	635.9
20	6.2	36.4	59.2	2182.7	50.8	918.3	584.9
30	5.5	39.6	79.3	2239.9	55	1376.5	606.2
40	6.4	38.1	62.7	950.8	53.1	813.7	606.6
50	4.5	34.7	92.7	1069.7	54.3	993	562.9
60	5.2	41.1	70.6	1024.5	54.7	920.8	572.7

Site 5							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	8.8	35.8	50.1	934.2	45.9	524.4	807.8
5	8.7	44.3	62.8	1280.7	53.3	580.4	889.4
10	7.8	39.8	58	1158.7	49.2	581.1	811.2
15	7.4	42.1	50.1	938.4	48.6	570.7	769.7
20	7.8	39.2	55.4	1037.2	49.3	609.7	772.2
25	7.1	35.8	48.1	943	45.4	592.1	711.2
30	6.7	35.3	43.6	830	42.7	568.5	690.4

Site 6							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	5.7	30.4	25.3	602.7	29.2	617.3	538.5
5	4.8	33.8	27.6	627.4	31.1	625.2	500.8
10	4.5	38.9	31	692.6	32.9	656.8	523.6
15	3.4	37.4	31	734.8	31.9	646.3	375
20	4.2	42.6	35.5	793.2	36	707.1	419
30	3.3	42.3	34.7	727.9	37.1	730	374
40	3.3	40.4	36.4	822.1	36.3	705.7	376.5
50	2.7	47.9	40.5	792.4	41	762.9	346.3
60	3.2	47.4	42.5	749.5	41.9	809.8	368.9
70	4	49	46.3	709.7	43.9	809	438.2
90	3.3	49.3	43.4	718.9	42.1	791.7	374.4
110	2.7	49.7	40.4	728	40.3	774.4	310.6
130	2.7	41.9	40.6	682.9	38.2	738.9	323.2
150	3.2	46.4	38.5	694.5	37.9	691.3	302.2
170	3.5	45.5	40.3	760.5	38	750.3	322.2
190	8.2	51	43.7	660.4	40.3	843.8	704.9
210	3.2	45.6	42.7	711.9	40.3	766.4	346.2
230	4	50.3	43.4	735.8	43	850.3	384.4

Table 5: Heavy metal concentrations in the Wye (Sites 3 and 4) and Derwent (Site 6) floodplains, showing variations with the distance from the Wye and Derwent channels (mg/kg)

Whilst it is envisaged that the majority of contaminants have been released into the environment gradually, albeit at levels which are elevated against the natural background signal of the ores, catastrophic engineering failures of structures within mine complexes can also play a role. Whilst historical knowledge of such failures is limited, an event at Glebe Mine in 2007 provides a flavour of their potential impact.

The Glebe Mine Tailings Dam Spill

After a prolonged period of heavy rainfall in January 2007, the tailings dam at the Glebe Mine processing complex at Stoney Middleton failed. Property was damaged in the village, and it has been estimated that 113 tonnes of fine-grained fluorspar mine tailings were released into the Stoke Brook and subsequently into the Derwent itself (Environ Liverpool, 2008; Worrall, 2009). In the immediate aftermath of the spill, the local environmental health department undertook sampling of the affected area. These samples exceeded the Swedish contaminated soil guideline values for As, Zn and particularly Cd and Pb, for both the affected and unaffected gardens (Wilding 2007; Table 6). The sampling methodology involved the removal of the tailings layer from the affected gardens to reach the 'uncontaminated' soil beneath. Nevertheless Pb showed a *c*. 23% concentration increase in the tailings soil compared with the unaffected control. The analogous figures for As, Cd and Zn were 11%, 1% and 19% respectively. The interregnum between the accident and the sampling was a maximum of 21 days. Therefore, taken at face value, these data indicate the significant and comparatively high mobility of Pb from the Glebe mines tailings source.

During the course of the clean-up work it was discovered that a much larger spill had occurred in 1968 with much of the tailings still remaining *in-situ* on the floodplain. No obvious ill effects of this early accident have been reported in the interim, leading some to question whether the clean-up operation was necessary other than for cosmetic reasons (e.g., Worrall, 2009). Indeed, the consultants employed by Glebe Mines concluded that, although the tailings were characterised by high concentrations of heavy metals and fluoride, these contaminants were relatively immobile after the tailings were dispersed into the environment (Environ, Liverpool, 2008). Moreover, background contaminant concentrations, determined by analyzing sediment not impacted by the 2007 tailings spill, had similar concentrations of heavy metals (Wilding 2007; Environ, Liverpool, 2008). From these reports, the conclusion might therefore be drawn that the adverse effects of the 2007 spill were acute rather than chronic. However, the addition of a further contaminant burden on an already grossly contaminated river system should not be taken lightly.

Lead Smelting

A plethora of historic smelter sites may be identified on and around the Derbyshire orefield (Crossley and Kiernan, 1992) and undoubtedly a significant proportion of the catchment's historic contaminant load is sourced from their operation. The extant smelter at Mill Close was established in 1934, while the mine was still in production, and since 1940 it has been an isolated and productive source of Pb (Lageard *et al*., 2008). Therefore, pollution studies associated with its operation provide an indication of environmental impacts.

Analyte	Affected gardens (n=5; mg/kg)	Unaffected gardens (n=4; mg/kg)	Tailings (n = 1; mg/kg)	Swedish classification*
pH	7.76	7.45	9.26	
Aluminium	27800	24000		
Arsenic	25	22.25	24.6	Moderately serious
Barium	1510	1375	5130	-
Cadmium	4.62	4.56	14.4	Extremely serious
Chromium (Total)	30.4	30.75	18.6	Slightly serious
Iron	23200	23250		-
Lead	1960	1512.5	4620	Extremely serious
Mercury	0.26	0.28	0.42	Slightly serious
Magnesium	3300	2900		-
Manganese	1474	1475		-
Nickel	28.8	32	46.6	Slightly serious
Selenium	2	2.3	8.65	-
Strontium	104.8	68.25		-
Zinc	470	382.5	1790	Moderately serious
Fluoride	4.72	2.89		-

*Swedish, E. P. A. (2002). Categorised for gardens only. The boundary between “Slightly serious” and “Moderately serious” is used as the guideline value for sensitive land use.

Table 6: Mean results of soil sampling at five affected gardens and four unaffected gardens on Edge View, Stoney Middleton.

Lageard *et al.* (2008) performed geochemical analyses on soils in and around the Enthoven property in an attempt to correlate this with tree-ring data from the species *Pinus sylvestris* L. The results indicated that all of the soil samples taken from under the trees at the site exceeded the government guideline of 450 mg/kg Pb content for open spaces (DEFRA, 2002). Soil samples from Darley Dale, Birchover and Upper Matlock had Pb concentrations ranging between 443 and 787 mg/kg, with those in the control sites ranging between70 and 196 mg/kg. These data undoubtedly reflect historic pollution from the smelter site. There is evidence from the record of Pb concentrations in air that, despite the high production, aeolian contamination from the smelter is currently much better controlled than it was in the past (data from Enthoven and Derbyshire Dales District Council, both quoted in Lageard *et al*., 2008).

3.1.3c. The Lower Derwent Valley

The DVMWHS straddles the lower course of the Derwent, largely downstream of the area directly affected by mining contamination (i.e. mine and processing sites), although the confluence of the Ecclesbourne River, which drains the rich mining area around Wirksworth, and Derwent is within the WHS itself. Hence, any fluvially mobilized contamination must impinge on the lower Derwent. However, while some data are available on sediment contaminant concentrations in the Derwent's upper and middle courses, there is, with the exception of the Ecclesbourne River, a paucity of data for the lower course.

There is strong evidence that the Derwent contamination signature reaches the Trent downstream of the DVMWHS, and hence this implies that contaminated sediment is likely to be on the move throughout the catchment. Izquierdo *et al*. (2012) remark that Site 14 (8 km downstream from the Derwent confluence) revealed Pb concentrations close to 400 mg/kg, which significantly differs from that measured in the Trent upstream of the confluence. A word of caution is expressed by the authors that Pb with the apparent Derwent isotope signature may be partially derived from a local power station and railway marshalling yard. Moreover, the Pb distribution in the Trent may also be impacted by river dredging (pers. comm. Izquierdo 23/05/2014).

	Topsoils 0–15 cm					**Subsoils 35–50 cm**				
	Min	**p25**	**Median**	**p75**	**Max**	**Min**	**p25**	**Median**	**p75**	**p100**
Total Pb	84	167	241	363	860	43	113	241	507	1282
Total Zn	198	382	572	722	1474	158	290	419	999	2033
Total Cd	0.8	3.8	6.2	8	16	1	2.3	5.3	10	22

Table 7: Ranges of Cd, Pb and Zn of the alluvial soils sampled from the Trent Catchment, UK (mg/kg).

In general terms, as a function of declining gradients and hence velocity, the lower course of a river is subject to deposition of the eroded sediment sourced from the steeper, faster-flowing upper reaches. Hence, on a gross scale the DVMWHS is potentially at risk from sediment sourced higher in the catchment. Structural controls on the river, such as weirs associated with the mills of the World Heritage Site, have had a profound impact on river gradients and hence sediment movement thorough the valley system, and may lead to the concentration of contaminants above these structures. Any changes associated with these structures, such as their modification in the light of the Water Framework Directive, may have implications for sediment storage and remobilization (see Section 3.4, Modelling Results).

Sediment samples have been taken from a number of positions at 22 sites along the length of the Ecclesbourne River and from seven of its tributaries; samples from each position and site were graded into particles of three different size modes and analyzed for their total Pb, Zn and Cd contents (Moriarty *et al*., 1982). It is interesting that the Pb and Cd sediment concentrations in sediments at the mouth of the Ecclesbourne (i.e. at the Derwent confluence) are approximately the same as those measured at Mill Close by Bradley and Cox (1990). It should be noted, however, that Zn concentration is appreciably higher at Ecclesbourne than at Mill Close, implying a significant point source from within the Ecclesbourne catchment (Table 8).

Site #	Distance	Lead			Zinc			Cadmium		
	Upstream (km)	Grade 1	Grade 2	Grade 3	Grade 1	Grade 2	Grade 3	Grade 1	Grade 2	Grade 3
6	5.26	676.08	851.14	630.96	741.31	467.74	309.03	3.47	2.75	2.4
8	5.27	912.01	794.33	741.31	602.56	446.68	302	3.72	2.88	2.95
11	8.51	2884.03	2137.96	1174.9	2137.96	1380.38	363.08	11.22	12.59	5.01
13	8.58	3890.45	1905.46	1698.24	851.14	1288.25	562.34	4.47	12.88	6.76
17	12.63	8912.51	8511.38	15135.61	5128.61	6309.57	2884.03	64.57	85.11	35.48
19	12.75	8317.64	6760.83	5495.41	8511.38	6025.6	3162.28	120.23	77.62	25.12
20	13.58	7762.47	15848.93	4265.8	15135.61	6456.54	1995.26	213.8	75.86	24.55
22	14.55	19498.45	25703.96	12022.64	19498.45	6918.31	4466.84	275.42	74.13	54.95
23	14.56	22387.21	19498.45	23442.29	6025.6	10715.19	8709.64	52.48	117.49	87.1
28	14.84	21877.62	14454.4	11220.18	9549.93	8128.31	3388.44	112.2	95.5	36.31

Table 8: Comparison of metal concentrations and grain size in sediments from the River Ecclesboune. Mean concentration mg kg $^{-1}$ for two positions per site.

3.2. Analysis of Landform Assemblages

Landform Assemblages were mapped from lidar data along the entire length of the DVMWHS to help characterise geomorphological activity across the valley floor and to elucidate its development over the last thousand years (Figure 3 and figure 4). Of particular interest to this study is the degree of lateral channel mobility in the past, since any increased future mobility would have significant implications for the archaeological resource. Palaeochannel landforms identified on the valley floor are also significant since they act as natural sediment traps; if this includes organic materials, particularly biological remains such as pollen, plant macrofossils and insects, these have the potential to provide proxy records of climate, land-use and vegetation history.

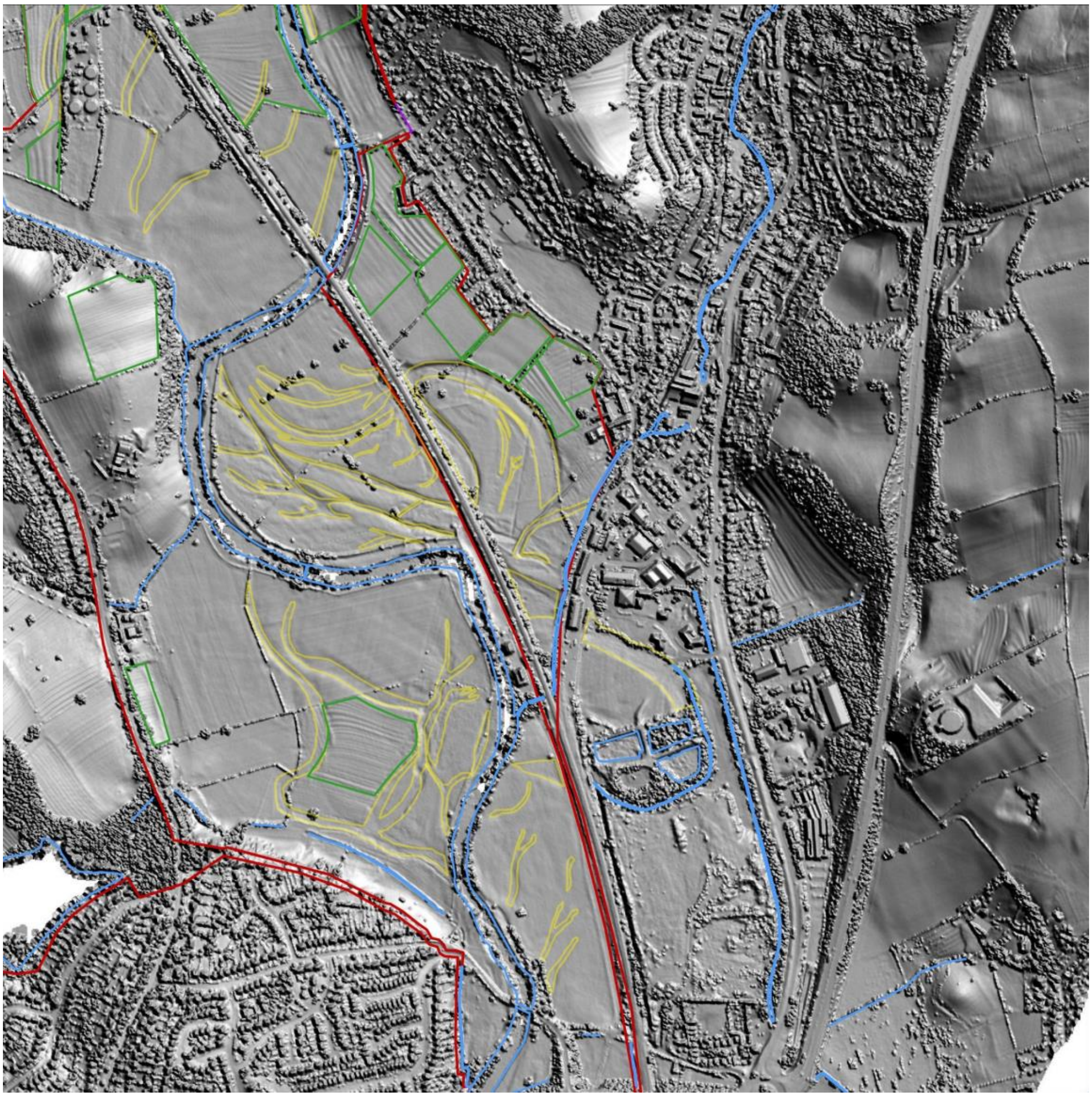

Figure 3: Processed lidar image showing palaeochannels, ridge and furrow and other earthworks on the valley floor between Little Eaton (top right) and Allestree (Bottom left). Palaeochannels are outlined in yellow and HER polygons are outlined in green. Source data © Environment Agency

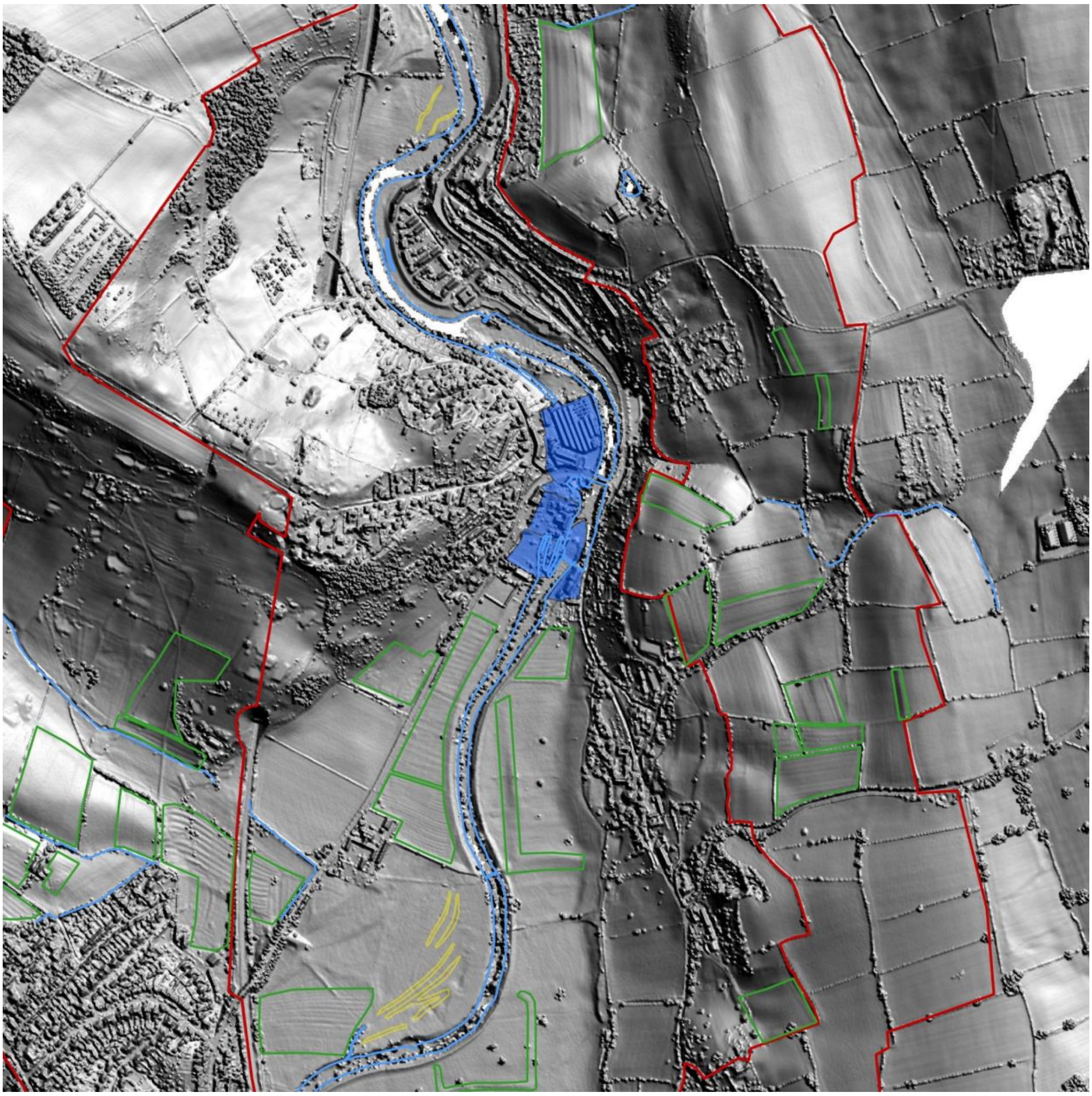

Figure 4: Processed lidar image showing palaeochannels, ridge and furrow and other earthworks on the valley floor where it widens immediately downstream of Milford. The historic assets of the Milford mill complex are shaded blue, palaeochannels are outlined in yellow and HER polygons are outlined in green. Source data © Environment Agency

It should be stressed that simply identifying landform assemblages cannot provide an absolute chronology for landscape development, although their relationship to archaeological remains and to each other can help to establish a broad relative chronology; this is certainly the case for parts of the lower Derwent Valley within the DVMWHS, where a significant number of palaeochannels can be observed to cut ridge and furrow earthworks that on morphological grounds are likely to relate to medieval arable cultivation on the floodplain.

For the majority of the DVMWHS corridor upstream of Milford, the river is constrained within a relatively narrow valley floor and there is little 'accommodation space' upon the floodplain to allow either the development of landforms or their preservation once formed. The construction of both the Cromford Canal and Midland Railway may well have helped constrain its channel at various parts along the valley. Where palaeochannels are preserved, they are simple, linear features close to the modern channel, for example, upon the valley floor between Cromford Mill and Belper.

Downstream of Milford, the valley floor widens significantly and the contemporary channel is highly sinuous. Mapping of landform assemblages has identified a significant number of palaeochannels in this part of the valley floor and demonstrates that within this reach, channel sinuosity is not a recent phenomenon. The palaeochannels can be divided into three types: (1) major sinuous channels with wavelength amplitudes and dimensions similar to the modern channel; (2) minor distributaries irregularly scattered across the floodplain surface; and (3) minor but regular channels in parallel groups that are indicative of ridge and swale topography. The latter group of landforms is particularly significant, since this suggests that the channel has moved by lateral migration. Consultation of historic mapping suggests that such movements are earlier than the 1st edition Ordnance Survey maps of the region but for reasons discussed below a significant proportion might date to the comparatively recent past (see, for example, Fig. 7).

As noted earlier, the identification of landforms associated with relict river channels cannot provide absolute age estimates, but their relationship to datable earthworks or archaeological features can assist in the development of a robust relative chronology. Within this part of the Derwent Valley, analysis of lidar data has identified significant areas of ridge and furrow of varying dimensions and morphology, adding significantly in this respect to the Derbyshire HER resource. An unknown proportion of this 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 (e.g. Elliott *et al* 2004, 174-175), 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 in the study area where river channels truncate ridge and furrow earthworks that in terms of their morphology and layout most probably date from the High Medieval period, notably in the Derwent floodplain near Darley Abbey (cover image), Little Eaton (Fig. 3) and Milford (Fig. 4). This may signify a phase of medieval agricultural expansion across the floodplain, followed by the abandonment of arable fields increasingly afflicted by flooding and fluvial erosion. This erosion may be associated with the changing intensity of natural fluvial processes, which in turn may correlate with increased river discharge. Changing floodplain hydrological conditions are ultimately driven by climate, although land-use is important for priming landscapes for change. 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. More vigorous fluvial erosion has been linked to the climatic changes of the Little Ice Age in other parts of the Trent river basin (e.g. Elliott et al 2004, 154-155) and there is significant scope for further research into this process in the wider Trent catchment and beyond.

3.3. Analysis of Flood Records

Around 1725, in his tour through the island of Great Britain, Daniel Defoe described both the Derwent and the Dove as '…furiously rapid streams', noting also that the former was '... a frightful creature when the hills load her with water' (Defoe 1725: Letter 8). This provides a useful insight into the nature of the river prior to its regulation (Petts, 1987), and would fit well with the evidence presented in this project.

A review of secondary documentary sources relating to specific flood records and anecdotal accounts relating to events within the Derwent Valley and Trent-Derwent confluence zone provides valuable insights into changes in flood frequency and magnitude over the last millennium. These can be compared with regional and national chronologies developed on the basis of statistical (probability frequency) analysis of radiocarbon dates (Macklin *et al*., 2005; 2010).

The River Trent catchment, which includes the Derwent Valley, has one of the longest flood records in the UK, extending back to AD1141 (Potter 1964; Table 9). However, it covers a significant area with varied topography, from true wilderness uplands through to the lowlands of the Humberhead Levels. This creates a challenge when deciding which records to consider of relevance to the Derwent, apart from those specifically within the valley itself, and is a particular consideration when analysing summer flooding, which is often associated with locally intense, slowly moving convective (thunder) storms (Lewin, 2010; Foulds et al., 2014): for example, the flash flood that affected the Darley Moor area of the River Dove on 6th August 1957 (Barnes and Potter, 1958) and the River Wye at Ashford-in-the- Water on 25th/26th April 1983 (Boardman and Spivey, 1987). In this assessment, floods from the main Trent Valley are restricted to those in the immediate vicinity of the Derwent, with particular reference to the Trent-Derwent confluence zone.

A corpus of 564 flood records for the Trent catchment has been assembled by Macdonald (pers. comm.; 2013), building on the earlier work of a number of authors (notably Potter, 1964). For the Derwent Valley itself, Macdonald's first flood record is from January 1677 and relates to thawing snow, but the entire record up until 1931 includes a mixture of summer and winter events. These events fall within a period of known increased flood frequency and magnitude, both in the UK and Europe, that is largely related to the Little Ice Age (Rumsby and Macklin, 1996; Brown, 1998; Merrett and Macklin, 1999; Macklin and Lewin, 2003; Benito *et al*., 2010) and which it seems, from evidence compiled as part of this report, might relate to a period of increased river channel mobility.

The records assembled by Macdonald add to a wider corpus of flood records amassed for the Derwent and Trent by a variety of authors, although the tables below show that these records do not mirror each other entirely (Tables 9 and 10). Other analyses extend the Derwent record back to 1587, whilst the Trent-Derwent confluence zone records can be extended back to 1141. The confluence records are of particular interest in the present context, as, it seems logical to assume that if the lower Derwent is in spate then parts of the river farther upstream must be similarly affected.

However, a key problem when interpreting such records is assessing the severity of a flood if specific information on flood heights is lacking (thereby preventing the calculation of accurate discharge values). Furthermore, it should not be assumed that climatic conditions alone are responsible for the severity of events. For example, the 1842 'Great Flood' of Derby, which is estimated to have directly affected 10,000 people, may well have been exacerbated by urban encroachment, which led to increased run-off around the Markeaton Brook: a tributary of the Derwent (Conway, 1993).

Records of flooding events affecting the River Derwent and Trent-Derwent confluence zone (from Macdonald 2013; supplemented by unpublished data provided by Neil Macdonald)

Year	Date	Cause	Primary ref.	Secondary ref.	Notes
1677	03-Jan	Thaw	Britton, 1935		Flooding at Darley Dale ice and water
1698	10	Rain	Stratton, 1969		Summer flooding of Derby
1708	01-Feb		Shaw, 1999		Ashbourne flooded
1709			The British Chronologist, 1789		Flooded washed away bridge at Hazelford over Derwent
1715	03-Jul	Rain	Shaw, 1999		Dove flooded
1718		Rain	The British Chronologist, 1789		Alport ford flooded
1824	12-Oct		Marriott and Gaster, 1886		Rank 4 of floods at Belper between 1824-1886
1837	21-Dec		Marriott and Gaster, 1886		Rank 8 of floods at Belper between 1824-1886 (4'1")
1839	31-Jul		Marriott and Gaster, 1886		Rank 6 of floods at Belper between 1824-1886 (4' 2.5")
1840	16-Nov		Marriott and Gaster, 1886		Rank 11 of floods at Belper between 1824-1886 (3' 10.5")
1842	01-Apr		Annual Register, 1842		Derby flooded
1845	28-Dec		Marriott and Gaster, 1886		Rank 1 of floods at Belper between 1824-1886 (4' 5")
1849	08-Oct		Marriott and Gaster, 1886		Rank 1 of floods at Belper between 1824-1886 (4' 5")
1852	05-Feb	Rain	Marriott and Gaster, 1886		Rank 9 of floods at Belper between 1824-1886 (4' 0")

1869	04-Jan	Thaw	British Rainfall, 1869		R. Derwent
1875	20-Oct	Rain	Trent Bridge markings; British Rainfall, 1875	Marriott and Gaster, 1886; FSR, 1975	Rank 7 of floods at Belper between 1824-1886 (4' 2")
1880	01-Jan		Marriott and Gaster, 1886		Rank 9 of floods at Belper between 1824-1886 (4' 0")
1881	09-Feb	Thaw	Marriott and Gaster, 1886		Rank 4 of floods at Belper between 1824-1886 (4'3'')
1883	30-Apr	Rain	British Rainfall, 1883		R. Derwent in flood
1885	22-Oct	Rain	British Rainfall, 1885		R. Derwent in flood
1886	05-Apr	Rain	Symon's, 1886		Rank 3 of floods at Belper between 1824-1886 (4' 3.5")
1887	21-Jan	Thaw	FSR, 1975, 266-269	British Rainfall, 1887	R. Derwent and Trent flooded
1888	29-Dec	Rain	FSR, 1975, 266-269	British Rainfall, 1888	Trent and R. Derwent in flood
1892	28-Jun	Rain	British Rainfall, 1892		R. Derwent in slight flood
1901	31-Dec	Thaw	Bryan, 1903		R. Derwent flooded
1909	24/25-Dec	Thaw	Meteorological Office, 1968	*FSR, 1975, 266-269	Derwent and Trent valley
1911	21-Dec		British Rainfall, 1911		Trent and R. Derwent in flood
1912	27-Jul	Rain	British Rainfall, 1912		R. Derwent flooded
1931	06-Sep		FSR, 1975, 266-269	British Rainfall, 1931	R. Derwent worst since 1881

Table 9: Records amassed by Macdonald (pers comm.; 2013) for the Trent catchment, with specific reference to the river Derwent and Trent-Derwent confluence zone

Floods noted on the River Derwent and Trent-Derwent confluence zone between the 15th and 19th centuries, compiled from other sources			
Date	**Primary Source**	**Citation**	**Notes**
1st-5th?April 1842	Derby Reporter 7.4.42	Conway 1993, EMG	Known as the Great Flood. 2ft 4” above flood of 1795. Caused by exceptional storm
10th Feb. 1795		Conway 1993, EMG	Rain on snow - St Werburgh’s flooded
November 1770 x 3 events	Derby Mercury 30.11.70	Conway 1993, EMG	Rain of snow
December 1740		Conway 1993, EMG	Pavement of rebuilt St Werburgh’s uprooted
5th November 1698	Cox, 1879, p176	Conway 1993, EMG	St Werburgh collapsed
1676-77	St. Helen’s Darley Parish Register	Cox 1877, p173-4; Sleigh 1884 p3; Smith 1953, p29	
1677		Conway 1993, EMG	St Werburgh damaged
1673		Conway 1993, EMG	St Werburgh damaged
1659		Conway 1993, EMG	St Werburgh damaged
1648	St. Helen’s Darley Parish Register	Cox 1877, p 173Smith 1953, p33	Derwent flood, resulting in death of a child
1610		Conway 1993, EMG	3 prisoners confined in the gaol were drowned
1587	Hutton, 1791 p255	Conway 1993, EMG	A remarkable flood broke down St Mary’s Bridge and carried away the mills at the bottom of St Michael’s Lane

Floods noted on the Middle Trent between the 11th and 14th centuries (from Potter 1964)			
Date	**Primary Source**	**Citation**	**Notes**
1403	Potter, 1964	Brown, 1998	A severe flood that breached Spalford Bank and caused channel change at Wilne
1310-1330	Potter, 1964	Brown, 1998	A period of severe winters with damage to bridges almost every winter
1322	Potter, 1964	Brown, 1998	Severe winter floods
1315	Potter, 1964	Brown, 1998	Rainfall floods
1309/10	Potter, 1964	Brown, 1998	Severe winter flood destroyed several bridges, including Hethbeth Bridge at Nottingham and possibly Bridge 3 at Hemington, built in the 1230s and 1240s (Ripper and Cooper 2009, 223). Ripper and Cooper (2009, 223) have suggested that Bridge 3 at Hemington might have been destroyed in 1309/10 or in the major floods of 1279 (not listed by Potter) or 1305-6 (noted below), although the bridge could of course have sustained damage on several occasions
1305/6 (Dec-Jan)	Potter, 1964	Brown, 1998	Severe winter freeze ended by 3 days of rain; flood damage may have included destruction of Hemington Bridge 3 (see above).
1255 (July)	Potter, 1964	Brown, 1998	A summer flood exacerbated by flood debris
1216/17	Potter, 1964	Brown, 1998	Severe winter snow, river frozen. This flood and/or the 1205 flood (below) may have caused significant damage to Bridge 2 at Hemington, built in the late 12th or early 13th century (Ripper and Cooper 2009, 222-223)
1205	Potter, 1964	Brown, 1998	Severe winter snow; river frozen
1141 (2nd Feb.)	Potter, 1964	Brown, 1998	First recorded flood of the Trent, caused by rain on snow. The banks of the Trent were breached at Spalford Bank, while Bridge 1 at Hemington, built in 1097 or soon after (Ripper and Cooper 2009, 222-223), may have sustained significant damage.

Table 10: Flood episodes and severe weather records for the Derwent and Trent compiled from several historical and contemporary sources

Taking the local flood history in its entirety, and relating it back to the defined archaeological periods used for the purposes of this project, ten major floods are documented for Period 1 (AD 1066-1539) and 31 for Period 2 (AD 1540-1900). Reconstructing flood histories for Period 3 (AD 1901-present-day) is much more problematic, since the first reservoirs within the upper Derwent Valley were completed in 1912 (Howden) and 1914 (Derwent), although it was not until the completion of Ladybower Reservoir in 1943 that total flood regulation of the catchment was achieved. However, five major floods are documented from 1901-1940.

In the last two decades, much emphasis has been placed on identifying regional and national patterns of flood history and hydrological change through the statistical (frequency probability) analysis of radiocarbon dates derived from fluvial deposits (Macklin *et al*., 2005; 2010). This research is part of broader initiatives to understand long-term palaeoclimatic variability and the underlying driving mechanisms (Charman, 2010), although many of the issues are still poorly understood (Swindles *et al*., 2012).

Based on statistical analysis, Macklin *et al*. (2005; 2010; 2012) recorded increased flood frequency around AD 1090, AD 1290 and AD 1380, which might imply some correlation with the Medieval Warm Period. Whilst Lewin (2010) has noted that impact of flooding is poorly understood for the MWP, a number of other researchers (Table 9, 10, and 11) have suggested landscape instability around the 9th and 11th centuries. Human activity is again usually implicitly linked with many of these narratives. The link between landscape change post-AD1450 with climate change is more robust, and has also been correlated with a number of flood events in the uplands of northern England and Wales (Merrett and Macklin, 1994; Foulds *et al*., 2014).

Author	**Timing**	**Location & consequences**	**Potential drivers**
Brown 2009	post 800 AD	High colluvial and alluvial rates, Raunds	Open field expansion and climate change
Chiverrell *et al*., 2007	950-1150AD	Solway Firth upland gullying	Population expansion
Chiverrell *et al*., 2007	post 1450 AD	Solway Firth upland gullying	Population expansion and climate change
Chiverrell *et al*., 2008	680-1250 AD post 1450 AD	Howgills Fells upland gullying	Population expansion and climate change
Foulds & Macklin 2006	950-1100 AD 1350 AD 1750 AD	Periods of floodplain instability in the Tyne	Land use change, metal mining and climate change
Jones *et al*., 2010	420-1120 AD 1410-1880 AD	Increased flooding in Welsh rivers	Climate change
Macklin *et al*., 2013	1050-1150 AD 1250 AD 1350 AD	Period of river incision in the upland-piedmont zone associated with increased flood frequency and magnitude	Climate change

Table 11: Episodes of increased fluvial activity noted across the UK, together with potential drivers of hydrological change

3.4. CAESAR-Lisflood modelling

3.4.1 Impact of climate change on future erosion and deposition

As mentioned in Section 2.2, future rainfall predictions were used to generate future flood events. These were 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 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. It follows that some of these 20 random simulations may be larger than others and hence the volume and pattern of erosion and deposition will vary between events; therefore rates were combined and averaged to produce mean erosion and deposition patterns, which are presented in Figures 4 and 5. The World Heritage Site reach of the Derwent has been split into an upper and lower section to allow larger, more detailed images to be shown. In the figure key, the range from yellow to red corresponds to increasing erosion, whereas increasingly dark shades of blue to purple correspond to increasing levels of deposition.

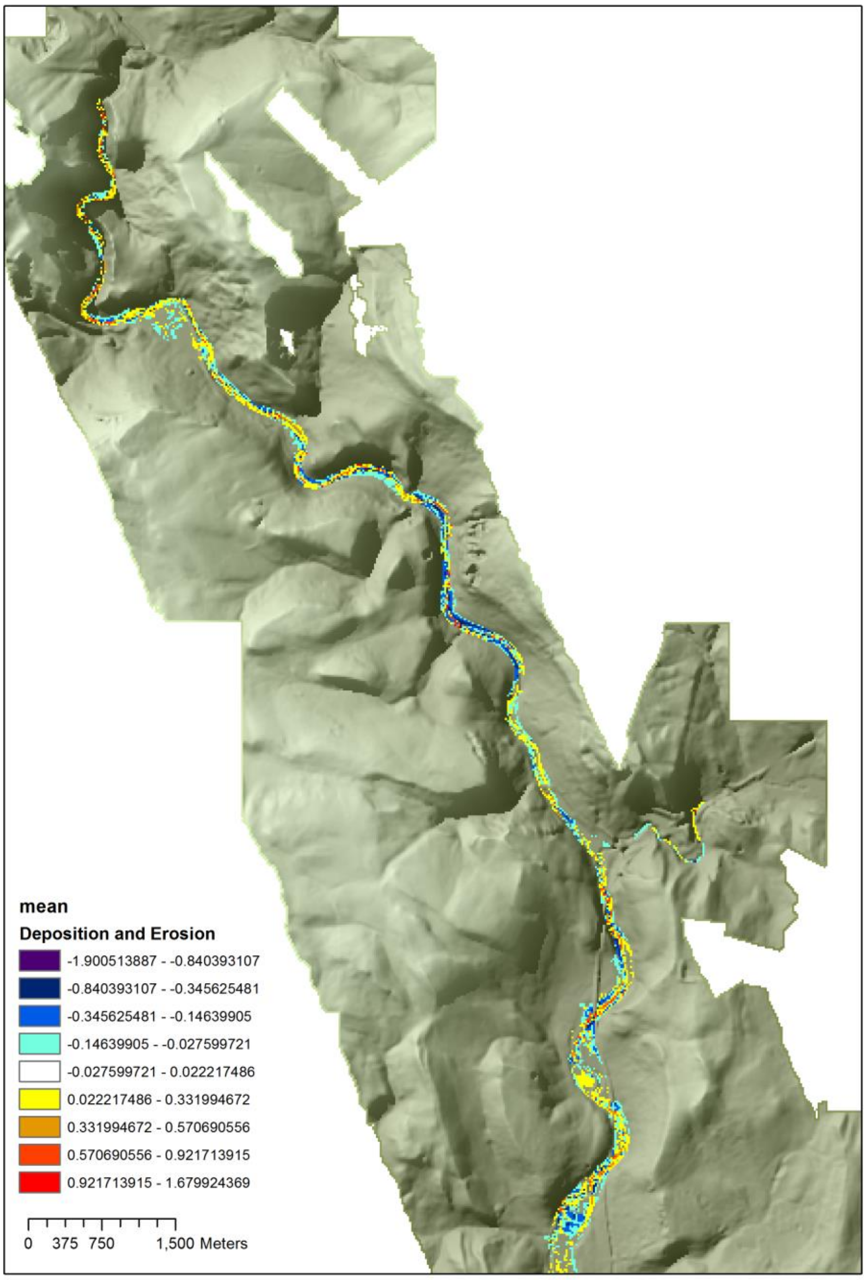

Figure 5: Erosion and deposition patterns in the upper WHS reach (yellow to red: increasing erosion; light blue to purple: increasing deposition) Source data © Environment Agency

Figures 5 and 6 show that whilst erosion and deposition occur throughout the WHS reach of the Derwent during the 30 year simulations, from a geomorphological perspective the levels of both are not especially significant. Only in very few places is mean erosion or deposition greater than 1m (vertically). In most locations where there is any change, it is in the order of a few centimetres. This indicates that, with its present geomorphological configuration, the overall landscape of the World Heritage Site would be relatively stable to any changes caused by climate change up to 2050. Whilst there may be some localised areas of erosion and sedimentation, there are no predicted dramatic shifts in the location of the channel or areas of high erosion and deposition. Piedmont river systems (like the Derwent) can be sensitive to changes in flood frequency and magnitude, and one danger is that reaches may become unstable, shifting from single thread to braided, more rapidly changing patterns. There are no indications of this whatsoever within the simulations carried out here.

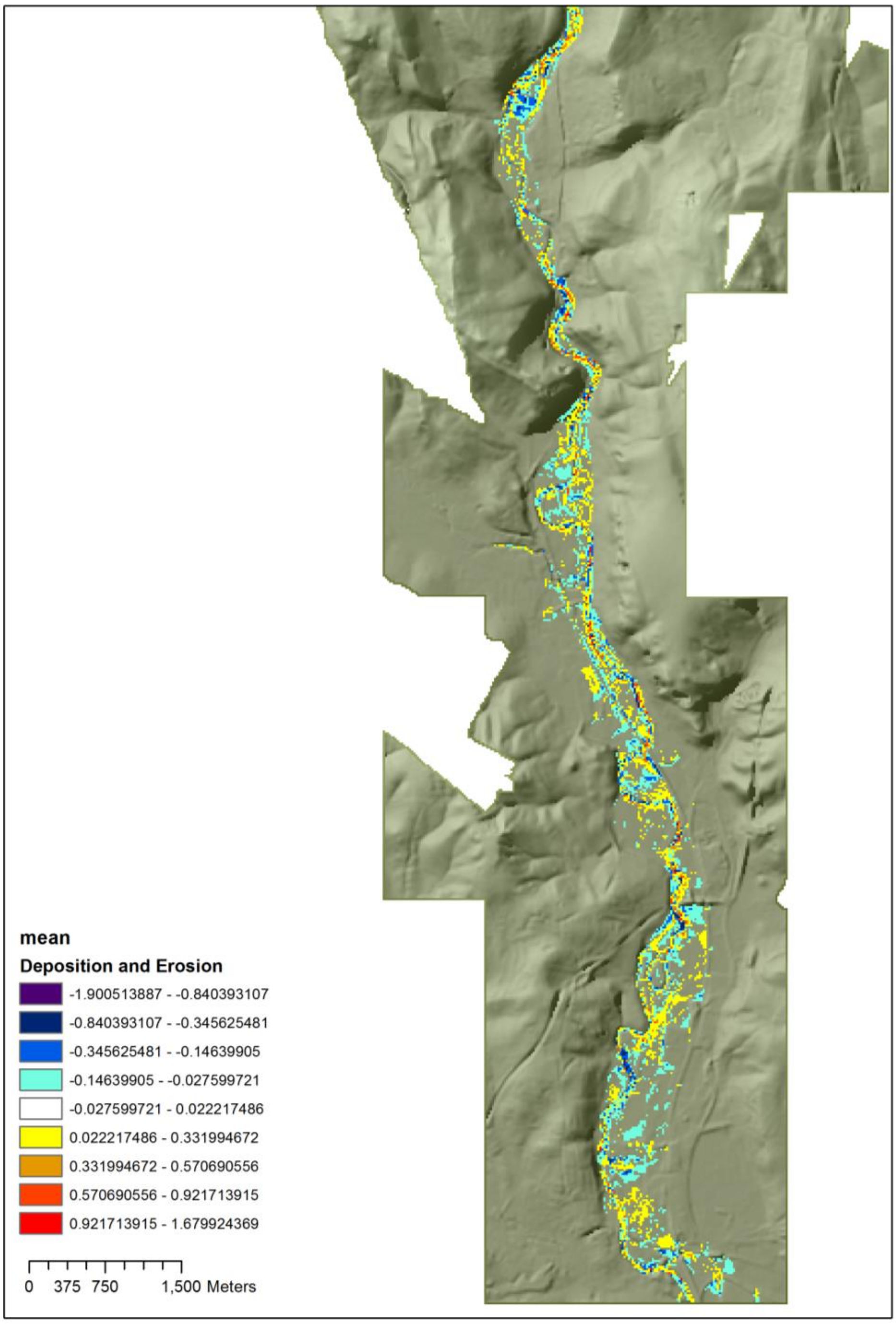

Figure 6: Erosion and deposition patterns in the lower WHS reach (yellow to red: increasing erosion; light blue to purple: increasing deposition) Source data © Environment Agency

The patterns of erosion and deposition that are predicted by the model are entirely within the parameters that may be expected within a comparatively stable river system. For example, Figure 7 highlights the area from upstream of Darley Abbey to Derby Silk Mill. Here we see evidence of some erosion, but the main fluvial process is deposition across the wide floodplain.

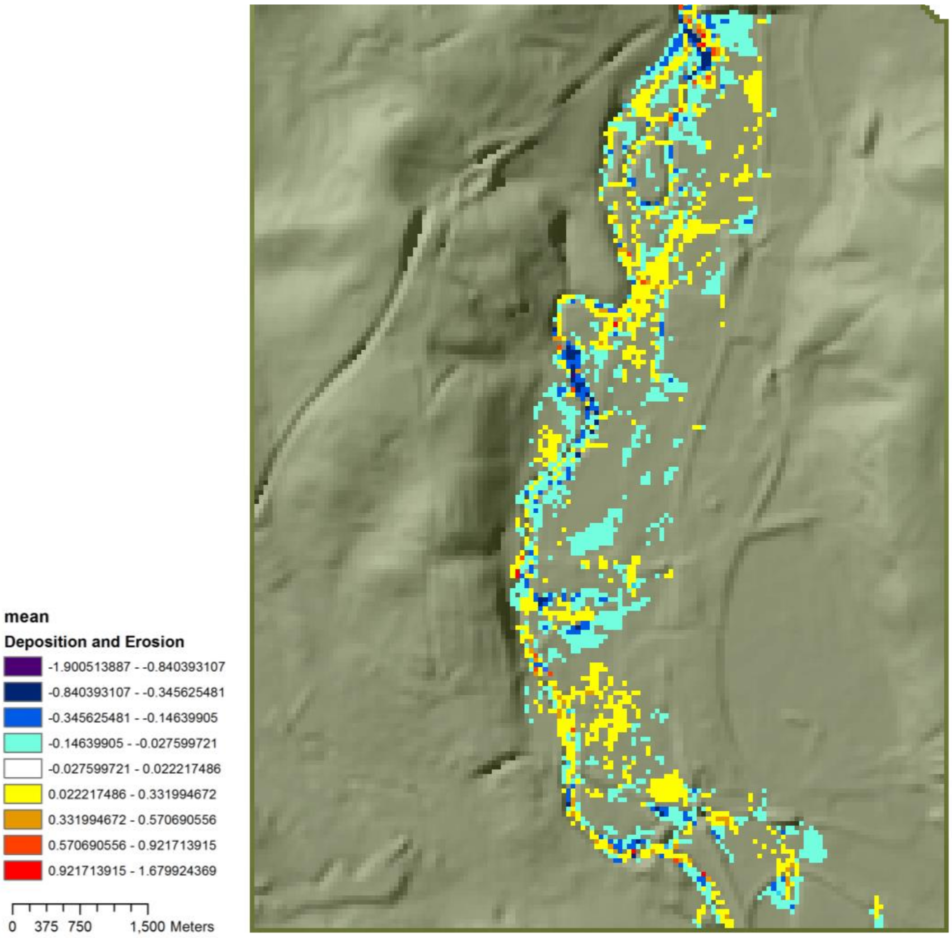

Figure 7: Mean erosion and deposition patterns for the Derwent from upstream of Darley Abbey to Derby Silk Mill, showing that the floodplain would mainly be affected by increasing sediment deposition (yellow to red: increasing erosion; light blue to purple: increasing deposition)

Upstream at Whatstandwell (Figure 8), and at several other locations, the simulations predict some lateral movement of the channel by the extension or migration of meander bends. However, such geomorphological activity is to be expected, and as shown in Figure 8 the predictions from the model simulations are broadly in keeping with the lateral erosion that from studies of historic maps may be shown to have occurred over the last 150 years.

