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Contaminated sediment flux from eroding abandoned historical metal mines: Spatial and temporal variability in geomorphological drivers

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ABSTRACT

Abandoned historical metal mines represent significant long-term sediment source locations contributing highly contaminated anthropogenic legacy sediments to river systems. Despite this, our understanding of spatial and temporal variability in the rates and geomorphological drivers of specific contaminated sediment source locations across abandoned mines remains poorly constrained. In this study, sediment flux from two abandoned historical lead mines in the North Pennines, UK, was monitored over an 18 month period using repeat terrestrial laser scanning, enabling the spatial and temporal significance of several common geomorphological processes to be quantified for the first time. A novel contaminated sediment budget approach is used to integrate topographical change data with a pXRF survey of surface sediment metal concentrations. Approximately 434 t (289 t a^{-1}) of eroded sediment entered the stream from a source area of 0.023 km^2. The majority of the erosion was driven by two dominant processes, with gullying accounting for 60% and bank erosion contributing 30%. Redeposition of eroded material within the survey area was minimal (3%), indicating very high levels of coupling between source locations and the stream network and the export of the vast majority of eroded sediments (97%) from the mined area. Rates for all erosive processes were highly episodic and primarily driven by high magnitude, low frequency storm events. Metal concentrations in surface sediments exhibited considerable spatial variability, with notable hotspots around the former ore processing areas and on the tailings heaps. However, 84% of all sediments sampled were in excess of available soil guideline values for Pb and 65% in excess of equivalent guideline values for Zn, indicating that abandoned mine sites still have the potential to be significant sources of contaminant metals and pose a risk to the wider environment. In total, an estimated 4.59 t of Pb and 2.14 t of Zn entered the stream network in a sediment-associated form during the 18 month monitoring period. Although these overall contaminated sediment inputs are high, they are restricted to particular geomorphological processes, are spatially variable in terms of the magnitude of specific source locations, and are delivered in fairly discrete events. This provides invaluable information for the future management of other abandoned mines and targeted mitigation of their potential legacy effects.

1. Introduction

River catchments impacted by historical metal mining are often highly contaminated, leading to a significant and persistent legacy affecting sediment and water quality (Macklin et al., 2006; Mayes et al., 2010; Luís et al., 2011). Studies worldwide have demonstrated that fluvial systems in former mining areas are frequently still adjusting to historical disturbances related to the influx of large volumes of mine waste (Knighton, 1989; Singer et al., 2013) and typically still contain abnormally high levels of metals at abandoned mine source locations and stored in catchment wide floodplain sediments (Clement et al., 2017; Pavlowsky et al., 2017). In a European context, the Water Framework Directive (WFD) has established clear ecological and chemical water quality target guidelines that have included consideration of pollution caused by abandoned mining operations (European Commission, 2000). However, the focus of such schemes has primarily been on monitoring point source contaminant flux, such as waters draining directly out of mine adits. In contrast, regulatory attention given to more diffuse sources of pollution, and in particular sediment-borne contaminants, has until recently been lacking (Macklin et al., 2006). This is despite the recognition that ~90% of metal contaminants in former mining catchments are commonly sediment-associated rather than in an aqueous form (Hudson-Edwards et al., 2008).

The issue of defining contaminant sources within river catchments as either point or diffuse is dependent on the scale of investigation. For example, at the scale of an entire catchment, abandoned mines

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would typically be considered as point source locations for contaminated sediments. However, within the context of an individual mine the precise locations of the pollutant inputs will vary spatially owing to the arrangement of former mine workings (levels, waste heaps, etc.), the physical characteristics of the land surface and the distribution of processes driving topographic change. Unlike point sources, such as adit outflows, the spatial location of these sediment sources also changes through time as the condition and stability of the surface is altered and the dominance of different geomorphological processes varies. This spatial and temporal variation means that, at least at the intrasite scale, contaminated sediment inputs are therefore more accurately defined as dispersed in nature rather than as discrete point sources. These dispersed sources share a number of characteristics with more 'classic' diffuse sources (e.g., floodplain deposits), including spatial and temporal variability in metal concentrations and the potential for reworking and redistribution of contaminated sediments (Hudson-Edwards et al., 2008).

The hydrological conditions under which point and diffuse contaminant sources dominate are characteristically different. Although point source mine water discharges dominate stream metal loadings during low flows, diffuse inputs are particularly significant during high flow events, when metal-rich sediments are susceptible to entrainment and transport (Mayes et al., 2008; Byrne et al., 2013; Foulds et al., 2014). Diffuse contamination from mining includes direct input of polluted groundwater to surface waters via the hyporheic zone, runoff from mine wastes, and mobilisation of metal-rich floodplain sediments (Dennis et al., 2009; Palumbo-Roe et al., 2012). Owing to their diffuse nature, quantifying such inputs can be problematic, with most studies estimating diffuse source contributions using the residual from mass balance calculations based on measured point source water inputs and stream loadings (Mayes et al., 2008; Mighanetara et al., 2009; Banks and Palumbo-Roe, 2010). Such approaches provide useful approximations of the scale and general location of diffuse inputs but specific details on metal delivery mechanisms to fluvial environments are usually only inferred, limiting their value to practitioners involved in the management or remediation of formerly mined catchments.

