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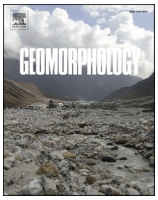

Anthropogenic legacy sediment budgets in heavily disturbed historical mining catchments

Mark Kincey[a,*], Jeff Warburton[b]

[a] *School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK*
[b] *Department of Geography, Durham University, South Road, Durham, UK*

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ABSTRACT

Unregulated metal mining mobilises high volumes of waste sediments to river systems within impacted catchments, increasing sediment yields, contaminating floodplain stores, and profoundly altering long-term patterns of channel planform evolution. However, quantifying the actual scale of historical mine sediment production and dispersal remains a significant challenge, due largely to the variable quality, character and availability of disparate datasets relating to past mining operations. In this study, we reconstruct anthropogenic sediment production associated with historical lead mining between 1700 and 1948 for a globally significant orefield in the North Pennines, UK, that includes the headwater catchments of two major river systems: the River South Tyne and the River Tees. Using a range of interdisciplinary methods including digital terrain analyses and ore-to-waste sediment scaling ratios, we find that mining produced 4.4×10^5 t of lead ore during the study period, but also mobilised an estimated 7.2×10^6 t of associated waste sediment. Approximately 67 % of this waste sediment cannot be accounted for within extant anthropogenic sediment storage landforms within the catchment areas. Surface working using managed water supply (hushing) was the key sediment production process, with 64 % of waste sediment originating from surficial hushing but only 36 % from subterranean mining. The high connectivity of hushes with river channels resulted in minimal (<1 %) long-term sediment storage in the form of hush outwash fans. We find pronounced spatial and temporal variability in legacy sediment production and storage, which has important implications for understanding reach-scale patterns of channel response to historic mining operations.

1. Introduction

Anthropogenic activities, including mining, have impacted on the character and flux of sediments at the global scale (Liang et al., 2021; Syvitski et al., 2022), with estimates suggesting that metal mining alone impacts 164,000 km^2 of river floodplain worldwide (Macklin et al., 2023). The magnitude of sediment mobilisation by mining is so significant that it now parallels equivalent global values for natural geomorphic processes of mass transport (Rivas et al., 2006; Tarolli and Sofia, 2016). Alongside the creation of discrete landforms and deposits of anthropogenic alluvium (Macklin et al., 2014), mining has also generated widespread networks of subterranean structures, which are far larger and more complex than other non-human forms of bioturbation (Zalasiewicz et al., 2014). This global scale of impact has contributed to the suggestion that legacy mine sediments should be included amongst the stratigraphic event markers used in the definition of a proposed Anthropocene epoch (Foulds et al., 2013; James, 2013; Wagreich and Draganits, 2018).

In contrast to many other countries where contemporary or very recent mining activities are leading to widespread present-day environmental impacts (e.g., Mackay et al., 2013), the situation in the UK is dominated by historical mining operations and their legacy effects (Howard et al., 2015). Estimates of historical mining within the UK suggest that approximately 38.5 km^3 of mining-related material, including mineral, overburden and waste, have been mobilised since 1850 (Price et al., 2011). The mobilisation of large volumes of waste sediments during historical mining has had a profound effect on fluvial geomorphology in particular, with increased sediment yields and associated contaminant release dramatically altering impacted catchments (Macklin, 1997).

Studies in mining-impacted catchments across the Earth have demonstrated that the large and often rapid increase in sediment supply

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* Corresponding author at: School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne NE1 7RU, UK.
E-mail address: mark.kincey@newcastle.ac.uk (M. Kincey).

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generated by metal mining can lead to the crossing of geomorphologically significant thresholds (Clement et al., 2017; Davies and Lawrence, 2019; Dethier et al., 2018; Lewin et al., 1983; Pavlowsky et al., 2017). For example, channel transformation due to mine waste inputs typically involves the change from a single sinuous channel of wandering planform to a braided system, caused primarily by aggradation following an increase in sediment supply and triggered by a major flood event. Time series of channel evolution indicates that the initial fluvial response can often be linked to the intensification of mine production (Bertrand and Liébault, 2019; Knighton, 1989; Macklin, 1986b), coupled with natural variability in flood frequency and magnitude (Macklin and Rumsby, 2007; Singer et al., 2013). When the supply of waste sediments persists, through either continued mining or the reworking of earlier anthropogenic legacy deposits, the increase in active gravel floodplain area and braided planform in many of these systems also endures. Typically, channel incision and the rationalisation of the system back to a single channel planform only occurs following the cessation of large-scale mining and an accompanying reduction in sediment supply (Macklin and Lewin, 1989), combined with stabilisation by riparian vegetation (Dawson et al., 2022).

1.1. *Sediment sources and pathways associated with historical mining*

At a catchment scale, mines can therefore be considered as discrete sources within the overall sediment cascade, which are capable of introducing large volumes of sediment of varying character to the wider geomorphic system. Although sediment budget frameworks have previously been used to conceptualise sediment dynamics in formerly mined catchments (e.g., Lewin et al., 1977), these have tended to focus on post-mining erosion processes and so overlook the detail and complexity of anthropogenic processes associated with the historical mining landscape.

Focusing specifically here on historic lead mining, waste sediments were generated, altered, transported and deposited by anthropogenic processes at various stages of the complex mining workflow (Fig. 1; Table S1). For example, waste sediments produced during the initial extraction phase could be stored underground, transported directly to a stream or transported to a surface spoil heap (Palumbo-Roe and Colman, 2010). The ore-bearing material would typically be temporarily stored close to the mine entrance before being transported to a dressing floor for ore processing. The dressing floors could be local to the mine itself or at another centralised processing site. The dressing process to extract the ore resulted in further waste sediments, which would either have been dumped directly in nearby streams or transported to tailings heaps. The ore itself would then be transported to another location for smelting, which would again generate additional waste alongside the actual lead metal. Importantly from a geomorphological perspective, at each of these stages the character of the mined sediments is altered in terms of

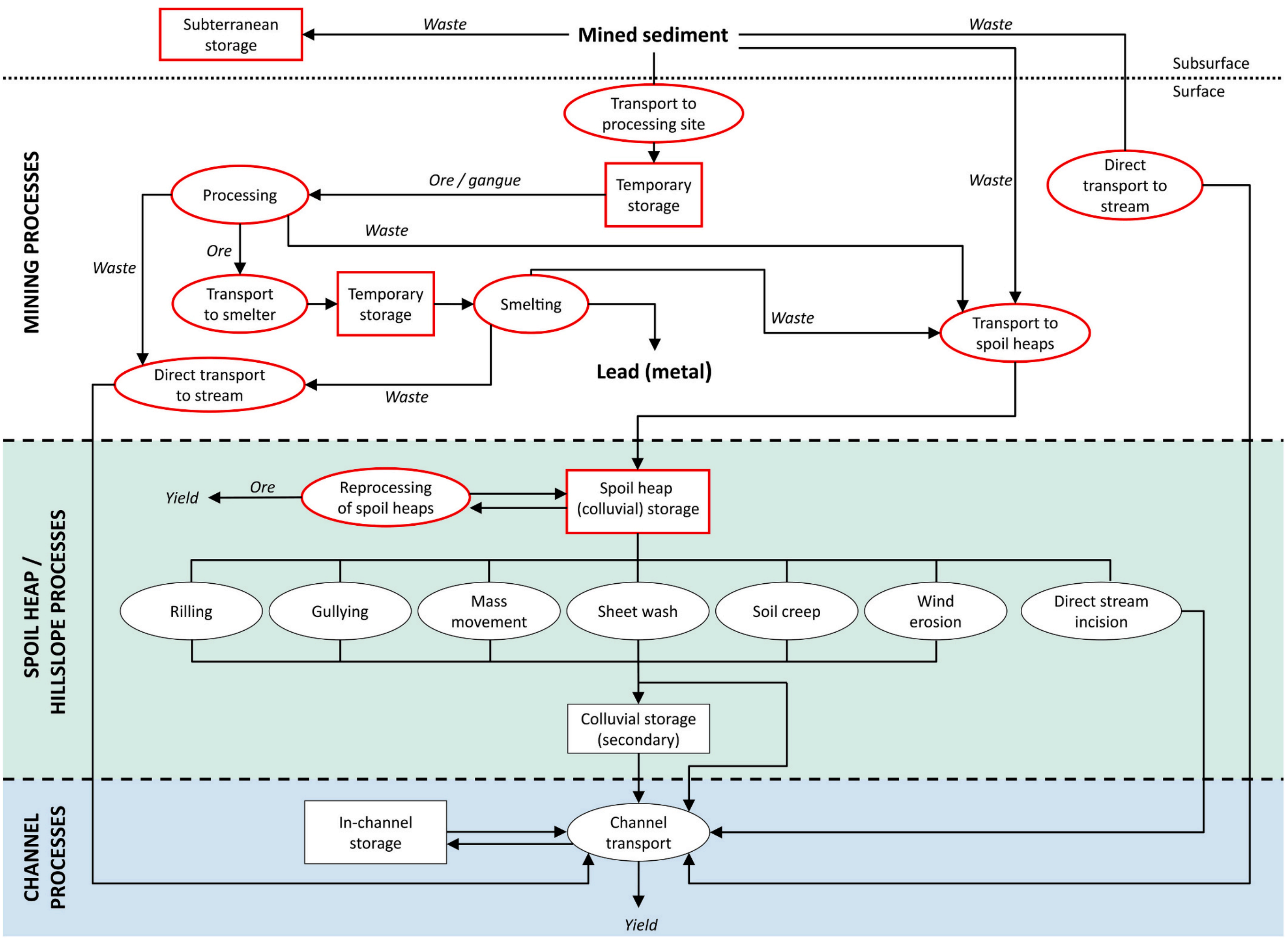

Fig. 1. Conceptual framework for a typical mining impacted upland catchment, showing the key anthropogenic and geomorphic processes and transport pathways for mine sediments. Anthropogenic elements are shown outlined in red, with processes represented as ovals and storage elements as rectangles. The framework is divided into the three main domains present within the overall upland sediment cascade; the mining domain (white), the hillslope domain, including anthropogenic storage elements such as spoil heaps (green), and the channel domain (blue).

its physical and geochemical attributes.

The waste heaps resulting from the dumping of barren rock or processing waste can be considered as storage landforms within the overall sediment transfer system in the mine domain (Fig. 1). The sediments stored within these landforms can then be remobilised after their initial deposition through either anthropogenic reprocessing (Dawson, 1947) or natural geomorphic processes (Toy and Hadley, 1987). A wide range of geomorphic drivers have been identified as leading to the erosion of mine waste heaps, with their occurrence and significance depending on the local environmental context and the specific characteristics of the waste heap (Kincey et al., 2018). Sediment eroded from these waste heaps can then either remain in colluvial storage, and therefore part of the hillslope domain, or enter the channel network and be dispersed as suspended or bedload transport (Fig. 1).

1.2. Reconstructing historical mining-related sediment volumes

The fluvial impacts of mine waste sediments released during the active period of metal mining have already been the focus of considerable attention (e.g., James, 2013; Lewin et al., 1977; Macklin and Lewin, 1989; Miller, 1997). However, many of these studies have tended to utilise ore output statistics as proxy data for understanding associated mining intensities, mainly due to a lack of detailed information regarding corresponding waste sediment volumes. Implicit in this approach is the limitation that actual waste sediment volumes are usually unknown and so linkages between sediment input and channel response cannot be accurately quantified. It also largely overlooks variability in mining techniques and the impact of unsuccessful mining ventures, which may still have generated significant quantities of surface disturbance and waste sediment despite recording minimal ore outputs, or even no ore at all. The use of total mine ore output values as a proxy for sediment release to river channels is further restricted by a lack of consideration of temporal variation in production rates. Individual mine outputs fluctuate significantly through time, resulting in temporal variability in waste sediment production and delivery which has important implications for the mode and rate of channel planform transformations (Trimble, 2012).