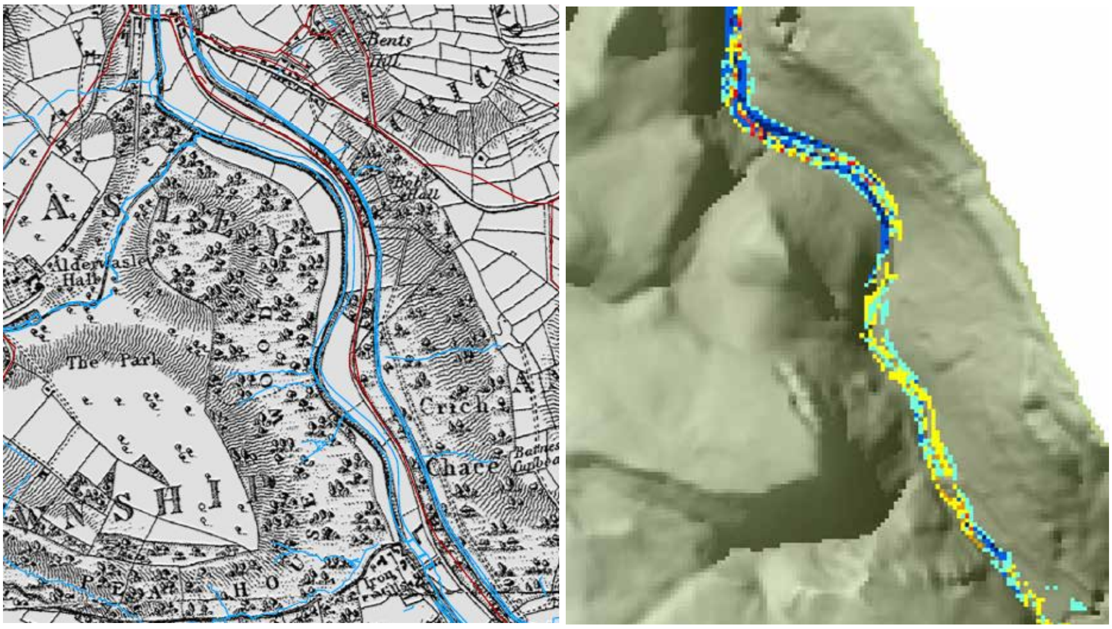

Figure 8: Left: Historic (1835) and present (blue outline) channel position of the Derwent at Whatstandwell. Right: Mean erosion and deposition patterns predicted by CAESAR-Lisflood modelling at the same site, predicting that with increased rainfall, slight lateral movements and increased deposition would occur simultaneously with lateral channel movement (yellow to red: increasing erosion; light blue to purple: increasing deposition)

Comparisons between the twenty predictions of erosion and deposition were made by plotting the standard deviation of erosion and deposition for the upper and lower sections of the WHS reach of the Derwent (Figures 8 and 9). These plots show that there is largely a good agreement between all the simulations, but highlight some important contrasts between the behaviour of the river in its upper and lower reaches. Lower parts of the Derwent (Figure 9) show a greater agreement between simulations, suggesting that this part of the valley floor may be more stable and less susceptible to changes in the size of flood events. Contrastingly, the upper reaches show greater variations in the response of the river to different flood events, with only some simulations indicating erosion and deposition, indicating therefore that changes in river behaviour are harder to predict in these upper reaches. However, the channel in the upper reaches of the Valley is far more constrained, within a narrower valley floor, and hence these landscape impacts are limited laterally. For example, the valley floor is not wide enough for the channel to avulse or move over to another part of the valley.

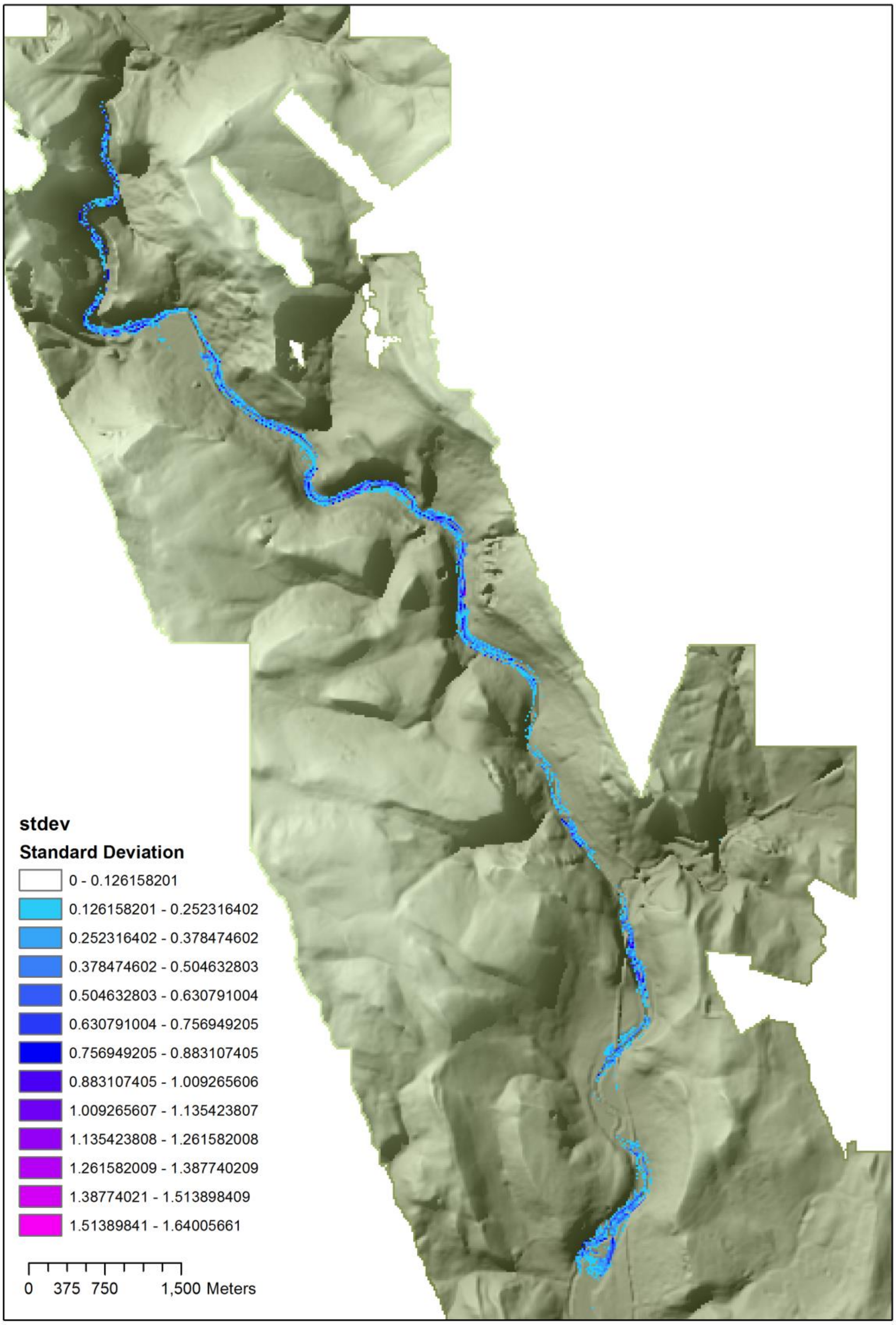

Figure 9: Standard deviation of erosion and deposition for the upper WHS reach. Gradation from light blue to purple depicts the increasing deviation from the mean.

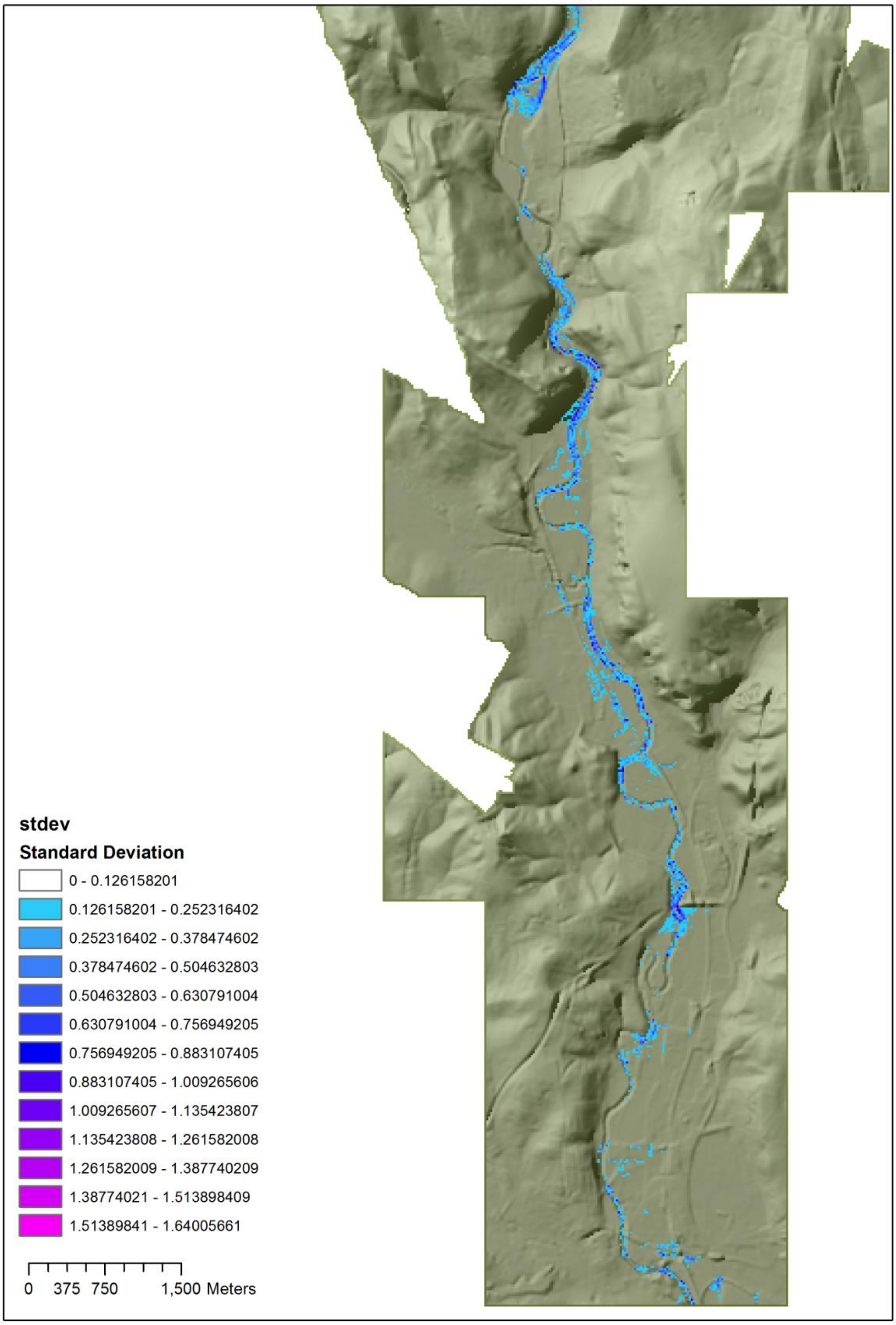

Figure 10: Standard deviation of erosion and deposition for the lower WHS reach. Gradation from light blue to purple depicts the increasing deviation from the mean.

3.4.2. Simulation of Landscape Change after Weir Removal

3.4.2a. Changes in Fluvial Erosion and Deposition

Figures 11 and 12 show differences in the levels of erosion and deposition over 30 simulated years between simulations with and without weirs. Both simulations started with the same topography, were driven by the same rainfall and experienced the same floods, the only difference being the modification of individual cells of the Digital Elevation Model representing weirs within the model to take account of changing gradients and flow conditions amongst other parameters. These results clearly show that erosion has occurred around a number of weirs and that this erosion has moved upstream in response to increases in the local water surface gradients that drive velocity and thus erosion. This incision is widespread and has moved, in most circumstances, *c*.1km upstream as the river establishes a natural gradient unmodified by river furniture such as weirs.

Interestingly, there is comparatively less deposition in response to this increased erosion. It might be expected that downstream of the removed weir there would be enhanced deposition as the grade of the stream bed rose to meet the decreasing upstream elevations. However, the amounts of deposition (denoted by shades of blue) are less and of smaller depths than the levels of erosion. There are only one or two locations within the upper reach where deposition amounts are shaded darker blue, indicating depths of deposits exceeding 1m. In addition, erosion and deposition are focused within the channel, signifying a concentration of erosion and deposition on the current river bed.

Importantly, changes in river bed elevation will have a direct impact upon the conveyance (carrying capacity) of the channel and therefore the risk of flooding at certain sites. Generally, incision will lead to increased conveyance and thus reduced flood risk, and vice versa for deposition. Therefore, as the weir removal leads to more erosion than deposition, the impact on flooding would be beneficial. However, erosion may also lead to localised instabilities in (for example) bank protection measures and potentially the undermining of bridge foundations. Changing the bed gradient in this way will also alter the velocities of river flows, which will impact in turn upon conveyance and thus flood risk. Further modelling could be carried out to show whether or not this has an effect upon flood risk along the Derwent reach studied.

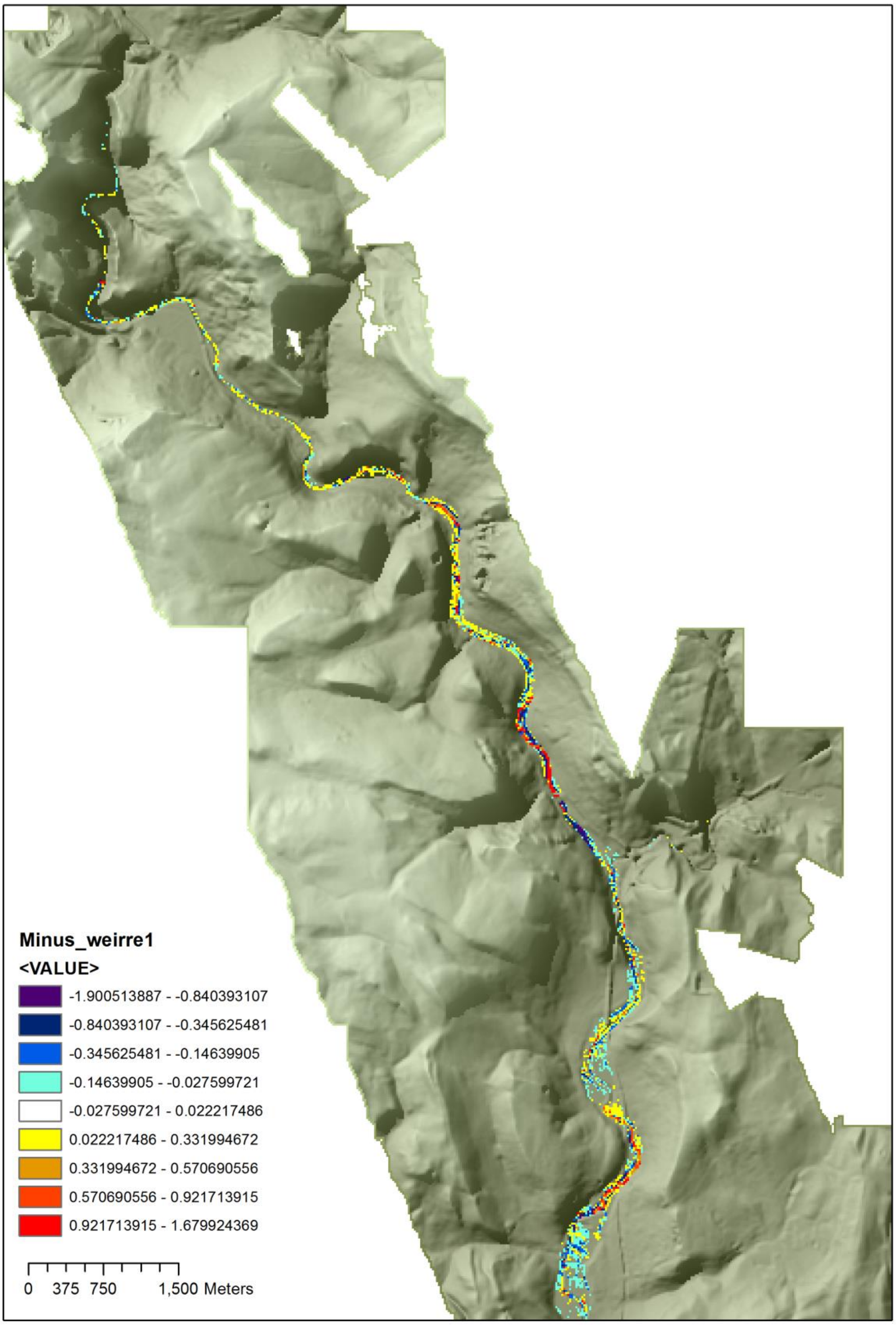

Figure 11: Difference in erosion and deposition between simulations with and without weirs for the upper 10km of the Derwent reach studied (yellow to red: increasing erosion; light blue to purple: increasing deposition)

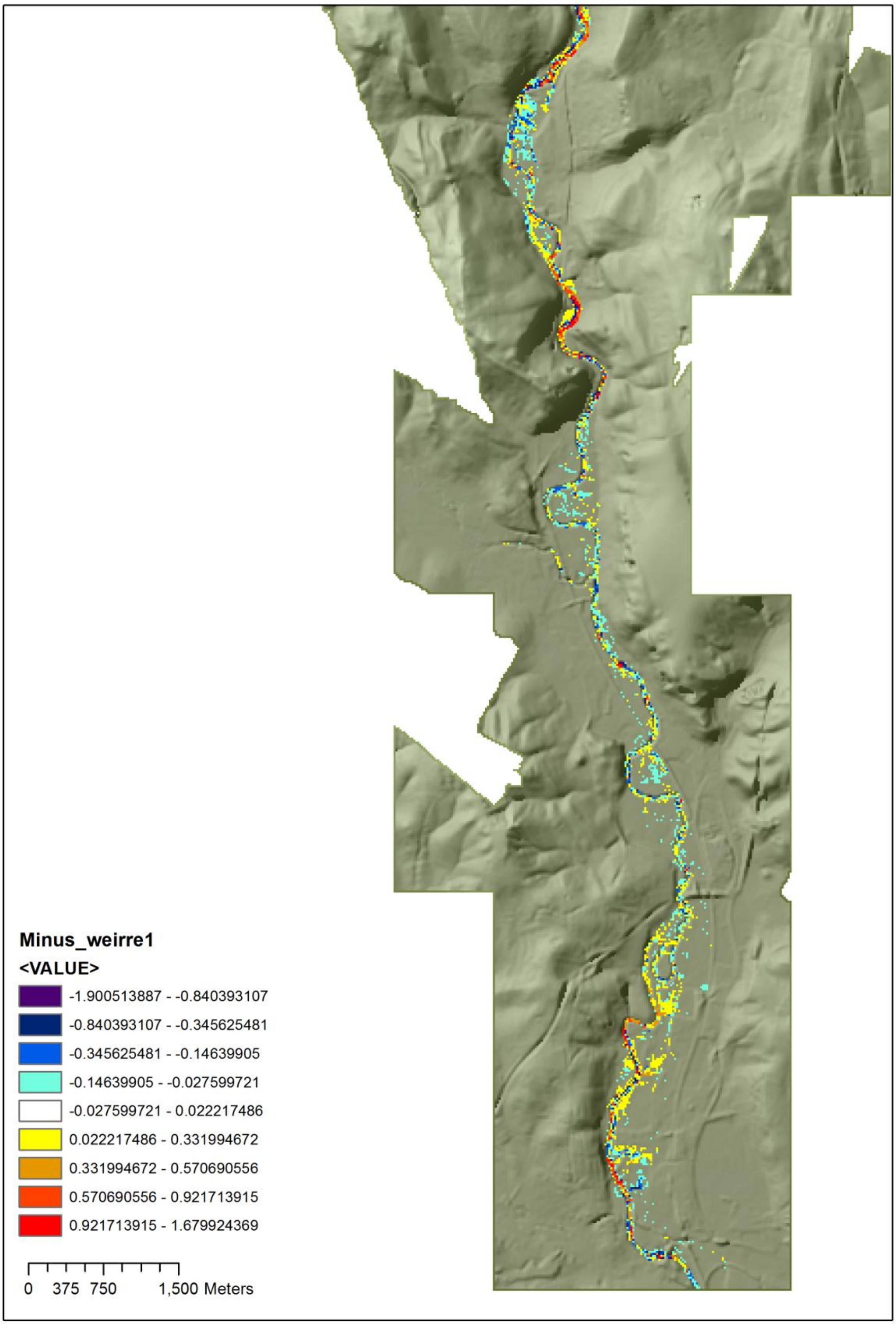

Figure 12: Difference in erosion and deposition between simulations with and without weirs for the lower 10km of the Derwent reach studied (yellow to red: increasing erosion; light blue to purple: increasing deposition)

3.4.2b. Sediment Yield Changes

Figure 13 shows the cumulative sediment yields from the simulated reach of the Derwent with and without weirs. Sharp rises in the sediment yield levels (Figure 12) correspond to flood events where larger amounts of sediment are removed from the reach.

Simulations without the weir structures show a greater than 100% increase in sediment yield where more erosion than deposition was observed, thus supporting the findings above. It was expected that differences would be greatest in the first ten years following weir removal, as the channel bed adjusted to its new gradient. In effect, the freshly removed weirs left a greater amount of sediment to be removed at the beginning of the simulations. However, the rates of sediment removal appear to remain continuously higher for the simulation without weirs, indicating that the reach is continuing to adjust to weir removal beyond the 30 years that were simulated.

Increases in the sediment that is transported downstream may have detrimental environmental and management issues in the wider catchment. The deposition of sediments farther downstream could lead to possible siltation and deposition issues in the urbanised zone of Derby and beyond. Such a scenario is therefore likely to have a negative impact on conveyance and thus flood risk in the City and in the wider expanse of the Derwent Valley down to the confluence of the Derwent and the Trent.

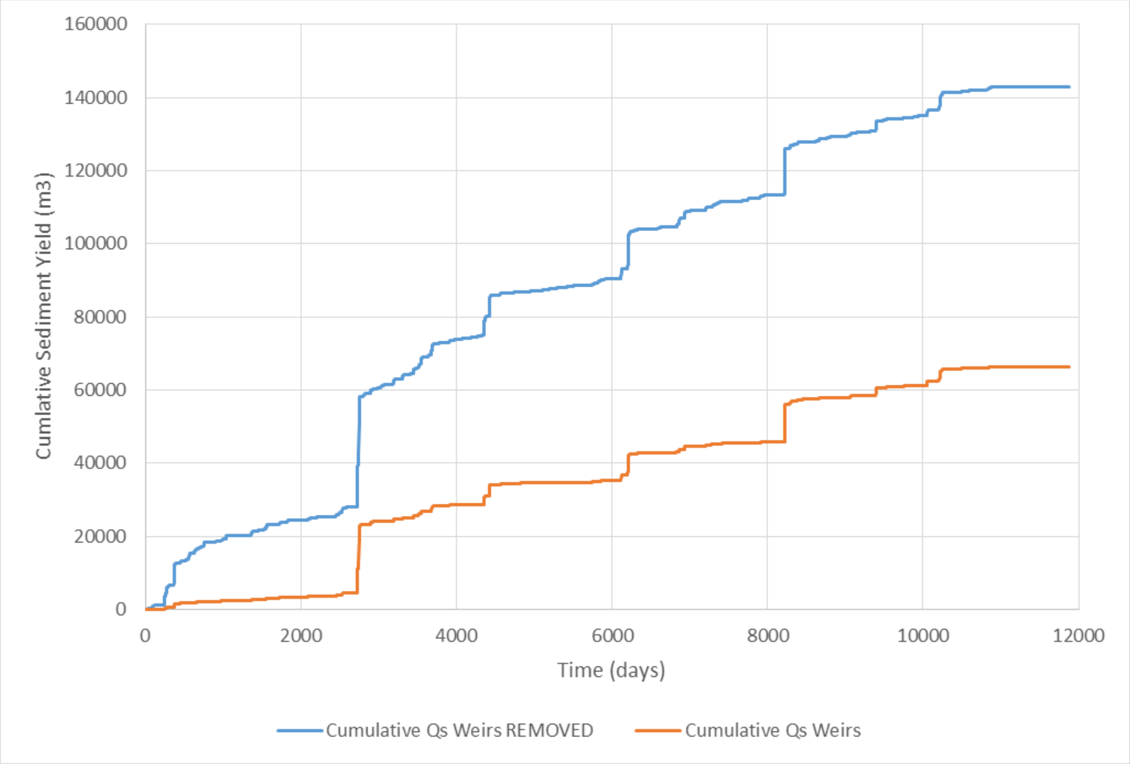

Figure 13: Cumulative sediment yields from the simulated reach with and without weirs.

4. DISCUSSION

4.1. Landscape evolution over the last millennium

This project has assembled a considerable amount of information from landforms, sediments, archaeological and built environment data, advancing significantly our understanding of the landscape history of the Derwent Valley over the last millennium, particularly within the World Heritage Site and its Buffer Zone. It has provided valuable information on the type, pattern and intensity of past geomorphological processes, which in turn may aid our understanding of the potential impact of changing climatic conditions upon the riverine environment and the archaeological and built environment resource.

The project has identified a number of major palaeochannels within the DVMWHS, although they are not well developed upstream of Milford, reflecting the limited 'accommodation space' upon the floodplain, which restricts palaeochannel preservation. Where palaeochannels are preserved upstream of Milford, they are simple, linear features close to the modern channel and relatively modern.

Downstream of Milford, the valley floor widens significantly and the contemporary channel is highly sinuous. Mapping of landform assemblages identified a significant number of palaeochannels, which can be divided into three types: (1) major sinuous channels with wavelength amplitudes and dimensions similar to the modern channel; (2) minor distributaries irregularly scattered across the floodplain surface; and (3) minor but regular channels in parallel groups that are indicative of ridge and swale topography. Whilst no coring was undertaken to ascertain the nature of the infilling sediments, it seems probable, from analogy with sites elsewhere in similar topographic contexts, that both the major and minor channels will contain organic materials of palaeoenvironmental value.

Inspection of historic maps suggests that the palaeochannels south of Milford predate the 1st Edition Ordnance Survey; although no absolute dates are available for any of these features, their relationship to archaeological remains does provide an insight into relative chronologies. Analysis of the lidar data has identified significant areas of ridge and furrow of varying dimensions and morphology, and there are several areas where past fluvial activity appears to truncate ridge and furrow earthworks. Assuming that the ridge and furrow dates principally to the High Medieval period (Section 3.2), we can postulate a period of agricultural expansion across the floodplain before a process of abandonment and floodplain erosion. It is tempting, therefore, to correlate this deterioration with the climatic downturn of the Little Ice Age.

Review of palaeoflood data indicates that ten major floods are documented for Period 1 (AD 1066-1539) and 31 for Period 2 (AD 1540-1900). Reconstructing flood histories for Period 3 (AD 1901 to the present day) is much more problematic due to regulation of the Derwent between 1912 and 1940, but five major floods are documented for the period 1901-1940. These data clearly demonstrate that the period of maximum flood frequency (Period 2) coincides with the climatic deterioration associated with the Little Ice Age (1450-1850), agreeing in this respect with other studies in the UK and Europe (e.g. Foulds *et al*., 2014).

The deposits mapped as Head by the BGS appear to have a close relationship to terrace fragments at the valley margins. By analogy with deposits elsewhere within the UK, these deposits are probably of Late Pleistocene or early Holocene date and demonstrate the movement of material between the valley sides and valley floor (slope-channel coupling), in turn supplying sediment to the river system. From analogy with river systems across the UK, it is likely that there have been a number of periods of increased slope-channel coupling, particularly in later prehistory but also during the Middle Ages, and most probably associated with a combination of land-use change and climatic deterioration (Foulds and Macklin, 2006; Brown 2009). However, to date, no detailed studies have been undertaken of the timing of alluviation or the vegetational and land-use histories of the Derwent Valley, and these are certainly aspects of research that would benefit from further study.

Some indication of the timing of part of the fine-grained alluvial sequence is provided by the base-metal contaminated alluvium, which is a common feature of the floodplain soils and reflects the impact of mining activity within the catchment (discussed below).

4.2. History of Metal Contamination

There are no currently operating base-metal mines in Derbyshire, and hence contamination issues relate only to historic mining. The majority of the evidence for base-metal mining dates from the High Medieval period onwards, although it was during the 18th and 19th centuries that mechanisation spurred the development of the industry (in particular, the development of steam engines which, by allowing groundwater to be pumped away from workings, allowed ever deeper prospection).

For the entire Derbyshire orefield, overall ore production has been estimated to be in the millions of tons, the bulk of this being sourced from within the Derwent catchment. Estimates for individual ores range from 3-6 million tons of Pb and ¼-½million tons of Zn (Ford and Rieuwerts, 1970) to 2.5 million tonnes of Pb (Palumbo-Roe and Coleman, 2010). The Mill Close mine at Darley Bridge produced around 70 % of Derbyshire Pb, and almost all of the Zn, during the late 19th and early 20th centuries and was the last major mine to close in 1939, following severe flooding (Brearley, 1977; cited in Zhang, 2008).

Whilst dedicated Pb extraction may have finished, Glebe Mines (Stoney Middleton) produced around 100 tons of Pb concentrate annually, although indirectly as a valuable bi-product of fluorspar mining (Lusty, 2010). However, two severe spills from a mine tailings dam occurred from the company's waste depositary in 2007; the company subsequently went into liquidation and operations ceased (Deloitte, 2012).

4.3. Risk Assessment

Despite gaps in our knowledge of the Derwent Valley, empirical evidence amassed by this study indicates that the DVMWHS is a dynamic landscape, which has undergone considerable transformation over the last millennium. In the light of future climatic and environmental change, this understanding of past events and processes may help to contextualise potential future geomorphological activity, although the catchment-scale regulation of the river during the early part of the 20th century, together with more recent flood management initiatives, have undoubtedly resulted in some changes to the natural response of the local hydrological system.

4.3.1. Geochemical risks

Based on data analysed as part of this project for both the Derwent catchment and the Trent main river downstream, and drawing upon the experience of Professor Hudson-Edwards and Dr Kossoff in other mining-contaminated catchments, it is very likely that the area around the DVMWHS is contaminated with Pb, Zn and Cd arising from historic mining and remobilisation of mining-contaminated sediment. Moreover, it is likely that over time further contaminated sediments will be mobilised from the Derwent catchment upstream to be deposited in and around the DVMWHS.

In many cases, the Pb, Zn and Cd concentrations in the sediment that is already deposited around the DVMWHS exceed national and international guidelines for soils and human health, suggesting that the sediment may pose risks to ecosystems, infrastructure and health. The main risks to humans are the inhalation or ingestion of metal-contaminated sediment. If expanded outdoor leisure activities are promoted under a scenario of future ameliorating climate, these health risks may well need to be considered (including the location of picnic facilities, the stabilization of areas of bare ground and access points to the river).

The infrastructure of the WHS itself may be at risk in two ways from contaminated sediments. First, the remains may be at chemical risk from the contaminated sediment interacting with water on the floodplain. This could result in the formation of various types of mineral scale and local changes of the acid/alkaline balance, thereby potentially attacking the fabrics of the textile mills and other buildings that form important elements of the World Heritage Site's historic environment resource. Secondly, if contaminated sediments on the valley floor are actively remobilized as opposed to passively dispersed), the river may become braided (multi-channelled) in character, which in turn could result in the erosion and destabilisation of key heritage assets.

For the middle and lower parts of the Derwent river system, the soil contamination data collated in this review were largely sourced from sampling carried out in the late 1970s and 1980s. There is a paucity of contemporary data describing soil contamination for this floodplain, and collection of such data would help to understand changing contamination levels and hence environmental conditions. Such a programme of work would be beneficial from the perspective of assessing and refining the likely impacts of future climate change on the wider landscape and heritage assets.

Furthermore, there is an absence of data on the condition of historic mine sites, especially the stability of mine waste around entrances and processing areas and its potential for remobilisation within the fluvial system under changing conditions. The Glebe Mine tailings dam spill demonstrated the potential for catastrophic failure, which could release large volumes of toxic materials into water courses and cause significant long-lasting environmental impacts (Kossoff *et al.*, 2014). The erosion of unvegetated and/or disturbed mining sites in response to the greater surface runoff that would accompany predicted changes in rainfall intensity is equally significant (Howard *et al.*, 2015) from the perspective of both human health and erosion of the historic environment resource.

4.3.2. Modelling Erosion and Deposition

Modelling simulations of the Derwent Valley between Derby and Matlock Bath indicate that, from a geomorphological perspective, there should be minimal issues with sedimentation or erosion problems in response to changing flood patterns up to 2050. 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 contaminants within the wider floodplain may not be remobilised significantly as a consequence of future changes in climate (Figure 14). We can, however, identify stretches of the river where intensified erosion or deposition may be expected to impose pressures upon the the historic environment resource, especially as some materials are likely to be contaminated with heavy metals: for example, bankside erosion adjacent to historic mill complexes or the burial beneath accumulating floodplain deposits of denuded ridge and furrow earthworks. Zones of enhanced erosion and deposition for the upper, middle and lower reaches of the Derwent where it flows through the World Heritage Site are highlighted in Figures 14A-C, together with the key historic mill assets. Some of the mill complexes, such as those at Masson (Fig 14A) and Milford (Fig.14B), appear little affected by increased erosion, but others, particularly at Belper (Fig.14B) and Darley Abbey (Fig.14C), are more vulnerable to intensified fluvial erosion and hence will require tighter monitoring and management. Beyond the mill complexes, the maps presented in this report and the GIS from which they are derived 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 historic environment resource: for example in the vicinity of Whatstandwell, where the model predicts unusually intense fluvial erosion (Fig. 14A), 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 (Derwent Valley Mills Partnership 2011, 67; Figs 4 and 14B).

Regarding flood risk, the erosion and deposition predictions suggest that there is little likelihood of significant changes in the overall channel shape or shifts in channel position. There will be little change, therefore, 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. It is important to note that these results are all based on the assumption that there are no major changes in channel or floodplain infrastructure and that the existing flood defences and fixed structures (notably weirs and bank protection) will be maintained in the future. For the reaches of the Derwent upstream of Derby and within the DVMWHS, the removal of historic weirs may be expected to have a less severe impact upon the geomorphology than might have been expected prior to the analyses reported in this document. In general, the removal of dams and weirs can have a profound impact on river behaviour, promoting erosion, deposition and increased channel instability. However, the simulations described in this document indicate that, whilst there is erosion and deposition, the effects of these processes are not severe and appear relatively well-constrained within the present day channel belt. There may well be local impacts of incision and deposition that are not indicated here, but overall the predicted impact is not profound. However, comparison of the locations of erosion hotspots and archaeological or built environment assets, summarised in the maps accompanying this document, is essential for developing an understanding of how potential changes might affect the historic environment record and formulating appropriate mitigation strategies.

Erosion and deposition would also have significant impacts upon the in-stream and riparian ecology. Areas behind weirs that are presently slow flowing and ponded would change to environments with faster flows, and it is likely that pool and riffle sequences would develop through time. This would in effect remove one type of habitat (ponding and slow water) yet restore a different (pool riffle) channel habitat.

Downstream impacts, beyond the World Heritage Site, are less certain. The sediment that is presently backed up or stored behind the weirs along the Derwent would be released if weirs were removed, and a large proportion of this sediment would be evacuated downstream below the limits of the simulations conducted during this project (i.e. beyond the World Heritage Site). This wider area includes the City of Derby, and it is quite possible that weir removal could lead to sedimentation and siltation issues within the City and in river reaches farther downstream, towards the Trent-Derwent confluence. Such developments could, of course, have a negative impact both upon channel management and flood risk scenarios.

The release of trapped sediment arising from weir removal could also prove problematic if these sediments were contaminated with heavy metals from past mining and industrial activity. Weirs, dams and mill ponds provide ideal locations for sediment to be trapped and become deposited. As the simulations have showed, removing weirs re-activates these areas of deposited sediment, releasing them into the river and allowing them to move downstream. If released sediments are contaminated with heavy metals, this may have other environmental and health implications. Removal of the weirs would, therefore, also require extensive removal and safe disposal of the sediments trapped behind them.

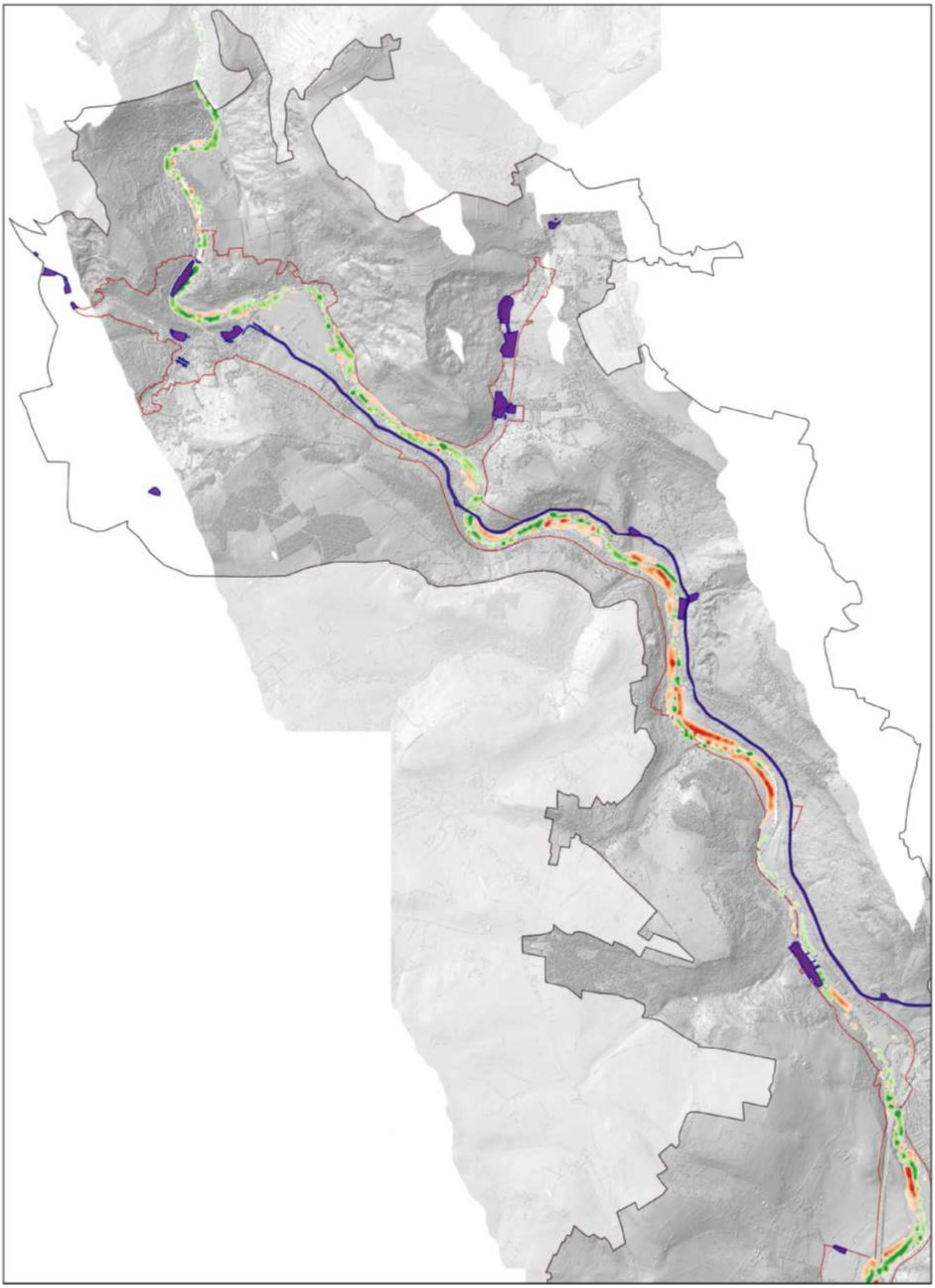

Figure 14a: Modelling of erosion (red) and deposition (green) in relation to HER entries in the upper part of the study area (1:25000 @ A3) Source data © Environment Agency

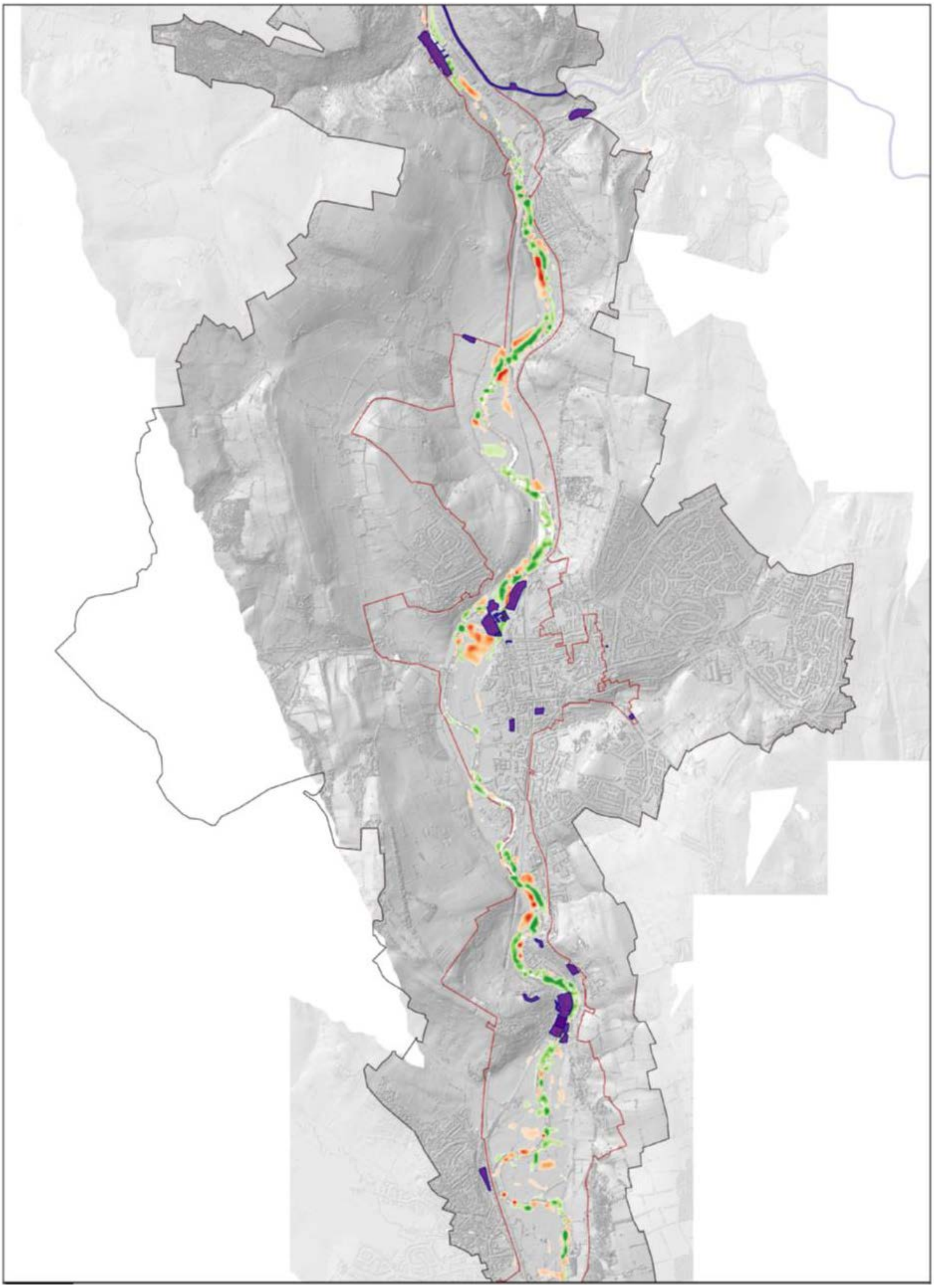

Figure 14b: Modelling of erosion (red) and deposition (green) in relation to HER entries in the middle part of the study area (1:25000 @ A3) Source data © Environment Agency

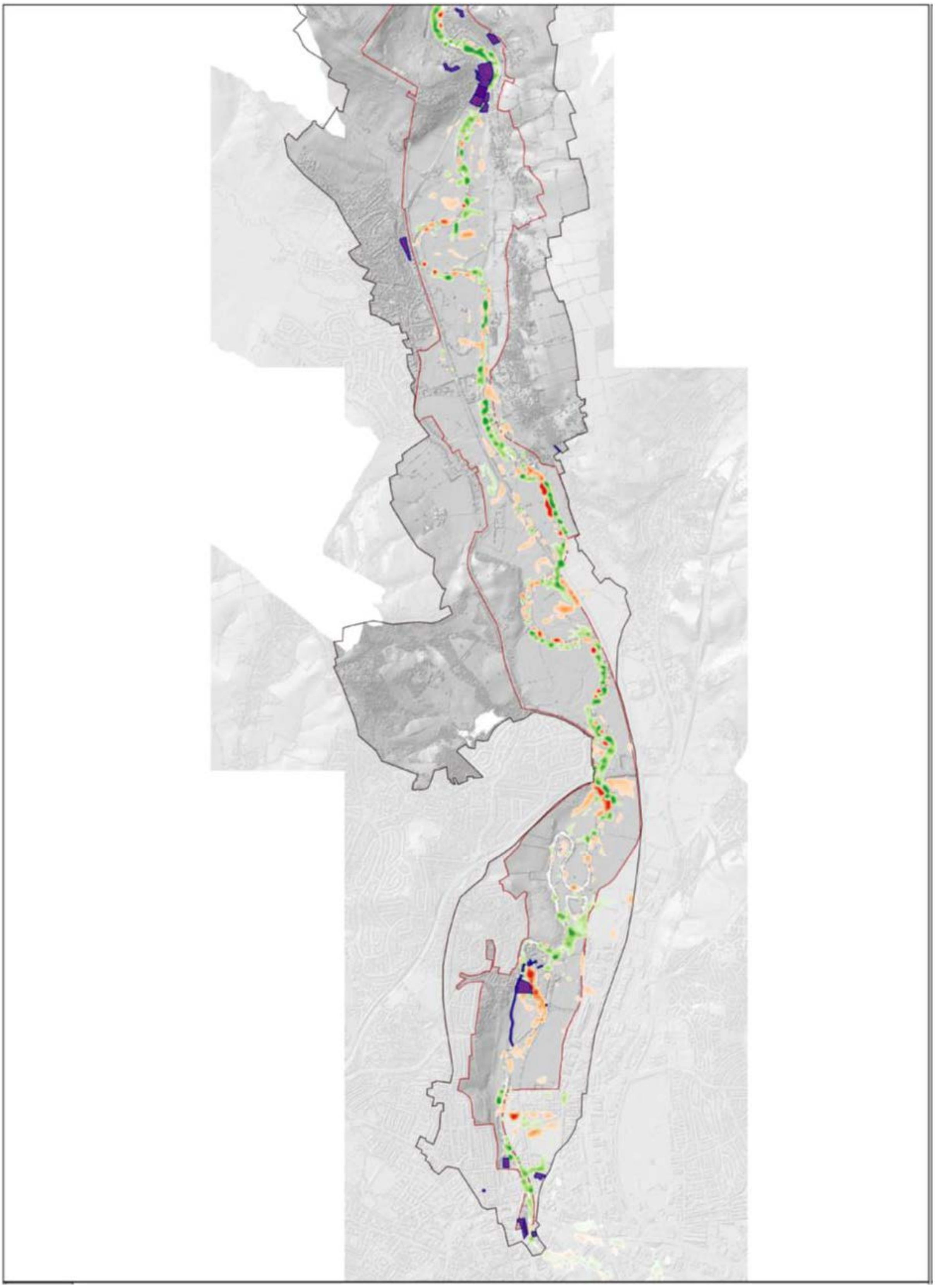

Figure 14c: Modelling of erosion (red) and deposition (green) in relation to HER entries in the lower part of the study area (1:25000 @ A3) Source data © Environment Agency

4.4. Implications for DVMWHS research and management frameworks

This project has contributed significantly to the developing Research Framework of the DVMWHS (www.derwentvalleymills.org) and in particular to Agenda Theme 10 (Landscape and Environment) and sub-themes 10B (hydrological development), 10D (flood histories) and 10E (impact of past mining activity on river pollution). Furthermore, it has identified gaps in our knowledge, including vegetation history and land-use changes, which support further research priorities identified in the research framework.

4.5. Generic lessons

4.5.1 Approaches to Resilience and Disaster Planning

This project provides a methodological approach to assessment of the potential impact of future climate and environmental change on the DVMWHS, based upon an understanding of past landscape inheritance and evolution, geomorphological processes and human interaction with the environment. It emphasizes the need to look beyond individual heritage assets, in this case principally the historic mills and other buildings that define the World Heritage Site, and to take a holistic (tool-kit) approach in which these assets are considered part of the wider landscape system.

As a methodological approach, this tool-kit has generic applicability beyond the DVMWHS for other World Heritage Sites within the UK, but it could equally be applied to less well-protected, lower status heritage assets. Furthermore, it also could be applied in different geomorphological and climatological settings and to shorter term events (including extreme events), provided that the heritage practitioner can identify features of landscape inheritance, past geomorphological environments and processes.

Whilst much of the study can be undertaken by heritage practitioners, it must be recognised that this study requires a multi-disciplinary team approach, in this case engaging specialists with skills in geochemistry and computer modelling. Once a framework for past environments, processes and events is established, it can provide a platform for analysing future change based on a range of scenarios.

4.5.2. World Heritage site management

The potential impacts of climate change on World Heritage Sites are being increasingly recognised (Colette, 2007; UNESCO (2007, 2008; Perry 2011; Howard, 2013), reflecting a wider growing concern of likely impacts on heritage assets (English Heritage, 2003; Cassar, 2005; English Heritage, 2006a; Howard *et al*., 2008; Kincey *et al*., 2008; Murphy *et al*., 2009; English Heritage, 2010; Croft, 2013). This literature forms part of a wider corpus of work focused upon the potential impacts of climate change and extreme weather on society and the need for improved planning and preparation (e.g. Defra, 2012; Royal Society, 2014).