The two main sources of diffuse sediment (particulate) contaminants are direct erosion and entrainment of in situ metal-rich mine sediments (e.g., waste heaps) and the remobilisation of previously deposited channel or floodplain sediments (Gozzard et al., 2011). The long-term wider catchment-scale remobilisation and redistribution of mine sediments has received considerable attention by the scientific community for several decades (Lewin et al., 1977; Miller, 1997; Dennis et al., 2003; Clement et al., 2017). Underpinning much of this research has been the recognition that understanding the fluvial geomorphology of a catchment is fundamental to being able to predict the distribution, magnitude, and residence time of associated metal contamination (Brewer et al., 2003; Macklin et al., 2006; Hudson-Edwards et al., 2008; Dennis et al., 2009). In contrast, comparable recent research into the initial mobilisation of in situ sediments directly from abandoned mine source locations has been noticeably lacking despite its significance for a range of other related disciplines such as archaeology (Kincey et al., 2017) and ecology (Batty, 2005).

The importance of in situ mine waste deposits as source locations for contaminated sediments is reflected in policy documents at national (Environment Agency, 2007) and European levels (e.g., the EU Mine Waste Directive, European Commission, 2006). Internationally, even in countries where solid mining waste is not a specifically regulated waste, such as the United States, research into the appropriate management of legacy mine sites is still seen as a central priority (ITRC (Interstate Technology and Regulatory Council), 2008). However, actually translating knowledge of mine waste site locations and characteristics into an understanding of specific sediment contaminant sources is problematic. In the UK, a recent national assessment of metal mine pollution focused primarily on water quality data, with associated information regarding diffuse sediment contaminants being largely qualitative in nature (Mayes et al., 2009). Where comparable national assessments of sediment-related diffuse pollution have been attempted, these have by necessity been restricted to the use of a relatively simplistic classification of risk based on the mapping of waste deposits and broad topographic characteristics (Turner et al., 2011; Mayes et al., 2015). Local site-scale appraisals of diffuse inputs of contaminated sediments have been undertaken (Forth, 1999), but these have generally tended to either involve qualitative descriptions of visually identified sediment transfer processes (Wray, 1998) or to focus on large-scale catastrophic events, such as tailings dam failures (Macklin et al., 2003; Kossoff et al., 2014). However, the baseline understanding generated through such local-scale assessments is fundamental to being able to develop a comprehensive and accurate understanding of the drivers of surface change and contaminated sediment flux at abandoned mines. Without this detailed process-based knowledge, the validity of broader regional or national assessments cannot be properly evaluated and our ability to introduce effective management schemes or policies remains restricted.

Although not primarily focused on contaminant flux, numerous studies have attempted to quantify erosion rates in historically mined areas, often driven by debates surrounding the most effective method for reclaiming land disturbed by recent (late twentieth century) surface mining activities (Soulliere and Toy, 1986; Toy and Hadley, 1987). Such research has indicated that erosion and sediment transfer rates are significantly higher in former mining landscapes than in comparable unmined areas (Lusby and Toy, 1976; Tarolli and Sofia, 2016). This situation is exacerbated even further in former metal mining areas, where the phytotoxic nature of heavily contaminated mine sediments reduces the capacity for vegetation cover resulting in highly unstable surface deposits (Ostrander and Clark, 1991). Previous studies of erosion at abandoned mines have, however, tended to focus on either the role of individual geomorphic processes (Haigh, 1980; Davies and White, 1981; Esling and Drake, 1988) or particular landform characteristics (Nyssen and Vermeersch, 2010; Martín-Moreno et al., 2013), meaning that our ability to fully understand the relative contribution of the wide range of interrelated factors influencing erosion rates is still limited.

This current study integrates repeat terrestrial laser scanning (TLS) and portable X-Ray Fluorescence (pXRF) survey to quantify contaminated sediment flux at Whitesike and Bentyfield mines, two adjacent abandoned lead mines located along Garrigill Burn, a tributary of the South Tyne in the North Pennine uplands, Cumbria, UK. The novel sediment budget approach, based on high resolution quantification of surface change and sediment contamination, demonstrates a rigorous methodology for investigating abandoned mines and provides valuable insights into the processes determining rates of contaminant flux in heavily disturbed landscapes. The study site represents an ideal case study for assessing the significance of contaminated sediment flux in former metal mining districts worldwide. Significant documented erosion and water quality issues sit awkwardly alongside the diverse and sometimes competing designation priorities of administrative bodies responsible for the preservation of the natural and cultural heritage environments. This range of challenges and pressures are characteristic of the complex multifaceted and interdisciplinary nature of abandoned mines, making the key findings from the study transferable to the management of other former mining landscapes worldwide.

2. Study site

Whitesike and Bentyfield mines are a pair of adjacent historical lead mines located ~5 km southeast of Alston, Cumbria, UK (54°46′36.48″ N, 2°23′07.84 W) (Fig. 1). The mines occupy a small (3.51 km^2), steep catchment in the middle reaches of Garrigill Burn, an east-west flowing tributary of the upper South Tyne. Catchment elevations range from 330 m AOD at the confluence with the South Tyne to 614 m AOD at the watershed with the Nent catchment on Flinty Fell, with an overall channel gradient approaching 9%. The steep, narrow valley and mining