Studies that have attempted to directly quantify waste sediment volumes generated by mining have typically been restricted to the analysis of hydraulic mining of alluvial deposits, where initial worked sediment volumes were either actually recorded by the mining companies (Knighton, 1987) or can be calculated from surviving landforms (Nelson and Church, 2012). Quantitative estimates of the scale of sediment release from historical mining operations which involved a combination of hydraulic and deep mining techniques remain very poorly constrained, often being restricted to a relatively coarse spatial resolution and short time series due to the nature of available records (Davies et al., 2018).

This study addresses this gap in understanding by using a sediment budget framework to directly quantify and interpret landscape disturbance and anthropogenic sediment production resulting from both subterranean and surficial historical lead mining. The focus is on an intensively mined area of the North Pennines, UK, a globally significant orefield during the 18-20th centuries and an area that includes the headwater catchments of the River South Tyne and the River Tees, two of the major river systems in Northern England (Kincey et al., 2022). We provide the most detailed assessment to date of spatial and temporal variability in mining intensity within this region, based on a combination of new GIS-based mapping and documentary research, and subsequent estimates of sediment volumes being calculated using a novel integration of ore-to-waste scaling relationships and digital terrain analyses.

2. Study area

2.1. Physical landscape

The focus for the study is an area of 197 km^2 incorporating the catchments of the upper South Tyne, the River Nent and Black Burn, the two major tributaries of the South Tyne, and the upper Tees above Cow Green Reservoir (Fig. 2). This area was one of the most intensively mined regions of the United Kingdom in terms of metalliferous mining, and at its height contributed over 20 % of national production (Kincey et al., 2022). The study catchments share many of the principal physical characteristics found throughout the North Pennine region. Their relatively steep headwater channels, composed of intermittent bedrock and gravel-bed reaches, drain the summits of the Alston Block (maximum elevation 891 m), a coherent geological structural unit forming the core of the North Pennine upland area. The geology of the catchments is dominated by the interbedded limestones, sandstones, siltstones and mudstones of the Carboniferous cyclothems (c. 359–299 MA) (Dunham, 1990). The extensive mineralisation of the orefield is the result of the fracturing of the Carboniferous strata during subsequent regional uplifting, coupled with the convection of early Permian saline waters driven by heat generated from the earlier Devonian Weardale Granite (Stone et al., 2010).

From a fluvial geomorphological perspective, all the catchments have narrow confined channel reaches interspersed with discrete sedimentation zones, many of which show evidence for mining-related river planform change (Macklin, 1997). Previous studies have investigated channel response to historical mining for selected study reaches within the River South Tyne (Aspinall et al., 1986; Macklin et al., 1998; Macklin, 1986b; Macklin and Lewin, 1989; Passmore and Macklin, 2000) and its tributaries the River Nent (Macklin, 1986a) and Black Burn (Macklin, 1997), as well as the River Tees (Wishart, 2004). However, the actual magnitude of mining-related surface disturbance and sediment release has not previously been quantified.

2.2. Historical development of metal mining in the North Pennines

Galena (lead ore) and sphalerite (zinc ore) are the most abundant ore minerals occurring throughout the North Pennine Orefield and have been the focus of much of the historical mining activities, with the galena typically also bearing relatively high levels of silver (Dunham et al., 2001). The earliest documented evidence for lead mining in the area is from the 12th Century AD, (Fairbairn, 1993; Raistrick and Jennings, 1989), although archaeological evidence suggests that active mining extends back considerably earlier (Oakey et al., 2012). Intensification of mining occurred particularly from the late 1600s onwards (Raistrick, 1988; Turnbull, 2006), before peaking during the 19th century, becoming the preeminent ore field in the United Kingdom (Kincey et al., 2022). A combination of international competition and the exhaustion of accessible and high-quality ore bodies then led to the rapid decline and subsequent collapse of the industry in the late 1800s (Burt, 1984; Hunt, 1970). Localised mining persisted through into the mid-20th century but at a much-reduced scale, with lead mining effectively ceasing entirely by 1948 (Kincey et al., 2022).

Mining techniques and approaches changed through time, depending on the expertise and resources available and the accessibility of the mineral vein, often resulting in complex arrangements of surface and subsurface landforms (Fig. 3). Hushing was a widely used technique for both prospecting and mining of shallow mineral deposits within the North Pennines up until the early 19th century (Cranstone, 1992; Fairbairn, 1992). This process involved the controlled release of water to assist the removal of surface deposits and resulted in the creation of characteristic linear gullies, sometimes well over a kilometre in length and several hundred metres wide. By the 1840s, hushing had largely ceased and was usually prohibited in subsequent mining leases due to the damage caused to nearby land (Bainbridge, 1856). Deeper deposits

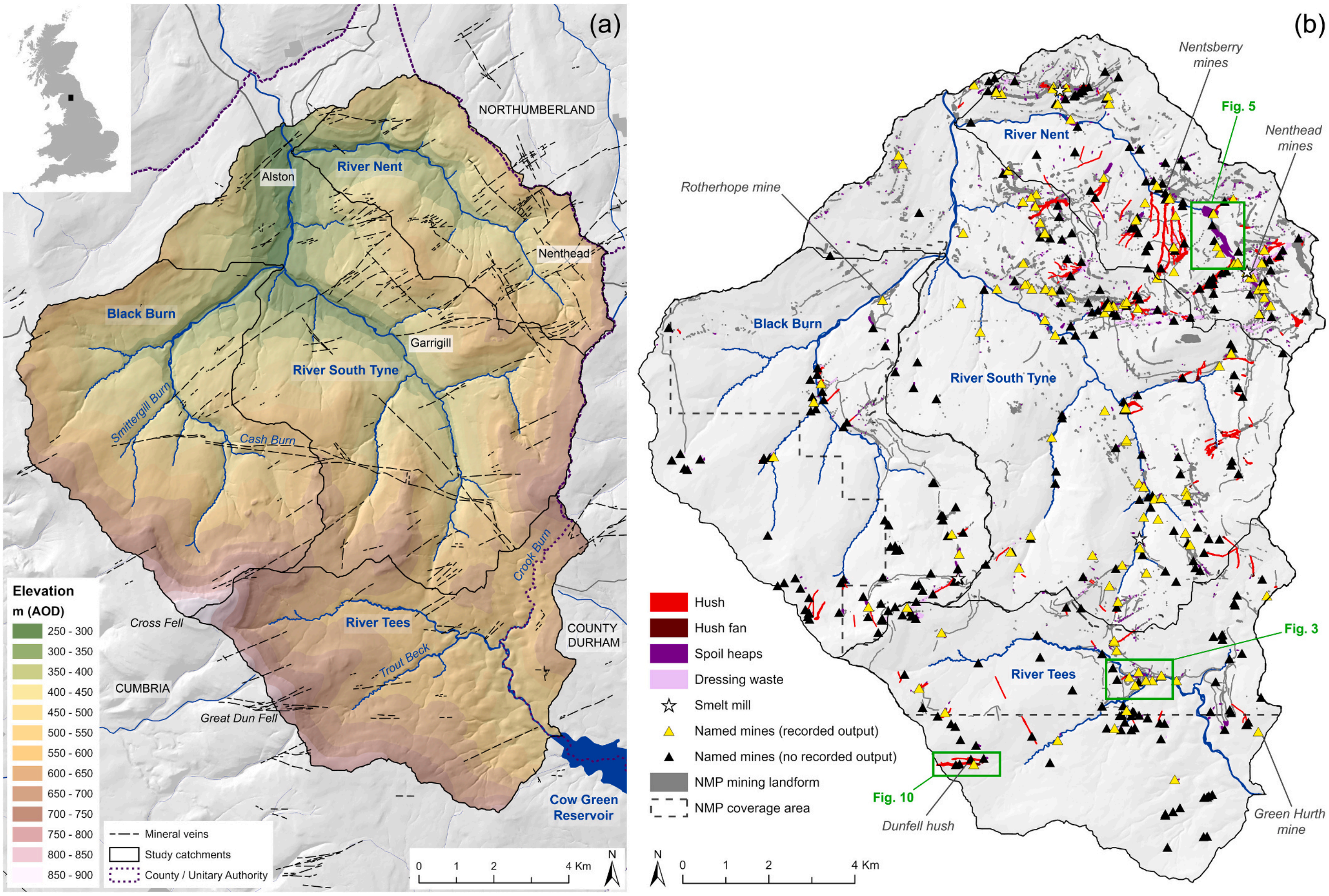

Fig. 2. Location of the study catchments within the North Pennines, UK. (a) Shaded relief elevation map showing the main rivers, catchment boundaries and mapped mineral veins (DEM data © GetMapping 2009). (b) Distribution of named mines and mapped mining landforms (NMP data © Historic England).

were initially mined via vertical shafts sunk to intersect a mineral vein, before horizontal tunnels known locally as 'levels' or 'adits' became commonplace in the 18th century, serving as both drainage conduits and access routes for miners and haulage wagons. The subsequent separation of the lead ore from the country rock and other minerals was achieved through various stages of processing, often using large volumes of running water and so typically occurring close to water courses (Fig. 4).

3. Material and methods

3.1. Characterising the mining landscape

Ore production statistics from mines within the study area were compiled from 1700 to 1948, a period reflecting the significant burgeoning of the industry in the 18th century through until 1948 when lead mining on Alston Moor effectively ceased (Robertson, 2012). The UK's Mining Record Office was established in 1845, meaning that an unbroken annual series of lead production statistics is available from this date until the eve of the First World War in 1913 (Burt and Waite, 1983). Lead production either side of the annual government statistics was reconstructed from a range of other published and unpublished sources relating to ore output from named mines (for full source information see Kincey, 2016). All recorded production data were converted into metric tonnes where necessary, using the conversion factors in Fairbairn (1993).

General information regarding mine companies, the nature of the workings (e.g., opencast) and associated mineral veins were collated from the range of mine gazetteer publications that are available for the North Pennines (Dunham, 1990; Fairbairn, 1993; Fairbairn, 2009; Smith and Murphy, 2011), as well as unpublished (e.g., Hutton, 2002; McAnelly, 2004) and online sources (e.g. Durham Mining Museum, 2014). All mine information and production data were tabulated and geolocated within ArcGIS using a combination of documented grid references and historical Ordnance Survey maps and mine plans.

To directly assess anthropogenic surface landscape disturbance, the distribution of mining-related landforms was also mapped (Fig. 3b). Transcriptions of industrial archaeological landforms for ~80 % of the study area had already been generated as part of Historic England's National Mapping Programme (NMP), based on interpretation of a combination of aerial photography and airborne laser scanning data (e.g., Oakey et al., 2012). Gaps in NMP data coverage were filled using additional detailed mapping of features visible on comparable airborne datasets, generating a consistently mapped dataset across the entire study area.