UNESCO published a strategy in 2007, requesting that World Heritage Sites integrate climate change issues within their Management Plans as they are updated. English Heritage has begun to implement this policy, with the consideration of climate change issues in the revised plan for Stonehenge and Avebury (English Heritage, 2015), although a recent survey by Phillips (2014) suggests that site managers across a number of WHS may need more support in the consideration and implementation of such plans.

The climate change guidance and associated risk assessment developed for the Stonehenge and Avebury World Heritage Site (SAWHS) was based upon the results of a workshop and field visit by a group of invited participants. The assessment identified 22 possible impacts, which are considered under the two climate change scenarios considered most likely, namely a) wetter conditions and b) hotter conditions. These impacts have then been assessed in turn in terms of their likelihood, severity and the timescale of change (Table 12). It is debatable whether climate change can be neatly packaged into two contrasting climate types, since it is probable that weather patterns will become more variable, leading to shorter intense periods of wetter or dryer conditions: as reflected perhaps by current shifts in the position of the jet stream. Therefore, this document prefers to assume more intense activity of current weather patterns.

Likelihood	**Severity**	**Timescale**
1. Very likely/definitely 2. Likely 3. Not very likely	1. Wide impact/very severe impact 2. Limited impact / moderate impact 3. Very limited impact/low impact	S. Short range (already apparent) M. Medium range (10-20 years) L. Long range (by the end of the 21st century)

Table 12: Assessment of scores for patterns of change. Reproduced from English Heritage's *Climate Change and Risk Assessment for SAWHS* (2015)

The DVMWHS project described in this document provides a valuable opportunity to apply the SAWHS model to a second World Heritage Site in the UK, and one which contrasts with Stonehenge and Avebury in a number of ways (Table 13).

	DVMWHS	**SAWHS**
Solid Geology	Carboniferous and Permo-Triassic limestones, sandstones, siltstones and mudstones	Cretaceous chalk
Superficial geology	Glacial till on interfluves, river terrace, head and alluvial deposits in valley floor	Clay with flints on interfluves, river terrace, head, alluvium and colluvium in valley floors
Natural hazards	Evidence of slope failure in upper part of system	None
Physiography	Large piedmont river valley	Plain with relatively small incised dry valleys of periglacial origin and river valleys (e.g. Avon, Kennet)
Agriculture	Mixed farming landscape and significant areas of woodland	Largely treeless, managed grassland
Industry	Significant past textile and mining industries, resulting in significant pollution and harnessing of natural processes	None
Heritage Assets	Predominantly Medieval to Modern	Principally prehistoric
Major Infrastructure Assets	Main rail line, road and canal in central axis of valley floor	Limited road network
Settlement	Densely populated	Sparsely populated

Table 13: Contrasting characteristics of the DVMWHS and the SAWHS

A key problem when applying such a scheme to the Derwent Valley is that the World Heritage Site is one part of a much larger, dynamic catchment system, where wider management issues may have significant repercussions for the Site and its Buffer Zone. The following Table 14 provides a risk assessment specifically for the DVMWHS, which assumes that there will be no change to major changes to the regulation and management of the river system, including flood defences.

DVMWHS RISK ASSESSMENT				
		Likelihood	Severity	Timescale
1	Increased riverine flooding	3	2	L
1.1	CAESAR modelling suggests that the overall channel capacity is sufficient to cope with additional precipitation levels, although local problems may occur and damage the built heritage.			
1.2	Historic Water Management Assets (HWMAs) and other hard structures within channels (e.g. bridges, revetments etc.) may fail under pressure, especially if blocked by vegetation etc.			
1.3.	Localised erosion of archaeological remains may occur on the floodplain			
2	Increased surface water flooding	1	2	S
2.1	Blockage of culverts and lack of capacity within existing artificial drainage infrastructure will probably cause local damage to the built heritage			
2.2	Spread of hard standing and impermeable surfaces will increase local runoff and damage built heritage			
2.3	Localised erosion of archaeological remains may occur through processes such as gullying			
3	Changing patterns of erosion and deposition of the river in the immediate floodplain	2	2	M
3.1	Localised bank erosion where natural and artificial protection fails or is limited may lead to erosion of archaeological remains and potential undermining of HWMAs			
3.2.	Localised erosion may lead to remobilisation of contaminants			
3.3.	Localised deposition within the channel and across the floodplain will result in reduced flow capacity and will enhance the flood risk to built environment resources.			
4.	Increased slope-channel coupling of both contaminated and uncontaminated sediments	2	2	M

4.1	Changing agricultural land-use practices may contribute to soil degradation, leading to the erosion of archaeological remains and pollution of the built heritage if delivered via flooding.			
4.2.	Changing land-use practices in previously mined landscapes may enhance sediment erosion, thereby damaging local archaeological remains and increasing contaminated sediment delivery to the valley floor.			
4.3	Changing geotechnical conditions (e.g. changing groundwater flow patterns, pore-water pressures etc.) may provide favourable conditions for slope failure and hence the erosion of archaeological remains, subsidence of built heritage assets and enhanced sediment delivery to valley floors.			
5	Remobilisation of contaminated sediments within the fluvial system	1	1	M
5.1	Fluvial erosion may rework contaminated alluvium and change system thresholds, thereby enhancing the erosion of HWMAs and associated remains.			
5.2	Contaminated sediments may be deflated to new areas with toxic materials, which in turn may coat historic remains and, through chemical interaction, cause deterioration of local building fabrics.			
5.3.	Changing water chemistry may affect speciation of elements and the mobility of contaminants and through the changing chemistry may attack the fabric of historic assets.			
5.4	Deflated contaminants may be inhaled and ingested directly, affecting human health and the tourist economy.			
5.5	Deflated contaminants may be inhaled and ingested by livestock, indirectly impacting upon the food chain and local economy.			
6	Extreme weather events, such as storms and gales, causing damage to built environment and archaeological remains	2	1	S
6.1	High winds may directly damage the built remains of the WHS and/or uproot vegetation, which can undermine archaeological remains.			
6.2	Increased thunderstorms may lead to a greater risk of lightning strike, damage to buildings and wildfires.			
6.3	Flooding may directly damage the built remains of the WHS and erode both archaeological remains and sediments.			

7	Freeze-thaw damage to monuments	2	2	M
7.1	Freeze-thaw processes may damage the built remains of the WHS.			
8	Subsidence damage	2	2	L
8.1	Mass movement processes may damage the built remains of the WHS.			
8.2	Wetting and drying associated with flooding and groundwater changes may damage the built remains of the WHS.			
9	Changes in vegetation cover	3	2	S
9.1.	In rural areas, overgrazing and overpopulation by livestock may result in bare ground and damage to archaeological remains.			
9.2	Increased tourist use of the floodplain may result in bare areas and damage to monuments.			
9.3.	Changing climate may alter land-use, crop patterns and water abstraction, impacting directly on archaeological remains and sediment movement.			

Table 14: Risk assessment for the DVMWHS

The table above provides a provisional list of risks to the DVMWHS from future climate change. This analysis is rather less robust than that conducted around Stonehenge and Avebury, since the DVMWHS is part of a wider catchment system and we have not considered environmental impacts beyond the WHS. Such impacts may be considerable: for example, the upland blanket peats have been shown by this study to contain significant quantities of heavy metals deposited by atmospheric pollution, and if these were to be remobilised into the river system and moved downstream into the WHS, the impacts could be significant. Clearly, risk assessments in systems with complex environmental connections need to look beyond the scale of the immediate site, and we would recommend extension of the landscape assessment and modelling conducted here to the wider catchment of the Derwent.

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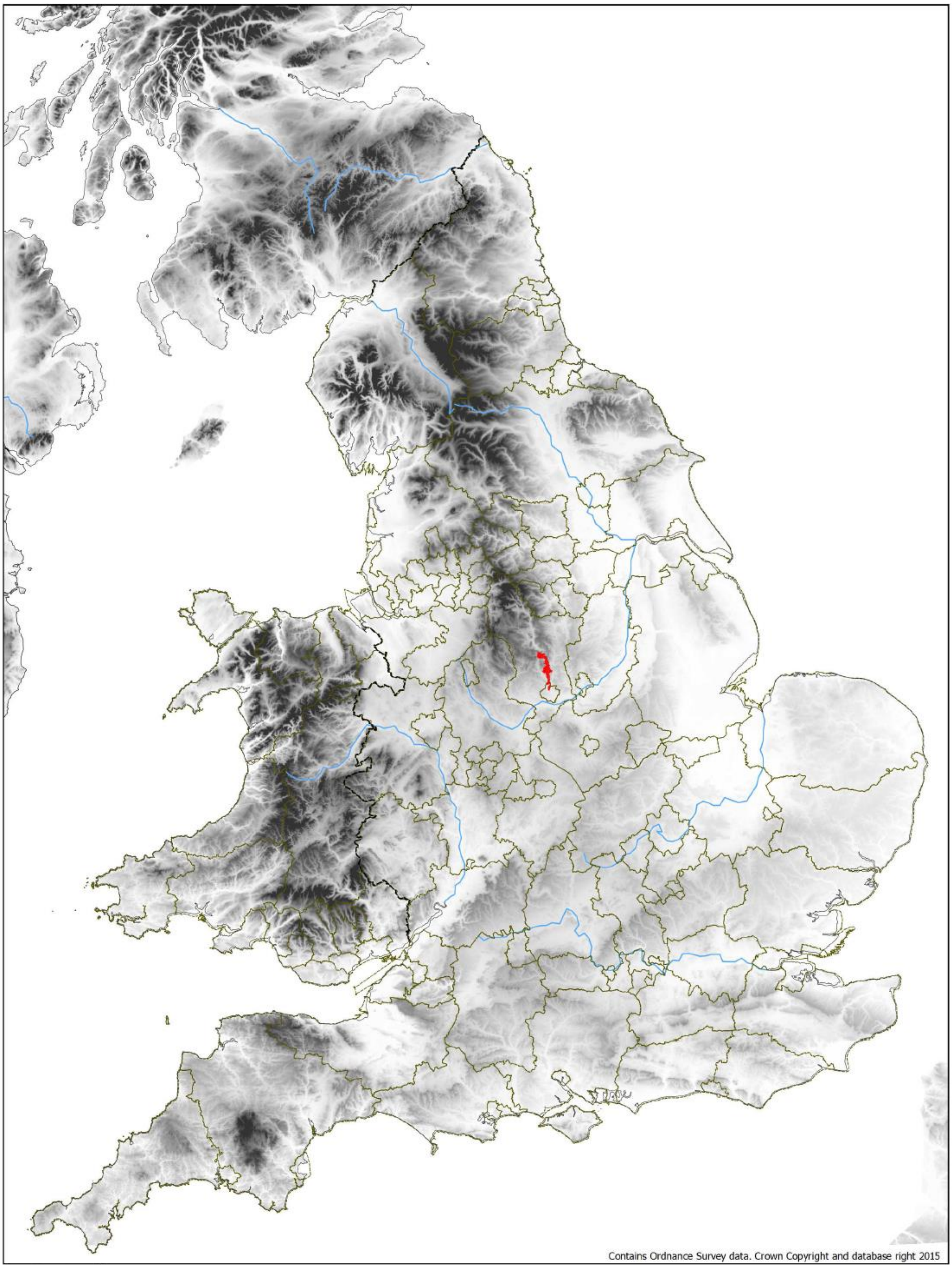


Figure 15: Location of the Derwent Valley Mills World Heritage Site (red) within the United Kingdom (1:2750000 @ A4) Contains Ordnance Survey data. Crown Copyright and database right 2015.

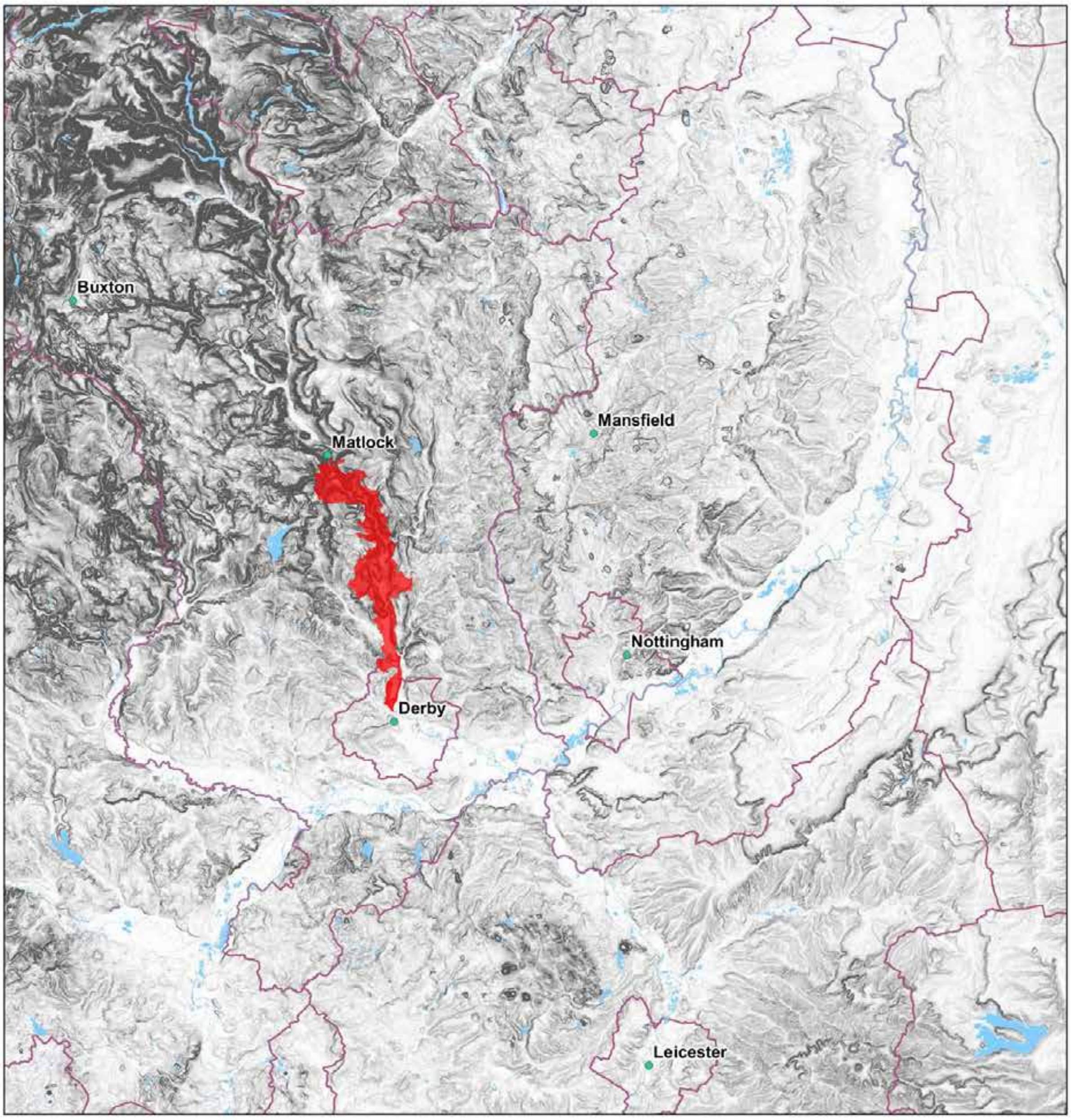


Figure 16: WHS study area within its regional setting (1:350000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

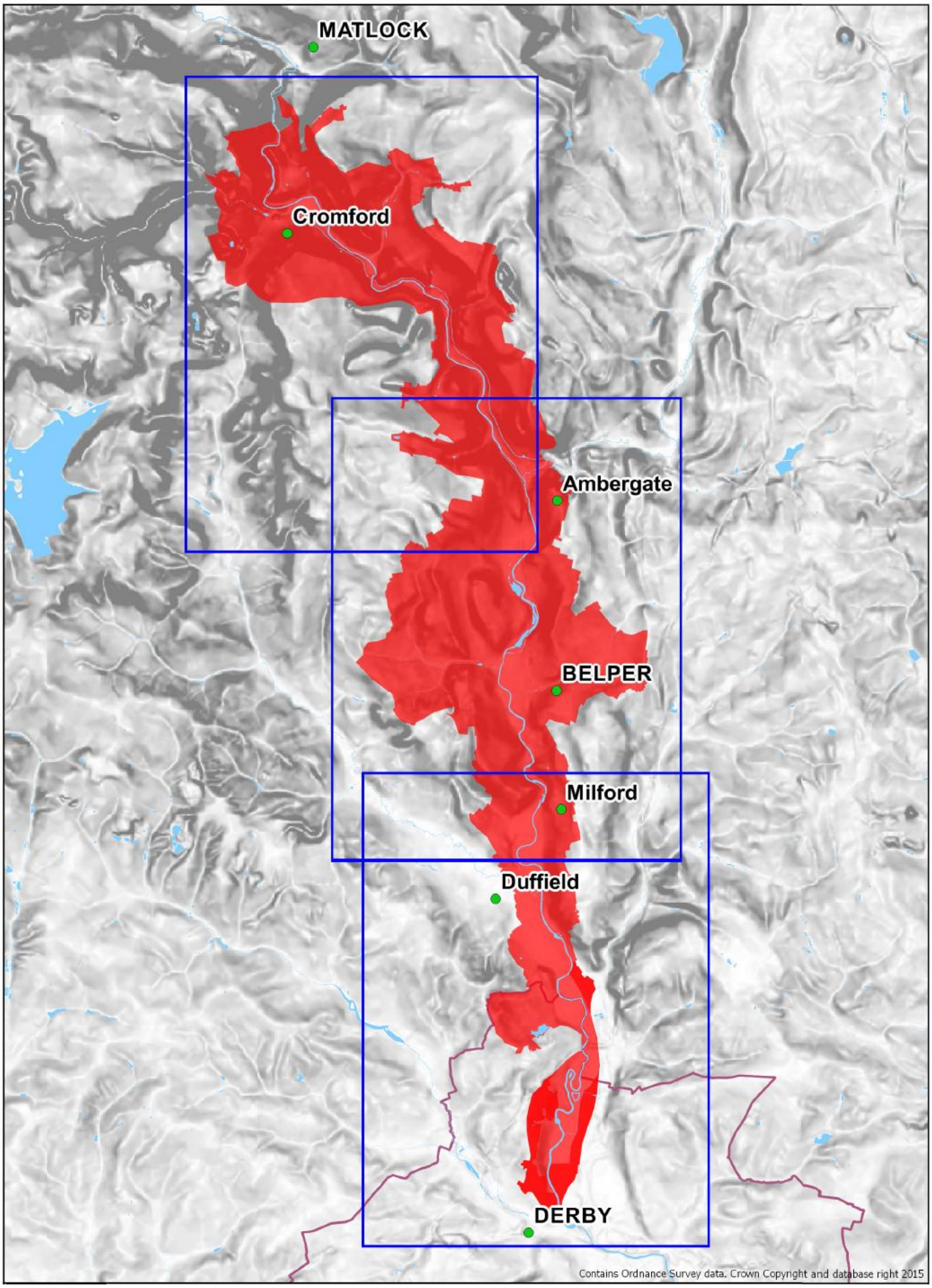
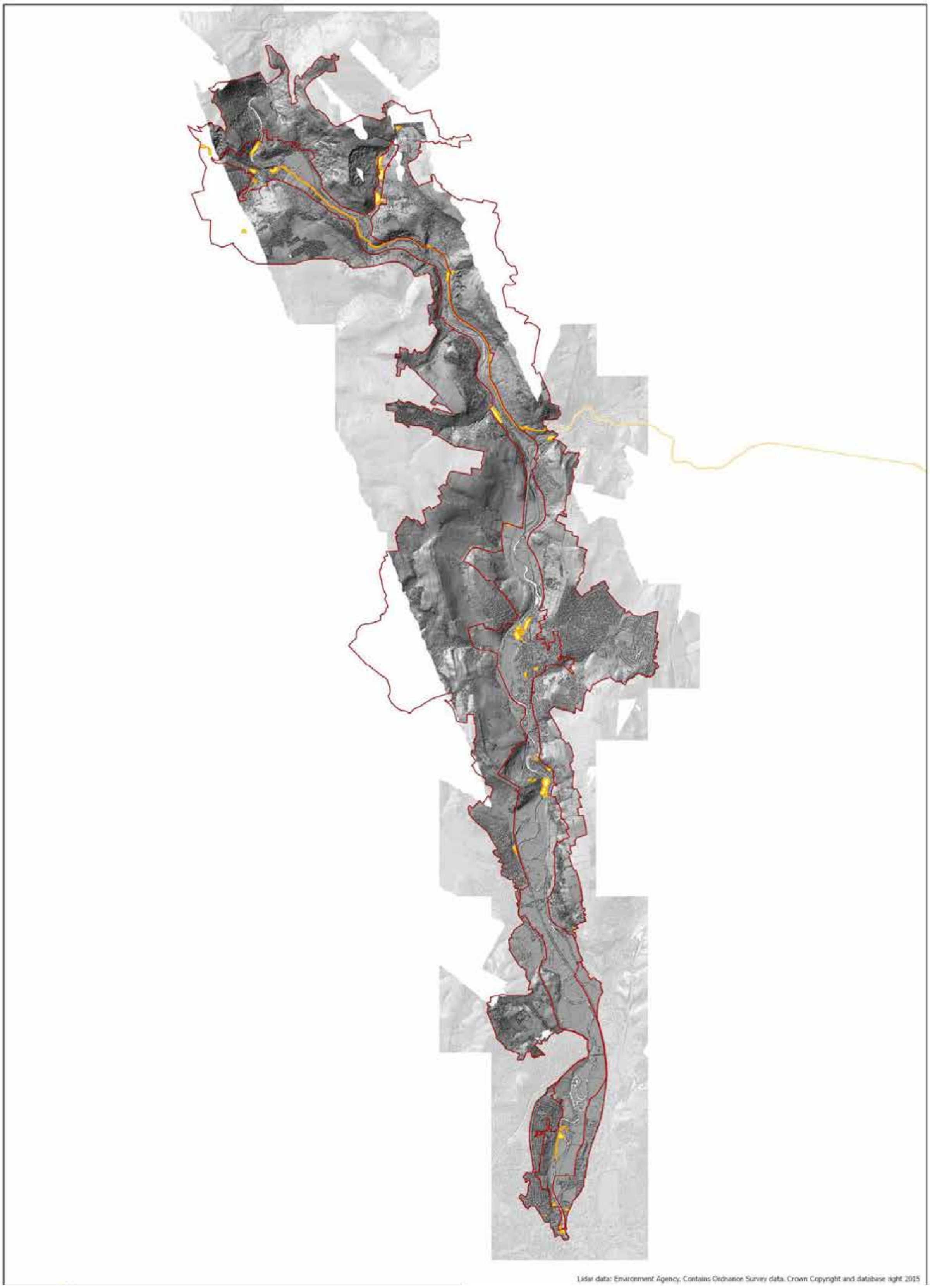


Figure 17: Overall map of the study area shoing layout of the 1:25000 plans of the upper, middle, and lower reaches of the study area (1:100000 @ A4) Contains Ordnance Survey data. Crown Copyright and database right 2015.



Lidar data: Environment Agency. Contains Ordnance Survey data. Crown Copyright and database right 2015

Figure 18: Derwent Valley Mills WHS showing related HER assets overlain on lidar surface model (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency.

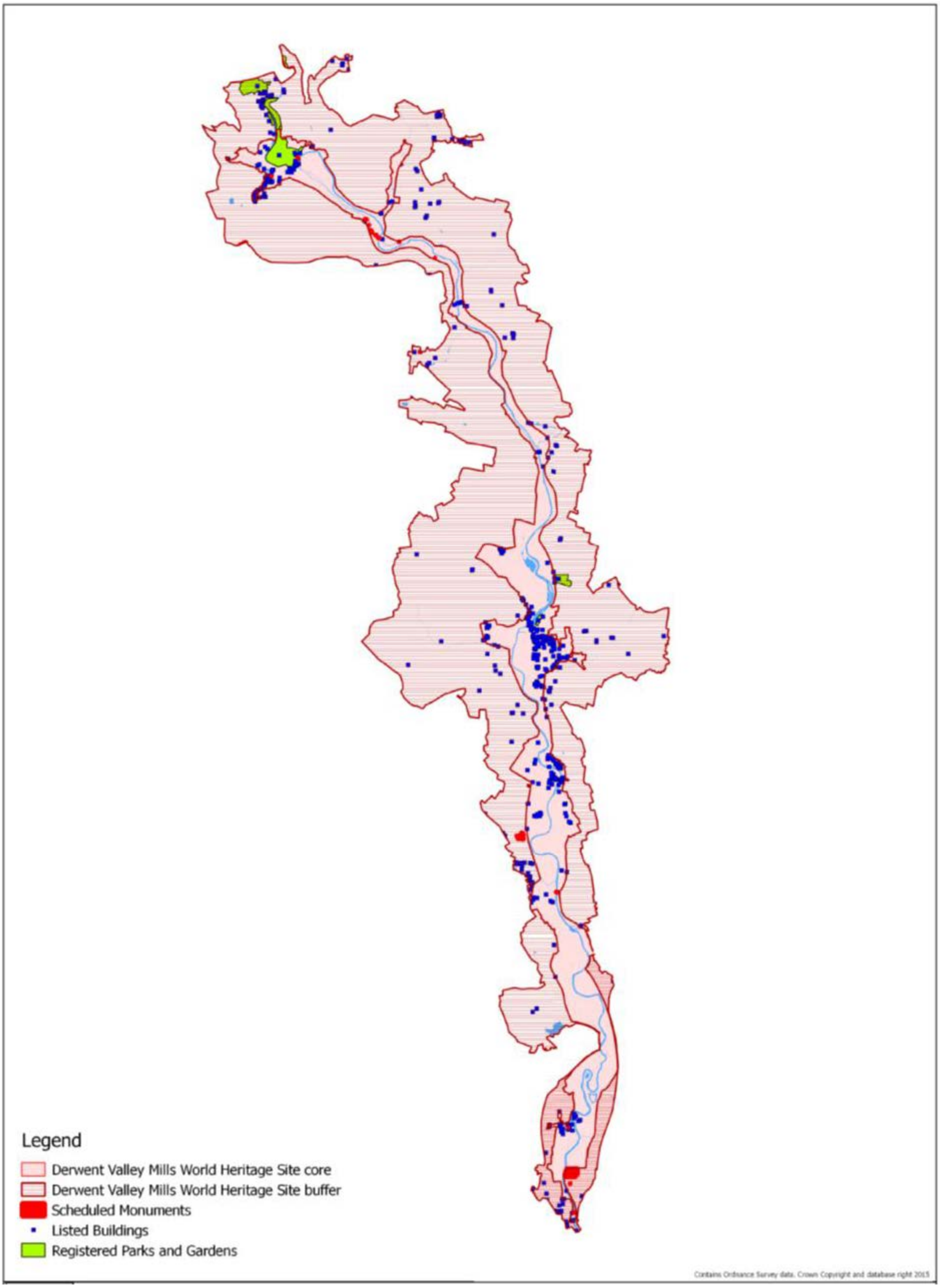


Figure 19: Designated historic assets within the WHS core and buffer zones (1:65000 @ A3). Contains Ordnance Survey data. Crown Copyright and database right 2015.

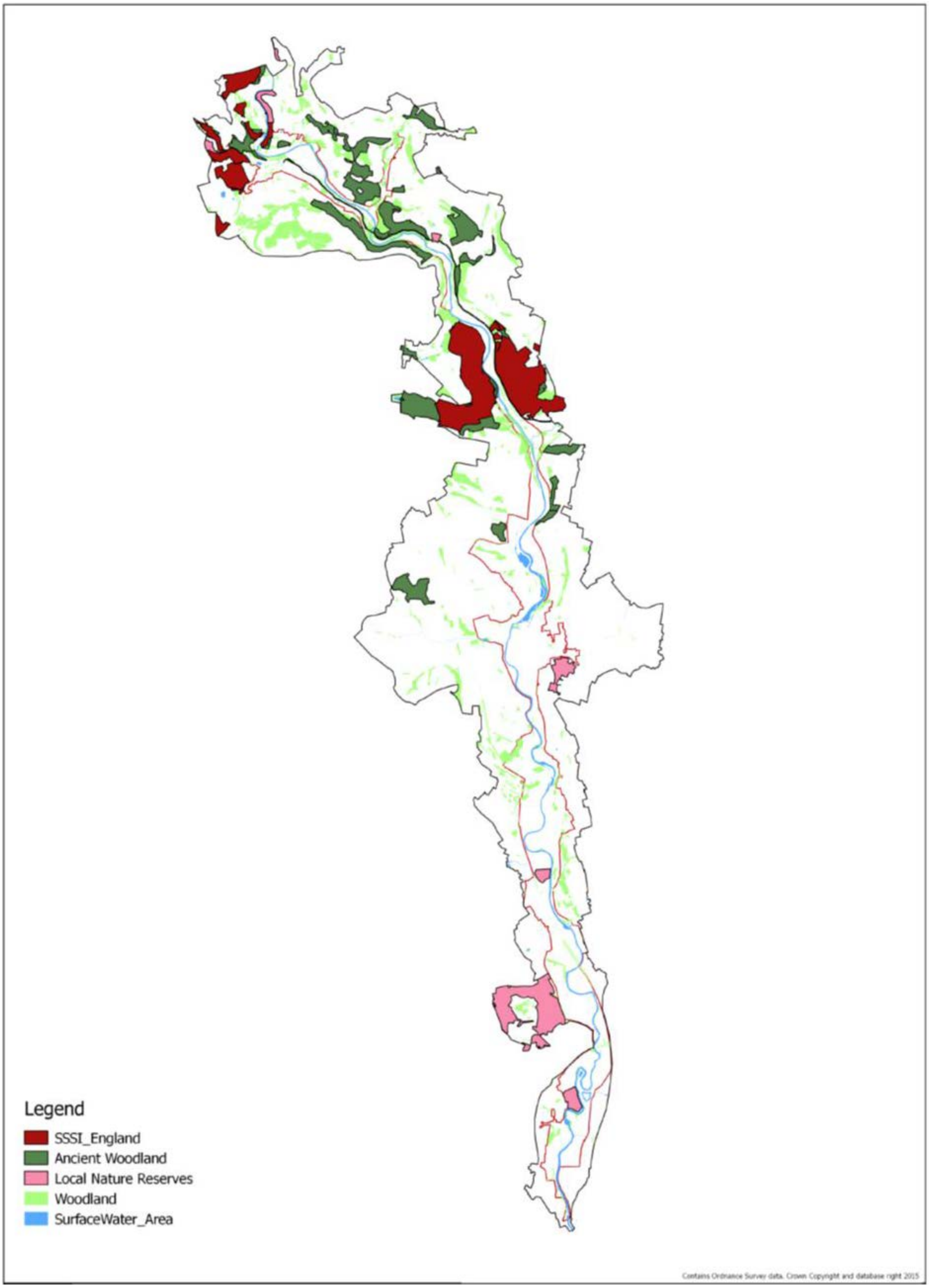


Figure 20: Land use/vegetation within the core and buffer zones of the WHS (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Natural England.

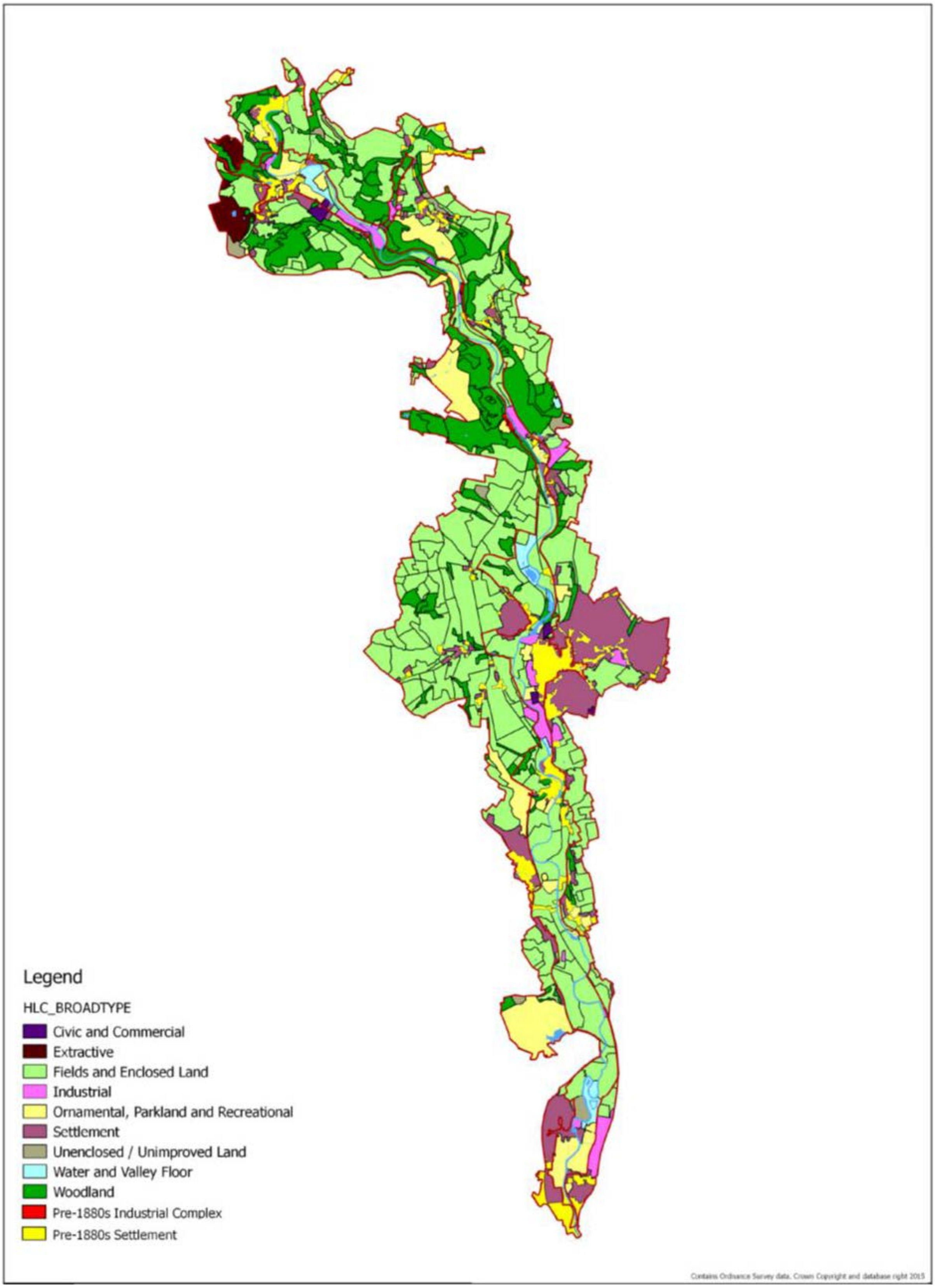


Figure 21: Historic Landscape Characterisation of the study area (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Derbyshire HER.

Figure 22: Ordnance Survey 2” hand drawn survey (1820s-1830s) of the upper half of the study area (1:31680 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

Figure 23: Ordnance Survey 2" hand drawn survey (1820s-1830s) of the lower half of the study area (1:31680 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

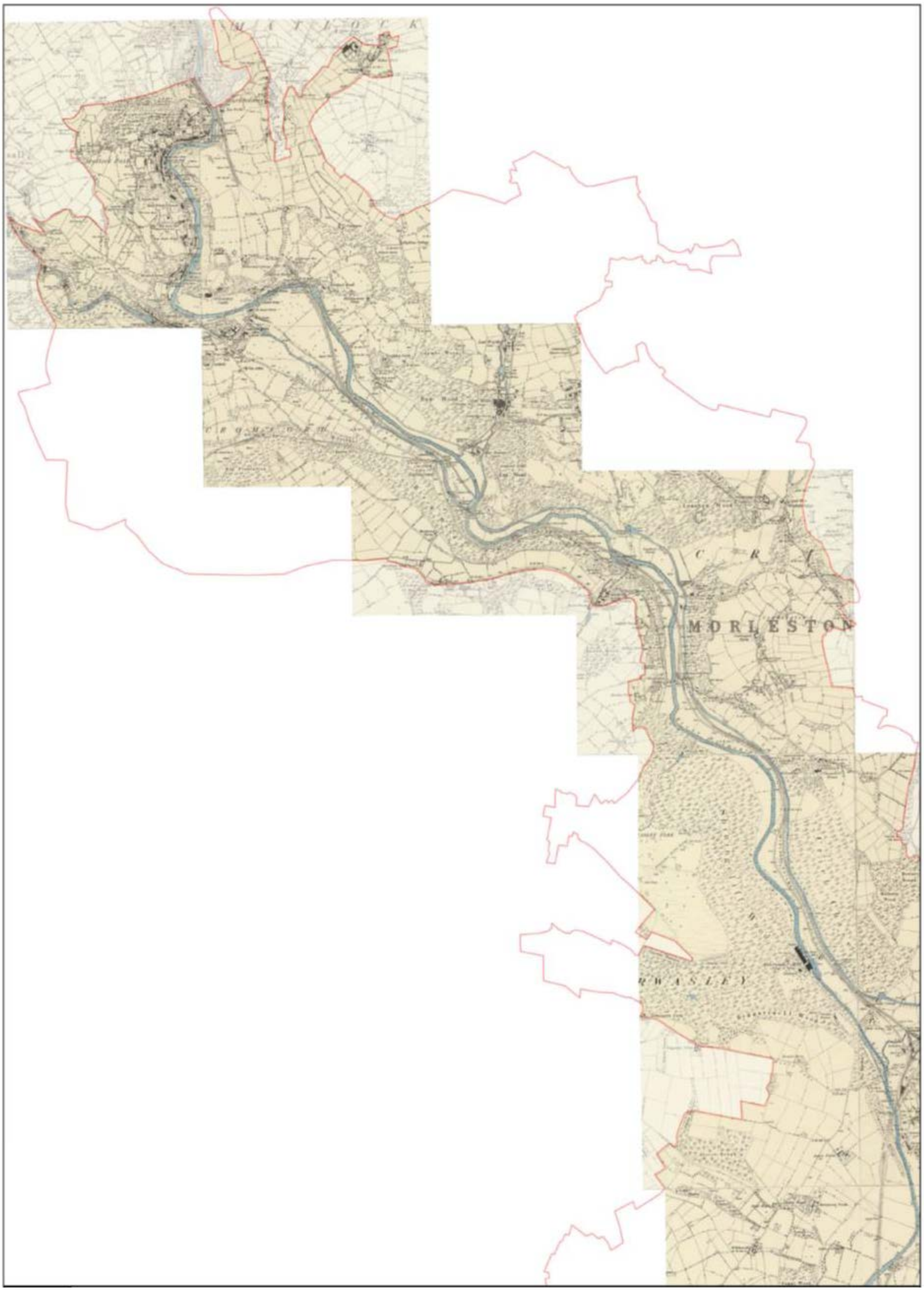


Figure 24: Ordnance Survey 6” hand drawn survey (1880s) of the upper reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

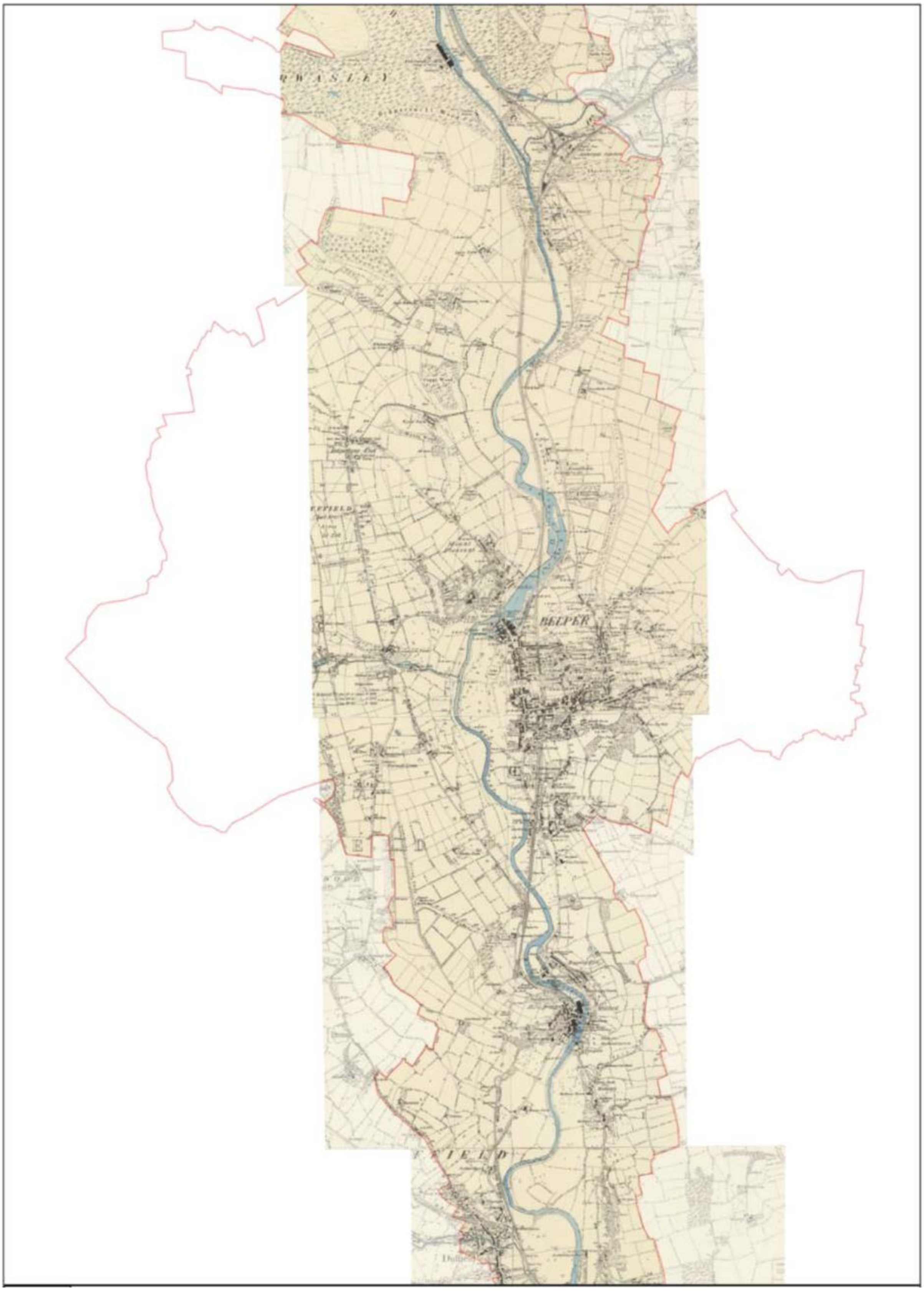


Figure 25: Ordnance Survey 6” hand drawn survey (1880s) of the middle reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

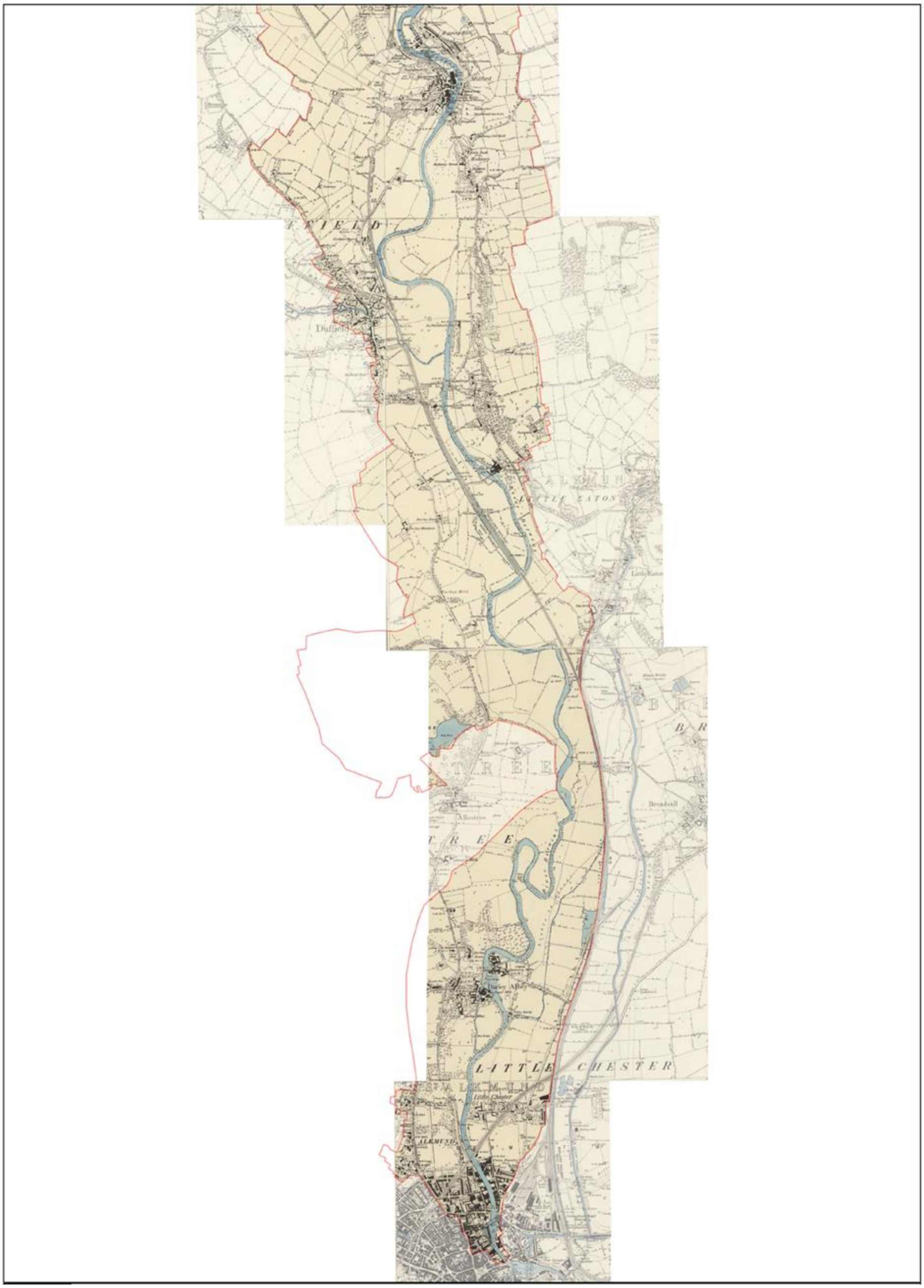


Figure 26: Ordnance Survey 6” hand drawn survey (1880s) of the lower reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.

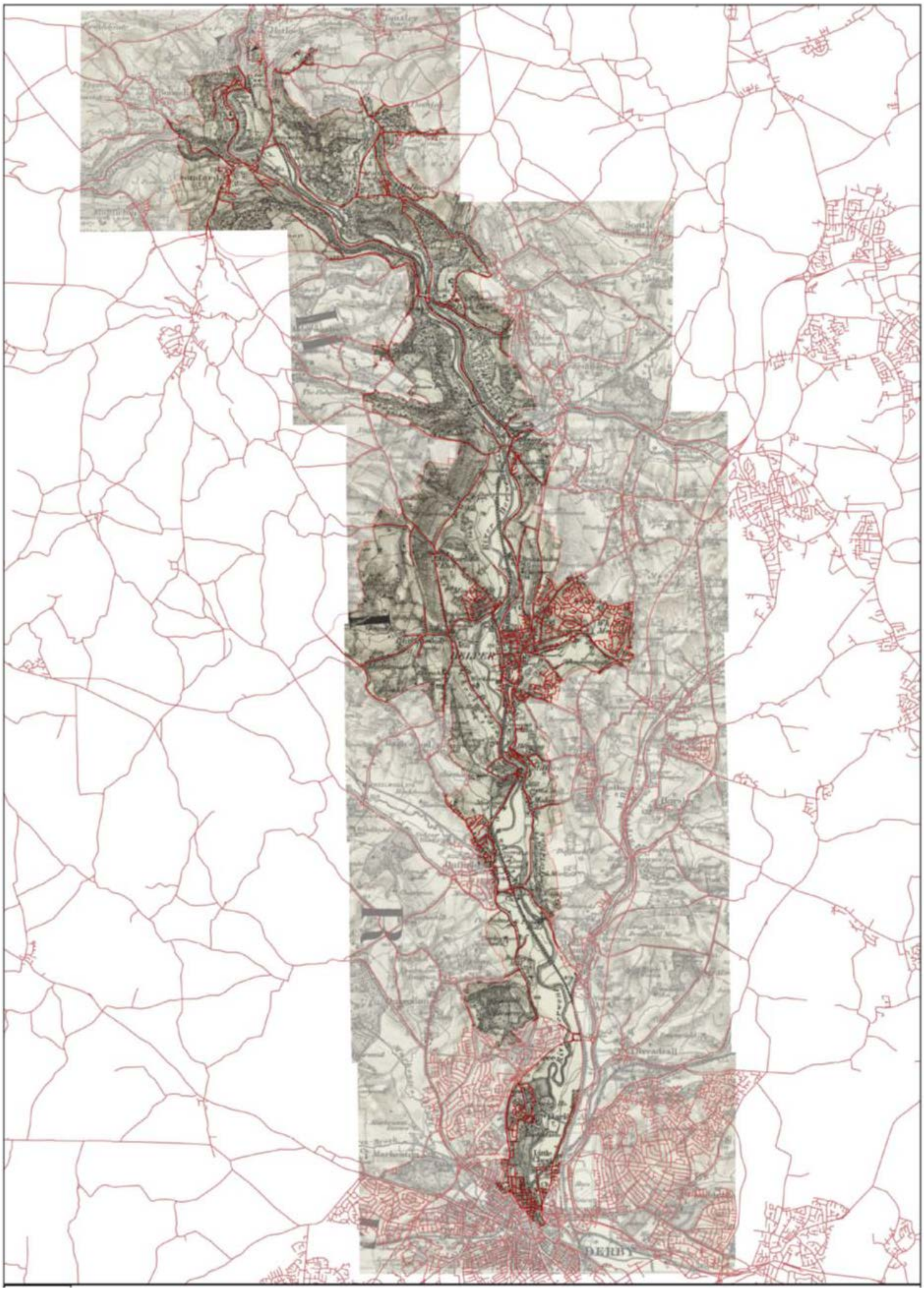
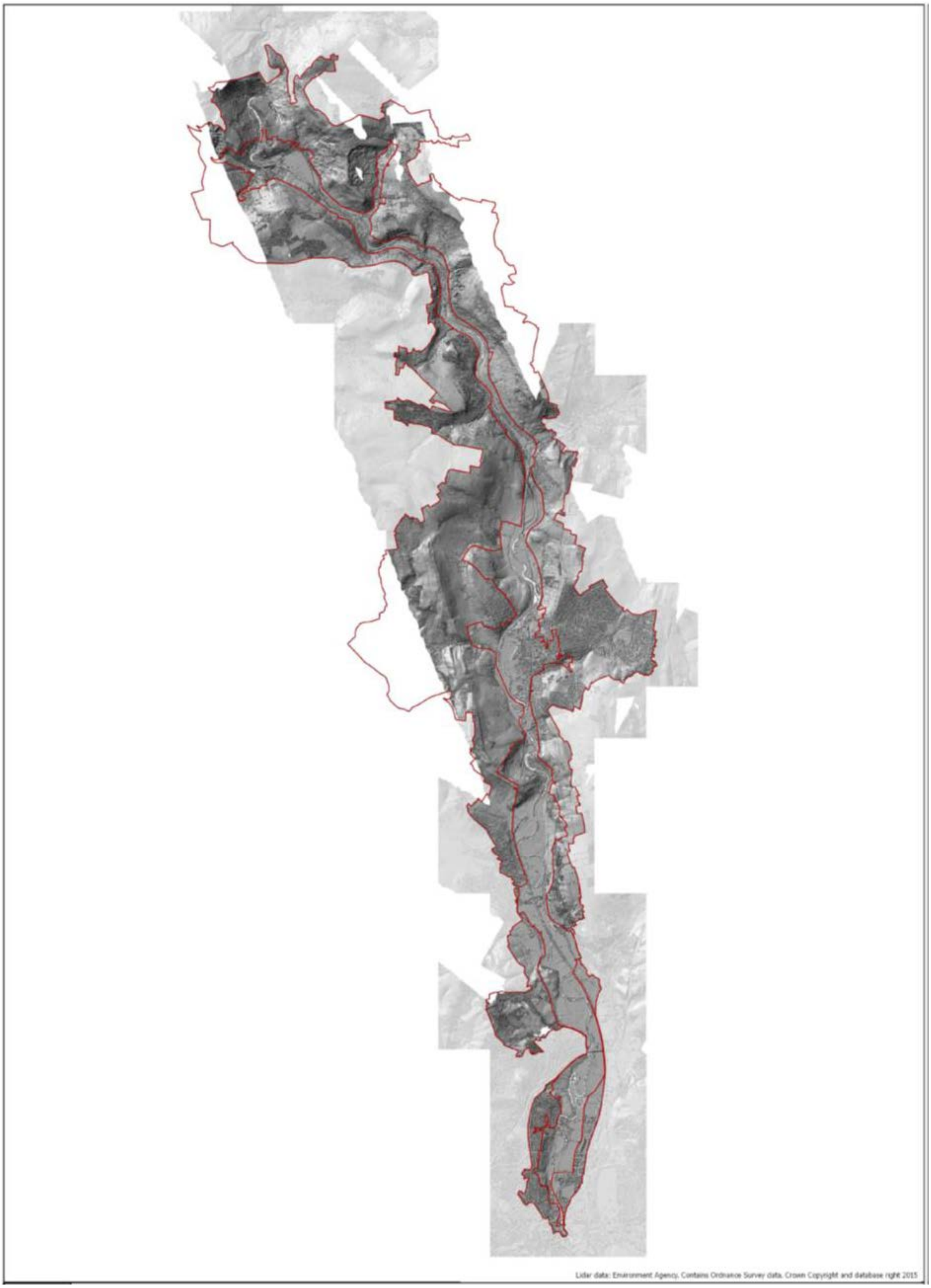


Figure 27: Ordnance Survey 1” mapping (1880s) with modern road network overlay (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015.



Lidar data: Environment Agency. Contains Ordnance Survey data. Crown Copyright and database right 2015

Figure 28: Overall lidar hill-shaded surface model (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency

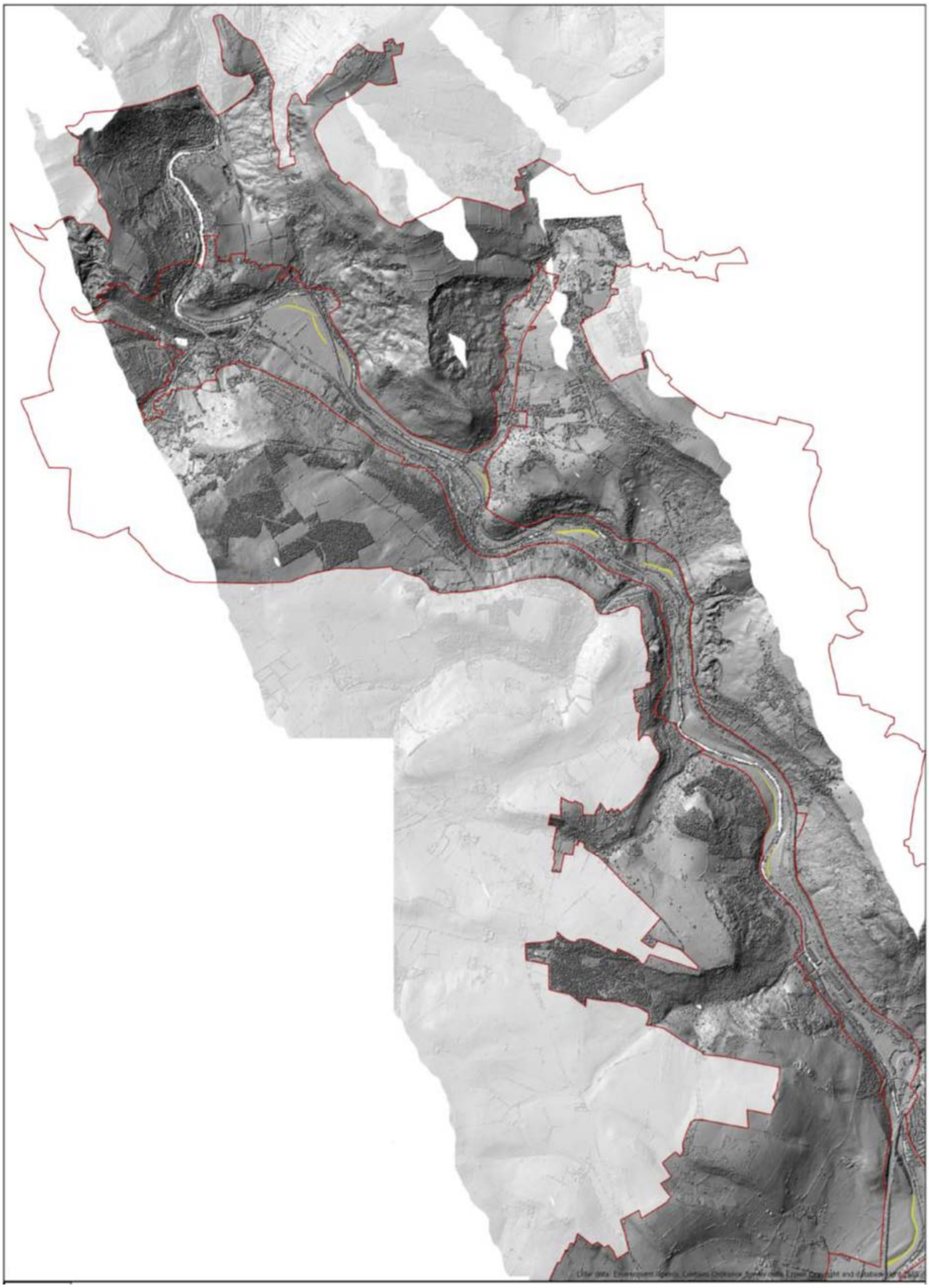
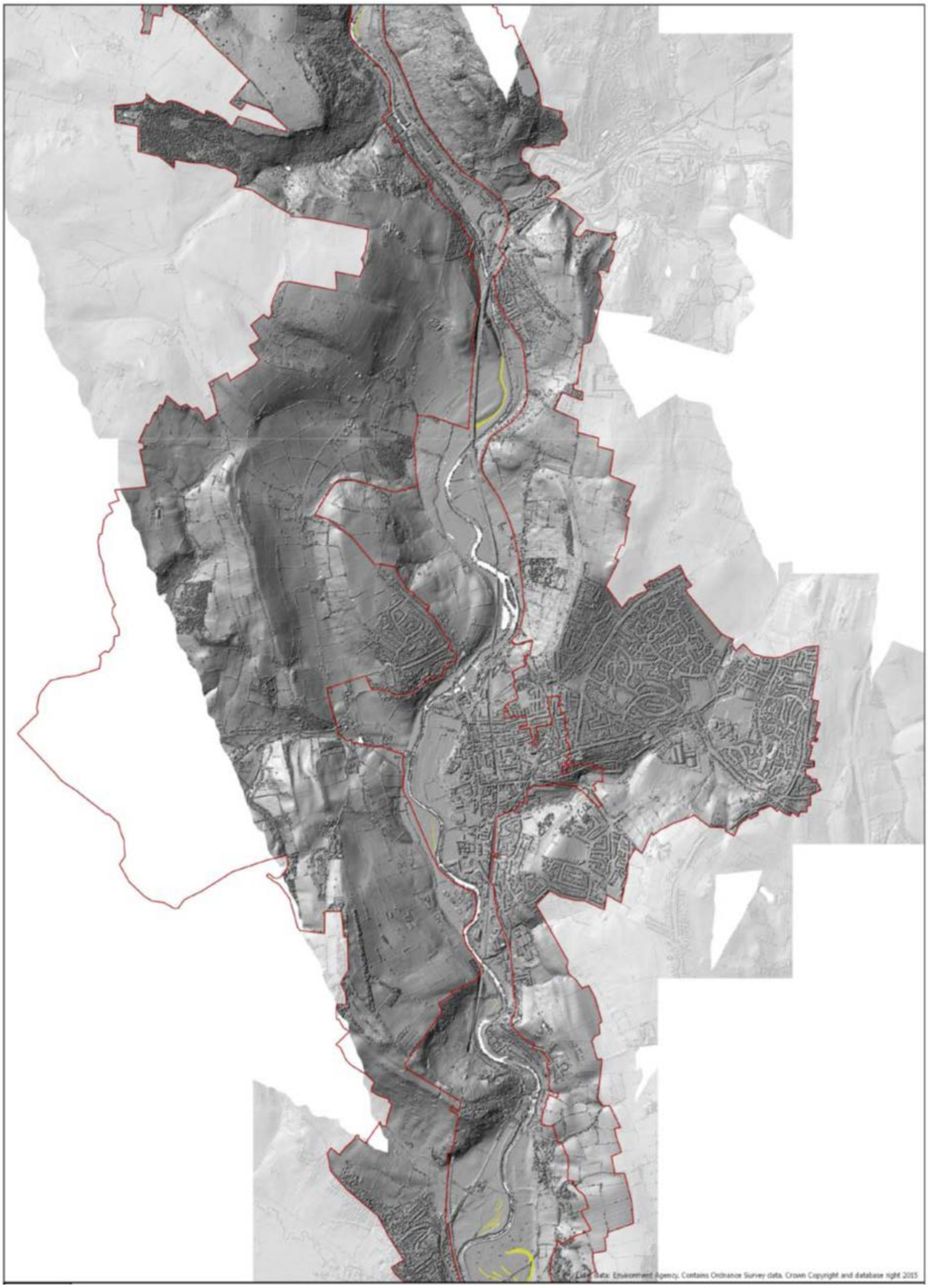


Figure 29: Landform assemblage of the upper reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency



Lidar data: Environment Agency. Contains Ordnance Survey data. Crown Copyright and database right 2015

Figure 30: Landform assemblage of the middle reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency

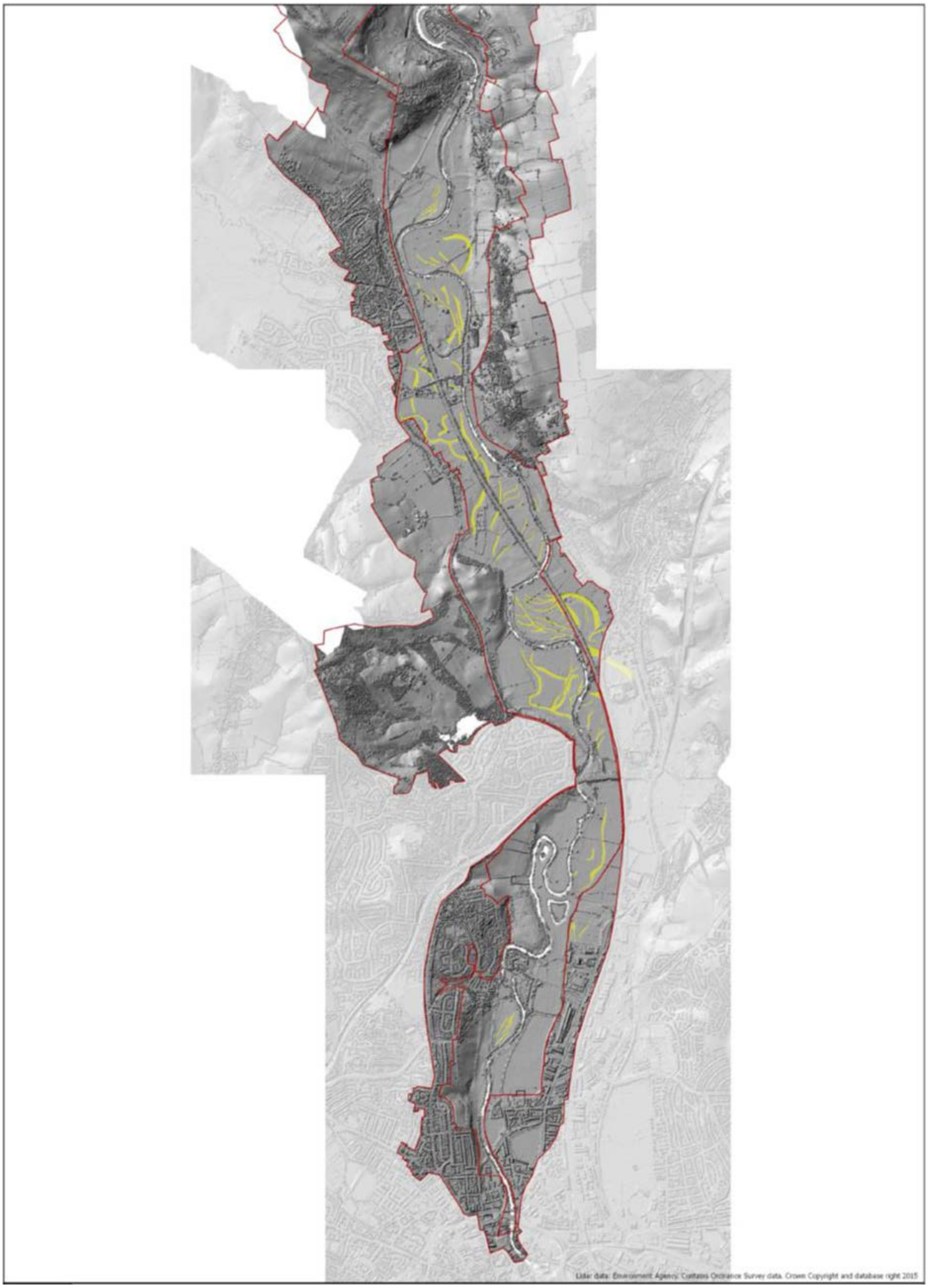


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Figure 31: Landform assemblage of the lower reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency

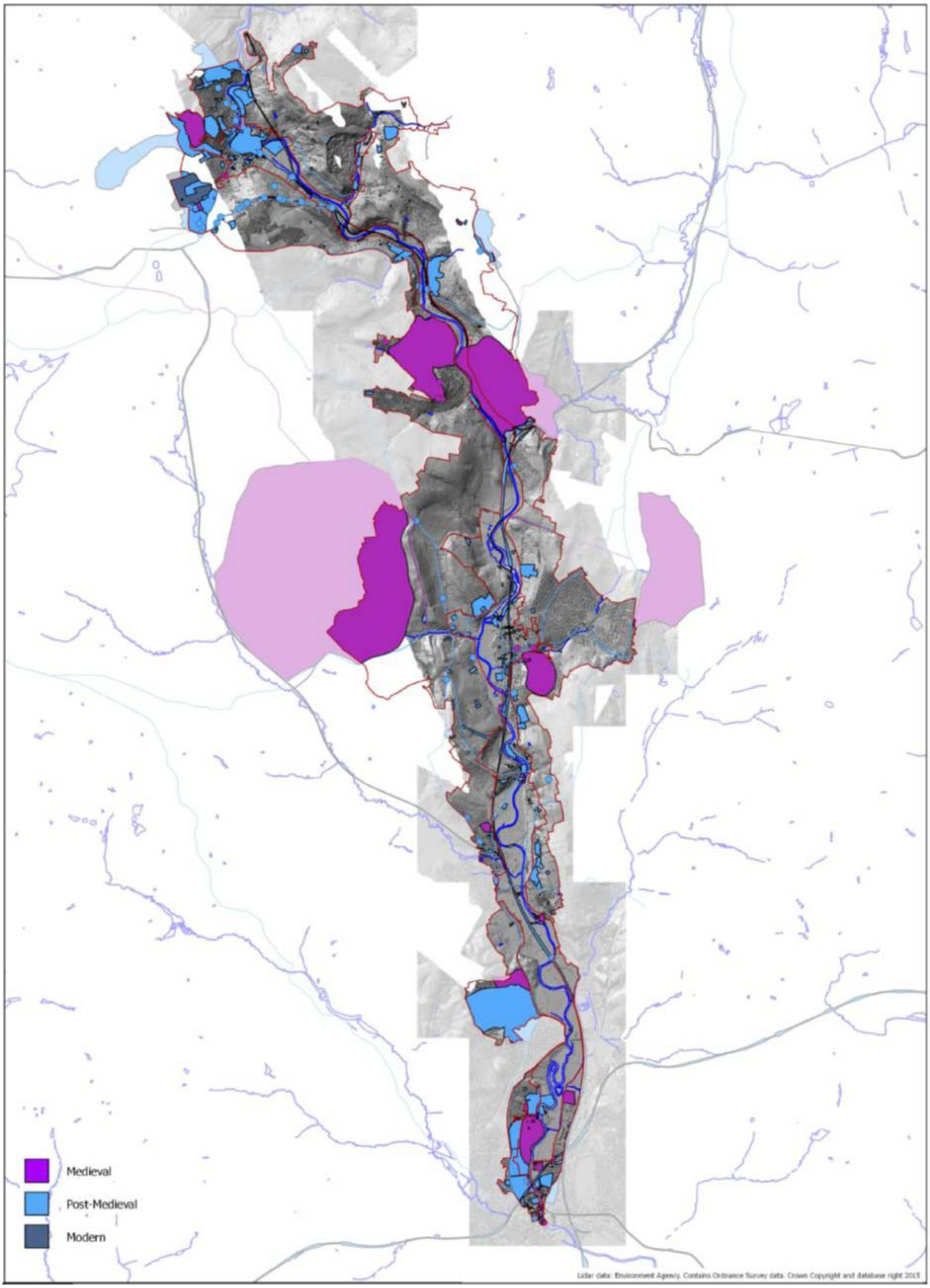

Figure 32: Overall map of HER assets in the study area (1:65000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

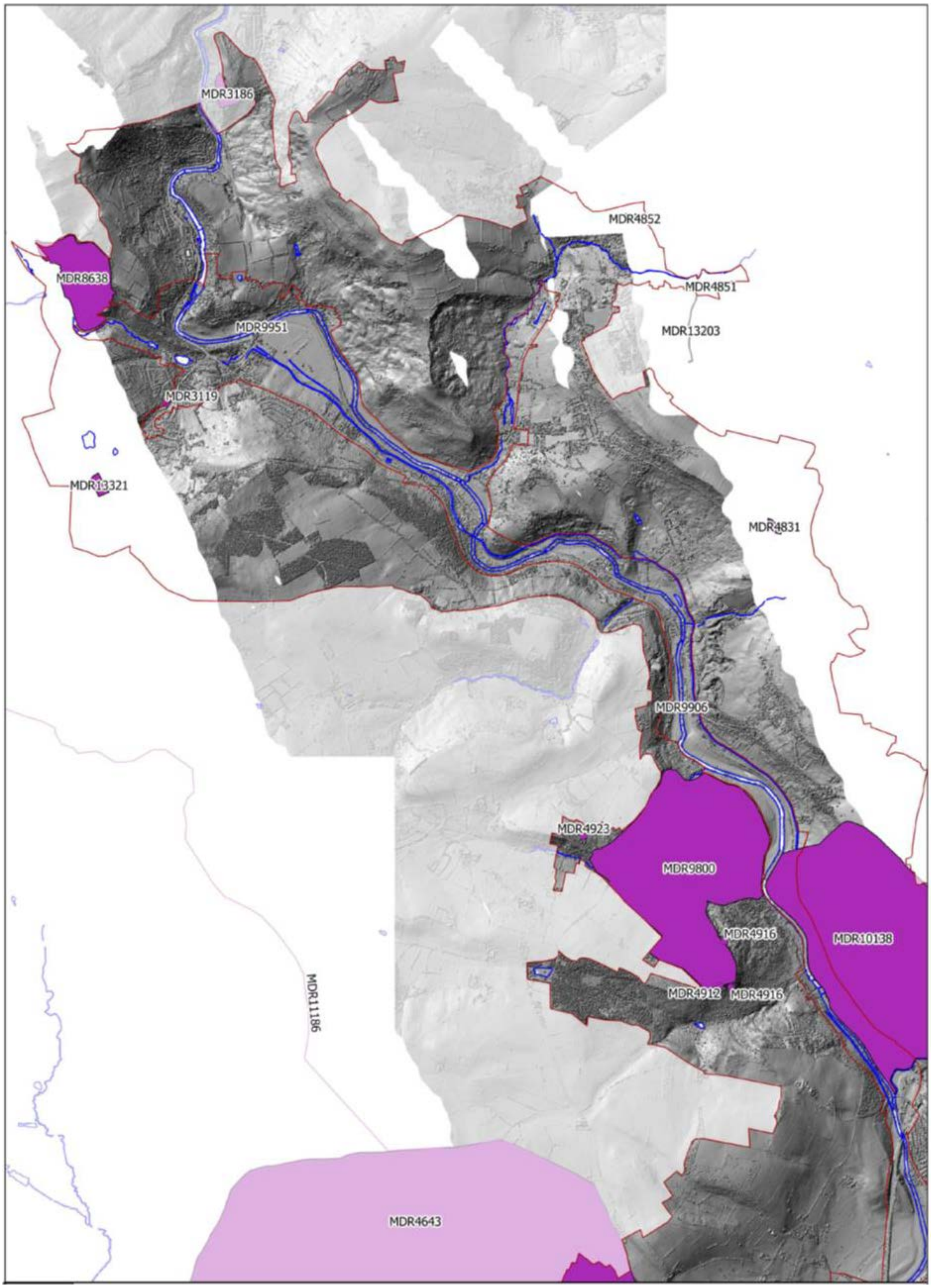

Figure 33: Medieval HER assets in the upper reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

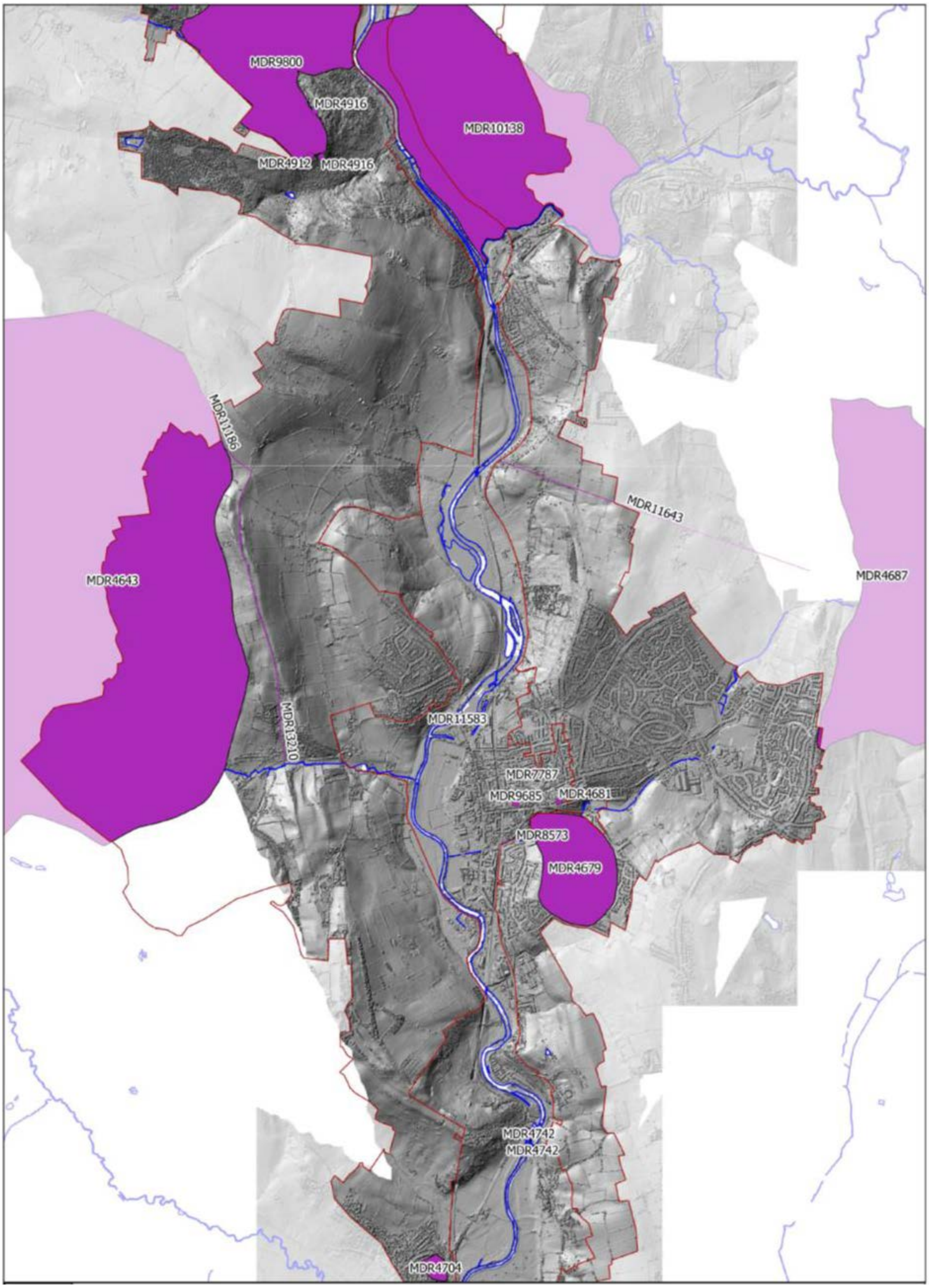

Figure 34: Medieval HER assets in the middle reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

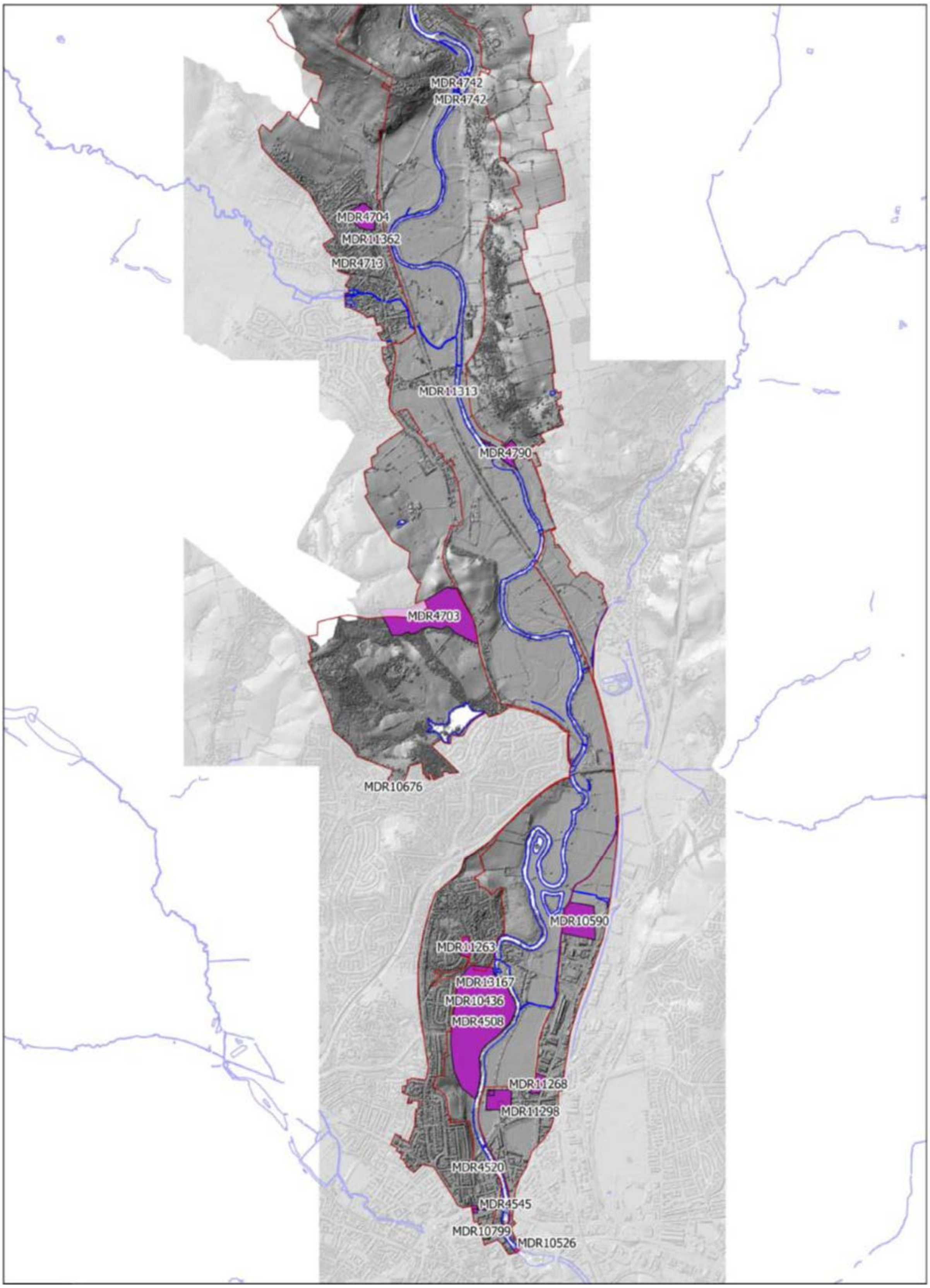

Figure 35: Medieval HER assets in the lower reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

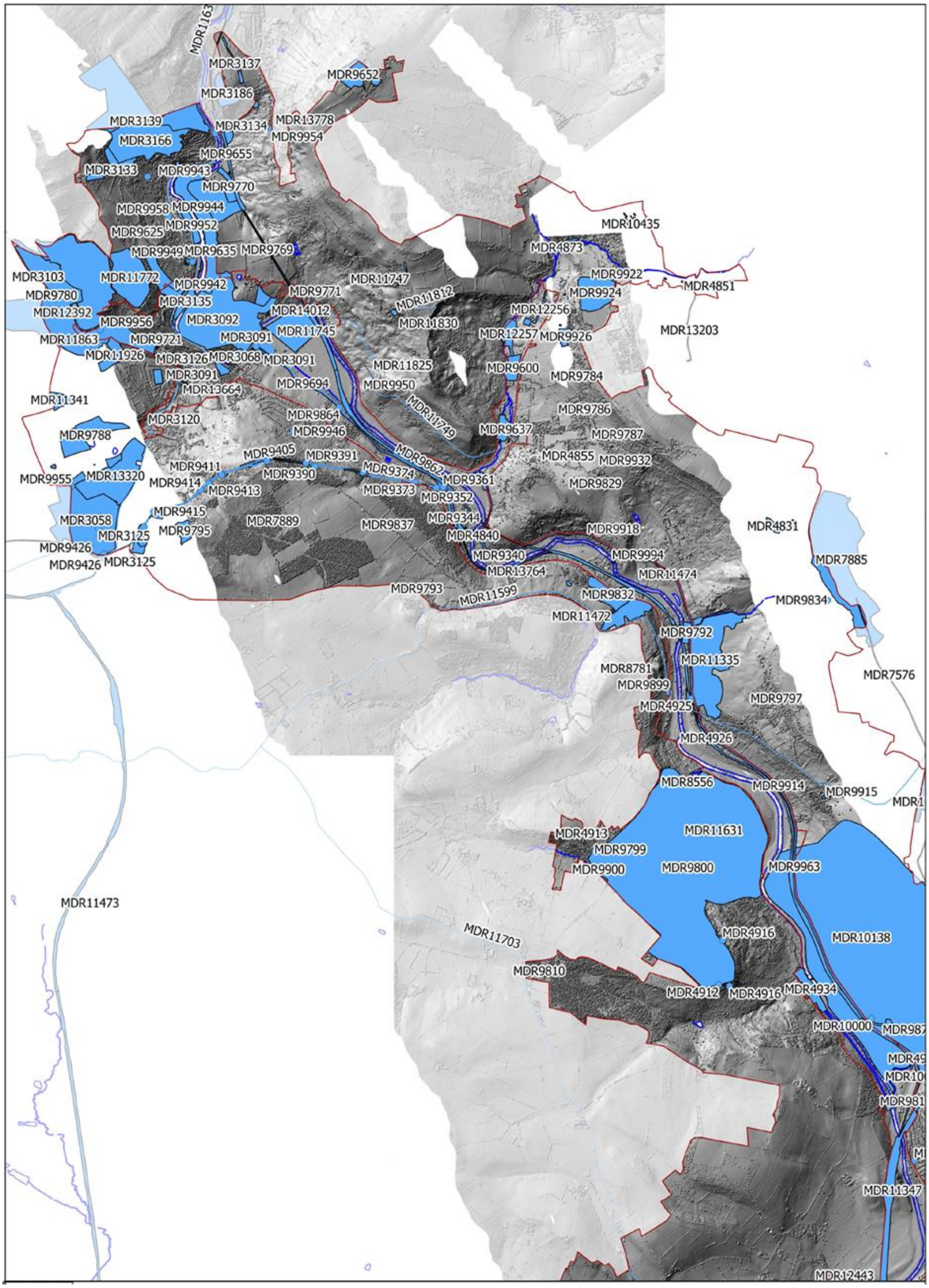

Figure 36: Post-medieval HER assets in the upper reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

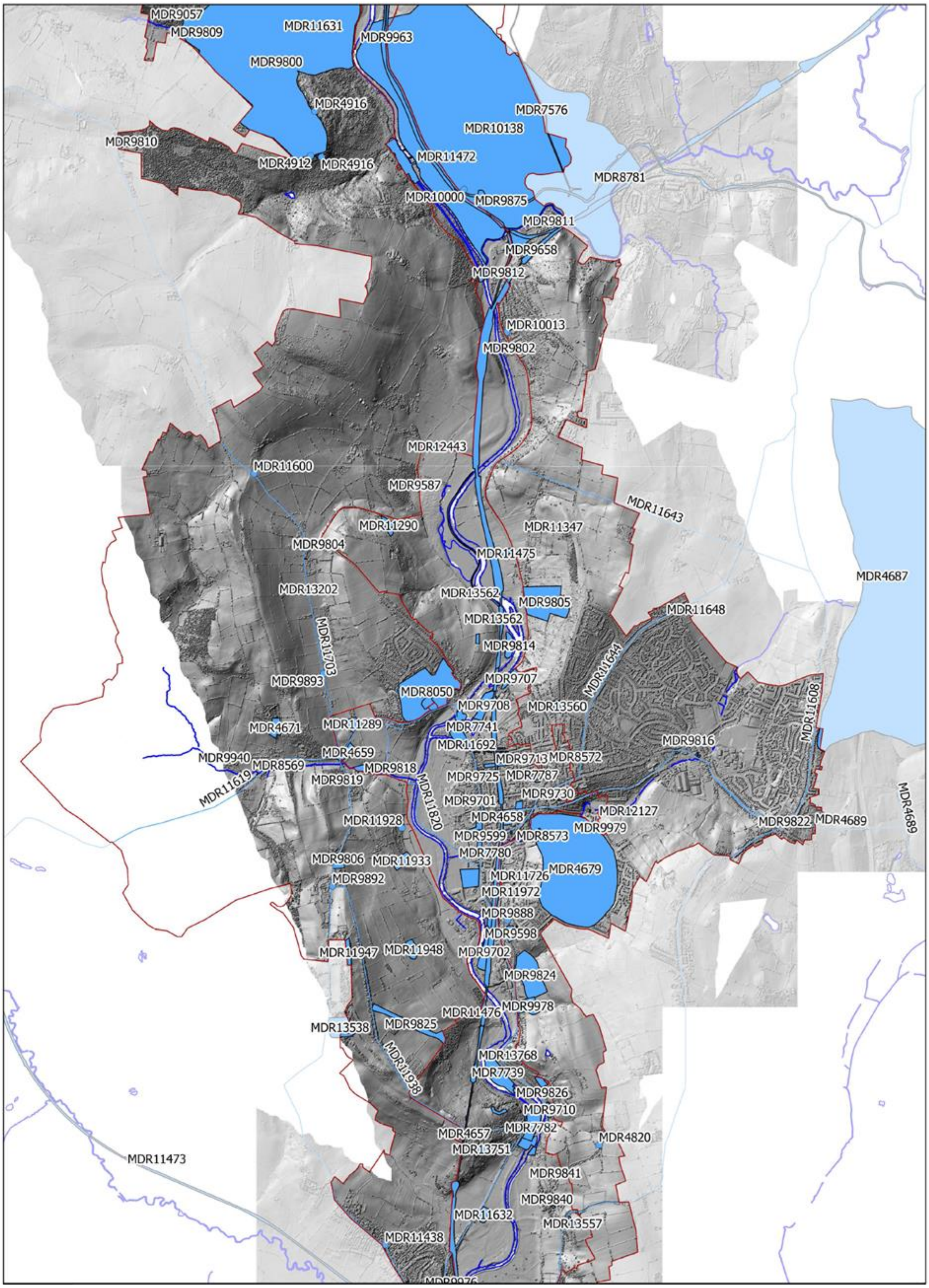

Figure 37: Post-medieval HER assets in the middle reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

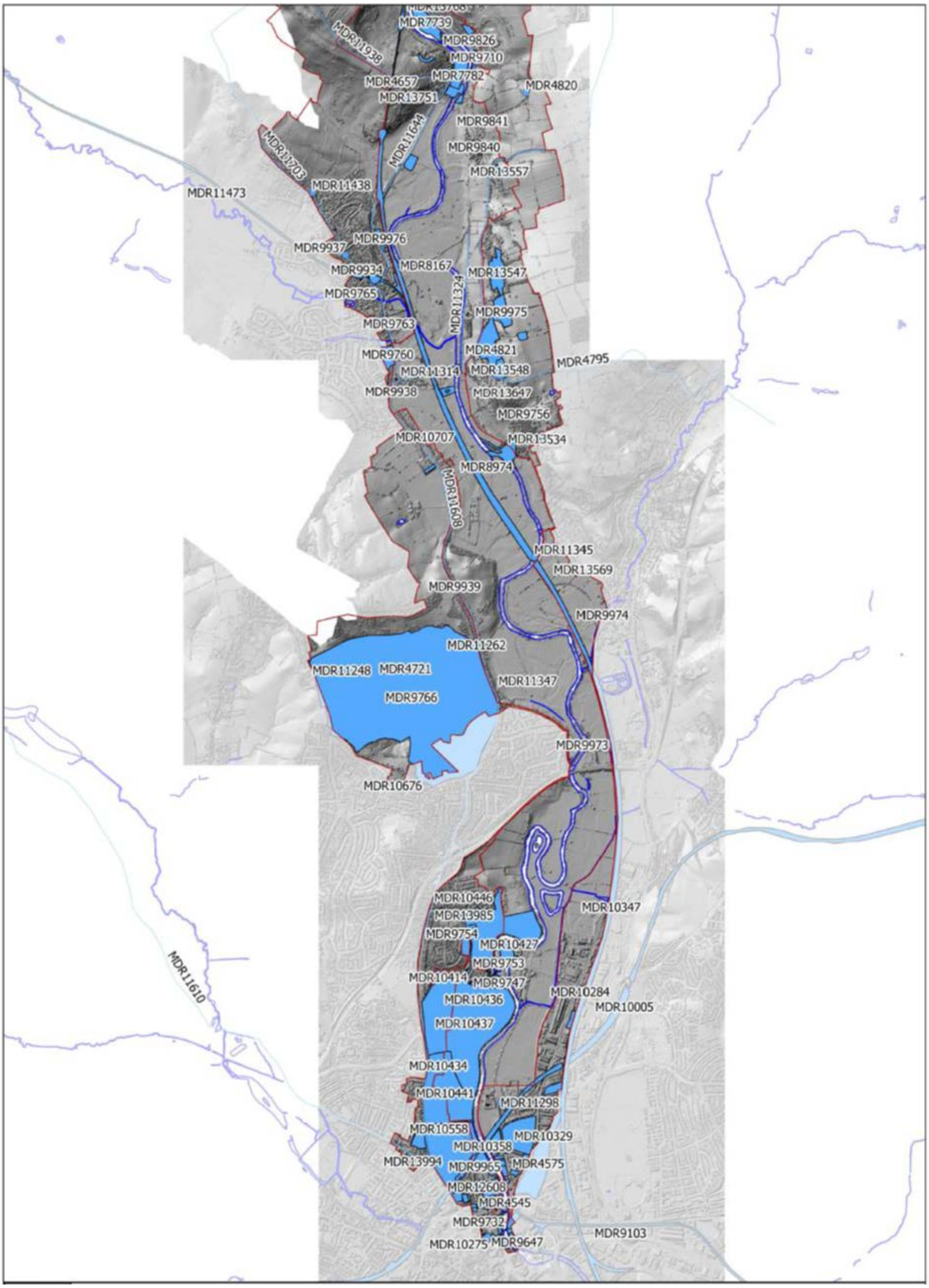

Figure 38: Post-medieval HER assets in the lower reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

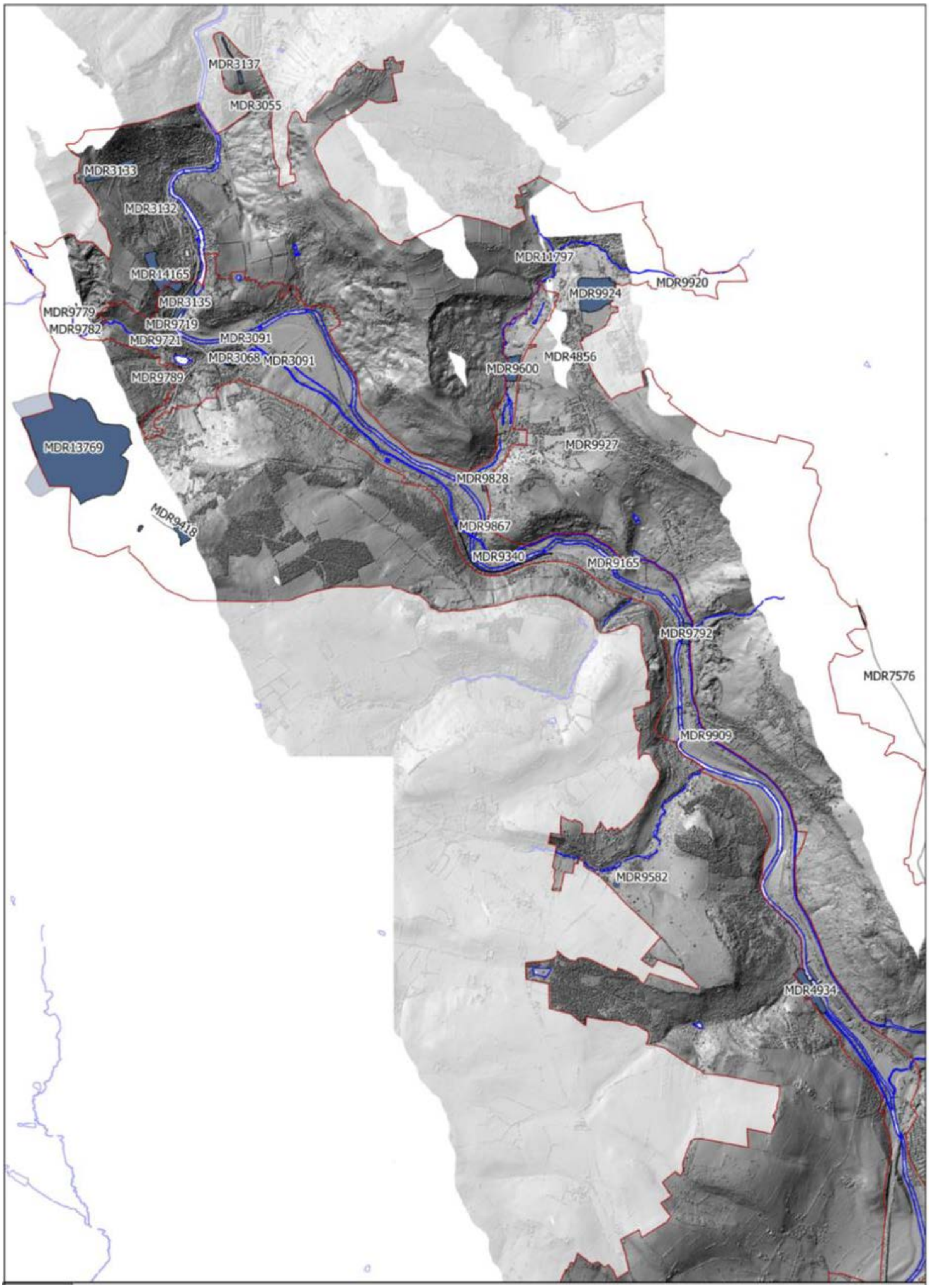

Figure 39: Modern HER assets in the upper reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