3.2. Quantifying mining-related sediment sources

3.2.1. Ore-to-waste scaling relationship

To better understand how ore output relates to waste sediment ratios, we used available examples of mine records in the North Pennines which document both the mass of ore produced and the total subterranean distance that was mined. This dataset includes a group of 37 mines in the Upper Wear catchment, adjacent to the study area, for which both total ore production and total worked distance have been recorded (Dunham, 1944), combined with a series of nine historical mine abandonment plans from within the project study area. These abandonment plans were scanned and scaled appropriately within ArcGIS, before being digitised as a series of vector features. The combined length of the

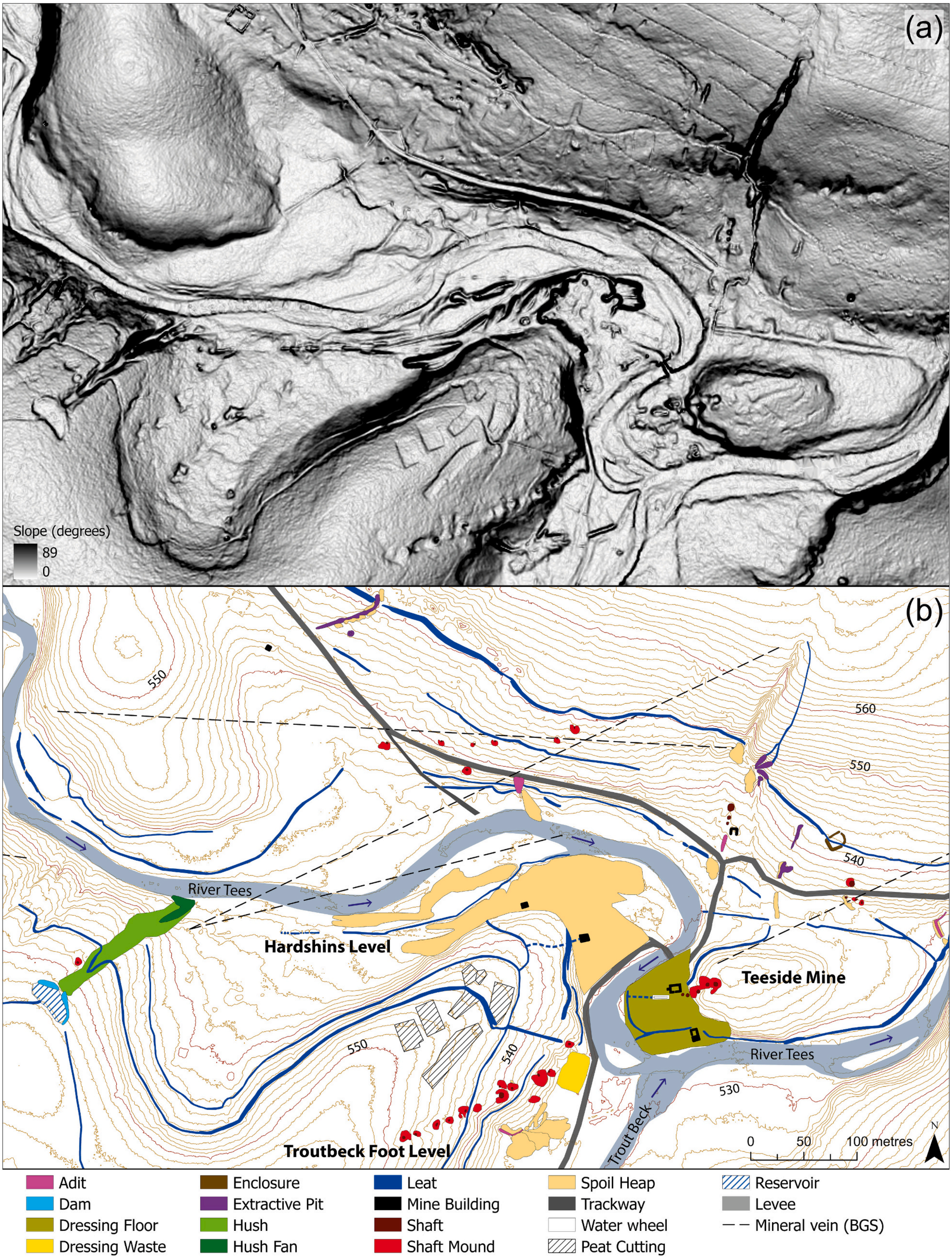

Fig. 3. Teeside Mine, upper Tees catchment, Cumbria. (a) Slope derivative from a 1 m resolution airborne lidar digital elevation model (Lidar Data from the NERC ARSF are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC)). (b) Mapped mining-related landforms for Teeside Mine and its immediate surroundings (data are adapted from Historic England's NMP results). This location exhibits a complex arrangement of surface and subsurface mining landforms, all in close proximity to the main River Tees and its confluence with Trout Beck.

Fig. 4. Historical photograph (c. late 19th century) of Smallcleugh Mine, Nenthead, showing miners loading ore from the bouse teams (storage bins) ahead of ore dressing work at Rampgill Mill. The extensive disturbance and mine waste tips throughout the upper Nent catchment can be seen in the background, with the River Nent itself channelised immediately alongside the track to the left of the photograph. Processing waste from this period of mining was often deposited close to the river or even discharged directly into the channel. Image © The Simon Danby Collection, 2021.

digitised features on each plan was then calculated and used to represent the total mined distance.

Converting the linear distances to volumes was achieved using the upper and lower cubic fathom estimates proposed by Dunham (1944), which suggest that mine tunnel fathoms typically varied between 6 ft. x 6 ft. x 3 ft. (3.06 m^3) and 6 ft. x 6 ft. x 4 ft. (4.08 m^3). These values were used to generate upper and lower tunnel volumes that were subsequently adjusted using standard average bulk densities for rock (2.65 t m^{-3}) and Pb (11.36 t m^{-3}) to obtain the total estimated excavated rock mass. The regression equation produced by comparing the documented ore output to the mean estimated waste rock mass was then used to approximate the amount of waste generated by the other mines in the study area ($R^2 = 0.73$, p-value ≤ 0.001; Table S2).

3.2.2. *Quantification of sediment volumes for surface mining landforms*

The documentary sources used to reconstruct mine outputs typically do not include earlier opencast mine workings (e.g., hushes) or the amount of waste material stored in surface landforms (e.g., spoil heaps). Digital terrain analysis using airborne laser scanning (ALS) data was therefore used to construct a more complete and representative mining-related sediment budget which incorporates these surface landforms (Fig. 5).

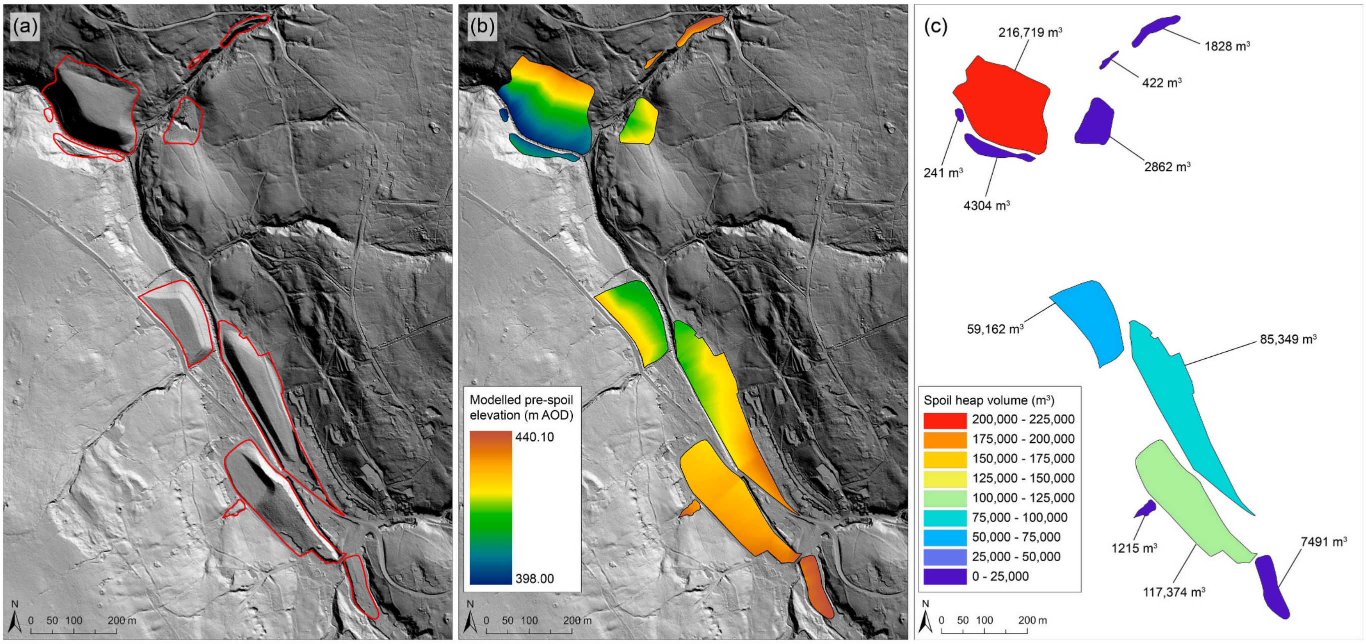

Fig. 5. Spoil heap volume calculation workflow for an area of the upper Nent, showing (a) mapped spoil heaps overlain on 1 m resolution airborne lidar hillshade model, (b) modelled pre-spoil elevation surfaces, and (c) resulting volumetric estimates for each individual spoil heap. Airborne lidar data © Historic England.

Hush volumes were calculated through the extraction of 1 m spaced ALS-derived elevation points around the perimeter of the mapped hush and the subsequent interpolation of a modelled pre-hush land surface. The difference between the modelled pre-hush surface and the modern post-hush terrain was then used to calculate the volume removed by the hushing process in each case. A similar approach has been successfully applied to analyse hydraulic mining landforms along the Fraser River, British Columbia (Nelson and Church, 2012) and the Sierra Nevada of northern California (James et al., 2019; Nakamura et al., 2018), as well as to reconstruct historical elevation changes across urban areas using nineteenth century topographic maps (Hil et al., 2020). Due to gaps in ALS coverage within the study area, 78 out of the total 120 mapped hushes (65 %) were directly included in this analysis. The regression equation summarising the relationship between the quantified hush areas and volumes was therefore used to provide an estimate of the volumes for hushes outside of the ALS coverage ($R^2 = 0.89$, p-value ≤ 0.001; Table S2).

Since hushing involves the removal of surficial sediments as well as rock deposits, converting hush volumes into approximate sediment mass values required estimates to be made of the depth and character of the overburden for each individual hush. Information regarding the distribution of overburden deposits was obtained from available superficial geological data, which allowed areas to be categorised as either till, peat or colluvium. In the absence of any local field data, all overburden layers were assigned a standardised depth of 2 m and average bulk density values applied based on suggested regional characteristics (Baynes, 2012; Jarvis, 1984). A dry bulk density value of 1.8 t m^{-3} was assigned to till deposits, 0.078 to peat, 1.3 to colluvium and 2.65 to the underlying rock.

The volume of mine waste retained within storage landforms was calculated based on the mapped extent of waste heaps, dressing waste and hush deposition fans. The pre-mining topography of waste heaps and hush fans was again reconstructed based on interpolation between ALS-derived elevation points constructed around the perimeter of each individual landform (Fig. 5). However, in this case, the pre-mining topography was then subtracted from the modern topography to calculate the volume of sediment stored. The resulting area-volume regression equations could then be used to estimate the volumes of the remaining waste heaps ($R^2 = 0.88$, p-value ≤ 0.001) and hush fans ($R^2 = 0.73$, p-value ≤ 0.001) for which no ALS data were available (Table S2).

Broader spreads of processing (dressing) waste were also mapped but their volume could not be quantified in the same way due to their lack of clear topographic expression relative to the surrounding land surface. A conservative depth estimate of 0.5 m was therefore applied to calculate the volume of dressing waste, based on observations of exposures visible during field surveys. Waste landform volumes were converted into approximate mass values using a bulk density of 1.755 ±0.21 t m^{-3}, based on an average of published bulk density measurements taken from six comparable mining areas (DeLong et al., 2012; Huang et al., 2012; Martín-Moreno et al., 2013; Nelson and Church, 2012; Quille and O'Kelly, 2010; Sheoran et al., 2010).

3.2.3. *Estimating waste sediment mass generation during ore smelting*

Quantifying the efficiency of the smelting process is possible for the period 1845–1913 due to the concurrent recording of both lead ore and lead metal values by the government mineral statistics. The average percentage of lead metal extracted from lead ore for the study area mines during this period is 74 %, with that for the entire UK being only slightly lower at 73 % (Burt, 1984). Smelter efficiencies for earlier periods are generally poorly constrained but some indicative figures have been recorded (e.g. Dunham, 1944). The total annual mine ore outputs were therefore adjusted to equivalent lead metal totals using averaged recovery values of 58 % for the period 1700–1799 and 74 % for the period 1800–1948. The difference between the total ore output and the estimated lead metal total was then taken to be the resulting mass of waste sediment resulting from the smelting process.

4. Results

4.1. *Spatial variability in mining-related landscape disturbance*

A total of 465 named mine workings were identified within the study area, including 156 (34 %) within the South Tyne catchment, 128 (28 %) within the Nent, 101 (22 %) in the Tees and 80 (17 %) in the Black Burn area (Fig. 2; Table S4). Normalising for catchment area shows the Nent is the most intensively disturbed catchment relative to its size, with an average of 4.36 named mines per km^2. The Tees and South Tyne have similar densities, with 2.19 and 2.17 named mines per km^2 respectively, with the Black Burn catchment having an average of only 1.62 named mines per km^2. The mapping of individual mining landforms is also useful in developing understanding of the overall distribution and intensity of anthropogenic surface disturbance. The percentage of the catchment area impacted by mining was much greater in the Nent (4 %) than in any of the other catchments (≤ 1 %) or the study area as a whole (1.5 %).

Of the total number of named mine workings only 141 (30 %) actually have any recorded ore output associated with them, based on the available documentary evidence. A lack of documented output could indicate that these were unproductive mine trials, that their output has been aggregated into recordings from another centralised mine location, or that the documentary evidence for their output has not survived (Burt and Waite, 1983). In the absence of further data, the quantitative analysis of mine outputs therefore has to work on the assumption that the ~30 % subset represents the most significant mines in terms of production and therefore impact, although this point will be considered further in Section 5.

4.2. *Temporal variability in mine production, 1700–1948*

The total recorded lead ore output from all named mines within the study area during the period 1700–1948 was $\sim 4.4 \times 10^5$ t, representing an average of ~1800 t of lead ore per year. The Nent catchment contributed the majority of this ore output (59 %), followed by Black Burn (17 %), the South Tyne (16 %) and the upper Tees (8 %) (Table S4). When adjusted for catchment size this again demonstrates the Nent to be the most heavily impacted area, with an average output of ~8800 t km^{-2}, compared with ~1600 t km^{-2} for Black Burn, ~945 t km^{-2} for the South Tyne and ~620 t km^{-2} for the upper Tees.

The time series of mine outputs shows clear peaks in production in c.1820 and 1845–55, with the mines producing a combined total of >8500 t of Pb in a single year at their zenith in 1849 (Fig. 6). A marked increase in production then occurred from the second half of the 18th century onwards, likely due to both the burgeoning of the industry and the increased survival of documentary records after this time (Fig. 6). A sharp decline in the 1870s saw production from named mines drop to ~2200 t in 1874, before rising again slightly in the 1880s. In contrast, output from records which relate to the Alston Moor area, but which could not be ascribed to individual mine locations, show a major additional peak in production between c.1882 and 1902 (Fig. 6). From 1885 onwards the recorded output again fell sharply, reaching a low of only ~370 t in 1909. Despite a recovery during the 1920s and early 1930s, annual production had decreased by 1939, with lead mining effectively ceasing in the area by 1948.

When analysed at the scale of individual mines, the intensity of ore production varied considerably through both space and time (Fig. 7). Spatially, while the high ore output in the upper and middle Nent comes from a cluster of active mines, the highest outputs in the lower Black Burn and lower Tees catchments derived from very high producing individual mines (Rotherhope Fell and Green Hurth mines respectively). Additional concentrations of moderately high producing mines are also located along the higher order tributaries on the eastern slopes of the

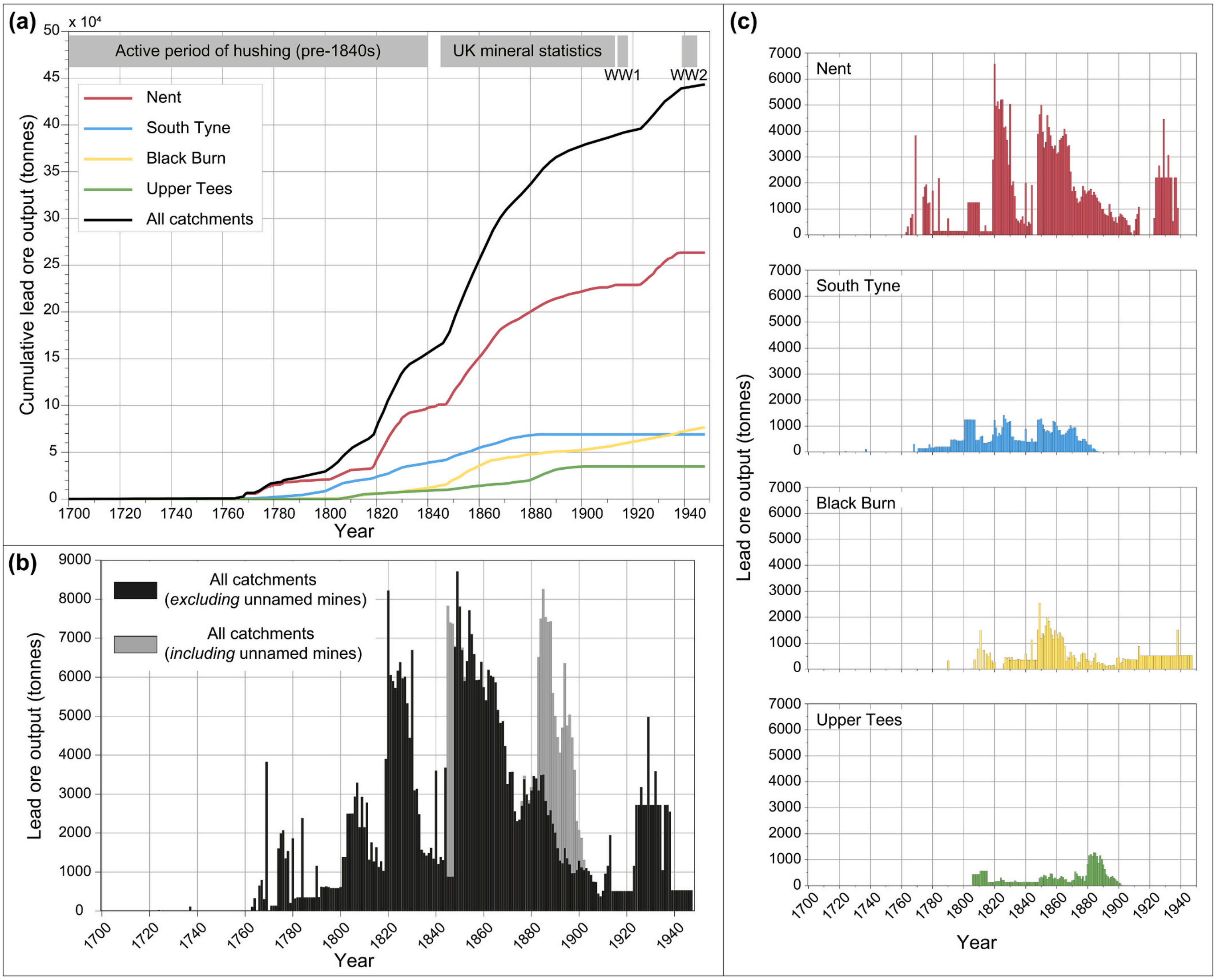

Fig. 6. Cumulative annual lead ore output by individual catchment area for the period 1700–1948 (a), and temporal variability in lead ore output displayed as histograms for the overall study area (b) and by individual catchment area (c). Key periods in the time series are indicated by grey bars, including the period in which hushing was permitted within Alston Moor (pre-1840s), the period of official governmental recording of mineral statistics (1845–1913), and the timing of the two world wars. Since ore output from hushing is not recorded in documentary sources, the output from this period is likely to represent an underestimate of actual totals. For the output from the total study area shown in (b), additional production peaks relating to general mine output records with no specific location are also included for reference (grey bars), alongside the main dataset used in this study (black bars).

middle South Tyne valley, adjacent to the lower Nent around Blagill, on the high ground marking the watershed between Black Burn and the Tees, and to a lesser extent along the valley floor of the upper South Tyne and the confluence of the Tees and Trout Beck.

The time series maps show that production during the 18th century was almost entirely restricted to the South Tyne and Nent catchments (Fig. 7). The early- to mid-19th century saw output intensify both in terms of volume of extracted material and the spatial extent and number of productive operations. The period between 1850 and 1874 recorded both the highest total combined ore output (136,092 t) and the highest frequency of productive mines ($n = 100$). The decline of the industry is clearly evident from 1875 onwards, with a reduction in total ore output and the centralisation of remaining production into a reduced number of productive mines (Fig. 8). Although overall production remained relatively high compared to pre-18th century levels, only six mines recorded ore output between 1900 and 1924, dropping to just two mines for the final years of the lead industry until 1948.

4.3. *Estimating the magnitude of waste sediment outputs*

4.3.1. *Waste estimates from documented mine outputs*

When the regression equation derived from the direct comparison of ore outputs and total mined distances (Section 3.2.1) is applied to all mines within the study area, an estimated total mine waste output of $\sim 2.56 \times 10^6$ t is obtained (Table 1). Including combined ore outputs from all mines this is equivalent to a total mined development amount of $>3 \times 10^6$ t, meaning that waste sediments represent ~85 % of the estimated excavated mass.

At catchment-scale, the Nent has the highest estimated waste sediment output ($\sim 1 \times 10^6$ t), followed by the South Tyne ($\sim 9.7 \times 10^5$ t), the upper Tees ($\sim 4.3 \times 10^5$ t) and Black Burn ($\sim 2.6 \times 10^5$ t) (Table 1). This ranking of catchment impacts is noticeably different from the original ore output values (see Section 4.2 and Table S5). For example, Black Burn had the second highest recorded ore production but has the lowest estimated waste sediment yield. Similarly, the South Tyne had the second lowest recorded ore output but the second highest waste sediment estimate. This reflects the fact that even mines producing a

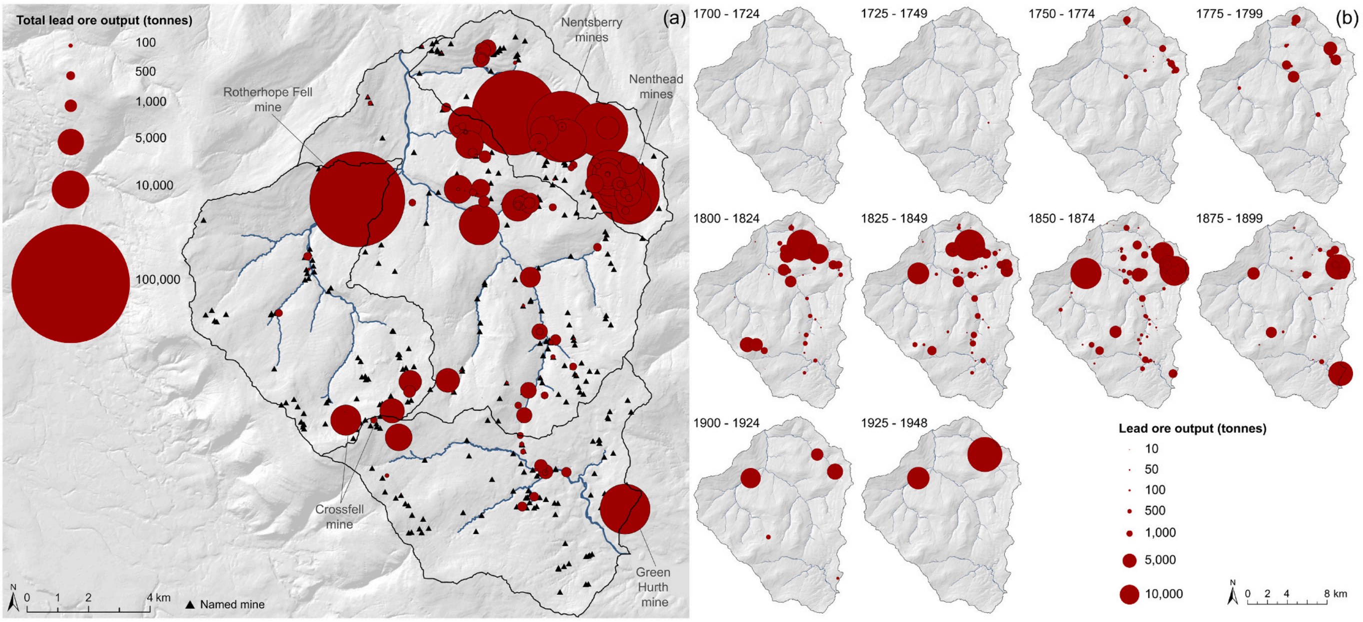

Fig. 7. Spatio-temporal variability in lead ore output from named mines, shown as (a) total documented lead ore output from all named mines for the period 1700–1948, and (b) 25-year interval time series of ore outputs showing changing spatial patterns of mining impacts through time.