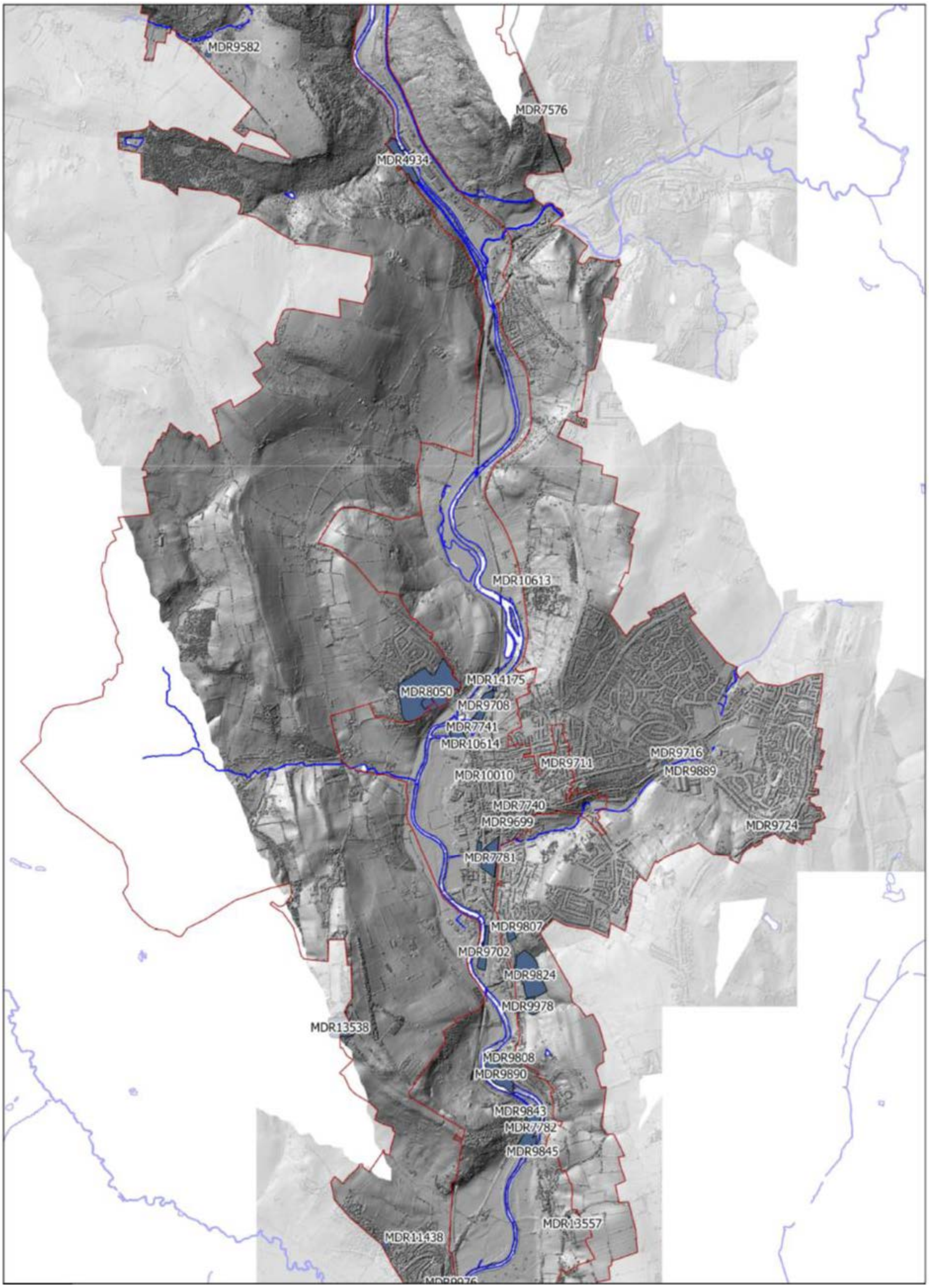

Figure 40: Modern HER assets in the middle reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

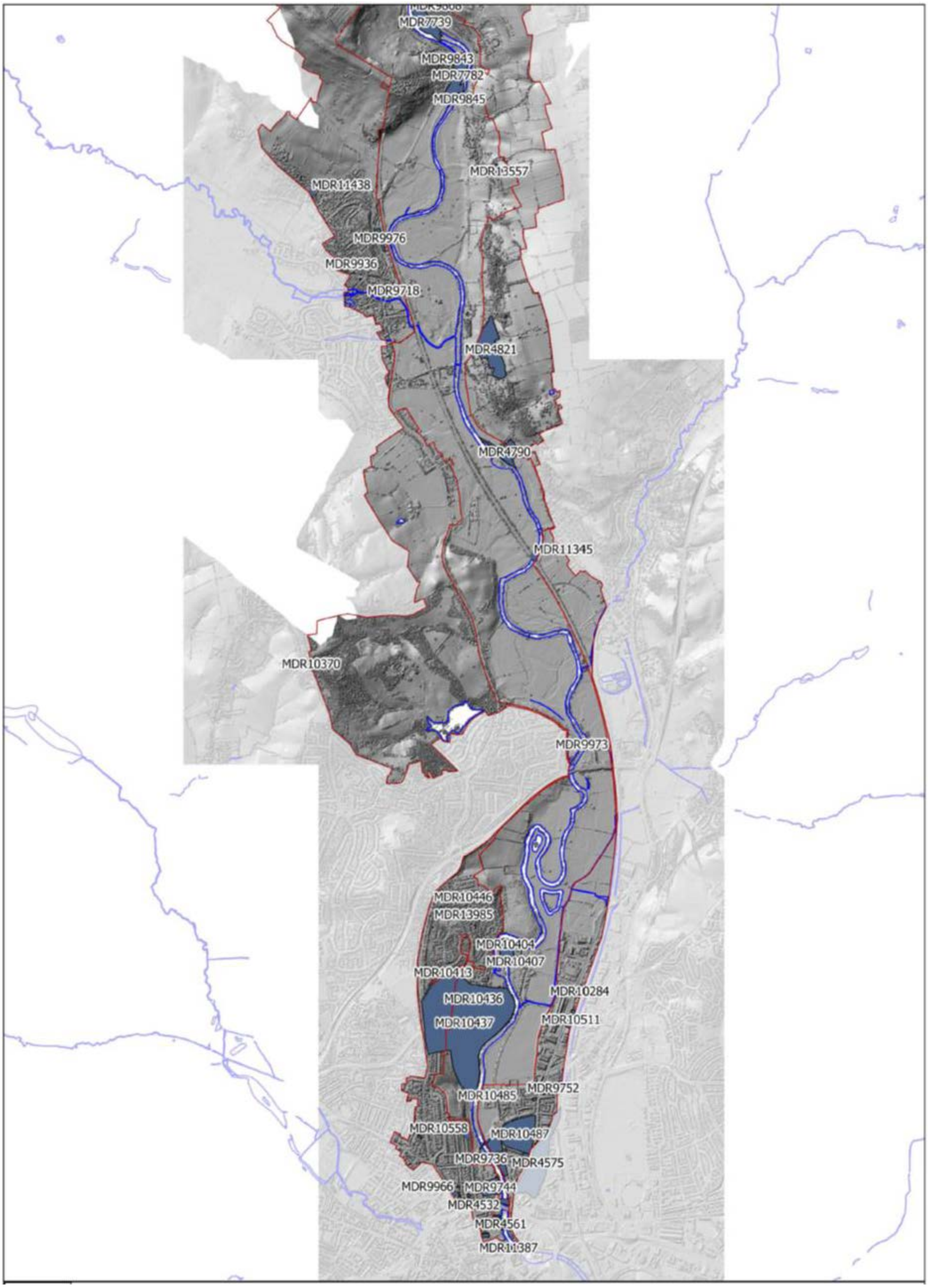

Figure 41: Modern HER assets in the lower reach of the study area (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

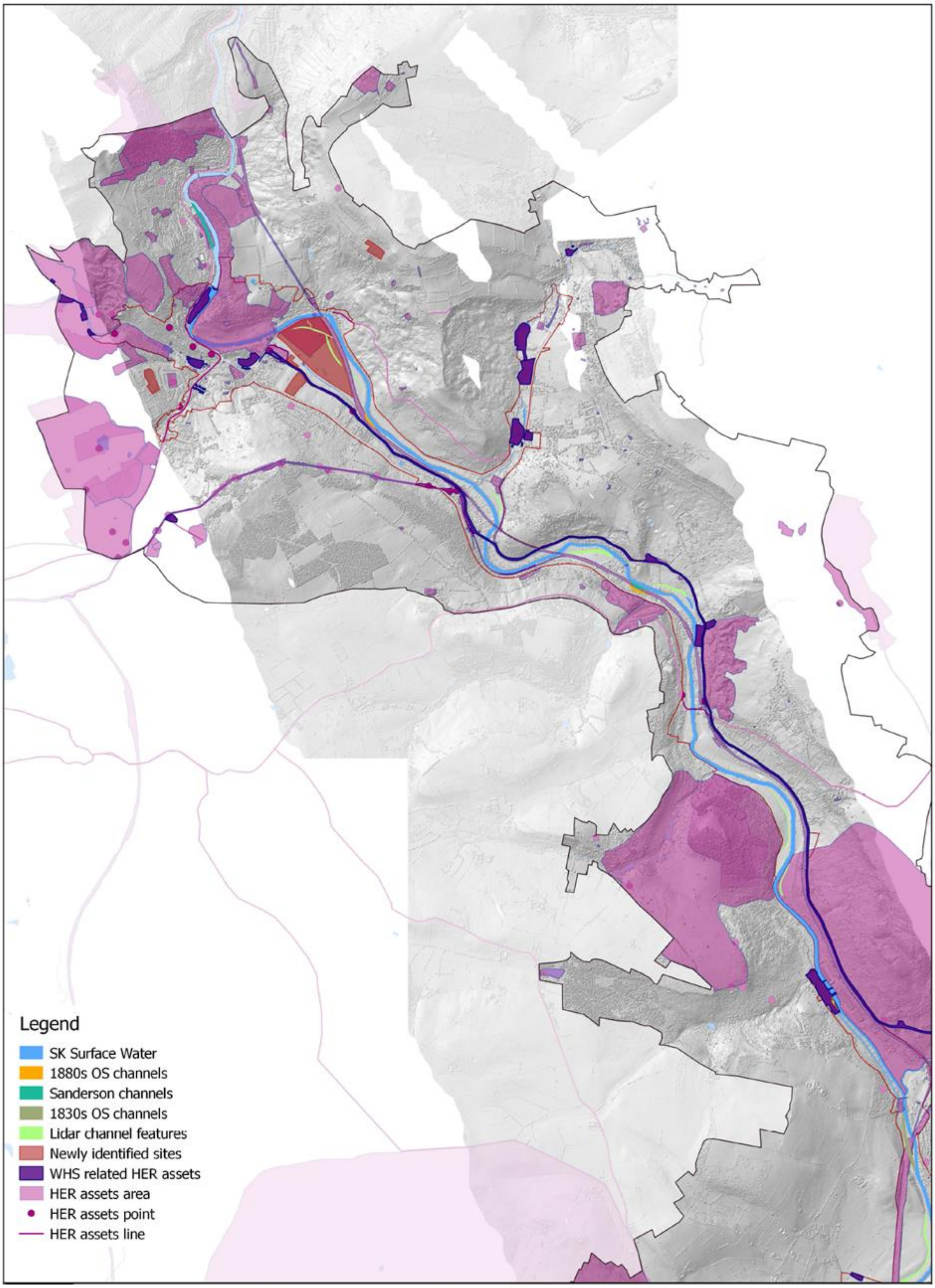

Figure 42: HER assets and newly identified features within the upper reach of the WHS (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

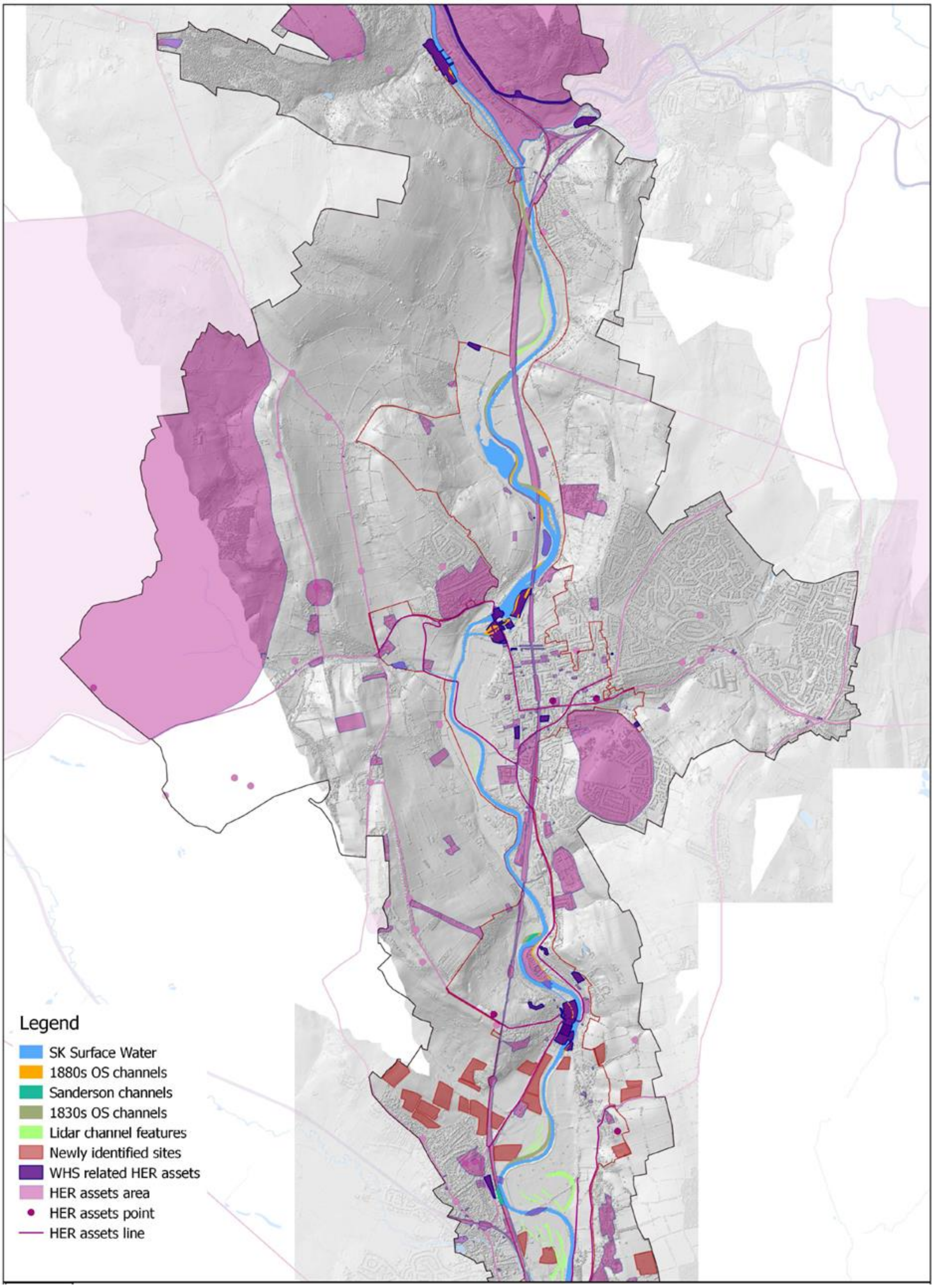

Figure 43: HER assets and newly identified features within the middle reach of the WHS (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

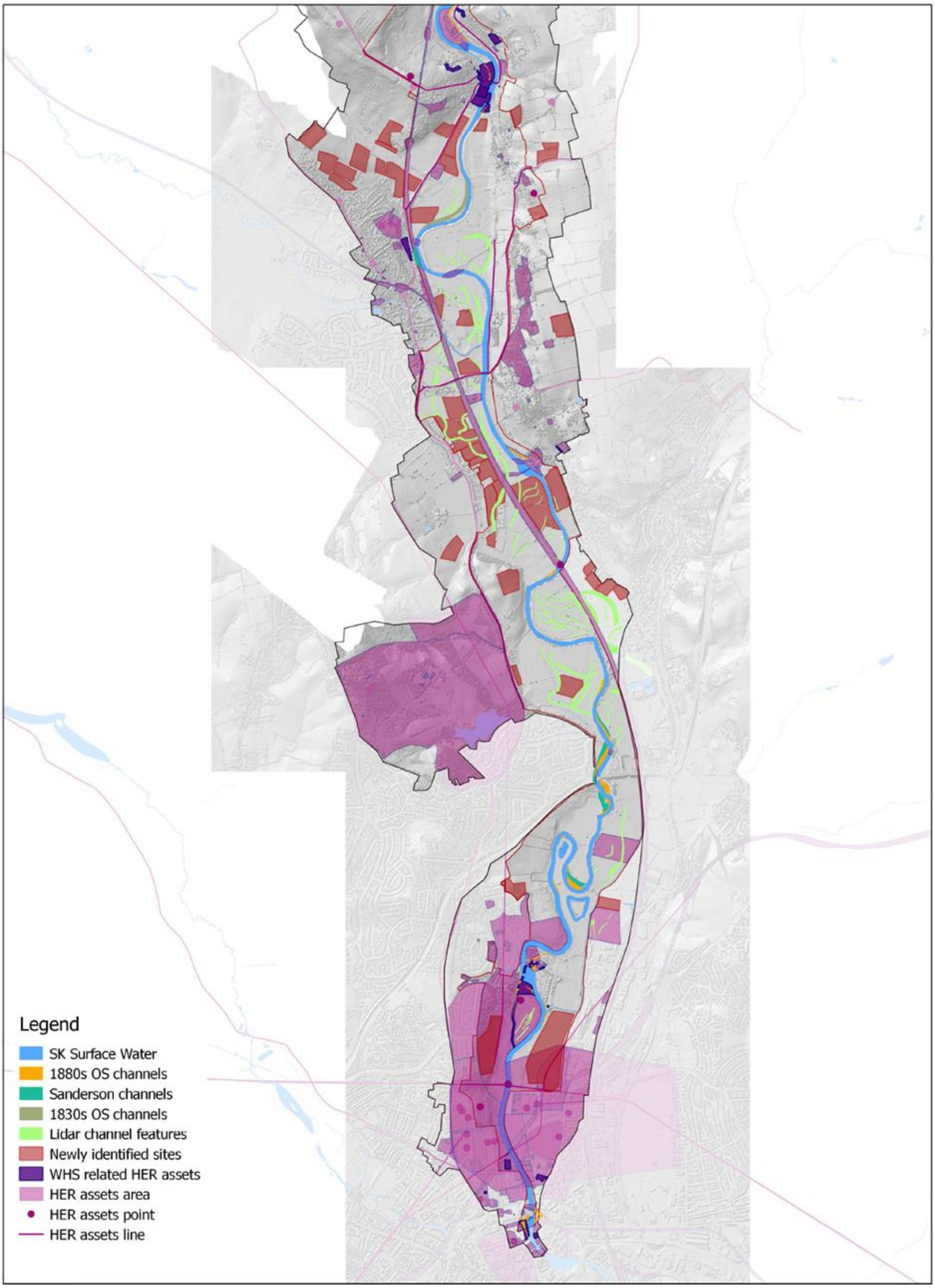

Figure 44: HER assets and newly identified features within the lower reach of the WHS (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

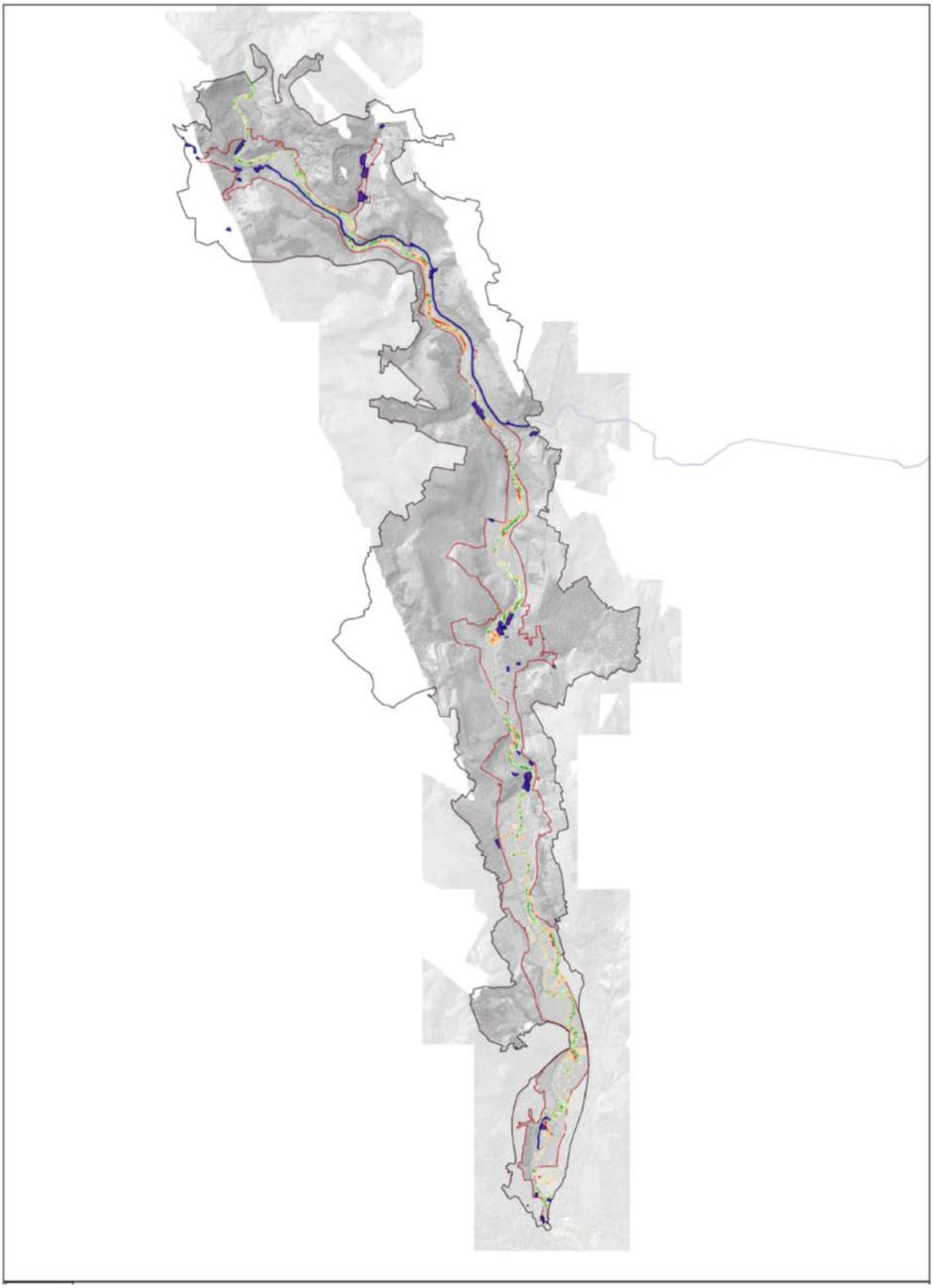

Figure 45: Modelling of erosion (red) and deposition (green) of sediment against HER assets related to the WHS (1:25000 @ A3) Contains Ordnance Survey data. Crown Copyright and database right 2015. Source data © Environment Agency; Derbyshire HER

ANNEX 1

Modelling future development of the River Derwent through the Derwent Valley Mills World Heritage Site

Professor Tom Coulthard,

Department of Geography, Environment and Earth Science, University of Hull, UK

Executive summary

Computer simulations were carried out using the CAESAR-Lisflood model to test how the reach of the River Derwent containing the Derwent Valley Mills World Heritage Site (DVMWHS) would respond to changes in future flooding (due to climate change) and how these changes might impact upon the infrastructure of the World Heritage Site (WHS).

This work package was undertaken as part of a wider English Heritage sponsored project co-ordinated by Trent & Peak Archaeology (TPA) and Landscape Research & Management (LR&M) aimed at '*better disaster planning and building in resilience for heritage*' (NHPP 2C1, 6193, 6194, 6195). The wider project was entitled '*Managing climate change in the Derwent Valley: understanding threats and informing management of the World Heritage Site and its Buffer Zone in the light of future environmental change*' (EH PD 6927).

Results suggest that the WHS sites along the Derwent will be largely untroubled by erosion and deposition caused by larger flood events up to 2050, though there may be some localised erosion and deposition. These local problems may have implications for the conservation of the historic assets of the WHS and need to be compared to the spatial record of HER assets.

In addition, the upper parts of the WHS (upstream of Belper) show a greater sensitivity to erosion and deposition than the downstream reaches. Under current management regimes, it appears that erosion and deposition will have little impact on future flooding, though larger floods due to climate change may well inundate some areas more than at present.

Simulations that take into account the removal of historic weirs demonstrate erosion at the sites of the weirs, which subsequently migrates for upstream for around a kilometre. However, there appears to be comparatively little deposition generated by this localized erosion, immediately downstream of the weir sites – and analysis of the sediment yields suggests that most of the sediment eroded is evacuated from the system (below the DVMWHS). This sediment may have some impact on future flood risk by reducing the conveyance (channel capacity) in downstream areas such as Derby and the lower Derwent valley.

Introduction: Background to the Caesar-Lisflood Model

The aim of this component of the project is to use the CAESAR-Lisflood model (**C**ellular **A**utomaton **E**volutionary **S**lope **A**nd **R**iver model) to simulate long-term river erosion and deposition in the River Derwent along the reach of the valley designated as a WHS (DVMWHS).

CAESAR-Lisflood (Coulthard et al., 2013) is a cellular hydraulic and sediment transport model, designed to predict how the morphology of river catchments and river reaches evolves over time. This includes identifying water inundation areas, channel erosion and deposition and slope processes (i.e. landslips) over timescales ranging from days to hundreds of years. CAESAR-Lisflood is driven by data representing surface topography, land cover and rainfall. It provides outputs of river sediment discharges and valley floor topographies at selected time steps. CAESAR-Lisflood has been developed and evaluated over a 17 year period by the author and has been used to simulate morphological changes in river systems of a range of sizes in many parts of the world (Coulthard et al., 2000, 2012; Hancock and Coulthard, 2012; Hancock et al., 2011; Welsh et al., 2009).

Here, CAESAR-Lisflood was used to determine which parts of the River Derwent could be susceptible to future flooding, erosion, deposition and channel instability and how these areas might relate to the historic asserts of the DVMWHS and its wider buffer zone. Model outputs were partially validated by comparing them to historical channel change (derived from large scale maps supplied by TPA) and field data. Then the river was tested to see how it responded to changes in flows due to future climate change.

Methods

CAESAR-Lisflood (CL from herein) simulates erosion and deposition by running water over a digital representation of the surface made of regular square cells or pixels each with an elevation – usually called a Digital Elevation Model (or DEM). Here the DEM was made from airborne laser altimetry data (LiDAR) that provides an elevation point approximately every 2m across the ground surface; the LiDAR was supplied by the Environment Agency. In order to model at this (2m) scale for the entire length of the WHS along the river corridor (approximately 24km), this would have meant a DEM of several million cells, which adds considerable numerical complexity making model runs very slow. Therefore, this 2m resolution DEM was re-sampled to 10m and 20m grid cells to allow the model to run faster. Whilst this change of scale may result in some reduction of detail (i.e. identification of subtle and complex features/landforms on the floodplain), the 20m resolution chosen still provides a good representation of the valley floor, floodplain and the channel, as well as areas of archaeological interest. The DEM is shown in Figure 1.

Figure 1: 20m DEM of the modelled reach of the DVMWHS;   Source data © Environment Agency

As CL carries out erosion and deposition on this DEM it is necessary to also add areas that can or will not change. These may include weirs, bridges, solid river bank revetments, defences and any other man-made structures that interfere with the natural hydraulics of the river in the WHS valley floor corridor. These anthropogenic features were identified and mapped during field survey and using Google Maps and then added to the CL model.

To drive erosion and deposition within the model, river flows and floods within the Derwent must first be simulated and calibrated. In order to do this, flow data was obtained from the National Rivers Archive, where a good (complete) section of data for all three rivers associated with the catchment was provided for a 23 year period of 1971-2004 (Figure 2).

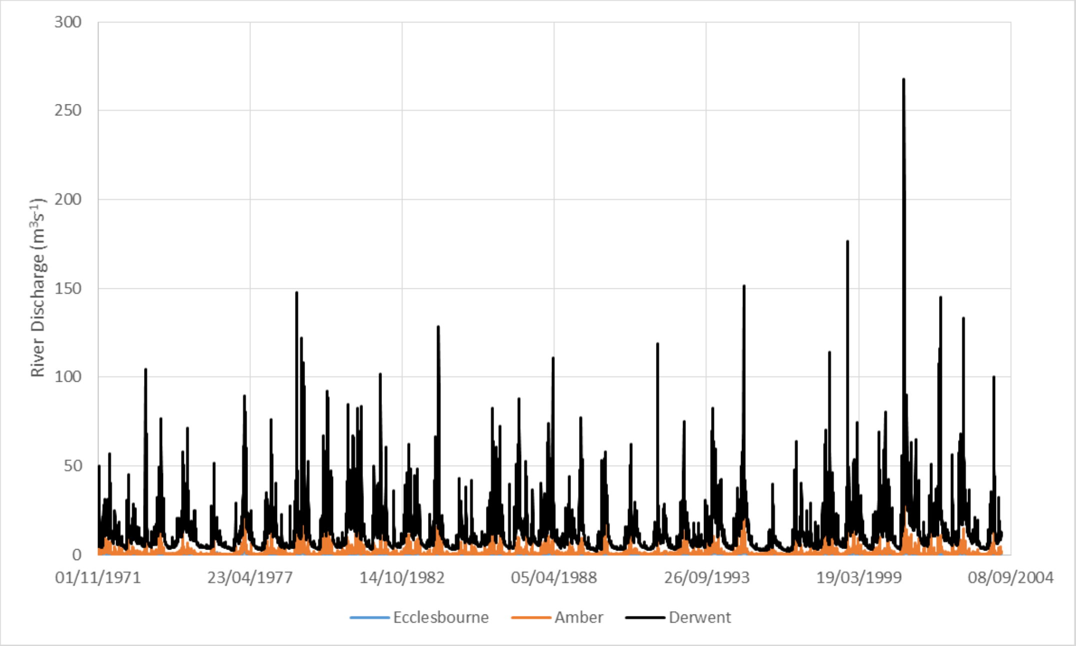

Figure 2: Flow data for the Derwent at Derby, The Ecclesbourne and Amber rivers from 1971-2004

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

For the hydrological calibration, the upstream models were then run for 30 year periods (starting with the present day channels shape and position) using synthetic rainfall modelled using a baseline criteria (computer generated rainfall based on present-day rainfall patterns) from the UKCP09 weather generator. As synthetic rainfall is generated according to probabilities of existing rainfall patterns there is a random component – so this process was repeated 100 times. From these 100 simulations, daily river flow averages were taken and used to generate a frequency distribution of daily rainfall totals. To calibrate the model, this process was repeated 6 times, each time varying a key (m) parameter in the hydrological model, which alters the size and length of floods. Figure 3 shows the frequency of the daily flows for all six of these sets of simulations and those from the actual flow data in the Derwent at Derby. From these data, a visual calibration was made to set m at 0.025.

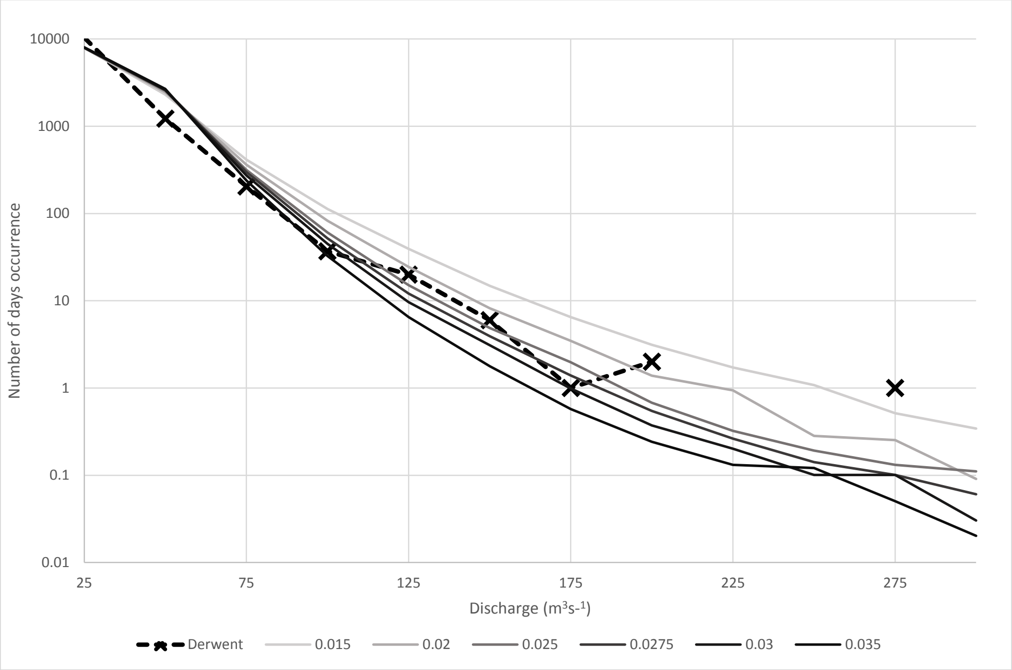

Figure 3: Frequency distribution of daily flow magnitudes for the Derwent and baseline simulations with a range of m values (0.015 to 0.035)

To model the impact of future climate change on the DVMWHS, future rainfall predictions were needed (to generate future flood events). These were 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 Derwent. From these 100, 20 were randomly selected and used to generate 30 year periods of flows and future erosion and deposition patterns within the DVMWHS reach.

An important aspect of the WHS infrastructure are the weirs that were constructed to provide power for the 'modern' factory mills and these features have had a profound impact on the hydrology of the valley floor. However, new legislation such as the European Water Framework Directive and new initiatives such as the development of hydropower schemes along the Derwent mean that many of these features are under pressure to be modified; furthermore, the antiquity of many of the weirs and the ongoing cost of maintenance have implications for their future sustainability.

With these issues in mind, one of these future rainfall scenarios was used in the WHS reach to model the system with the weirs removed to assess how the Derwent may respond to such measures.

Results and Discussion 1. The Impact of climate change on erosion and deposition within the DVMWHS

Impact of climate change on erosion and deposition

As the rainfall (and thus flood) input to each simulation is slightly different this means that 20 patterns of erosion and deposition will be generated for each scenario. Consequently some of these 20 simulations may have experienced larger or smaller floods than others. Therefore, the amounts and patterns of erosion and deposition were combined and the mean erosion and deposition is presented in Figures 4 and 5. Here the WHS reach has been split into an upper and lower section to allow larger more detailed images to be shown. In the figure scale key, red corresponds to increasing erosion whereas increasing blue colours correspond to increasing deposition.

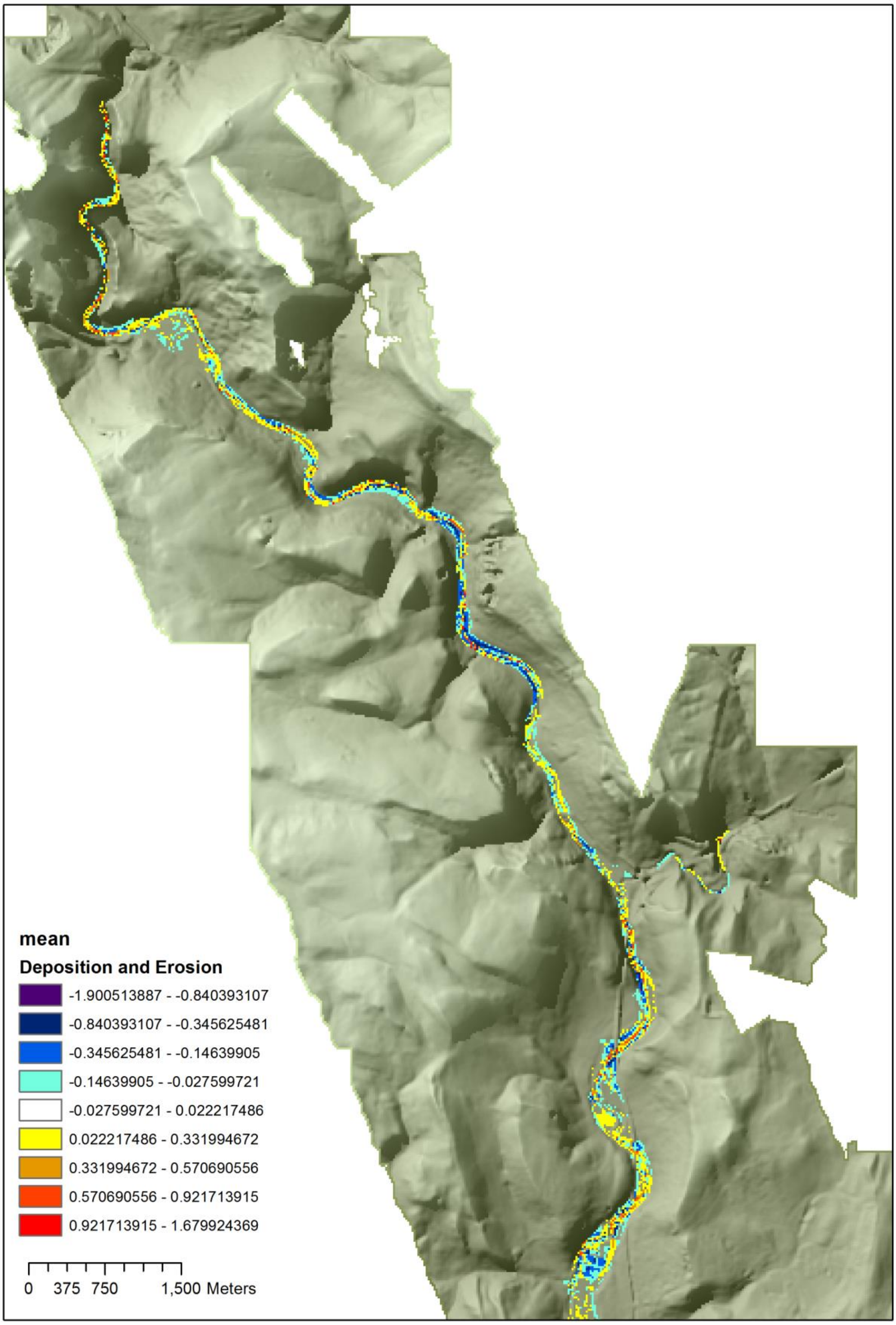

Figure 4: Erosion and deposition patterns in the upper WHS reach; Source data © Environment Agency

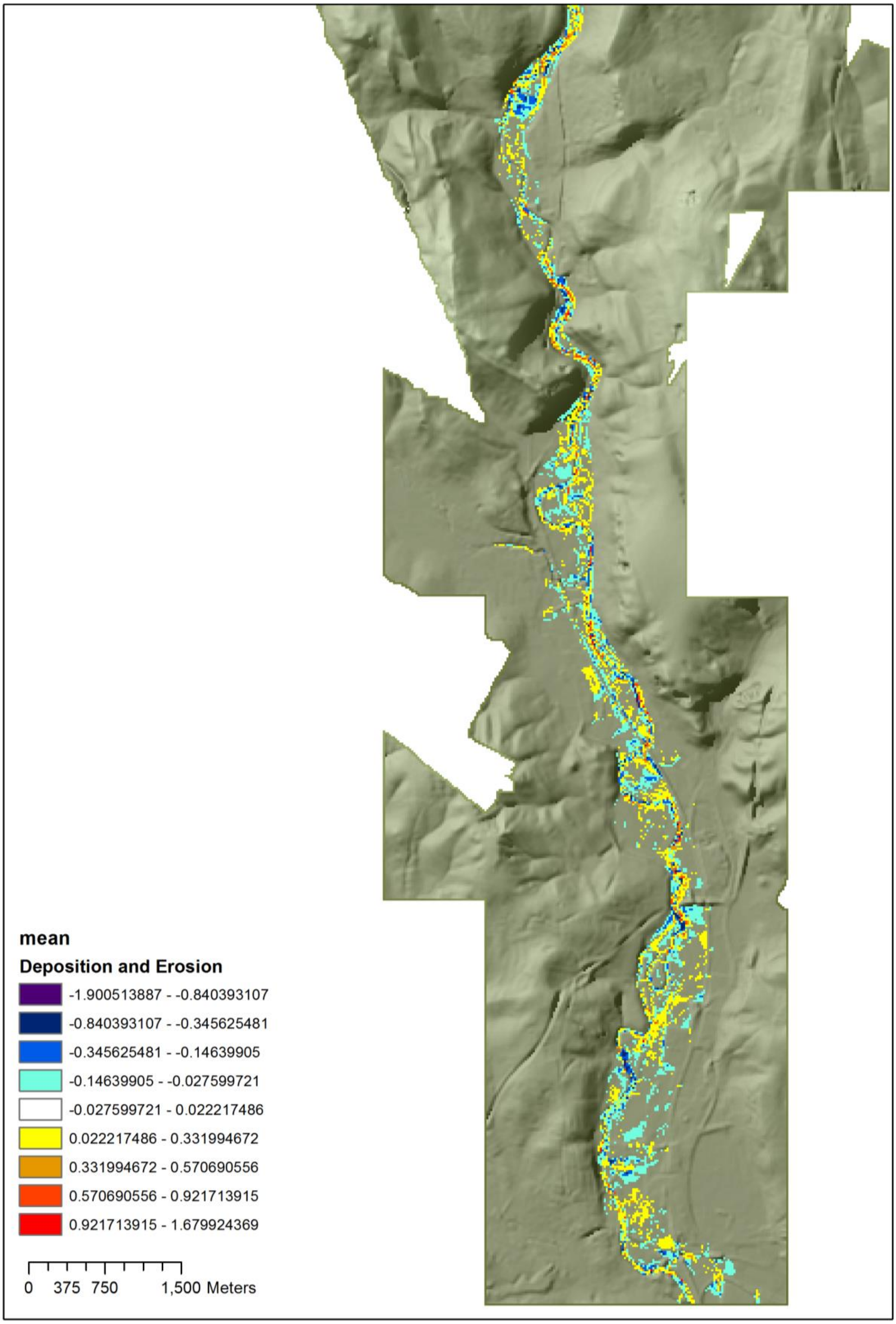

Figure 5: Erosion and deposition patterns in the lower WHS reach; Source data © Environment Agency

Figures 4 and 5 show that whilst erosion and deposition occurs throughout the WHS reach during the 30 year simulations, overall from a geomorphological perspective it is not especially significant. Only in very few places is mean erosion or deposition greater than 1m (vertically). In most locations where there is any change it is in the order of a few centimetres. This indicates that with its present configuration the overall landscape of the WHS would be relatively stable to any changes caused by climate change up to 2050. Whilst there may be some localised areas of erosion and sedimentation, there are no predicted dramatic shifts in the location of the channel or areas of high erosion and deposition. Piedmont river systems (like the Derwent) can be sensitive to changes in flood frequency and magnitude, and one danger is that reaches may become unstable – shifting from single thread to braided, more rapidly changing patterns. There are no indications of this whatsoever within the simulations carried out here.

Patterns of erosion and depiction that occur are entirely within those parameters that may be expected within a comparatively stable river system. For example, Figure 6 highlights the area from upstream of Darley Abbey to Derby, which is part of the WHS. Here we see evidence of some erosion, but largely of deposition across the wide floodplain.

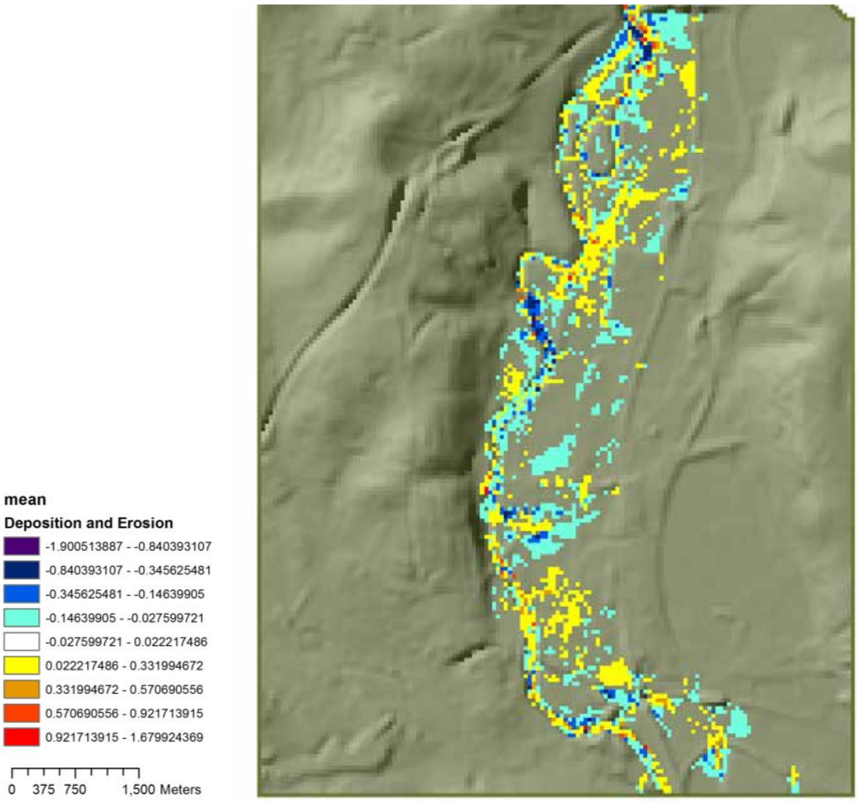

Figure 6: Mean erosion and deposition patterns for the Derwent from upstream of Darley Abbey to Derby Silk Mill; Source data © Environment Agency

Upstream at Whatstandwell (Figure 7), and at other locations, the simulations predict some lateral movement of the channel – where meander bends have extended or migrated. However, such geomorphological activity is to be expected, and Figure 7 shows how lateral erosion in simulations are in keeping with lateral erosion that has occurred over the last 150 years (as shown on historic maps).

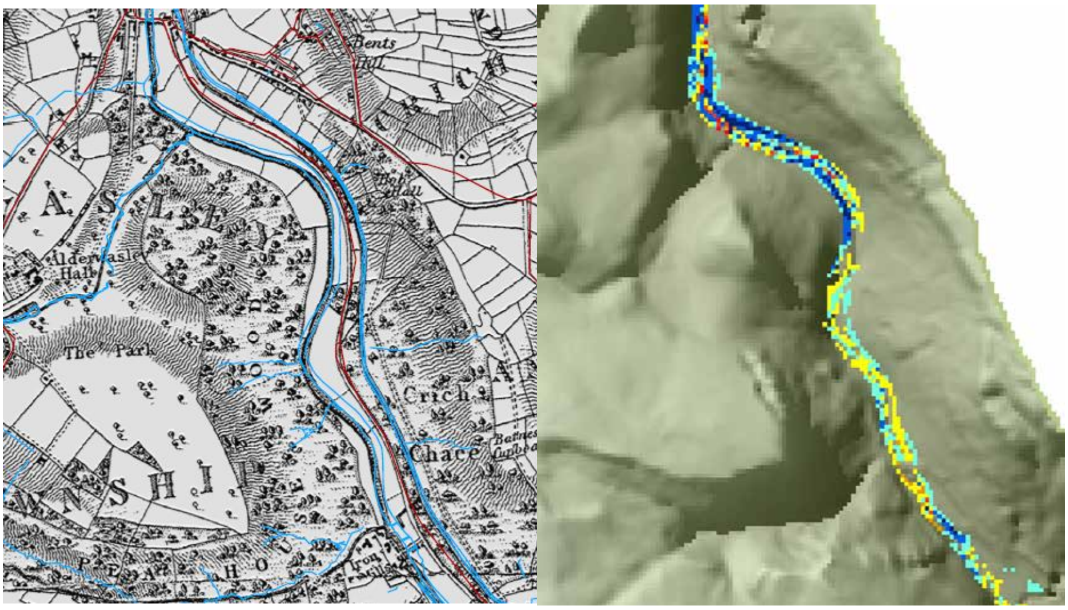

Figure 7: Left: Historic (1835) and present (blue outline) channel position of the Derwent at Whatstandwell. Right: Mean erosion and deposition patterns predicted by CL at the same site; Source data © Environment Agency

Having 20 different predictions of erosion and deposition allows a comparison of where these predictions agree and where they do not. Figures 8 and 9 illustrate this by plotting the standard deviation of erosion and deposition for the upper and lower sections of the WHS reach. These figures show that there is largely a good agreement within all the simulations – though where there are differences, this provides some insights into the behaviour of the river system. Lower parts of the Derwent (Figure 9) show a greater agreement between simulations, which suggests that this part of the valley floor may be more stable and less susceptible to changes in the size of flood events. Contrastingly, the upper reaches show greater variation indicating a larger response to different flood events. This means that some simulations indicate erosion and deposition occurring whereas others do not – in effect changes in these upper reaches are harder to predict. However, in these upper reaches, as the channel is far more constrained within a narrower valley floor, these variations in changes are limited laterally. For example, the valley floor is not wide enough for the channel to avulse or move over to another part of the valley.