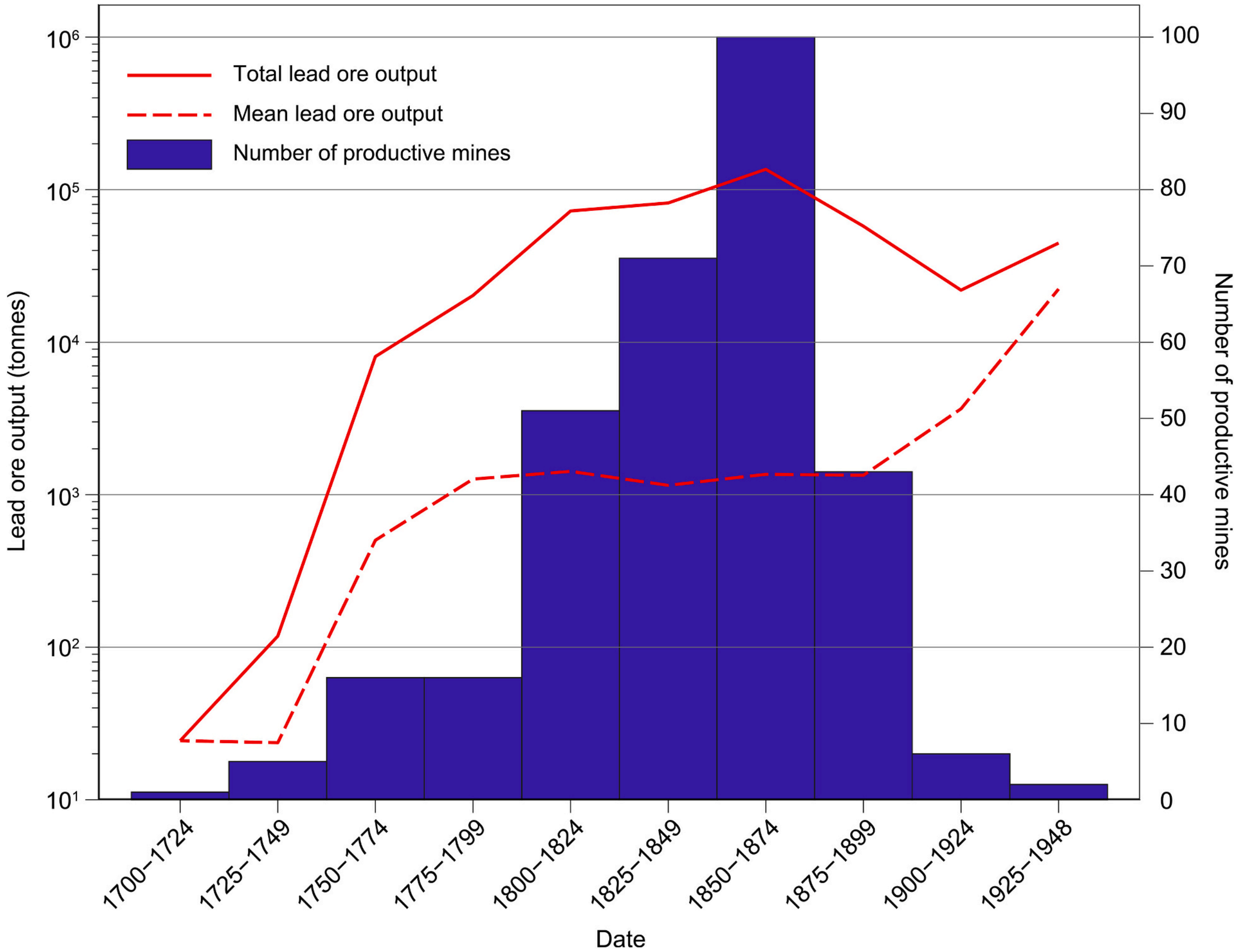

Fig. 8. Number of operational mines and lead ore output per 25-year period between 1700 and 1948. The spread of mining and associated mining impacts across a large number of mines can be seen during the mid-19th century, followed in the late 19th to early 20th century by centralisation of production into a reduced number of mines.

Table 1
Waste sediment extraction and sediment storage totals.

Catchment	Waste sediment based on production statistics (t)	Sediment output from hushing (t)	Total waste output (t)	Spoil heap storage (t)	Dressing waste storage (t)	Hush fan storage (t)	Total storage (t)	Total storage as % of total waste output (%)	Total unmeasured residual (t)	Residual as % of total waste output (%)
Nent	1,009,757	2,849,055	3,858,812	1,382,450	169,402	4126	1,555,978	40	2,302,834	60
South Tyne	971,291	934,752	1,906,043	433,280	45,623	9096	487,999	26	1,418,044	74
Black Burn	186,813	179,669	366,483	97,019	62,299	8414	167,732	46	198,751	54
Upper Tees	390,464	650,812	1,041,275	126,373	32,853	3678	162,904	16	878,371	84
Total area	2,558,325	4,614,288	7,172,613	2,039,121	310,176	25,313	2,374,610	33	4,798,003	67

minimal amount of lead ore would still typically have had to excavate a substantial volume of rock before a mineral vein was encountered, meaning that even relatively barren mines could generate significant yields of waste sediment.

4.3.2. Surficial working and hydraulic mining (hushing)

The total mass of material estimated to have been mobilised through hushing was ~4.6×10^6 t. When analysed by individual catchment it is again clear that the impacts were greatest within the Nent, with a total of ~2.8×10^6 t from hushing within this area alone (62 %) (Fig. 9). The other three catchments were substantially less affected by hushing, with ~9.3×10^5 t for the South Tyne (20 %), ~6.5×10^5 t for the upper Tees (14 %) and ~1.8×10^5 t for Black Burn (4 %).

The magnitude of impact of hushing was not evenly distributed within each catchment, with a relatively small number of very large hushes dominating the dataset (Figs. 9 and 10). For example, 34 hushes (28 %) have estimated sediment totals of <1000 t, while 64 hushes (53 %) have outputs <5000 t. In contrast, the ten largest hushes together comprise 69 % of the entire hush sediment total, with six of these being within the Nent catchment and two each for the Tees and South Tyne. As an example, Dowgang Hush in the upper Nent catchment has an individual estimated mass value of ~9.1×10^5 t; almost equivalent to the hush total for the entire South Tyne area and more than that for the upper Tees and Black Burn combined.

Only 38 hushes had visible fan deposits at their outlets, representing just 32 % of the total inventory of 120 hushes. The combined mass of sediment stored in these fans was calculated to be ~25,300 t, equivalent to <0.55 % of the total mass estimated to have been mobilised from the hushing process across the overall study area (Fig. 10). Although there were slight variations between areas, fan storage of mobilised hush material did not exceed 2 % of the sediment production total for any of the individual catchments.

4.3.3. Additional waste from ore smelting

Estimates of smelter efficiency (Section 3.2.3) suggest that ~3.2×10^5 t of lead metal and ~1.2×10^5 t of associated waste were obtained from the total ore output recorded for all study area mines during smelting. The equates to ~7.3×10^4 t of smelter waste from mines in the Nent catchment, ~2.0×10^4 t from Black Burn and the South Tyne, and 9.2×10^3 t from the upper Tees. Although these results provide an indication of the approximate amount of smelter waste that originated from mines within each of the study catchments, it does not necessarily mean that the waste was actually deposited in these same locations. There would have been a preference to minimise transport costs by using a smelt mill as close to the processing floors as possible but there were several historical reasons why this did not always occur, especially relating to who held the lease for the mine and what restrictions, if any, had been placed on the sale of the ore (Fairbairn, 1993). A total of 24 smelt mills across Northern England are known to have received processed ore from the mines considered here, only four of which are

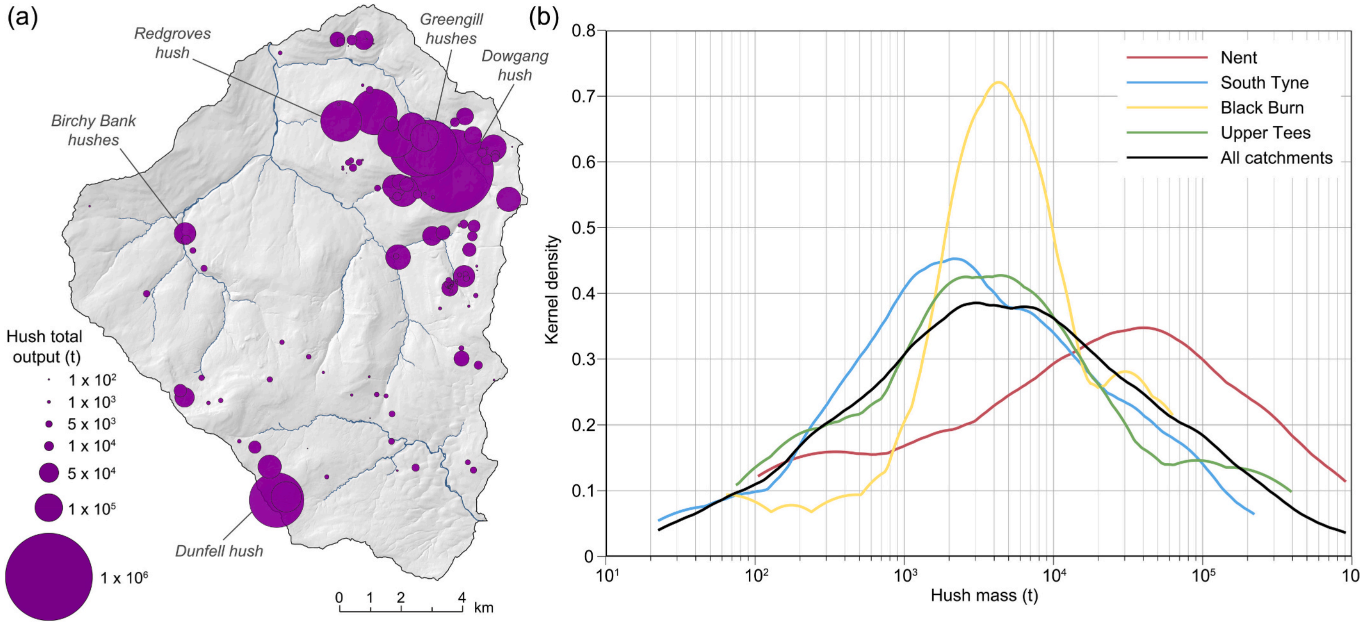

Fig. 9. Spatial variability in hushing impacts across the study catchments. (a) Distribution of mapped hushes, displayed as proportional symbols representing the estimated total sediment output from each hush in tonnes. (b) Kernel density curves displaying the distribution of hush magnitude (mass in tonnes) for each of the catchment areas.