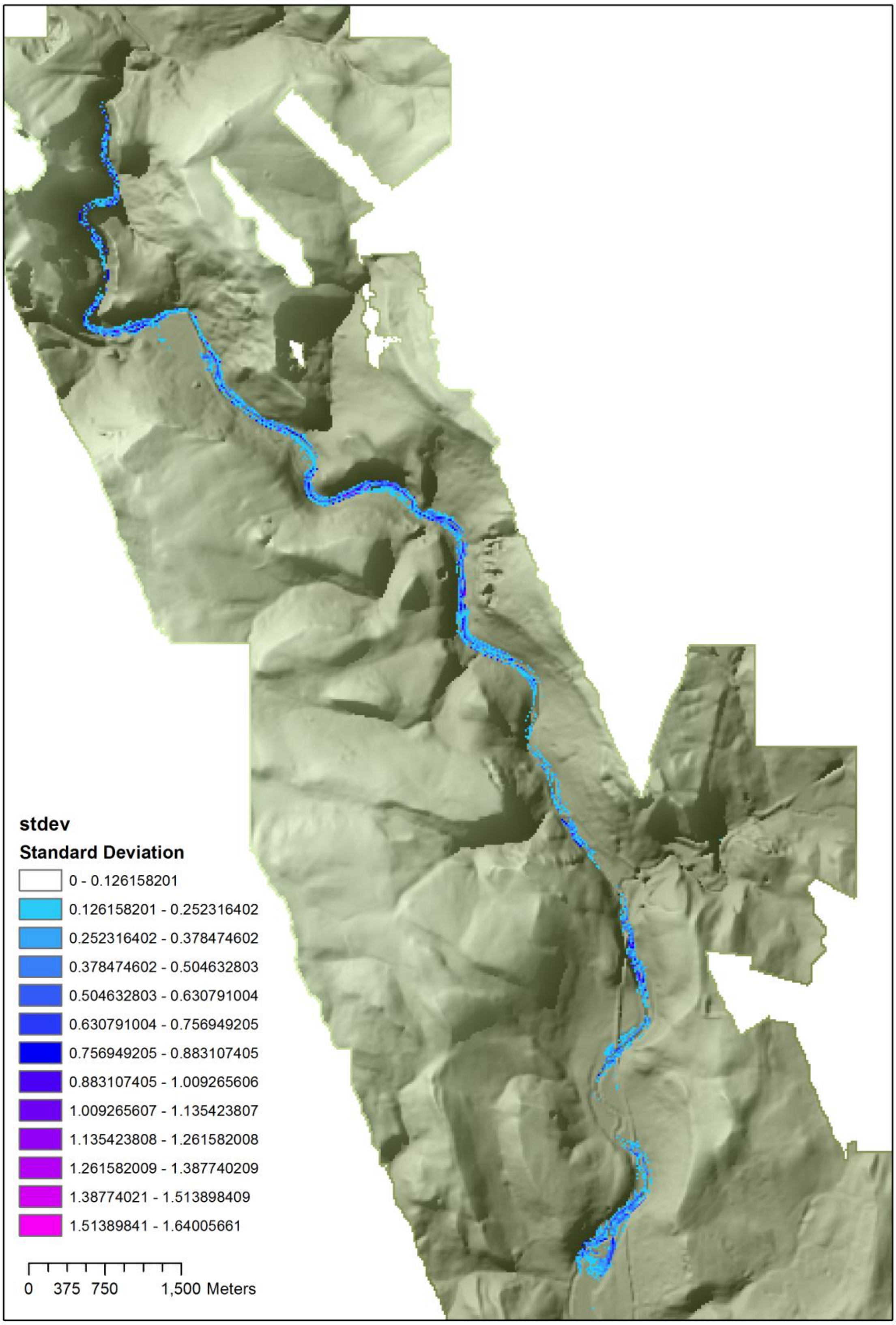

Figure 8: Standard deviation of erosion and deposition for the upper WHS reach; Source data © Environment Agency

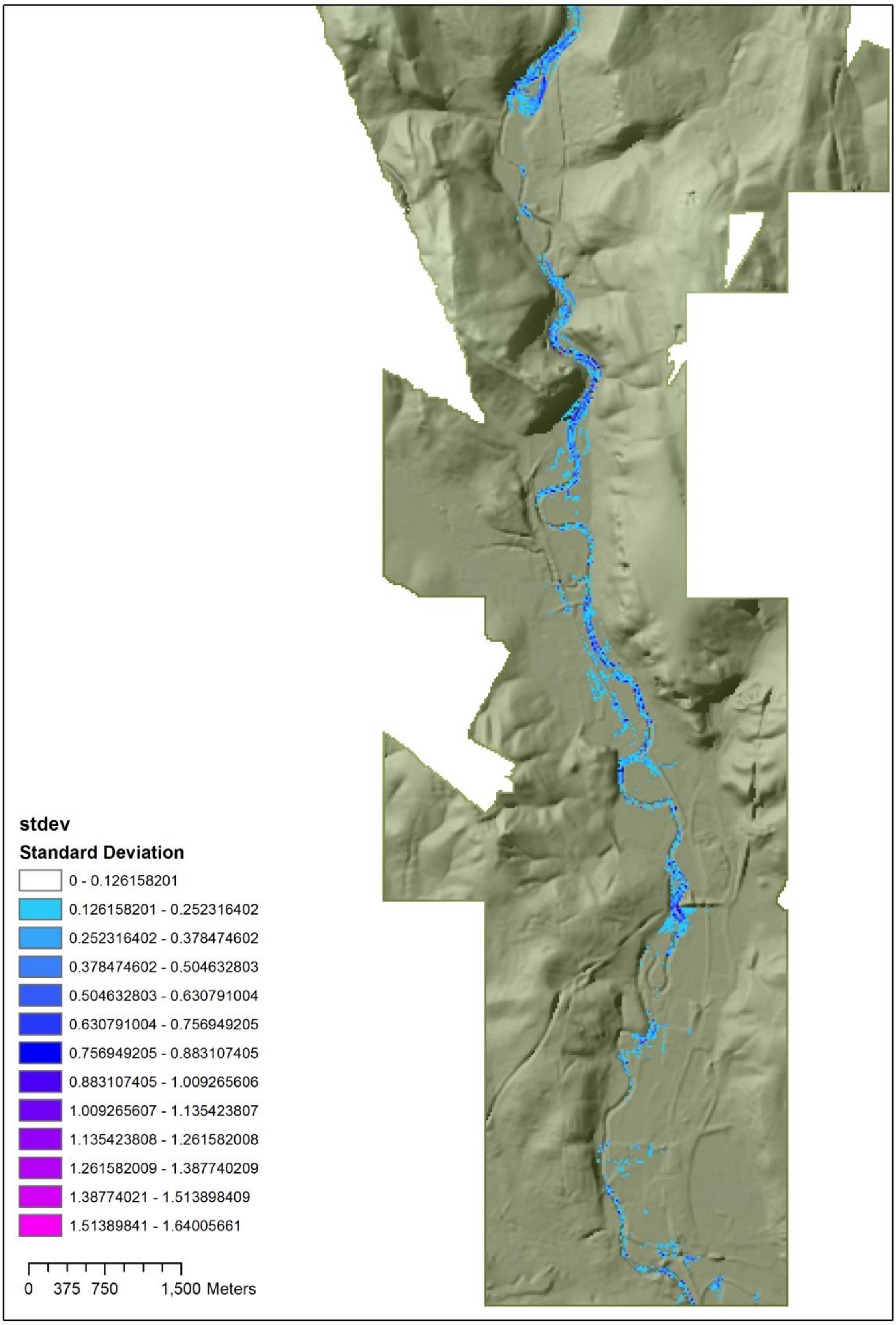

Figure 9: Standard deviation of erosion and deposition for the lower WHS reach; Source data © Environment Agency

Summary of Results and Discussion 1

Considering future management of the DVMWHS, these simulation results indicate that from a geomorphological perspective, there should be minimal issues with sedimentation or erosion problems in response to changing flood patterns up to 2050. However, within the reach of the WHS, there may be some localised issues that need to be managed appropriately and these areas will be further investigated by dovetailing the model results with the HER within the wider project GIS.

Regarding flood risk, as there is comparatively little change in the channel shape (due to erosion and deposition) and no changes or shifts in channel position, there will be little change in the areas flooded for the same size flood events. However, larger flood events that may feature due to climate change may well inundate areas that are at present rarely if at all flooded – but there will be no change for equivalent size flood events.

A geochemical review of valley floor sediments undertaken as part of the wider study indicates that much of the Derwent floodplain sediment is contaminated as a result of the base metal mining industry of the southern Peak District, which may have other environmental and health implications. If these sediments are eroded and thus moved from their present stores in the floodplain they may represent an environmental hazard – both now and in the future. However, the results of the future climate change scenarios are largely positive, as a stable channel pattern and low levels of lateral erosion mean that any contaminants within floodplains are less likely to be re-mobilised due to any future changes in climate.

It is important to note that these results are all based on the assumption that there are on major changes in the channel/floodplain infrastructure and that existing flood defences and fixed structures (e.g. weirs and bank protection) will be maintained in the future.

Results and Discussion 2. Simulation Following Weir Removal

Erosion and deposition changes

Figures 10 and 11 illustrated below show, the differences in erosion and deposition in metres over 30 simulated years, between simulations with weirs and with the weirs removed. Both simulations started with the same topography, were driven by the same rainfall, and experienced the same floods – the only difference being the lowering of cells representing weirs. These results clearly show that erosion has occurred around a number of weirs and that this erosion has moved upstream in response to increased local water surface gradients (that drive velocity and thus erosion). This incision is widespread and has moved, in most circumstances, *c*.1km upstream as the river establishes its pre-weir gradient.

Interestingly, there is comparatively less deposition in response to this erosion. Downstream of weir removal it might be expected that there would be enhanced deposition as the grade of the stream bed rises to meet the decreasing upstream elevations. However, the amounts of deposition (denoted by blues) are less and of smaller depths than erosion. There are only one or two locations within the upper reach where deposition amounts are shaded darker blues (>1m). Most of the erosion and deposition occurred within the channel – meaning erosion and deposition on the river bed where presently where the river flows.

Importantly, changes in river bed elevation will have a direct impact upon the conveyance (carrying capacity) of the channel and therefore the risk of flooding at certain sites. Generally, incision will lead to increased conveyance and thus reduced flood risk, and vice versa for deposition. Therefore, as the weir removal leads to more erosion than deposition the impact on flooding would be beneficial. However, erosion may also lead to localised instabilities in (for example) bank protection measures and potentially bridge foundation undermining. Changing the bed gradient in this way will also alter the velocities of river flows and this will also have an impact upon conveyance and thus flood risk. Further modelling can be carried out to show whether or not this has an effect upon flood risk along the Derwent reach studied.

Sediment Yield Changes

Figure 12 shows the cumulative sediment yields from the reach for the simulation with and without weirs. Sharp rises in the Figure 12 correspond to flood events where larger amounts of sediment are removed from the reach.

Simulations without the weir structures show a greater than 100% increase in sediment yield – which backs up the findings above – where there was more erosion than deposition observed. It was expected that differences would be greatest in the first 10 years simulated as under conditions of weir removal, the channel bed adjusted to its new found gradient. In effect the freshly removed weirs left a greater amount of sediment to be removed at the beginning of the simulations. However, the rates of sediment removal appear to remain continuously higher for the no weir simulation indicating that the reach is continuing to adjust to the weir removal beyond the 30 years simulated.

Increases in sediment supplied downstream may have detrimental environmental and management issues. The sediment has to go somewhere, and it would end up being deposited or moved further along the Derwent through the city of Derby. This could lead to possible siltation and deposition issues in the urbanised zone and further. Such a depositional scenario is therefore likely to have a negative impact on conveyance and thus flood risk in the city and wider lower Derwent valley.

Summary of Results and Discussion 2

For the reaches of the Derwent (upstream of Derby and within the DVMWHS), the removal of historic weirs has an overall less severe impact on the geomorphology than might be expected. In general, the removal of Dams and Weirs can have a profound impact on river behaviour, promoting erosion, deposition and leading to increases in channel instability. However, these simulations indicate that whilst there is erosion and deposition the effects are not severe and appear relatively well-constrained within the present day channel belt/area. There may well be local impacts of incision and deposition that are not indicated here, but overall the impact is not profound. However, comparison of erosion hotspots to the HER as part of the wider project is essential to understand how any potential changes might affect the Historic Environment record.

Erosion and deposition would have corresponding impacts upon the in-stream and riparian ecology. Areas behind weirs that are presently slow flowing and ponded would change to have faster flows and it is likely that pool and riffle sequences would develop through time. This would in effect remove one type of habitat (ponding and slow water) yet restore a different (pool riffle) channel habitat.

Downstream impacts are less certain. The sediment that is presently backed up or stored behind the weirs along the Derwent is released with the weir removal, and a large proportion of this sediment is evacuated downstream below the limits of these simulations (i.e. beyond the WHS). The area beyond simulation includes the city of Derby and it is quite possible that weir removal might lead to sedimentation/siltation issues within the City itself and reaches immediately downstream. This could have a negative impact on channel management and flood risk.

The release of trapped sediment from weir removal may also prove problematic if these sediments are contaminated with heavy metals from past mining and industrial activity. Weirs, dams and mill ponds provide ideal locations for sediment to be trapped and become deposited. As the simulations above showed, removing weirs re-activates these areas of deposited sediment releasing them into the river and allowing them to move downstream. If released sediments are contaminated with heavy metals, this may have other environmental and health implications. Removal of the weirs would therefore also require extensive removal and safe disposal of the sediment trapped behind them.

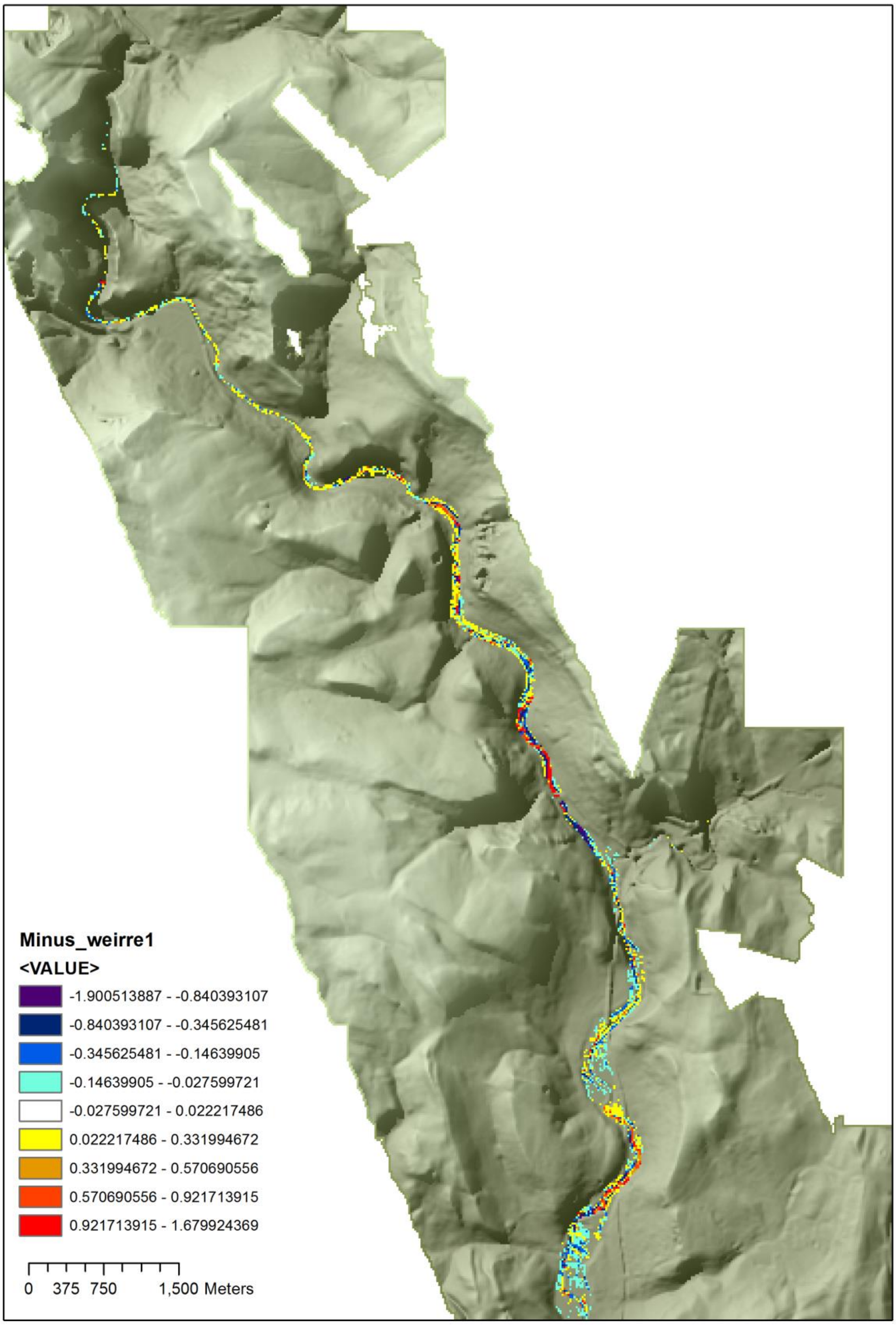

Figure 10: Difference in erosion (red) and deposition (blue) between with and without weir simulations for the upper 10km of the Derwent reach studied; Source data © Environment Agency

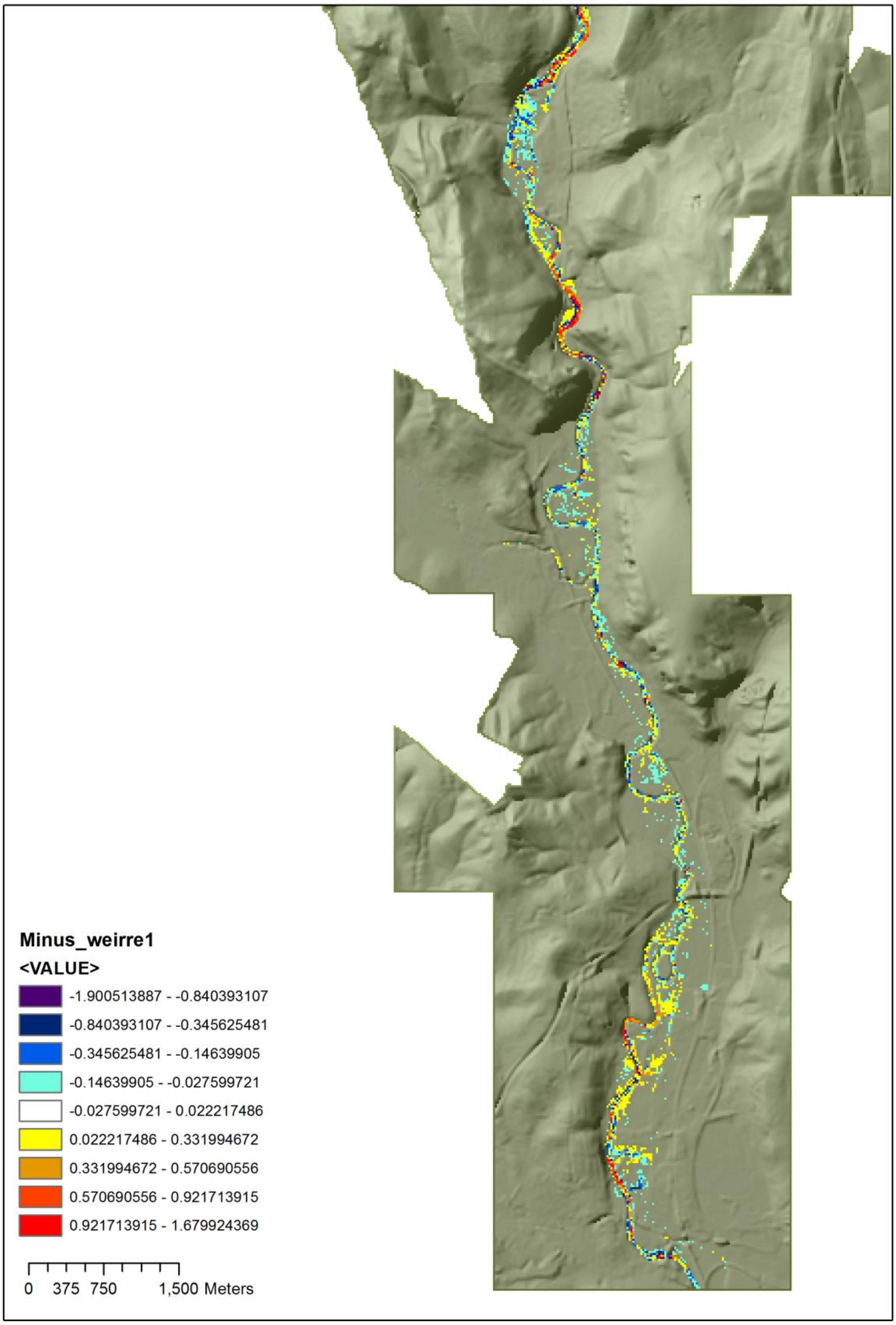

Figure 11: Difference in erosion (red) and deposition (blue) between with and without weir simulations for the lower 10km of the Derwent reach studied; Source data © Environment Agency

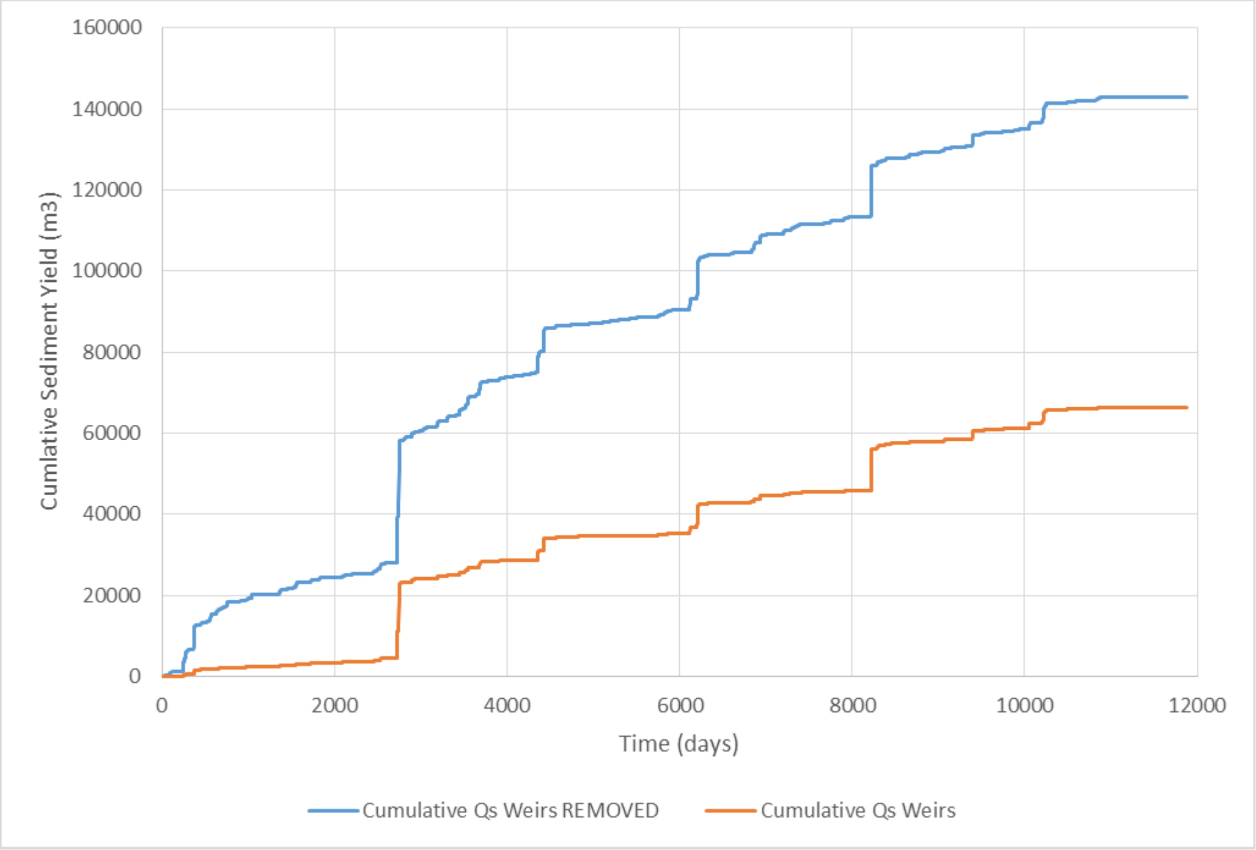

Figure 12: Cumulative sediment yields from the simulated reach with and without weirs

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ANNEX 2

The impact of mining contamination on the Derwent Valley World Heritage Site

Dr David Kossoff & Professor Karen Hudson-Edwards

Department of Earth & Planetary Sciences

Birkbeck, University of London

1. Introduction

The United Kingdom (UK) once had a huge base-metal mining industry. During the mid-19th century the UK was the most important mining nation in the world, producing 75% of the world's copper [Cu], 60% of the tin [Sn] and 50% of the lead [Pb] (Harvey and Press, 1989; Zhang, 2008). During the latter part of that century and the beginning of the next, however, UK base-metal mining went into a terminal decline. This was the result of declining domestic grades combined with the discovery of plentiful deposits overseas (Byrne *et al*., 2012). It has been conservatively estimated that the UK has over 3,000 abandoned metal mines (Jarvis *et al*., 2007). Many of these mines and their associated adits, ruined buildings, equipment and, most significantly, spoil heaps will remain a potential contaminant source certainly for several centuries to come or, possibly, even longer (Younger and Wolkersdorfer, 2004). After agricultural contamination, mining poses the most widespread contamination threat to water-status objectives in England and Wales, with 26 out of 356 groundwater bodies (7.3%, but 14% by land surface area) and 226 out of 5868 surface water bodies (3.9%, but 7% by river length) are ‘at risk’due to mine water contamination (Gandy *et al*., 2007). Hence, although the UK does not perhaps immediately spring to mind as being potentially at risk from mining activity, this view is very much a misconception; albeit that the contamination is of historic, rather than contemporary, origin. The Derwent catchment is a prime example of just such a potentially at risk area; hence, by extension, so is the Derwent Valley Mills World Heritage Site (DVMWHS).

In order to appreciate the severity of contamination it is useful to have signpost values. There are differing international regulatory levels set on safe contaminant levels in soils. Table 1.1, adapted from Rothwell *et al*. (2005), provides examples of these data for the most prominent Derbyshire contaminants: cadmium [Cd], Pb, and zinc [Zn] (Section 3a).

In this context it is relevant to compare the regulatory values to that of the applicable average top-soil concentrations throughout England and Wales. Zhang (2008) provided these data and they are reproduced in Table 1.2.

Elements such as Cd, Pb and Zn have two principal environmental modes of occurrence. Firstly, they can either be incorporated as a structural component of the mineral structure or lattice. Table 1.3 gives some examples of such minerals with particular relevance to the Derbyshire ore field.

Country	Contaminated land guideline(a)	Pb concentration (mg/kg)	Zn concentration (mg/kg)	Cd concentration (mg/kg)	Reference
UK	SGV: residential land	450		10 a)	DEFRA (2002)
	SGV: allotment			1.8 a)	
	SGV: commercial/industrial land	750		230 a)	DEFRA (2002)
Sweden	Guideline value: polluted soils	<80 - >800	<350 - >3,500	<0.4 - >4	SEPA (2002)
Netherlands	Target level: polluted soil sediment	85	140	0.8	VROM (2000)
	Intervention value: polluted soil/sediment	530	720	12	VROM (2000)
Canada	CSoQGs: agricultural land	70	200	1.4	CCME (2002)
	CSoQGs: residential/parkland	140	200	10	CCME (2002)
	CSoQGs: commercial land	260	360	22	CCME (2002)
	CSoQGs: industrial land	600	360	22	CCME (2002)
Australia	SIL: residential land	300	8,000	20	NEPC (1999)
	SIL: parkland	600	30,000	100	NEPC (1999)
	SIL: commercial/industrial land	1500	400,000	800	NEPC (1999)

Table 1.1 Contaminated land guidelines for selected countries.

Metal	Minimum	Mean	Median	Maximum	CV%	Skewness	Kurtosis
Cd	<0.2	0.8	0.7	40.9	115.8	17.6	574.4
Cr	0.2	41.2	39.3	838	68.5	9.46	205.4
Cu	1.2	23.1	18.1	1508	160.1	21.2	654.6
Mn	3	760.9	577	42603	128.7	17.9	638.6
Pb	3	74	40	16338	360.8	42.7	2449.6
Ni	0.8	24.5	22.6	440	71	6.95	132.9
Zn	5	97.1	82	3648	112.6	13.6	299.6

Table 1.2 Summary of the concentrations of selected heavy metals in top-soils (0-15cm) in England and Wales (mg/kg) Source: McGrath and Loveland, 1992 (CV%: coefficient of variation = SD/Mean %)

Element	**Principal host**	**Subsidiary hosts**			
		Sulphides	**Carbonates**	**Phosphates**	**Sulphate**
Cd	Sphalerite (ZnS)	Wurtzite (ZnS), Greenockite (CdS), Pyrite (FeS2)	-	-	-
Pb	Galena (PbS)	Pyrite (Fes2)	Cerussite Pb(CO3)	Pyromorphite (Pb5(PO4)3Cl)	Anglesite (PbSO4), Baryte ((Ba, Pb)SO4)
Zn	Sphalerite (ZnS)	Wurtzite (ZnS), Pyrite (FeS2)	Smithsonite (ZnCO3)	-	-

Table 1.3: Derbyshire contaminant metals and their principal mineral hosts

Secondly, elements can be attached to the surface, or sorbed, to host minerals. In this context the clay family (e.g., montmorillonite –$[Na, Ca)_{0.33}(Al,Mg)_2(SiO_4O_{10})(OH)_2.nH_2O]$ is an important host together with the manganese- and, particularly iron-oxide and hydroxide minerals (e.g., pyrolusite –$[MnO_2]$ and goethite – $[Fe(OH)_3]$). In general terms sorbed elements are more available, or mobile, than those which are structurally incorporated and therefore they are of potential greater environmental impact. In reality, however, structural incorporation and adsorption together do not represent a binary classification, with a continuous spectrum of mobility being reported (Antoniadis and Tsadilas, 2007). An element's position on that spectrum is very much dependent on local conditions such as acidity, the availability of oxygen and the pertaining general chemical environment (Krauskopf and Bird 1995).

2. Mining and the Derbyshire Derwent

2a) Geological Background

The southern section of the Pennines is formed by an anticlinal dome of Carboniferous limestone $[CaCO_3]$. The limestone is over 1,000 m thick and is interbedded with igneous basaltic lavas, tufts and dolerites collectively locally known as toadstone. To the east, west and north the limestone is flanked by Carboniferous shales and sandstones (Millstone Grit). A variety of mineralisation (characterised geologically as Mississippi Valley Type) known as the fluoritic sub-type formed during the Permo-Triassic when hydrothermally-driven veins invaded the limestone along bedding planes, faults, joints and between adjacent bedded strata (Cox and Singer, 1986; Ineson and Ford, 1982). The introduced minerals were principally galena, sphalerite, fluorite $[CaF_2]$, quartz $[SiO_2]$, pyrite, chalcopyrite $[CuFeS_2]$ and barite (Table 1.3; Burek and Cubitt 1979; Lee et al., 2013; Li and Thornton, 1993[a]). The mineralisation comprises a large number of long (up to km scale) and narrow (m scale) ribbon-like masses of ore (oreshoots) of limited vertical extent (Palumbo-Roe and Colman, 2010). There are also a number of significant replacement ore-bodies and, when these were accessible, the miners described them as bonanzas; a good example being the Hubberdale Mine Pipe (Flagg, Derbyshire) find in the 1760s (Ford and Rieuwerts, 1970). Trace elements are associated with the major minerals. For example, sphalerite can contain around 0.1-0.2 % Cd, while pyrite can host arsenic [As], antimony [Sb], cobalt [Co] and nickel [Ni] (Palumbo-Roe and Colman, 2010). Additionally there are a host of other minerals present in comparatively minor amounts (reference the map produced from the spreadsheet; Table 2.1).

Pb	Cu	Fe	Zn (cont)	Mn
Anglesite PbSO4	Aurichalcite (Zn,Cu)5(CO3)2(OH)6:	Goethite alpha Fe3+OOH	Tetrahedrite Cu6(Cu4(Fe,Zn)2)Sb4S13	'Mn oxides'
Baryte Ba,Pb SO4	Azurite Cu3(CO3)2.(OH)2	Hematite Fe2O3	Unamed zinc hydroxide	Pyrolusite MnO2
Caledonite Pb5Cu2(SO4)3(Co3)(OH)6	Bornite Cu5FeS4	Lepidocrocite Gamma Fe3+OOH	Wülfingite Zn(OH)2	Rhodensite (MnCO3)
Cerrussite PbCO3	Brochantite Cu4(SO4).(OH)6	Limonite' FeO(OH).nH2O	Wurtzite: ZnS	'Wad' mixture of Mn oxides
Desclozite Pb(Zn, Cu) (VO4)(OH)	Caledonite Pb5Cu2(SO4)3(Co3)(OH)6	Marcasite FeS2	As	Wulfenite Pb(MnO4)
Dundasite PbAl2(CO3)2(OH)4.H2O	Chrysocolla (Cu,Al)2H2Si2O5(OH)4.nH2O	Magnetite Fe3O4	Arsenopyrite (FeAsS)	Ni
Galena PbS	Chalcanthite CuSO4.5H2O	Melanterite FeSO4.7H2O	Enargite Cu3AsS4	Millerite NiS
Hydrocerussite Pb3(CO3)2(OH)2	Chalcocite Cu2S	Ochre hydrated Fe oxide	Mimetite Pb5(AsO4)3Cl	S
Lanarkite Pb2(SO4)O	Chalcopyrite CuFeS2	Pyrite FeS2	Ag	Native Sulphur
Leadhillite: Pb4(CO3)2(SO4)(OH)2	Native Copper	Pyrrohotite Fe1-x S x= 0-0.2	Native Silver	Sb
Linarite PbCu(SO4)(OH)2	Cuprite Cu2O	Siderite FeCO3	Au	Stibnite Sb2S3
Litharge PbO	Desclozite Pb(Zn, Cu) (VO4)(OH)	Vivianite Fe2+3(PO4)2.8H2O	Native Gold	Tetrahedrite Cu6(Cu4(Fe,Zn)2)Sb4S13
Mattheddleite Pb5(SiO4)1,5(SO4)1.5(Cl,OH)	Enargite Cu3AsS4	Zn	Ba	Sr
Massicot PbO	Ettringite Ca6Al2(SO4)3(OH)12.26H2O	Ashoverite Zn(OH)2	Baryte Ba,Pb SO4	Celestine SrSO4
Matlockite PbFCl	Langite Cu4(SO4)(OH)6.2H2O	Aurichalcite (Zn,Cu)5(CO3)2(OH)6:	Witherite BaCO3	U
Mimetite Pb5(AsO4)3Cl	Linarite PbCu(SO4)(OH)2	'Calamine'	Cd	Torbernite Cu(UO2)2(PO4)2.12H2O
Minium Pb3O4	Malachite Cu2 (CO3).(OH)2	Desclozite Pb(Zn, Cu) (VO4)(OH)	Greenockite CdS	V
Phosgenite Pb2 CO3Cl2	Rosasite (Cu,Zn)2(CO3)(OH)2	Hemimorphite Zn4Si2O7(OH)2.H2O	Hawkeyite CdS	Desclozite Pb(Zn, Cu) (VO4)(OH)
Phosphohedyplane Ca2Pb3(PO4)3Cl	Serpierite Ca(Cu,Zn)4(SO4)2(OH)6.3H2O	Hydrozincite Zn5(CO3)2(OH)6	Hg	Vanadinite Pb5(VO4)3Cl
Pyromorphite Pb5(PO4)3Cl	Tenorite CuO	Rosasite (Cu,Zn)2(CO3)(OH)2	Cinnibar HgS	Zr
Susannite Pb4(CO3)2(SO4)(OH)2	Tetrahedrite Cu6(Cu4(Fe,Zn)2)Sb4S13	Serpierite Ca(Cu,Zn)4(SO4)2(OH)6.3H2O	Native Mercury	Zircon ZiSiO4
Un 2: Unamed 2 a lead oxide	Torbernite Cu(UO2)2(PO4)2.12H2O	Smithsonite ZnCO3		
Vanadinite Pb5(VO4)3Cl		Sphalerite ZnS		
Wulfenite Pb(MnO4)		Sweetite Zn(OH)2		

Table 2.1 Derbyshire heavy metal/metalloid mineralogy (Data from http://www.mindat.org/lsearch.php?from=nsearchandalp=1andloc=derbyshire).

2b) The Derwent catchment

The Derwent catchment has an area of 1194 km^2 .The river rises in the Peak District on Howden Moor and flows for some 80 km in a southerly direction until it joins the River Trent, just to the south of Derby.

The altitude at source is 590m and the river flows through deeply incised limestone gorges (Bradley and Cox, 1990). The upper reaches of the river are underlain by Millstone Grit and have a very high annual rainfall, in excess of 1,450 mm per annum. Here, the acidic soils and raised bogs which develop on the Millstone Grit are highly waterlogged. Conversely the limestone bedrock, which largely underlies the middle- and lower-course, is highly permeable. Despite the permeability, floods are reported to occur 2-3 times per year in the middle course, usually during the winter season and early spring. Depending on their extent, the floods may inundate the entire floodplain (Zhang, 2008). The limestone area is mainly laid down to pasture with dairy farming being prominent, with some sheep and beef cattle (Geeson et al., 1998). The upper course comprises the Derwent reservoirs and areas upstream; it was not subject to metal mining. Despite this, however, Pb contamination is of concern (Section 3d). The middle course comprises the reach downstream of the reservoirs as far as the head of the Matlock Gorge and was very much subject to metal mining. The lower course comprises the section between the end of the Matlock George and the Trent confluence; it was directly subjected to metal mining on a more limited scale than the middle course. For example, the mining-contaminated Ecclesbourne (Section 3f), which drains the southern margin of the orefield at Wirksworth, joins the Derwent below Matlock. The lower course includes the area designated as the DVMWHS site between Cromford Mills and the Silk Mill in central Derby. These terms upper-, middle- and lower-course will be used later in this document when talking about specific valley floor zones.

2c) Derbyshire metal mining and working history

There are no currently operating dedicated base-metal mines in Derbyshire; hence, contamination issues are of historic rather than contemporary origin. Lead was an important and widely traded commodity within the Roman Empire, used in plumbing and to sweeten food and wine (Waldron, 1973). Britain was a significant Pb producing region for the Empire and, within Britain, Derbyshire was one of the most significant ore fields (Dearne, 1990).

Recently the historical record of mining has been pushed back a further 1,500 years with discoveries dating to the Bronze Age being unearthed at the Ecton Hill copper mines and 7th century BC Pb mining artefacts at Mam Tor and Gaslow(Guilbert, 1996; Barnatt, 1999; Barnatt and Smith, 2004).

Medieval Pb working in Derbyshire was an important local and, by extension, national industry. It is noteworthy, for example, that accounts in the Doomsday Survey (c. AD 1086) list seven smelters and a number of mines at Bakewell, Ashford, Matlock, Crich and Wirksworth (White, 1991). Many of the great medieval cathedrals were roofed and plumbed with Derbyshire Pb both domestically and abroad (van

Duivenvoorde et al., 2013). For example, there was a substantial and long-standing Pb export trade to the Low Countries, the Baltic and Scandinavia (Riden, 1987). By the 17th century Pb was second only to wool in value as a British export (Slack, 2000; Willies and Parker, 1999). In today's terms, until the impact of the industrial revolution, mining enterprises were small scale, with outputs from mines and smelters often no more than a few tons per year.

Additionally there were a multitude of local laws and customs constraining the development of the industry. For example, along the mineralised veins, otherwise known as rakes, a new mine title was granted every 28-32 yards, often with each title having the right to sink an individual shaft (Palumbo-Roe and Colman, 2010). The large topographical footprint of the mines and the associated processing facilities, coupled with the small-scale of the individual enterprises, resulted in a multitude of, albeit small, potential contaminant point sources.

Later, during the 18th and 19th centuries as industrialisation preceded, fewer mines produced greater outputs. Because of the permeable nature of the limestone an important constraining factor was the ability to drain the mine. Hence the construction of drainage channels, locally known as soughs, began in the early 17th century was necessary as the miners had to go ever deeper for the ore (Ford and Rieuwerts, 1970). Drainage was facilitated by the newly available pumping technology of the industrial revolution, which allowed previously inaccessible ore seams to be worked (Willies and Parker, 1999). These soughs largely remain *in situ* as landscape features and some have evolved to become an integral part of the present water supply infrastructure (James, 1997; Kirkham, 1968). A further boon to the profitability of the Derbyshire orefield was the introduction (in the early years of the 18th century) of the reverberatory furnace, or cupola, which allowed for the cheaper and more efficient smelting of Pb ores (Merry, 1988).

It is of note that historic accounts of Pb poisoning, or to use the local term Belland, are comparatively rare from Derbyshire. They are, however, to be found in the historical record; for example, Dr. Thomas Percival a local Bakewell practitioner, reported the following in the late 18th century (Meiklejohn, 1954:*"The men first complain of a weight, pain of the stomach and costiveness, which are generally relieved, if they apply early for advice, by a vomit, and pills of soap, rhubarb and aloes: or by any aperient medicines of the liquid kind, with oil added to them. But if these symptoms be neglected, the patients complain of their saliva becoming sweet, of clammy sweats, lassitude, feebleness of the legs, a total loss of appetite, obstinate costiveness, and a fixed pain in the abdomen, with severe retchings."*Fortunately, there was considerable local awareness of the potentially dangerous nature of the industry and there are reports of affected men periodically changing work from the Pb mines to, for example, the lime kilns with the latter alleviating the symptomology brought on by the former.

In this context it should be noted that the principal Pb ore mineral was galena, which is more stable than other Pb ores such as cerrusite and anglesite (Porter et al., 2004). Consequently, galena-hosted Pb is not as bio-available and, it follows, not as toxic. When galena is exposed to the atmosphere (as on the surface of a floodplain) it oxidises and forms secondary minerals such as anglesite and cerrusite. Hence, the new secondary Pb mineral host(s) will have greater impact on ecosystems through the mechanism of increased bio-availability.

2d) Quantifying mineral production

To the author's knowledge a comprehensive document quantifying the Pb ore field's historic production has not yet been published. This perhaps is not surprising as there are an estimated 25,000 Pb mine shafts in the Peak District (Willies and Parker, 1999). There are, however, many records held for example by the various local mining regulatory bodies (Barmote Courts), Chatsworth House and the offices of Derbyshire County Council. Many authors have reviewed these historic sources and the literature therefore has a large number of production figures (Table 2.2).

For the Derbyshire ore field as a whole overall ore production has been estimated to be in the millions of tons, the bulk of this being sourced from within the Derwent catchment (Ford and Rieuwerts, 1970, in particular the map on p.16). Ford and Rieuwerts (1970) give a figure of 3-6 million tons of Pb ore and ¼-½million tons of Zn ore, while Palumbo-Roe and Coleman (2010) give an estimate of 2.5 million tonnes of Pb. Maximum Pb production is often reported as having occurred during the 18thcentury. For example, Willies (1986), after examining the historic records, estimated that 100,000 tons of ore were produced in the Winster Barmote through the course of the 18th century, with production falling to 44,500 tons for the 19th century. Additionally, comparative 18th and 19th century ore production data for the Winster Liberty (local mining district) have been reported by Merry (1988) (Tables 2.3 and 2.3a).

It is noteworthy that these data indicate that by 1760 the influence of the large companies had become dominant. The seven largest mines all belonged to the major companies and produced six-fold the combined production of the 22 other mines in the Liberty (Table 2.4).

Mine	Location	Ore Production figures	Total Tonnage (per year)	Reference
Tideslow rake	SK15377796	2,600 loads (650 tons ore) in 1195	650 (650)	Ford and Rieuwerts, 1970
Peak Forest Liberty (incorporating Tideslow mines)	Area around Eldon Hill SK 117809	550 loads in 1245	220 (220)	Ford and Rieuwerts, 1970
Colehills and Dale End	SK292543	490 loads, or about 122 tons of lead ore per year around 1540	122 (122)	Slack, 2000
Stainsborough mines	SK2653	21 tons produced from 6 mines in 1639	21 (21)	Slack, 2000
The Wirksworth Liberty	SK284550	1640-1645 2,049 tons ore produced. In 1908 just 12 tons were produced	2049 (410) / 12 (12)	Slack, 2000
Raventor	SK284550	3,145 tons ore between 1770 and 1773. However, in 1872 just 4 tons were produced	3,145 (1050)	Slack, 2000
Ball Eye Mine	SK287574	£50,000 of ore raised in three years during 1730s. Approximately equivalent to 17,0000 tons	17,000 (5666)	Ford and Rieuwerts, 1970
Odin Mine	SK132835	Worked throughout the 18th century annual ore production ranging between 100 and 800 tons.	~ 45,000 (~ 450)	Ford and Rieuwerts, 1970
Torrtops Vein	SK156726	133 loads intermittently mined between 1729 and 1742.	129 (5.6)	Rieuwerts, 2008
Burfoot mines	~ SK156726	613 loads taken between 1727 and 1742 with 700 loads taken between 1788 and 1792. and a good year in 1793 with 1,455 loads	1107 (16.8)	Rieuwerts, 2008
Magpie mine	SK172681	As much as 100 tons of ore annually in the 1740s from the adjacent Maypitts Mine. With bonanza years in 1827 and 1871 with 800 and 850 tons, respectively produced	1,000 (100)	Ford and Rieuwerts, 1970

Hubberdale Mine	SK144692	14,600 loads between 1767 and 1769	5840 (1945)	Ford and Rieuwerts, 1970
Huckow Edge Vein near Alport	SK216646	£33,000 of ore raised between 1790 and 1800	1650 (165)	Ford and Rieuwerts, 1970
Chrichman mine	SK293586	Peak production of 65 tons in 1805	65 (65)	Ford and Rieuwerts, 1970
Yatestoop mine	SK240610	Raised 25,000 loads of ore during the early 1800s	10,000 (2000)	Ford and Rieuwerts, 1970
Crich	SK343557	A pipe discovered in 1828 containing an estimated 1,000 tons of nearly pure ore		Kirkham, 1968
Brassington Liberty	SK220542	An annual production of 250 tons ore between 1847 and 1864. However, production had all but ceased by 1888	4250 (250)	Slack, 2000
Mill Close Mine	SK258617	36,000 of tons of ore raised between 1859 and 1886. 534,319 tons Pb and 91,232 tons Zn concentrate produced between 1861 and 1958, with 222,041 tons extracted between 1920 and 1929.	434,319 (4500) Pb and 91,232 (940) Zn	Ford and Rieuwerts, 1970; Kirkham, 1968
Eyam fluorspar mines	SK218775	4,000 tons of galena a year, reported in 1970	4,000 (4,000)	Ford and Rieuwerts, 1970

Table 2.2: Examples of Derbyshire ore production (where possible, the authors have retained the use of the term ton as this is the unit [spelling] given in all of the references. Likewise, for consistency, ton has been used elsewhere in this document unless cited authors employ the term **tonne**.)

Mine	**Lead ore Loads (Dish)**	**Mine**	**Load (Dish)**
Plackett	675 (7)	Brown edge	9 (1)
Longtor	108 (1)	Longtor	8 (5)
Limekiln	67 (4)	Briddons	7 (2)
Orchard	60 (5)	Portway	6 (7)
Longtor	58 (3)	Oldgrove	5 (8)
Yatestoop	29 (6)	Bank	5 (6)
Pitts	24 (6)	Fearnsby	5 (4)
Dunkirk	17 (5)	Longtor lead	5 (1)
Barnend	15 (3)	10 other mines	24 (6)
Lickpenny	12 (2)	Caved ore	39 (5)
Sheldons	11 (6)	Hillock ore	26 (7)

Table 2.3: Winster Lead ore production - 1760 extracts from box L110, Chatsworth House, quoted in Merry. 9 Dishes equate to approximately 1 Load and 4 Loads equates to 1 ton. Source reference, Willies (1968)

Year	Lead ore Loads (Dishes)	No. of mines
1832	534(8)	15
1833	344(0)	18
1834	343(0)	17
1835	422(0)	19
1836	447(2)	23
1837	481(1)	24
1838	429(4)	15
1839	433(5)	21
1840	511(7)	23
1841	565(7)	20
1842	675(0)	23
1843	4589(3)	19
1844	3809(2)	18
1845	1978(3)	21
1846	1485(4)	23
1847	1803(1)	22
1848	1844(8)	21

Table 2.3a: Lead ore production for the Winster Liberty 1832-1848, quoted in Merry. Source reference Thompson 1970

Mine	Location	Pb (tons)	Zn (tons)
Great Hucklow	SK176780	>10,000	>10,000
Tideswell	SK152733	100-500	-
Wardlow	SK181747	<100	-
Stoney Middleton	SK204760	100-500	-
Taddington	SK148729	100-500	-
Ashford	SK172681	501-10,000	100-500
Hassop	SK215706	100-500	-
Sheldon	SK 418 369	501-10,000	<100
Bakewell	SK213694	<100	-
Monyash	SK135735	<100	-
Middleton	SK270565	501-10,000	-
Youlgreave	SK212634	100-500	-
Winster	SK240610	100-500	-
Mill Close	SK 5925 62210	>10,000	>10,000

Table 2.4: Ore Production between 1845 and 1913. Data from Bradley & Cox (1990)

The 19th century saw significantly lower production in the Liberty (Willies, 1986; Table 2.3a). The bonanza in the middle years of that century, apparent from the data, was largely one of poor grade'' brown'' ore and also short lived (Willies, 1986); thereby, further emphasizing the industry's post-18thcentury decline.

While this generalisation likely holds good for much of the orefield, the Mill Close mine at Darley Bridge is an exception. This mine produced around 70 % of Derbyshire Pb, and almost all of the Zn, during the late 19th- and early 20th-century (Table 2.2). Indeed, this mine was the last to major mine close in 1939, following severe flooding (Brearley, 1977 cited in Zhang, 2008). Bradley and Cox (1990) give a representational map of orefield Pb and Zn production between 1845 and 1913. Their data are presented numerically in Table 2.4.

For the Peak District orefield the Pb-bearing mineral galena was the most significant mineral resource but it was not the only commercial mineral extracted. Sphalerite was also raised in significant quantities (Tables 2.2; 2.3). Copper mineralisation was significant in a Derbyshire-wide context, but was a very minor feature of the Derwent catchment. The Pb and Zn carbonates, cerrusite and smithsonite, respectively, have been worked for white paint production, with the latter also historically mined for medicinal use and brass production (Ford and Rieuwerts, 1970). Another significant resource for paint production were the manganese [Mn]-rich mixed phase sources wad (mixed iron [Fe] and Mn oxides) and umber (mixed Mn oxides). Indeed, although again records are incomplete, it has been estimated that some 10,000 tons of wad and umber were produced from the 18th to early 20th century. These Mn-rich sources were further employed as a siccative (drying agent), in glass making and in the bleaching of textiles (Ford, 2001). Baryte too has been used for paint production, but its principal recent and current use is as a drilling mud in the oil and gas industry. Ford and Rieuwerts (1970) reported Derbyshire baryte production at 40,000 tons per year, the bulk of which originated within the Derwent catchment. This figure now is much reduced with ongoing production very much an ancillary of fluorspar [CaF_2] processing (Lusty, 2010). Fluorspar remains an important industrial mineral in a wide variety of chemical, metallurgical and ceramic processes and Palumbo-Roe and Coleman (2010) give a sum total estimated total production figure of 4.3 million tonnes. Lusty (2010) records Glebe Mines, Derbyshire, as producing 18,536 tons of fluorspar in 2009, a 49% decline over the previous year and 67% decrease compared with 2005. The company was also the last significant Pb producer in the UK with *c.*100 tons of concentrate being produced annually as a valuable bi-product. Two severe leaks (tailings dam spills) occurred form the company’s waste depositary at Stoney Middleton in 2007 (Section 3e). The company subsequently went into liquidation and its mines and processing plant were closed (Deloitte, 2012). However, these have since reopened under new ownership (British Fluorspar, 2014).

Lead smelting remains a significant ongoing local industry, despite the absence of contemporary mining. The H. J. Enthoven and Sons secondary Pb smelter at Darley Dale near Matlock (on the site of the Mill Close mine) is the largest capacity single site lead producer in Europe with a production of c. 80,000 tonnes of Pb, 5,000 tonnes of propylene and 20,000 tonnes of gypsum products per year. The plant is a recycling enterprise with the lead input stream being principally comprised of spent batteries (Enthoven and Sons, 2014; Section 3e).

3. Mining contamination of Derwent catchment soils

3a) Introduction

Floodplains are the site of much of the world's agricultural production, principally as a function of their often fertile alluvial soils. Floodplains are sinks for river-borne sediment carrying nutrients and, sometimes, contaminants from upstream areas. The distribution of contaminants varies from floodplain to floodplain as functions of river plan-form, rates of aggradation and style of sedimentation and erosion (Macklin and Lewin, 1986). Therefore, if a particular floodplain's susceptibility to contamination is to be accurately assessed a location-specific study is a pre-requisite. It is normally the case that the concentration of contaminants decreases downstream with the influx of fresh uncontaminated sediment and tributary flow (Hudson Edwards et al., 2001; Macklin et al., 2003), but exceptions occur (e.g., Walling and Owens, 2003).

Under stable conditions metals can be stored in floodplain deposits for centuries, perhaps even millennia. Their remobilization can occur as the result of the geomorphological reworking of the river channel causing, for example, bank erosion. Reduction in the water table too can mobilise metals by exposing them to the resultantly higher potential for atmospherically-mediated oxidation. Changes in acidity can also affect metal mobility; for example, Zn's mobility generally increases as acidity rises, while that of As declines (Olías et al., 2004). Constraining the ongoing evolution of the chemical parameters of pH (acidity) and Eh (the potential for oxidation) can therefore be of predictive value in terms of likely metal mobility. Additionally, flooding is one of the main causes of the remobilisation and transport of the sediment and its associated contaminants. Flood velocity decreases with distance from the river channel therefore, as a function of Stokes Law, coarser sediments are deposited proximally to the river channel itself, while the finer fractions are more distally dispersed (Smolders et al., 2003; Zhang, 2008).

Acid mine drainage may be defined as the heightened mobility of potentially toxic and metalloids as a consequence of the development of acidity; the acidity resulting from ongoing or previous mining-related activity. The Derwent catchment largely has a calcium carbonate lithology. The soil developed from this parent rock acts as a very efficient acid buffer, removing acidity (free protons, H^+) from solution ($CaCO_{3(s)} + 2H^+_{(aq)} = Ca_{(aq)}^{2+} + CO_{2(g)} + H_2O_{(l)}$).

Hence, as a generality, acid mine drainage is not a problem for the Derbyshire Derwent because the buffering capacity of the system is high (Kossoff et al., 2012). Despite this, metal and metalloid concentrations in the catchment are generally high enough to pose potential and actual concern.

It is noteworthy that fluvial transport does not provide the only contaminant transportation mechanism, or vector, impinging on the catchment. The upper catchment, although not subject to mining input, is nevertheless significantly impacted by wind-borne fine-grained Pb contamination largely from extra-catchment sources such as the Manchester and Sheffield conurbations. Additionally, through the vector of the wind smelting activities have in the past (and, to a lesser extent, in the present) left their mark on contaminant distribution pattern of the catchment.

It is also both of interest and utility to define whether the catchment itself is subject to widespread contamination or whether that contamination is confined to point source hot spots.

3b) Examples of mining contaminant pathology

The mining history of the Derwent catchment suggests that Pb and zinc [Zn] should be the primary contaminants of concern. Additionally, Cd is invariably associated with Zn as it can substitute for Zn in the principal Zn-bearing minerals sphalerite and wurtzite (Table 1.3; Kossoff et al., 2011). Exposure to Pb can adversely affect virtually every organ and system in the body, particularly those of the young. One of its most severe and most widespread pathologies is as a neurotoxin, which severely impacts on child development (Selinus and Alloway, 2005). There is also a substantial body of evidence that Derbyshire livestock are susceptible to Pb toxicity (e.g., Abrahams and Blackwell, 2013 and references therein), Cadmium too is highly toxic, for example as a carcinogen, at very low levels of exposure (Duruibe et al., 2007). Zinc is an essential micro-nutrient for both plants and animals (Sinclair and Krämer, 2012; WHO, 1996). There is some evidence that the excessive intake of Zn may be toxic to humans too, but the consensus is that it is a comparatively rare pathology (WHO, 1996). Elevated concentrations of Zn, however, are poisonous for plants (phytotoxic) (e.g., Palazzo et al., 2003), but, because Zn may serve to mitigate the effects of Cd, their toxicity is subject to their relative proportions (McLaughlin and Singh, 1999; Köleli et al., 2004). Indeed, high Zn/Cd ratios could militate against the entry of Cd into the food chain. For this reason, low ratios resulting from either the relative fall in Zn concentration, or the relative increase in Cd concentration, may constitute a serious human health hazard. Fluorine [F], has been implicated in human and animal pathology (fluorosis). Derbyshire neck is a vernacular term given to enlarged goiters because of their high local prevalence at least up until the 1930’s. It has been suggested that fluorosis might have been, at least, a contributory cause of this disease (Saikat et al., 2004). Recent research, however, has strongly indicated that the historic local prevalence of this disease relates principally to the low bioavailability of iodine [I] in the calcareous soils developed on the Derbyshire limestone (Mehra et al., 2014). There has also been some limited research undertaken on livestock in Derbyshire and their potential susceptibility to fluorosis. Geeson et al. (1998) and Abrahams and Blackwell (2013), in a follow up study, examined the relationship of both herbage and soil F concentrations to fluorosis in sheep. Fluoride soil concentrations in the immediate vicinity of mineralization were indeed measured at very levels (Section 3e; Table 3.20). It has been proposed that high concentrations on ingested F may be cumulative with those of Pb; for example, in the etiology of the temporary stiffness in the back legs of lambs (Abrahams and Blackwell, 2013). Fluoride bioavailability in soil is however markedly low, even lower, in percentage terms, than that of Pb (Thornton 2002; Abrahams and Blackwell, 2013). Hence, it is likely that fluorosis in livestock is a comparatively minor and, furthermore, a highly localised problem.

3c) Lead contamination in Derbyshire

There has always been a long standing concern that high Pb concentrations, both in the Derwent catchment and in Derbyshire as a whole, could impact on human health, particularly child health (Section 3b). To address this concern several epidemiological studies have been carried out over the years. The presented studies report a considerable amount of data on soil contamination. Unfortunately, these data were largely not site-specific (c.f., Cotter-Howells and Thornton, 1991), but they do serve to illustrate the extent of Pb contamination within Derbyshire. The broad conclusion drawn was that, although Derbyshire soil Pb levels are high, on the whole plumbism (lead poisoning) is not a widespread problem. There are, however, reports in the literature describing the Pb poisoning of cattle, particularly in the Tideslow area (Colbournand Thornton, 1978; Marples, 1979). Interestingly the Tideslow deposit was mined for cerrusite and hence the Pb is likely to be more available than is the case with the more commonly mined galena (Section 2c).

a) Barltrop et al. (1975) were interested in constraining the relationship of soil-, hair-and blood-Pb concentrations in Derbyshire. Samples were taken from several villages situated on the limestone which grossly differed in Pb soil concentrations. Unfortunately, their data analysis, although based on usefully high sample numbers, does not report specific locations. Nevertheless it does further emphasize the high level of Pb contamination in parts of Derbyshire (Table 3.1).

Barltrop et al. (1975) concluded that absorption, as measured by blood and hair Pb contents, does increase with soil Pb content. The observed increases, however, were small, particularly considering the very high soil Pb concentrations encountered, and the values were within the normal range. Although children were found to have greater mean Pb concentrations than their mothers (paired t-tests, $P < 0.05$) this was both irrespective of the child’s pica habits (defined as the direct consumption of soil and dirt by children) and the area in which the child lived. The authors go on to speculate that this may reflect the comparatively greater dietary intake of the child on a body weight basis.

b) Thornton et al. (1990) undertook a wide-ranging survey of Pb contamination throughout the United Kingdom. They too confirmed that Derbyshire soil Pb concentrations (presumably encompassing the Derwent) were anomalously high in terms of both geometric mean and the associated range (Table 3.2).

	Blood lead ug/100ml		**Hair**	**Soil**	**Housedust**
	Child	Mother	ppm	ppm	ppm
All	23.2 (82)	16.6 (74)	10.2 (82)	1,978 (72)	1,189 (64)
	13-45	9-44	2-62	130-28000	190-25,000
Low soil lead area	20.9 (34)	14.7 (30)	7.5 (34)	518 (29)	565 (23)
	15-45	9-40	2-36	130-3000	190-2,450
High soil lead area	25.0 (48)	18.0 (44)	12.8 (48)	4,881 (43)	1,803 (41)
	13-43	11-44	2-62	1,050-28000	420-25,000
Soil lead < 1,000 p.p.m.	20.7 (29)	14.1 (25)	7.7 (29)	420 (24)	531 (20)
	15-33	9-40	2-36	130-900	190-2,450
Soil lead: 1,000 p.p.m.-10,000 p.p.m.	23.8 (43)	18.7 (41)	10.5 (43)	3,390 (40)	1,564 (36)
	13-45	11-44	2-62	1050-9100	390-25,000
Soil lead > 10,000 p.p.m.	29.0 (10)	14.8 (8)	20.2 (10)	13,969 (8)	2,582 (8)
	21-43	13-19	10-39	1,0000-28,000	1,000-5,100
Geometric means and ranges. Number of samples in parenthesis					

Table 3.1: Derbyshire Lead soil content (Baltrop et al., 2005)

	All study locations less hotspots	**London Boroughs**	**Derbyshire Mining Villages**	**Remaining Geochemical Hotspots**
House dust				
n	4,638	683	100	492
Geometric mean	561	1,010	1,870	631
Range	5-36,900	5-36,900	606-7,020	74-40,300
Road dust				
n	400	65	9	38
Geometric mean	786	1,354	2,160	564
Range	45-9,660	172-9,660	1,190-4,620	176-3,180
Playground dust				
n	220	34	5	18
Geometric mean	289	430	4,390	400
Range	11-6,860	93-6,860	1,190-13,400	53-21,700
Garden soil				
n	4,126	578	89	433
Geometric mean	266	654	5610	493
Range	13-14,100	60-13,700	1,180-22,100	49-8,340
Vegetable plot		soil		
n	193	29	5	25
Geometric mean	270	571	8,730	454
Range	24-2,560	137-2,560	1,140-26,500	90-3,250
Public garden soil				
n	221	35	5	22
Geometric mean	185	294	3,030	348
Range	20-1,820	28-1,260	2,140-4,920	98-8,510

Table 3.2: Lead concentrations in survey locations derived according to sample type (μg/g). After Thorton et al. (1990)

The authors also note that: “It is of interest that in locations other than Derbyshire, concentrations of Pb in house dusts on average exceeded those in soils by a factor of 2, reflecting internal sources such as paint. In Derbyshire the opposite was found, with Pb in soil three times greater than that in house dust.’’This, no doubt, is a function of both the Derbyshire Pb mining past and the rural nature of the county, forestalling industrial/traffic aeolian (wind-borne) transportation (c.f., Cotter-Howells and Thornton, 1991). This is not the case in the upper catchment of the Derwent where the peat soil is very much impacted by aeolian transportation largely originating from outside the county boundaries (Rothwell et al., 2005, 2007; Shotbolt et al., 2008).

3d) Quantification of upper course soil contamination

The principal source of the upper course contamination is wind-borne. Sheffield is only some 30 km distant from the Howden reservoir and contamination from the middle course mining area almost certainly contributed too. The Manchester conurbation to the west, however, provided, and to some extent still provides, the bulk of the contamination as a function of the prevailing westerly winds. After fallout the principal redistribution mechanism downstream is fluvial. Some examples follow:

a) Rothwell et al. (2005) found that the Upper North Grain (UNG) was a heavily eroding blanket peat catchment. Moreover, concentrations of Pb in the near-surface peat layer at UNG were in excess of 1,000 mg/kg. The UNG is one of many small headwater streams which join the River Ashop, which feeds the Ladybower Reservoir which, in turn, feeds the Derwent itself. This reservoir, along with others in the area in this local area, supplies drinking water to Nottingham, Sheffield, Derby and the East Midlands.

Rothwell et al. (2005) carried out a vertical sectioning of the peat showing an exponential decline in Pb concentrations with increasing depth (Table 3.3).

Depth (m)	Pb (mg/kg)
5	1,050
10	380
15	150
20	60
25	50
30	10
35	nd
40	nd
45	nd
50	nd

Table 3.3: The variation of Pb concentration with depth in the upper Derwent catchment

The initial rise in magnetic and lead profiles at 15 cm depth can be dated using analogous pollen and sulphur studies to *c*. AD 1800. With the use of magnetic fingerprinting techniques the authors demonstrated how contaminated sediment might be mobilised by storm events. Initially a Pb flush was observed with sediment concentrations reaching 395 mg/kg. After the initial flush sediment-associated Pb values drop sharply. The suspended sediment associated with the Pb flush had the magnetic fingerprint of the near-surface peat, thereby establishing the provenance of the contaminated sediment.

b) Rothwell et al. (2007) further examined the upper catchment as a source of contaminants downstream. They were interested in constraining the influence of storm events on contaminant mobilisation and reported the associated dissolved, rather than sediment-borne, concentrations. By analysing normal or baseflow conditions the authors determined that the aqueous concentration of Pb was strongly and significantly correlated with that of dissolved organic carbon (DOC). With the onset of a storm event aqueous concentration of Pb rose significantly alongside that of DOC, the dilution effect provided by the storm not withstanding (Table 3.4). The storm behaviour of Zn, by contrast, was more conservative, possibly as a function of comparatively less complexation (attachment) with the freshly mobilised DOC.

Parameter	Baseflow UNG Main	Stormflow UNG Main	Stormflow UNG Upper
DOC mg/L	3.62 +/- 2.18	27.9 +/- 5.47	26.2 +/- 7.08
pH	6.8 +/- 0.65	3.87 +/- 0.16	3.88 +/- 0.08
Cu µg/L	1.32 +/- 1.05	5.84 +/- 2.65	6.99 +/- 4.9
Ni µg/L	1.67 +/- 1.93	1.91 +/- 0.54	1.62 +/- 0.6
Pb µg/L	1.09 +/- 0.17	7.06 +/- 2.06	7.54 +/- 3.14
Ti µg/L	2.04 +/- 0.41	2.33 +/- 0.8	1.8 +/- 0.45
V µg/L	0.08 +/- 0.18	1.56 +/- 0.31	1.55 +/- 0.49
Zn µg/L	67.2 +/- 11.2	57.6 +/- 22.7	59.3 +/- 18.8

Table 3.4: Summary statistics for dissolved organic carbon (DOC) concentration, pH and dissolved metal concentrations for stream water samples collected from Upper North Grain during baseflow and stormflow conditions

Table 3.4 reveals that as well as Pb and Zn, Cu, Ni and vanadium [V] are leached from the upper catchment soils, The authors go on to describe that, after the initial contaminant flush, concentrations decline, perhaps because of a decline in the availability of DOC as a function of the length and severity of the storm(s).

c) Shotbolt et al. (2008) conducted a Pb mass balance analysis for the Howden Reservoir catchment. The atmospheric Pb flux onto the Howden catchment was estimated at *c*. 107 kg a^{-1}, while the aquatic Pb flux was estimated at between 29·9 and 71·7 kg a^{-1}. The authors therefore concluded that catchment soils were acting as a sink for Pb and the reservoir acted as a secondary store for Pb eroded from the catchment soils, with *c*. 80% re-deposited in its sediments. It was estimated that 2·3% of the catchment soil Pb pool had been retained in the reservoir sediments over its 91 year lifespan. Although the catchment was currently acting as a Pb sink, the rate of change in the soil Pb pool was very small and should conditions change a large quantity of Pb may become available to the larger catchment, which may have potential implications for long term landscape management, including heritage assets.

3e) Quantification of middle course soil contamination

The principal source of the middle course high contaminant element concentration is historic metal mining and, to a lesser extent, naturally high background levels. There are, however, potential point sources of contamination arising from ongoing processing activities. In the context of historic background contamination, current activities are comparatively minor contributors to the contaminant burden. This section will firstly describe historic contamination together with natural background levels. It will then close with short descriptions of the Stoney Middleton tailings dam failure (2007) and the ongoing emissions of the Einthoven Pb smelter.

a) Rawlins et al. (2012) published a soil geochemical atlas of England and Wales, building on the earlier work of McGrath and Loveland (1992). Despite the scale being gross it was possible to identify the Derwent catchment as having hotspots containing the highest concentration of Cd (20.7-47.5 mg/kg), Pb (3,960-10,000 mg/kg), thallium [Tl], 7.74-18.1 mg/kg) and Zn (1,530-3,360 mg/kg) in England and Wales. Other significantly elevated elemental concentration hot spots on a national scale are silver [Ag] (1.4-2.8 mg/kg), barium [Ba] (4,690-5,360 mg/kg), Co (77-88 mg/kg), germanium [Ge](7.2-8.4 mg/kg), Mn (1.05-1.2 wt. %), molybdenum [Mo](19.2-21.6 mg/kg), Ni (245-280 mg/kg) and Sb (7-10.5 mg/kg).

b) Burek and Cubitt (1979) carried out an extensive comparative survey of Derbyshire superficial deposits and the underlying geology. It should be noted that the authors consciously tried to avoid areas of obvious Pb mineralisation when collecting their samples. Hence the data, which are presented in Table 3.5, are likely to be an underestimate mining-derived contamination of the surficial deposits.

The authors also produced element maps (Pb; Cd, Zn, Mo and V), which are not reproduced here because of copyright. However, the authors note that for Pb, most of the region’s surficial deposits have a concentration of 400 ppm. There are, however, five notable exceptions where concentrations reach as high as 1,200 ppm: the former mining areas of Pin Dale, Longstone Edge, Eyam Edge, Raper Pit and Bradwell Moor. It is also noteworthy that the limestone contains on average ~ 10 ppm Pb emphasizing the extent of background Pbenrichment of Derbyshire soils.

Zinc distribution largely reflects that of Pb distribution with highs at Pin Dale, Bradwell Moor, Eyam Edge, Longstone Edge and Raper Pit. An additional notable high value is recorded around the village of Sheldon near the Magpie mine. In general Zn superficial deposit values are of the order of 500 ppm, with mining-associated samples reaching concentrations of up to 1,000 ppm. However, in areas which overlie till and Namurian Shales the background concentration rises to c. 700 ppm, thereby emphasizing the importance of the shales in the enrichment of surficial deposits.

Sample	**Major elements**							
	CaO	SiO2	Al2O5	MgO	K2O	Fe2O3	TiO2	MnO
Limestone Eyam (n = 15)	53.2	1.7	0.53	0.47	0.07	46.2		257
Monsal Dale (105)								
Upper Pale	54.3	1.1	0.09	0.38	0.02	240		114
Dark (96)	53.3	2.45	0.26	0.64	0.05	581		114
Lower Pale (105)	54.4	0.62	0.08	0.27	0.01	333		137
Bow Low (79)	56	0.15	0.01	0.21	0	199		136
Wood Dale (14)	55.4	0.16	0.03	0.26	0.01	146		86
						Total Fe		
Olivine Dolerite Sill (9)	8.6	49	14.1	8.3	0.44	10.6	1.74	1500
Millstone Grit (11)	0.01	97.9	0.57	0.06	0.16	0.45	0.36	600
Dolomitic limestone (15)	31.6	1.34	0.06	20.17	0.03	0.34		856
Coal measures (4)							0.3-0.6	600-8,500
Triassic NRS							0.3-0.6	2,100
Superficial Deposits (117)	2.4	72.7	14.2	0.9	1.5	4.5		1,766
Till (98)	18.5	44.7	11	1.5	1.3	4.5	0.2	1343
Shale	11	58.7	9.8	1.3	1.5	2.6	0.26	832
Weathered Tuff (2)	1.4	55	26.6	2.6	3.2	10.8	0.8	1942
Basalt (1)	4	40.7	21.15	3.67	4.7	12.3*	0.9	450
Carboniferous Arenacesous Rocks (58)	0.2	95.15	1.91	0.14	0.2	0.7	0.2	600
All major oxides except Fe2O3 are in % unless otherwise marked. All trace elements in ppm.								
( ) is the total number of samples analyzed.								
*Fe2O3, not total.								

Table 3.5: Part 1. Comparison of bedrock and till geochemistry with superficial sediment data (majors % except Mn and Fe, where noted)

Sample	**Trace elements**														
	Ba	Cd	Co	Cr	Cu	Ga	Li	Mo	Ni	Pb	Sn	Sr	V	Zn	Zr
Limestone Eyam (n = 15)					16					31				16	10
Monsal Dale (105)					12					6				19	
Upper Pale					15				8	7		550		27	
Dark (96)					12					4				20	
Lower Pale (105)					6					2				17	
Bow Low (79)					9					15				12	
Wood Dale (14)															
Olivine Dolerite Sill (9)	80		35	310	66	18	25		230			220	170		100
Millstone Grit (11)	10		20	60	20	10		2	45	75-180	5	10	85		500
Dolomitic limestone (15)					24					15				209	
Coal measures (4)			97	97	55			2	130-200	50	9			85-200	
Triassic NRS			25	50	10			2	25	95	8		40	2,200	
Superficial Deposits (117)	1186	83	22	136	59	17	50	18	100	479		144	195	557	528
Till (98)	1925		37	152	59	17	78	83	132	399		256	146	365	255
Shale	1473	244	75	162	162	14	45	127	304	39	0	362	945	823	76
Weathered Tuff (2)	166	112	94	512	96	26	98	0	566	64	0	26	322	570	406
Basalt (1)					55			0		0				260	
Carboniferous Arenacesous Rocks (58)		10-1500		10	35	10-100	10	31	2	15		10	10-270	30	600

Table 3.5: Part 2. Comparison of bedrock and till geochemistry with superficial sediment data (majors % except Mn and Fe, where noted)

For Cd in particular the emission spectrophotometry methodology employed by the authors is not as robust as alternative modern techniques. The quantitative data reported in this article for Cd should therefore be treated with caution. Notwithstanding this word of caution, the Cd hotspot pattern largely follows that of Zn, again showing much higher concentrations in the surficial deposits compared to the underlying limestone. Just as with Zn, the background concentrations are higher in areas overlying the Namurian Shales; for example, around Bakewell.

Molybdenum (Mo) concentrations, too, are high over many areas of mining and Namurian Shale bedrock. Moreover, high Mo concentrations have been associated with Cu deficiency in livestock grazed on these soils (see also Marples, 1979). In contrast V concentrations are highly correlated with the presence of the Namurian Shale bedrock, rather than mining activities (see also Colbourn, 1978). High values of this element are recorded in the Bakewell region and Wardlow Mires where V concentrations exceed 450 ppm.

The authors conclude by pointing out that the manner of contamination of the superficial deposits is principally through mining activities. The weathering and glaciation of the Namurian Shales, however, has independently contributed considerable concentrations of trace metals to the overlying till and superficial deposits.

c) Marples (1979) undertook a detailed comparative study of the soils affected by mining contamination and those overlying the shales. The latter, although unaffected by mining, potentially have a high ‘contaminant’concentration derived from the parent rock source. Three sites were chosen to represent the shale soils: Onecote, Bent Farm (Bradbourne) and Netherton Hall Farm (Bradbourne). Onecote lies outside of the Derwent catchment, but is included here as it provides further supporting data on shale-sourced ‘contaminant’concentrations. Mining contaminated soils were represented by samples taken from an extensive transect in the Youlgreave area and a more limited one at Tideslow rake. Further samples were taken from transects at the site of the Stone Edge smelter and an uncontaminated limestone soil at Wormhill.

	Cadmium (µg/g)		Zinc (µg/g)		Lead (µg/g)		Iron (%)		Manganese (µg/g)		Calcium (%)		pH
Depth	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	
<u>The Onecote Bradbourne study area</u>													
Onecoate	**(Transect from 4050 3561 to 4023 3549)**												-
(n.b. River Hamps)	1.5	1.2	71	310	100	73	1.8	3.9	112	2280	0.36	0.28	4.1
2	2.3	1.9	152	140	316	200	3.6	3.2	440	316	0.54	0.28	4.9
3	14.6	21.2	740	1260	190	190	2.72	3.4	600	640	1	3.6	6
4	7		344		1760		3.16		1280		0.67		4.8
5	1.5	0.9	55	41	70	49	1.12	1.12	180	96	0.76	0.32	6.1
6	2.7	1.6	97	102	88	50	1.92	2.91	278	166	0.44	0.18	5.2
7	7	9.3	170	210	120	65	3.72	4.45	312	6400	0.37	0.4	4.2
8	14.6	13.9	480	624	144	104	3.76	3.88	600	400	0.8	1.68	6.8
9	1.9	0.7	58	56	132	115	0.92	1.6	104	36	0.53	0.27	5.4
10	1.6	0.7	85	62	90	40	2.05	1.4	600	148	0.24	0.22	4.6
11	1.9	0.7	70	43	172	44	1.36	2.52	108	108	0.47	0.26	4.7
Mean	5.1	5.2	211	285	289	93	2.4	2.8	419	1059	0.6	0.7	5.2
Bent Farm	(Transect across Bletch Brook)								Near to 4189 3525				
1	23.8	34.2	400	2640	280	208	4.4	6.2	840	216	0.01	0.84	5
2	1.9		164		292		2.56		400		0.49		5.2
3	1.8	0.8	110	71	165	150	2.84	4.36	236	328	0.5	0.37	4.7
4	3.4	2.5	225	200	315	90	5.52	5.85	328	240	1	0.84	5
5	2.6		252		128		6.25		1160		0.68		5.1
6	1.5	1.9	200	185	90	72	5.12	5	1520	1480	0.51	1.2	4.5
Mean	5.8	9.9	225	774	212	130	4.4	5.4	747	566	0.5	0.8	4.9
Netherton Hall Farm	(Transect across Havenhilldale Brook)								Near to 4189 3525				
1	3.1	3.6	164	160	360	248	3.36	4.88	680	2280	0.36	0.24	4.3

2	10.4	11.9	560	848	1480	1520	3.44	3.76	880	800	1.52	1.86	6.7
3	3.5	1.1	192	110	380	248	2.4	2.24	640	280	2.28	0.4	6.8
4	3.5	1.2	357	276	500	552	2.8	2.56	252	216	0.17	0.24	3.9
5	10.5	13.1	600	836	320	840	3.22	2.06	384	194	0.58	5.7	5.2
6	4	6.1	460	480	196	228	3.44	3.84	960	1720	0.76	4.8	6
7	5	8.2	368	720	250	230	2.44	3.32	680	1440	0.4	0.88	6
Mean	5.7	6.5	386	490	498	552	3.0	3.2	639	990	0.9	2.0	5.6
Overall mean	5.6	7.2	274.0	516.3	333.0	258.4	3.3	3.8	602.1	871.7	0.7	1.2	

	Cadmium (µg/g)		Zinc (µg/g)		Lead (µg/g)		Iron (%)		Manganese (µg/g)		Calcium (%)		pH
Depth	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	0-15	30-45	
<u>The Youlgreave-Wormhill-Tideslow-Stonedge Study Area</u>													
-													
Youlgreave	(Transect from 4175 3681 to 4231 3621)											-	-
1	10.5	9.4	1840	1760	1760	71000	1.76	1.52	1400	960	8	10.4	4.6
2	3.7	2.4	428	200	8720	1480	1.18	2.6	564	1080	3.58	1.6	4.5
3	4.3	4.7	120	168	390	500	1.92	2.16	680	1200	0.4	0.48	5.2
4	1.1	1.5	102	88	344	212	1.52	1.76	560	640	0.56	0.32	6.1
5	2.6	0.9	94	50	450	300	1.68	1.92	480	480	0.6	0.17	5.2
6	3	1.9	134	114	390	310	2.6	2.16	690	880	0.48	0.28	5.5
7	6.8		260		270		1.6		2640		1.52		6.6
8	10.7	8.5	1240	1100	1640	1360	2.24	1.12	560	320	7.04	10	7.1
9	3.4	3	156	196	680	542	2.08	2.08	880	1360	0.84	0.21	6.3
10	11.9		672		2400		2.64		2560		0.19		4.1
11	34.8		3120		7600		1.9		1000		8.6		6.6
12	0	3.6	41	208	108	52	0.8	0.96	192	312	0.86	0.11	5
13	21.8	2.6	1720	1280	12000	17000	4.4	4	6400	6480	0.64	2.84	5.8
14	26.6	24	8000	6000	2200	17000	7.52	5.84	3680	3800	0.61	5.2	7
15	24.6	30.5	4240	4600	24000	30000	4.8	4.6	4200	3600	8	10	6
Mean	11.1	7.8	1478	1314	4197	11646	2.6	2.6	1766	1759	2.8	3.5	5.7

Table 3.6: Analytical data for Derbyshire soil surveys

Tideslow	(# from two small traverses across Tideslow Rake)							Near4151 3779					
1	2.9	9.8	252	336	1200	800	2.64	2.96	1260	1830	1.06	0.9	6.8
2	27.2	22.6	940	1032	46000	44000	1.28	1.2	840	480	12.4	9.6	6.9
3	3.6	1	100	93	460	280	2.08	2.24	800	1240	0.48	0.24	5.4
4	1.8		94		1280		1.8		360		0.44		5.2
5	2.6		168		1000		1		320		0.72		5.6
6	90.6		4400		48000		2.12		3640		26.8		6.8
7	2		67		230		1.66		500		0.5		5
Mean	18.7	11.1	860	487	14024	15027	1.8	2.1	1103	1183	6.1	3.6	6.0
Overall mean	14.9	9.4	1169.0	900.3	9110.5	13336.5	2.2	2.3	1434.3	1471.3	4.4	3.5	
Wormhill	(Chosen as it lies outside the orefield, samples taken from the limestone plateau, dale slopes and dale bottoms))											Near4126 3727	
1	2.2	3	188	176	176	136	3.6	4.04	1360	1800	0.72	0.64	5.4
2	0.9	0.8	82	70	69	20	2.96	4.84	840	800	0.56	0.4	6.2
3	1.8	1.5	140	112	112	60	3.72	4.6	1040	1080	0.72	0.64	5.6
4	3.8	3.6	240	210	220	195	3.68	2.88	2440	2520	0.92	7.4	6
5	2.3	1.8	165	145	290	250	3.64	4.04	960	1320	0.48	0.28	5.7
Mean	2.2	2.1	163	143	173	132	3.5	4.1	1328	1504	0.7	1.9	5.8
Stonedge	(Samples taken from the surrounding moorland and cultivated fields in the vicinity)									Near4334 3670			
1	0.2	0.3	13	21	330	105	1.04	0.88	4	8	0.02	0.01	4.2
2	0	0.8	14	14	880	220	0.27	2.44	0	12	0.03	0.01	3.5
3	20.4		2400		48000		2.16		164		1.92		5.5
4	17.4	4.2	1400	408	24000	6800	0.96	2.96	172	40	2.72	0.8	5.2
5	0	0	17	14	244	64	0.96	1.6	20	720	0.04	0.01	4
Mean	7.6	1.3	769	114.3	14691	1797.3	1.1	2.0	72	195	0.9	0.2	4.5

Table 3.6: Analytical data for Derbyshire soil surveys

The Onecote and Bradbourne soils were naturally enriched in Cd. Moreover, in the low lying waterlogged soils concentrations were at their highest (> 30 µg/g Cd). Cadmium and Zn enrichment is apparent in both the top- and sub-soil. However, the overall mean for the sub-soils (5.6 and 274 µg/g, respectively) is greater than that of the top-soils (7.2 and 516µg/g, respectively), suggesting a parent rock source. The Pb concentration profile, however, is reversed with the topsoil (333 µg/g) being higher than that of the subsoil (258 µg/g) (Table 3.6). Additionally, within the shale soil system the concentrations of Zn and Cd are significantly higher in the valley floors compared with the slopes.

Mining contaminated soils at Youlgreave and Tideslow exhibited a gross Cd, Pb and Zn enrichment over the Wormhill limestone control. Furthermore, both the top- and sub-soil concentrations of all three elements were greater than in the shale naturally enriched sites. It is noteworthy, however, that average sub-soil Pb (13,336.5 µg/g) concentrations exceeded those of the topsoil (9,110.5 µg/g). This observation might reflect parent rock enrichment, but it is more likely, however, to reflect both the long history of mining and the overall high stability/low availability of Pb in the soil system.

The Stone Edge site is referred to in detail in Sections j and l. For this study it is noteworthy that topsoil concentrations of Cd and Zn exceeded the sub-soil analogues approximately six-fold while, contrastingly, that of Pb was slightly higher in the sub-, rather than the top-soil. Marples (1979) also notes that contamination only extended to areas *c*. 1,000 m from the smelter site. In this context it is relevant to note that contamination around Tideslow was even more restricted, to within *c*. 30 m of the rake.

Correlation analysis of the data shows that Cd and Zn have a significant positive correlation coefficient (Section 2a). Cadmium, Pb and Zn appear to be associated with Mn in the top soil, and Zn is likely associated with Fe. Cadmium, Pb and Zn show a positive correlation with soil pH, tending to be more concentrated in neutral and calcareous soils.

d) Matthews (1982) further investigated comparative contaminant distribution in a soil overlying the Namurian Shales and a mining contaminated soil overlying the limestone.

Table 3.7 compares data from Bent Farm (Bradbourne) (41875 35225) shale with Tideslow (41568 37815) limestone. The mean Pb concentration on the mining contaminated soil (3,665 ppm) was considerably in excess of that in the soils overlying the shales (259 ppm). For Cd and Zn, however, the shale soils showed higher concentrations (7.9 ppm and 373.8 ppm, respectively) than the mining-contaminated analogues (2.4 ppm and 123.4 ppm, respectively). Additionally, the shale contaminant concentrations were analyzed as a function of the valley slope profile. Lead concentrations changes were not significant as a function of slope position. Zinc and Cd, however, were markedly concentrated in the soils sampled from the waterlogged valley floor.

Soil Profile	**Sample Depth**	**Element Concentration (µg/g)**							**(%)**
		Cd	**Cu**	**Pb**	**Zn**	**Mn**	**V**	**Ca**	**Fe**
1	0-15	3.2	28	224	184	284	188	4000	3.1
	15-30	2.2	23	218	164	96	190	2840	3.7
	30-45	0.8	23	160	114	44	191	1800	3.3
	45-60	1.2	51	260	140	28	185	1840	6.2
	60-75	1.2	54	120	116	16	114	1360	5.2
	75-90	1.6	32	144	97	16	107	1280	3
	90-105	2	22	132	80	12	107	1120	1.2
	Mean	**1.7**	**33.3**	**179.7**	**127.9**	**70.9**	**154.6**	**2034.3**	**3.7**
2	0-15	7.6	51	224	328	256	224	5600	2.7
	15-30	5.2	34	176	292	196	263	3080	2.6
	30-45	5.6	31	156	300	760	244	2880	2
	45-60	4.8	37	148	260	520	272	3200	2.6
	60-75	7.6	73	160	420	480	319	5600	3.2
	75-90	8	88	200	528	480	278	4800	4.1
	90-105	4.4	40	208	292	216	163	3400	4.6
	Mean	**6.2**	**50.6**	**181.7**	**345.7**	**415.4**	**251.9**	**4080.0**	**3.1**
3	0-15	2.0	43	272	272	440	209	6800	2.8
	15-30	1.2	40	264	184	400	245	3280	2.8
	30-45	1.2	34	400	132	172	240	1640	1.9
	45-60	1.2	33	448	114	164	261	1240	1.8
	60-75	0.8	35	460	124	120	248	1000	1.8
	75-90	1.6	38	456	144	80	262	840	1.7
	90-105	0.8	38	560	132	76	268	800	1.7
	Mean	**1.3**	**37.3**	**408.6**	**157.4**	**207.4**	**247.6**	**2228.6**	**2.1**
4	0-15	3.6	46	232	215	274	205	3540	2.8
	15-30	3.6	30	224	180	240	270	3000	3.0
	30-45	3.2	25	168	172	156	197	2560	2.4
	45-60	2.0	22	128	152	96	151	1800	2.3
	60-75	1.6	34	120	176	136	160	1360	2.3
	75-90	2.0	432	160	168	260	159	1520	2.6
	90-105	2.4	57	256	192	840	224	1760	3.7
	Mean	**2.6**	**92.3**	**184.0**	**179.3**	**286.0**	**195.1**	**2220.0**	**2.7**
5	0-15	19.6	96	384	276	296	211	4800	3.0
	15-30	16.0	109	380	232	136	238	4400	3.3
	30-45	6.8	60	300	244	64	237	3440	3.6
	45-60	4.0	50	364	298	64	250	3440	3.6
	60-75	10.4	64	400	320	84		3320	4.4
	75-90	10.4	64	400	320	84	271	3320	4.4
	90-105	128.0	62	180	5,720	104	154	4440	10.8
	Mean	**27.9**	**72.1**	**344.0**	**1058.6**	**118.9**	**226.8**	**3880.0**	**4.7**

Table 3.7: Metal content of soils from Bent Farm Derbyshire

It could be that the concentration peak at the valley floor reflected the migration of clays with a high proportion of sorbed Zn and Cd. Alternatively the Fe distribution (which increases in concentration from 3.7 wt. % at the top of the slope to 4.7 wt. % at the base) constrains the Zn and Cd concentrations, perhaps by the reductive dissolution of Zn- and Cd-bearing Fe oxides in the waterlogged valley floor. However, Matthews (1982) speculates that the *in situ* weathering of the exposed shales at the valley floor is the principal cause of the elevated Zn and, in particular, Cd concentration. It is also notable that the concentration of Zn and, particularly Cd, increase at depth in the soil profile taken at the valley floor. It is likely that, in the anoxic deeper sediments, Cd sulphides (greenockite and hawleyite) and Zn sulphides (sphalerite and wurtzite) become increasingly stable with depth.

e) Colbourn and Thornton (1978) analyzed Pb concentrations on five mining-affected sites (Table 3.8). The sample sites underlain by limestone had very high top- and sub-soil Pb concentrations, while concentrations on the Coal Measures were lower and, lower still, on the Millstone Grit at similar distances from the individual rake and smelter sites (Table 3.8). It is likely that the alkaline nature of the limestone soils compared to the more acidic ones developed on the Millstone Grit resulted in the comparative retention of Pb on the limestone. The data presented in Table 3.8 also suggest that floodplain Pb contamination is laterally more extensive around smelter sites in comparison to sites where mining only took place. This, no doubt, is a function of the aeolian distribution described for the upper catchment (Section 3d) occurring on a more local scale.

Site and major source (Grid reference)	**Distance from source (m)**					
	0-100	*100-250*	*250-500*	*500-750*	*750-1000*	*1000-2000*
1. Brook Bottom Ore washing floor (SK 144 771)	19,400 (9)*	1,625 (7)*	490 (6)*			
2. Tideslow rake(SK 152 782)	11,000 (9)*	1,990 (9)*	610 (6)*			
3. Great Hucklow rake and smelter (SK 178 778)	14,100 (6)*	4,000 (8)*	2,300 (13)*	2,200 (5)*	570 (4)*	760 (3)*
4. Ladywash spoil heap and smelter (SK 223 772)	1,830 (5)*	860 (10)*	540 (9)*	570 (3)*	230 (3)*	
5. Foxlane smelter (SK 295 755)	30,000 (2)*	2,400 (2)*	2,700 (8)*	750 (3)*	360 (12)*	190 (3)*
Natural background ranges over limestone 125-215 µg Pb/g (sites 1,2,3)						
Millstone Grit 75-180 µg Pb/g (sites 3 and 4)						
Coal Measures 115-300 µg Pb/g (site 5)						

Table 3.8: Lead distribution in topsoil around pollution sources (mean total Pb concentration µg/g). *: No. of samples in parentheses

f) Bradley and Cox (1990) quantified soil floodplain concentrations at Darley Dale immediately downstream of the Mill Close Mine site. Sixteen sediment cores were collected in transect across the floodplain, and each core was sectioned at 5cm increments on site. The authors state that the sedimentation reflects the wide range of source areas for sediment in the upper catchment (Table 3.9).

	n	x	SD	SE	Min	Max
Pb	157	620	176	14	131.4	1179
Zn	157	194	198	15.8	9.3	1696.1
Cu*	157	17.2	8.2	0.7	2.9	64
Cd	157	2.5	2.1	0.2	0.08	12.5
LOI	157	8.6	5.9	0.5	1.6	32.4
* Cu is below shale rock background concentrations						

Table 3.9: Summary statistics (mg/kg) of total concentrations of lead, zinc, copper and cadmium in Derwent floodplain sediments

Lead concentrations showed no clear trend either vertically with depth or horizontally with distance from the river channel. It can therefore be concluded, at least from this site, that soil Pb concentrations reflect a long-standing contaminant input. Zinc and Cd concentrations, however, demonstrate an exponential increase from depth to the surface and maximum concentrations on an elevated terrace some 450m from the river. The vertical upward increase in concentrations likely reflect the latter years at Mill Close where Zn extraction assumed increasing importance as the deeper levels were worked (Kirkham, 1968). It might be speculated that the terrace Cd and Zn hotspot reflects an exceptionally high flood, which mobilized a portion of these surface-rich sediments. These in turn remained isolated from the ongoing year to year fluvial mobilization downstream.

At the time of the study of Bradley and Cox (1990) mining had ceased for around thirty years and therefore, the authors aimed to analyze post-mining sediment and constrain floodplain metal concentrations. For this period in particular sediment accumulation is distinguishable by the presence of ^{137}Cs, a radioisotope released into the environment by atmospheric nuclear weapons testing. From analysis of these data, together with that of the rate of sedimentation, the authors calculated that the supply of metals to their study reach can be estimated as 360 kg Pb, 100 kg Zn, 10kg Cu, and 2 kg Cd each year. Moreover, the authors further went on to analyze how much of this loading would be bio-available and reported that, per square metre, this contaminant load was equivalent to an input of 266 mg Pb, 36mg Zn, 5.2mg Cu, and 0.1mg Cd per year. In summary these authors found that contaminant mobility remained high on the floodplain despite the cessation of mining.

Macklin et al. (1994), reviewing the Bradley and Cox (1990) data, commented that "if ^{137}Cs dates are correct, sediments with the highest concentrations of Pb and Zn were deposited after the Mill Close Mine had closed, highlighting the importance of secondary sources (e.g. contaminated soil and sediment) of metal contaminants in river catchments and suggesting that in some cases dating of overbank sequences by their relation to mining records could be ''misleading."Macklin et al. (1994) thereby emphasized that contaminant soil floodplain analysis based purely on mining point source inputs told a markedly incomplete story in the absence of supporting geomorphological work.

g) Cotter-Howells and Thornton (1991) analyzed soil samples from the village of Winster upon the high ground to the southwest of Darley Dale (SK241604). They found soil Pb concentrations in garden and vegetable soils to be 27 and 36 times, respectively, higher than the national averages (Table 3.10). Despite this Pb blood levels in the local children remained low compared to those in a Birmingham cohort (Table 3.10). The authors account for this apparent dichotomy by identifying the highly insoluble mineral pyromorphite [$Pb_5(PO_4)_3Cl$] as a prominent local Pb-bearing phase. It was proposed that pyromorphite acted as a stable Pb sink, which prevented the expression of health problems in the children of the village. At the time of this study, however, the Birmingham children were no doubt exposed to Pb derived from leaded petrol in much higher concentrations than their rural cohorts. Hence, it can be concluded that the mineralogical form of the Pb-bearing minerals greatly impacts on the ensuing toxicology.

Sample	Winster (present study)		Birmingham study (Davies et al., 1990)		UK national survey [1] (Culbard et al., 1988)	
	n	GM (Range)	n	GM Range[2]	n	GM Range
Garden soil (Pb µg g^{-1})	42	7,140 (2,400-22,800)	86	313 (92-1,160)	4,126	266 (13-14,100)
Vegetable soil (Pb µg g^{-1})	11	9,580 (2,235-22,160)	-	NIA	193	270 (24-2,560)
Housedust (Pb µg g^{-1})	45	1560 (462-6,240)	94	424(138-2,093)	4,638	561(5-36,900)
Lead loading (Pb µg m^{-2})	44	275 (14.2-3,560)	93	60(4-486)	-	NIA
Handwipes (µg Pb per pair of hands)	10	13.1 (3.8-39.5)	704	5.7 (1.9-15.1)	-	NIA
Children's blood (Pb µg dL^{-1})						
1-3 year-olds	3	6.9 (3.8-39.5)	97	11.7 (6-24)	-	NIA
1-8 year-olds	10	9.4 (6.2-20.7)			-	NIA

[1] including London but excluding geochemical hotspots, [2] 5th and 95th percentiles, NIA - not analysed, GM - geometric mean.

Table 3.10: Lead in environmental samples, handwipes and children’s blood in Winster, Birmingham and a UK national survey

h) Tye et al. (2004) reported data on Derwent catchment soils as part of a wide-ranging study. Relevant data are reported from Ticknall (SK360238) and Cloughs Wood (near Winster) (Table 3.11).

Soil	Land use	pH	Carbon %	DOC (mg/L)	Cu (mg/kg)	Pb (mg/kg)	Ni (mg/kg)
Sandy silt loam	Agricultural: grassland	6.28	5.2	15.5	14.7	376	21.7
DMS 1	Minespoil; deciduous wood	5.06	11	60.6	36.9	2470	49.4
DMS 2	Minespoil; grassland	7.41	3.62	12.6	141	1360	60
DMS 3	Minespoil; grassland	7.05	3.9	10.8	176	7200	62.9
DMS 4	Minespoil; spoil heap	7.28	2.21	11.3	97.8	7700	84.4

Table 3.11: Characteristics of historically contaminated soils

i) Marzouk et al. (2013), as part of a study comparing chemical extraction methodology, reported further data from Cloughs Wood and, additionally, Black Rocks (Table 3.12). The authors described presumably historic aeolian "smelter fallout''as being a factor in soil contaminant enrichment. It is likely that this was significant in the middle course when the smelters were operating. However, since smelter closures wind contaminant redistribution is likely to be minimal compared with fluvial redistribution.

Soil sample	Veg cover	pH	Carbonate content %	LOI	Trace metals (mg/kg)		
					Pb	Zn	Cd
BR-MS	Spoil heap	7.42	31.5	4.31	23,700	43,300	669
CW-MS1	Spoil heap	7.29	2.07	5.33	29,900	39,800	580
CW-MS2	Spoil heap	7.05	3.37	8.74	29,300	27,600	412
BR-W	Woodland	6.36	0.42	56.1	1,300	1,260	19.1
CW-G	Grassland	5.72	0.16	19.3	10,300	3,470	51.3
CW-W1	Woodland	5.13	0.07	30.1	667	143	3.66
CW-W2	Woodland	4.3	1	11	553	121	2.54
CW-W3	Woodland	3.46	n.d.	41.9	2,450	112	5.7
BR = Black Rock 53 09 08 N 1 36 57 W					CW = Cloughs Wood 53 05 53 N 1 33 52 W		

Table 3.12 Vegetation cover and selected properties of the soils from Black Rocks and Clough Wood, Derbyshire, England, in order of descending soil pH value.

j) Li and Thornton (1993a) undertook a study comparing mining contaminated soil at Winster and Tideslow against local controls (Table 3.13). They made a further comparison with the smelter site at Stone Edge (Table 3.14). The study included a comparatively wide range of elements (Pb, Zn, Cd, Ag, mercury [Hg], As and Sb), together with the sampling of three different depth horizons.