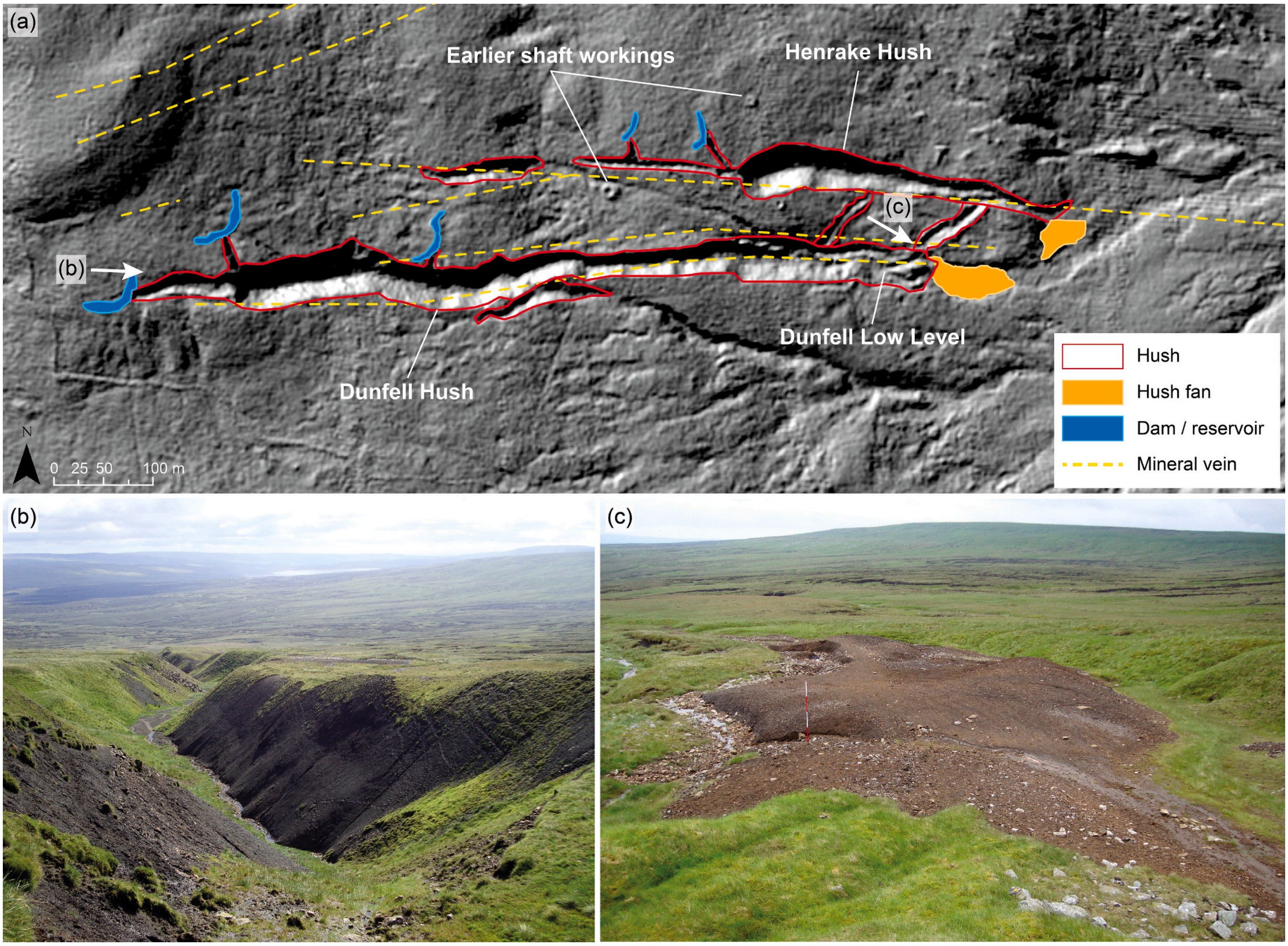

Fig. 10. Landscape impacts of hushing in the upper Tees catchment. (a) Airborne lidar hillshaded DEM of Dunfell and Henrake hushes, located close to the summit of Great Dunfell. The main hush channel measures nearly a kilometre in length and over 50 m wide in places, and displaced an estimated 394,000 t of material. (Lidar Data from the NERC ARSF are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC)). (b) Photograph of Dunfell Hush, facing east. The scale of impact of the hushing process on the local landscape can be clearly seen in the foreground. Cow Green Reservoir, the lowest elevation in this study catchment, can be seen at the middle top of the photograph. (c) Photograph of deposition fan at the outlet of Dunfell Hush (facing south-east). The stream to the left of the fan is one of the headwater tributaries of Trout Beck, which joins the River Tees ~4.5 km downstream. The size of the deposition fan is minimal in comparison to the amount of sediment that must have been mobilised during hushing, indicating how effective the hushing process was and how connected hushed sediments were with the river channels.

actually located within the study area itself (Fairbairn, 1993; Fairbairn, 2009; Smith and Murphy, 2011) (Fig. 2). Although this means that the deposition of the estimated smelt waste cannot be linked to a specific spatial location, even at the scale of an individual catchment, the waste totals involved here are small in comparison to other elements of the sediment budget, equivalent to just 1.67 % of all other waste sediment inputs, and so the overall impact is minimal (see Section 4.3.5).

4.3.4. *Significance of anthropogenic sediment storage landforms*

A total of 999 waste heaps were recorded within the study area, including 483 (49 %) within the South Tyne catchment, 353 (35 %) for the Nent, 100 (10 %) for the Tees and 63 (6 %) for Black Burn (Fig. 2). The distribution of the waste heaps predictably shows marked similarities to the spatial distribution of named mines. The total estimated mass of sediment stored in waste heaps across the entire study area combined is ~2.0×10^6 t. The majority of this is located within the Nent catchment, with a total of ~1.4×10^6 t, representing 68 % of the total waste heap storage. The South Tyne has the second highest total with ~4.3×10^5 t (21 %), followed by the Tees with ~1.3×10^5 t (6 %) and Black Burn with ~9.7×10^4 t (5 %).

Dispersed dressing waste deposits covered a total area of ~3.5×10^5 m^2, equivalent to an estimated ~3.1×10^5 t of sediment. Despite being the smallest catchment, the Nent again had the highest amount of waste with ~1.7×10^5 t (55 %), followed by Black Burn with ~6.2×10^4 t (20 %), the South Tyne with ~4.6×10^4 t (15 %) and the upper Tees with ~3.3×10^4 t (10 %).

4.3.5. *Unmeasured residual between production and storage volumes*

The total waste production estimate for the entire study area is ~7.2×10^6 t, compared to a total sediment storage estimate of ~2.4×10^6 t (Table 1; Fig. 11). This suggests that the mine wastes stored in surface sediments represent only ~33 % of the total estimated waste generated by the mining operations, with the remaining ~4.8×10^6 t (67 %) being unaccounted for. It should be noted that the estimated waste totals from the smelting process (~1.2×10^5 t) have not been included in this residual calculation due to the difficulties in assigning smelt waste to specific catchment areas. However, when the estimated waste outputs from smelting are included in the sediment budget calculations, the residual total only alters by ~0.5 %, resulting in an estimated ~32 % of total waste being held in storage within the study catchments.

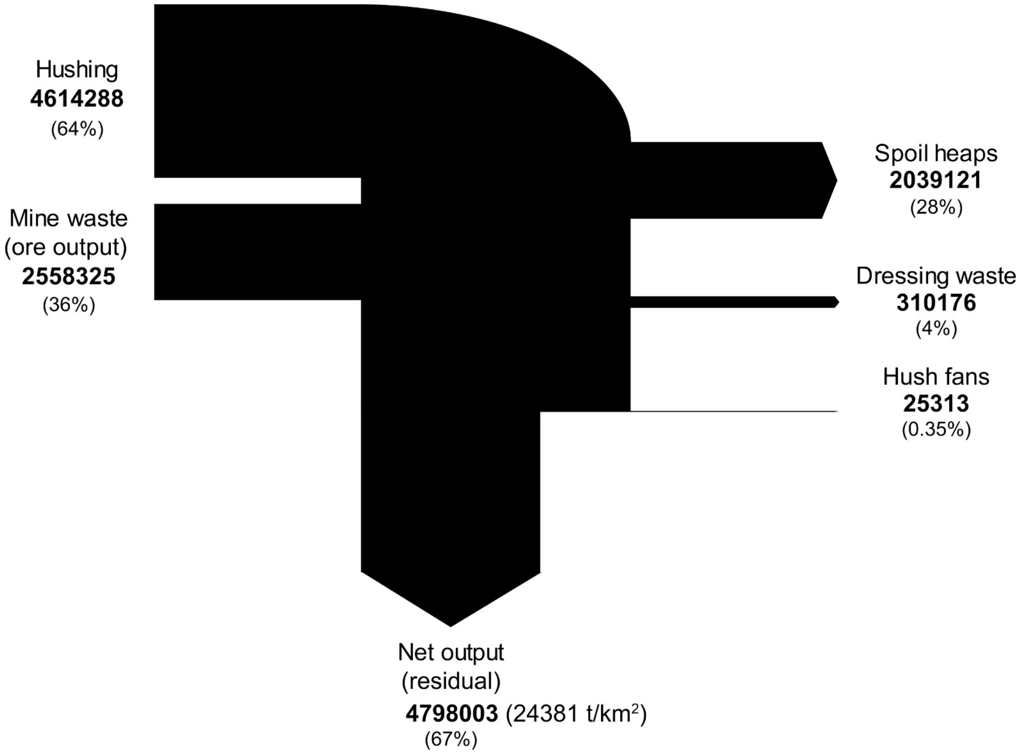

Fig. 11. Anthropogenic sediment budget representing the estimated magnitude of mining-related sediment production and storage processes for the entire study area during the period 1700 to 1948. Inputs are shown on the left and storage components on the right, with the thickness of the bars for each component being proportional. All values in bold are in tonnes. Percentage values relate to the proportion of the total sediment inputs.

There are, however, some notable differences between the residual proportions when analysed by individual catchment area (Table 1; Fig. 12). The Black Burn catchment has the highest proportion of mine wastes stored in depositional landforms (46 %), with only ~2×10^5 t of unaccounted for waste. The Nent contains the second highest proportion of mine wastes stored as surface sediments (40 %) but because of the high output for this catchment it also has the highest amount of unaccounted for waste (2.3×10^6 t). The depositional landforms within the South Tyne catchment represent 26 % of the total mine waste, equating to 1.4×10^6 t of unaccounted for waste material. The Tees has the lowest proportion of waste stored as surface sediments (16 %), meaning that 84 % of the waste (8.8×10^5 t) remains unaccounted for within the catchment area.

An important additional point to consider in this analysis is the relationship between the different types of mine workings and the mapped storage landforms. The overwhelming majority of spoil heaps and dressing waste will relate to mining via subterranean level, small-scale opencast workings or the waste from secondary dressing processes. In comparison, hushes are rarely associated with large spoil heaps due to the nature of the extraction process involved. This means that the spoil heap and dressing waste totals are actually more usefully compared to the estimated waste sediment totals based on the mine ore outputs and the hush sediment totals relate more specifically to only the hush fan deposits. When analysed in this way, the waste landforms associated with subterranean level mining account for ~92 % of the total mine waste estimated from the ore outputs. In contrast, sediment deposited in hush fans comprises only ~0.55 % of the amount produced during the hushing process.

Analysis of the equivalent results for the individual catchments again reveals a high degree of variability between areas. The Black Burn catchment spoil heap and dressing waste storage accounts for 85 % of the ore output waste total for this area, while the values for the South Tyne and Tees are 49 % and 41 % respectively. In contrast, the sediment storage total for the Nent is actually 54 % higher than the total amount of waste estimated based on the ore outputs from mines within this catchment. Likely reasons for this difference in production and storage estimates will be considered in more detail in Section 5. Sediment stored in hush outlet fans comprises <1 % of the material estimated to have originally been mobilised through hushing for the Nent, South Tyne and Upper Tees catchments. The storage total for Black Burn is higher due to the presence of a number of relatively large fan deposits in the middle reaches of the catchment, although even here the value is <5 % of the total hush output estimate.

5. Discussion

5.1. Sediment production processes and storage

Mining within the four study catchments resulted in ~4.4×10^5 t of lead ore being produced during the period 1700–1948 (Table S5), but also mobilised an estimated 7.2×10^6 t of waste sediments when all mining processes including hushing are jointly considered (Table 1). This is equivalent to a sediment mobilisation rate of 146.8 t km^2 a^{-1} and indicates that documented lead ore output only represents ~6 % of the total mass of material potentially mobilised by mining in the area. This discrepancy between the recorded lead ore totals and the associated waste sediment totals demonstrates the limitations of only using documented mine outputs when reconstructing the anthropogenic legacy sediment contributions from historic metal mining. A key point here being that unproductive mines could still generate considerable volumes of waste sediments that would result in long-term legacy impacts to the surrounding landscape.