	Soil Profile	Statical Measure	Pb	Zn	Cd	Ag	Hg	As	Sb
Mining Sites (Winster village and Tideslow Farm) *n = 6*	T	*R*	3,280-28,900	478-3,180	4.40-38.3	0.40-3.00	0.18-0.80	16.8-42.3	3.96-42.5
		M	18,000	1,530	19.8	1.83	0.5	28.9	24.5
	S1	*R*	2,620-30,100	427-3,180	4.10-35.7	0.40-3.66	0.13--1.07	10.2-41.1	3.52-47.5
		M	15,400	1,330	18.7	1.47	0.43	25.7	25.8
	S2	*R*	1,850-29,000	304-3,000	2.90-38.8	0.40-2.00	0.09-1.07	12.4-36.5	2.18-53.0
		M	17,700	1,390	18.9	1.3	0.41	24.2	21.4
Site Near Mining Area (New Farm) *n = 3*	T	*R*	308-516	151-184	0.70-1.40	<0.40	0.11--0.13	9.91-13.0	1.52-2.06
		M	399	164	1.13	<0.40	0.12	11.5	1.88
	S1	*R*	169-465	134-177	0.50-1.30	<0.40	0.08-0.11	7.32-9.25	1.20-1.50
		M	309	153	1.07	<0.40	0.09	8.3	1.35
	S2	*R*	136-458	142-202	0.50-2.20	<0.40	0.06--0.09	6.52-8.19	0.92-1.34
		M	266	163	1.8	<0.40	0.08	7.2	1.15

Note: T-topsoil (0-15 cm), Sl--5ubsoil (15-30 cm) and S2--5ubsoil (30-45 cm). *M*-mean concentrations and *R*-range of concentrations. n-number of samples.

Table 3.13: Concentrations (mg/kg) of trace elements in soils in the mining area, Derbyshire

Sample site	Statical Measure	Pb	Zn	Cd	Ag	Hg	As	Sb
Smelter Site (Stone Edge)	T	30,000	380	6.1	0.6	0.21	44.4	154
Site 1	Sl	27,000	690	5.3	<0.40	0.13	26.2	82
	S2	11,600	301	1.5	<0.40	0.11	17.5	32.5
	T	22,200	1500	19.7	<0.60	0.09	31.2	105
Site 2	Sl	5,150	621	8.8	<0.40	0.05	10	33
	S2	596	171	0.5	<0.40	0.05	10.7	12.9
	T	9,770	1380	3.6	<0.40	0.1	16.8	49.8
Site 3	Sl	675	584	2.2	<0.40	0.05	4.84	8.76
	S2	518	415	1	<0.40	0.04	3.87	6.4
Sites surrounding Stone Edge Smelter	T	180	125	<0.20	<0.40	0.1	5.97	1.1
Site 1	Sl	121	64.6	<0.20	<0.40	0.05	6.78	1.02
	S2	56	58.4	<0.20	<0.40	0.05	*4.45*	0.6
	T	112	88	<0.20	<0.40	0.07	7.07	1.28
Site 2	Sl	124	81.2	<0.20	<0.40	0.07	6.93	1.12
	S2	88	61.8	<0.20	<0.40	0.04	5.01	0.68
	T	172	18.6	<0.20	<0.40	0.05	6.87	0.92
Site 3	Sl	145	21.8	<0.20	<0.40	0.05	6.63	0.94
	S2	64	44	<0.20	<0.40	0.03	7.55	0.6

Note: T-topsoil (0-15 em), Sl-s-subsoil (15-30 em) and S2-subsoil (30-45 em).

Table 3.14: Concentrations (mg/kg) of trace elements in soils at a Pb smelting site, Derbyshire (note Table 3.14 lacks the range values given in Table 3.13

The elements associated with galena mineralisation (Plant and Raiswell, 1983), including Zn, Cd, Ag, As, Sb and Hg, were very high in soils sampled from this mining area (Table 3.13).These results strongly indicate that, in addition to Pb, Zn and Cd, contamination of soils by Ag, Sb, Hg and As is likely at the old Pb mining sites.

Stone Edge cupola is situated on the Millstone Grit series rather than the Carboniferous Limestone underlying the other mining sites analyzed in Li and Thornton's (1993a) article. The ore processed at this smelter, however, was mainly sourced from the Winster mines. It is interesting that, when compared to the mining site, the concentrations of Sb and Pb are notably higher at the smelter site. In contrast, concentrations of Hg and Ag are lower, likely as a function of their high volatility during smelting process. Antimony is particularly interesting in this regard as it is considerably enriched throughout the whole soil profile at the smelter site compared to the mining site. Moreover, in comparative terms Sb is much more conservative than its chemically similar group 15 neighbour As. It is possible that the Sb secondary phases, tripuhyite ($Fe^{3+}Sb^{5+}O_4$) and schafarzikite ($Fe^{2+}Sb^{3+}_2O_4$), are particularly stable at this site and form an underestimated environmental sink for Sb (Leverett et al., 2012; Kossoff et al., 2014).

At both sites concentrations of Pb, Cd, Hg and Sb uniformly decline with depth, no doubt reflecting the recent nature of the contamination, at least in geological terms. The depth profile of As and Zn is more variable, with the concentration of both of these elements occasionally increasing with depth. This might reflect the heightened mobility of these elements (c.f., in the case of Zn, Rothwell et al., 2007).

k) Li and Thornton (1993b) confined the data reported to the three elements As, bismuth [Bi] and Sb. The As and Sb values are in broad agreement with those given in Li and Thornton, (1993a) with the addition of the Bi data (Table 3.15). Just as with Li and Thornton, 1993a), interesting comparisons were made between a site contaminated by old mining (Winster) and one contaminated by smelting (Stone Edge) and data derived from three depth sections of the soil profile were given. For this paper, herbage concentrations from Derbyshire were additionally reported.

The Bi soil data reported established that, at least for these sites, contamination was not significant. Bismuth concentrations were very close to mean level of world soils (0.20 mg/kg, Bowen, 1979) both at the mining and smelter site. Antimony, however, was much higher than the upper end of the 'normal' soil range (10 mg/kg), particularly at the smelter site. Arsenic concentrations at both sites were also well above the mean level for the world soil (6 mg/kg), but within the upper range (40 mg/kg). In the case of Bi, concentrations in soils were very similar at the mining and control sites, which may indicate that Bi is not enriched within the Pb mineralisation of the Carboniferous Limestone.

The old mining area (Winster village and Farm A)		Measure	As	Sb	Bi
(n = 7)	Herbage	M	0.04	0.08	0.04
		R	0.03-0.05	0.03-0.13	<0.01-0.08
	Topsoil	M	30	23.4	0.33
	(0-15 cm)	R	19.9-38.9	6.47-51.4	0.24-0.44
	Subsoil	M	24.2	21.8	0.18
	(15-30 cm)	R	13.1-34.6	4.16-51.5	0.04-0.37
	Subsoil	M	25.1	17.1	0.25
	(30-45 cm)	R	10.1-34.4	2.20-33.9	<0.02-0.64
The control site (Farm B)					
(n = 3)	Herbage	M	0.04	0.04	0.02
		R	0.03-0.06	0.03-0.06	<0.01-0.03
	Topsoil	M	8.33	1.43	0.41
	(0-15 cm)	R	7.69-8.97	1.41-1.44	0.38-0.44
	Subsoil	M	6.69	1.11	0.46
	(15-30 cm)	R	6.18-7.20	1.04-1.18	0.45-0.47
	Subsoil	M	6.59	1.2	0.28
	(30-45 cm)	R	6.49-6.69	1.04-1.26	0.28-0.29

Table 3.15: part 1. As, Sb and Bi concentrations (mg/kg) of soils and herbage in old mining and smelting areas, Derbyshire

The old lead smelter site (Stone Edge)			As	Sb	Bi
(n = 3)	Herbage	M	0.03	0.06	0.01
		R	0.04-0.09	0.05-0.07	0.01-0.02
	Topsoil	M	30.8	103	0.45
	(0-15 cm)	R	16.8-44.4	50.0-154	0.33-0.54
	Subsoil	M	13.7	41.3	0.22
	(15-30 cm)	R	4.84-26.2	8.76-81.8	0.20-0.25
	Subsoil	M	10.7	17.3	0.31
	(30-45 cm)	R	3.87-17.5	6.40-32.5	0.10-0.43
	Slag (n = 2)		49.3	941	0.1
The smelter surrounding area					
(n = 3)	Herbage	M	0.07	0.1	0.02
		R	0.07--0.08	0.09-0.13	0.01-0.02
	Topsoil	M	6.64	1.1	0.29
	(0-15 cm)	R	5.97-7.07	0.92-1.28	0.26-0.32
	Subsoil	M	6.78	1.03	0.11
	(15-30 cm)	R	6.63-6.93	0.94-1.12	0.06--0.28
	Subsoil	M	5.67	0.63	0.18
	(30-45 cm)	R	4.45-7.55	0.60-0.68	0.09-0.32
M-arithmetic mean; R-range; n-sample number					

Table 3.15: Part 2. As, Sb and Bi concentrations (mg/kg) of soils and herbage in old mining and smelting areas, Derbyshire

The herbage As, Bi and Sb concentrations given in Table 3.15 appear to suggest that there is not significant contamination occurring. This would be misleading, however, as the sampling methodology involved three rinses in deionised water, which may have removed some of these elements. Indeed, the authors report that for a Cornish sample the unwashed pasture had a concentration of 62 mg/kg As, which was 16 times higher than the washed sample. Hence the herbage data report in Table 3.15 should be treated with caution. Another study found that Pb concentrations in Derbyshire grown vegetables were 2-4 times higher than those in urban gardens (Moir, 1992). Additionally, 13% of the vegetables, in particular lettuce and spinach, exceeded the current statutory limit of 1 µg/g fresh weight in saleable food (Thornton, 1996).

l) Merry (1988) reported on the Cd, Pb and Zn concentrations at Winster and Stone Edge (Table 3.16) and showed that the lateral dispersion from the mineral veins at Winster was “very limited’’, but that at the smelter site lateral contamination was considerably more extensive. This is to be expected as aeolian distribution transports material over comparatively further distances than natural weathering, though this distance is limited; for example, Cd concentrations fall from their peak of 30 ppm to below the detection limit (1.5 ppm) within 200 m in a southerly and easterly direction and 1 km in a northerly direction.

Merry (1988) also reported that the percentage of the total soil Pb and Zn extractable by 0.5M acetic acid varied at the two sites (Table 3.16a). At Stone Edge c. 2.5 times more Pb and Zn (25.8% Pb and 30.6% Zn) were extracted in this fraction than at Winster (8.75% Pb and 11.41% Zn). The heightened contaminant availability at Stone Edge is almost certainly as a function of the smelting process.

Element	Site	Depth (cm)	Mean	Standard Deviation	Range
Pb	Winster	0-15	3,226	2.6	522-14.940
		30-45	1,954	2.6	159-14,180
	Stone Edge	0-15	5,841	10.4	239-33,040
		30-45	3,342	8.7	62-33,530
Zn	Winster	0-15	841	723.0	235-3,302
		30-45	799	1252.0	122-8,650
	Stone Edge	0-15	488	861.0	15-3,433
		30-45	157	200.0	11-768
Cd	Winster	0-15	8	7.1	2.1-34.1
		30-45	6.74	7.8	0.8-40.1
	Stone Edge	0-15	………	………	< DL to 36
		30-45	………	………	< DL to 20.3

Table 3.16 Statistical Distribution of total lead, zinc and cadmium soil concentrations from Winster (n = 64) and Stone Edge (n = 15) (mg/kg).

Table 3.16 a Acetic Acid extraction of Pb				
Site	Extractable Pb	Total Pb	% of Total	Soil
	(mg/kg)	(mg/kg)	Extrable	pH
W 501T	240.4	2550	9.4	5.91
W 502S	45.6	767	5.9	6.11
W 505T	416.4	2925	14.2	6.75
W 506S	53.6	522	10.3	6.30
W 509T	144.4	1503	9.6	6.68
W 510S	22.8	359	6.4	6.20
W 513T	254.4	2942	8.6	5.91
W 514S	77.2	1137	6.8	6.09
W 517T	182.8	1728	10.6	5.54
W 518S	16.0	284	5.6	5.40
SE 101T	88.8	318	27.9	5.18
SE 102S	72.8	197	37.0	4.86
SE 105T	193.2	821	23.5	5.73
SE 106S	50.8	163	31.2	6.32
SE 213T	58.0	443	13.1	5.46
SE 214S	8.0	87	9.2	5.19
SE 217T	10256.0	27110	37.8	5.59
SE 218S	10056.0	33530	30.0	6.98
SE 329T	70.8	351	20.2	4.08
SE 330S	17.6	62	28.4	4.49

Table 3.16 a Acetic Acid extraction of Zn

Site	Extractable Zn	Total Zn	% of Total	Soil
	(mg/kg)	(mg/kg)	Extrable	pH
W 501T	69.4	521	13.3	5.91
W 502S	11.9	152.4	7.8	6.11
W 505T	73.4	613	12.0	6.75
W 506S	12.9	136	9.5	6.30
W 509T	50.6	301.6	16.8	6.68
W 510S	11.0	179.2	6.1	6.20
W 513T	65.9	375	17.6	5.91
W 514S	20.9	229.8	9.1	6.09
W 517T	35.6	279	12.7	5.54
W 518S	12.5	136	9.2	5.40
SE 101T	6.2	29.6	21.1	5.18
SE 102S	6.2	22.4	27.7	4.86
SE 105T	22.0	84.8	26.0	5.73
SE 106S	5.7	31	18.5	6.32
SE 213T	152.5	361	42.2	5.46
SE 214S	70.8	129.6	54.6	5.19
SE 217T	365.2	963	37.9	5.59
SE 218S	692.0	1361	50.8	6.98
SE 329T	3.4	20.8	16.2	4.08
SE 330S	2.5	22.2	11.4	4.49

Table 3.16 a Acetic Acid extraction of Cd

Site	Extractable Cd	Total Cd	% of Total	Soil
	(mg/kg)	(mg/kg)	Extrable	pH
W 501T	3.16	5.70	55.4	5.91
W 502S	0.84	1.80	46.7	6.11
W 505T	4.28	7.90	54.2	6.75
W 506S	1.76	3.60	48.9	6.30
W 509T	1.72	3.10	55.5	6.68
W 510S	0.32	0.30	106.7	6.20
W 513T	2.08	3.90	53.3	5.91
W 514S	1.12	2.60	43.1	6.09
W 517T	1.52	2.40	63.3	5.54
W 518S	0.60	1.10	54.5	5.40
SE 101T	<DL (2)	<DL	………	5.18
SE 102S	<DL	<DL	………	4.86
SE 105T	0.80	<DL	………	5.73
SE 106S	<DL	<DL	………	6.32
SE 213T	4.84	6.75	71.7	5.46
SE 214S	1.20	<DL	………	5.19
SE 217T	1.04	3.00	34.7	5.59
SE 218S	6.76	12.00	56.3	6.98
SE 329T	<DL	<DL	………	4.08
SE 330S	<DL	<DL	………	4.49

Table 3.16: Acetic acid extraction of lead, zinc, and cadmium

m) Zhang (2008), as part of a PhD thesis, reported on the concentrations of Cd, chromium [Cr], Cu, Mn, Ni, Pb and Zn in the Manifold and Derwent catchment floodplains. Four sites were chosen in the Derwent catchment: three in the highly contaminated Wye tributary catchment (sites 3, 4 and 5) and one on the Derwent, 2km downstream from the site of the former Mill Close Mine (site 6).

Table 3.17 presents floodplain total soil metal concentrations. It is apparent from these data that Cd, Pb and Zn in the Wye and Derwent floodplains are much higher than their respective local background and national average concentrations. The River Wye is 15 miles long and is one of the major tributaries of the River Derwent. It flows in a south easterly direction through Bakewell to join the River Derwent at Rowsley. Just as with the Derwent itself, the river floods two or three times a year; unlike the Derwent, however, these floods usually actually do inundate the entire floodplain. Table 3.18 presents site specific data for contamination of the Wye floodplain soils.

Table 3.19 reports data from floodplain traverses from the Wye and Derwent and thereby gives a measure of the horizontal (lateral) distribution of contamination. The distribution of Cd, Pb, Zn and Mn across the three sample localities on the Wye floodplain (sites 3, 4 and 5) exhibit a relatively constant pattern across the floodplain. For the Derwent (site 6), however, contaminant soil concentrations tend to increase away from the river channel. This is particularly so at 190 m distance where there is a marked rise in the Cd and, particularly Zn profiles (c.f., Bradley and Cox, 1990). This possibly might represent the course of a palaeochannel; however, it is likely that the explanation lies in the deposition of contaminated fine-grained sediment by river flooding. It should be noted that distance downstream increases with sample number and, of the seven elemental concentrations reported, only Ni consistently falls. This is the consequence of additional point sources along the course of the Wye supplying fresh contaminant loads.

(x) sample #	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Manifold (19)	7.9 (4.2)	40.0 (7.1)	227.7 (129.9)	2,370 (1,168.0)	45.8 (7.5)	331.7 (142.1)	660.1 (310.7)
Background Manifold[1]	0.4		17			52	145
Wye (24)	5.9 (1.4)	39.5 (5.1)	55.8 (13.6)	1 132.3 (438.6)	51.2 (6.3)	712.6 (195.0)	638.0 (115.6)
Derwent (18)	3.9 (1.3)	43.9 (5.7)	38.0 (5.8)	719.2 (54,2)	37.7 (4.2)	737.6 (69.3)	407.2 (99.3)
Background in Wye and Dewent[2]	1.0 (0.4)		32.2 (6.4)	806 (211)	53.3 (15.1)	350 (121)	170 (29.4)
National levels[3]	0.8 (0.9)	41.2 (28,2)	23.1 (37.0)	760.9 (979.3)	24.5 (17.4)	74 (267.0)	97.1 (109.3)

(2) Bradley and Cox, 1986 (2) Li, 1993 (3) McGrath and Loveland, 1992 (CV% was given instead of s. d.) (CV%, coefficient of variation =SD/Mean* 100, therefore, s. d. =CV% x mean/100)

The Manifold lies outside of the Derwent catchment. It is included here to give an overall view of the Peak district.

Table 3.17 Total heavy metal concentrations (± s. d. in the floodplain soils (mg/kg) with relevant background and national average levels

Floodplain	**Cd**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**Zn**
Site 3 (n=8)	4.9	42.4	52.5	916.5	53.8	637.6	561.9
Site 4(n=9)	5.2	37.3	61.2	1413.5	51.5	886.2	596.1
Site 5(n=7)	7.8	38.9	52.6	1017.5	47.8	575.3	778.8

Table 3.18 Heavy metal concentrations in the Wye floodplain soils (mg/kg).

Site 3							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	4.2	31.4	30.3	764.4	41.7	516.6	481.1
5	4.4	38.4	39.6	885.5	49.5	581.3	500.1
10	5	41.8	54	910.3	54.9	581	557.9
15	5.5	49.8	69.2	997.6	65.8	692.1	628.3
20	5.3	48.7	66.3	985.3	62.5	758.6	618.4
25	4.8	36.9	51.1	952.9	45.3	514.1	543.8
30	5.4	45.3	52.5	985.3	55.4	681.1	596.1
35	4.9	47.1	57.2	850.3	55.4	775.9	569.4
Site 4							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	3.9	27.3	32.4	733.9	37.7	570	469.6
5	4.8	40.3	52.1	1155.4	51.2	807.1	813.3
10	4	37.9	44.4	1042.3	48.3	774.9	512.4
15	6.2	40.3	57.6	2322.3	58.2	801.1	635.9
20	6.2	36.4	59.2	2182.7	50.8	918.3	584.9
30	5.5	39.6	79.3	2239.9	55	1376.5	606.2
40	6.4	38.1	62.7	950.8	53.1	813.7	606.6
50	4.5	34.7	92.7	1069.7	54.3	993	562.9
60	5.2	41.1	70.6	1024.5	54.7	920.8	572.7
Site 5							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	8.8	35.8	50.1	934.2	45.9	524.4	807.8
5	8.7	44.3	62.8	1280.7	53.3	580.4	889.4
10	7.8	39.8	58	1158.7	49.2	581.1	811.2
15	7.4	42.1	50.1	938.4	48.6	570.7	769.7
20	7.8	39.2	55.4	1037.2	49.3	609.7	772.2

25	7.1	35.8	48.1	943	45.4	592.1	711.2
30	6.7	35.3	43.6	830	42.7	568.5	690.4
Site 6							
Distance from channel (m)	Cd	Cr	Cu	Mn	Ni	Pb	Zn
1	5.7	30.4	25.3	602.7	29.2	617.3	538.5
5	4.8	33.8	27.6	627.4	31.1	625.2	500.8
10	4.5	38.9	31	692.6	32.9	656.8	523.6
15	3.4	37.4	31	734.8	31.9	646.3	375
20	4.2	42.6	35.5	793.2	36	707.1	419
30	3.3	42.3	34.7	727.9	37.1	730	374
40	3.3	40.4	36.4	822.1	36.3	705.7	376.5
50	2.7	47.9	40.5	792.4	41	762.9	346.3
60	3.2	47.4	42.5	749.5	41.9	809.8	368.9
70	4	49	46.3	709.7	43.9	809	438.2
90	3.3	49.3	43.4	718.9	42.1	791.7	374.4
110	2.7	49.7	40.4	728	40.3	774.4	310.6
130	2.7	41.9	40.6	682.9	38.2	738.9	323.2
150	3.2	46.4	38.5	694.5	37.9	691.3	302.2
170	3.5	45.5	40.3	760.5	38	750.3	322.2
190	8.2	51	43.7	660.4	40.3	843.8	704.9
210	3.2	45.6	42.7	711.9	40.3	766.4	346.2
230	4	50.3	43.4	735.8	43	850.3	384.4

Table 3.19: Heavy metal concentrations variation with distance from the Wye and Derwent channels (mg/kg)

n) Geeson et al. (1998) reported data on highly-elevated Derbyshire F concentrations (Section 3b). They chose to analysis soils from the Tideswell area with most, but not all, of their sample sites lying within the Derwent catchment. Fluorine concentrations in the topsoil samples ranged from 223 – 69,870 mg/kg (Fuge and Andrews, 1988, reported a general UK background soil concentration of 200 – 400 mg F/kg). Other elements reported included Pb (range of 172 – 61,600 mg/kg), Cd (range of 1.0 –67 mg/kg) and Zn (range of 84 –2,468 mg/kg) (Table 3.20).

o) The Glebe Mine tailings spill

After a prolonged period of heavy rainfall in January 2007 the tailings dam at the Glebe Mine processing complex at Stoney Middleton failed. Property was damaged in the village and it has been estimated that 113 tonnes of fine-grained fluorspar mine tailings were released into the Stoke Brook and into the Derwent itself (Environ Liverpool, 2008; Worrall, 2009).

These river systems were ecologically diverse and had considerable amenity value in the context of the Peak District National Park. In the immediate aftermath of the spill the local environmental health department undertook sampling of the affected area. These samples exceeded the Swedish contaminated soil guideline values for As Zn and particularly Cd and Pb, for both the affected and unaffected gardens (Wilding 2007; Table 3.21)

The sampling methodology employed involved the removal of the tailings layer from the affected gardens to reach the ‘uncontaminated' soil beneath. Nevertheless Pb showed a *c*.23 % concentration increase in the tailings impacted soil compared with the unaffected control. The analogous figures for As, Cd and Zn were 11, 1 % and 19 %, respectively. The interregnum between the accident and the sampling was a maximum of 21 days. Therefore, taken at face value, these data indicate the significant and comparatively high mobility of Pb from the Glebe mines tailings source.

Farm	Field	Plot	OM %	pH	F (µg g^{-1})	Pb (µg g^{-1})	Zn (µg g^{-1})	Cd (µg g^{-1})	Cu (µg g^{-1})	Mg (µg g^{-1})	Ca (%)	Fe (%)	Al (%)
A	1	a	15.2	6.6	4280	6480	880	10.8	52	1840	3.36	1.91	1.68
	1	b	14.1	6.1	492	1600	108	1.0	16	1240	0.56	1.99	1.00
	1	c	11.2	6.3	638	2000	120	1.0	16	840	0.68	2.11	0.92
	1	d	14.8	6.4	1030	480	70	0.2	12	860	0.64	1.25	0.72
	2		22.0	7.2	46,670	30,240	2468	67.0	69	2400	23.80	2.27	2.34
	3		14.9	6.6	33,200	11,200	1170	13.6	64	3440	4.80	2.91	3.60
	4		16.0	6.8	4600	2640	ND	3.8	32	2320	1.64	2.63	1.88
B	1		10.4	6.4	5010	2260	716	14.4	24	2540	1.06	2.62	2.38
	1	a	8.8	5.9	2710	1400	436	9.0	20	1000	0.84	1.07	1.64
	1	b	6.5	5.5	6767	1680	520	7.8	24	3360	1.12	4.23	2.40
C	1		13.7	6.1	2820	880	208	3.0	64	1720	1.24	5.99	2.32
	1	a	13.0	6.4	2980	800	220	0.6	72	2120	1.48	7.59	2.68
	1	b	8.5	6.1	1810	640	164	2.2	60	1520	0.92	5.03	2.04
	2		13.6	5.9	2050	5200	144	1.0	60	1460	1.00	5.19	2.28
	3		7.0	6.8	63,500	10,000	1173	15.0	107	4000	10.40	6.39	4.96
	3		6.8	7.3	80,600	14,400	1768	20.0	110	3520	12.80	5.79	4.24
D	1		20.9	6.5	69,870	61,600	948	1.0	64	3640	14.00	2.11	2.12
E	1		12.9	6.0	388	6400	176	2.4	32	4000	0.58	2.89	2.10
	1	a	13.3	6.2	553	348	136	2.2	28	3840	0.60	2.83	1.92
	1	b	9.1	5.9	460	328	132	13.4	28	4400	0.60	2.71	2.32
F	1		6.0	5.2	223	172	84	ND	12	1360	0.28	1.63	1.20
	1	a	6.4	5.4	220	148	68	0.6	16	1320	0.24	1.55	1.08
	1	b	5.8	5.0	472	312	80	0.6	16	1400	0.28	1.55	1.16
G	1		6.0	6.0	1600	1600	164	1.8	40	1240	1.00	2.63	1.32
Normal range or average concentration in soils													
i. Archer and Hodgson, 1987						10.9–145	29–210	<1.0–3.9	5.8–62				
ii. Fuge and Andrews, 1988					200-400								
iii. McGrath			6.0	6.0		40	82	0.7	18	3000	0.32	2.7	2.8

Table 3.20: Total fluorine and other determined characteristics of soils (0–15 cm, milled <200 mm fraction) at each farm sampling site

Analyte	Affected gardens (n=5; mg/kg)	Unaffected gardens (n=4; mg/kg)	Tailings (n = 1; mg/kg)	Swedish classification*
pH	7.76	7.45	9.26	
Aluminium	27800	24000		
Arsenic	25	22.25	24.6	Moderately serious
Barium	1510	1375	5130	-
Cadmium	4.62	4.56	14.4	Extremely serious
Chromium (Total)	30.4	30.75	18.6	Slightly serious
Iron	23200	23250		-
Lead	1960	1512.5	4620	Extremely serious
Mercury	0.26	0.28	0.42	Slightly serious
Magnesium	3300	2900		-
Manganese	1474	1475		-
Nickel	28.8	32	46.6	Slightly serious
Selenium	2	2.3	8.65	-
Strontium	104.8	68.25		-
Zinc	470	382.5	1790	Moderately serious
Fluoride	4.72	2.89		-
*Swedish, E. P. A. (2002). Categorised for gardens only.				
The boundary between “Slightly serious” and “Moderately serious” ts used as the guideline value for sensitive land use.				

Table 3.21: Mean results of soil sampling at five affected gardens and four unaffected gardens on Edge View, Stoney Middleton

Clean-up operations were delayed until June 2008. This was undoubtedly a complex problem; however, the importance of Glebe Mines to the local community in terms of employment, together with difficulties associated with insurer's liability, were contributory factors to the delay (Worrall, 2009). During the course of the clean-up work it was discovered that a much larger spill had occurred in 1968 with much of the tailings still remaining *in-situ* on the floodplain. No obvious ill effects of this early accident have been reported in the interim, leading some to question whether the clean-up operation was necessary other than for cosmetic reasons (e.g., Worrall, 2009). Indeed, the consultants employed by Glebe Mines concluded that, although the tailings were characterised by high concentrations of heavy metals and fluoride, these contaminants were relatively immobile after the tailings were dispersed into the environment (Environ, Liverpool, 2008). Moreover, background contaminant concentrations, determined by analyzing sediment not impacted by the 2007 tailings spill, had similar concentrations of heavy metals (Wilding 2007; Environ, Liverpool, 2008). From these reports the conclusion might therefore be drawn that the adverse effects of the 2007 spill were acute rather than chronic. However, the addition of a further contaminant burden on an already grossly contaminated river system (some of this contamination, no doubt, being derived from previous dam failures) should not be taken lightly. This review has established that contaminants are being remobilised within the Derwent catchment (e.g., Bradley and Cox, 1990) and that the addition of a further contemporary- (rather than historic-) burden should be avoided. Furthermore, remediation should be the responsibility of the polluter and/or their insurer (Commission of the European Communities, 1993).

p) The Enthoven Lead smelter

Historically there were a plethora of historic smelter sites on and around the Derbyshire orefield. This review has made some reference to these and undoubtedly a significant proportion of the catchment's historic contaminant load is sourced from their operation.

The Pb smelter at Mill Close was established in 1934, while the mine was still in production. Moreover, since 1940 the smelter has been an isolated and productive source of Pb (Lageard et al., 2008). Lageard et al.(2008) performed soil analysis in and around the Enthoven property in an attempt to correlate this with tree-ring data from the species *Pinus sylvestris* L. They found that the results indicate that the soil taken from under the trees at the plant all exceeded the current DEFRA guideline of 450 mg/kg for open spaces (DEFRA, 2002). Soil samples from Darley Dale, Birchover and Upper Matlock had Pb concentrations ranging between 443 and 787 mg/kg, with those in the control sites ranging between70 and 196 mg/kg (Table 3.22).

Site location	Tree-ring core sample numbers	Data range: tree-rings (years Ad)	Data range: Pb-in-wood (mg kg^{-1})	Soil pH	Solid geology [a)]	Pb in soil (mg kg^{-1})
Main area Enthoven	K26	1954-1998	8-28	5.2	Gritstone	2033
	K8	1949-1998	4-30	3.8		3405
	K27	1909-1998	3-11	3.9		8935
	K5	1909-1998	3-38	3.5		8043
Darley Dale	D1B	1939-1998	1-35	6.8	Gritstone	787
	D3B	1899-1998	3-22	5.9		595
	D4A	1909-1998	2-28	5.8		452
Birchover	F12	1914-1998	2-30	3.6	Gritstone	443
	F24	1924-1998	1-9			
	F15	1904-1998	2-34			
Upper Matlock	F17	1919-1998	7-37	3.5	Gritstone	699
	F22	1949-1998	1-10			
	F5	1939-1998	7-38			
Controls						
Wildboarclough	F13	1929-1998	2-8	5.4	Gritstone	196
	F28	1929-1998	0.6-5	5.2		141
Delamere	R6	1959-1998	0.7-6	4.2	Sandstone	70
	R6B	1954-1998	0.7-1			
	R5	1954-1998	0.4-5			
[a)] Solid geology based on Harrison and Adlam (1985).						

Table 3.22: A summary of sampling sites, tree-ring cores and results of dendrochemical and soil analysis

These data undoubtedly reflect historic pollution from the smelter site. There is evidence from the record of Pb concentration in air that, despite the high production, aeolian contamination from the smelter is currently much better controlled than it was in the past. In 1982 the Pb concentration in the air was *c*. 1.7 µg m^{-3}, and this had fallen to 0.2-04 µg $m^{-3}$by 1998 as a function of improved plant practice (data from Enthoven and Derbyshire Dales District Council, both quoted in Lageard et al., 2008). In this context it worth noting that the Environmental Protection Agency sets a rolling three month average Pb "not to be exceeded''concentration limit in air of 0.15 µg/m^3 (EPA, 2008). Lageard et al. (2008) concluded by observing that the lead-in-wood record can be related to both a well-documented pollution chronology at the Mill Close site and also known atmospheric circulation patterns in the Derwent valley (see also White, 1991). It therefore follows that a significant portion of the historic contaminant burden in the middle Derwent is attributable to aeolian distribution from smelting, particularly at the Mill Close site. Moreover to some, albeit controlled, extent this process is ongoing. To further emphasize this point Bellis et al. (2001), in a study of tree bark Pb concentrations around the smelter, concluded that the emissions would contribute directly to an increased Pb exposure via the inhalation of atmospheric aerosols. Bellis et al. (2001) then went on to suggest, amongst other measures, that surveys of blood Pb be undertaken of children and residents. However, just as with the Stoney Middleton processing plant, the Enthoven smelter is a significant local employer (195 employees) in an area where employment opportunities are limited. Moreover, the continued operation of processing industries in the Peak District do reflect the history and rich traditions of the area; perhaps much more immediately than do the generality of 'heritage'sites. To that extent maybe these industries continued operation within as rigorous, as is practically possible, limits should be facilitated, rather than hindered.

3f) Quantification of lower course soil contamination

As noted earlier, the lower section of the Derwent Valley between the end of the Matlock Gorge and its confluence with the River Trent, with the exception of the Ecclesbourne, has much less evidence of metal mining. There is, however, indirect evidence for geochemical contamination from analysis of the River Trent sediments.

a) Moriarty et al. (1982) analyzed the River Ecclesbourne, a mining-contaminated tributary of the Derwent, which drains the southern margin of the orefield, most notably the mining area in and around Wirksworth. The Ecclesbourne joins the Derwent at Duffield in the heart of the DVMWHS. Sediment samples were taken from a number of positions at 22 sites along the length of the river, and from seven tributaries. Samples from each position and site were graded into particles of three different sizes, and then analyzed for their total Pb, Zn and Cd contents. The authors, for the purposes of their discussion, report the data in log form; these have been transformed to normally expressed concentrations in Table 3.23. The authors conclude that: "The major difference in concentrations was between sites, with a general trend for concentrations to decrease downstream and there appear to be 'pulses' of sediments with relatively high concentrations that move down the river.”

Site #	Distance	Lead			Zinc			Cadmium		
	Upstream (km)	Grade 1	Grade 2	Grade 3	Grade 1	Grade 2	Grade 3	Grade 1	Grade 2	Grade 3
6	5.26	676.08	851.14	630.96	741.31	467.74	309.03	3.47	2.75	2.4
8	5.27	912.01	794.33	741.31	602.56	446.68	302	3.72	2.88	2.95
11	8.51	2884.03	2137.96	1174.9	2137.96	1380.38	363.08	11.22	12.59	5.01
13	8.58	3890.45	1905.46	1698.24	851.14	1288.25	562.34	4.47	12.88	6.76
17	12.63	8912.51	8511.38	15135.61	5128.61	6309.57	2884.03	64.57	85.11	35.48
19	12.75	8317.64	6760.83	5495.41	8511.38	6025.6	3162.28	120.23	77.62	25.12
20	13.58	7762.47	15848.93	4265.8	15135.61	6456.54	1995.26	213.8	75.86	24.55
22	14.55	19498.45	25703.96	12022.64	19498.45	6918.31	4466.84	275.42	74.13	54.95
23	14.56	22387.21	19498.45	23442.29	6025.6	10715.19	8709.64	52.48	117.49	87.1
28	14.84	21877.62	14454.4	11220.18	9549.93	8128.31	3388.44	112.2	95.5	36.31

Table 3.23: Comparison of metal concentrations and grain size in sediments from the river Ecclesboune. Mean concentration mg kg $^{-1}$ for two positions per site

It is also noteworthy that grain size analysis demonstrated that the contaminants were evenly dispersed throughout the sediment. Whilst this is true for the Ecclesbourne, analysis of larger rivers, particularly in their downstream portion, normally shows that the smaller-sized fractions contain the highest concentrations of contaminants. This is rationalized by their comparatively high surface area to volume ratio facilitating metal sorption, principally to the Fe and, to a lesser extent, Mn oxy/hydroxides (Section 1; Singh et al., 1999; Smedley and Kinniburgh, 2002). The immediate input of mine waste of comparatively large diameter grain size coupled with the short course of the Ecclesbourne appears to mediate against such a fractionation.

It is interesting that the Pb and Cd sediment concentrations in sediments at the mouth of the Ecclesbourne (i.e., at the Derwent confluence) are approximately the same as those measured at Mill Close by Bradley and Cox (1990). It should be noted, however, that Zn concentration is appreciably higher at Ecclesbourne than at Mill Close, implying a significant point source from within the Ecclesbourne catchment.

Reynolds (1981) also provided data on contaminant concentrations in the Ecclesbourne stream sediments. Mean Pb, Zn and Cd concentrations were 6,011, 1,042 and 14.8 ppm, respectively, broadly in line with those reported by Moriaty et al. (1982) (Table 3.24).

Site	Pb	Zn	Cd
315	538	512	10.8
344	3480	1640	26.4
318	19200	1760	32
328	10000	1360	19.2
321	9600	1080	12.4
324	3600	1360	16
336	5120	600	6.4
325	1560	544	5.6
327	1000	520	4
Mean	6011	1042	14.8
Control sites			
331	56	87	1.6
332	64	112	2.0

Table 3.24: Contaminant concentration in the Ecclesbourne

b) Izquierdo et al. (2012, 2013) published two studies on contamination in the River Trent, of which the Derwent is a tributary. These data are of potential significance to the DVMWHS as, if it is established that the Trent receives sediment elevated in contaminants sourced from the Derwent mining industry, it follows that so too must the valley floor of the DVMWHS. Indeed in the 2012 paper the authors remark: “Site 14 *(8 km downstream from the Derwent confluence)* revealed Pb concentrations close to 400 mg/kg and a Pennine ore/Midlands coal signature (^{206}Pb/^{207}Pb>1.175).’’This isotope signature significantly differs from that measured in the Trent upstream of the confluence (^{206}Pb/^{207}Pb<1.140). Hence, the evidence is that the

Derwent catchment is a significant point source of contamination for the Trent. A word of caution is expressed by the authors that Pb with the apparent Derwent isotope signature may be partially derived from a local power station and railway marshalling yard. Moreover, the Pb distribution in the Trent may also be impacted by river dredging (pers. comm. Izquierdo, 23/05/2014). The 2013 paper gives Cd, Pb and Zn ranges for the Trent study (Table 3.25). In the 2012 paper the authors use the supplied data to highlight the differences between topsoil (0-15 cm) and subsoil (15-30 cm) metal concentrations, and drew the following conclusion "For many of the paired topsoil and subsoil samples the metal concentrations were reasonably similar (Table 3.26). Again, this is likely to reflect the way alluvial soils develop (erosion and re-deposition) and the consistent long term source of major metal contamination (e.g. the Peak District ore deposits)."

Hence, on balance it appears that the Derwent does indeed supply the Trent with contaminated sediment and that this sediment in turn must traverse and impinge on the WHS.

	Topsoils 0–15 cm					**Subsoils 35–50 cm**				
	Min	**p25**	**Median**	**p75**	**Max**	**Min**	**p25**	**Median**	**p75**	**p100**
Total Pb	84	167	241	363	860	43	113	241	507	1282
Total Zn	198	382	572	722	1474	158	290	419	999	2033
Total Cd	0.8	3.8	6.2	8	16	1	2.3	5.3	10	22

Table 3.25: Ranges of Cd, Pb and Zn of the alluvial soils sampled from the Trent Catchment, UK (mg/kg)

Measurements	Sample	Depth (cm)	Total Pb (mg/kg)	E-value	% Pb E
I	2	0-15	124	32	26
I	3	0-15	261	92	43
I	4	0-15	116	58	50
I	5	0-15	108	36	34
I	6	0-15	84	24	28
I	7	0-15	135	52	38
II	8	0-15	237	72	30
II	9	0-15	192	53	27
II	10	0-15	205	36	17
II	11	0-15	221	66	30
II	12	0-15	159	55	35
II	13	0-15	241	44	14
II	14	0-15	373	170	45
III	15	0-15	860	193	22
III	16	0-15	340	80	23
III	17	0-15	212	45	21
III	18	0-15	319	88	27
III	19	0-15	376	74	20
III	20	0-15	547	125	23
III	21	0-15	680	315	43
III	22	0-15	470	78	17
III	23	0-15	302	81	27
III	24	0-15	353	104	30
III	25	0-15	389	100	26
IV	26	0-15	90	11	12
IV	27	0-15	175	48	27

Table 3.26: Part 1: Total, labile and % E values for soils collected from the Trent Catchment

Measurements	Sample	Total Zn (mg/kg)	E-value	% Zn E	Total Cd (mg/kg)	E-value	% Cd E
I	2	408	97	24	7	5.6	80
I	3	536	131	24	8.7	8.2	94
I	4	198	25	13	2.9	2.5	86
I	5	300	59	20	3.1	2.8	91
I	6	234	46	20	3.4	3	89
I	7	308	32	20	4.7	3.3	70
II	8	772	252	33	8	6.5	81
II	9	734	174	24	5.9	3.3	56
II	10	693	174	25	8.1	5.6	69
II	11	572	170	30	6.6	5.8	87
II	12	644	186	29	6.9	5.6	80
II	13	886	324	37	7.9	6	75
II	14	387	85	22	2.9	1.9	65
III	15	1474	412	28	15.9	8.8	55
III	16	677	186	27	5.3	3.7	70
III	17	290	42	14	2.5	1.4	58
III	18	596	175	29	5.1	4.1	79
III	19	696	150	22	6.5	4.2	65
III	20	937	224	24	9.1	6.2	68
III	21	1029	271	26	9.1	7.5	82
III	22	892	228	26	8	5.1	63
III	23	557	126	23	4.2	2.7	64
III	24	572	139	24	5	3.8	75
III	25	709	202	28	6.2	4.6	74
IV	26	235	40	17	0.8	0.5	68
IV	27	376	69	18	1	0.7	74

Table 3.26: Part 2: Total, labile and % E values for soils collected from the Trent Catchment

Measurements	Sample	Depth (cm)	Total Pb (mg/kg)	E-value	% Pb E
I	1	35-50	422	229	54
I	2	35-50	119	18	15
I	4	35-50	95	37	39
I	5	35-50	139	57	41
II	8	35-50	80	30	37
II	9	35-50	43	15	36
II	10	35-50	106	22	21
II	11	35-50	97	34	35
II	12	35-50	132	49	37
II	13	35-50	387	91	24
II	14	35-50	300	169	56
III	15	35-50	1282	273	21
III	16	35-50	328	71	22
III	17	35-50	817	188	24
III	18	35-50	877	192	22
III	22	35-50	1012	159	16
III	24	35-50	592	139	23
IV	26	35-50	123	12	9
IV	27	35-50	241	70	29

Table 3.26: Part 3: Total, labile and % E values for soils collected from the Trent Catchment

Measurements	Sample	Total Zn (mg/kg)	E-value	% Zn E	Total Cd (mg/kg)	E-value	% Cd E
I	1	671	193	29	10.6	8.8	83
I	2	379	63	17	5.8	3.7	63
I	4	158	-	NM	2.9	2.2	75
I	5	208	37	18	1.9	1.5	79
II	8	287	-	NM	2.6	2.2	84
II	9	177	56	32	1.2	0.8	70
II	10	364	-	NM	5.3	3.4	65
II	11	291	89	31	2.4	2.2	90
II	12	570	192	34	3.3	2.3	69
II	13	1479	511	35	18.9	14	74
II	14	288	65	23	2.2	1.6	72
III	15	2033	594	29	21.9	12.9	59
III	16	623	175	28	6.3	4.2	68
III	17	1431	399	28	13	7.8	60
III	18	1117	271	24	9.6	5.4	56
III	22	1668	398	24	16.6	7.7	46
III	24	880	184	21	7.4	5	68
IV	26	294	71	24	1	0.5	53
IV	27	419	55	13	1.1	0.7	65

Table 3.26: Part 4: Total, labile and % E values for soils collected from the Trent Catchment

4. Conclusions and Implications for Heritage Management

- The Derbyshire Derwent's catchment is heavily contaminated by the potentially toxic metals lead, cadmium and zinc. In the upper course this contamination is wind-borne and sourced from the neighbouring industrial conurbations, in particular Manchester. The upper course contamination is currently isolated from the lower reaches of the river system by the intervening reservoir complex. A significant amount of contaminated sediment is held in storage within these reservoirs. Under current management regimes (i.e. retention of the reservoir complex), it is unlikely that significant amounts of sediment will be released from the upper part of the system, even under scenarios of future climatic change. Furthermore, the implementation of changing management practices in the uplands (e.g. reduction of peat erosion through the blockage of gripping systems) may further aid the stabilization of the contaminated sediments.

- Below the reservoirs in the middle course of the Derwent Valley, the contamination mostly arises from historic mining, although there are high background concentrations of zinc and, particularly, cadmium in the shale bedrock. The principal contaminant transport mechanism in the middle course is fluvial, although wind-borne transport was significant, particularly around past (and present) smelter sites. The principal catchment rock within the mining area is limestone, which forestalls the development of acidity normally brought on by the weathering of mine waste materials (i.e. the calcium carbonate increases pH). Hence, the Globally-widespread problem of acid mine drainage is not present in Derbyshire and therefore this is not an issue for the Derwent and its tributaries that drain through the heart of the DVMWHS.

- The DVMWHS straddles the lower course of the Derwent, largely downstream of the area directly affected by mining contamination (i.e. mine and processing sites), although the confluence of the Ecclesbourne brook and river Derwent is within the within the site itself. Hence, any fluvially mobilized contamination must impinge on the site. There is strong evidence that the Derwent contamination signature reaches the Trent, downstream of the DVMWHS and hence this implies that contaminated sediment is likely to be on the move throughout the catchment.

- In general terms, as a function of declining gradients and, hence velocity, the lower course of a river is subject to deposition of the eroded sediment sourced from the steeper, faster flowing upper reaches. Hence, on a gross scale the DVMWHS is potentially at risk from sediment sourced higher in the catchment. Structural controls on the river, such as weirs associated with the mills of the WHS have had a profound impact on river gradients and hence sediment movement thorough the valley system and may lead to the concentration of contaminants above these structures. Any changes associated with these structures, for example, their modification in the light of the Water Framework Directive, may have implications for sediment storage and remobilization.

- Environmental analysis suggests that much of the contamination, particularly that of lead, appears to be locked-up in stable phases and thereby rendered unavailable for plants and animals. Yet there is also evidence that, over time and under the environmental conditions pertaining on the floodplain, this is subject to change with bioavailability increasing. For the middle-and lower-course, the soil contamination data collated in this review was largely sourced from sampling carried out in the late 1970s and 1980s. There is a paucity of contemporary data describing soil contamination for this floodplain and collection of such data would help to understand changing contamination levels) and hence environmental conditions. Such a programme of work would be beneficial to assess and refine the likely impacts of future climate change on the wider landscape and heritage assets.

- While there are some data available on sediment contaminant concentrations in the Derwent's upper and middle courses, there is a paucity of data for the lower course (with the exception of the Ecclesbourne). Based on data we have analyzed for the Derwent catchment and the Trent catchment downstream, and on experience in other mining-contaminated catchments, we can say that it is very likely that the area around the DVMWHS is contaminated with Pb, Zn and Cd arising from historic mining and remobilization of mining-contaminated sediment, and that over time, further contaminated sediment will be mobilized from the Derwent catchment upstream to be deposited in and around the DVMWHS.

- The Pb, Zn and Cd concentrations in the sediment that is already deposited around the DVMWHS, and that will be in the future, may exceed national and international guidelines for soils and human health, suggesting that the sediment may pose risks to ecosystems, infrastructure and human health. The main risks to humans are the inhalation or ingestion of metal-contaminated sediment and if expanded outdoor leisure activities are promoted under a scenario of ameliorating climate, these health risks may well need to be considered (e.g. location of picnicking facilities, stabilization of areas of bare ground, access points to the river).

- The infrastructure of the WHS itself may be at risk in two ways from contaminated sediments. Firstly the remains may be at chemical risk from the contaminated sediment interacting with water on the floodplain resulting in the formation of various types of mineral scale and locally changing the acid/alkaline balance and thereby potentially attacking the fabrics of the heritage buildings themselves. Secondly, if contaminated sediments on the valley floor are actively remobilized (as opposed to passively dispersed), the river may become braided in character, which in turn could result in the erosion/destabilization of heritage assets.

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