Of the total amount of sediment mobilised by mining, ~4.8×10^6 t (67 %) is not accounted for by extant sediment storage landforms within the catchment areas and is assumed to have been transported downstream. In their analysis of Holocene fluvial sediment storage along the South Tyne downstream of the present study area, Passmore and Macklin (2001) estimated that ~1.2×10^6 m^3 of sediment was stored

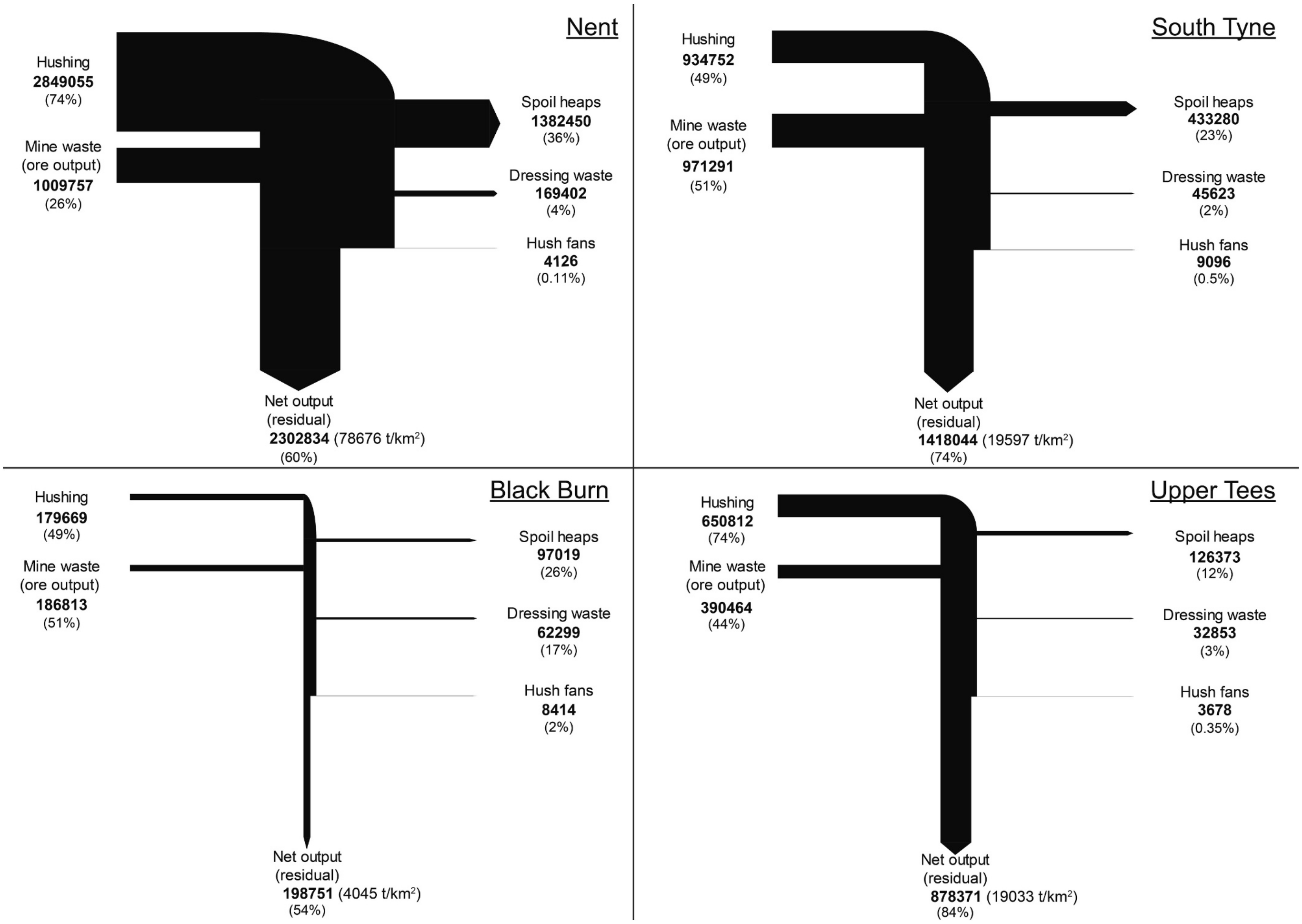

Fig. 12. Anthropogenic sediment budgets for each of the four study catchments, representing the estimated magnitude of mining-related sediment production and storage processes during the period 1700 to 1948. Inputs are shown on the left and storage components on the right, with the thickness of the bars for each component being proportional. All values in bold are in tonnes. Percentage values relate to the proportion of the total sediment inputs for each particular catchment.

within floodplain deposits dating from 1660 CE to present, broadly coincident with the period covered by the present study. Assuming a standard density for sand and gravel of 1.65 kg/m^3, this is equivalent to ~2.03 × 10^6 t of sediment, which is approximately 52 % of the residual sediment estimated by this study to have been mobilised by mining from the catchments draining into the lower reaches of the South Tyne (i.e., the upper South Tyne, Black Burn and River Nent). The implication is that much of the stored floodplain sediment could be from mining-related sources, which is consistent with observations of high metal concentrations in sediments within the wider catchment (Macklin, 1986b).

The hydraulic mining technique of hushing was the key anthropogenic sediment production process within the study area and dominated waste sediment output, with ~4.6 × 10^6 t (64 %) of sediment mobilised through hushing but only ~2.56 × 10^6 t (36 %) originating from subterranean mining (Fig. 11). This reflects both the widespread use of hushing within the North Pennines prior to the 1840s, but also the relative inefficiency of the hushing process. In contrast to targeted subterranean mining, in which ore bodies were accessed via relatively narrow shafts or adits (tunnels), hushing involved the removal of all overburden sediments and overlying rock adjacent to the mineral veins. As with other comparable forms of surficial mining, such as placer mining in the US (James et al., 2019, 2022) and hydraulic sluicing in Australia (Davies and Lawrence, 2019; Davies et al., 2018), this inefficiency resulted in a massive scale of historic landscape disturbance. This environmental impact is reflected in the amount of waste sediment mobilised by hushing within the study area and the scale of the hushing-related landforms that are still widespread within the landscape (Figs. 9–10), but also historic accounts documenting extensive damage to land and agriculture as a result of the hushing process (Bainbridge, 1856).

Storage of material in sediment fans at the outlet of the hush channels is minimal in comparison to the scale of sediment estimated to have been mobilised by the hushing process (Fig. 10), with hush fans representing only ~0.5 % of the total volume originating from the mapped hushes (Fig. 11). This indicates that as well as being the dominant anthropogenic sediment production process, hushes were responsible for the majority of sediment delivery to the river systems, and therefore also probably for much of the mining-related downstream channel changes observed in studies of the planform evolution of the major rivers in the North Pennines (e.g., Macklin, 1997).

One key outstanding question relating to hushing is the degree to which hush landforms were solely created through anthropogenic mining activities, with a recent analysis of the extremely large hushes at Coldberry Gutter and Pike Law, located in Teesdale but outside of the present study area, suggesting a more complex origin related to both natural and anthropogenic processes (Evans and Young, 2022). Arguments put forward to support this include that the erosive power of water released from dams at the top of the hushes would have been insufficient to generate a gully of this size, and that the fans at the base of the hushes are too small to contain all the material evacuated from the hush channels (Evans and Young, 2022). In certain cases, it is likely that there were natural geomorphic landforms present in the location of later anthropogenic hushes and that the present landscape represents a combination of both of these sets of processes.

However, there are also compelling process-based reasons for characterising hushes as overwhelmingly anthropogenic landforms, at least in relation to those considered within the present study area. The lack of substantial fan deposits at the outlets of the hush channels in the study area likely relates to a combination of the direct physical coupling between the hushes and the main river channels, meaning that the sediment transported out of the hushes was highly connected to the rivers, and the mechanism by which the hushing process was conducted (Fig. 10). Rather than being a catastrophic process in which impounded water was released to generate a gully above a mineral vein during a single erosive event, hushing was instead likely to be an iterative process involving repeated manual excavation of surface material followed by the periodic, deliberate use of water as an anthropogenically controlled erosional agent (Cranstone, 1992). The ore material would have been trapped in a grate at the base of the hush and processed close to the site. This method would preclude extensive fan development, due to the repeated release of water and deliberate connectivity with the downslope stream network. Where hush fans are present in the modern landscape, these will also at least in part be due to post-mining erosion of the hush gully, rather than being entirely mining age landforms. Given their significance, clarifying the origins, dating, and underlying formation processes responsible for hushes should therefore be a priority for future research.

In contrast to hushing, the volume of sediment stored within extant depositional landforms in the contemporary landscape (i.e., spoil heaps, dressing waste) represents ~92 % of the total waste sediment estimated to have been mobilised through subterranean mining (Table 1). The significance of these landforms from a geomorphological perspective is that they essentially act as anthropogenically-constructed sediment storage landforms, removing mine sediments from the broader sediment transfer system and at least temporarily preventing their connection to the river network. In broad terms our results therefore suggest that the sediment delivery ratio for historic mining was very low and landscape storage of mobilised sediment was effective. However, there is considerable spatial variability in the production:storage residuals between each catchment, indicating that ore outputs and therefore also waste sediment totals may be considerably underestimated; a point that will be considered in more detail below.

5.2. *Uncertainties associated with the sediment volume estimates*

Constructing sediment budgets using historical data is particularly challenging given the variety of uncertainties associated with the completeness and accuracy of the often disparate sources of information required. In many cases, these issues mean that a formal error analysis of all terms in the historical sediment budget is simply not possible (Downs et al., 2018). Previous attempts to reconstruct historical anthropogenic sediment production using documentary sources have, by necessity, therefore presented approximate sediment volumes without any quantitative error estimates (Davies et al., 2018; Davies et al., 2020). Even in cases where sediment volumes have been measured directly using digital terrain analysis, quantitative uncertainties are often omitted from budget calculations (Dethier et al., 2018; Riley et al., 2020). This is generally due to unresolved issues such as a lack of information about pre-mining topography and a recognition that noise associated with measurement error is likely to be minimal when compared to the magnitude of the actual legacy sediment volumes being considered (James et al., 2019). In studies which do attempt to quantify error associated with historical sediment dynamics this is typically restricted to only certain aspects of the sediment budget terms, such as the precision and accuracy of landform mapping (Royall and Kennedy, 2016).

For this study, when the total waste sediment storage estimates are compared with the total estimated waste production based on the ore output and hush data, the scale of mine waste that is unaccounted for (the residual) can be calculated through subtraction. The error terms that could be quantified for each step in these budget calculations are reported in detail in Table S3. The largest uncertainties associated with this present study are almost certainly due to underestimation of mine outputs from the earlier part of the time series, especially prior to the introduction of government mineral statistics in 1845. This relates to both earlier unrecorded production from the mines which are included within the ore output time series, as well as output from those which are named but for which no production records could be located.

An additional unquantified factor relates to the potential secondary usage of mine wastes, for example through later reprocessing of waste heaps to extract remaining metals or to provide aggregate material for road construction. Reprocessing for metal extraction is known to have occurred in particular locations in the North Pennines (e.g., Dawson, 1947), but there are no consistent data available to quantify this at scale. Similarly, mine wastes can provide a useful source of road construction material (Mitchell et al., 2024; Segui et al., 2023), and there are individual accounts of waste material being used for this purpose within other historic metal mining areas across the UK (Mills et al., 2014; Riley et al., 2020). However, there are no reliable data available to allow the meaningful quantification of this post-mining reuse of waste deposits across the entire study area, and given the limited scale of these practices any errors associated with this element of the sediment budget are expected to be negligible in comparison to those associated with underestimation of early mine outputs.

In line with other similar studies of historical sediment dynamics, the lack of quantitative error information for several key elements of the sediment budget precludes any attempts to propagate errors through into the final residual calculations in a meaningful way (Davies et al., 2018; Dethier et al., 2018; James et al., 2019). It is also important to note that since the budget is based on historical anthropogenic processes, the residual term is calculated via subtraction rather than directly measured. Although unmeasured residuals in sediment budgets can hide a multitude of errors associated with measured components (Kondolf and Matthews, 1991), this is deemed necessary given the nature of the historical input data (James et al., 2019).

5.3. *Spatial and temporal variability in mining impacts*

Pronounced spatial variability in the intensity of historic mining and related estimates of waste sediment release is apparent within the study area at multiple scales of analysis. Importantly, this spatial variability also extends to the residual between the estimated amount of waste sediment mobilised by mining and the amount that still resides within the landscape. At a catchment scale, the River Nent is the smallest catchment but is the most highly impacted in terms of density of mine sites and landforms, documented ore outputs, the scale of hushing, and the magnitude of estimated waste sediment mobilisation (Figs. 2, 6–8; Tables S4-S5). In contrast, the Black Burn catchment had the lowest density of named mines but the second highest recorded ore output, indicating high output from a small number of workings at specific locations within the catchment. In particular, Rotherhope Mine, located immediately adjacent to the main Black Burn channel and just upstream of the confluence with the South Tyne, was amongst the highest producing mines within the entire study area. This emphasises the importance of identifying specific individual sediment source locations within a catchment and their connections to the wider fluvial system, and again highlights the limitations of relying on aggregated ore output statistics as a proxy for legacy mine impacts.

A considerable proportion of the total estimated amount of sediment mobilised by mining is still present within the landscape in the form of storage landforms for the Black Burn (85 %), South Tyne (49 %) and Tees (41 %) catchments (Table 1). However, we also find that storage totals within the Nent catchment are actually 54 % higher than the amount of waste sediment estimated to have been mobilised by subterranean mining in that area. This relates to a range of factors that demonstrate the complexities of reconstructing past sediment fluxes from partial historical datasets (Davies et al., 2018). One key factor is the incompleteness of historical ore production records, with actual production and therefore waste sediment mobilisation within the Nent likely to have been far higher than surviving records suggest, meaning that the ratio of sediment storage to mobilisation total is overestimated. Much of the documented ore output that is known to come from the study area, but which could not be directly linked to a specific location (Fig. 6), is therefore likely to have come from mines within the Nent catchment. One implication of this is that our estimates of the magnitude of historic mining, and its associated waste sediment mobilisation, probably represent a considerable underestimate of the actual scale of landscape impacts, which in turn is linked to temporal variability in the completeness of mining records.

From a temporal perspective, lead mining undoubtedly reached its peak within the North Pennine area of the UK during the 18th – 20th centuries (Fig. 6). However, we also know that metal mining had already been an important industry within this area for centuries, if not millennia, before this time (Oakey et al., 2012). This is typical of other mining catchments globally, with increasing evidence for much longer timescales of metal mining and associated geomorphic disturbance than just the recent peak periods of production (Fernández-Lozano et al., 2020; Silva-Sánchez and Armada, 2023). One key finding from this study is that the main period of river disturbance within the North Pennines region is likely to have been pre-1840, and linked to the widespread practice of hushing, rather than the later peak of mine production associated with the documented ore output statistics used in most reconstructions of fluvial impacts and channel evolution in the area (Fig. 6). Hushing was banned in the region in the 1840s (Fairbairn, 1992), but we also know from other UK orefields that the practice of hushing was carried out for centuries earlier (Timberlake, 2004). Therefore, to fully understand channel response to historic legacy sediment inputs there is a pressing need to better constrain the dating of hush landforms, clarify the degree to which hushes were formed within pre-existing post-glacial landforms (e.g., Evans and Young, 2022), and reconstruct rates of post-abandonment erosion of the hush channel and outwash fans.

Even within the time series of later mine production records there are considerable temporal fluctuations that have important implications for the timing and location of sediment production and delivery to river channels (Fig. 6). Crucially, the geomorphic impact of historic mining on river channels is not simply dependent on the total amount of waste sediment produced within a catchment area, but also on the specific locations producing this sediment and the timing of this production (Trimble, 2012). For example, total ore output during the early decades of the 20th century remained relatively high, but this output only came from six mine locations within the entire study area (Figs. 7–8). In contrast, earlier decades saw comparable total ore output but from numerous operational sites distributed across the landscape.

Accurate reconstruction of historical geomorphic impacts therefore needs to consider where mining was taking place at different points in time, but also the nature and scale of mining operations at each location. Unregulated historic metal mines are generally known to have widespread impacts in terms of contaminant release (Macklin et al., 2023), but the degree to which an individual mine will generate contaminants will vary based on the specific ore processing and waste disposal techniques utilised (Lidman et al., 2023). For example, an unproductive mine would have minimal localised processing operations and could therefore generate high volumes of waste sediment but relatively limited local contamination. In contrast, a mine acting as a centralised processing or smelting site for the wider region could have low documented ore output but extensive local contamination issues. As such, previous studies that rely solely on either ore output statistics or the spatial distribution of mine sites overlook the complexity involved in mining operations and their associated environmental impacts, which has implications for both reconstructions of waste sediment volumes and associated contaminant issues (Fischer et al., 2020).

Another fundamental factor linked to the geomorphic impacts of mine sediments is the occurrence of storm events of a sufficient magnitude to mobilise sediment from temporary storage, transfer it from source locations to river channels, and transport the sediments through the fluvial system. Our time series of waste sediment outputs therefore provides a measure of changing sediment supply, but storms act as the key triggers of the episodic channel change recorded in studies of the river systems in the area (Rumsby and Macklin, 1994). Regional flood chronologies for Northern England show a number of multi-decadal periods of more frequent flooding that are coincident with increased mining activity within our time series, most notably during the late 18th century when hushing was prevalent, the mid-to-late 19th century when documented ore output peaked, and during the first half of the 20th century when production was still high but becoming increasingly centralised at fewer mine locations (Archer and Fowler, 2021; Macklin and Rumsby, 2007; Schillereff et al., 2019) (Figs. 7–8). Importantly, our results show that prior to the cessation of hushing in the 1840s, most of the sediment supply was dominated by direct linkages between mining landforms (primarily hushes) and the river channels, so the primary impact of storm events would have been on the transport of sediment through the river system. After 1840, the supply of mine sediments to rivers became less directly connected, with storms then acting as one of the key mechanisms by which legacy sediments were transported from source locations to the river channels. Future work should look to directly compare these flood chronologies with high spatial and temporal resolution records of mining activity and sediment production, such as the one described here, to help better understand the pattern and timing of river channel response.

5.4. Long-term post-mining legacy implications

It is important to recognise that mining landforms and sediment source locations are not static following their initial construction or deposition. Instead, abandoned historical metal mines often represent persistent long-term sediment source locations, typically with elevated erosion rates relative to comparable unmined catchments (Tarolli and Sofia, 2016; Toy and Hadley, 1987). This reworking and redistribution of mine waste sediments also has major implications for the dispersal of metal contaminants within impacted river catchments, with well-documented and widespread consequences for water quality, sediment geochemistry and ecological functioning (Lidman et al., 2023; Onnis et al., 2023).

Quantifying the significance of the magnitude of post-abandonment erosion relative to mining-age sediment production is complicated by a lack of extensive field data on contemporary erosion rates. However, an approximation can be made by extrapolation of recorded erosion rates from Garrigill Burn, a tributary catchment within the South Tyne for which high resolution monitoring data are available (Kincey et al., 2018). Upscaling the erosion rates from mines within this catchment to all mapped mine locations across the entire study area provides a total annual erosion rate of approximately 28,446 t a^{-1}. Over a 100-year period, this erosion rate equates to a post-abandonment sediment flux equivalent to ~59 % of the total waste sediment produced during the overall 1700–1948 period of mining. Projecting this forward, within the next ~70 years the amount of sediment eroded from abandoned metal mines within the study area is expected to be equivalent to the total amount of waste sediment produced by the mining operations themselves.

Within this overall estimate is again considerable spatial variability, with the Nent and South Tyne catchments expected to take another ~80 years before the amount of post-abandonment erosion is equivalent to the waste sediment production, but the Upper Tees taking considerably longer at ~150 years. In contrast, in the Black Burn catchment sediment production through post-abandonment erosion of mining remains is estimated to have exceeded sediment production from historical mining operations ~50 years ago.

These values of course contain numerous assumptions and over-simplifications regarding variability in erosion rates in both space and time, and the absolute timescales are undoubtedly imprecise. For example, studies utilising landscape evolution modelling of post-mining landforms have shown that specific erosion rates vary spatially due to differences in initial landform surface conditions (Hancock et al., 2016), and that post-mining erosion rates tend to decrease through time due to stabilising surface processes, such as armouring of exposed sediments (Hancock and Willgoose, 2021; Welivitiya et al., 2021). However, despite these assumptions, both field- and modelling-based studies do indicate that erosion rates on post-mining landforms are consistently higher than those on pre-mining or un-mined surfaces (e.g., Lowry et al., 2019; Toy and Hadley, 1987). In addition, the field measurements used here were captured between 2012 and 2014 (Kincey et al., 2018), so represent erosion occurring ~100 years after the mining had ceased, suggesting that any notable decline in erosion rates is ongoing and is still significantly above background (unmined) levels. As a result, even allowing for the considerable uncertainties associated with this level of spatial and temporal extrapolation of erosion rates, the results do indicate that although the historic mining operations themselves were a considerable source of waste sediments, they also caused extensive disturbance that generated a long-term legacy of enhanced erosion and sediment supply within affected catchments.

Globally, approximately 349 million t of lead and 713 million t of zinc were extracted prior to the late twentieth century (Singer, 1995). A large proportion of this historical extraction occurred through poorly regulated mining operations, like those outlined in this present study (Nriagu, 1996; Price et al., 2011), resulting in a globally significant impact on river systems and floodplain environments in particular (Macklin et al., 2023). This interdisciplinary study has demonstrated that reasonable quantitative estimates of the geomorphic impacts of historical mining can be reconstructed, even in situations involving a complex range of mining techniques and only partially complete historical records. Applying this interdisciplinary approach to other major orefields globally will significantly enhance our understanding of past human-environment interactions and the timing of geomorphic responses to anthropogenic landscape disturbance.

6. Conclusions

This study has quantified anthropogenic sediment production and storage from historical metal mining, providing new insights into variability in the magnitude of landscape disturbance and sediment inputs to rivers, and the persistence of legacy sediments within the impacted catchments. We draw the following key conclusions from our analysis:

- Waste sediments represent ~85 % of the total mass estimated to have been excavated through metal mining between 1700 and 1948. The majority of this waste sediment mobilised by mining (67 %) is not accounted for by extant sediment storage landforms within the catchments, indicating that ~4.8×10^6 t of waste sediments has reached the river systems since 1700.
- The surficial mining technique of hushing was the key anthropogenic sediment production process, accounting for 64 % of all mining-related waste sediment. Local storage of hushed sediment in outwash fans was minimal (<1 %), reflecting the high degree of connectivity between hushes and river channels.
- In contrast, ~92 % of waste sediment generated through subterranean mining is estimated to be stored within extant depositional landforms, such as spoil heaps. However, there is considerable spatial variability in the ratio of production to storage between catchments, and it is likely that both ore outputs and waste sediment totals are underestimated.
- Ore output records by themselves represent a relatively poor predictor of legacy sediment totals, typically as a result of incomplete production records and the significant impacts coming from unproductive mining operations. These records also do not generally include output from earlier opencast mine workings (e.g., hushes), or the amount of waste material stored in surface landforms (e.g., spoil heaps), meaning that they omit key elements of geomorphic significance.
- Spatial and temporal variability in mining operations had a significant impact on the timing, nature, and scale of associated impacts on the environment. The main period of river disturbance in this region is likely to have been pre-1840 when hushing was widespread within the mining industry. In contrast, in the early 20th century, total mine ore outputs were high, but this production came from a very limited number of locations, meaning that geomorphic impacts were also more spatially focused.
- Future work should look to expand upon this interdisciplinary approach to understanding mining-impacted landscapes, for example by refining our understanding of hushing as an anthropogenic process capable of fundamentally altering upland landscapes, and by more directly linking the time series of sediment production described here to flood and channel change chronologies.

CRediT authorship contribution statement

Mark Kincey: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jeff Warburton:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109518.

Data availability

The list of named mines, their locations and time series of lead ore outputs have been made available as a downloadable Excel file as part of the supplementary material accompanying this paper. The National Mapping Programme (NMP) aerial survey mapping data from the Miner-Farmer project are copyright Historic England, but the spatial data from the aerial mapping are freely available for both online viewing (link), and data download (link). More information on the National Mapping Programme (NMP) is available via their website (link). The lidar data obtained by the NERC Airborne Research Facility (ARF) are freely available from the Center for Environmental Data Analysis (CEDA) (link).

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